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Review

Bismuth-Doped Fiber Lasers and Amplifiers Operating from O- to U-Band: Current State of the Art and Outlook

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Abstract: The development of unique optical materials that provide amplification and lasing in new wavelength ranges is a major scientific problem, the solution of which is becoming the basis for the emergence of new optical technologies, which are primarily targeting the expanding of operating wavelengths in silica glass. In fact, one of the notable advances in the field of fiber optics over the past two decades has been the production of a new type of laser-active fibers (namely bismuth-doped fibers), which has made it possible to cover previously inaccessible (for rare-earth-doped fibers) spectral ranges, in particular O-, E-, S-, and U-telecom bands. The advance in this direction has led to further growth of the technological capabilities in the telecom industry for amplification and generation of optical radiation in various wavelength bands, which will result in the near future to overcoming the problem known as "capacity crunch" by means of expanding the data transmission range. Recently, bismuth-doped fibers have been actively studying in order to improve their characteristics, which would allow for efficient implementation of optical devices based on bismuth-doped fibers (BDFs) with deployed telecommunications systems. This is one of the dynamically developing areas, where progress has already manifested in form of emergence of new achievements, in particular commercially available various types of BDFs, as well as a series of novel fiber-optic amplifiers for the O- and E-bands. In this review, a number of scientific studies that have already led to a noticeable progress in the field of optical properties of BDFs and the practical implementation of optical devices (lasers and amplifiers) based on them are presented and discussed, with much attention to the achievements of recent years.

Keywords: fiber; laser; bismuth; gain; amplifier

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1. Introduction

For more than two decades, bismuth-doped optical fibers (BDFs) have been an object of considerable attention as promising active materials exhibiting unusual optical properties, which makes it possible to generate and amplify optical signals in various spectral bands of near IR (for example [1–3] and the references therein). The revealed optical properties inherent to BDFs are primarily determined by the properties of bismuth (Bi) as a chemical element with the electronic configuration of (Xe) $4f^{14}\,5d^{10}\,6s^2\,6p^3$, which belongs to the pnictogens (nitrogen family). This predetermines the existence of a variety of possible forms of bismuth (Bi^+, Bi^{2+}, Bi^{3+}, etc.), the strong dependence of their properties on the glass host composition and structure, including the local environment, which is manifested in the noticeable changes in the position and shape of absorption and luminescence bands [4,5]. This behavior is characteristic of luminescence in the visible region, which arises due to radiative transitions between the intrinsic levels of Bi^{3+} and Bi^{2+} ions, and IR luminescence, which are assigned to bismuth active centers (BACs). Despite the fact that the nature of BACs is still open to discussion, clear patterns have been identified, allowing one to classify the BACs. In particular, taking into account the relationship between the presence of a certain structural chemical element in the glass matrix and a spectral peak position of the IR luminescence band, four types of BACs associated with Al, P, Si, and Ge atoms have been revealed [5]. Thus, depending on the type of BACs, the IR luminescence band locates in different wavelength regions: 1.15 µm for BAC-Al, 1.33 µm for BAC-P, 1.43 µm for BAC-Si and 1.73 µm for BAC-Ge. These types of BACs manifesting themselves as distinct emission, and absorption patterns have been repeatedly demonstrated by different research groups [6,7]. The formation of such BACs leads to the appearance of optical gain and the possibility of lasing in such media. However, only fibers with low Bi concentration are the most attractive in terms of practical application [2], which is caused by the formation of undesired complexes of reduced forms of bismuth ions in high-concentrated BDFs due to the ability of Bi to be quickly reduced down to the metallic state at high temperatures during the manufacturing process [8]. That is why one should employ relatively long lengths of BDFs for optical devices. The long lengths might be undesirable for some tasks; for example, for creating pulsed laser systems or devices with narrow spectral linewidth. In addition, the level of BACs concentration has a significant impact on the development of fiber devices pumped by multimode laser diodes (cladding-pumped schemes).

It should be emphasized that, from a practical point of view, BDFs might be considered as a key element for new telecommunication technologies, where data transmission via fiber-optic communication link is carried out, not only in the C+L-band, but also beyond them using multi-wavelength bands technology [9]. The operation in the extended spectral bands is a very realistic scenario in the near future as a cost-effective stage necessary to avoid possible overload of communication systems due to global traffic that is growing by 30–40% annually. Successful deployment of multi-wavelength bands technology requires efficient and reliable fiber amplifiers, which can be well integrated into existing optical communication systems [10,11]. The technological solution in terms of multi-band optical fiber amplifiers based on BDFs currently looks the most promising, and it is evidenced by the interest of a large number of companies such as Amonics, Innolume Corp., OFS Fitel, LLC and Viavi Solutions, Nuphoton Tech., which have started to produce commercial devices for O-, E-telecom bands. This trend is expected to intensify that provides all conditions for the rapid implementation of this technology.

Recently, a series of review articles on bismuth-doped fibers has been published, where the optical properties of BDFs and the essential parameters of BDF amplifiers (BDFAs) for various wavelength ranges [12–15] were demonstrated and discussed. Nevertheless, in our opinion, trends that have emerged become attractive for the further research and development programs on the fabrication and study of BDFs, both for scientific and practical purposes. This is confirmed by the fact that a number of new papers appeared, which we shall consider in this review. In particular, we would like to highlight the following areas:

- Bismuth-doped fibers: toward higher Bi doping level and broadband amplification;
- Pulsed and CW lasers with different configurations based on bismuth-doped fibers: progress and future prospects;
- Fiber optic amplifiers for O-, E-, S-, and U-bands: from experiments to commercial devices.

