We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900
Open access books available

186,000
International authors and editors

200M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

BOOK CITATION INDEX
CLARIVATE ANALYTICS
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Development of Bismuth-Doped Fibers (BDFs) in Optical Communication Systems

Rifat M. Dakhil Alsingery and Ahmed Mudhafer

Abstract

This chapter will provide background information in the development of BDFs and their applications in optical communication systems. Herein, the main focus is briefly described previous studies on BDFs that have attracted much interest over the last two decades. This necessary information and concepts are very much relevant to understanding this book, mainly due to the doping of Bi in the studied bismuth and erbium-doped silicate fibers (BEDFs). The remaining chapter is consisting of the following sections: Sec.2: General introduction about optical fibers. Sec. 3 discusses the general spectral characteristics of BDFs. Sec.4: Including the active centers (namely the bismuth (Bi) active centers (BACs)) responsible for the spectral properties in Bi-doped fibers. Sec.4 Discusses the Bismuth Doped Fiber Amplifier (BDFA).

Keywords: bismuth-doped fibers (BDFs), optical communication, Bi active centers (BACs), bismuth doped fiber amplifier (BDFA)

1. Introduction

A previous work by C.Kato et al. stated that the loss of 20 dB/km in a dielectric waveguide could be minimized if it uses pure dielectric material [1]. This encourages many researchers to discover methods to minimize failure in optical silica fibers. Since its proper mechanical and optical properties, silica was used as the material for the improvement of optical fibers. A low-loss was established in 1970 by merging with a 20 dB/km loss [2].

Besides, with ultra-pure precursors with impurities of ppb-order (parts per billion), the growth of low-loss (0.2 dB/km) single-mode fibers about 1550 μm is demonstrated to be possible [3]. **Figure 1** displays the attenuating spectrum of conventional single-mode fiber. The wavelength range of 1260–1625 nm is split into several subwavelength bands. A specific ITU-T wavelength range is allocated to each band, as listed in **Table 1**.

After the introduction of low-loss fiber, erbium (Er)-doped (EDFA) technology was introduced in 1987 as an advance to revolutionize optical fiber communication. It allowed transatlantic fiber communication [5]. The progression of fiber development to advance low-loss fiber in conjunction with EDFA technology led to the use of the low-loss range for optical fiber communications from 1530 to 1625 nm (C L band). Throughout the years, several techniques including dense wavelength

1970 by merging with a 20dB / km loss[2].
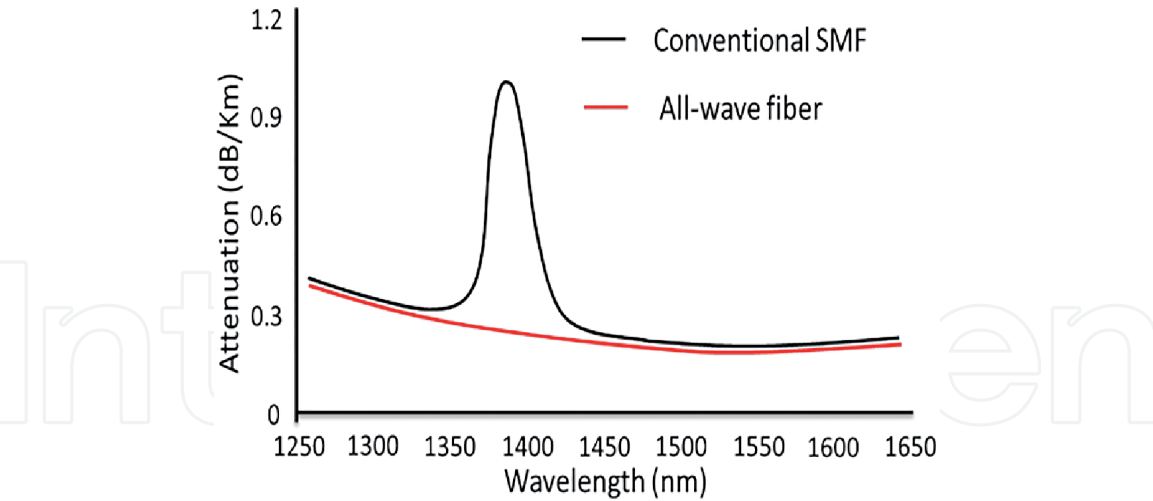
Figure 1.
Attenuation spectra of conventional SMF and all-wave fiber [4].

Bands	O	E	S	C	L
Wavelength (nm)	1260–1360	1360–1460	1460–1530	1530–1565	1565–1625

Table 1.
ITU-T profile of optical wavelength bands in telecommunications.

division multiplexing (DWDM), wavelength multiplexing division (WDM), and coarse wavelength multiplexing division (CWDM) with new modulation formats as quadrature phase-shift keying (QPSK) as 16-QPSK, Quadrature Phase-shift Keying (QPSK) and 64-QPSK used to increase capacities for existing silica optical fibers, in the C + L band. Nonetheless, the stated transmission capacity of Standard Single-Mode Fiber (SMF) achieves the non-linear Shannon limit [6]. **Figure 2** shows growth in the global population's use of the internet every ten years. More than 60% of the world's population is projected to be connected by 2020. The enhanced internet connectivity and comprehensive Internet-based applications such as cloud computing, social media, e-commerce, and e-learning are the drivers of significant demand for fiber transmission. New approaches to improving the potential for existing optical fiber networks must also be considered economically rather than merely adding more traditional single-mode fibers to meet end-user needs. Many researchers have proposed many approaches. One of these approaches is using a low-loss window (1260–1625 nm) of silica optical fibers by improving useful fiber lasers and amplifiers. The other is the development of new fibers such as multi-mode fibers (MMF), multi-core fibers (MCF), and multi-element fibers (MEF) for space-division multiplexing (SDM) in a C band from 1530 to 1565 nm. A further challenge is looking for a different transmission band in a 2000 nm wavelength region with new fibers [6]. The early stages of fiber optic communication in C-bands of about 1550 nm employed silica fibers with a loss of about 0.2 dB / km and a peak of about 1380 nm as shown in **Figure 1**. Recently, Lucent technologies and Optical Fiber Solutions (OFS) have delivered low-loss optical fiber in the entire 1260–1625 nm wavelength range. Such ultra-low-loss fibers are known as dry fibers and give a bandwidth of about 53THz for optical fiber. The mitigation for these ultra-low loss fibers in the 1260–1625 nm wavelength range is less than 0.4 dB/km, as shown in **Figure 1** [4, 8]. Besides, new optical networks have been developed. For nearly every feature, they provide dramatically improved performance over
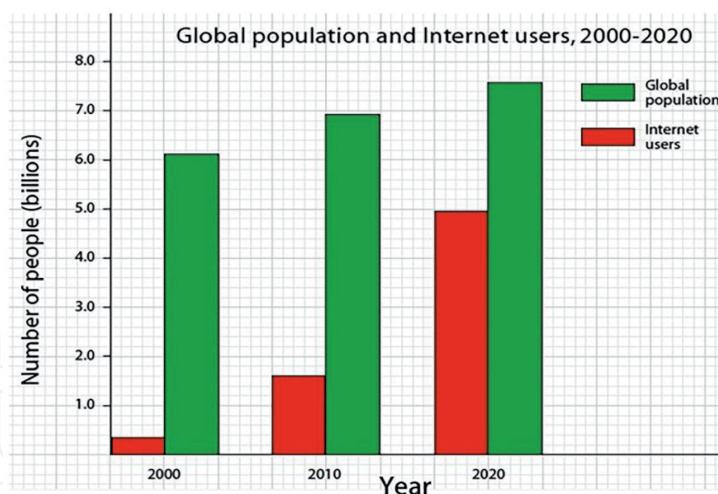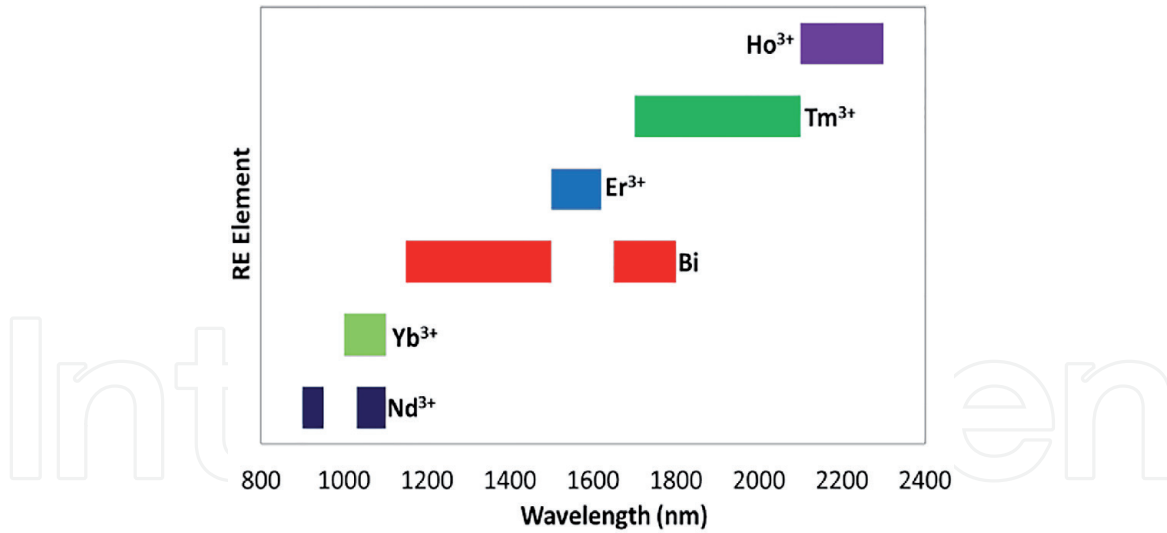
Figure 2.
The bar chart shows the increase in internet users per each ten-year gap [7].

