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Chapter

OAM Modes in Optical Fibers for Next Generation Space Division Multiplexing (SDM) Systems

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Abstract

Due to the renewed demand on data bandwidth imposed by the upcoming capacity crunch, optical communication (research and industry) community has oriented their effort to space division multiplexing (SDM) and particularly to mode division multiplexing (MDM). This is based on separate/independent and orthogonal spatial modes of optical fiber as data carriers along optical fiber. Orbital Angular Momentum (OAM) is one of the variants of MDM that showed promising features including the efficient enhancement of capacity transmission from Tbit to Pbit and substantial improvement of spectral efficiency up to hundreds (bs⁻¹ Hz⁻¹). In this chapter, we review the potentials of harnessing SDM as a promising solution for next generation global communications systems. We focus on different SDM approaches and we address specifically the MDM (different modes in optical fiber). Finally, we highlight the recent main works and achievements that have been conducted (in last decade) in OAM-MDM over optical fibers. We focus on main R&D activities incorporating specialty fibers that have been proposed, designed and demonstrating in order to handle appropriates OAM modes.

Keywords: Space Division Multiplexing (SDM), Mode Division Multiplexing (MDM), Orbital Angular Momentum (OAM), Specialty optical fibers

1. Introduction

Bandwidth-hungry applications and services, such as HDTV, big data, quantum computing, 5G/6G communication, industry 4.0 and game streaming, in addition to the exponential increase of users and connected devices (Internet of Things: IOT), may cause a capacity crunch in near future [1–3]. While other physical limitations behind the capacity crunch are based on the nonlinear Shannon limit and the scalability of actually deployed devices. The cited emerging applications (i.e. paradigms) has pushed telecommunications community (researchers & industries) to grow through multiple stages by developing higher capacity optical networks in optical fiber based links targeting to deal with the evolution of the market need for telecoms and Internet data services and paving the road to surpass the upcoming capacity limit challenges [4].

Recently, the capacity and the spectral efficiency of optical fibers have been substantially improved (i.e. scaling by several orders of magnitude) by using different multiplexing techniques and advanced optical modulation formats. These multiplexing techniques are based on the exploitation of degrees of freedom of the optical signal to encode data information. The time, as time division multiplexing (TDM: interleaving channels temporally), the polarization, Polarization division multiplexing (PDM), the wavelength, as wavelength division multiplexing (WDM: using multiple wavelength channels) and the phase (quadrature) are examples of such techniques [5].

Research and industrial community had recently oriented their effort towards Space Division Multiplexing (SDM) techniques that is based on the exploitation of the spatial structure of the light or the physical transmission medium to encode information. Simply, SDM consists of increasing the number of data channels available inside an optical fiber. Two attractive embodiments of SDM are core division multiplexing (CDM) and mode division multiplexing (MDM) [6]. CDM is simply considered as the increasing of parallel single mode cores, carrying information, embedded in the same cladding of optical fiber (known as multicore fiber MCF) or single core fibers bundles [7]. Mode division multiplexing (MDM) is based on excitation and propagation of several spatial optical modes as individual/separate/independent data channels within common physical transmission medium targeting to boost the capacity transmission [8]. MDM is realized by multimode fibers generally over short haul interconnect transmission or few mode fibers as transmission medium for long haul transmission link. Numerous mode basis have been used for mode division multiplexing showing its effectiveness to scale up from Terabit to Petabit the capacity transmission and unleash from dozen to hundred (bit/s/Hz) the spectral efficiency over optical fiber.

It is well known that light can carry Angular Momentum (AM) that expresses the amount of dynamical rotation present in the electromagnetic field representing the light. The AM of light beam is divided into two distinct forms of rotation: Spin Angular Momentum (SAM) and Orbital Angular Momentum (OAM) [9]. The SAM is related to the polarization of light (e.g. right or left in circular polarization) while the OAM is related to the spiral phase front of exp. ($jl\phi$) where l is a topological charge number (arbitrary unlimited integer), and ϕ is the azimuthal angle. Orbital angular momentum (OAM) of light, (known as twisted light), an additional degree of freedom, is arguably one of the most promising approaches that has recently deserved a special attention in optical fiber networks. Benefiting from two inherent features, which are:

(1) The orthogonality: where as a definition two signals are orthogonal, if data sent in these two dimensions can be uniquely separated from one another at the receiver without affecting each other's detection performance. Two OAM modes with different charge number 1 do not interfere.

(2) The unlimitleness: the charge number l is theoretically infinite. Hence, Each OAM mode (each specifically l) is an independent data channels. OAM modes has been harnessed in multiplexing/de-multiplexing (OAM-MDM) or in increasing the overall optical channel capacity [10, 11].

As any promising technology, OAM-MDM through optical fibers is facing several key challenges, and lots crucial issues that it is of great importance to handle with it in order to truly realize the full potential of this technique and to paving the road to a robust transmission operation with raised performances in future communication systems.

In strict sense 'Mode division multiplexing', means that the modes (channels) are separate and should remain uncoupled and not interfere with each other (i.e. orthogonal). Hence, mode coupling (e.g. channels crosstalk) is the major obstacle for OAM-MDM. Channels crosstalk is obviated by either fiber design or multiple input multiple output digital signal processing (MIMO DSP) [9–11].

By carefully manipulating the fiber design parameters, it is possible to supervise the interactions between propagated modes and even control which modal basis is

incorporated: LP-fibers where the separation between vector modes are inferior to $1 \times 10-4$, or OAM-fibers where the intermodal separation exceeds $1 \times 10-4$, since either LP or OAM modes are constructed from fiber eigenmodes themselves [9]. This better facilitates understanding each fiber parameter impact and smooth the way of transition from design stage to fabrication process. Adding to that, exploit MIMO DSP is considered as the extreme choice to decipher channels at the receiving stage since it is heavy and complex. Its complexity is came from its direct proportionality to the transmission distance and to the number of modes. This allow it to become impractical in real time and threats the scalability of MDM in next generation optical communication system. For OAM-MDM systems using optical fibers, the fiber design stage is considered as the most crucial part and there is still a lot of opportunities for improved designs. New fiber designs for OAM mode transmission over short/medium and longer distances or among higher number of modes or possess a high performance metrics have been proposed and examined.

With the different related key challenges, this chapter offers a review of the state-of-the-art of SDM advances especially on OAM-MDM over optical fibers. In the first section, we discuss the SDM approaches as a solution to the expected capacity limit. The different mode basis supported in optical fibers are presented and discussed as either cylindrical vector modes, LP modes or OAM modes. The second section acts as a survey on recent advances (over last ten years) in OAM-MDM over optical fibers. We review the research effort invested in harnessing OAM as a degree of freedom to carry data in optical fiber networks. We summarized the key obtained results in the main family of optical fibers (i.e. conventional fibers and OAM specialty fibers) using OAM modes.

2. SDM over optical fibers

Space division multiplexing (SDM) has attracted high interest. It has revealed multiple directions of exploration and development. SDM consists of exploiting space-independent communication channels in both guided waves (e.g. optical fibers) or free space optical link (FSO). The channels' type vary depending in which factor of SDM we are exploiting; diversified cores, multiplexed LP modes or modes carrying OAM, multiple cores each supporting few multiplexed LP modes and so on.

Two main subset in SDM could be explored: core division multiplexing (CDM) where information is transmitted through cores (or fibers) of multicore fibers or mode division multiplexing (MDM), where information is transmitted through propagating modes of few or multimode fibers.

2.1 Core division multiplexing (CDM)

In principle, two main schemes are used. The first is based on the use of Singlecore Fiber bundle (i.e. fiber ribbon) where parallels single mode fibers are packed together creating a fiber bundle or ribbon cable. The overall diameter of these bundles varies from around 10 mm to 27 mm. Fiber bundles deliver up to hundreds of parallel links. Fiber bundles have been commercially available [12, 13] and deployed in current optical infrastructure for several years already. Fiber bundles are also commercially used in conjunction with several SDM transceiver technologies [14].

The second scheme is based on carrying data on single cores (each core supports single mode) embedded in the same fiber known as Multicore Fibers (MCFs). Hence, each core is considered as an independent single channel (**Figure 1**).



The most important constraint in MCFs is the inter-core crosstalk (XT) caused by signal power leakage from core to its adjacent cores that is controlled by core pitch (distance between adjacent cores denoted usually as Λ) [15]. There are in Principle, two main categories of MCF: weakly coupled MCFs (=uncoupled MCF) and strongly coupled MCFs (=coupled MCF) depending on the value of a coupling coefficient 'K' (used to characterize the intercore crosstalk) [16–18]. Using the so-called supermodes to carry data, the crosstalk in coupled MCF must be mitigated by complex digital signal processing algorithms, such as multiple-input multiple-output digital signal processing (MIMO-DSP) techniques [19]. On the contrary, due to low XT in uncoupled MCF, it is not necessary to mitigate the XT impacts via complex MIMO. In principle, three crosstalk suppression schemes in uncoupled MCF could be incorporated, which are trench-assisted structure, heterogeneous core arrangement, and propagation-direction interleaving (PDI) technique [7].

The first paper on communication using MCF demonstrate a transmission of 112-Tb/s over 76.8 km in a 7-cores fiber using SDM and dense WDM in the C + L ITU-T bands. The spectral efficiency was of 14 b/s/Hz [20]. The second paper [21] shows an ultra-low crosstalk level (≤ -55 dB over 17.6 km), which presents the lowest crosstalk between neighboring cores value to date. Other reported works, show high capacity (1.01Pb/s) [22] over 52 km single span of 12- core MCF. In [23], over 7326 km, a record of 140.7 Tb/s capacity are reached.

2.2 Mode division multiplexing (MDM)

Carrying data on optical fiber modes known as mode division multiplexing. In that scenario, each propagating mode is considered as independent channel [5, 24]. Two types of fiber are dedicated to support that strategy. One is based on the use of multimode fibers (MMF) while the second exploits the known few-mode fibers (FMF). The main difference between both is the number of modes (available channels). Since MMF can support large number of modes (tens), the intermodal crosstalk becomes large as well as the differential mode group delay (DMGD), where each mode has its own velocity, reducing the number of propagating modes along the fiber becomes viable solution. This supports FMF as a viable candidate for realizing SDM [5]. The concept of mode division multiplexing over a few/multimode fiber is illustrated in **Figure 2**.

Other kinds of optical fiber that can be used in MDM such as photonic crystal fibers (PCFs). Based on the properties of photonic crystals, PCF confines light by band gap effects, using air holes in their cross-sections, or by a conventional higher-index core modified by the presence of air holes. The PCF is built of one material (SiO2, As2S3, Polymers, etc), and air holes are introduced in the area surrounding the core providing the change of the refractive index contrast between the core and



Figure 2. *The concept of mode division multiplexing over a FMF/MMF.*

the cladding. The transposition of air holes laid to form a hexagonal or circular lattice. **Figure 3** recapitalizes the principle SDM approaches over optical fibers [25].

2.3 Guided modes of optical fibers

We look into the different modal basis that can be supported by optical fibers. Like all electromagnetic phenomena, the propagation of optical fields along optical fiber is governed by Maxwell's equations. Several modal basis can describe the



Mode Division Multiplexing

Figure 3. Different approaches for SDM over optical fibers.

propagation in optical fibers. In this chapter, fiber guided modes that we will meet are vector modes (i.e. fiber eigenmodes), linear polarized modes (i.e. LP modes) and orbital angular momentum modes (i.e. OAM modes). In the following, we provide general notions including mathematical expressions of modes of each mode basis.

2.3.1 Cylindrical vector modes

In the absence of the current in the medium, Maxwell equations are reduced to two homogeneous vector wave equations given by the following expressions [26]:

$$\left(\vec{\nabla^2} + k^2 n^2 \right) \vec{E} = -\vec{\nabla} \left(\vec{E} . \vec{\nabla} \ln n^2 \right)$$

$$\left(\vec{\nabla^2} + k^2 n^2 \right) \vec{H} = \left(\vec{\nabla} \times \vec{H} \right) \times \vec{\nabla} \ln n^2$$

$$(1)$$

Where E and H are the electric and magnetic field respectively and n is the refractive index profile function. If we apply the boundary conditions according to the geometry and fiber refractive index, we get eigenvalues equation. Each solution of that equation is guided mode known by effective index neff. In cylindrical coordinates, for example, the electrical and magnetic fields are expressed as:

$$\begin{cases} \vec{E} = \left[\vec{r}E_{r} + \vec{\phi}E_{\phi} + \vec{z}E_{z}\right]\exp\left(j\beta z - j\omega t\right) \\ \vec{H} = \left[\vec{r}H_{r} + \vec{\phi}H_{\phi} + \vec{r}H_{z}\right]\exp\left(j\beta z - j\omega t\right) \end{cases}$$
(3)

Where Er, Hr are radial components, E ϕ and H ϕ are azimuthal components. \vec{r} , $\vec{\phi}$ and \vec{z} are unitary vectors. $\beta = 2\pi n_{eff}/\lambda$ is the propagation constant of guided mode, $\omega = 2\pi c/\lambda = kc$ is the pulsation; λ and c are the wavelength and light velocity both in vacuum, respectively. Guided modes in circularly symmetrical optical fiber are denoted as transverse electric ($TE_{0,m}$) or transverse magnetic modes ($TM_{0,m}$), if $E_z = 0$ or $H_z = 0$ respectively. Other kind of modes are $HE_{\nu,m}$ and $EH_{\nu,m}$ those where $E_z \neq 0$ or $H_z \neq 0$ (transverse components) are noted as hybrid modes. The designation $HE_{\nu,m}$ stands for a hybrid mode for which Hz is dominant compared to E_z , while for $EH_{\nu,m}$, E_z is dominant compared to H_z . The indexes ν and m are the azimuthal and radial indices. ν is related to the number of symmetry axes in the radial dependency of the fields, and m is related to the number of zeros in the radial dependency of the fields.

Because of the circular symmetry, the field must keep the same value after a full 2π azimuthal rotation, thus, the components E_z and H_z have a dependency according to $cos(\nu\phi)$ or $sin(\nu\phi)$. hence, in circularly symmetrical optical fiber, hybrid modes are composed by two modes: one *even* while the other is *odd*. In the even mode, the radials components (E_r) and azimuthal component (H_{ϕ}) are with *cos* ($\nu\phi$) (i.e. Ox symmetry). The components E_{ϕ} and H_r have dependency according to $sin(\nu\phi)$ (i.e. Oy symmetry). The radial, azimuthal and longitudinal electrical field components of even and odd modes are given by the following expressions:

$$\begin{cases} E_r^{even} = e_r(r) \cos{(\nu \varphi)} \\ E_{\varphi}^{even} = -e_{\varphi}(r) \sin{(\nu \varphi)} \\ E_z^{even} = e_z(r) \cos{(\nu \varphi)} \end{cases}$$
(4)

$$\begin{cases} E_r^{odd} = e_r(r) \sin \left(\nu \varphi\right) \\ E_{\varphi}^{odd} = e_{\varphi}(r) \cos \left(\nu \varphi\right) \\ E_z^{odd} = e_z(r) \sin \left(\nu \varphi\right) \end{cases} \tag{5}$$

The modes $HE_{\nu,m}^{even/odd}$, $HE_{\nu,m}^{even/odd}$, $TE_{0,m}$ and $TM_{0,m}$ are usually denoted as vector modes, cylindrical vector modes or fiber eigenmodes.

2.3.2 Scalar modes: LP modes

Frequently, the refractive index difference between core and cladding in optical fiber is very small ($n_{core} \approx n_{cladding}$). We are then under the weakly guiding condition, and some approximations can be applied. The term " $\nabla \ln n^2$ " is neglected in expression 1. The wave equation becomes scalar. The resulted modes are linearly polarized designated usually as LPIm modes. LP modes are quasi-TEM guided modes, and have negligible E_x and H_x components. Therefore, they only have one component in the E field and one component in the H field (by convention, either E_x and H_y , or E_y and H_x in cartesien coordinates). This is why we call them scalar modes. The even modes are with $\cos(l\phi)$, while odd modes are varies with $\sin(l\phi)$. *l* is the azimuthal number while m has the same definition as in vector modes [26]. The electric field components of even and odd modes (after variable separation: radial and azimuthal) are given by the next expressions:

$$E_{x}^{even} = e_{x}(r) \cos\left(l\phi\right) \tag{6}$$

$$E_{y}^{even}=e_{y}(r)\cos\left(l\varphi\right) \tag{7}$$

$$E_{x}^{odd} = e_{x}(r)\sin\left(l\phi\right) \tag{8}$$

$$E_{v}^{odd} = e_{y}(r)\sin\left(l\phi\right) \tag{9}$$

Practically, the LP modes come from linear combination between cylindrical vector modes. The correspondence between the linearly polarized modes and the conventional cylindrical vector modes is shown below (**Table 1**).

2.3.3 OAM modes

Optical fiber can support OAM modes by correctly superposing the even and odd modes for each $HE_{l,m}$ and $EH_{l,m}$ vector mode with $\pm (\pi/2)$ phase shift [27, 28]. Taking into consideration the circular polarization of OAM states (spin); OAM modes are denoted as $OAM_{\pm l,m}^{\pm}$ where \pm superscript describes the spin angular momentum (circular polarization), l and m subscript denote the azimuthal and

Cylindrical vector modes	LP modes	Cylindrical vector modes	LP modes
$\mathrm{HE}^{\mathrm{odd}}_{\mathrm{1m}}$	LP_{0m}^{y}	$HE_{2m}^{even}-TM_{0m} \\$	LP_{0m}^{eveny}
HE_{1m}^{even}	LP_{0m}^{x}	$HE_{(l+1)m}^{odd} + EH_{(l-1)m}^{odd}$	$\mathrm{LP}_{\mathrm{lm}}^{\mathrm{oddx}}$
$HE_{2m}^{odd} + TE_{0m} \\$	$\mathrm{LP}_{\mathrm{1m}}^{\mathrm{oddx}}$	$HE_{(l+1)m}^{odd}-EH_{(l-1)m}^{odd}$	LP_{lm}^{oddy}
$\mathrm{HE}_{2m}^{odd}-\mathrm{TE}_{0m}$	LP_{1m}^{oddy}	$HE^{even}_{(l+1)m} + EH^{even}_{(l-1)m}$	LP_{lm}^{evenx}
$HE_{2m}^{even} + TM_{0m}$	LP ^{evenx} _{0m}	$HE^{even}_{(l+1)m}-EH^{even}_{(l-1)m}$	LP ^{eveny} _{lm}

Table 1.

The correspondence between LP modes and the CV modes.

radial indices respectively. *l* is the topological number (number of twist in intensity profile), *m* describes the number of nulls radially (rings) in the intensity profile of the OAM mode. The magnitude of SAM equal $\pm s\hbar$ where s = +1 (left) or s = -1 (right). The magnitude of OAM equals $\pm l\hbar$. The total angular momentum AM is the sum of SAM and OAM with a magnitude of $(\pm l \pm s)\hbar$.

For the $TM_{0,m}$ and $TE_{0,m}$ modes, the combination between them with a \pm ($\pi/2$) phase shift, carries the same magnitude of SAM and OAM but with opposite sign, making the total angular momentum equal to zero. This mode is not stable and cannot propagate, because the propagation constants of $TE_{0,m}$ and $TM_{0,m}$ modes are different. Therefore, we call this an unstable vortex. OAM modes made from $HE_{1,m}$ modes would have a spin, but no topological charge (l = 0). Therefore, this is not a true OAM mode, but simply a vector mode with circular polarization. However, we will consider it as $OAM_{0,m}$, in a more general definition.

OAM modes made from $HE_{l,m}$ modes are rotating in the same direction as the spin (aligned spin-orbit modes), and OAM modes made from $EH_{l,m}$ modes are rotating in the opposite direction as the spin (anti-aligned spin-orbit modes). If we take an even and an odd mode, with a $\pi/2$ phase difference, and we sum the fields (expressions 1.5 and 1.6), we can get as a resulting field:

$$\begin{cases} E_r = e_r(r) \exp(\pm j\nu\phi) \\ E_\phi = j e_\phi(r) \exp(\pm j\nu\phi) \\ E_z = e_z(r) \exp(\pm j\nu\phi) \end{cases}$$
(10)

The synthetic formula are as given in the following expressions

$$\begin{cases} HE_{l+1,m}^{even} \pm i \times HE_{l+1,m}^{odd} = OAM_{\pm l,m}^{L/R} \\ EH_{l-1,m}^{even} \pm i \times EH_{l-1,m}^{odd} = OAM_{\pm l,m}^{R/L} \\ TM_{0m} \pm jTE_{0m} = OAM_{\pm 1m}^{\pm} \end{cases}$$
(11)

To summarize, for a given topological charge l, there are four possible *OAM* modes: two different spin rotation, and two different phase rotation. This is illustrated in **Figure 4**. The only exceptions are for $OAM_{\pm 1,m}$, where spin and topological charge always have the same sign, and for $OAM_{0,m}$, where there is no topological charge (only spin) [28].