2. Bi-Doped Fibers

Until now, the production of all kinds of BDFs, differing in terms of the chemical composition of the fiber glass core, has been carried out mostly by the traditional modified chemical vapor deposition (MCVD) process, which uses either an all-gas-phase or solution doping technique. The gas phase process is more flexible in terms of doping profile formation and fine turning of fiber core parameters, even despite all the complexities associated with modifying a MCVD lathe, primarily to ensure high-temperature delivery of the bismuth precursor up to the deposition zone. In this regard, the solution doping process is more standardized in technological stages due to its simplicity and long-term commercialization in the industry, which leads to its wider use by the majority of scientific groups working in this direction. However, it should be noted that for some types of BDF, especially, with a gain band in a wavelength region of 1300–1400 nm, the solution doping process creates certain difficulties due to the strong absorption band near 1380 nm associated with an increased content of OH groups caused by the used starting components (water, alcohols or acids solutions of the bismuth precursor). In case of the vapor phase deposition technique, this problem is effectively solved by selecting a suitable bismuth precursor and the technical process itself. For BDFs with a high-germanate glass core, the solution doping technique cannot be applied principally due to the strong difference in the chemical properties of the core and cladding glasses which does not allow for producing a porous glass layer with the required characteristics. Regardless of the doping technique, the MCVD preform fabrication process typically consists of two stages: the deposition of porous layers at temperatures of 1375–1550 °C (depends on the layer composition) and their impregnation (from the gas phase or through immersion in a solution) with bismuth-containing components. The other procedures during fabrication process are performed according to the standard methods, repeatedly described in previously published works (for example, [8]). Most of the results in the field of studying the luminescent properties and gain characteristics of BDFs (GeO_2–SiO_2 fibers, P_2O_5–SiO_2 and Al_2O_3–SiO_2 fibers) are reviewed in a number of papers from FORC RAS, ORC at Southampton University, and OFS Fitel (e.g., [2,12–15]).

Currently, the main attention of researchers is focused on the development of improved BDFs that provide optical amplification in the wavelength regions of the O-, E-, S-, and U-bands. As mentioned above, this is dictated by the demand for efficient fiber amplifiers for advanced optical communication systems. The state of the art in this regard is the investigation of fibers with a high Bi content, as well as the possibility of producing BDFs with an ultra-wideband gain spectrum. It should be noted that if the previous studies of concentration series of samples were limited primarily to BDFs with a peak absorption of 1 dB/m, now an ever increasing number of scientific articles is being published, where authors study in detail the properties of BDFs with a greater absorption (up to 10 dB/m) [16,17]. These works are related to BDFs with germanosilicate glass core having a gain band at around 1400 nm attributed to BACs-Si. The BDFs with a core based on germanosilicate glass are promising for development lasers and amplifiers for the wavelength range 1400–1530 nm (E+S-band) to expand erbium-doped fiber amplifiers operating wavelengths, i.e., outside conventional C+L-band (the spectral region 1530–1620 nm). Therefore, it is of great interest to compare the properties of BDFs with relatively high Bi concentrations. Since the certain BACs content is in the dependence of the total bismuth concentration (only a part of bismuth ions converts into the BACs) [18], to achieve the specified level of BACs absorption, the total amount of bismuth dopant in the optical fibers should be increased to 0.1 wt.%. A typical absorption spectrum in the wavelength range 350–1700 nm, where the distinctive BAC-Si bands peaked at 420, 820, 1410 nm can be observed, is depicted in Figure 1a. It should be noted that alongside the expected increase in BACs absorption one can observe the noticeable change in the level of broadband absorption in the form of a tail extending from the UV range. This becomes obvious when comparing the normalized absorption spectra shown in Figure 1a. In contrast to the active dopant absorption, this kind of absorption (so-called unsaturable loss) remains unchanged, even when laser radiation is launched into the fiber core. The unsaturated losses are attributed to cluster forms of bismuth, which have a higher yield with the increasing Bi content. Figure 1b summarizes the results from a number of papers in a form of a dependence of the active absorption and unsaturable loss values on the small-signal absorption at a wavelength of 1310 nm, which is directly proportional to the total Bi content. It is worth noting that the concentration dependence in this case is non-linear for unsaturable loss and linear for BACs-Si absorption, which is similar to those of other types of bismuth-doped fibers (with a core made of phosphosilicate [8] and high-GeO_2 silica glass [15]).

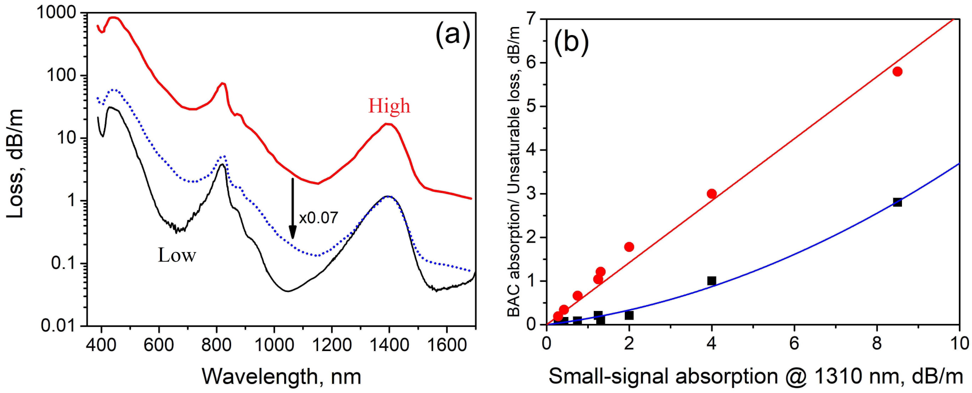

Figure 1. (**a**) The small-signal absorption spectra of BDFs with "low" and "high" Bi concentrations. For comparison, we present a normalized absorption spectrum of highly concentrated BDF, obtained by multiplying by the indicated number; (**b**) BACs absorption (circles) and unsaturable loss (squares) as a function of small-signal absorption at a wavelength of 1310 nm.