traditional single-mode fiber, including increased usable bandwidth, superior macro-bend performance, and ultra-low dispersion polarization mode (PMD).

10 THz belongs to the Er amplification band between 1530 and 1625 nm with 53THz bandwidth provided by these dry fibers. A bandwidth can, therefore, be increased four times by using dry fibers. All of these dry fiber technologies have provided the ultimate flexibility in network construction and provided economic approaches to optimize data transition capability. However, the industry requires useful fiber amplifiers and lasers to use this utterly low-loss belt for optical communications, which are central to communication between an optical fiber. Regrettably, there are no active rare-earth (RE) doped fiber amplifiers and lasers that support the band of 1260–1530 nm. Given numerous attempts to implement various RE dopers in silica fibers to improve lasers and amplifiers in this wavelength range, potential devices available for use are still lacking. The amplifiers development and lasers in the 1260–1625 nm wavelength band, which uses bismuth (Bi) and Er-doped fibers to use the ultra-low loss window of ultra-low loss optical fiber.

2. Bismuth-doped fibers (BDFs)

Doping of the core zone with RE material is necessary for optical fiber fabricated to improve lasers and amplifiers. Various RE elements and their favorite emission bands in silica host are shown in **Figure 3**. Conventional RE elements, including ytterbium (Yb), Er, and holmium (Ho) or thulium (Tm), cover the wavelength bands about 1000, 1500, and 2000 nm [10]. However, any RE-doped silica does not cover the band between Er and Yb. The Energy level diagram of Yb, Er, Tm is shown in **Figure 4**. neodymium (Nd) and Praseodymium (Pr)-doped fibers explored extensively in silica host to improve lasers and amplifiers about 1300 nm. Nevertheless, highly phonon energy in a silica host made the dopants ineffective. They changed to a low phonon energy host, as fluoride glass enabled them reasonably active. Fluoride glasses, though, are not appropriate for splicing with traditional silica fibers as required in many applications for all-fiber compact devices. Despite this, the fabrication of these fibers is complex and not mature sufficient, in contrast to conventional changed chemical vapor deposition (MCVD)-solution doping technique. Furthermore, as shown in **Figure 4**, in the case of Pr, ground-state absorption (3H4-3F4), excited-state absorption (ESA) (1G4-1D2) at the signal wavelength, and pump ESA (1G4-3P0) are prejudicial to improve effective lasers and Pr-doped fiber amplifiers at 1300 nm.

Figure 3.
The Spectrum regions covered via different RE doped elements in silica host [9].
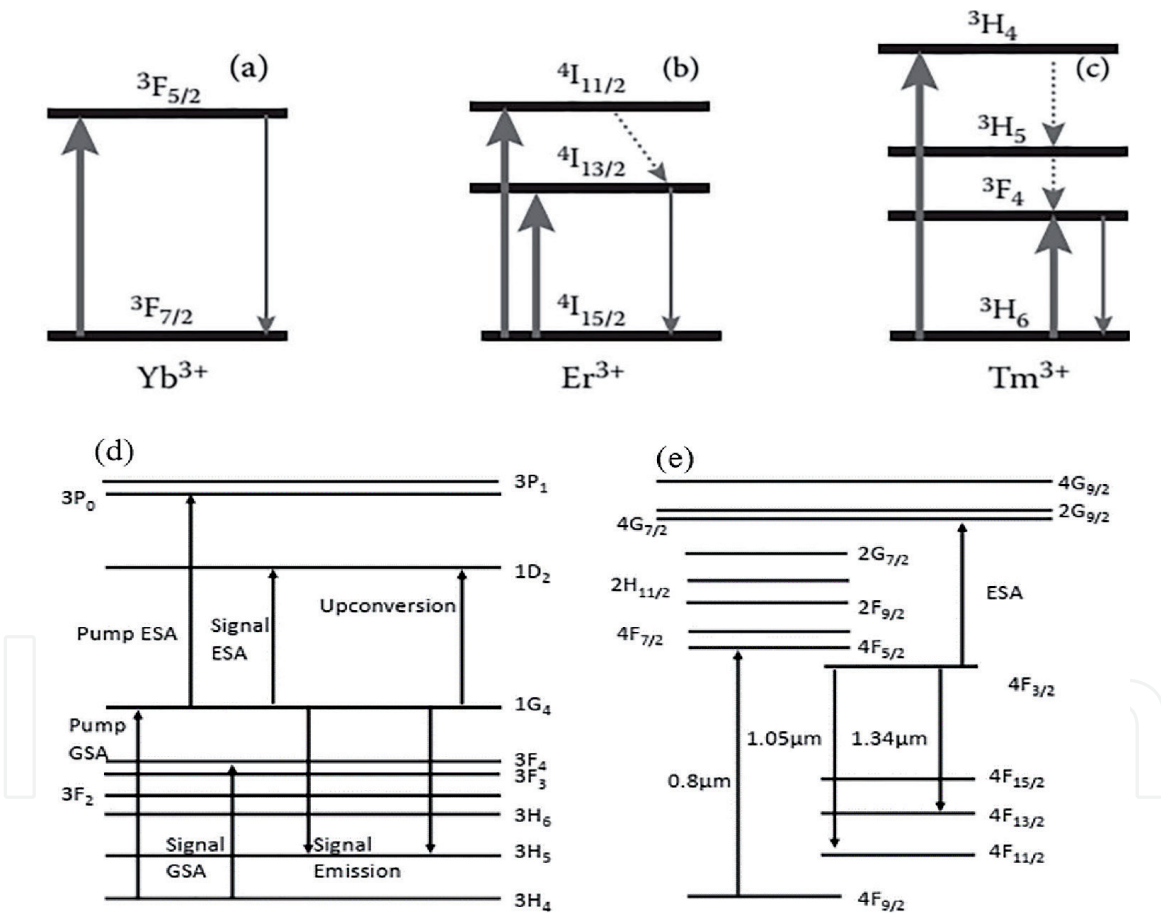
Figure 4.
Energy level diagram of (a) Yb³⁺, (b) Er³⁺, (c)Tm³⁺ [10] (d) Pr³⁺ and (e) N^{d3+} [11].