Moreover, others OAM construction formulas are explored based on two spatially orthogonal linear polarized (LP) modes owning orthogonal polarization



Figure 4. *The four OAM mode degeneracies (reproduced from* [28]).

directions (with a $\pm \pi/2$ phase shift) which can be obtained by solving the scalar version of Maxwell equation (the scalar Helmholtz (wave) equation) under the weakly guiding approximation [29]. The LP-OAM synthetic formula are as follows:

$$\begin{cases} LP_{lm}^{ax} \pm iLP_{lm}^{bx} \\ LP_{lm}^{ay} \pm iLP_{lm}^{by} \end{cases} = F_{l,m}(r) \cdot \begin{cases} \vec{x} OAM_{\pm l,m} \\ \vec{y} OAM_{\pm l,m} \end{cases}$$
(12)

where \vec{x} and \vec{y} are the linear polarization along the x-axis and y-axis respectively, $F_{l,m}(r)$ is the radial field distribution. The difference between *OAM* modes generated from fiber vector modes (*CV-OAM*) possess circular polarization while those generated from LP modes (*LP-OAM*) are the linear polarization (has no *SAM*).

3. OAM-MDM through optical fibers

OAM has seen application in optical communication due to the theoretically unprecedented quantities of data that can be modulated, multiplexed, transmitted and demultiplexed through either free space link (FSO as Free Space Optics), or optical fibers. Optical communications has exploited the physical dimension of optical signal to encode and transmit individual/separate/independent data stream through the same transmission medium (optical fiber or FSO). Since, the OAM is linked to the spatial phase distribution of light beam, it has been included under the space dimension as a subset or embodiment of SDM (space division multiplexing). In addition, since OAM is independent of wavelength, quadrature, and polarization, it provides an additional dimension for encoding information [30, 31]. The interest on OAM in communication (including optical, radio, underwater) has grown dramatically. Figure 5(a) and (b), which highlights the number of published papers (conferences paper, books, journal papers and patents), translates that huge interest. In **Figure 5(a)**, we plot the number of published papers dealing with OAM in optical communication in last decade while Figure 5(b) shows the number of papers dealing with OAM in optical fibers, both are according to *Google Scholar*.

The worldwide backbone of high-capacity wired communications is optical fiber. The uses of OAM basis in optical fiber was a challenge to communication community. For a long time, optical fibers were only used for the generation or the transformation of OAM modes, and not for supporting their transmission [32]. The notion of transmitting OAM modes was demonstrated (theoretically, numerically,



Figure 5.

Number of papers published dealing with (a) OAM in optical communication over ten years (ranging from 2011 to 2020), (b) OAM in optical fibers over the same period (according to Google scholar).

and experimentally) through conventional optical fibers (classical deployed fibers), or specialty fibers that have been specifically designed to transmit robust OAM modes. In the following, we present kinds of optical fibers based on the consideration of their refractive indexes, (e.g. graded, step, ring, etc.), geometrical features (MMF, SMF, and FMF etc.) and transmission caracteristics (MDM, CDM, PCF, kind of appropriate modes, etc.) and so on. We highlight the main design and principles results achievements.

3.1 Conventional fibers

Two examples of conventional optical fibers are multimode fiber MMF (e.g. OM1, OM2, OM3, OM4) where generally their refractive index are graded (GIF) and single mode fiber (e.g. G_{652}) where the profile is step index (SMF). Conventional MMFs have large cores that are usually approximately 50 µm and can support hundreds of modes. Due to severe inter-modal dispersion limitations, MMF were replaced by single mode fibers (SMFs) that have a relatively small core radius (not exceeding 10 µm). The refractive indexes of both fibers (OM3, and G_{652} defined by ITU-T) are depicted in **Figure 6(a)** and **(b)**.

The most commonly used modal basis for fibers are LP modes. LP modes are not exact fiber modes, and can be simply viewed as combinations of fiber eigenmodes transverse (TE, TM, HE and EH) as indicated above.

Other type of fibers are few mode fibers (FMF) which consist of an improved version of MMF. They support a limited number of modes, as one of the key components for SDM for optical networks. The first paper that mentioned the possibility of transmitting OAM modes through optical fiber is from Alexeyev et al. in 1998 [33]. The authors demonstrated that the solution for OAM modes could exist in optical fibers (MMF). Considering the propagation of OAM modes through the cited fibers, the analysis of OAM in conventional graded index multimode fiber was reported (theoretically and numerically) [34]. In that paper, Chen and his co-authors presented a comprehensive analysis of the ten-OAM modes groups supported in OM3, including mode coupling, chromatic dispersion, differential group delay, effective mode area and nonlinearities.

Later on, the same team demonstrated experimentally the transmission of four-OAM mode group in OM3 MMF using mode exciting and filtering elements at the 2-fiber extremity. Moreover, they demonstrated two OAM mode groups transmission over 2.6-km MMF with low crosstalk free of MIMO-DSP [35]. In 2018, Wang et al. reported the successful transmission of OAM modes over 8.8-km OM4 MMF [36]. Wang and co-workers demonstrates a 120-Gbit/s quadrature phase-shift



Figure 6. Refractive indexes of (a) graded index fiber (multimode fiber) and (b) step index fiber (single mode fiber).

keying (QPSK) signal transmission over 8.8-km OM 4 MMF with 2×2 and 4×4 MIMO-DSP. In second stage, they demonstrate the data-carrying two OAM mode groups (6 OAM states) multiplexing transmission over 8.8 km MMF without MIMO equalization.

The OAM in SMF (ITU-T G.652) was investigated, in [37]. The investigation was performed over 3 visible wavelengths (red at 632.8 nm, green at 532 nm, and blue at 476.5 nm) when G.652 becomes a few mode fiber. The synthetized OAM modes was investigated through effective mode area, nonlinearity, tolerance to fiber ellipticity and bending. The authors analyzed and estimated the fiber attenuation and bandwidth/capacity for OAM modes over six levels of wavelengths.

Few mode fibers (FMFs) with classical refractive index profile (step/graded), was used to transmit OAM modes. The transmission of OAM modes over FMF required a MIMO-DSP in combination with coherent detection to equalize the intermodal crosstalk. It was demonstrated in [38] the transmission of four OAM beams over 5-km FMF. Each transmitted OAM state carrying 20 Gbits/s QPSK data. MIMO DSP was used to mitigate the mode coupling effects. A graded index few mode fiber has been designed in [39] in order to support 10 OAM orders with high purity (\geq 99.9%) enabling low intermodal crosstalk (\leq -30 dB). Later, in [40] Wang et al. demonstrated the viability of OAM modes transmission over both 50-km and 10-km FMFs. By adopting LDPC codes, the DMD and mode coupling was improved. In [41], Zhu et al. proposed and demonstrated a heterogeneous OAM based fiber by splicing 2 FMFs and MMF (OM3). Over 2 OAM modes, Zhu and coworkers transmit 20-Gbit/s QPSK data without MIMO-DSP. Recently, we proposed a family of graded index few mode fibers (four fibers) that supports 12 OAM states [42]. The evaluated differential group delay (DGD) and OAM purity demonstrate the viability of proposed fibers for short/medium haul connections.

3.2 OAM specialty fibers

OAM has changed the common features of optical fiber design guidelines. Cutting with the often-classical notion for imposing the center core to be the highest index of refractive (graded & step). In addition, the improvement of optical fibers fabrication technologies (materials & schemes) has made the fibers characterization no more challenging. New optical fibers with complicated shapes and high refractive index contrast have been experimentally characterized (demonstrated). The Modified Chemical Vapor Deposition (MCVD) is in principle one of the most fiber fabrication method that has been extensively used.

3.2.1 OAM-fibers recommendations and design guidelines

Mainly three common features between OAM specialty fibers are identified. The first consists of the high contrast between core and cladding refractive indexes (jumps/contrasts) increasing the mode effective indices separation (Δn_{eff}), hence enabling low induced crosstalk. The same feature involves the formation of OAM modes from cylindrical vector modes and avoid them to couple into LP modes. It is proved that minimum Δn_{eff} of 10^{-4} is enough to keep robust OAM modes. This key value guarantees the minimum interaction between channels and prevents mode coupling inducing channels crosstalk XT. It has been demonstrated that through MCVD, a contrast of 0.14 is achievable with GeO₂-SiO₂ composition [43]. The second is about the refractive index profile that matches the donut shape of intensity profile of OAM mode (Ring shape: **Figure 7**). Thus, the Ring shaped (known also as depressed core fibers) has been extensively designed in OAM context instead of solid core fibers. Finally, the interfaces between fiber core and cladding preferred



OAM mode (a) phases pattern (e.g. $OAM_{4,1}$), (b) normalized intensity, (c) fiber cross-section with ring shape.

to be smoothed (instead of step (abrupt variation)) in order to eliminate the spinorbit-coupling inducing OAM mode purity impairment and intrinsic crosstalk.

3.2.2 Vortex fibers (VFs)

The first specialty FMF designed for OAM modes is vortex fiber [44]. The designed fiber possess a good separation between co-propagating modes. Vortex fiber was first introduced to create cylindrical vector beams represented by $TE_{0,1}$ and $TM_{0,1}$ modes (also known as polarization vortices). Proposed by Ramachandran and al., Vortex fiber has a central core able to transmit the fundamental mode, surrounded by a lower trench, and an outer ring able to transmit the first OAM mode group. In first experience, they reported a transmission through more than 20 m fiber. Two years later, transmission of OAM through a 1 km fiber was reported [45–49]. **Figure 8** reported an optical microscope image of the end facet of the vortex fiber and the numerically calculated properties of the vortex fiber. All the experiments on OAM modes on the designed vortex fiber were summarized in [48].

3.2.3 Air Core fibers (ACFs)

Air core fiber (ACF) was proposed in [50]. 12 OAM modes were transmitted through 2 m of the fabricated ACF. Later on, 2 OAM modes were transmitted over 1 km of the fiber [51]. Among the main contributions, the authors demonstrated that OAM modes with higher l value are less sensitive to perturbations like bends and twists [52].

Within ROAM (revolution orbital angular momentum) project (EU H2020), Laval University (COPL) proposed and fabricated an ACF that achieved the record



Figure 8. (a) Optical microscope image of vortex fiber, (b) numerically calculated properties [48].

of OAM modes transmitted through an optical fiber. Benefiting from the high refractive index contrast (air/silica), the fabricated fiber supports the transmission of 36 OAM states [53]. **Figure 9** shows the refractive index of ACF. Nevertheless, the designed fiber possess a very high loss (up to few dBs per meters) which make it unsuitable for communication. Recently, 10.56 Tbit/s has been demonstrated over 1.2 km ACF, without MIMO DSP, by carrying data over 12 OAM modes combined with wavelength division multiplexing (WDM) [54]. Latest air core ring fiber is designed to support more than 1000 OAM modes (using As₂S₃ as ring material) across wide wavelength band covering S, O, E, S, C, and L Bands [55].

3.2.4 Inverse parabolic graded index fibers (IPGIFs)

Ung et al. proposed the inverse parabolic graded index FMF (IPGIF) to support OAM modes [56, 57]. The refractive index of IPGIF is given by the following expression:

$$n(r) = \begin{cases} n_2 \sqrt{\left(1 - 2N\Delta\left(\frac{r^2}{a^2}\right)} & 0 \le r \le a \quad (core) \\ n_3 & r \ge a \quad (cladding) \end{cases}$$
(13)

Where a, n_1 , n_2 , n_3 are the core radius, the refractive index at the core cladding interfaces, the refractive index at the core center and the refractive index of the cladding, respectively. The parameter N controls the shape of the IPGF. The refractive index of IPGF is presented in **Figure 10**. Based on a first-order perturbations, the authors highlighted the factors (refractive index, core radius and curvature shape) that directly related to enhance the intermodal separation in proposed IPGIF. Large refractive index gradient, high transverse field amplitude and large field variation are reasons of high intermodal separation enabling low crosstalk.

The designed IPG-FMF possess a good effective indices separation $(\Delta n_{eff} > 2.1 \times 10^{-4})$ between its supported vector modes, and the transmission of eight OAM states $(OAM_{\pm 0,1}, OAM_{\pm 1,1} \text{ and } OAM_{\pm 2,1})$ was demonstrated over 1 *m* which makes IPGIF suitable for short distances MDM transmission. On the other hand, the transmission of $OAM_{\pm 1,1}$ over more than 1 km was demonstrated by experiment, which makes the novel fiber as a promising candidate for long-distance



Figure 9. *Refractive index profile of an air (hollow) core fiber (ACF).*



Figure 10. *Refractive index profile of inverse parabolic graded index fiber (IPGIF).*

OAM based MDM multiplexing system. Later on (2017), the multiplexing/ transmission and demultiplexing of 3.36 Tbits/s was demonstrated over 10-meters inverse parabolic graded index fiber by using four OAM modes and 15 wavelengths (WDM) [58].

3.2.5 Ring Core fibers (RCFs)

Due to the emerging interest in OAM-guiding fibers, already designed fiber for LP modes was investigated through OAM. The Ring core fiber (RCF), which has been introduced to minimize the differential group delay between LP modes, was tailored to support and transmit OAM modes. This interest on ring core fiber come from its refractive index profile that closely matches the annular intensity profile of OAM beams (**Figure 11**). C. Brunet et al. present an analytic tool to solve the vector version of Maxwell equations in RCF [59]. A fully vectorial description was reported in order to better tailor the RCF to OAM context. Using the modal map developed in [59], the group designed and manufactured a family of RCF (five fibers) suitable for OAM transmission [60]. In [61] S. Ramachandran et al. demonstrated the stability of OAM modes in RCF.

Recently, an RCF supported 50 OAM states divided into 13 mode groups (MGs) has been numerically investigated using small MIMO DSP blocks [62]. Experimentally, the transmission of two OAM mode-group is demonstrated over a 50 km ring core fiber without the use of MIMO DSP [63]. Emerging papers considering the



Figure 11.

Examples of RCF refractive index profiles: (a) RCF (higher center) (b) RCF (lower center) and (c) RCF, a_1 and a_2 are inner and outer core radius respectively.

design of RCFs and the propagation demonstration of OAM modes through it that we should mentions [64, 65].

3.2.6 Graded index ring Core fibers (GI-RCFs)

The ring notion touched the graded shape and a family of graded index ring core fibers (GI-RCF) has been proposed, designed and fabricated to support OAM mode group. **Figure 12** shows the refractive index of GI-RCF. In [66], Zhu and co-workers designed and fabricated the GI-RCF for OAM modes. The fiber supports 22 OAM modes with low insertion loss (less than 1 dB/km). The crosstalk between the highest order mode groups is less than 14 dB after10-km propagation. With such fiber, a successful transmission of 32 Gbaud QPSk-data overall 80 channels is experimentally demonstrated. A transmission capacity of 5.12 Tbits/s and a spectral efficiency of 9 bit/s/Hz, over 10 km propagation was reported [67].

The second demonstration was performed over 18-km propagation. Recently, the same group demonstrate the transmission of 12 Gbaud (8QAM) over 224 channels (2 OAM \times 112 wavelengths). A transmission capacity of 8.4 Tbits/s was achieved without MIMO DSP because of the large high-order mode group separation of the OAM fiber [68].

To increase even further the capacity of the fiber link, OAM transmission was reported over uncoupled multi core fibers. While a complete review on this topic exceed the scope of this chapter, we can nevertheless mention some contributions. Li and Wang designed seven-ring core fiber (MOMRF) supporting 154 data-channels in total (22 modes × 7 rings) [69]. The proposed fiber featuring low-level inter-ring crosstalk (-30 dB for a 100-km-long fiber) and intermodal crosstalk over a wide wavelength range (1520–1580 nm). Later, in [70], Li and Wang proposed a compact trench multi OAM ring fiber (TA-MOMRF) with 19 rings each supporting 22 modes (18 OAM states). The authors stated that such fiber is suitable for long distance OAM transmission enabling Pbit/s total transmission capacity and hundreds bit/s/Hz spectral efficiency. In [71], the authors proposed a coupled multi core fibers to support OAM modes (multi-orbital-angular-momentum (OAM)



Figure 12. Design of the GIRCF.

multicore supermode fiber (MOMCSF). The designed supermode fiber show favorable performance of low mode coupling, low nonlinearity, and low modal dependent loss.

3.2.7 Inverse raised cosine few mode fibers (IRC-FMFs)

Using IPGI fiber as a benchmark, we proposed a novel fiber that is based on inverse raised cosine function (IRCF). The standard raised cosine function (RCF) when applied to a wideband signal steeply removes the high out-of-band signals, making the filtered signal highly purified. Moreover, RCF is used in the same context because it eliminates intersymbol interference [72]. The IRCF profile is given by the following expression [73]:

$$n(r) = \begin{cases} n_2 & \text{if } 0 \le r \le a \frac{1-\alpha}{2} \quad (Core) \\ -\frac{1}{2(n_2 - n_3)} \left(1 + \cos\left[\left(\frac{\pi}{a \times \alpha}\right) \left(r - a \frac{1-\alpha}{2}\right)\right] \right) & \text{if } a \frac{1-\alpha}{2} \le r \le a \frac{1+\alpha}{2} \quad (Core) \\ n_3 & \text{if } r \ge a \frac{1+\alpha}{2} \quad (Cladding) \end{cases}$$

$$(14)$$

where *a* is the core radius, n_1 and n_2 are respectively the maximum and the minimum refractive indices of the core, n_3 is the refractive index of the cladding (r > a), and α is the profile shape. The refractive index of IRCF is shown in the **Figure 13**. The IRC profile is practically thinner (or more concentrated around the fiber axis) than the IPGI profile [73]. However, it is worthy to note that our profile becomes much smoother when reaching the maximum index value n_1 . When compared with IPGI-FMF, the inverse-raised-cosine function offers a large modal separation. The enhanced separation is likely to hinder mode coupling, reducing the system crosstalk and improving the transmission. Moreover, IRC-FMF has the potential to handle OAM modes with high purity hence low intrinsic crosstalk [73, 74].



Figure 13. Index profiles of the IRC fiber (solid lines), with α ranging from 0 to 1 (reproduced from 73).

3.2.8 Hyperbolic tangent few mode fibers (HTAN-FMFs)

Based on hyperbolic tangent function (HTAN), we proposed and designed a ring core few mode fiber that we refer to as hyperbolic tangent few mode fiber (HTAN-FMF). The function HTAN was not common in optical fiber profiling. It is widely used in various fields/domains such as digital neural networks, image processing, digital filters, and decoding algorithms [75–77] but not common in waveguide and optical fiber designs. Intuitively, one of the most attractive criteria in hyperbolic tangent function, used as an activation function in neural network, is its strong gradient centered around the inflection point (switch point). This is the same criteria required from an optical fiber profile in order to enhance the intermodal separation. The refractive index of HTAN-FMF is given by the following expression [78]:

$$n(r) = \begin{cases} n_2 \text{ if } 0 \le |r| \le a \frac{(1-\alpha)}{2} (Core) \\ \frac{n_1 + n_2}{2} + \frac{\Delta n}{2.Tanh(\pi)} \times \left[Tanh\left(\frac{\pi \times (r-a_1)}{a_1 \times \alpha}\right) \right] \text{ if } a \frac{(1-\alpha)}{2} \le |r| \le a \frac{(1+\alpha)}{2} (Core) \\ n_1 \text{ if } a \frac{(1+\alpha)}{2} \le |r| \le a (Core) \\ n_3 \text{ if } |r| \ge a (Cladding) \end{cases}$$

$$(15)$$

Where n_1 , n_2 , n_3 are the refractive index at the core-cladding interface, at the core center, and at the cladding region, respectively. a, a_1 and α are the core radius, the half of core radius ($a_1 = a/2$) and the shape parameter respectively. Δn is the actual refractive index difference (i.e. $\Delta n = n_1 - n_2$) which corresponds to the extent of hyperbolic tangent function inside the core. The shape parameter α controls the shape behavior of HTAN function. The refractive index of HTAN is illustrated in **Figure 14**. The proposed HTAN-FMF achieves a wide intermodal separation (between cylindrical vector modes) especially between TE_{0,1}, HE_{2,1}, and TM_{0,1}



Figure 14. *Refractive index profile of HTAN fiber for different values of profile shape* α [78].

 $(\geq 3 \times 10^{-4})$. This enables low-level crosstalk channels carrying data during propagation and outperforms what is existing in the literature [78]. On the other hand, even with an exterior abrupt variation, the inner smooth behavior of HTAN-FMF guarantees the enhancement of the obtained OAM mode purities (\geq 99.9%) leading to intrinsic crosstalk as minimum as -30 dB during propagation. Moreover, the obtained results in term of chromatic dispersion (max CD = -60 ps/(km.nm)), differential group delay (max DGD = 55 ps/m), and bending insensitivity, demonstrate that the HTAN-FMF could be a viable candidate for enhancing the transmission capacity and the spectral efficiency in next generation OAM mode division Multiplexing (OAM-MDM) systems [78].

3.3 Photonic crystal fibers

Photonic crystal fibers (PCF) has shown its design flexibility to guide appropriate OAM modes. With adjustable parameters, PCF can offer more flexible design structures to provide unique fiber properties. Due to that, several kinds of OAM-PCF with various structures (hexagonal, circular, kagome...) and materials (As₂S₃, SiO₂, polymer ...), having promising features have been designed and even fabricated. PCF have been proposed and fabricated to ensure good transmission quality of OAM modes. While a review on this topic exceed the scope of this thesis, we can nevertheless mention some details and contributions. PCFs supporting one, 2, 10, 12, 14, 26, 34, 42 and 48, first order OAM modes have been proposed featuring good transmission properties [79–89].