Despite the attempts to fabricate highly concentrated BDFs, the main conclusion from the analysis of the experimentally obtained data is the fact that significant qualitative progress has not been made, i.e., the parameters of the samples prepared in different research groups are quite consistent with the established pattern depicted in Figure 1a. A similar situation is typical for BDFs with a special refractive index profile (RIP) design (W-index and Graded-index BDFs), where the RIP and radial distribution of BACs are varied [18,19]. Therefore, it is quite expected that with an increase in the small-signal absorption (greater than a certain level), the optical gain of the active medium will become lower due to a decrease in the relative BAC concentration. The impact of Bi concentration on the shape of absorption of BACs-Si responsible for IR luminescence has not been established. The typical emission band of BACs-Si peaked at 1415 nm, having a width of 115 nm, which is demonstrated in Figure 2a. One of the possible configurations of the BACs-Si responsible for the near IR luminescence obtained from ab initio numerical simulation by V. Sokolov et al. [20] is presented in Figure 2a (inset). The optical transitions of such centers can be used to achieve amplification of optical signal in a spectral region of 1400–1500 nm. Determining the density of the active centers formed in BDFs is of obvious interest. Recently, a series of experiments performed by S. Alyshev et al. allowed determining the BACs content ($\sim 10^{17}$ cm^{-3}), as well as the conversion coefficient indicating the fraction of bismuth ions participating in the formation of the BACs. As it turned out, this coefficient comes up to 35% and depends on the concentration of bismuth and germanium oxide in the core glass [18].

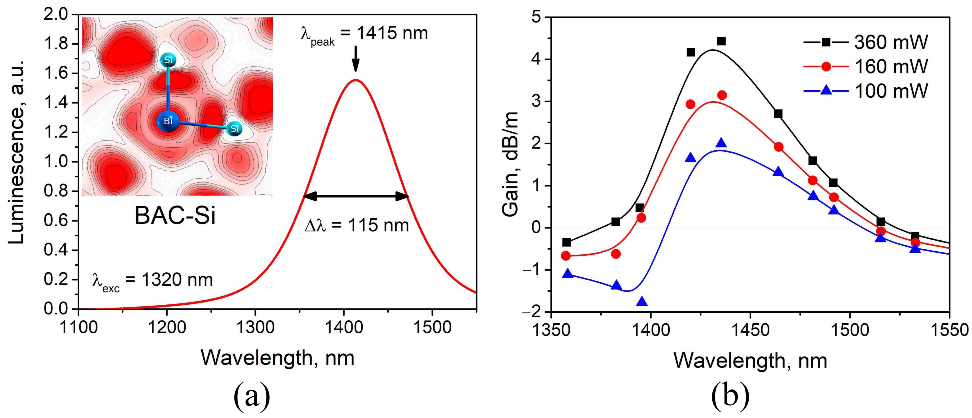

Figure 2. Luminescence (**a**) and gain (**b**) spectra of BACs-Si. Inset in (**a**): a possible structure of the BAC-Si.

V. Fuertes et al. [21] presented experimental data on a thorough examination of the dependence of the optical properties of this type of BDFs on the technological parameters of the solution doping MCVD process, including temperature and drawing speed of fibers, the preform sintering temperature, etc. From the obtained data, it was concluded that the thermal history of the manufacturing process plays an important role in the formation of near-IR emitting BACs in the germanosilicate glass matrix. It can be underlined that formation of BACs occurs at high temperature stages, and the mechanism is typically based on a transformation of bismuth precursors (redox reactions) while the active dopant penetrates into the host glass generating certain structural units.

It should be noted that, typically, the level of the optical gain of bismuth-doped germanosilicate fibers for efficient laser systems did not exceed 1 dB/m due to the causes mentioned above. Nevertheless, from the previously published works, in some fibers a gain value of more than 4 dB/m can be achieved when they are core-pumped at a wavelength of 1320 nm with a power of 360 mW as shown in Figure 2b [22]. In addition, a high gain of 3 dB/m was recently obtained by S. Liu et al. by pumping at 1360 nm [23]. As can be noted in Figure 2b, a long-wavelength tail of the gain spectrum extends beyond 1530 nm, giving the potential opportunity to use such fibers in combination with erbium-doped fibers to provide a wider amplification spectrum in the E+S+C+L range. This approach was realized in the work of F. Maes et al. in 2022, where the gain >20 dB in the spectral region from 1431 nm to 1521 nm was obtained [24].

In addition, taking into account the high gain achieved in the wavelength region <1430 nm, one can say that BAC-Si can definitely be used to create an active medium with an ultra-broadband gain spectrum in the O+E-band by combining with BACs associated with phosphorus (BACs-P) having a gain band in a shorter-wavelength region. A number of advances in this direction have been demonstrated using various approaches. In particular, one of the possible ways for developing ultra-broadband active medium is to fabricate a Bi-doped P_2O_5–SiO_2 fiber with a depressed cladding structure (W-index structure). Following this approach, Y. Ososkov et al. could obtain the optimal ratio between BACs-P and BACs-Si concentration (see Figure 3a) [25]. In this case, one can use a single-core- or cladding-launched pump wavelength to provide excitation for both BACs types simultaneously. Another way is to use a BDF with step-index profile induced by addition of P_2O_5 (or P_2O_5/GeO_2) where BACs-Si and BACs-P can be formed (for example, see Figure 3b). But in this case, it is necessary to use either configuration with different segments of BDFs containing other types of BACs or bi-directional core-pumping at dual wavelengths, etc. [26,27]. In all mentioned cases, one can obtain the gain spectrum with a bandwidth of greater than 100 nm (Figure 3c).