For neodymium (Nd), the ESA at a signal wavelength (4F3/2-4G7/2) with a get competition between 1005 nm (4F3/2-4F11/2) and 1.34 μm (4F3/2-4F13/2) are detrimental to improve 1.3 μm amplifiers and lasers [11]. The last research subjects on BDFs covered the main areas of (i) design of BDFs with new materials and compositions, (ii) studying the fabrication techniques and processes to make BDFs with better properties, (ii) spectral characterization method to assess BDFs for desired applications, (iii) post-fabrication techniques and their impacts on spectral properties, (iv) applications of BDFs into gain media, or sensing device or any other,

(v) evaluation of optical devices made with BDFs using various configurations and operational conditions, (vi) studying the nature of BACs responsible for producing the emission in BDFs, (vii) unraveling the energy levels of the active centers, and many other similar topics. Among these subjects, the nature of BACs is essential for understanding the spectral characteristics and their effects on applications; however, the issue has not been resolved yet and required more addressing.

3. Characteristics and applications of BDFs

3.1 Spectral emission properties and Bi active centers (BACs)

Visible emissions from Bi-doped glasses and crystals were deeply clarified [12–17]. Recently, broadband emissions in the near-infrared (NIR) region from 1200 nm to 1500 nm have been demonstrated in Bi-doped glasses (BDGs) by Fujimoto et al. [18]. Peng also reported broad NIR emission from Bi glasses. et al. as well [19]. With around 1300 nm of optical amplification shown produced by the BDG.s [20]. The first Bi-doped fiber (BDF) and a laser-based on that BDF were reported by Dianov et al. in 2005 [21]. Different BDFs and BDGs have been improved for potential applications as lasers and amplifiers in the second telecommunication window range at around 1.3 μm. It was found that the bandwidth and intensity of emission produced from the BDFs are influenced mainly by the host type and other co-doping materials. Bi can produce emissions in various wavelengths in the NIR wavelength region over (1200–1500) nm, as reported in BDFs and BDGs. For instance, emissions in several BDFs and BDGs (such as silicate, germanate, alumino-silicate, alumino-phosphate, barium-aluminoborate types) have been reported in earlier work [19, 22–27]. Typical emissions of Bi in some recent work are presented in **Figure 5**.

Emissions in BDFs and BDGs are accompanied by active centers or BACs. BACs largely determine the spectroscopic properties, performance, and operations of BDFs. Hence, to design a fiber for a specific application, it is essential to know the BAC details and their relationships to the spectral properties. As an approach to studying the nature of BACs can be broadly categorized into two main groups: (a) spectral analyses to determine the type of BAC and (b) instrumental analyses to identify the chemical bonding and electronic states of Bi, which is responsible for forming a particular type of BAC. The spectral analysis gives information about a specific BAC's spectral characteristics, determined mainly by the composition types in the fiber or glass. Absorption, emission (luminescence or fluorescence), and emission lifetime are some of the most common and basic spectral properties analyzed to identify the BAC types. Besides, an emission-excitation spectroscopic graph described recently was found to be very important to recognize the particular emission [29]. At the initial phase of Bi fiber research, it was thought that Bi emission could be produced only in the presence of Al [23]. However, later, Bi emission was detected in pure silica-doped fibers without any Al co-doping, and lasing was realized in such BDFs [30]. The concept that BACs are linked with other ions in addition to Bi was subsequently considered through the investigation into several Bi fibers and glasses, which were fabricated with different compositions and their relations. Following this advance, Bi fibers with the most straightforward glass compositions were made and BACs in them were characterized, enabling the identification of certain BAC types, e.g., BAC-Si, BAC-Al, BAC-Ge and BAC-P associated respectively with Si, Al, Ge, and P, along with their respective characteristic spectral properties [29–33]. Instrumental analyses of the BAC study concentrate on how to reveal possible valence and the electronic configuration of specific BAC. This approach included analyses of the nuclear magnetic
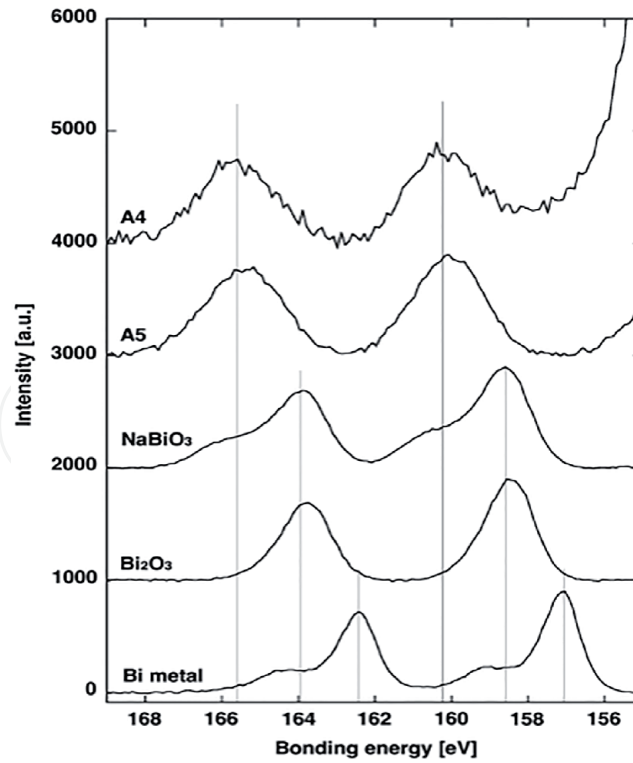
Figure 5.
Characteristic Bi XPS reported by Fujimoto [28].

resonance (NMR), X-ray photoelectron spectroscopy (XPS), electron spin resonance (ESR), X-ray diffraction, and extended X-ray absorption fine structure (EXAFS), *etc.* [28]. Previous research gave rise to different hypotheses about BACs, such as Bi+, Bi0, BiO, Bi clusters [31, 34, 35], and Bi3+ or Bi5+ by Fujimoto *et al*. [28, 32], being responsible for the NIR emissions. Dianov recognized two experimental facts related to BACs: (i) Bi3+ and Bi2+ emit visible emission. However, no NIR emission, and (ii) NIR emissions are observed because of the reduction of Bi3+ and Bi2+ to a lower oxidation state. Therefore, the probable origins of NIR emissions in Bi-doped glass and fiber associated with low valence Bi ions and other dopants that form the BAC-Si, BAC-Al, BAC-Ge, and BAC-P were investigated [25, 31, 34]. Following this, the monovalent BACs formed by Bi+ were of definite interest in understanding the NIR emission origin in BDFs. Bi+ was described as having a ground configuration of $6s^26p^2$ and its energy level split by a spin-orbit coupling interaction into the ground state $3P_0$ and the excited states $1S_0$, $1D_2$ and $3P_{2,1}$ corresponding to the energy bands around 500 nm, 700 nm, 800 nm and 1000 nm [25, 36]. Recently, energy levels of BAC-Si and BAC-Ge were described. The origin of NIR emission was reported as likely from Bi⋯ ≡ Si-Si ≡ and Bi⋯ ≡ Ge-Ge ≡ complexes formed by the interstitial Bi atoms (Bi0) and intrinsic glass defects and ≡ Si-Si ≡ and ≡ Ge-Ge ≡ oxygen vacancies [29, 37]. The energy levels of BAC-Si and BAC-Ge recommended in previous work are presented in **Figure 6** shows the excitation and emission characteristics associated with these particular BACs.