The race is still ongoing to increase the number of OAM modes in PCF featuring good transmission proprieties. To the best of our knowledge, the most supporting OAM modes number in a circular PCF reaches 110 over C + L communication bands [90]. The designed fiber featured large effective indices separation (are at the order of 10^{-3}), low nonlinear coefficient, low confinement loss (under 10^{-7} dB/m), and relatively flat chromatic dispersion. Such fiber could find potential application in high capacity OAM-MDM system. By analysis of these recent mosaic OAM-PCFs literature, we can come to the general requirements in PCF design that ensure good transmission quality of OAM modes in the following five points or guidelines [91–94].

- Fiber index profile that matches the intensity profile of OAM modes (ring shape).
- The supported modes belonging to the same OAM mode family should possess a large index separation ($\geq 10^{-4}$) to be free from complex and heavy multiple input multiple output digital signal processing (MIMO DSP) at the receiver side. This is achievable with high material contrast between the fiber core and the cladding. Instead of using pure SiO₂ as a background material for the PCFfiber, other available materials could be used such as Silicon (Si), As₂S₃, and Polymer.
- Large core thickness is required targeting to increase the supported OAM mode number.
- The excited OAM modes should be of the first order. Hence, it is preferable to avoid exciting the higher radial orders modes because it causes trouble in multiplexing and demultiplexing operations due to the intensity and phase variety distribution.

• The guided OAM modes would possess good transmission features such as low confinement loss, flat dispersion, large effective mode area, and low nonlinear coefficient over a large wavelength range (at least covering C + L bands defined by ITU-T).

4. Conclusion

In this chapter, we have attempted to provide recent advances in SDM based Optical fibers. We showed that SDM is currently the unexhausted technology that can deal with the capacity need and boost data traffic. Furthermore, an interesting embodiment of SDM, which is based on carrying data on fiber modes (MDM) has been presented and discussed. The different mode basis supported in optical fibers are presented and discussed. Furthermore, we reviewed the research activities that are based on harnessing OAM modes to encode data channels either in classical optical fibers (i.e. with classical refractive index profiles) or in special fibers with appropriate ring profiles. We presented the main research activities and recent trends in OAM-MDM over the last ten years.

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References

[1] Cisco VNI Global IP traffic forecast "2016–2021".

[2] A. Chralyvy, Plenary paper: The coming capacity crunch. In: 2009 35th European Conference on Optical Communication, 2009, pp. 1–1.

[3] Ellis, A. D., Mac Suibhne, N., Saad, D., & Payne, D. N. Communication networks beyond the capacity crunch. (2016).

[4] R. Essiambre and R. Tkach. Capacity trends and limits of optical communication networks. In Proceedings of the IEEE, May 2012, vol. 100, no. 5, pp. 1035–1055.

[5] Richardson, D. J., Fini, J. M., & Nelson, L. E. Space-division multiplexing in optical fibres. Nature photonics. 2013, 7(5), 354–362.

[6] Saridis, G. M., Alexandropoulos, D., Zervas, G., & Simeonidou, D. Survey and evaluation of space division multiplexing: From technologies to optical networks. IEEE Communications Surveys & Tutorials. 2015; 17(4), 2136–2156.

[7] Saitoh, K., & Matsuo, S. Multicore fiber technology. Journal of Lightwave Technology. 2016; 34(1), 55–66.

[8] Yaman, F., Bai, N., Zhu, B., Wang,
T., & Li, G. Long distance transmission in few-mode fibers. Optics Express.
(2010); 18(12), 13250–13257.

[9] L.A. Rusch, M. Rad, K. Allahverdyan, I. Fazal, E. Bernier, Carrying data on the orbital angular momentum of light, IEEE Commun. Mag. (2018), 56 (2) 219–224.

[10] Bozinovic, N., Yue, Y., Ren, Y., Tur,
M., Kristensen, P., Huang, H., &
Ramachandran, S. Terabit-scale orbital angular momentum mode division multiplexing in fibers. Science. (2013), 340(6140), 1545–1548. [11] Wang, J., Yang, J. Y., Fazal, I. M., Ahmed, N., Yan, Y., Huang, H., & Willner, A. E. Terabit free-space data transmission employing orbital angular momentum multiplexing. Nature photonics, (2012), 6(7), 488–496.

[12] "Sumitomo Electric." [Online]. Available: http://www.sumitomoelectric. com/.

[13] "OFS." [Online]. Available: http:// www.ofsoptics.com.

[14] "Samtec." [Online]. Available: http://www.samtec.com.

[15] T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber," Opt. Express. 2011, vol. 19, no. 17, pp. 16576–16592.

[16] Kingsta, R. M., & Selvakumari, R. S. A review on coupled and uncoupled multicore fibers for future ultra-high capacity optical communication. Optik. (2019), 199, 163341.

[17] M. Koshiba, K. Saitoh, and Y. Kokubun, "Heterogeneous multi-core fibers: proposal and design principle," IEICE Electron. Express. 2009, vol. 6, no. 2, pp. 98–103, Jan.

[18] Y. Kokubun and M. Koshiba, "Novel multi-core fibers for mode division multiplexing: proposal and design principle," IEICE Electron. Express. Apr. 2009, vol. 6, no. 8, pp. 522–528.

[19] C. Xia, N. Bai, I. Ozdur, X. Zhou, and G. Li, "Supermodes for optical transmission," Opt. Express. Aug. 2011, vol. 19, no. 17, pp. 16 653–16 664.

[20] Zhu, B., Taunay, T. F., Fishteyn, M.,Liu, X., Chandrasekhar, S., Yan, M. F.,& Dimarcello, F. V. 112-Tb/s space-division multiplexed DWDM

transmission with 14-b/s/Hz aggregate spectral efficiency over a 76.8-km seven-core fiber. Optics Express. (2011), 19(17), 16665–16671.

[21] T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, Low-Crosstalk and Low-Loss Multi-Core Fiber Utilizing Fiber Bend. In: Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2011, OSA Technical Digest (CD) (Optical Society of America, 2011).

[22] H. Takara, A. Sano, T. Kobayashi, H. Kubota, H. Kawakami, A. Matsuura, Y. Miyamoto, Y. Abe, H. Ono, K. Shikama, Y. Goto, K. Tsujikawa, Y. Sasaki, I. Ishida, K. Takenaga, S. Matsuo, K. Saitoh, M. Koshiba, and T. Morioka. 1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) crosstalk-managed transmission with 91.4-b/s/Hz aggregate spectral efficiency. In: the European Conf. Exhibition Optical Communication, Amsterdam, the Netherlands, 2012.

[23] K. Igarashi, et al., 1.03-Exabit/s· km Super-Nyquist-WDM Transmission over 7,326-km Seven-Core Fiber. ECOC-2013, PD1.E.3.

[24] S. Berdague, and P. Facq, Mode Division Multiplexing in Optical Fibers. App. Opt. (1982), 24(11), 1950–1955.

[25] Russell, P. Photonic crystal fibers. Science, (2003), 299(5605), 358–362.

[26] J. Bures, Guided Optics, ser. Physics textbook. Wiley, 2009.

[27] Zhang, H., Mao, B., Han, Y., Wang,Z., Yue, Y., & Liu, Y. Generation of orbital angular momentum modes using fiber systems. Applied Sciences, (2019), 9(5), 1033.

[28] Brunet, C., & Rusch, L. A. Optical fibers for the transmission of orbital angular momentum modes. Optical Fiber Technology, (2017), 35, 2–7. [29] Ramachandran, S., & Kristensen, P.Optical vortices in fiber.Nanophotonics. (2013), 2(5–6), 455–474.

[30] Yao, A. M., & Padgett, M. J. Orbital angular momentum: origins, behavior and applications. Advances in Optics and Photonics. (2011), 3(2), 161–204.

[31] Padgett, M. J. Orbital angular momentum 25 years on. Optics express.(2017), 25(10), 11265–11274.

[32] R. Kumar, D. S. Mehta, A. Sachdeva, A. Garg, P. Senthilkumaran, and C. Shakher. Generation and detection of optical vortices using all fiber-optic system. Optics Communications. 2008, vol. 281, no. 13, pp. 3414–3420.

[33] A. N. Alexeyev, T. A. Fadeyeva, and A. V. Volyar, "Optical vortices and the flow of their angular momentum in a multimode fiber," Semiconductor Physics, Quantum Electronics & Optoelectronics. 1998, vol. 1, no. 1, pp. 82–89.

[34] Chen, S., & Wang, J. Theoretical analyses on orbital angular momentum modes in conventional graded-index multimode fibre. Scientific Reports. (2017), 7(1), 3990.

[35] Zhu, L., Wang, A., Chen, S., Liu, J., Mo, Q., Du, C., & Wang, J. Orbital angular momentum mode groups multiplexing transmission over 2.6-km conventional multi-mode fiber. Optics express. (2017), 25(21), 25637–25645.

[36] Wang, A., Zhu, L., Wang, L., Ai, J., Chen, S., & Wang, J. Directly using 8.8km conventional multi-mode fiber for 6-mode orbital angular momentum multiplexing transmission. Optics express. (2018), 26(8), 10038–10047.

[37] Chen, S., & Wang, J. Characterization of red/green/blue orbital angular momentum modes in conventional G. 652 fiber. IEEE Journal of Quantum Electronics. (2017), 53(4), 1–14.

[38] G. Milione, H. Huang, M. Lavery, A. Willner, R. Alfano, T. A. Nguyen, and M. Padgett, "Orbital-angularmomentum mode (de)multiplexer: a single optical element for MIMO-based and non-MIMO-based multimode fiber systems. In: Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2014).

[39] Zhang, Z., Gan, J., Heng, X., Wu, Y., Li, Q., Qian, Q., & Yang, Z. Optical fiber design with orbital angular momentum light purity higher than 99.9%. Optics express. (2015), 23(23), 29331–29341.

[40] Wang, A., Zhu, L., Chen, S., Du, C., Mo, Q., & Wang, J. Characterization of LDPC-coded orbital angular momentum modes transmission and multiplexing over a 50-km fiber. Optics express, (2016), 24(11), 11716–11726.

[41] Zhu, L., Wang, A., Chen, S., Liu, J., & Wang, J. Orbital angular momentum mode multiplexed transmission in heterogeneous few-mode and multimode fiber network. Optics letters.
(2018), 43(8), 1894–1897.

[42] Rjeb, A., Seleem, H., Fathallah, H., & Machhout, M. Design of 12 OAM-Graded index few mode fibers for next generation short haul interconnect transmission. Optical Fiber Technology. (2020), 55, 102148.

[43] H. Doweidar. Considerations on the structure and physical properties of B2O3–SiO2 and GeO2–SiO2 glasses.J. Non-Cryst. Solids. (2011), 357(7), 1665–1670.

[44] S. Ramachandran, P. Kristensen, and M. F. Yan, Generation and propagation of radially polarized beams in optical fibers. Opt. Lett. Aug. 2009, vol. 34, no. 16, pp. 2525–2527,. [45] N. Bozinovic, P. Kristensen, and S. Ramachandran, Long-range fibertransmission of photons with orbital angular momentum. In: CLEO: 2011 -Laser Applications to Photonic Applications. Optical Society of America, 2011.

[46] Bozinovic, N., Kristensen, P., & Ramachandran, S. Are orbital angular momentum (OAM/vortex) states of light long-lived in fibers. In: Laser Science (p. LWL3). Optical Society of America.

[47] N. Bozinovic, S. Ramachandran, M. Brodsky, and P. Kristensen. Recordlength transmission of entangled photons with orbital angular momentum (vortices). In: Frontiers in Optics, (2011, October). Optical Society of America, 2011.

[48] N. Bozinovic, Y. Yue, Y. Ren, M.
Tur, P. Kristensen, H. Huang, A. E.
Willner, and S. Ramachandran, Terabit-scale orbital angular momentum mode division multiplexing in fibers. Science.
2013, vol. 340, no. 6140, pp. 1545–1548.

[49] S. Golowich, P. Kristensen, N. Bozinovic, P. Gregg, and S. Ramachandran. Fibers supporting orbital angular momentum states for information capacity scaling. In: Proc. of FIO. OSA, 2012.

[50] P. Gregg, P. Kristensen, S. Golowich, J. Olsen, P. Steinvurzel, and S. Ramachandran, "Stable transmission of 12 OAM states in air-core fiber: In CLEO: 2013.Optical Society of America, 2013.

[51] P. Gregg, P. Kristensen, and S. Ramachandran. OAM stability in fiber due to angular momentum conservation. In CLEO: 2014. Optical Society of America, 2014.

[52] Gregg, P., Kristensen, P., & Ramachandran, S. Conservation of orbital angular momentum in air-core optical fibers. Optica. (2015), 2(3), 267–270.

[53] C. Brunet, P. Vaity, Y. Messaddeq, S. LaRochelle, and L. A. Rusch, Design, fabrication and validation of an OAM fiber supporting 36 states. Optics Express. (2014), 22, no 21, pp. 26117–26127.

[54] K. Ingerslev, P. Gregg, M. Galili, F. Da Ros, H. Hu, F. Bao, M. A. U.
Castaneda, P. Kristensen, A. Rubano, L.
Marrucci, and K. Rottwitt.12 mode,
WDM, MIMO-free orbital angular
momentum transmission. Opt. Exp.
Aug. 2018, vol. 26, pp. 20225–20232.

[55] Y Wang, C. Bao, W. Geng, Y. Lu, Y. Fang, B. Mao, Y.-G. Liu, H. Huang, Y. Ren, and Z. Pan. Air-core ring fiber with >1000 radially fundamental OAM modes across O, E, S, C, and L bands. IEEE Access. 2020, vol. 8, pp. 68280–68287.

[56] Ung, P. Vaity, L. Wang, Y. Messaddeq, L. A. Rusch and S. LaRochelle. Few-mode fiber with inverse-parabolic graded-index profile for transmission of OAM-carrying modes. Optics Express. (July 2014), 22, no. 15, pp. 18044–18055.

[57] Ung, B., Wang, L., Brunet, C.,
Vaity, P., Jin, C., Rusch, L. A., &
LaRochelle. S. Inverse-parabolic gradedindex profile for transmission of cylindrical vector modes in optical fibers. In: Optical Fiber Communication Conference, (2014, March), (pp. Tu3K-4). Optical Society of America.

[58] J. Zhu, et al. 3.36-Tbit/s OAM and Wavelength Multiplexed Transmission over an Inverse-Parabolic Graded Index Fiber. In: CLEO 2017, San Jose, p. SW4I.3, May 2017.

[59] C. Brunet, B. Ung, P.-A. Bélanger, Y. Messaddeq, S. LaRochelle, and L. A. Rusch.Vector mode analysis of ring-core fibers: design tools for spatial division multiplexing. Journal of Lightwave Technology. (2014), 32.23, 4046–4057.

[60] C. Brunet, B. Ung, L. Wang, Y. Messaddeq, S. LaRochelle, and L. A.

Rusch. Design of a family of ring-core fibres for OAM transmission studies. Optics Express. (2015), 23.8: 10553– 10563.

[61] Ramachandran, S., Gregg, P.,Kristensen, P., & Golowich, S. E. On the scalability of ring fiber designs for OAM multiplexing. Optics express. (2015), 23 (3), 3721–3730.

[62] S. Chen, S. Li, L. Fang, A. Wang, and J. Wang. OAM mode multiplexing in weakly guiding ring-core fiber with simplified MIMO-DSP. Opt. Exp. 2019, vol. 27, no. 26, pp. 38049–38060.

[63] R. Zhang, H. Tan, J. Zhang, L.
Shen, J. Liu, Y. Liu, L. Zhang, and S. Yu.
A novel ring-core fiber supporting
MIMO-free 50 km transmission over
high-order OAM modes. In: Proc. Opt.
Fiber Commun. Conf. (OFC), 2019,
pp. 1–3.

[64] Zhang, J., Wen, Y., Tan, H., Liu, J., Shen, L., Wang, M., & Yu, S. 80-Channel WDM-MDM transmission over 50-km ring-core fiber using a compact OAM DEMUX and modular 4×4 MIMO equalization. In: Optical Fiber Communication Conference (pp. W3F-3). Optical Society of America, (2019, March).

[65] Banawan, M., Wang, L., LaRochelle,
S., & Rusch, L. A. Quantifying the
Coupling and Degeneracy of OAM
Modes in High-Index-Contrast Ring
Core Fiber. Journal of Lightwave
Technology. (2020), 39(2), 600–611.

[66] Zhu, G., Chen, Y., Du, C., Zhang, Y., Liu, J., & Yu, S. A graded index ringcore fiber supporting 22 OAM states. In: Opto-Electronics and Communications Conference (OECC) and Photonics Global Conference (PGC), 2017 (pp. 1–3). IEEE.

[67] G. Zhu, et al. Scalable mode division multiplexed transmission over a 10-km ring-core fiber using high-order orbital angular momentum modes. Optics Express. vol. 26, pp. 594–604.

[68] Zhu, L., Zhu, G., Wang, A., Wang, L., Ai, J., Chen, S. ... & Wang, J. 18 km low-crosstalk OAM+WDM transmission with 224 individual channels enabled by a ring-core fiber with large high-order mode group separation. Optics letters. (2018), 43(8), 1890–1893.

[69] Li, S., & Wang, J. Multiorbital-angular-momentum multi-ring fiber for high-density space-division multiplexing. IEEE Photonics Journal. (2013), 5(5), 7101007–7101007.

[70] Li, S., & Wang, J. A compact trench-assisted multi-orbital-angularmomentum multi-ring fiber for ultrahigh-density space-division multiplexing (19 rings× 22 modes). Scientific reports. (2014), 4, 3853.

[71] S. Li and J. Wang. Supermode fiber for orbital angular momentum (OAM) transmission. Opt. Express. Jul. 2015, vol. 23, pp. 18736–18745.

[72] Proakis, J. G., Salehi, M., Zhou, N., & Li, X. (1994). Communication systems engineering (Vol. 2). New Jersey: Prentice Hall.

[73] Rjeb, A., Guerra, G., Issa, K.,
Fathallah, H., Chebaane, S., Machhout,
M., & Galtarossa. A. Inverse-raisedcosine fibers for next-generation orbital angular momentum systems. Optics
Communications. (2020), 458, 124736.

[74] Rjeb, A., Fathallah, H., & Machhout, M. Orbital Angular Momentum Mode Coupling Analysis due to Ellipticity and Birefringence in Inverse-raised Cosine Fiber. In: 2020 17th International Multi-Conference on Systems, Signals & Devices (SSD) (pp. 929–932). IEEE, (2020, July).

[75] Garg, G., Sharma, P. An Analysis of Contrast Enhancement using Activation Functions. International Journal of Hybrid Information Technology. (2014), 7(5), 2.

[76] Johansen, H. K., Sørensen, K., "Fast hankel transforms", Geophysical Prospecting, 27(4), 876–901, (1979).

[77] Goyal, A., Kwon, H. M. Hyperbolic tangent function avoided for encoded pilot low density parity check decoding. In: The European Conference on Wireless Technology, (pp. 149–152). IEEE, (2005, October).

[78] Rjeb, A., Fathallah, H., Khaled, I., Machhout, M., & Alshebeili, S. A. A Novel Hyperbolic Tangent Profile for Optical Fiber for Next Generation OAM-MDM Systems. IEEE Access. (2020), 8, 226737–226753.

[79] Wong, G. K. L., Kang, M. S., Lee, H.
W., Biancalana, F., Conti, C., Weiss, T., & Russell, P. S. J. Excitation of orbital angular momentum resonances in helically twisted photonic crystal fiber.
Science. (2012), 337(6093), 446–449.

[80] Yue, Y., Zhang, L., Yan, Y., Ahmed, N., Yang, J. Y., Huang, H., ... & Willner, A. E. (2012). Octave-spanning supercontinuum generation of vortices in an As 2 S 3 ring photonic crystal fiber. Optics letters, 37(11), 1889–1891.

[81] Zhang, H.; Zhang, W.; Xi, L.; Tang,
X.; Tian, W.; Zhang, X. In: Proceedings of the Asia Communications and
Photonics Conference, 2015, Hong Kong,
China, pp. 1–3, 19–23 (November 2015).

[82] Zhang, H., Zhang, X., Li, H., Deng, Y., Zhang, X., Xi, L., ... & Zhang, W. A design strategy of the circular photonic crystal fiber supporting good quality orbital angular momentum mode transmission. Optics Communications. (2017), 397, 59–66.

[83] Zhang, H., Zhang, W., Xi, L., Tang, X., Zhang, X., & Zhang, X. A new type circular photonic crystal fiber for orbital angular momentum mode transmission.

IEEE Photonics Technology Letters. (2016), 28(13), 1426–1429.

[84] Hu, Z. A., Huang, Y. Q., Luo, A. P., Cui, H., Luo, Z. C., & Xu, W. C. Photonic crystal fiber for supporting 26 orbital angular momentum modes. Optics express. (2016), 24(15), 17285–17291.

[85] Tian, W., Zhang, H., Zhang, X., Xi,
L., Zhang, W., & Tang, X. A circular photonic crystal fiber supporting 26
OAM modes. Optical Fiber Technology. (2016), 30, 184–189.

[86] Chen, C., Zhou, G., Zhou, G., Xu, M., Hou, Z., Xia, C., & Yuan, J. A multiorbital-angular-momentum multi-ring micro-structured fiber with ultra-highdensity and low-level crosstalk. Optics Communications. (2016), 368, 27–33.

[87] Xi, X. M., Wong, G. K. L., Frosz, M.
H., Babic, F., Ahmed, G., Jiang, X., ... & Russell, P. S. J. Orbital-

angular-momentum-preserving helical Bloch modes in twisted photonic crystal fiber. Optica. (2014), 1(3), 165–169.