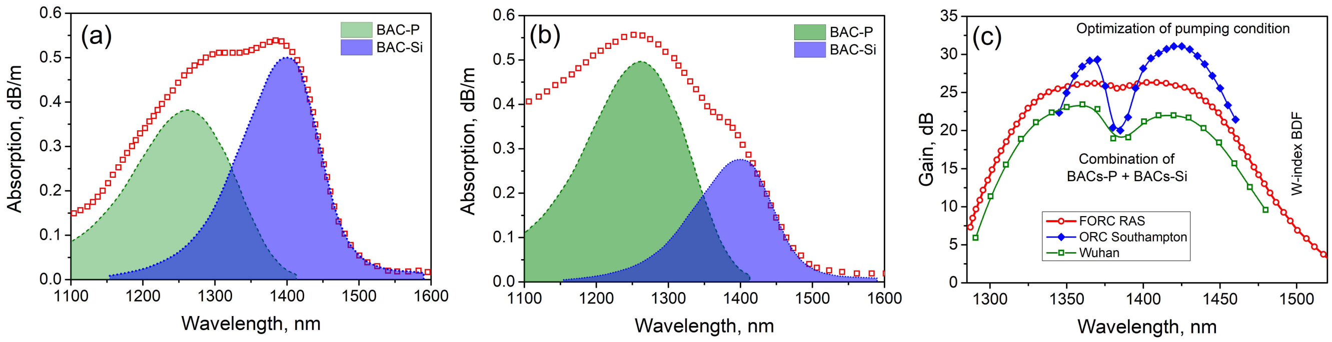

Figure 3. (**a**,**b**) Absorption spectra (red squares) of BDFs fabricated at FORC RAS (all-gas-phase deposition technique) and Wuhan National Lab. (solution doping process), correspondingly. The absorption bands related to BACs-Si and BACs-P are also presented. (**c**) Gain spectra obtained in the experiments by different research groups using various approaches.

Thus, the relevance of studying all types of BDFs, perhaps with the exception of those formed in aluminosilicate fibers, seems very important in practice. However, it should be noted that the parameters of most BDFs are already such that these media are successful implementation in commercial devices. As for the achievements in the realization of new optical devices based on advanced BDFs, a number of notable results will be presented and discussed in the following sections.

3. CW and Pulsed Bismuth-Doped Fiber Lasers

In contrast to the work on optical BDF amplifiers (BDFAs), which will be discussed below, there have been few publications devoted to BDF lasers (BDFLs) in recent years. This trend is natural; firstly, because the main results in the pursuit of classical laser systems had already been repeatedly demonstrated on all types of BDFs. This has led to the fact that BDFLs cover the spectral range from 1140 to 1775 nm. These results have already been covered in several earlier reviews; the reader can find detailed information on such lasers, for example, in [3]. In this section, we would like to talk about recent, more specific achievements in the area of developing new configurations of BDFLs, in particular multi-wavelength lasers, cladding-pumped fiber lasers, and some types of pulsed BDFLs.

3.1. Multiple Wavelengths BDFLs

Multiple-wavelength or, in several particular cases, dual-wavelength lasers, when we speak of BDFLs, can be very interesting and prospective solutions in telecommunications, gas sensing, medical use, microwave generation, and laser remote control. Additional applications may be related to the ultra-wide spectral range of amplification characteristic inherent to BDFs that allows one to achieve lasing at wavelengths inaccessible to the fibers doped with rare-earth elements. There are various ways to obtain multiple wavelength lasing. In case of bismuth-doped active medium, its specific properties such as a broadband gain spectrum and a considerable inhomogeneous broadening help achieving multiple-wavelength lasing. A simple and reliable approach is realized by G. Nemova et al. [28,29].

A dual-wavelength BDFL was realized using two fiber Bragg gratings (FBGs). To control lasing wavelength, the authors chose a cascaded scheme consisting of two partially separated cavities. Using pumps, one can change population inversion in the first or the second sub-cavity. A couple of high-germania BDF provided amplification in 1.6–1.8 µm spectral region. In combination with FBGs at 1727 and 1729 nm (see Figure 4), a stable continuous wave generation was achieved. After carrying out experiments and numerical simulations, the authors were able to build a contour map showing pump power conditions necessary to obtain certain regimes of laser operation (Figure 4).

H. Ahmad et al. conducted a series of works on multiple wavelength lasing. Unlike the previous scheme, the author used a ring cavity and several interesting filtering techniques, such as a Lyot filter [30], a stimulated-Brillouin-scattering (SBS) [31] and two-mode-fiber (TMF) filter [32]. The active medium in all laser modifications was BDF with phosphosilicate glass core, so the operating range of the lasers was in the region 1.3–1.4 µm. All of the considered filtering methods provided rather small wavelength spacing from 0.07 to 0.6 nm between neighboring spectral lines. At the same time, the number of simultaneously supported lines was more than 10. The study of lasing stability in terms of wavelength drift and output power showed stable operation over time. For the SBS method, the worst-case power fluctuations did not exceed 0.9 dB, while the use of the Lyot filter provided an even better stability of 0.6 dB. Wavelength fluctuation for all methods was below 0.1 nm. Perhaps the only obvious drawback of such systems is a rather low efficiency, which was slightly less than 0.15% at its best scenario. Some additional information on such lasers can be found in Table 1.

Table 1. Parameters of BDFLs.

Method	Wavelength Spacing, nm	Number of Lasing Lines	Center Wavelength, nm	Output Power, mW	Pump Power, W	Ref.
Lyot filter	0.192	21	1312	1	0.675	[30]
SBS	0.07	14	1320.3	0.52	1.02	[31,33]
TMF filter	0.69	18	1323.89	0.46	1.03	[32]
FBGs	2	2	1728	0.05	0.35	[29]