Although BAC-Si and BAC-Ge were described with much information about their kind and spectral characteristics, in-depth knowledge of BAC-Al and BAC-P lags far behind. BAC-Al and BAC-P showed notably different spectral behavior in BDFs than those of BAC-Si and BAC-Ge. One of the essential distinctive features is the Stokes shifts in the emission and excitation produced from these two centers, while for BAC-Si and BAC-Ge, no such Stokes shifts were pronounced [29]. Electron-photon interaction giving increase to the detrimental emission processes joined with these two centers was expected as the reason for
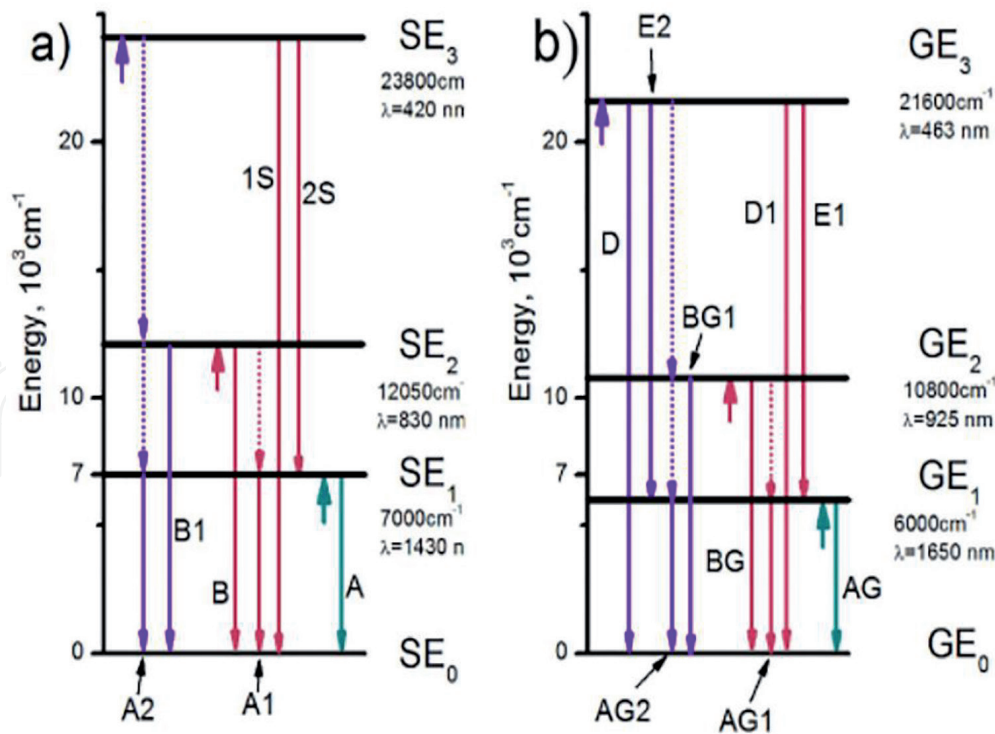
Figure 6.
*Reported energy levels of (a) BAC-Si and (b) BAC-Ge [31].*

the Stokes shifts. Furthermore, BAC-Al was quite different from BAC-Si and BAC-Ge based on their susceptibility to electron irradiation [38]. All of these specifications made it hard to discover the complete energy diagram of these active centers.

3.2 Luminescence properties of BDFs

The properties of near-infrared (NIR) broadband luminescence of Bi-doped silica fibers are sensitive to the composition of glass in addition to the conditions of fabrication. The partial shielding of the unfilled subshell 4f by filled 5 s and 5p in RE ions prevents significant interaction from the host environment. In comparison to RE elements, Bi has filled internal subshells, and external 6 s and 6p electrons interact significantly with the host, showing host-dependent absorption and emission properties. Co-dopants can also dramatically alter the spectrum of luminescence, as shown in **Figure** 7.

Herein, Bi-doped fibers with aluminosilicate hosts are described as Bi-doped aluminosilicate fibers (BASEs). They have shown a luminescence peak at 1150 nm. In contrast, Bi-doped fibers with phosphorus silicate and Germane silicate core composition hereafter described as Bi-doped phosphorus silicate fiber and Bi-doped German silicate fibers (BGSFs) are known to transfer the emission band to a longer wavelength side of about 1300 and 1450. Recently, by using high GeO2 concentration (50 mol%) within the fiber core, the Bi emission window is extending to a covered wavelength band of 1600–1800 nm. Luminescence in Bi-doped phosphor germane silicate fibers (BPGSFs) is broad compared to phosphorous (P) and other Bi-doped fibers co-doped with germanium (Ge). This makes it possible by changing the fiber core composition using Bi-doped optical fibers to show lasers and amplifiers for cover the full spectrum region about 1150–1800 nm. In **Figure 6**, the pump wavelength bands are referred to by the arrow. Wavelength bands of the pump about 1050, 1230, and 1310 nm for BASFs, BPSFs, and BGSFs,
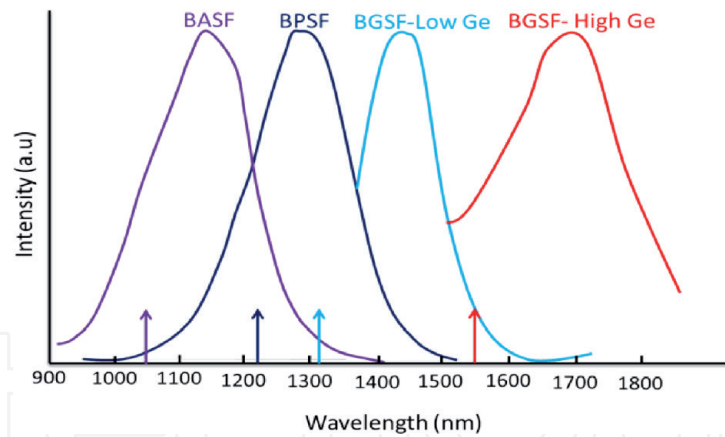
Figure 7.
The Spectrum regions covered via different Bi-doped fibers with various hosts [39].

respectively, usually are utilized. In the case of BGSFs with a high concentration of
GeO2, the pump wavelength band is about 1550 nm [39, 40].