[88] Zhang, H., Zhang, X., Li, H., Deng, Y., Zhang, X., Xi, L., ... & Zhang, W. A design strategy of the circular photonic crystal fiber supporting good quality orbital angular momentum mode transmission. Optics Communications. (2017), 397, 59–66.

[89] Rjeb, A., Habib Fathallah, Saleh Chebaane, Mohsen Machhout Design of Novel Circular Lattice Photonic Crystal Fiber suitable for transporting 48 OAM modes. Accepted for publication in Optoelectronics Letters (2021). [In Press].

[90] Zhang, L., Zhang, K., Peng, J., Deng, J., Yang, Y., & Ma, J. Circular photonic crystal fiber supporting 110 OAM modes. Optics Communications. (2018), 429, 189–193.

[91] Li, H., Ren, G., Zhu, B., Gao, Y., Yin, B., Wang, J., & Jian, S. Guiding terahertz orbital angular momentum beams in multimode Kagome hollowcore fibers. Optics letters. (2017), 42(2), 179–182.

[92] Zhang, H., Zhang, X., Li, H., Deng, Y., Xi, L., Tang, X., & Zhang, W. The orbital angular momentum modes supporting fibers based on the photonic crystal fiber structure. Crystals. (2017), 7(10), 286.

[93] Zhang, H., Zhang, X., Li, H., Deng, Y., Zhang, X., Xi, L., & Zhang, W. A design strategy of the circular photonic crystal fiber supporting good quality orbital angular momentum mode transmission. Optics Communications. (2017), 397, 59–66.

[94] Li, H., Zhang, H., Zhang, X., Zhang,
Z., Xi, L., Tang, X. ... & Zhang, X.
Design tool for circular photonic crystal fibers supporting orbital angular momentum modes. Applied optics.
(2018), 57(10), 2474–2481.



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Chapter

Application of Fiber Optics in Bio-Sensing

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Abstract

The unique properties of optical fibers such as small size, immunity to electromagnetic radiation, high sensitivity with simpler sensing systems have found their applications from structural monitoring to biomedical sensing. The inclusion of optical transducers, integrated electronics and new immobilization methods, the optical fibers have been used in industrial process, environmental monitoring, food processing and clinical applications. Further, the optical fiber sensing research has also been extended to the area of detection of micro-organisms such as bacteria, viruses, fungi and protozoa. The validation of optical fibers in bio-sensing applications can be observed from the growing number of publications. This chapter provides a brief picture of optical fiber biosensors, their geometries including the necessary procedure for their development. This chapter could be a milestone for the young researchers to establish their laboratory.

Keywords: optical fiber, biosensors, biomedical sensing, environmental monitoring, micro-organisms detection

1. Introduction

The inclusion of optical fibers in bio-sensing applications was started by two different, but interrelated discoveries, such as the laser light and optical fibers. The theoretical work of C. H. Townes and A. L. Schawlow was used by T. H. Maiman to develop the first laser. A optical signal obtained through laser is highly collimated, inherently coherent, and quasi monochromatic with the data transfer capability. The optical signal propagates in optical fiber by obeying the principle of total internal reflection (TIR) with very low losses and the first working model of optical fiber was proposed in 1965 [1]. The working model of optical fiber was put forwarded 100 years after the demonstration of concept of light. Since, then the main focus was to improve the transmission of optical signal through fibers. Nowadays, the key focus is on long distance high speed communication with low transmission losses such as 2 dB/km [2]. The unique properties of optical fibers such as immunity to electromagnetic (EM) interference and miniature footprints, the optical fiber has found niche application in sensing [3].

A schematic of conventional single mode fiber (SMF) used in the field of telecommunication is shown in **Figure 1**, consisting of three layers such as a silica core having diameter of in order of several microns ($\sim 2-9 \ \mu m$) and doped with germanium to boost up its refractive index (RI), a silica cladding of diameter of 125 μm



and a coating of plastic jacket. Although, the plastic coating does not play any role in light propagation but provides the mechanical strength to the fiber. The optical fibers can be fabricated by using some other materials such as chalcogenide [4], plastic [5], and composites, with different composite materials in core and cladding. Based on the core size, operating wavelength, and RI difference of core and cladding, an optical fiber can work in the regime of single or multimode. In single mode fibers, the distribution of optical signal profile in core is Gaussian, while in multimode signal profile is more complex [2].

The optical sensors detect the variation in optical properties of propagating signal, that occurs due to the physiochemical change in targeted environment. The optical fiber based sensors classified into two categories on the basis of sensing region such as extrinsic or intrinsic sensors. The sensors directing or collecting optical signal to and from external environment are termed as extrinsic sensors [6]. The sensors in which the properties of optical signal vary within the fiber are known as intrinsic sensors [7]. In general, extrinsic sensors being used for the detection of external stimuli such as physical or biochemical parameters. The optical fiber based measurement techniques have received a great attention especially in the field of structural monitoring, railway and aerospace, chemical and biological sensing, medical diagnosis and environmental monitoring.

Since, the key application of SMF were in the field of telecommunication, and hence, fabricated in such a way that the influence of external field can be minimized on propagating signal. However, for the efficient operation of optical fiber sensors, the interaction of optical signal with external environment should need to be maximized. This can be attained by adopting different optical fiber processing schemes which frequently utilizes the interaction of leaking fields with external environment. The commonly used geometry of optical fiber in sensing applications are discussed in following subsections.

1.1 Cladding less evanescent based optical fiber sensors

The easiest way to increase the interaction of evanescent waves (EW) with external medium is removal of cladding, and a schematic of cladding less optical fiber sensor is illustrated in **Figure 2**. The changes in propagation of optical signals due to variation in external environment facilitates the EW spectroscopy [8]. The facilitation of EW spectroscopy is highly sensitive and powerful technique to quantitatively and qualitatively investigate the environment present in the vicinity of sensing region of sensor. The EW leaks from core to cladding and the distance

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Figure 2.

Schematic of cladding less optical fiber sensor structure [3].

is termed as penetration depth. The penetration depth of EW can be evaluated as [9]:



where, λ is the propagating wavelength, n_s is the RI of surrounding environment and n_{eff} is the RI of guided mode propagating in the core.

The absorption spectrum of surrounding medium attenuates the EW which hindered the propagating mode. This can be understood from Lambert–Beer Law which is given as:

$$\frac{I}{I_0} = c^* \alpha^* L \tag{2}$$

where, c is the concentration of absorption substance, α is the attenuation constant of EW, and L is the path length in which optical signal interacts with the surrounding medium. I₀ and I are the intensities of the optical signal before or after the interaction to the external environment, respectively. The optical fiber sensor structure presented in **Figure 2** can be attained by removing the cladding part by using conventional approach such as treating the fiber with hydrofluoric (HF) acid [10]. To remove the cladding, fiber structure should need to be immersed in HF acid at constant stirring at 50 rpm. In cladding less optical fiber sensors the interaction of optical signal with surrounding can be enhanced by bending it in U-shape [11]. The U-shape bend is also useful for monitoring because source and detector will be on same side. Although, the cladding less fiber can also be attained by using other techniques such as plasma etching, but it will turn into expensive systems.

1.2 Tapered optical fiber sensor

An access to EW can also be obtained by tapering the optical fiber structure. The tapering of optical fiber usually done within the dimensions varying from



Figure 3. Schematic of tapered optical fiber structure [12].

submillimeter to several millimeters. The tapered region of the optical fiber maintains the uniform diameter with conical ends to merge it with unaltered part of optical fiber as illustrated in Figure 3. The tapering of fiber is done by heating the fiber structure by using flame or CO_2 laser beam. The properties of tapered optical fiber sensor is based on the diameter of conical ends, diameter of tapered region, and RI of surroundings. The proportion of EW power in tapered fiber structure, increases with decrease in diameter of tapered region and with decreasing RI difference of external environment and of fiber [13]. The tapered optical fiber provides numerous advantages to the sensors such as compactness, higher sensitivity and flexibility. The tapered optical fiber classified into categories such as adiabatic and non-adiabatic. When the tapered transition region is small in such a way that maximum optical power confines within the core, then such structure are termed as adiabatic tapered fibers [13]. However, in non-adiabatic one the diameter of tapered region is less than 10 μ m and the propagating modes couples into higher order modes [14]. The tapered optical fibers have been utilized in various sensing applications [15–17]. In case of tapered fiber structures, the interaction of EW with surrounding medium can be analyzed by two different.

approaches. In first approach, the attenuation of signal is to be measured which is propagating through tapered region and depends on the RI of surrounding medium [18]. In second one, the variation in surrounding medium affects the RI of modes propagating in the tapered section of fiber and works interferometrically, by using mode theory [19].

1.3 Interferometers

The optical fiber interferometers provide very high sensitivity because of their unique operational mechanism and usually known as modal interferometers (MI). In MI basically, the propagating modes splits into two modes at sensing region which are traveled in different RI regime that causes a difference in their phase and wavelength. The different properties of propagating modes lead to the interference in fundamental and higher order modes and results into a transmission spectrum with fringes. The phase of the fringes ca be given as:

$$\varphi = \frac{2\pi}{\lambda} (\delta n_{\rm eff}) L \tag{3}$$

where, L is the center to center distance between two modes and λ is the operating wavelength [20]. A SMF and thin core fiber (TCF) based Mach-Zehnder interferometer (MZI) is presented in **Figure 4**. The first strand of SMF carries a single mode which splits into two parts at TCF due to variation in core diameter. In second strand of SMF the modes from TCF gets recombined at SMF. The difference in phase of recombined modes leads to the addition or cancelation of phase at output of MZI [20].

The optical fiber based Michelson interferometers were also proposed and a schematic is illustrated in **Figure 5**. In Michelson interferometer, the core modes



Figure 4. Schematic of SMF and TCF fiber based Mach-Zehnder interferometer [21].

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Figure 6.

Schematic of optical fiber based FPI sensor [22].

distributed into higher order modes at tapered section and after striking to gold film reflects back and recombined at the tapered section. Therefore, an interference between the modes occurs at the tapered region that causes the generation of fringes. The presence of external medium in the region separating the taper and gold films introduces the interfering features in the received signal. In similar physical length, Michelson interferometer provides higher sensitivity because the twice interaction of optical signal with sensing region. These interferometers works on the basis of measurement of wavelength or amplitude of the spectrum.

received at the output. An another type of optical fiber based interferometer is Fabry-Perot interferometer (FPI). The FPI is consisting of a cavity between two reflectors and illustrated in **Figure 6**. Alternatively, a FPI can be developed by coating a thin metallic layer at the tip of the fiber which acts as a mirror and the distance between metallic layer and surrounding medium as an another mirror. A change in the RI of cavity or its length can modulate the signal. The modulated signal will be further used to measure the targeted measurand that modulates the signal.

1.4 Grating based optical fiber sensor

An optical fiber grating is consisting of slots placed periodically with an equal proportion. The slots in optical fiber structure leads to the modulation of the propagating optical signal. The grating can be incorporated by exposing the fiber structure to the ultra-violent or femtosecond laser with desired geometry [23]. The optical fiber based grating structure were also found to be a good candidate for the sensing applications [23]. A schematic of FBG sensor with its measurement setup is illustrated in **Figure 7**. The grating structure couples the forward and backward propagating modes of the core at the particular wavelength that satisfies the Bragg condition. A Bragg grating is considered as reflector which reflects a specific wavelength band



Schematic of measurement setup of FBG sensor [24].

along the optical fiber and transmitted all others. The reflected Bragg wavelength is governed by a mathematical expression which can be given as [23]:

$$\lambda_{\rm Bragg} = 2\eta_{\rm eff} \tag{4}$$

In Bragg grating based sensors, the interaction of EW with surroundings can be maintained or enhanced by modifying the fiber geometry such as tapering, etching of cladding of sensing region. Therefore, to overcome this limitation, tilted Bragg grating can be utilized in which the gratings are designed at a specific angle with respect to the axis of the core. The interaction of cladding modes with EW changes the wavelength of propagating cladding modes [25]. The interaction of EW with surrounding medium leads to the induction of inherent sensitivity to the external RI and to the nano-coatings placed over the cladding layers. While considering the fact long periodic (LPG) grating structures were come into origin. The LPG are generally created with in the length of 100 microns to 1 mm as illustrated in **Figure 8**. LPG usually couples the light form the core modes to the co-propagating modes of the structure [27]. The cladding mode suffers higher attenuation, therefore, the transmission spectrum of LPG can be analyzed by using the series of resonance bands.

From the above discussion, it can be concluded that optical fiber based sensors have wide applications in bio-sensing applications. A short summary of above discussed different geometries of optical fiber sensor structures is tabulated in **Table 1**. The tabulated form is easy enough to get a brief introduction to the required geometry of sensor.



Figure 8. Schematic of NP coated LPG sensor structure [26].

Measurand	Light parameters	Units
Absorption, concentration	Intensity	dB, %
RI, absorption, concentration, pressure, temperature, strain	Wavelength shift, intensity	dB, %, nm
RI, absorption, concentration, pressure, temperature, strain	Intensity, wavelength shift, phase	dB, %, nm, degrees
pressure, temperature, strain	Intensity, wavelength shift	dB, %, pm
RI, absorption, concentration, pressure, temperature, strain	Intensity, wavelength shift	dB, %, nm
-	Measurand Absorption, concentration RI, absorption, concentration, pressure, temperature, strain RI, absorption, concentration, pressure, temperature, strain RI, absorption, concentration, pressure, temperature, strain	MeasurandLight parametersAbsorption, concentrationIntensityRI, absorption, concentration, pressure, temperature, strainWavelength shift, intensityRI, absorption, concentration, pressure, temperature, strainIntensity, wavelength shift, phasepressure, temperature, strainIntensity, wavelength shiftRI, absorption, concentration, pressure, temperature, strainIntensity, wavelength shift, phasepressure, temperature, strainIntensity, wavelength shiftRI, absorption, concentration, pressure, temperature, strainIntensity, wavelength shift

2. Biochemical measurands in healthcare

The optimum properties of optical fibers such as higher sensitivity and low limit of detection are the crucial parameters, but in addition, the selectivity is also an important concept in biochemical measurement. The selectivity or specificity is important to avoid the interference of other biomolecules or biomarkers presented in targeted analytes. There are two approaches based on which the selectivity of biosensor can be attained. The first approach is to use special material fibers such as chalcogenide glasses, fluoride or silver halide glasses [28]. These fibers are transparent to IR wavelength, and on the contrary, biomolecules pursue the highly absorption features [29, 30]. However, the use of chalcogenide fibers is not useful because of their potential toxicity and still an effort is required to improve their responses towards biomolecules [28]. In second approach, there is indirect sensing of analytes by placing a biochemical layer over the sensing region. The biochemical layer changes the optical properties on the basis of surrounding RI. Such biosensors provide the quantitative and qualitative information of the chemical reagent under examinations. The chemical layer over the sensing region means the wavelength of output optical signal is managed by the properties of biochemical layer instead of absorption spectra. The sensitivity of such biosensors is depends on the length of sensing area, amount of EW and optical properties of the coated biochemical layer [31].

2.1 Chemical optical Fiber sensors

The diagnosis of biomolecules present in human bodies can be detected in two phase such as in gases or in liquid. In gas phase, the analysis can be done by analyzing the gases exhaled from skin or breath. In liquid phase, the analysis of biomolecules can be done by testing the samples such as urine, saliva, blood, sweat and tears.

2.1.1 Diagnosis in gas phase

The biomarkers released from human bodies are useful to develop the noninvasive techniques. The diagnosis of these biomarkers is important to find the presence of disease [32, 33]. The breath sniffing method is useful to analyze the patient suffering from renal failure in rats [34] and lung cancer detection [35]. Oxygen and carbon dioxide are the two gases that are routinely checked in clinical applications. The detection of these two gases was also performed by using optical fiber sensor by using pH indicator separated with well separated with emission bands [36]. Ammonia is one of the major component that affects the body

metabolism and can disturb the functioning of kidney and liver [37, 38]. In normal conditions, the ammonia releases from body skin from slight alkaline blood and its detection is used to diagnose the disease related to kidney and liver [39]. The ammonia diagnosis was carried out by using optical fiber sensors. Initially, the detection was done by employing pH detector based on indications [40]. Since then, reflector sensor tips [41], EW based fiber grating [42], and lossy mode resonance (LMR) [43] were reported. The sensitivity and limit of detection of such optical fiber sensor was extremely good in comparison of existing works.

The diagnosis of various organic compound is hardly done at clinical level, but number of studies were reported. Although, the optical fiber sensors for the detection of organic compounds are not very sensitive [44]. An EW based optical fiber sensor was put forwarded for the detection of gas exhaled from human skin [45]. The proposed sensor is also capable of analyzing the physiological changes by applying a pattern recognition technique. The optical fiber sensors have also been utilized for the diagnosis of humidity, which is one of the important factor in case of critical conditions [46]. The increase in humidity in human bodies leads to the dryness in mucosa and cause difficulties in breathing. However, instead of such critical need, the optical fiber based humidity sensors cannot be used in medical applications because of slow response and recovery time.

2.1.2 Diagnosis in liquid phase

The diagnosis of biomarkers present in human bodies can be done by measuring the pH of liquid. The pH of liquid present in stomach is varies from 1.3 to 3.5, and of urine and pancreas is from 8.0 to 8.8 [47]. A tilted FBG based sensor structure was reported to detect the pH of human body fluids [48]. The sensor is working on the basis of coated polymer films whose thickness varies according to the variation of body fluid concentration and leads to the change in optical properties of the signal. Despite of reported articles, the pH sensors have been utilized *in vivo* applications and are commercially provided by the Ocean Optics [49] and PreSens [50] with enough capabilities to be utilized in medical applications.

The pH detection in bio-fluids is also useful to detect the presence of drugs which will be helpful for pharmaceuticals and could be a milestone to develop therapeutic aids for human and animals [51]. The detection of antibiotics in human blood stream can be a useful step to prevent the overdose or to provide the effective dose for specific disorder. A LPG based vancomycin sensor was reported which can be used to treat some severe gram-positive infections [52]. The sensor is capable of detecting the very low concentration of antibiotics present in blood stream which were at the concentration of 10 nM with high specificity towards other biomolecules. Similarly, propofol is an anesthetic usually used in surgery and in regular use in intensive care units. Therefore, the detection of presence of propofol in human body is also an important factor, and a work was put forwarded for its detection while employing the optical fibers [53]. The reported work demonstrated a strong linearity with whole blood samples of human bodies.

3. Characterization and analysis process of optical fiber biosensors

The different geometries of optical fiber sensors should need to be characterized before involving them in sensing of biomolecules. The development of optical fiber biosensors involves four different process such as fiber geometries, used nanoparticles, detection of biomolecules and sensing analysis of developed sensor
probes. Therefore, this section presents a brief discussion of about the necessary characterization of optical fiber sensors at all the steps.

3.1 Optical fiber sensor geometry

The validation of drawn fiber sensor geometry such as tapered fiber, MZI etc. can be done by using scanning electron microscopy (SEM). SEM is a kind of electron microscopy which employs a focused beam of the electron to analyze the surface of optical fibers. The SEM image of a tapered optical fiber probe is illustrated in **Figure 9**. In **Figure 9**, there are two SEM images where the first one is representing an image of tapered optical fiber sensor and another image such as **Figure 9(b)** is representing the distribution of nanoparticles coated over the sensing region of fiber structure. In some other cases, the diameter analysis of tapered optical fiber sensor structure was measured directly by using the fabricating machine, but the accuracy of the measured diameter was not up to the mark, and illustrated in **Figure 10** [55].

3.2 Nanoparticles

The optical fiber sensor structures also utilize the immobilization of nanoparticles over the sensing region to enhance the sensitivity by means of introducing the concept of localized surface plasmon resonance (LSPR) phenomenon.



Figure 9.

SEM image of SERS probe of a tapered optical fiber sensor structure: (A) tapered optical fiber, and (B) distribution of nanoparticles over the fiber [54].



Figure 10. Analysis of tapered optical fiber sensor structure: (a) diameter analysis, and (b) transmitted spectra [55].

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The characterization of nanoparticles can be done by using UV-spectrophotometer and by observing their distribution through transmission electron microscopy (TEM) images. TEM is also a technique that employs a focused beam of electrons to visualize the distribution of particles in nanometer dimensions. The UVspectrophotometer provides the resonance peak of the nanoparticles through the absorbance spectrum and is useful to confirm their initial synthesis. The resonance peak of all the nanoparticle is different and usually falls in the visible spectrum of white light. The peak resonance wavelength in absorbance spectrum of gold and zinc oxide nanoparticles appears at 519 nm and 370 nm for the particles size of less than 15 nm and 50 nm, respectively, and illustrated in Figure 11. The initial confirmation of nanoparticles can be carried forward to analyze their distribution which usually done by using capturing the microscopic image by using TEM. The TEM images of gold and zinc nanoparticles are illustrated in Figure 12. From the TEM images it can be concluded that the distribution of nanoparticles is uniform and easily visible. Further, the morphology of the nanoparticles or layered nanomaterials is also an important factor to assure the synthesis of nanoparticles,



Figure 11. Absorbance spectrum of nanoparticles: (a) gold, and (b) zinc oxide [55].



Figure 12. TEM images of nanoparticles: (a) gold, and (b) zinc oxide [55].