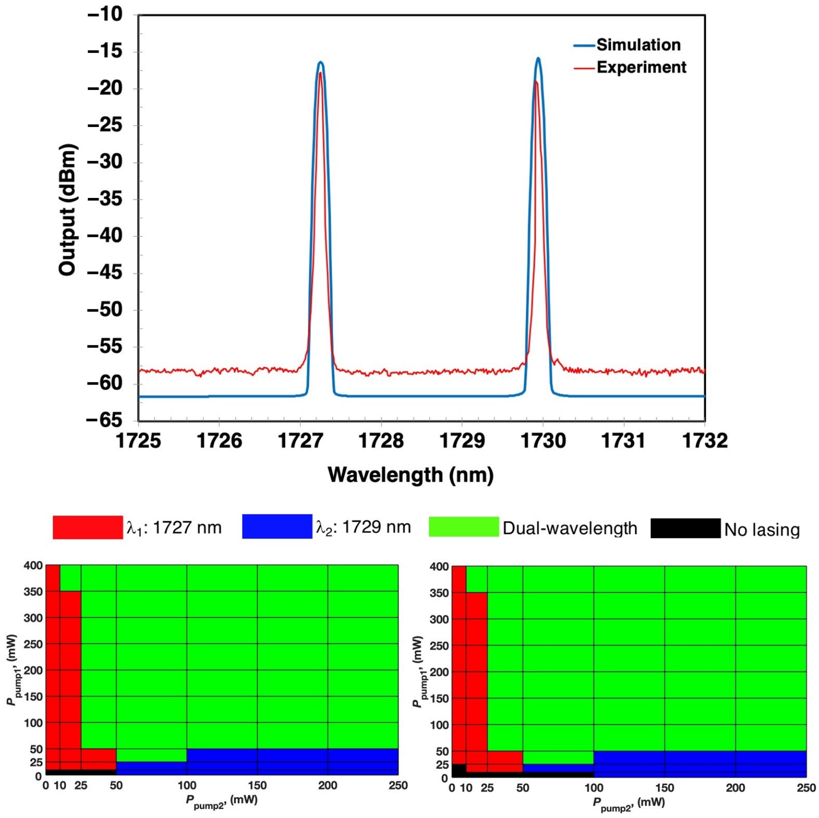

Figure 4. Output emission spectra of the dual wavelength BDFL (**top**); contour maps of BDFL regimes at different pump powers: experiment (**bottom, left**) and simulation (**bottom, right**).

3.2. Cladding-Pumped BDFLs

Another area of research that has been developed in recent years is cladding-pumped lasers. The lasers of this type are characterized by a number of advantages comparing to core-pumped analogues such as power scalability and higher cost efficiency. The fact that all commercially available Yb-doped fiber lasers with an output power above 1 kW are cladding-pumped only also speaks in favor of this technique. Although the pumping via cladding is well-studied when it comes to rare-earth-doped fiber devices, the cladding pump approach was completely overlooked in the case of BDFLs. This fact is justified since, in contrast to rare-earth-doped fibers, the Bi-doped ones have several obstacles that prevent efficient use of this technique. First, of all, the unsaturable losses are significantly higher for BDFs and growth faster than linearly with the increase in Bi content. This circumstance prevents an increase in the concentration of BACs beyond certain limit and forces the use of low-concentration fibers in lasers and amplifiers. Despite these difficulties, in 2022, the first cladding-pumped BDFL was successfully demonstrated [34]. A BDF based on germanosilicate glass with a low concentration of Ge served as an active medium in that work. To achieve higher pump absorption, excitation to the second excited state (N_3 in Figure 5a) was implemented, in contrast to resonance excitation via laser level N_2, as is performed in the core pumping technique. This became possible thanks to the fact that the corresponding optical transitions reside in the spectral range around 800 nm, where efficient multimode laser diodes are available. However, the output power that the authors managed to achieve was just 50 mW. In addition, the efficiency of the built laser barely reached 0.5%. Nevertheless, the results are very promising for further optimization and opens up prospects for various practical applications.

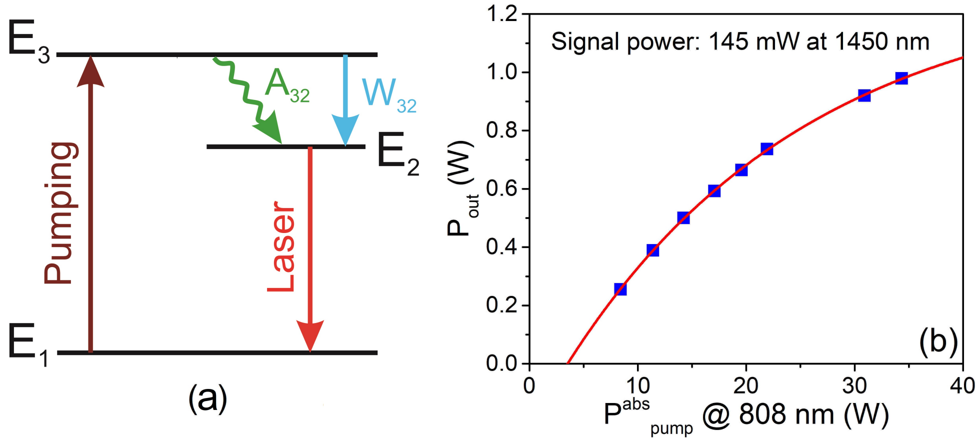

Figure 5. (**a**) BAC laser energy levels diagram with possible transitions; (**b**) output power from a booster based on the BDF pumped into the inner cladding as a function of pump power.

Further efforts were aimed at the scaling up the output power of such lasers. In [35], germanosilicate BDFs with rectangular inner cladding were demonstrated. This approach ensured a higher pump absorption inside the cladding due to a better overlap of the propagating modes with the Bi-doped region. Optimization of the BDF cladding shape and core diameter resulted in a valuable improvement in the output power that increased up to ≈260 mW. The efficiency of the lasers varied in the range of 3–5%, depending on the chosen BDF. During the laser experiments, an interesting effect was found. It turned out that, at relatively high pump powers of about 3–4 W, the laser suffers output power saturation. The nature of this phenomenon is related to the population at N_3 level and relaxation from N_3 to N_2 (A_{32} in Figure 5a). According to the performed experiments, the observed limit is due to a rather slow, finite transition rate from N_3 to N_2. As a result, excitation leads to overpopulation of N_3 that cannot be depopulated effectively by spontaneous transitions only. A detailed study of the detrimental effect is described in [36]. In the same work, a possible way to minimize the consequences of the effect is suggested. For this, it is necessary to initiate a stimulated transition from N_3 to N_2. Thus, when additional radiation corresponding to the N_3 to N_2 transition was applied to the cavity, a significant reduction in saturation was observed. It is worth noting that the power saturation is more prominent in germanosilicate BDFs than in phosphosilicate ones. The lasers based on phosphosilicate BDFs have shown no such effect within the limits of the pump power available (up to 30 W). With high probability, due to the faster relaxation from N_3 to N_2 in phosphosilicate BDFs, the threshold of the effect in phosphosilicate core fibers is several times higher than that for germanosilicate ones.