3.3 Applications of BDFs

BDFs have many applications in different optical systems because of their wave-
length based discriminative transmission losses [41]. A 1651 nm single-frequency
laser diode is providing with a Bi-doped fiber power amplifier, and its performance
is evaluated experimentally [42]. This amplifier is using to increase the performance
of methane detection systems, such as remote stand-off systems or photoacoustic
spectroscopy (methane has a molecular absorption line of almost 1651 nm). Two
amplifier configurations are shown and output power of larger than 80 mW in both
cases. The results obtained provide valuable perspective for compact and straight-
forward fiber amplifiers in the spectral region of ~1630–1750 nm with a power
output of over 100 mW. The experimental set-up schematic diagrams are displayed
in **Figure 8(a)** and **(b)**. Two configurations are investigating, both with signal and
pump radiation continues to using a WDM coupler to launch pump light at 1550 nm
into the BDF and offer the amplified radiation output at 1651 nm. Standard, com-
mercially available WDM coupler that is proposed to operating at 1625 nm and
1550 nm (from the Opto-Link Corporation). Its transmission is calculated to be
~95% at 1550 nm, but only ~65% at 1651 nm. A polarization-independent optical
circulator is using in a second configuration (**Figure 8(b)**) broadband as an alterna-
tive a WDM coupler. The circulator (including from OptoLink Corporation) has
been proposed for a wavelength of 1525–1610 nm. Nevertheless, its 1550 nm (port
1 - port 2) and 1651 nm (port 2 - port 3) transmissions were quite the same, almost
80 percent.

The Er-Doped Fiber Amplifier (EDFA) is currently one of the most crucial
elements for various fiber optic systems [43]. Nevertheless, driven by a continually
growing demand, network traffic, which has grown exponentially for decades,
would result in the overloading of these"capacity crunch" systems, since EDFA is
limited to 1530–1610 nm in the spectrum. New technology will need to be pursued,
and the development of optical amplifiers for new spectral regions can be a promis-
ing solution. Some of the fiber-optic amplifiers are made with materials doped with
rare-earth. As a result, full bands for the gain band of Er-doped fibers are still avail-
able in shorter (1150–1530 nm) and longer wavelength (1600–1750 nm) regions. A
novel fiber amplifier is operated at a spectrum region of 1640–1770 nm pumping via
commercial laser diodes at 1550 nm. This amplifier is achieved by use Bi-doped high-
Germania silicate fibers fabricating by an MCVD technique. The experimental set-up

of a typical Bi-doped fiber amplifier is illustrated schematically in **Figure 9**. The BDFA is built using a scheme with Bi-directional pumping (backward and forward pumping). As a pumping source, commercial laser diodes are using with an ultimate output power of 150 mW each. The active fiber was core-pumped through commercial WDMs based on SMF-28. WDMs Transmission spectra are shown in **Figure 8**. Optical isolators are spliced to the amplifier of the input and output. The first is using to reduce the effect of amplified spontaneous emission (ASE) of a Bi fiber on the signal source. The second prevented possible lasing. Bold points act as splices, where an optical loss is ~1 dB because of the difference between the active fiber mode field diameter and that of conventional fibers (SMF-28).

The proposed dual pumping scheme of 830 and 980 nm aims at broadening and flattening Bi/Er multicomponent fiber (BEDF) spectral performance [44]. The distinct BACs of germanium (BAC-Ge), aluminum (BAC-Al), phosphorus (BAC-P), and silique (BAC-Si) have spectral properties characterized by single pumping, respectively, of
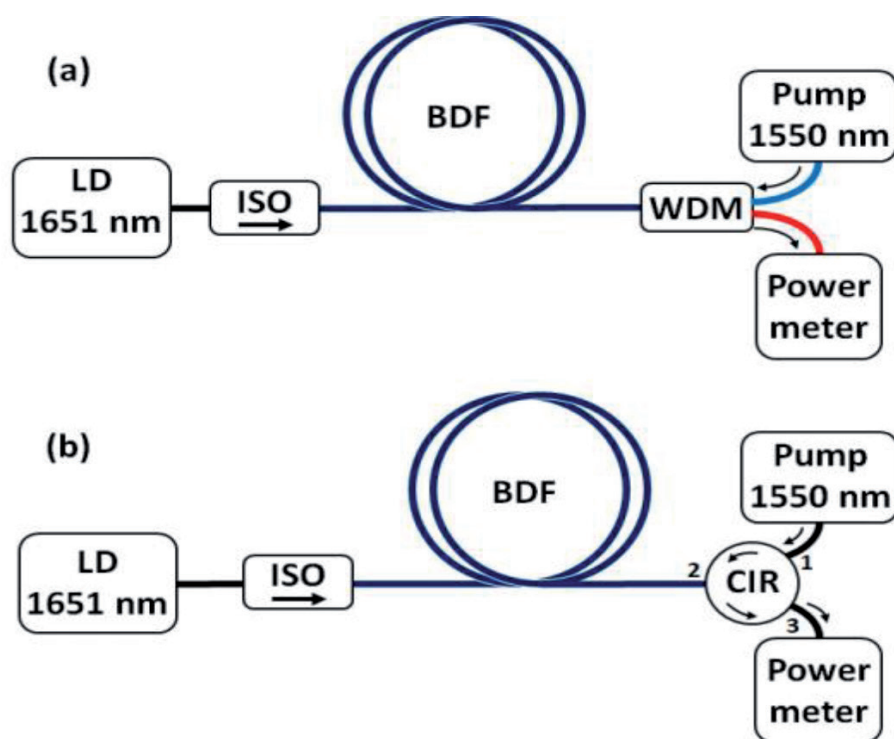
Figure 8.
Two BDF amplifiers configurations: (a) set-up with a WDM coupler using for pump light launch in BDF and processing of amplified signals at 1651 nm; (b) optical circulator set-up. ISO-optical insulator, LD-diode projector.
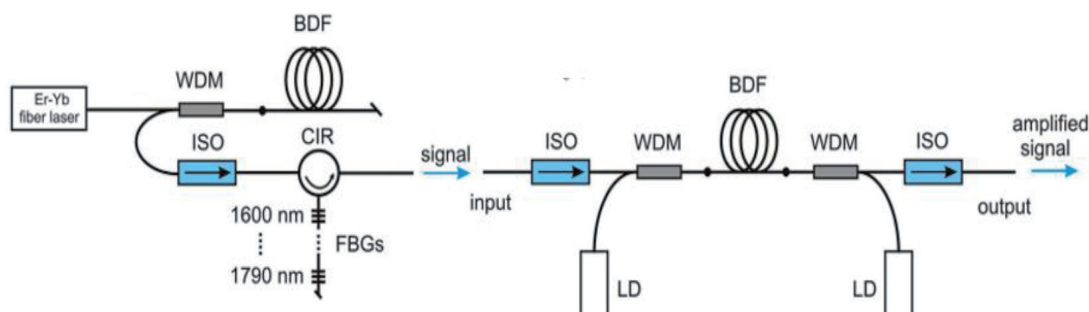
Figure 9.
Experimental BDFA set-up. The figure left side shows a home-built light source producing a wavelength comb of 1615 nm - 1795 nm, which is uniformly spaced with a phase of 15 nm. The figure right side illustrates the amplifier itself. Notably, ISO: An optical isolator, LD: Laser diode operating at 1550 nm, FBG: Fiber Bragg grating and CIR: Optical circulator.
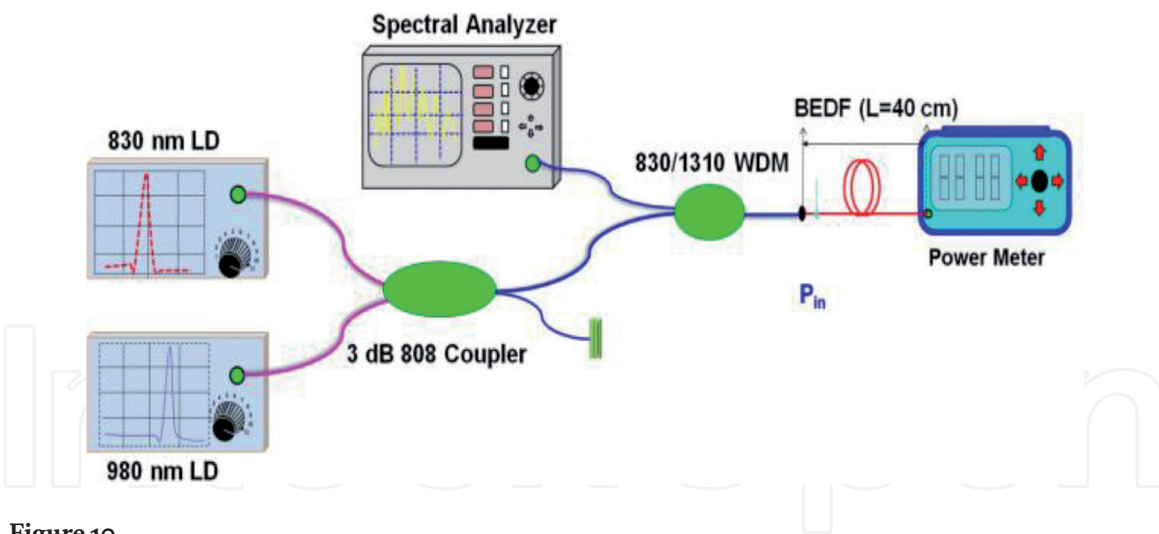
Figure 10.
Dual pumping experimental set-up for backward luminescence measurement.