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and can be done by taking the images by using atomic force microscopy (AFM). An AFM image of zinc oxide nanoparticles is illustrated in **Figure 13**.

3.3 Biomolecules

The preparation of samples of targeted biomolecules is also an important factor which helps in increase the performance of sensor probe. The analysis of samples of the targeted biomolecules can be done by preparing them in different pH base solutions. The similar kind of approach has been used to analyze the validity of ascorbic acid (AA) samples and illustrated in **Figure 14**. The performed test was basically done to check the solubility of artificial samples of AA [55]. The analysis was done by dissolving the artificial sample of AA in different pH solutions and the samples of lowest and highest concentration were prepared. Then, the peak resonance wavelength was measured for the highest and lowest sample concentration and their difference is plotted with respect to each pH solution. For the reported work, it was concluded that the AA samples are highly soluble in phosphate buffer solution (PBS) whose pH is about 7.4.

3.4 Sensing analysis

The sensing analysis of the sensor probe can be done in several steps. The first step is to sense all the samples through the sensor probe. For each measurement



Figure 14. Solubility test of ascorbic acid samples in different pH solutions [55].

respective peak resonance wavelength can be recorded which is useful to plot the autocorrelation coefficient of the sensor probe. The autocorrelation curve is used to evaluate the linearity, regression coefficient, sensitivity and resolution of the sensor. Then, the analysis of sensor can be done in terms of stability, reusability, reproducibility and selectivity.

The stability of any optical fiber biosensor can be evaluated by measuring the base solution through a sensor probe more than 10 times. The results can be plotted in terms of number of measurements and peak resonance wavelength. Then, the standard deviation (SD) can be evaluated to observe the stability and for a good sensor SD is usually less than 0.1.

The reusability is an another important parameter to analyze the performance of optical fiber sensor. Reusability can be evaluated by measuring two different concentration of bio-molecules through the same sensor probe. The measurement of any concentration should need to be performed three times to attain higher accuracy. The sensor head must need to be rinsed properly after all the measurements by using base solution. Then, the results can be plotted in terms of recorded spectra or in terms of peak absorbance wavelength. The resonance wavelength for similar concentration should be same for each measurement to attain the higher reusability.

The reproducibility is also an another important factor to analyze the performance of any optical fiber sensor. The reproducibility test can be done by measuring the similar concentration of bio-samples through one sensor probe. The measurement must need to be done at least 5 times to attain the higher accuracy. The outcome of the measurements can be plotted in terms of recorded spectra and in terms of peak resonance wavelengths. The higher reproducibility of the probe can be claimed if the peak resonance wavelength for all the measurements is similar.

The selectivity or specificity of the optical fiber sensor is a crucial factor of an optical fiber biosensor which helps in to remove the interference of other biomolecules present in real liquid samples of human bodies. The higher specificity of any optical fiber sensor can be attained by functionalizing the sensor head with appropriate enzyme which oxidize only in the presence of targeted bio-samples. For instance, the AA oxidized only in the presence of ascorbate oxidase.

4. Conclusions

This book chapter presents a brief discussion about the different optical fiber geometries which have been utilized for the development of different optical fiber sensors and biosensors. The mostly common used geometry of optical fibers is cladding less, tapered, interferometers, and gratings. The second section of the chapter presents the brief discussion about the presence of biochemical markers usually used in bio-sensing applications. The detection of biochemical markers is generally done in two phases such as in gas phase and in liquid phase. The third section of the chapter presents a brief discussion of the characterization and sensing process of the optical fiber based biosensors. The characterization of optical fiber sensor is done by capturing the images through TEM, SEM and AFM. The analysis of nanoparticles can be done by recording the absorbance spectrum by using UVspectrophotometer. The sensing analysis of the optical fiber sensor can be done by performing the stability, reusability, reproducibility and selectivity test of the sensor probe. The optical fiber based biosensors are emerging in current era and can be employed in various health care applications.

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References

[1] Hecht J, City of Light, The Story of Fiber Optics (New York: Oxford University Press) 1999, p 114.

[2] Parries M C, Optical fiber Contemp. Phys. 1989; 30: 303–304. DOI: 10.1080/ 00107518908225520.

[3] Correia R, James S, Lee S-W, Morgan S P and Korposh4 S. Biomedical application of optical fiber sensors. J. Opt., 2018; 20: 073003.

[4] https://thorlabs.com/newgrouppage9.cfm?objectgroup. (Accessed July 29, 2021)

[5] https://thorlabs.com/catalogPages/1100.pdf. (Accessed July 29, 2021).

[6] Grattan K and Meggitt B. Chemical and Environmental Sensing. 1999; Boston, MA: Kluwer Academic.

[7] Mehvar M, BIS C, Scharer C M, Young M M and Luong J H. Fiber-optic biosensors-trends and advances. Anal. Sci., 2000: 16, 677–672.

[8] Korposh S, Kodaira S, Lee S-W, Batty W J and James S W. Nano-assembled thin film gas sensor: II. An intrinsic high sensitive fibre optic sensor for ammonia detection. Sensor Mater., 2009: 21, 179– 189.

[9] Grattan K and Meggitt B. Chemical and Environmental Sensing, Boston, MA: Kluwer Academic, 1999.

[10] Singh L, Singh R, Zhang B, Kaushik
B K, Kumar S. Localized Surface
Plasmon Resonance Based Hetero-Core
Optical Fiber Sensor Structure for the
Detection of L-Cysteine. IEEE
Transactions on Nanotechnology, 2020:
19, 201-208. 10.1109/TNANO.
2020.2975297.

[11] Fang Y-L, Wang C-T and Chiang C-C. A small U-shaped bending-induced interference optical fiber sensor for the measurement of glucose solutions. Sensors, 2016: 16 1460. DOI: 10.3390/ s16091460.

[12] Tian Y, Wang W, Wu N, Zou X,
Wang X. Tapered optical fiber sensor for label-free detection of biomolecules.
Sensors (Basel). 2011: 11 (4), 3780-3790.
DOI: 10.3390/s110403780.

[13] Jarzebinska R, Korposh S, James S, Batty W, Tatam R and Lee S-W. Optical gas sensor fabrication based on porphyrin-anchored electrostatic selfassembly onto tapered optical fibres. Anal. Lett. 2012: 45, 1297–309. DOI: / 10.1080/00032719.2012.673097.

[14] Vahala K J. Optical microcavities. Nature, 2003: 424, 839–846. DOI: 10.1038/nature01939.

[15] Edwards P S, Janisch C T, He L, Zhu J, Yang L and Liu Z. Fibre taper based Raman spectroscopic sensing. Photonics Conf. (IPC) (IEEE), 2012, 501–2.

[16] Brambilla G. Optical fibre nanotaper sensors. Opt. Fibre Technol. 2010: 16331–42. DOI: org/10.1016/j. yofte.2010.08.009

[17] Brambilla G. Optical fibre nanowires and microwires: a review. J. Opt., 2010: 12, 043001

[18] Lucas P, Coleman G J, Jiang S, Luo T and Yang Z. Chalcogenide glass fibers: optical window tailoring and suitability for bio-chemical sensing. Opt. Mater., 2015: 47, 530–536. DOI.10.1016/j. optmat.2015.06.034.

[19] Farnesi D et al. Quasi-distributed and wavelength selective addressing of optical micro-resonators based on long period fiber gratings. Opt. Express, 2015: 23, 21175–80. DOI.org/10.1364/ OE.23.021175 Application of Fiber Optics in Bio-Sensing DOI: http://dx.doi.org/10.5772/intechopen.99866

[20] Lee B H, Kim Y H, Park K S, Eom J B, Kim M J, Rho B S and Choi H Y. Interferometric fiber optic sensors. Sensors, 2012: 12, 2467–2486.

[21] Huang, X., Li, X., Yang, J. et al. An in-line Mach-Zehnder interferometer using thin-core fiber for ammonia gas sensing with high sensitivity. Sci Rep., 2017: 7, 44994. DOI .org/10.1038/ srep44994.

[22] Zhang W, Wang R, Rong Q, Qiao X, Guo T, Shao Z, Li J, Ma W. An optical fiber Fabry-Perot interferometric sensor based on functionalized diaphragm for ultrasound detection and imaging. IEEE Photonics, 2017: 9, DOI: 10.1109/ JPHOT.2017.2694480.

[23] Kashyap R. Fiber Bragg Gratings, 2010. (San Diego, CA: Academic).

[24] Venkatesan, V. N., Ramalingam, R. Numerical and experimental investigation of FBG strain response at cryogenic temperatures. IOP Conf. Series: Materials Science and Engineering, 2017: 171, 012133. DOI: 10.1088/1757-899X/171/1/012133.

[25] Maguis S. et al. Biofunctionalized tilted fiber Bragg gratings for label free immune-sensing. Opt. Express, 2008:
16, 19049–62. DOI: .org/10.1364/ OE.16.019049.

[26] Urrutia A., Goicoechea J., and Arregui, F. J. Optical Fiber Sensors Based on Nanoparticle-Embedded Coatings. Journal of Sensors, 2015: 2015, 805053. DOI: 10.1155/2015/805053.

[27] Seitz W R. Chemical sensors based on fibre optics. Anal. Chem., 1984: 56, 16–34. DOI: org/10.1021/ac00265a711.

[28] Wilhelm A, Lucas P, DeRosa D and Riley M. Biocompatibility of Te–As–Se glass fibers for cell-based bio-optic infrared sensors. J. Mater. Res., 2007: 22, 1098–1104. DOI: 10.1557/ jmr.2007.0127. [29] Anne M-L et al. Chalcogenide glass optical waveguides for infrared biosensing. Sensors, 2009: 9, 7398. DOI: 10.3390/s90907398

[30] Wiercigroch E. et al. Raman and infrared spectroscopy of carbohydrates: a review. Spectrochim. Acta A, 2017: 185, 317–335. DOI: 10.1016/j. saa.2017.05.045

[31] Korposh S, James S, Tatam R and Lee S-W. Fibre-optic chemical sensor approaches based on nanoassembled thin films: a challenge to future sensor technology. Optical Fiber, 2013 ed S W Harun (Rijeka: InTech) ch 9. DOI: 10.5772/53399.

[32] Turner A P F and Magan N. Electronic noses and disease diagnostics. Nat. Rev. Microbiol., 2004: 2, 160–166. DOI: 10.1038/nrmicro823

[33] Pavlou A K, Magan N, Jones J M, Brown J, Klatser P and Turner A P F. Detection of Mycobacterium tuberculosis (TB) in vitro and in situ using an electronic nose in combination with a neural network system. Biosens. Bioelectron., 2004: 20, 538–544. DOI: 10.1016/j.bios.2004.03.002.

[34] Haick H, Hakim M, Patrascua M, Levenberg C, Shehada N, Nakhoul F and Abassi Z. Sniffing chronic renal failure in rat models via an array of random network of singlewalled carbon nanotubes. ACS Nano, 2009: 3, 1258–1266. DOI: 10.1021/nn9001775

[35] Peng G et al. Diagnosing lung cancer in exhaled breath using gold nanoparticles. Nat. Nanotechnol., 2009: 4, 669–673. DOI: 10.1038/ nnano.2009.235.

[36] Wolfbeis O S, Weis L J, Leiner M J P and Ziegler W E. Fiber-optic fluorosensor for oxygen and carbon dioxide. Anal. Chem., 1988: 60, 2028– 2030. DOI: 10.1021/ac00170a009. [37] Weiner I D, Mitch W E and Sands J M. Urea and ammonia metabolism and the control of renal nitrogen excretion. Clin. J. Am. Soc. Nephrol., 2014: 10, 1444–1458. DOI: 10.2215/CJN.10311013.

[38] Schmidt F M, Vaittinen O, Metsälä M, Lehto M, Forsblom C, Groop P H and Halonen L. Ammonia in breath and emitted from skin. J. Breath Res., 2013: 7, 017109. DOI: 10.1088/ 1752-7155/7/1/017109.

[39] Turner C, Španěl P and Smith D. A longitudinal study of ammonia, acetone and propanol in the exhaled breath of 30 subjects using selected ion flow tube mass spectrometry. SIFT-MS Physiol. Meas., 2006: 27, 321–337. DOI: 10.1088/ 0967-3334/27/4/001.

[40] Wolfbeis O S and Posch H E. Fibreoptic fluorescing sensor for ammonia. Anal. Chim. Acta, 1986: 185, 321–7. DOI: .org/10.1016/0003-2670(86)80060-5.

[41] Wang T, Yasukochi W, Korposh S, James S W, Tatam R P and Lee S-W. A long period grating optical fiber sensor with nano-assembled porphyrin layers for detecting ammonia gas. Sensors Actuators B, 2016: 228, 573–580. DOI: 10.1016/j.snb.2016.01.058.

[42] Rodríguez A J et al. A fiber optic ammonia sensor using a universal pH indicator. Sensors, 2014: 143, 4060–73. DOI: .org/10.3390/s140304060.

[43] Tiwari D, Mullaney K, Korposh S, James S W, Lee S-W and Tatam R P. An ammonia sensor based on Lossy mode esonances on a tapered optical fibre coated with porphyrinincorporated titanium dioxide. Sensors Actuators B, 2017: 242, 645–652. DOI: 10.1016/j. snb.2016.11.092.

[44] Shirasu M and Touhara K. The scent of disease: volatile organic compounds of the human body related to disease and disorder. J. Biochem., 2011: 150, 257–266. DOI: 10.1093/jb/mvr090 [45] Elosua C, Matias I R, Bariain C and Arregui F J. Volatile organic compound optical fiber sensors: a review, Sensors, 2006: 6,1440–1465.

[46] Hernandez F U et al. Optical fibre sensing during critical care. Proc. SPIE, 2017: 10340, 1034012.

[47] Schwalfenberg G K. The alkaline diet: Is there evidence that an alkaline pH die benefits health. J. Environ. Public Health, 2012: 2012, 727630. DOI: 10.1155/2012/727630

[48] Shao L-Y, Yin M-J, Tam H-Y and Albert J. Fiber optic pH sensor with selfassembled polymer multilayer nanocoatings. Sensors, 2013: 13, 1425– 1434. DOI:10.3390/s130201425

[49] https://oceanopticscom/measureme nttechnique/ph-sensing.

[50] https://presensde/products/ph/se nsorshtml.

[51] Tiwari G et al. Drug delivery systems: an updated review. Int. J. Pharm. Invest., 2012: 2, 2–11. DOI: 10.4103/2230-973X.96920

[52] Korposh S, Chianella I, Guerreiro A, Caygill S, Piletsky S A, James S W and Tatam R P. Selective vancomycin detection using optical fibre long period gratings functionalised with molecularly imprinted polymer nanoparticles. Analyst, 2014: 139 2229–36. DOI: 10.1039/c3an02126b

[53] Li L, Ding H, Lia B D W and Chen J. Rapid detection of propofol in whole blood using an automated on-line molecularly imprinted pretreatment coupled with optical fibre detection. Analyst, 2012: 137, 5632. DOI: 10.1039/ c2an35523j

[54] Zhu, G., Singh, L., Wang, Y. et al. Tapered Optical Fiber-Based LSPR Biosensor for Ascorbic Acid Detection. Application of Fiber Optics in Bio-Sensing DOI: http://dx.doi.org/10.5772/intechopen.99866

Photonic Sens.: 2020). DOI: 10.1007/ s13320-020-0605-2.

[55] Urrutia A., Goicoechea J., and Arregui, F. J., Optical Fiber Sensors Based on Nanoparticle-Embedded Coatings. Journal of Sensors, 2015: 2015, 805053. DOI: 10.1155/2015/805053.

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Chapter

Photonics for AI and AI for Photonics: Material and Characteristics Integration

Sunil Sharma and Lokesh Tharani

Abstract

We are living in the technological era, where everything is integrated with each other. If we are discussing regarding communication, it is integrated with one or two technologies. If we are discussing regarding automation, discussing regarding Image processing, discussing regarding embedded system, they all are integrated with a combination of technologies. Correspondingly Artificial Intelligence (AI) and Photonics are also integrated with each other. Now a day as AI is utilizing with photonics in abundant fields as well photonics is also serving AI to facilitate ultrafast AI networks to offer a novel class of Information Processing Machines (IPM). This chapter is based on identification and implementation of photonics for AI utility and AI for photonics. In this category a Dual core Photonics crystal fiber (PCF) is proposed which serve to identify infected cells of human being along with the integration of AI. This proposed design of PCF is providing relative sensitivity and confinement loss in an optimized manner with the impact of AI. Here potency of AI as well as of Photonics is explained to serve their applications related to each other.

Keywords: Artificial Intelligence, Fiber Optics and Photonics, Optical Networks, Photonic Crystal Fiber, Integration

1. Introduction

Latest technological development in photonics has multiplied only due to integration of photonic platform with conception of Opto-electronic elements [1]. The Photonic Integrated Circuits (PICs) [2] have facilitated the ultrafast Artificial Neural Networks (ANN) [3], to propose a novel class of Information Processing Machines (IPM) [4]. There are number of reasons available which reveals that photonics is somewhere associated with AI. In this direction the latest example can be considered as development of Neuro-morphic [5] electronics, which shows that *high processor delay* can be eliminated by offering a consequent technology to extend the vicinity of AI. It offer sub-nanosecond [5] delay and consequently conquers challenges in terms of present and future aspects.

This latest developed technology 'Neuro-morphic electronics system' [5] is integrated with most recognized technology which is known as semiconductor photonics. It is composed of third and fifth group of elements i.e. GaAs and InP [2].



Figure 1. GaAs & InP Composed Photonic Integrated Circuits [2].

Below **Figure 1** represents the photonic integrated technology indicating fabrication, characteristics like growing and mixing of GaAs and InP materials to provide efficient, robust, and monolithic optoelectronic integration platform. It was developed and observed by Sandia National laboratory services.

The developmental growth of photonic crystals, components and meta-materials [6] lead to the advancement of photonics in the area of designing, modeling and technological integration. This kind of integration investigates AI with photonics. This promising domain is someway sustained by 'photonic materials' [7] which assist to find out and intend innovative applications of AI. It should be noted down that how photonics is contributing for the implementation of AI tools and techniques.

The contributing field of photonics towards AI includes Neuro-morphic electronic system, Optical Neural Network (ONN), Nano Photonics,



Figure 2.

Proposed dual cores PCF with different mode indexes.

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meta-materials, optical sensing, optical imaging [8], optical computing, Information Processing Machines etc. These above mentioned optics emerging domains can be integrated with AI tools [9] to enhance the efficiency and performance of these systems.

Figure 2 represents the design structure of dual core silica PCF with an effective index mode of 1.4053. By changing the mode index value we can have light confinement variation which is shown below in **Figure 3** (**a** & **b**).

As shown below in **Figure 4** indicates contribution of photonics in terms of machine intelligence with Neuro-morphic computing along with Optical neural network and optical sensing for AI technology. These latest technologies helped AI to diagnose critical disease.



Figure 3.

(a, b) Light Confinement through proposed design for different values of Index Modes (c) Identification of infected cells with AI (d) Relative sensitivity (e) confinement loss of proposed design.



Figure 4.

Contributing field of photonics for AI (a) AI with Neuro-morphic computing (b) Optical Neural Network (c) Optical sensing and computing [5].

2. Photonics materials and their characteristics for AI

We all are witnessing an inconceivable age of drastically development in applications that necessitate expansion in AI [10]. If we are discussing about the ingenious novel outcomes that are gradually trending towards the market place and many more are preferred and expected. Fiber Optics & Photonic materials [11] are widely used for these products like new display, personalized mobile devices, novel sensors, and new information processing machining products for both storage and data processing. It is trending in very clear manner that the areas of Fiber Optics & Photonic materials are fundamental technologies for the globe. Inventing and uncovering new materials [12] in the Fiber Optics & Photonics domain will be exceedingly critical to see more and more novel outcomes to improve normal people's lives.

Materials that have been exposed at the crucial point of life, always changes the history of human being along with the country. Materials that are used to senses, materials that are used to stores, materials that can be used as energy efficient, some translucent materials which can be folded easily and some materials that are manufacturable at low cost. New discovered materials such as doped silica materials [13], resistance changing materials and spontaneously magnetize and polarize materials have been discovered and using widely for AI integration and their applications.

In the line of discovery of new materials, the Picometer [7] can also be considered as a vibrant example in the field of atomic structures. There are numerous atomic structures available that were simulated and their data were utilized for AI analysis to identify artificially controlled 'oxygen octahedral rotation' (OOR) patterns as shown in below **Figure 5**. Photonics for AI and AI for Photonics: Material and Characteristics Integration DOI: http://dx.doi.org/10.5772/intechopen.97781



It was used as Disorder-Driven Metal–Insulator Transition in Crystalline Vacancy-Rich Ge-Sb-Te Phase-Change Materials [7].

2.1 New Investigative Materials for AI

The discovery and development in the new materials plays an important role in the technological progress. As we have already seen that how silica has revolutionized the microelectronics industry. Materials discovery and design efforts require interplay between materials prediction, synthesis and characterization [12] have increased applications of computational tools and techniques, increased generation of material's databases, and accelerated advances in experimental methods significantly. Some of them are composed of three special elements i.e. germanium, antimony and tellurium which is defined as Ge-Sb-Te alloy [2] and can be termed as phase-change memory materials. This alloy is selected from the group of chalcogenide glass (As_2Se_3) [12] which can be used in rewritable optical discs.