The latest results on cladding-pumped lasers related to the development of quasi-single-mode BDFLs using multimode BDFs published recently [37]. In order to preserve the output radiation as close as possible to single mode one, the researchers used a combination of graded-index BDFs with a 30 and 60 µm core and special fiber Bragg gratings (FBGs) inscribed directly in the active fiber. The FBGs not only provided feedback for the laser cavity, but also eliminated unnecessary high-order transverse modes. For this, the reflecting structure was inscribed in the paraxial area of the core, leaving the outer part transparent. This approach provided better overlap between the FBG and the LP_{01} mode of the fiber. While the FBG filtered high order-modes, the graded-index fiber helped to maintain the mode field inside the cavity unchanged. Eventually, this approach allowed for the output power to be further increased to ≈0.8 W and to almost 1 W, when additional amplifier was utilized (Figure 5b).

To summarize, from the first demonstration of the cladding pumped BDFLs, significant progress has been made. Although the laser efficiency is currently below the desired values, the approach has brought simplicity and cost efficiency, which is important for many applications. Further efforts in relation to the power scaling of such lasers should be aimed at solving at least two problems: (1) the saturation effect of output power; and (2) the increase in cladding absorption of the BDF. The saturation effect could be eliminated by varying the BDF core glass composition that partially modifies the phonon spectrum and increases the efficiency of population of the upper laser levels. To enhance cladding absorption, in addition to rectangular inner cladding, one can use the approach based on single-mode light propagation in special design of BDFs, so-called large-mode-area fibers, pedestal fibers or coupled multi-core fibers, etc.

3.3. Pulsed BDFLs

In discussing BDF lasers, so far, we have not mentioned anything about pulsed ones. In that regard, it should be noted that the BDFs have a number of benefits for the construction of pulsed systems with attractive characteristics. In addition to the most obvious advantage of being able to provide amplification in the undeveloped spectral IR bands, these active fibers are characterized by a fairly wide gain bandwidth crucial for pulsed lasers. On the other hand, there are some peculiarities inherent to BDFs that are undesired in Q-switched and mode-locked oscillators. The most important is a rather low gain per unit lengths in the BDFs. Nevertheless, there are pulsed regimes that are less sensitive to the active fiber length. One of them, which has been developed recently, is associated with the generation of rectangular pulses. Lasers of this type have been presented in [38,39]. These two works have a lot in common. Both lasers had a figure-of-nine cavity with nonlinear amplifying loop mirror (NALM) serving as a mode locker. A piece of a phosphosilicate BDF acted as the active medium, while a spool of SMF-28, 500 and 950 m long, provided a nonlinear phase shift. At the output, energetic rectangular nanosecond pulses in 1.3 µm wavelength region were obtained. According to the autocorrelation and pulse-to-pulse coherence, the lasers operated in dissipative soliton regime (DSR). This regime has attracted widespread attention since such pulses can be amplified and compressed to produce shorter, more powerful ones. At the same time, the duration and energy of DSR pulses are easy to control by changing the pump power of the laser. Some characteristics of the pulsed lasing are listed in Table 2 (lines 1–2).

The regime that is sometimes mistakenly taken for DSR, the so-called noise-like pulse (NLP) regime [40], was obtained in a similar figure-of-nine laser cavity but with utilizing a germanosilicate BDF [41]. The laser operated in the 1.4 µm spectral region and emitted pulses of comparable characteristics (Table 2, line 3). The experiments aimed at the development of passively Q-switched lasers based on BDFs also demonstrated promising results. In [42,43], the researchers presented ring cavities consisting of 60 m of a phosphosilicate BDF as an active medium and various film saturable absorbers placed in the space between two FC/PC connectors. The lasers performed well in terms of stability. Both configurations provided pulses with kHz repetition rate and nJ energy at wavelengths around 1.3 µm (Table 2, lines 4–5). Although the lasers are advantageous due to the passive Q-switch technique used, the pulse energy and duration in such lasers turned out to be much lower and longer comparing to the specifications of actively Q-switched counterpart published in 2019 [44] (Table 2, line 6).

To summarize this section, it should be noted that this review presents only some of the trends in the field of BDFLs and brief achievements there. However, a number of significant results were obtained in the field of BDFLs with distributed feedback, operating in the wavelength range 1.3–1.7 µm [45–47], as well as tunable laser systems based on BDFs [48,49]. However, these achievements are beyond the scope of this article, and may be described in detail elsewhere.

Table 2. Pulsed BDFL characteristics.

Wavelength, nm	Mode Locking and Q-Switching Method	Pulse Duration, ns	Pulse Energy, nJ	Pump Power, mW	Active Medium	Ref.
1310	NALM	48	30	1040	Bi:PSF *	[38]
1335	NALM	14	197.7	305	Bi:PSF	[39]
1450	NALM	13.6	172	155	Bi:GSF *	[41]
1314	Nb2C	17.5×10^3	53.7	1040	Bi:PSF	[42]
1314	WTe2	8×10^3	13.94	812	Bi:PSF	[43]
1330	AOM	80	11,500	1600	Bi:PSF	[44]

* PSF is P_2O_5–SiO_2 glass fiber; GSF is GeO_2–SiO_2 glass fiber.

4. Bi-Doped Fiber Amplifiers

When considering the development of the optical communications network over the last thirty years and extrapolating the dynamics into the future, like was performed by P.J. Winzer et al. [50], one inevitably comes to the obvious conclusion that it is very important to use the full potential of silica optical fiber technology to meet the ever-increasing demand for information carrying capacity. The most economically practical option, at least in short-to-midterm, seems to be the full employment of the already available transmission bandwidth of the deployed or being deployed optical fibers, which requires the development of new types of optical amplifiers capable of operating in O-, E-, S-, L-, and perhaps U-telecommunication bands. Bismuth-doped fiber amplifiers (BDFAs) are now emerging as one of viable options in tackling the problem, alongside other potential approaches.