980 nm and 830 nm. Depending on the BAC-Al (∼1100 nm) and BAC-Si (∼1430 nm) emission slope efficiencies under the single pumping of 830 and 980 nm, the dual pumping scheme with an optimizing pump power ratio of 25 (980 nm VS 830 nm) is determined to realize flat, ultra-broadband luminescence spectra covered the wavelength range 950-1600 nm. The dual pumping scheme is more illustrated on the on-off gain BEDF performance. The gain spectrum is flattening and broadening over 300 nm (1300-1600 nm) with an average gain coefficient of ∼1.5 dBm^{-1}, due to the pump power ratio of ∼8 (980 VS 830 nm). The spectral covering is about 1.5 and 3 times more expansive compared to single pumping of 830 and 980 nm pumping, respectively. Due to the optical characteristic of the energy level diagrams of 830 and 980 nm, the advantage of dual pumping is clarified. The proposed dual 830 and 980 nm pump scheme with the BEDF multicomponent shows great promise potential in a range of broadband optic applications, such as NIR-band tunable laser, a standard ASE source, and broadband amplifier. The luminescence measurement set-up is shown in **Figure 10**. The 980 and 830 nm pigtailed laser diodes (LD) were launched into the input end of 3 dB 808 couplers, and the 810/1310 WDM, the BEDF, was spliced with the output end of 1310 beam with ∼1 dB splice loss. The backward optical spectral analyzer (OSA) was used to record the emission signal to remove the effect of residual pump power. To monitor the unabsorbed pump power, a digital power meter was placed at the end of BEDF, and A short length (∼40 cm) of BEDF was tested.

4. Bismuth doped fiber amplifier (BDFA)

Doped fiber amplifiers (DFAs) are optical amplifiers that use a doped optical fiber as a gain medium to amplify an optical signal. They are related to fiber lasers. The pump laser and the signal to be amplified are multiplexed into the doped fiber, and the signal is amplified through interaction with the doping ions. As an example is the (BDFA), where the core of a silica fiber is doped with Bi ions and can be efficiently pumped with a laser. 1120 nm diode-pumped Bi-doped fiber amplifier is fabricated by N. K. Thipparapu et al. [45]. Bi-doped aluminosilicate fiber is fabricated using an MCVD solution doping and is distinguished by its gain and unsaturated loss. The amplifier performance was compared with the traditional pumping wavelength region of 1047 nm for a novel pumping wavelength of 1120 nm. Unsaturable losses in 1047 and 1120 nm pump wavelengths were 65% and 35%, respectively. At 1180 nm, the maximum gain of about 8 dB was observed for 100 m fibers with pumping at 1120 nm. The 1120 nm pump produced an enhancement

of gain of 70% compared with the 1047 nm pump. An additional 3.5 dB gain was achieved at 1047 and 1120 nm simultaneous pumping. **Figure 11** shows the schematic experimental set-up used for the measurement of gain in Bi-doped fiber. The set-up consists of an 1180 nm LD as input signal source and fiber pigtailed 1120 nm LD and/or 1047 nm Nd-YLF laser as the pump source. To abstain from the wavelength division multiplexers (WDMs) and back reflections to combining pump and signal sources, Isolators (ISO) was used. The spectrum of the output and input signal is taking through an OSA. The input signal was obtained little before the fiber under trial. In contrast, the output signal is determined by consideration of the WDM loss using to separating the pump from the signal.

O-band has recently been widely used for low-cost data transmission. The feature of O-band is that the transmitter wavelength(s) are laying close to the zero dispersive fiber wavelength (λ_0), and no compensation is therefore needed for either optical or electronic chromatic dispersion. O-band transponder total bit rate is enhanced to 425 Gb/s, for instance, using 8 LAN WDM 26.6 Gbaud/s PAM-4 modulated channels [46]. Using WDM and complex modulation formats minimize the power of both the receiver sensitivity and receiver per channel such that optical amplification is appropriate. O-band signal boosting can be achieved by employing Semiconductor Optical Amplifiers (SOA). However, they create considerable distortions due to the modulation of self- and cross- gain [47]. Although most of dispersion broadened channels are amplified [48], SOAs are not approbated for intensity modulation formats transmission like PAM-4 operating near $\lambda 0$ with relatively small channel count. Praseodymium doped fiber amplifiers (PDFA) with a bandwidth of 1280–1320 nm [49] were shown, but non-silica host glass was required, which makes PDFA complicated and costly. O-band amplification has been extensively studied in Bismuth-doped silica fibers [50]. A 150 m long BDFA with bandwidths of 1320-1360 nm has been reported using a complex dual-wavelength pumping system with only 6 × 10 Gb/s OOK channels [51]. Simple silica-based BDFA with 80 nm 6-dB gain-bandwidth flexibly centered within 1305-1325 nm, and parameters comparable to EDFAs is developed by V. Mikhailov et al. [52]. The amplifier can extend 400GBASE-LR8 transmission (8 × 26.6 Gbaud/s PAM-4 channels) beyond 50 km of G.652 fiber. The active fiber core consists of phosphosilicate glass doped with Bi (>0.01 mol%) produced using the MCVD process. The preform was cladding by a Heraeus F300 tube while all the core components, including P, Si, and Bi, were deposited from the gas phase. The index difference between the fiber core and the cladding was approx. 6 × 10–3, and the cut-off wavelength was near 1.1 μm. As the core diameter of 7 μm of fiber offered reasonable slice capability with silica-based fibers, the regular automatic splicer was
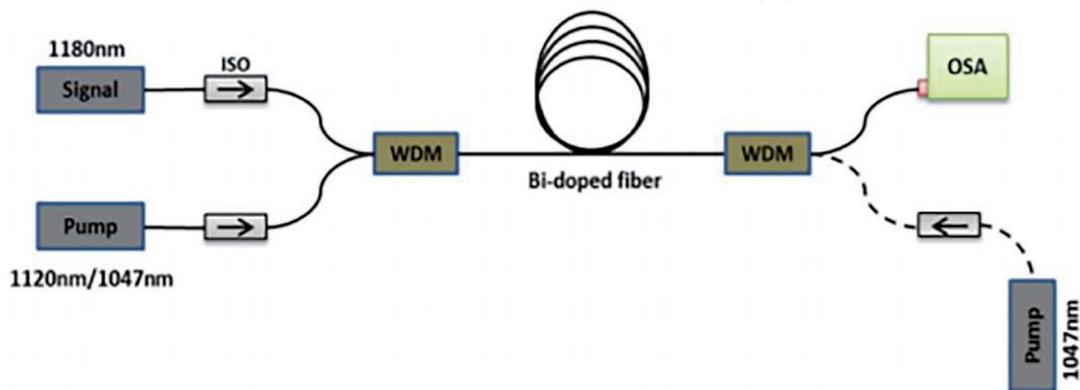
Figure 11.
Schematic of the experimental set-up to measure gain in Bi-doped fiber (the 1047 nm pump with the dashed line is used for Bi-directional pumping; otherwise, that port of the WDM is used to monitor the excess pump).
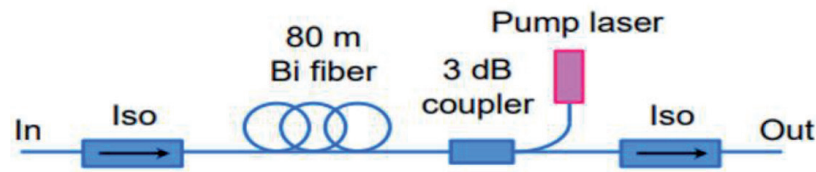
Figure 12.
Bi-fiber characterization set-up.