The above mentioned **Figure 6** is used as a non-volatile quasi-continuously reprogrammable platform. This phase-change memory material rapidly changes its atomic structure from crystalline to solid amorphous when swiftly melted in presence of temperature. These kinds of materials are widely used in 'electronic memory' applications of AI tools such as *data storage*. Even though there are countless integration is possible with Ge-Sb-Te alloy, the new material **GST467** [6] revealed by CAMEO (Closed-Loop Autonomous System for Materials Exploration and Optimization) is most favorable for phase-changing applications.

CAMEO found the best Ge-Sb-Te alloy that had the largest difference in "optical contrast" [6]. GST467 also found applications in photonic switching devices that can be used to control the direction of light in given circuit. These devices can also be utilized in Neuro-morphic computing [5], which is an emerging field focusing on development of devices which imitate the formation and role of neurons in human brain. Materials science or solid-state physics is plagued by the 'curse of dimensionality'.

3. AI for photonics

When the words "artificial intelligence" (AI) comes to mind, our first thoughts may be of super-smart computers or robots that perform tasks without needing any help from humans.



Figure 6.

 GST_{467} with AI (a) Schematic cross-section of the hybrid waveguide. (b) $\mathfrak{G}(c)$ Fundamental quasi-transversal electric (TE) mode profiles of the hybrid waveguide at 1550 nm for (d) complex refractive index of GST and GST as a function of wavelength. (e) XRD data of GST [6].

A multi-institutional team of research scholars from National Institute of Standards and Technology (NIST) [6] have developed an AI algorithm known as CAMEO. It was used for the discovery of potentially applicable new photonic material without any additional preparation and efforts from the scientist. These AI systems helped to reduce the trial-and-error time which generally scientists use up in the lab. Along with this these systems maximizes the productivity and efficiency of their research work. Another research scientists team at POSTECH (Pohang University of Science and Technology) [7] got succeed in creating a novel substance that generates electricity by effect of polarization at room temperature. The variation so observed would be confirmed in crystal structure by analysis of deep neural network. The above mentioned examples revealed the techniques behind making materials used in new memory devices by using artificial intelligence. So it is very much clear that the use of modern computational techniques like AI can be used to improve the rate of discovery of these new photonics materials and vice versa. Helping scientists in reaching their outcomes more efficiently and quickly by performing only few experiments with limited resources. All these things became possible only because of integration of AI and Photonics.

The optical properties are typically calculated by using Maxwell's Equations [13]. The desired optical response can be obtained by adjusting the initial design and performing multiple simulations until the outcome is achieved. Despite designing issues AI can help optics and nano photonics in different tasks, for example AI used to estimate the optical properties of black carbon fractal aggregates. Another

example is reported where they combines finite element simulations and clustering for the identification of photonic modes [14] with large local field energies and specific spatial properties. It is shown that the combination of machine learning with photonics [15] can revolutionize one of the most important fields in optical imaging.

4. Proposed dual core PCF design integrated with AI

The silica glass is easily available and have some characteristics due to this it is preferred for designing PCF structures. Below **Table 1** depicts some properties of silica glass [15].

Silica is the purest form of SiO_2 which is easily available from the sand as a raw material. This raw silica is used to convert into Electronic Grade Silicon (EGS) from various processes. This glass has superior transmission chatcteristics in the UV (Ultra-violet) and IR (Infra-red) spectra, a very low dielectric coefficient and excellent properties where fluorescence or polarization is an issue. This silica can be shaped too many forms and sizes. It has excellent resistance to non-fluorinated acids, solvents and plasmas. The finite-difference method is the most accurately and numerically efficient method to solve Maxwell's Equation [15] and needs less computational time.

By selection of Silica glass as a core material for designing of PCF structure, below mentioned **Figure 7** depicts the cross-sectional view of proposed dual core Silica PCF with circular sensing ring. The diameter of the air hole is 1.2 μ m. Here elliptical air hole is also used in the first layer and the semi major and semi minor axis for that ellipse is 1.2 and 0.8 μ m respectively. The pitch value for the proposed structure is 2 μ m.

After designing the structure of Dual Core PCF if there is a variation of index mode then due to different mode index values, there must be some variation measured in confining light through designed PCF. This variation is already mentioned in above **Figure 3 (a & b)**.

It indicates that as index mode value varies like 1.4053, 1.4055, 1.4088, 1.41.... The variation is observed in confining the light through core of the proposed fiber.

The proposed dual core PCF for sensing various applications like blood sample detection, alcohol detection, disease detection, White Blood Cells (WBC), Red Blood Cells (RBC) detection and for many more pathological detection can be integrated with AI technology which provides optimized results to diagnose infected cells. For this purpose below mentioned setup as shown in **Figure 8** is

Properties	Silica Glass
Density (g/cm ³)	2.2
Refractive Index (micrometer)	1.458
Light Transmission wavelength (micrometer)	0.18–2.5
Max Temperature (Degree Centigrade)	1120
Poission's Ratio	0.17
Specific heat capacity (J/Kg-K)	720
Speed of sound (m/s)	$180 imes 10^3$

Table 1.Properties of Silica Glass Material [12].

Setting	s			- 8	Graphics Convergence Plot 1	
Parameter	s				QQ@⊕∰ ↓ • ∅ ● ● ● ≥ ≥ ≥	6
· Param	eters			^		
** Name	Expression	Value	Description	1	12	
e	1.5(um)	1.5000E-6 m		8		
P	2[um]	2.0000E-6 m			10	
lamda	1.55[um]	1.5500E-6 m			8]	
r	d/2	6.0000E-7 m			of / / 000000 \	
x1	sqrt(3)/2	0.86603				1
y1	1/2	0.5				1
B1	0.6961663	0.69617			2 / /00000000000	- 1
C1	0.0684043e-6	6.8404E-8				
B2	0.4079426	0.40794			2 1 10000000000	1
C2	0.1162414e-6	1.1624E-7	1			
B3	0.8974794	0.89748				1
C3	9.896161e-6	9.8962E-6				/
n_silica	sqrt(1+(81*lamd	1.444				/
n_pml	5.5[um]	5.5000E-6 m			-10	
PML	14.3[um]	1.4300E-5 m				

Figure 7.

Proposed Dual Core PCF with Perfectly Matched Layer (PML) Boundary.



Figure 8. *Experimental Setup to Obtain Outcomes.*

arranged. With the help of this setup the proposed dual core PCF can be utilized with AI to serve better and improved outcomes. The above mentioned **Figure 3 (c)** represents the infected cell by using designed PCF structure integrated with AI. Relative sensitivity and confinement loss is also displayed in **Figure 3 (d & e)**.

In this setup the optical source is used to supply power to the Fiber. By using the splicing technique fiber can be connected with the proposed PCF. IN and OUT ports are used to control the unknown analytes whose refractive Index (RI) need to be identified. When analyte interacts then the variations in terms of lows and peaks occurs which can be observed and displayed using computer. The outcomes so obtained can be enhanced to provide efficient result with AI. Dual core silica PCF

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Parameter Tested	Refractive Index	Relative Sensitivity (%)	Confinement Loss (dB/km)
Ethanol	1.33	56.90	2.37×10^{-6}
Blood Serum	1.39	46.51	3.814×10^{-10}
Water	1.32	53.57	$8.063 imes 10^{-11}$

Table 2.

Test Performed for various parameters.

serve as a sensing element used to sense the selected parameter and the AI technology boost the effects of results so obtained.

With the Above mentioned proposed design the following tested have been performed using Dual core Silica PCF.

Depending upon the refractive index of blood serum, the intensity of light is modulated and detected at other end of PCF [16]. The relation between evanescent field absorbed by sensing species and intensity modulation at output end is observed.

Sensitivity is obtained by using

$$\mathbf{r}_f = f\left(\frac{n_r}{n_c}\right) \tag{1}$$

Where n_r is the refractive index of the fluid, n_c is core refractive index, r_f is relative sensitivity coefficient and 'f' is the ratio of optical power with in large holes to the total power which is given as

$$f = \int \left[\left(E_x H_y - H_x E_y \right)_{samples} / \int \left[\left(E_x H_y - H_x E_y \right) \right]_{total}$$
(2)

Confinement loss [17, 18] is calculated by

$$L_{C} = (40\pi/\ln (10) \lambda) \operatorname{Im} (\operatorname{neff}) [dB/km]$$
(3)

or it can be written as

$$L_{C} (dB/m) = 8.686 k_0 I_m (n_{eff}) \times 10^6$$
 (4)

Here $n_{e\!f\!f}$ signifies imaginary part of effective refractive index, and k_0 is the free-space number.

The data set of blood serum, ethanol and water for this case of investigation is selected as an input which can be passed through the setup and results so obtained have been optimized by using AI. These results obtained numerically and experimentally have been presented in above mentioned **Table 2**.

5. Discussion

The potency of the AI standards lies in its capacity to deal with anonymous computing troubles. It is practically identified that it is giving not only innovative or optimized solutions and forecasting, but also original substantial impending to the structure by using integration with technologies. Here we have presented an integrated discussion between AI and Photonics. The AI has been utilized to nurture tiny investigational datasets in iterative method to envisage new materials and execute multi objective optimization of properties for selected materials. Correspondingly Photonics is also offering new materials for booming realization and performing computation takes in an efficient manner to AI. The characteristics of the dual-core photonic crystal fiber (PCF) sensor are studied using the finite element method (FEM), and the structure is improved according to the numerical simulation results.

6. Conclusions

In the revolutionary field of optics and photonics, most of the work has so far been offered on purpose of photonics to the realization of AI to the intend, expansion and optimization of photonic meta-materials and various devices. AI techniques present prospects both to expand physical approaching and to investigate constraints in a more proficient manner.

Most successful paradigms of AI and photonics like Neuro-morphic electronic system, Optical Neural Network (ONN), Nano Photonics, meta-materials, optical sensing, optical imaging have also been demonstrated here in this chapter in which AI is boosting photonics and similarly photonics is also helping AI to perform efficiently. The proposed Dual core Silica PCF is used to identify infected cell in a human body. Due to easily presence of Silica glass and its vibrant characteristics it is preferred for the proposed PCF design. The refractive index of selected material is 1.458, Specific heat capacity is 720 J/Kg-K, Light Transmission wavelength is 0.18–2.5micrometer. It has been observed that the relative sensitivity for ethanol, blood serum and water is 56.90%, 46.51% and 53.57% respectively. Similarly the confinement loss for the proposed structure is 2.37×10^{-6} , 3.814×10^{-10} and 8.063×10^{-11} dB/km respectively for the same parameters as mentioned above.

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Conflict of interest

I declare no conflict of interest for this research article.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

[1] Piccinotti D., MacDonald K.F., Gregory S.A.,, Youngs I. and Zheludev N.I. (2020) Artificial intelligence for photonics and photonic materials, IOP Publishing Ltd. Rep. Prog. Phys. 84 012401

[2] Wang, J. J., Xu, Y. Z., Mazzarello, R., Wuttig, M., & Zhang, W. (2017). A Review on Disorder-Driven Metal-Insulator Transition in Crystalline Vacancy-Rich GeSbTe Phase-Change Materials. Materials (Basel, Switzerland), 10(8), 862. https://doi. org/10.3390/ma10080862

[3] Soler M, Estevez M.C., Rubio M.C., Astua A., and Lechuga L.M., (2020) How Nano photonic Label-Free Biosensors Can Contribute to Rapid and Massive Diagnostics of Respiratory Virus Infections: COVID-19 Case A CS Sensors, 5 (9), 2663–2678 doi: 10.1021/ acssensors.0c01180.

[4] V Goda K., Jalali B., Lei C., Situ G., and Westbrook P., (2020) AI boosts photonics and vice versa, APL Photon. 5, 070401, doi: 10.1063/5.0017902.

[5] Roy, K., Jaiswal, A. & Panda, P., (2019) Towards spike-based machine intelligence with Neur-omorphic computing. Nature 575, 607–617. https://doi.org/10.1038/s41586-019-1677-2.

[6] Zeng J., Khanolkar A., Xu P., Colburn S., Deshmukh S., Myers J., Frantz J., Pop E., Hendrickson J., Doylend J., Boechler N., and Majumdar A., (2018) GST-on-silicon hybrid nanophotonic integrated circuits: a non-volatile quasi-continuously reprogrammable platform," Opt. Mater. Express 8, 1551–1561

[7] Peng Chen, Mathieu N. Grisolia, Hong Jian Zhao, Otto E. González-Vázquez, L. Bellaiche, Manuel Bibes, Bang-Gui Liu, and Jorge Íñiguez, (2018) Energetics of oxygen-octahedra rotations in perovskite oxides from first principles, Phys. Rev. B 97, 024113

[8] Wei, J.; Yi, L.; Giacoumidis, E.; Cheng, Q.; Tao Lau, A.P., (2020) Special Issue on "Optics for AI and AI for Optics, Appl. Sci. 10, no. 9: 3262. https:// doi.org/10.3390/app10093262

[9] Soler M., Scholtz A., Zeto R., and Armani A.M., (2020) Engineering photonics solutions for COVID-19, APL Photonics 5, 090901, https://doi.org/ 10.1063/5.0021270

[10] Taha, B.A.; Al Mashhadany, Y.; Hafiz Mokhtar, M.H.; Dzulkefly Bin Zan, M.S.; Arsad, N., (2020) An Analysis Review of Detection Corona virus Disease 2019 (COVID-19) Based on Biosensor Application, Sensors, 20, 6764. https://doi.org/10.3390/ s20236764

[11] Yao K., Unni R. and Zheng Y.,
(2019) Intelligent nanophotonics: merging photonics and artificial intelligence at the nanoscale, De Gruyter | 2019 doi: https://doi.org/ 10.1515/nanoph-2018-0183

[12] Sharma R.K., S. Sharma and Vyas K., (2018) Analysis of Different Types of Core Materials in Photonic Crystal Fiber, 5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON), Gorakhpur, India, pp. 1–6, doi: 10.1109/ UPCON.2018.8597132

[13] Sharma S., Sharma R.K., Gupta R., Dash P. (2020) Design and Analysis of Elliptical Core Spiral Silica Photonic Crystal Fiber with Improved Optical Characteristics. In: Kumar A., Mozar S. (eds) ICCCE 2019. Lecture Notes in Electrical Engineering, vol 570.
Springer, Singapore. https://doi.org/ 10.1007/978-981-13-8715-9_9 Photonics for AI and AI for Photonics: Material and Characteristics Integration DOI: http://dx.doi.org/10.5772/intechopen.97781

[14] Jain A., Sharma R.K., Agarwal V., Sharma S. (2020) A New Design of Equiangular Circular Cum Elliptical Honeycomb Photonic Crystal Fiber. In: Ranganathan G., Chen J., Rocha Á. (eds) Inventive Communication and Computational Technologies. Lecture Notes in Networks and Systems, vol 89. Springer, Singapore. https://doi.org/ 10.1007/978-981-15-0146-3_6

[15] Sharma S., Tharani L., Sharma R.K. (2020) Designing a Nonlinear Tri Core Photonic Crystal Fiber for Minimizing Dispersion and Analyzing it in Various Sensing Applications. In: Mathur G., Sharma H., Bundele M., Dey N., Paprzycki M. (eds) International Conference on Artificial Intelligence: Advances and Applications 2019. Algorithms for Intelligent Systems. Springer, Singapore. https://doi.org/ 10.1007/978-981-15-1059-5_3

[16] H. Ademgil, Highly sensitive octagonal photonic crystal fiber based sensor, Optik-Int. J. Light Electron Opt.125 (20) (2014) 6274–6278

[17] V. Kaur and S. Singh, "Performance analysis of multichannel surface plasmon resonance sensor with dual coating of conducting metal oxide," J. Nanophotonics 12(1), 016012 (2018).

[18] U. S. Dinish et al., "Highly sensitive SERS detection of cancer proteins in low sample volume using hollow core photonic crystal fiber," Biosens. Bioelectron. 33(1), 293–298 (2012).

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Chapter

Laser Opto-Electronic Oscillator and the Modulation of a Laser Emission

Alexander Bortsov

Abstract

The autonomous optoelectronic generator (OEO) is considered in the chapter as a source of low-noise oscillations. Differential equations are considered and methods with OEO modulation with direct and external modulation are analyzed. The complexity of both approaches is related to the non-standard way of description of the nonlinear method modulation for the internal (direct) structure and the utilization of the specific Mach-Zehnder modulator for the first stage on external modulation. The purpose of the presentation is to consider the main features of OEO as a low-noise generator. This includes consideration based on the study of differential equations, the study of transients in OEO, and the calculation of phase noise. It is shown that different types of fibers with low losses at small bending radii can be used as a FOLD in OEO. The important role of the choice of a coherent laser for OEO with a small spectral line width is shown. The prospects of using structured fibers with low losses at bends of less than 10 mm in OEO are described. The results of modeling dynamic processes in OEO with direct modulation are presented.

Keywords: opto-electronic oscillator, phase noise, optical fiber, QW laser, microwave oscillator

1. Introduction. The opto-electronic oscillator structure

Development and creation of the compact ultra-low-noise microwave signal sources, which would be impact-resistant, is an important problem of modern radio-physics and radio engineering. Levels of the phase noise spectral density at the microwave source output must be for most of the applications –120 ... -170 dB/ Hz at generation frequency 8 ... 12 GHz for 1-kHz offset from a carrier. Constructions of these oscillators must sustain the strong mechanical impact loads in 200 ... 2000 N/cm and high accelerations up to 2 ... 10 g. Geometrical dimensions of the modern signal sources should often be approximately 10x10x10 cubic mm, especially for the satellite applications.

Development and implementation of new compact microwave and millimeterwave oscillators with improved performance would lead to revolutionary jump in radio electronics, perhaps, comparable to discovery of the quantum-dimensional lasers or (as in radio engineering) at arriving of the high-stability quartz crystal resonator. The new type of oscillators called as opto-electronic oscillator (OEO) described in this paper will permit to use in the mobile communications and in

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Internet systems of new radiofrequency channels for information transmission, including 30 ... 75-GHz ranges at the low power of transmitters. A number of publications devoted to OEO experimental investigations grows each year [1–8].

Opto-electronic oscillators will undoubtedly find wide application in the fiberoptical communication lines as well as in on-board radar systems on millimeter- and centimeter ranges, in communication systems as low-noise local oscillators in receivers and as a master clock in transmitters, in an optical lidar technology, as sensors of different physical quantities and in many other systems [8–16].

OEO diagrams with the direct modulation (OEO DM) presented in **Figure 1a** and the OEO structural diagram with *external modulation* of optical emission, which is often called as an opto-electronic oscillator with the Mach–Zehnder modulator (OEO MZ) presented in **Figure 1b**.

Let us consider the case of OEO operation with a small modulation index, and under the condition that the width of the spectral line of the optical laser







Figure 1.

Structural diagrams of the optoelectronic oscillator (a) with the direct modulation by current and (b) with external Mach-Zehnder modulator. Laser = the optical quantum generator (the laser or QWLD), MZ = the electro-optical MZ modulator, OA = the optical amplifier, OF = the optical filter, OF = the optical fiber, P_p = the pumping power, PD = the photo-detector, NA = the nonlinear amplifier, F = the RF filter, C = the RF coupler, CH1, CH2 = the optical channels of the MZ modulator.

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generation Δv_L is much smaller than the radio frequency f_0 of the OEO generation: $\Delta v_L < < f_0$. In this case, the spectrum of the modulated radiation can be represented by several harmonics. We will limit our analysis to the case of two or three optical harmonics, respectively, with frequencies $v_1 = v_1 - f_0$, $v_2 = v_0$, $v_3 = v_3 - f_0$. Two of these optical frequencies v_1 and v_2 are spaced from the central optical laser frequency v_0 by the sub-carrier frequency f_0 .

Figure 2a and **b** shows the analog model of statistical processes in OEO MZ with utilization of the random variables correlator. The correlator structure is described in [**16**]. It consists of the multiplier "*", two optical channels with different delays, and the delay cell defining by he delay in the optical fiber. The functional diagram **Figure 2a** and **b** illustrating principles of the correlator method and the frequency



Figure 2.

The functional diagram illustrating principles of the correlator method and the frequency discriminator method in OEO with the MZ modulator and in the circuit with direct amplitude modulation at suppression of the one harmonic. a) Diagrams (1–4) of optical frequency selection; b) L = the laser, T_{1M} and T_{2M} = delay lines have delay times in channels, " + " = (adding), "x" = (multiplication), "*" = (conjugate operation), " \int " = (integration), F = the low-pass filter, a = the amplifier.

discriminator method in OEO with the MZ modulator and in the circuit with direct amplitude modulation at suppression of the one harmonic.

2. OEO with direct modulation and OEO with the Mach Zehnder modulator

As in [8–16] when studying noise, OEO is considered here as an optoelectronic system in which oscillations are formed in the optical and radio frequency ranges. The oscillation frequency of the laser is approximately 200 Hz, and the radio frequency of the OAO generation is approximately 10 GHz. A VLD quantum-dimensional laser diode is used to generate laser radiation. The positive feedback ring is formed by an optoelectronic circuit consisting of a modulator, an optical fiber, a photodetector, an electronic amplifier, an electronic filter, and a directional coupler.

Fluctuations are formed at the OEO output. Laser fluctuations are of a quantum nature. When using a low-noise amplifier, the phase fluctuations of the laser determine mainly the noise of the OEO output.

3. OEO construction and its operation principle

Figure 1a shows a direct modulated OEO diagram. At the same time, the QWLD laser it works in the mode of amplitude modulation or intensity modulation. In **Figure 1b** the diagram of the OEO with external modulation is presented.