One way to address this issue to field researchers is the development of rare-earth-doped amplifiers with dopants other than Er, such as, say, Tm for the S-band and U-band, and Nd for the E-band. But this endeavor might necessitate the employment of low-phonon-energy glasses, whose compatibility with the silica-based technology and chemical durability might be questionable. Aside from that, some measures to counter out-of-band ASE in certain cases are also necessary (see [10] and the references therein). The second approach might be focusing on the usage of Raman amplifiers (RAs), both distributed and discrete (lamped). However, this pursuit might entail the need for large numbers of pump sources and/or high values of pump power, while not guaranteeing a better performance compared to BDFA. For example, Donodin et al. in [51] were investigating the performance of a relatively-short-span transmission line of 50 km operating in the long-wavelength part of E-band in the range 1430–1460 nm using 30 GBaud DP-16-QAM and DP-64-QAM signals. The line was built using a standard G.652.D fiber, and its performance was compared to three types of inline amplifiers: BDFA, distributed RA, and discrete RA. The research has shown that despite the better performance of the distributed RA in the linear small-signal regime due to a much lower noise figure (NF), the maximum signal-to-noise ratio (SNR) in all cases is achieved for BDFA in non-linear regime at higher signal input power, where non-linear effects steeply degrade the performance of both RAs.

The O-band is also an attractive target for exploration featuring, as research in [52] has shown, a very broad bandwidth of 17.6 THz, which is larger than combined C+L bands. In this paper, the authors reported gain of more than 20 dB and NF no greater than 5.2 dB over the entire range of 1255–1355 nm. The amplifier was pumped by a single standard multimode 915 nm laser diode through a conversion stage employing ytterbium-doped fiber laser providing 2 W of 1150 nm optical power with total electrical power consumption of 8.1 W at room temperature and 9.8 W at 70 °C. Crucially, the paper demonstrated the suitability of BDFA for data transmission by a real-time experiment utilizing a 400 Gb/s LR4 QSFP-DD PAM4 pluggable module. Along the same line, the authors of [53] utilized BDFAs to increase the transmission reach of the standard 400GBASE-LR4 and 400GBASE-LR8 direct detection PAM4 transmission systems from the specified 10 km to 20 km and 90 km, respectively, thus providing a cost-effective alternative to 400ZR and 400ZR+ technologies, which are based on coherent optics. Such relatively short-distance transmission systems are becoming increasingly important, as long as they are extensively used as data centers interconnect (DCI) solutions. Data transmission with coherent detection is also of potential interest in this spectral region. Due to near-zero material dispersion in the region, one may get away without digital dispersion compensation and hence reduce power consumption and complexity on the receiver side. The question here is whether it is going to be possible to counter non-liner effects, which thrive at zero dispersion. The answer to this question under certain conditions seems to be "yes", as per the study in [54]. In this paper, the researchers report a 9.6-THz DWDM transmission line in the spectral range 1283–1334 nm capable of achieving a data rate of 36.8 Tb/s over a distance of 135 km without digital signal processing (DSP).

In addition, the utilization of an O-band BDFA, among other innovations, allowed researchers to achieve a record transmission rate of 321 Tb/s over a distance of 50 km [55]. Combining Tm-, Er-, and Bi-doped amplifiers, along with distributed Raman amplification, the researchers were able to provide optical gain in a 27.8-THz ultra-wideband comprising E-, S-, C-, and L-telecom bands, which allowed them to successfully transmit signals over a single mode fiber (SMF) using as many as 1097 DWDM channels in the range from 1410.8 nm to 1623.1 nm. For a longer distance of 200 km, a still impressive transmission rate of 270.9 Tb/s was possible.

Wavelength division multiplexing (WDM), combined with increasing spectral efficiency due to utilization of coherent detection systems, can be the only decision so far. At the end of the day, if we are to continue to increase the information carrying capacity of a single fiber, we have to resort to space division multiplexing (SDM), which is to the systems based on multi-core fibers. In light of this, it is important to verify that Bi-doped amplifiers can be useful even in that area. That is exactly what was done in [56] by Elson et al. The researchers demonstrated that it is possible to increase the reach of optical link to 28 km of 400GBASE-LR8 transmission system using BDFA as preamplifier. The link was comprised three 4-core fibers from different manufacturers, and employed off-the-shelf transceivers providing a single fiber throughput of 1.6 Tb/s. The state-of-the-art results regarding data transmission based on the usage of BDFAs are summarized in Table 3. The table is not to be seen as a comprehensive source of information on the topic, yet it can provide a good sense of the continuous progress in the area.

Table 3. State-of-the-art data transmission systems based on BDFAs.

Band	Range, nm	Grid	Modulation	System	Speed	Distance, km	Fiber	Ref.
E-band		1430, 1445, 1460 nm	DP-16-QAM DP-64-QAM		30 GBd/s	50	G.652.D	[51]
O-band	1255–1355 (17.6 THz)	CWDM	PAM-4	LR4 QSFP-DD	4 × 100 Gb/s (53 GBd/s)	20	G.652	[52]
O-band	1283–1334 (9.6 THz)	DWDM	DP-16-QAM		40.9 Tb/s	45	G.657.A1	[54]
O-band	1283–1334 (9.6 THz)	DWDM	DP-16-QAM		36.8 Tb/s	135	G.657.A1	[54]
O-band	1274–1309 (6.3 THz)	LWDM	PAM-4	400GBASE-LR4	4 × 100 Gb/s (53 GBd/s)	20	G.657.A1	[53]
O-band	1271–1331 (10.8 THz)	CWDM	PAM-4	400GBASE-LR8	8 × 50 Gb/s (26 GBd/s)	90	G.657.A1	[53]