used to splice G.652and Bi- fibers. In order to investigate emission properties, 80 meters of Bi-fiber were subsequently pumped with a 3 dB wideband coupler with lasers of 1155, 1175, 1195, 1215, and 1235 nm (**Figure 12**).

Author details

Rifat M. Dakhil Alsingery* and Ahmed Mudhafer
Chemical and Petrochemical Techniques Engineering Department, Southern Technical University, Iraq

*Address all correspondence to: rifat.dakhil@stu.edu.iq

IntechOpen

References

[1] K. Kao and G. A. Hockham, "Dielectric fiber surface waveguides for optical frequencies," in *Proceedings of the Institution of Electrical Engineers*, vol. 113, no.7.IET, 1966, pp. 1151-1158

[2] F. Kapron, D. Keck, and R. Maurer, "Radiation losses in glass optical waveguides," *Applied Physics Letters*, vol. 17, no. 10, pp. 423-425, 1970.

[3] T. Miya, Y. Terunuma, T. Hosaka, and T. Miyashita, \Ultimate low-loss single mode fiber at 1.55μm," Electronics Letters, vol. 15, no. 4, pp. 106{108, 1979

[4] OFS. All Wave One Fiber-Zero Water Peak. [Online]. Available: http://http://fiber-optic-catalog.ofsoptics.com/Asset/AllWave-One-Fiber-160-web.pdf

[5] R. J. Mears, L. Reekie, I. Jauncey, and D. N. Payne, Low-noise erbium-doped fiber amplifier operating at 1.54μm," Electronics Letters, vol. 23, no. 19, pp. 1026-1028, 1987.

[6] D. Richardson, J. Fini, and L. Nelson, Space-division multiplexing in optical fibers," Nature Photonics, vol. 7, no. 5, pp. 354-362, 2013.

[7] Internet use reaches 5 billion worldwide. [Online]. Available: http://www.futuretimeline.net/21stcentury/2020.htm#internet-2020

[8] L. Technologies. All Wave Single Mode Optical Fiber. [Online]. Available:https://www.usbid.com/datasheets/usbid/2000/2000-q3/5822-3.pdf

[9] Thipparapu, Naresh Kumar. Development of bi-doped fiber amplifiers and lasers & broadband Er-doped multi-element fiber amplifiers. Diss. University of Southampton, 2018.

[10] L. Dong and B. Samson, Fiber Lasers: Basics, Technology, and Applications. CRC Press, 2016.

[11] P. C. Becker, A. A. Olsson, and J. R. Simpson, Erbium-doped fiber amplifiers: fundamentals and technology. Academic Press, 1999.

[12] A. B. G. Blase, "Investigations on Bi^{3+-}activated phosphors" *J. Chem. Phys.*, vol. 48, pp. 217-222, 1968.

[13] R. B. Laurer, "Photoluminescence in $Bi1_2SiO_{20}$ and $Bi1_2GeO_{20}$," *Appl. Phys. Lett.*, vol. 17, pp. 178-179, 1970

[14] M. J. Weber and R. R. Monchamp, "Luminescence of $Bi_4Ge_3O_{12}$: spectral and decay properties" *J. Appl. Phy*s, vol. 44, pp. 5495-5499, 1973

[15] F. Kellendonk, T. Belt and G. Blasse, "On the luminescence of bismuth, cerium, and chromium and ytterbium aluminium borate" *J. Chem. Phys.*, vol. 76, pp. 1194-1201, 1982.

[16] R. Retoux, F. Studer, C. Michel, B. Raveau, A. Fontaine and E. Dartyge, "Valence state for bismuth in the superconducting bismuth cuprates" *Phys Rev. B*, vol. 41, pp. 193-199, 1990.

[17] M. A. Hamstra, H. F. Folkerts, and G. Blasse, "Red bismuth emission in alkaine-earthmetal sulphates" *J. Mater. Chem.*, vol. 4, pp. 1349-1350, 1994

[18] Y. Fujimoto and M. Nakatsuka, "Infrared luminescence from bismuth-doped silica glass" *Jpn. J. Appl. Phys.*, vol. 40, pp. L279-L281, 2001.

[19] M. Y. Peng, J. R. Qui, D. P. Chen, X. G. Meng, I. Y. Yang, X. W. Jiang, et al., "Bismuth- and aluminum-codoped germanium oxide glasses for super-broadband optical amplification" *Opt. Lett.*, vol. 29, pp. 1998-2000, 2004

[20] Y. Fujimoto and M. Nakatsuka, "Optical amplification in bismuth-doped silica glass, " *Appl. Phys. Lett.*, vol. 82, pp. 3325-3326, 2003.

[21] E. M. Dianov, V. V. Dvoyrin, V. M. Mashinsky, M. V. Yashkov, and A. N. Guryanov, "CW bismuth fiber laser" *Quantum Electron.*, vol. 35, pp. 1083-1084, 2005.

[22] V. V. Dvoyrin, V. M. Mashinsky, E. M. Dianov, A. A. Umnikov, M. V. Yashkov and A. N. Guryanov, "Absorption, fluorescence and optical amplification in MCVD bismuth-doped silica glass optical fibres" in *Proc. Of the ECOC*, vol. 4, pp. 949-950, 2005.

[23] Y. Fujimoto and M. Nakatsuka, "27Al NMR structural study on aluminum coordination state in bismuth-doped silica glass" *J. Non-Cryst. Solids*, vol. 352, pp. 2254-2258, 2006.