The OEO DM diagram (**Figure 1a**) is formed by a QWLD laser; a single-mode optical fiber (FO); a photodetector (FD); an electronic amplifier (A); an electronic filter (F), for example, based on a dielectric microwave resonator. The OOO MZ diagram (**Figure 1b**), in addition to the QWLD laser, includes elements that form a closed loop: the Mach Zehnder modulator (MZ); a fiber-optic system (FOS) containing an optical filter (OF) and single-mode optical fiber (FO); photodetector (PD), such as a quantum photodiode size; narrow-band RF filter (F), nonlinear amplifier (A), and directional coupler (C). A fiber-optic delay line (RF FODL) is formed by a laser connected in series, OF, FO, and PD (**Figure 1a**), or by a laser connected in series, MZ, OF, FO, and PD (**Figure 1b**). OEO can be considered as a delayed feedback oscillator.

Figure 1a and **b** show a laser as a source of optical oscillations, which includes a closed-loop optical amplifier (OA) and an optical filter (OF). We consider the case of the laser radiation modulation mode for single-mode, single-frequency, and linearly polarized optical radiation. When self-excitation conditions are met in such OEO systems (**Figure 1**) generation of microwave range oscillations occurs. A fiber-optic delay line (RF FODL) is formed by a laser connected in series, OF, FO, and PD (**Figure 1a**), or by a laser connected in series, MZ, OF, FO, and PD (**Figure 1b**). OEO can be considered as a delayed feedback oscillator.

Figure 1a and **b** shows a laser as a source of optical oscillatons, which includes a closed-loop optical amplifier (OA) and an optical filter (OF). The pump or pumping power P_p of the laser is shown conditionally.

We consider the case of the laser radiation modulation mode for single-mode, single-frequency, and linearly polarized optical emission of the highly-coherent laser. When self-excitation conditions are met in such OEO systems, **Figure 1** generation of microwave range oscillations occurs.

In the diagram in **Figure 1**, the Laser is presented by closed into a loop the optical amplifier (OA), the optical filter (OF), which corresponds to the "traveling-

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wave" laser or the fiber-optical laser. The optical pump power P_p acts at the active amplifier. If the excitation conditions are met, the laser generates optical oscillations which pass from its output into MZ, then pass via two optical channels with different delays, combine together and through OF and FO acts to the lightsensitive PD area. An effective modulation by MZ is possible in microwave range only for single-mode single-frequency and linear-polarized emission of the highlycoherent laser. Quantum-Well (QW) laser diodes and the fiber-optical lasers with polarizers at their outputs are such emission sources.

The laser is the pump source for the radiofrequency network (**Figure 1b**) closed into a loop and formed by a modulator, an optical fiber, a photo-detector, an electronic amplifier, an electric filter, and a coupler.

As a result of oscillation processes, the spectra are formed with fluctuations having the various nature, but the spectral line width of radiofrequency oscillations is defined by parameters of two oscillating system: the laser and the radiofrequency oscillator.

4. Problem statement

At present, in large-dimension models of laser OEO (**Figure 1**) with the fiberoptical delay line the low phase noise level of -157 dB/Hz [5, 6] is achieved on the 10 GHz generation frequency at 1 kHz offset from a carrier.

Experimental and theoretical investigations of the power spectral density of the laser oscillator phase noise described in [16], show that reduction of the phase noise level of OEO in many respects depends on the laser phase noise level. At oscillation frequency 8 ... 10 GHz at standard offsets from 1 to 10 kHz, the power spectral density of the phase noise is $-120 \text{ dB/Hz} \dots -140 \text{ dB/Hz}$.

Appearance on the commercial market of nano-dimension optical fibers with low losses (down to 0.001 dB per one bend, at small bend radii up to 2...5 mm) becomes the stimulus for improvement of OEO radiofrequency generation methods. This allows implementation of comparably small (by geometric linear maximal dimensions) fiber-optical 5μ s delay lines of 10...30 mm.

In spite of the growth of publications devoted to OEO experimental investigations, the theoretical analysis and systematization of main mechanisms of the phase noise suppression in the low-noise laser OEO was not yet described in known literature. The laser phase noise influence on the OEO radiofrequency phase noise was not researched yet.

The purpose of the presentation is to consider the main features of OEO as a low-noise generator. This includes consideration based on the study of differential equations, the study of transients in OEO, and the calculation of phase noise. It is shown that different types of fibers with low losses at small bending radii can be used as a FOLD in OEO.

Following to an approach described in [16], for OEO noise analysis, we consider the system in **Figure 1**, in which two different oscillation processes are developed: laser oscillations with the generation frequency of approximately 200 THz and 10-GHz oscillations in the radiofrequency network closed into a loop. At that, the frequency multiplicity is approximately 20,000.

5. Laser in OEO

We will assume that the laser in OEO has high coherence and the spectral line width is much smaller than the average generation frequency, and the laser oscillations can be considered close to sinusoidal, and with a phase component of noise with normalized amplitude noises $m_{Lm}(t)$ and the phase noise component $\varphi_{Lm}(t)$:

$$E_L(t) = [E_{0L} + m_{Lm}(t)] \cos [2\pi\nu_{0L}t + \varphi_{0L} + \varphi_{Lm}(t)].$$
(1)

Here $E_L(t)$, E_{0L} , $m_{Lm}(t)$ are normalized non-dimensional quantities, respectively: the instantaneous intensity, the EMF intensity amplitude, and the EMF amplitude noise, ν_{0L} is the average laser oscillation frequency, φ_{0L} is the initial constant phase shift, *t* is the current time.

In the opto-electronic oscillator system, under fulfillment of excitation conditions in the electronic part of such an oscillator, the radiofrequency oscillations $u = u_g(t)$ give rise. At that, the radiofrequency signal passes to the electric MZ input from the output of a nonlinear amplifier through the C coupler during oscillation generation. The instantaneous voltage of this signal is

$$u_g(t) = [U_{10MZ} + m_{em}(t)] \cos [2\pi f t + \phi_{0e} + \varphi_{em}(t)], \qquad (2)$$

where $U_{0.1MZ} = U_{01C}$ is the amplitude of fundamental oscillation at the electric input of the MZ modulator or at the C output, f is the oscillation radiofrequency, ϕ_{0e} is the constant phase shift, $\varphi_{em}(t)$ are electronic phase fluctuations, $m_{em}(t)$ are electronic amplitude fluctuations.

The low-noise single-mode and single-frequency quantum-dimension laser diodes or the fiber optical lasers are used as the light sources in OEO.

The laser included in the OEO structure (**Figure 1**) is formed by (closed in the loop) the nonlinear OA, the narrowband optical filter (OF), and the optical delay line. The optical oscillation frequency ν_{0L} , which is generated by the quantum-dimension laser diodes in the autonomous steady-state, can be found (under excitation condition fulfillment) on the basis of the phase balance equations solution for the steady-state optical intensity oscillations in the optical resonator and in the laser active element.

To reveal the main mechanisms of the laser noise influence on the OEO radiofrequency noise, the laser can be described by a system of semi-classical equation with the Langevin's sources of the white noise (ξ_E, ξ_P, ξ_N) , relatively, for the EMF intensity E_L , a polarization of the laser active material P_n , a population difference N. We studied the laser equation system under its operation in the single-frequency single-mode regime. At that, oscillation are linear-polarized. The main assumption for utilization of semi-classical equations is that the carrier life time on the upper operation level and the time constant T_{0F} of the laser optical filter (OF) are much larger than the relaxation time of polarization T_2 . At that, the equation system with the Langevin's sources for the laser can be written as:

$$\begin{cases}
\frac{d^{2}E_{L}}{dt^{2}} + \frac{1}{T_{0F}}\frac{dE_{L}}{dt^{2}} + (2\pi\nu_{0F})^{2}E_{L} = \frac{2\omega^{2}P_{n}}{\varepsilon_{n}} + \xi_{E}; \\
\frac{d^{2}P_{n}}{dt^{2}} + \frac{1}{T_{2}}\frac{dP_{n}}{dt} + (2\pi\nu_{12})^{2}P_{n} = \frac{p_{e}^{2}}{h}NE_{L} + \xi_{P}; \\
\frac{dN}{dt} = \alpha_{N0} \cdot J_{0N} - \frac{N}{T_{1}} - \frac{1}{h}P_{n}E_{L} + \xi_{N};
\end{cases}$$
(3)

In (3) T_2 is the polarization time constant, the excited particles at the upper energy level, T_1 is the lifetime of the excited particles at the upper energy level,

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 T_{0F} is the time constant of the optical resonator, p_e is the combined dipole moment, h is the Planck constant, ν_{0F} is the natural frequency of the optical resonator on the specific n-th longitudinal mode, ν_{12} is the optical frequency of the transition, J_0 is the constant pump current, $\alpha_{N0} \cdot J_0 = (N_{02} - N_{01})/(N_{02}T_1)$ is the constant pump, ε_n is the permittivity, ν_{0F} is the intrinsic optical frequency of the resonator, P_n is the polarization of the active material, $N = (N_{02} - N_{01})$ is the population difference between the excited and unexcited levels produced by the pumping.

It should be noted that Eqs. (3) are similar to well-studied equations in the oscillator theory for the double-circuit autonomous oscillator with the inertial auto-bias chain with fluctuations.

6. Compact fiber optic delay line in OEO

At first, we would like to note that in RF FODL with geometric length of the optical fiber of 1... 5 km, the useful volume (in which emission propagates in the regime of one transverse mode) is not more that one cubic centimeter.

The extremely small geometric dimensions and dimensions of the FODL OEO are important for its use in on-board systems of flying unmanned vehicles, since it is possible to implement effective systems for suppressing force vibrations and accelerations and to make high-precision thermal stabilization systems.

It is comparable in size to other commercial low-noise sources of microwave oscillation. **Figure 3**, and represents a diagram of the maximum sizes for various oscillators that operate in the 10 GHz frequency range: 1 - the quartz resonator (QR), 2 – the disk dielectric resonator from ceramic alloys (DR), 3 – the disk dielectric resonator from leuco-sapphire (DDLS), 4 - OEO the fiber-optical delay line (OEO RF FODL) (delay time is 10–50), 5 - the optical disk microresonator (ODR).

Figure 3, and shows that the smallest dimensions of the resonator have ODR. The dimensions of modern microresonators, taking into account optical input and output devices, lie in the range of about 10...100 cubic microns. **Figure 3b** shows a



Figure 3.

Maximal dimensions of resonators and delay lines used in modern high-stable OEOs and microwave oscillators (a). Dependence of the resonator size in years (delay time is 50 μ s). 1 – QR – The quartz resonator, 2 – DR – The disk dielectric resonator from ceramic alloys, 3 – DDLS – The disk dielectric resonator from leuco-sapphire, 4 - FODL – The fiber-optical delay line (delay time is 10–50 μ s), 5 - ODR – The optical disk resonator. The plot of maximal overall dimensions' variations of the fiber reels in years(b).

graph of the geometric dimensions of the FODL coil of a single-mode optical fiber (the geometric length of the optical fiber is 5...10 km).

The development of microstructural optical fiber technologies with low bending losses suggests that in a few years the maximum geometric dimensions of RF FODL will be 10...50 mm. This becomes possible because microstructured nanofibers have a minimum loss of 0.001 dB per bend at a bending radius of 2...3 mm. It becomes possible to reduce the thickness of the optical shell and reduce the required volume. In this case, it is possible to apply the technology developed by the author [16] for creating fibers by the plasma method when heating the quartz fiber support tube in the temperature range from 1000° C to 19500° C.

The improvement of the technology of heating blanks of nitrogen-doped quartz glass with the help of microwave generators, the automatic movement of plasma columns along the support tubes will lead to the creation of small-sized low-noise OEO with overall dimensions of 0.5 cm3 with a delay of optical oscillation in it of 50 microseconds.

Figure 4 shows images of various RF FODL with the optical fiber length of 10 km used in OEO.

We note (**Figures 3** and **4**) that FODL geometric dimensions for the length of 10 km with the delay 50 μ s is about 100x100x20 (mm³), and dimensions of the optical disk resonator are 100x100x100 (μ m)³. The record small dimensions of FODL and optical disk resonators allow manufacturing of microwave and mmwave oscillators in the miniature implementation with relatively high characteristics in noises and frequency tuning.

At the present stage, the geometric dimensions of the FORD AO are approximately equal to the resonator made of leucosapphyre. If we talk about using them in oscillators when generating oscillations with a frequency of 10 GHz.

Note the advantage of the linear topology of the fiber optic delay line FODL in contrast to the leuco sapphire crystal. The optical fiber in the FODL is less susceptible to extreme forces, which results in higher mechanical strength. These technical characteristics are very important, since on-board systems are subject to destructive shock effects and accelerations of several g.



Figure 4.

Views of Fiber optic delay line (FODL) with the optical fiber length of 10 km with dimensions 100x100x20 mm^3 (a). View of FODL with optical fiber length of 0.2 km with dimensions 20x 20x100 mm^3 (b).

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Note that the FODL volume consists of only 10% of optical fiber wound on a quartz cylinder. Therefore, by reducing the critical bend radius when winding the optical fiber and the cladding diameter, it is possible to potentially significantly reduce the maximum dimensions of the FODL OEO.

Moreover, in contrast to the disk microcavity, which is used in synthesizers, the nonlinear optical Kerr effect, FODL in OEO operates in a linear mode. This means that when light passes through an optical fiber, nonlinear effects and additional optical harmonics do not appear. The width of the spectral line of the laser after passing through the optical fiber in the FOLD does not change.

Figure 5a and **b** shows profiles of commercial "perforated" optical fibers with the nano-dimension structure of the light-guiding thread.

Note that microstructured fibers with extremely low optical bending losses (**Figure 5**) are used in photonic devices to generate the second optical harmonic. But for this purpose, higher power (more than 20 MW) is used at the input to the single-mode fiber. As a rule, an optical amplifier is placed after the laser or modulator.

Plots of optical losses for different types of optical fibers are shown in **Figure 5a**. From this plot, we can conclude that fibers with HALF type perforation are promising for the development of small-sized delay lines.

Figure 5a shows the dependences of optical losses for different types of optical fibers, and **Figure 5b** shows the cross-sectional profile of a microstructured optical fiber with extremely small losses at small bending radii. Analysis of the research results and optical fibers, gives the right to declare. That the HALF type optical fiber is promising for creating compact FODL [16]. Application of special or nanodimension optical fibers (**Figure 5**) with low losses at small bend radii (1..3 mm) (0.001 dB/one bend) allows creation of miniature delay lines (1...50 μ s) with overall sizes from 10 to 30 mm [17, 18].

Thus, when using microstructured optical fibers in OEO, it is possible to significantly reduce the dimensions of the fiber-optic delay line of the FODL.



Figure 5.

a) 1) the plot of bending radius dependencies for standart optical fiber (OF) single-mode fiber G. 652 type with core diameter about 10 microns SMF-28e (corning). 2) the plot of bending radius dependencies for special microstructured optical fiber or hole-assisted light guide fiber (HALF). b) profile of commercial micro-structured "perforated" optical fiber with the nano-dimension structure of the light-guiding core.

7. OEO differential equations

To make the differential equations of a closed OEO circuit, it is necessary to keep in mind the following. The positive feedback circuit includes FOS (fiber optic system (FOS), which contains optical filters OF (**Figure 1**) optical amplifier (OA), modulators, photodetector (PD), electronic amplifier(A), electronic filter (F) and couple (C).

Taking into account the remark made, for the transfer function of the "feedback loop" K_{FB} , it is possible to write for the case of OEO DM (**Figure 1a**):

 $K_{DL} = K_{FB} = \frac{i_{1L}}{E_n^2} = \frac{j_{1L}}{E_n^2}$, where $E_n = E_L$ is the normalized strength in the QWLD output, which is equal to the value of the FOS input, $i_{1L} = i_m$ is a component of the AC input voltage MZ in the OEM MZ structure and is simultaneously a component of the AC input QWLD in the OEO DM structure. We obtain the following symbolic equation for the variable component of the current:

$$J_{1L} = \frac{\left[\cos\left(\Delta\phi_{OF}\right)\right]|E_{n}|^{2}(1/T_{EF})K_{OF}K_{PD}p\exp\left(-pT_{DL}\right)S_{NY}(J_{1L})}{\left[p^{2} + (1/T_{EF})p + \left(2\pi f_{0e}\right)^{2}\right]}.$$
 (4)

Taking into consideration the circuit of positive FB, we transfer to equation system in the time domain for OEO DM [16]:

$$\begin{cases} dE_{0L}^{2}/dt = G_{0} \cdot E_{0L}^{2} \cdot N_{L} - E_{0L}^{2}/T_{0F} \\ dN_{L}/dt = \alpha_{N00} \cdot J_{0L} + \alpha_{N01} \cdot J_{1L} - \frac{N_{0L}}{T_{1}} - G_{0}N_{L}E_{0L}^{2}, \\ d\varphi/dt = 2\pi\nu_{0P}(N_{L}) - 2\pi\nu_{0} + \sigma_{0L} + \rho_{0L}E_{0L}^{2}, \\ \frac{d^{2}J_{1L}}{dt^{2}} + \frac{1}{T_{F}}\frac{dJ_{1L}}{dt} + \left(2\pi f_{eF_{0}}\right)^{2}J_{1L} = S_{NY}\left[E_{0L}^{2}K_{FOS}K_{PD}, J_{1L}(t - T_{DL})\right]\frac{dJ_{1L}(t - T_{DL})}{dt^{2}}, \end{cases}$$
(5)

where the transfer function $K_{DL} = K_{FOS}K_{PD}$, K_{FOS} is the transfer function of FOS, which contains the optical fiber of two fibers of different length, K_{PD} is the transfer function of the photo-detector, which were defined in Chapter 2 in book [16].

Now we present for comparison the similar to (4.18) system from four timeequation for OEO MZ with QWLD [16]:

$$\begin{cases} dE_{0L}^{2}/dt = G_{0}E_{0L}^{2}N_{L} - E_{0L}^{2}/T_{0F}, \\ dN_{L}/dt = \alpha_{N00} \cdot J_{0L} - \frac{N_{L}}{T_{1L}} - G_{0}N_{L}E_{0L}^{2}, \\ d\varphi/dt = 2\pi\nu_{0P}(N_{L}) - 2\pi\nu_{0} + \sigma_{0L} + \rho_{0L}E_{0L}^{2}, \\ \frac{d^{2}U}{dt^{2}} + \frac{1}{T_{F}}\frac{dU}{dt} + \left(2\pi f_{eF_{0}}\right)^{2}U = S_{NY}\left[E_{0L}^{2}K_{MZ}K_{FOS}K_{PD} \cdot U(t - T_{FOLD})\right]\frac{dU(t - T_{FOLD})}{dt^{2}}$$
(6)

8. Dynamics of transients in OEO DM

Let us consider the transient process of the exit to the steady-state mode of the free generation of OEO DM at representation of the oscillator in **Figure 1a**. As it had

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been mentioned earlier, such a structure is described by the system of differential Eqs. (5). Let us describe in more detail the results of the study of the system of differential Eqs. (5) for OOO DM (**Figure 1a**).

On the base of mentioned OEO differential Eqs. (5), the analog model of OEO was constructed presented in **Figure 1a**.

Figure 5 presents the obtained solutions of system (5) and shows plots of the square of the intensity, population, and pump current, as well as phase portraits in the transient mode under the influence of a constant pump current in the form of a step pulse.

The one of difficulties at solution of (4) finding at the analog modeling is the determination of the nonlinearity of the RF nonlinear amplifier (A) in order to "compensate of the multiplicative QWLD nonlinearity".

At the same time, in the analog models, the following laser parameters were taken in solution (5) (the same as in Chapter 3 [16]): for the mesa-strip laser with the thickness of the dielectric film $d = 1.2 \ \mu m$: $g_0 = 10^3$, $\tau_D = 7,2 \cdot 10^{-12}$ s, $I_{\text{thr}} = 12$ mA, $\varepsilon_{sh} = 0$. The values of parameters of QWLD are: the life time of carriers $T_1 = \tau_{n1} = 0.5 \cdot 10^{-9}$ s, the threshold level population difference is $10^{18} \ 1/\text{cm}^3$, the life time of photons or the time constant of the optical resonator $T_{0F} = \tau_{ph} = 1,2 \cdot 10^{-12}$ s, the volume of the QWLD active zone is 10^{-11} cm^{-3} .

The modes with and without delay in the OEO feedback ring were investigated. (**Figure 6**).

The pulsations of the square of the intensity and population of the laser in the simulation of the transition process OOO DM are established. These dependences are shown in **Figure 6**. The nonlinear distortions are related to the multiplicative nonlinearity of the laser. And their level depends on the value of the DC pump current of the laser.

The period of laser pulsations in transients, which is approximately 0.4 ns, depends on the level of the pump current and is determined by the carrier lifetime.



Figure 6.

The transient process in OEO and in the laser. The constant pumping level $J_o = 30 \text{ mA}$. Activation of pumping occurs in the time moment t = 0. Time-functions of normalized values: a) the population difference N (10^{18} 1/ cm³), b) the normalized square of strength (E)² = (E_{oL})², (1.0 point = 1 mW), c) AC component of pumping current, d) the normalized square of strength (E)² = (E_{oL})², (1 point = 1 mW) at initial part [0,50]. The transient process is presented with the exit to the limit cycle on the time diagram E_{oL} , N_o. The scale on the time axis t: 5 points = 0,1 ns. The setting time for the laser oscillations is 40 points (or 0,8 ns). The setting time of OEO RF oscillations is on the time axis t 50 ... 250 points (or 40 ns).