[24] T. Suzuki and Y. Ohishi, "Ultrabroadband near-infrared emission from Bi-doped Li2O–Al2O3–SiO2 glass" Appl. Phys. Lett., vol. 88, p. 191912, 2006.29

[25] X. Meng, J. Qiu, M. Peng, D. Che, Q. Zhao, X. Jiang, et al., "Near infrared broadband emission of bismuth-doped aluminophosphate glass" *Opt. Express*, vol. 13, pp.1628-1634, 2005.

[26] M. Peng, X. Meng, J. Qiu, Q.Zhao and C. Zhu, "GeO2: Bi, M (M = Ga, B) glasses with super-wide super-wide infrared luminescence" *Chem. Phys. Lett.*, vol. 403, pp. 410-414, 2005.

[27] S. V. Firstov, I. A. Bufetov, V. F. Khopin, A. A. Umnikov, A. N. Guryanov, and E. M. Dianov, "Time-resolved spectroscopy and optical gain of silica-based fibers co-doped with Bi, Al and/or Ge, P, and Ti" *Laser Phys.*, vol. 19, pp. 894-901, 2009.

[28] Y. Fujimoto, "Local structure of the infrared bismuth luminescent center in bismuthdoped silica glass" *J. Am. Ceram. Soc.*, vol. 93, pp. 581-589, 2010.

[29] I. A. Bufetov, M. A. Melkumov, S. V. Firstov, K. E. Riumkin, A. V. Shubin, V. F. Khopin, et al., "Bi-Doped Optical Fibers and Fiber Lasers" *IEEE J. Sel. Top. Quant.* Vol. 20, 0903815, 2014.

[30] I. A. Bufetov, S. V. Firstov, A. V. Shubin, S. L. Semenov, V. V. Vel" Miskin, A. E. Levchenko, et al., "Optical gain and laser generation in bismuth-doped silica fibers free of other dopants" *Opt. Lett.*, vol. 36, pp. 166-168 2011.

[31] S. V. Firstov, V. F. Khopin, I. A. Bufetov, E. G. Firstova, A. N. Guryanov, and E. M. Dianov, "Combined excitation-emission spectroscopy of bismuth active centers in optical fibers" *Opt. Express*, vol. 19, pp. 19551-19561 2011.

[32] E. M. Dianov, "Bismuth-doped optical fibers: a challenging active medium for near-IR lasers and optical amplifiers" *Light Sci. Appl.*, vol. 1, pp. 1-7, 2012.

[33] E. M. Dianov, "Bismuth-doped optical fibers: a new active medium for NIR lasers and amplifiers" in *Proc of the SPIE*, vol. 8601, 2013.

[34] T. M. Hau, X. Yu, D. Zhou, Z. Song, Z. Yang, R. Wang, *et al.*, "Super broadband near-infrared emission and energy transfer in Bi–Er co-doped lanthanum aluminosilicate glasses" *Opt. Mater.*, vol. 35, pp. 487-490, 2013.

[35] A. N. Romanov, Z. T. Fattakhova, A. A. Veber, O. V. Usovich, E. V. Haula, V. N. Korchak, *et al.*," On the origin of near-IR luminescence in Bi-doped materials (II). Subvalent monocation Bi+ and cluster Bi53+ luminescence in AlCl3/ZnCl2/BiCl3 chloride glass," Opt. Express, vol 20, pp. 7212, 2012. 30

[36] L. Zhang, G. Dong, J. Wub, M. Peng, and J. Qiua, "Excitation wavelength-dependent near-infrared luminescence

from Bi-doped silica glass" *J. Alloy Compd.*, vol. 531, pp. 10-13, 2012.

[37] V. O. Sokolov, V. G. Plotnichenko, and E. M. Dianov, "The origin of near-IR Luminescence in bismuth-doped silica and Germania glasses-free of other dopants: firstprinciple study" *Opt. Mater. Express*, vol. 3, pp. 1059-1074, 2013.

[38] A. V.Kir'yanov, V. V. Dvoyrin, V. M. Mashinsky, N. N. Il' ichev, N. S. Kozlova, and E. M. Dianov, "Influence of electron irradiation on optical properties of Bismuth doped silica fibers" *Opt. Express*, vol. 19, pp. 6599-6608, 2011.

[39] I. Bufetov and E. Dianov, Bi-doped fiber lasers," *Laser Physics Letters*, vol. 6, no. 7, p. 487, 2009.

[40] S. Firstov, S. Alyshev, M. Melkumov, K. Riumkin, A. Shubin, and E. Dianov, Bismuth-doped optical fibers and fiber lasers for a spectral region of 1600-1800nm," *Optics Letters*, vol. 39, no. 24, pp. 6927-6930, 2014.

[41] D. Jain, N. K. Thipparapu, and J. K. Sahu, "Bismuth doped fiber for filtering applications," in 2019 Conference on Lasers and Electro-Optics Europe and European Quantum Electronics Conference, OSA Technical Digest (Optical Society of America, 2019), paper cj_p_39.

[42] Michal Nikodem, *Aleksandr M Khegai and Sergei V Firstov* "Single-frequency bismuth-doped fiber power amplifier at 1651 nm", 2019 *Laser Phys. Lett.* **16** 115102

[43] Firstov, S. V., Alyshev, S. V., Riumkin, K. E., Khopin, V. F., Guryanov, A. N., Melkumov, M. A., & Dianov, E. M. (2016). A 23-dB bismuth-doped optical fiber amplifier for a 1700-nm band. *Scientific reports*, 6, 28939.

[44] Zhao, Q., Luo, Y., Wang, W., Canning, J., & Peng, G. D. (2017). Enhanced broadband near-IR luminescence and gain spectra of bismuth/erbium co-doped fiber by 830 and 980 nm dual pumping. *AIP Advances*, 7(4), 045012.

[45] Thipparapu, N. K., Jain, S., Umnikov, A. A., Barua, P., & Sahu, J. K. (2015). 1120 nm diode-pumped Bi-doped fiber amplifier. *Optics Letters*, 40(10), 2441-2444.

[46] IEEE 802.3bs-2017 - IEEE Standard for Ethernet Amendment 10: Media Access Control Parameters, Physical Layers, and Management Parameters for 200 Gb/s and 400 Gb/s Operation, IEEE Standard, 2017.

[47] A.A.M Saleh et al., Effects of semiconductor optical amplifier nonlinearity on the performance of high-speed intensity modulation lightwave systems, IEEE Trans. Com., vol. 38, 1990.

[48] J. Renaudier, 100nm ultra-wideband optical fiber transmission systems using semiconductor optical amplifiers, Proc. ECOC, 2018, Mo4G.5.

[49] M. A. Melkumov, et al., Bismuth-doped fiber lasers and amplifiers: Review and prospects, Proc. Int. Conf. Laser Optics, 2016, S1-19.

[50] S. Barthomeuf, et al., High Optical Budget 25Gbit/s PON with PAM4 and Optically Amplified O-Band Downstream Transmission, Proc. ECOC, 2018, Mo4B.2.

[51] N. Taengnoi, et al., Amplified O-band WDM Transmission using a Bi-doped Fibre Amplifier, Proc. ECOC, 2018, Mo3E.2.

[52] Mikhailov, V., Melkumov, M. A., Inniss, D., Khegai, A. M., Riumkin, K. E., Firstov, S. V., ... & Puc, G. S. (2019, March). Simple broadband bismuth-doped fiber amplifier (BDFA) to extend O-band transmission reach and capacity. In *Optical Fiber Communication Conference* (pp. M1J-4). Optical Society of America.