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The setting time of the laser oscillations is 0.8 ns (or from 0 to 40 points in **Figure 6a** and **b**). The time of setting the RF oscillations of the OEO on the time axis t is 40 ns (or from 50 to 100 points in **Figure 6**). The oscillation frequency in the steady-state mode is close to the natural frequency of the electronic filter (F) and was approximately 10 GHz.

9. OEO DM system of the laser emission

As follows from the theory of oscillations, in a transient process, a special or critical point can be a stable node, with real and negative roots p1 and p2 of the characteristic equation of the system of differential Eqs. (5). When the feedback coefficient in the OEO ring increases, the special point A becomes unstable. In this case, the characteristic roots p1 and p2 must be positive.

As shown in **Figure 7**, there is a stable limit cycle around the unstable point A. The generation is impossible if the isoclinic lines $F_1(N_L)$ and $F_2(E_L)$ are not intercepted.

The process of establishing the laser radiation oscillation ends, and then, due to the positive feedback in the OEO DM ring, there are increasing oscillations of the laser charge current, which also modulate the inverse population of the laser. This leads to subsequent oscillations of the square of the electromagnetic field strength of the laser.

If there is a single singular point A in the upper half-plane (**Figure 7**) the condition of self-excitation of the laser is fulfilled. Therefore, the excitation of the OEO DM occurs in a gentle way. This is also true for the case of an arbitrary odd numbers of nontrivial singular points. OEO DM generation may not be possible if the isoclinic lines and are not intersect (**Figure 7**). If the number of singular points is even (if there are two singular points points), the condition of self-excitation of the OEO may not be met.

Laser generation can only be excited in a "hard" way, which is initiated by a pulse from an external source.

If we consider the case of an unstable point A, the oscillatory system develops a process of oscillation growth. The nonlinearity of the electronic amplifier limits the growth of oscillations and the conditions for the existence of a limit or closed stable cycle are met (**Figure 7b**).



Figure 7.

Transition mode scenario in OEO DM. A phase portrait of the normalized square force is presented. a) the phase portrait of the normalized square strength $(E)^2 = (E_{oL})^2$ and the population difference N and . Y-axis – The normalized square strength (or the intensity), X-axis – The population. The scale on the Y axis is 1.0 = 1 (V/m)². The scale on the X axis is 1.0 = 1 mW. N (1.0 point on the scale is 10^{18} 1/cm³). b) the enlarged image of the phase portrait is shown and the transient development with the exit to the limit cycle on the time diagram E_{oL} , N_o. The scale on the time axis t is 5 points = 0,1 ns.
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If we consider the question the stability of a given oscillation cycle, then its existence is determined by the sign of the partial derivatives of the right-hand sides with respect to one variable when analyzing the characteristic equation obtained in [16], Chapter 4.

The limit cycle is stable only if the corresponding expressions for the coefficients are greater than zero [16].

When considering the hard-excited OEO DM mode, it is necessary to note more complex dynamics, and the picture of the phase plane in the transition mode becomes diverse. The number of singular points (intersection points of isoclinic lines) becomes even. Therefore, long-term generation of OEO DM oscillations in hard mode is possible only when an external generator is operating.

The transients of the oscillation tuning in the OEO DM with no lag in the positive feedback loop are shown in **Figure 8**.

Modeling has shown that strong nonlinear distortions caused by the multiplicative nonlinearity of the laser occur at a large oscillation amplitude [16] and their level is determined by the choice of the operating point or the direct pump current of the laser.

For example, a level of 1 ... 10% of the maximum possible values is performed when a constant bias current is selected at a level of 1.5 to 5.0 exceeding the threshold laser pump current. It is established that the nature of the transient process is determined by the type of non-linearity of the electronic amplifier, the





Figure 8.

Plots of function of the dependences of the square of the electromagnetic field strength of the laser in the optical channel, the population of carriers and the pump current. In abscissa axis – The normalized time, in ordinate axis – a) N – The inversed population; b) $(E)^2 = (E_{oL})^2$ - intensity of laser; c), –Oscillations of OEO the electrical current of laser pumping.

selection of the natural frequency of the electronic filter, and the delay value in the FODL. At the same time, the duration of the OEO DM oscillation transition process changes significantly.

Positive feedback is included in the DE system, taking into account the photodetection of optical radiation, selectivity in the radio frequency, and nonlinear gain on a nonlinear amplifier.

What is new in the analysis of the OEO DM operation is that the Lotka-Volterra laser differential equations for the optical field intensity, inverted population, and optical phase with positive selective feedback with a delayed argument can be reduced to a single van der Pol differential equation for the pump electric current.

From our studies of differential Eqs. (5), it follows that in OOO DM, singlefrequency and two-frequency modes of relaxation oscillations are possible.

For a stable single-frequency mode of OOO DM generation, the following conditions must be met: a twofold excess of the electron filter time constant (F) over the electron relaxation time constant in the active layer of the laser.

10. Laser phase noise and OEO phase noise

Expressions for SSB PSD of the laser phase noise do not reflect the important property of the laser oscillating system: a presence of the relaxation resonance on the frequency ν_{00L} at the offset from a carrier ν_{0L} , i.e., at $F_{00L} = 2\pi(\nu_{00L} - v_{0L})$. We can take this "resonance peak" into account at linearization of system [16] with account of the population equation. At that, the expression for SSB PSD of the laser phase noise take a form:

$$S_{PL}/P_{0L} \approx \frac{S_{SL\,\mathrm{Im}}}{\left(FT_{0F}\right)^2} + \frac{S_{LE}D_{11}^2 + S_{LN}D_{22}^2}{T_1^4 \left(\left(F^2 - F_{00L}^2\right)^2 + \left(F\alpha_{00l}\right)^2\right)^2} \tag{7}$$

where $F_{00L} = (1/T_1)((T_{0F}/T_1)\alpha_0 - 1)^{1/2}$, α_0 is an excess of DC laser pumping over its threshold value, α_{00l} is a damping decrement, T_1 is the lifetime of the excited particles at the upper energy level, D_{11} and D_{22} are the constant coefficients, and S_{LE} , S_{LN} are relatively, spectral densities of impacts in [15, 16] the Langevinian noise of the laser ξ_E , ξ_N , relatively. Here ξ_E is the noise of the EMF intensity E_L , ξ_N is the noise of a population difference N. **Figure 9** shows the curve 1 of SSB PSD of the



Figure 9. Laser phase noise SSB PSD (curve 1), and OEO phase noise SSB PSD (curve 2).

laser phase noise calculated by formula (7) for $S_{SL \text{ Im}} \approx S_{LE} D_{11}^2 S_{LN} D_{22}^2 \approx -105 \text{dB/}$ Hz, $F_{00L} \approx 14 \text{ kHz}$, the time constant of the laser resonator $T_{OF} = 10^{-7} \text{s}$.

11. OEO as the EMF correlator

We studied OEO as a correlator of two random variables ξ_1, ξ_2 with probability density at the input of the correlator $p_1(\xi_1, \xi_2)$. The random variables in the extraction of two optical harmonics [16] are phase noise $\xi_1 = \varphi_{10Lm}(t)$ and $\xi_2 = \varphi_{20Lm}(t)$ corresponding harmonics with the amplitudes A_1E_{0L} and A_2E_{0L} . The resulting phase noise of the current in the load of the PD photodetector is the result of statistical averaging. The distribution probability $p_2(\eta)$ determines the appropriate correlation function of the output process. Where $f(\eta)$ is the nonlinear characteristic of the photo-detector, $\eta_{\tau} = \eta(t - \tau)$ of the $\eta(t)$ process in the correlator output. At that, $p_1(\xi_1, \xi_2)$ defines the probability density $p_2(\eta)$ of the statistical process in the correlator output (**Figure 2**) of the OEO MZ (**Figure 1b**) at the *closed loop* of OEO MZ for $\tau > T_{FOS}$.

The spectral density of radio frequency OEO oscillations $S_{RFL}(F)$ is determined by the formula:

$$S_{RFL}(F) = \frac{E_{0L}^4}{2} \frac{U_{10MZ}^2 S_L}{2} K_{\Gamma PN}^2 \cdot \left[1 - \frac{A_2}{A_1} \exp\left(-\frac{2(\Delta T_M + T_{FOS})}{T_c}\right) \right],$$
(8)

where S_{PL} - SSB PSD of the laser phase noise (7), $K^2_{2\Gamma PN}$ is the coefficient of the noise suppression, which depends upon T_{FOS} , the laser optical power E^2_{0L} , the transfer function of FODL $|K_{FODL}|$, U^2_{10MZ} is the square of the AC amplitude in the MZ electrical input. When considering OEO as a correlator of two random variables ξ_1, ξ_2 with a probability distribution density at its input $p_1(\xi_1, \xi_2)$, we can conclude from (8) that the SSB PSD of the laser phase noise is significantly determined by the ratio of the delay time in FOS and the laser coherence time, and it significantly depends on the ratio harmonics amplitudes A_2/A_1 .

12. OEO phase noise

From Eqs. (7) with account for nonlinear characteristic of the amplifier A (**Figure 1a**) as a cubic polynomial $i_A(u) = \alpha_{e0}u - \beta_{e0}u^3$ (where *u* is the instantaneous voltage at the amplifier input, and the average slope of this characteristics is $\sigma_U = \sigma_{e00} - (3/4)\beta_{e00}P_{0G}$) and we can obtain through laser and delay line parameters the power of the Opto-Electronic oscillator radiofrequency generation P_{0G} :

$$P_{0G} = \frac{\alpha_{e00}}{\beta_{e00}} \left(1 - \frac{1}{P_{0L} | K_{FOLD} | \alpha_{e00} \beta_{e00}} \right).$$
(9)

We introduce the designation: $Y_{00}/P_{0L} = y_M [1 + FT_{EF}]/|K_{FODL}|$,

where y_M is the input normalized conductivity of the MZ modulator. Similarly to (7) for laser PSD, we obtain from the general symbolic Equations [16] the equation for SSB PSD S_{Ψ} of the OEO phase noise.

SSB PSD S_{Ψ} reduced to the radiofrequency oscillation power P_{0G} is determined by expression derived in [14–16] according to the Evtianov-Kuleshov approach. The $K_{\Gamma PN2}^2$ coefficient depends on the delay time in the optical fiber and on the laser optical power and it is equal

$$K_{\Gamma PN}^{2} = \frac{\left\{ (Y_{00}/P_{0L}) \left[\sqrt{2} \sin \left(\pi/4 - FT_{FOS} \right) \right] - \sigma_{U} \right\}^{2}}{\left\{ \left[(Y_{00}/P_{0L}) \right]^{2} - (Y_{00}/P_{0L}) \cdot (1 + \sigma_{U}) \cos \left[FT_{FOS} \right] + \sigma_{U} \right\}^{2}}.$$
(10)

where y_M is the input normalized conductivity of the MZ modulator. Then the function of OEO phase noise PSD can be represented [14–16] as

$$S(F) = \frac{S_{\Psi}}{P_{0G}} = \frac{K_{\Gamma PN}^2 C_A h v N_{sp}}{P_{0G}},$$
(11)

where C_A - the constant coefficient, N_{sp} is a number of spontaneous photons received by PD.

Plots of (10) are shown in **Figure 9**. which are limited functions of OEO of the phase noise PSD with account of small noises of PD and the A amplifier, at laser phase noise for the offset frequency 1 kHz equaled to about -120 dB/Hz, at laser power 30 mW, the delay of $T_{BC} = 5 \cdot 10^{-6}$ s (the OF length is 1000 m), $\sigma_U = 1$. We see that the first peak is defined by the laser phase noise PSD, and average suppression of the phase noise for 50 kHz offset is more, that -10 dB/Hz.

It should be noted that at the optical fiber length of 2 km the uniform suppression of the laser phase noise is achieved in the offset range 1... 50 kHz.

Calculation of the phase noise suppression factor $K_2(F)$ suppression factor according to (9) is presented in **Figure 10** $\sigma_U = 1\sigma_U = 1 : T_{FOS}/T_F =$ 1, $P_{0L}|K_{FODL}| = 2$ (curve 1); $T_{FOS}/T_F = 10$, $P_{0L}|K_{FODL}| = 2$ (curve 2); $T_{FOS}/T_F =$ 10, $P_{0L}|K_{FODL}| = 4$ (3 curve). It can be seen that increase of delay time from $T_{FOS}/T_F = 1$ (curve 1) to $T_{FOS}/T_F = 10$ (curve 2) results in reduction of K_2 factor more than 10 times in the rated offset frequency $F \cdot T_F$ range 0.05 ... 0.5.

It is shown that at OF length, the further reduction of the OEO phase noise is possible using the PLL (phase-locked loop) system. Calculation results are well-agreed with experimental dependences of OEO phase noise PSD, which can be found in [14–16]. Here, we should remind that first publications on research of frequency stability in OEO with the help of FOLD were fulfilled in 1987–1989 at



Offset frequency

Figure 10.

The phase noise suppression factor $K_2 = K_{\Gamma PN}^2$ (9) versus the rated offset frequency $F \cdot T_F$: $T_{FOS}/T_F = 1$, $P_{oL}|K_{FODL}| = 2$, (curve 1); $T_{FOS}/T_F = 10$, $P_{oL}|K_{FODL}| = 2$ (curve 2); $T_{FOS}/T_F = 10$, $P_{oL}|K_{FODL}| = 4$ (3 curve).

Radio Transmitter Dept. of Moscow Power Engineering Institute (now NRU MPEI) while the OEO circuit was offered in [12, 13].

13. Experimental investigations

Experimental researches were devoted for several experimental OEO of microwave range with various pumping laser diodes, which emit at wavelengths of 1310 nm or 1550 nm. The maximal output power of optical emission for used laser diodes formed about 10 ... 20 mW. **Figure 11** shows the photo picture of one piece assembled on the base of the circuit in **Figure 1b**. As the photo-detector, we applied the PD on the base of InGaAs. The radiofrequency filter represented the dielectric resonator of microwave range with the loaded Q-factor of 1000. This resonator was made on ceramics and had a natural frequency 8.2 GHz. This breadboard model used the wideband (up to 12 GHz) modulation of laser emission, which was performed by the Mach-Zehnder modulator from Hitachi Co. The single-mode light guiders with lengths from 60 m to 4640 m were used for experiments. The stable generation of single-frequency oscillation at frequency close to 8.2 GHz was observed in OEO system for various OF lengths.

The delay of OEO signal was performed with the help of additional fiber-optical light guider with the 10 km-length and the additional photo-diode. The phase noise level at usage of different lasers formed the value $-100 \dots -127 \text{ dB/Hz}$, for offsets 1 ... 10 kHz from the microwave sub-carrier frequency under generation and it depends on the spectral line width of laser emission.

Essential reduction of the phase noise by 15 dB was observed in OEO using the differential delay line on the base of two optical fibers of different length. These experimental functions are well-agreed with theoretical at account of the stabilization effect at OF lengths more than 2000 m.



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Figure 11.

General view of the experimental breadboard of low-noise laser opto-electronic oscillator of microwave range. The mean oscillation frequency is 8 ... 10 GHz.

14. Conclusion

At that, formation of the final phase RF noises of OEO is examined as the result of the convolution operation of the laser optical spectrum and the RF spectrum of the oscillation. Thus, when using microstructured optical fibers in OEO, it is possible to significantly reduce the dimensions of the fiber-optic delay line -FODL. For a stable mode of OEO generation in the single-frequency mode, it is necessary to double the time constant of the electron filter (F) over the time constant of the relaxation of electrons in the active layer of the laser.

We have shown that the resonant curve of the electron-photon resonance of the laser has a significant influence on the formation of the power spectral density PSD of the phase noise in OEO. For stable operation of the OEO, the laser coherence time and the delay time in the optical fiber must be balanced. The use of microstructured fibers with low bending losses makes it possible to create compact fiber-optic delay lines for OEO.

Under assumption of the small and large oscillation amplitude at the modulator electrical input, we study OEO as a system in which two oscillation processes are developed on the optical frequency and in radiofrequency. The relatively simple expressions for phase noise PSD of the radiofrequency generation in optoelectronic generator in the mode with the single-side carrier with an account of the laser phase noise. The analysis fulfilled shows that under condition of predominance of laser noises being detected over v noises of the electronic amplifier and the OEO photo-detector of the filtering system.

For reduction of spurious influence of DC intensity component on the photodetector we offer to use the modulator operation mode with an offset of the optical channels "pi".

The suppression factor of the OEO laser phase noise at optical fiber lengths from 2 to 10 km is about $-8 \dots -10$ dB/Hz at offset of F = 1kHz. Utilization in OEO of the highly-coherent laser with the phase noise less than S(F) = -100 dB/Hz (at the same offset) is the condition of OEO small phase noises less than S(F) = -130 dB/Hz at the F = 1 kHz offset. The value of the OEO power spectral density is proportional to the spectral line width of the laser optical emission.

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References

[1] Aliou Ly, Vincent Auroux, Ramin Khayatzadeh «Highly Spectrally Pure 90-GHz Signal Synthesis Using a Coupled Optoelectronic Oscillator», IEEE Photonics Technology Letters, vol.30,no.14, pp.1313-1316, 2018.

[2] Dan Zhu, Tianhua Du, Shilong Pan «A Coupled Optoelectronic Oscillator with Performance Improved by Enhanced Spatial Hole Burning in an Erbium-doped Fiber», Journal of Lightwave Technology, pp.3726-3732,(2018).

[3] Zhuansun Xiaobo and etc, «Low phase noise frequency-multiplied optoelectronic oscillator using a dualparallel Mach–Zehnder modulator», Optical Engineering 57(08),p.086101, (2018).

[4] A. Banerjeea et al., «Study of Mutual Injection-Pulling Between Two Mutually-coupled Single-loop Optoelectronic Oscillators», Optik, 11 February 2021, pp.166492-166499, (2021).

[5] A. G. Correa-Mena and etc «Performance Evaluation of an Optoelectronic Oscillator Based on a Band-Pass Microwave Photonic Filter Architecture », Radioengineering, 26 (3),pp.642-646,(2017).

[6] C. X. Li et al., «A Novel Optoelectronic Oscillator with Series-Coupled Double Recirculating Delay Lines», Advanced Materials Research, Vols. 986-987, pp. 1730-1733, (2014).

[7] Xihua Zou, Xinkai Liu, et al., « Optoelectronic Oscillators (OEOs) to Sensing, Measurement, and Detection», IEEE Journal of Quantum Electronics 52 (1):0601116, (2016).

[8] X. S. Yao and L. Maleki,«Optoelectronic microwave oscillator»,J. Opt.Soc. Amer. B, Opt. Phys., vol. 13,no. 8, pp. 1725–1735, (1996).

[9] A. A. Savchenkov, A. B. Matsko, V. S. Ilchenko, and L.Maleki, "«Optical resonators with ten million finesse», Opt. Express 15, 6768-6773 (2007).

[10] C.W. Nelson et al. «Microwave optoelectronic oscillator with optical gain», IEEE, №12,v. 31,pp.152-157, (2007).

[11] J. J. McFerran, E. N. Ivanov, A. Bartels, G. Wilpers, C. W. Oates, S. A. Diddams, and Hollberg, " «Low-noise synthesis of microwave signals from an optical source»," Electron. Lett. 41, pp. 650-651 (2005).

[12] A. A. Bortsov, V. V. Grigoriants, Yu.
B. Il'in « Effect of the lightguide excitation efficiency on the frequency of a self-excited oscillator with a differential fiber optic delay line» , Telecommunications and Radio Engineering, 44(8), August, 1989, pp. 137-142. (1989).

[13] V.V. Grigor'yants, Yu.B. Il'in,
«Laser optical fibre heterodyne interferometer with frequency indicating of the phase shift of a light signal in an optical waveguide»,
Quantum and Quantum Electronics,21 (5),pp.423-427,(1989).

[14] Bortsov, A. A., S. M. Smolskiy
«Opto-Electronic Oscillator with Mach-Zehnder Modulator»,
Infocommunications Journal, Vol. XI,
No 1, March, pp. 45-53, (2019). DOI:
10.13140/RG.2.2.20992.69126.

[15] Alexander . A. Bortsov , Sergey M. Smolskiy «Optoelectronic oscillator as the time correlator with ultralow phase noise» , Opt. Eng. 59(6) 061618 , 3 February, (2020). DOI: 10.1117/1. OE.59.6.061618.

[16] Alexander.A. Bortsov, Yuri B.Il'in, Sergey M. Smolskiy «Laser Optoelectronic Oscillators» Springer Fiber Optics - Technology and Applications

Series in Optical Sciences, vol. 232. Springer, Cham, 522 p. 2020. –Available at: https://doi.org/10.1007/978-3-030-45700-6,(2020). DOI:10.1007/ 978-3-030-45700-6.

[17] Gerd Keiser, Optical Fiber Communications, McGraw Hill, 4th edition, 2008.

[18] Prajwalasimha S. N., Kamalesh V. N.
Macro Bending Loss in Single Mode
Optical Fibre Cable for Long Haul
Optical Networks, International Journal
of Emerging Technology and Advanced
Engineering, Volume 4, Issue 6, June,
2014.