Having discussed the applicability of BDFAs for the building of modern data transmission systems, let us now concentrate on the properties of the BDFAs themselves. Perhaps the most notable aspect regarding BDFAs is their versatility in terms of the ability to cover a broad spectral range of 1270–1775 nm. Apart from the results on data transmission application of BACs cited above, which, so far, have been focused on the O- and E-telecommunication bands, Bi-doped amplifiers for the S-band, and U-band have been reported. As mentioned above, BDFAs are capable of providing amplification of optical signals in O/E/S-band, as demonstrated in [57–59]. As was discussed, the versatility of BDFs comes from the fact that the Bi ion is capable of forming different types of BACs depending on the host glass composition. So, by an appropriate choice of the glass composition, one can have more than one type of BACs in the core in the proportion suitable for a broadband gain. In that manner, A. Khegai et al. in [57] managed to achieve O+E band amplification with a maximum gain of 26 dB, −3-dB-bandwidth of 116 nm, while pumping by a single laser source at 1265 nm with pump power of 200 mW. The employment of nonstandard fiber designs made it possible for the researchers in [58] to create O/E/S-band amplifiers, which could be pumped with commercially available multimode laser diodes at 793 and 808 nm. The fact that the pumping could be performed through an intermediate pump level instead of direct pumping into metastable level introduced the possibility of achieving a higher level of inversion, hence increasing the noise performance of the amplifiers. Secondly, the commercial availability of pump sources makes the amplifier a more viable solution. Moreover, if the usage of two pump sources at 793 and 808 nm simultaneously is acceptable, it is possible to pump two types of BACs exist in the active fiber in an optimal ratio, which allows to reach a relatively flat (with the gain flatness of <2 dB) broadband gain centered at about 1400 nm with −3-dB bandwidth of roughly 120 nm, maximum gain of about 27 dB and noise figure of approximately 5 dB. The data on the temperature stability of BDFA operation can be found, for example, in [59]. The paper investigates the temperature dependent gain (TDG) and NF of an E+S-band BDFA in the temperature range from −60 °C trough +80 °C. It was found that BDFA in this range can provide far greater thermal stability than EDFA: in the range 1440–1490 nm TDG coefficient was negative and in absolute terms below 0.005 dB/°C.

The exploration of potential detrimental effects, which the inhomogeneity of a Bi-doped-fiber gain can have on the performance of E+S-band BDFA, was conducted by Wang et al. in [60]. The research has shown that BDFA is indeed susceptible to the spectral hole burning effect, resulting in gain profile deformation while operating in the whole E+S range of 1410–1490 nm. In that case, the average gain deviation was as high as 12%. However, when the operation of the BDFA was restricted to the range of 1450–1490 nm (S-band), the average gain deviation dropped to the level of about 2%, which is more-or-less comparable with a typical EDFA. The inhomogeneous broadening in Bi-doped fibers brings another important question regarding pump optimization. This issue was experimentally addressed in [61] for E-band BDFA. The comparative analysis was made for bi-directional pumping scheme. For this pumping regime, it was found that for a small signal of −25 dBm the maximum gain of 38.9 dB and the lowest NF of 4.7 dB are achieved at the pumping wavelength of 1320 nm. For a high-level signal of +5 dBm it turned out, however, that in terms of NF the performance is better at 1310 nm pumping.

Given the fact that the Er-doped fiber amplifier (EDFA) is an essential component of modern telecommunication technologies, a natural step in broadening the telecom transmission range is to try to extend the EDFA amplification range by employing S-band BDFA in tandem with EDFA. Such an attempt by Maes et al. is documented in [62]. The authors demonstrated a hybrid amplifier based on bismuth-doped and erbium-doped fibers, which could provide more than 27 dB gain in the range from 1431 to 1521 nm and NF < 7 dB with PCE of 8.7%. Though it is unlikely that amplification in U-band will be of high demand for telecommunication networks in the foreseeable future, it is nonetheless too early to reject this possibility right away. Moreover, there are potential applications outside of the realm of data transfer systems, for example in the laser systems for remote gas analysis. So, it is useful to keep in mind the options that exist in this area, in particular Bi-doped fiber amplifiers. The first Bi-doped U-band fiber amplifier was reported in 2016 [63]. It provided a maximum gain of 23 dB at 1710 nm with −3 dB, a bandwidth of about 40 nm, and a minimum NF of 7 dB. Some progress has been made since then, but a complication arising from the necessity to work with the germanosilicate host glass with high Ge content makes the fabrication process of these fibers rather difficult. So, the technology is still immature and further improvements to the performance might still be possible. Summarized results on BDFA and their characteristics are given in Figure 6 and Table 4. Once again, the presented parameters are not intended to provide a comprehensive picture. Rather, they serve as a guideline on what is possible and eventually to light up promising directions.

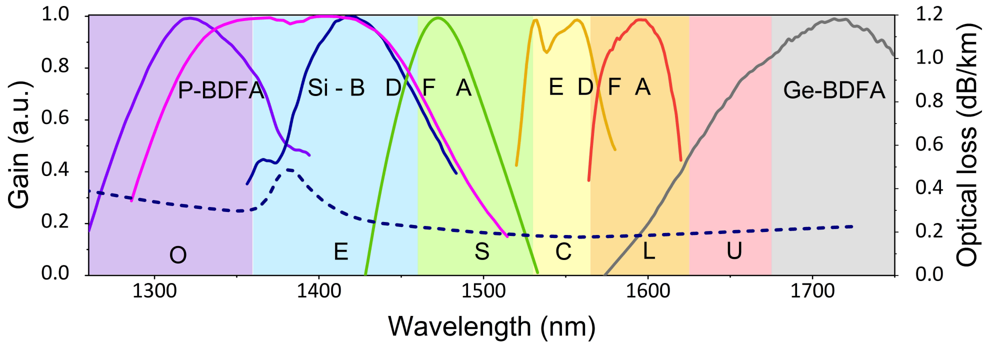

Figure 6. Amplification bands of various BDFAs (X-BDFA is based on BACs associated with X atoms: X = P, Si, Ge) and EDFAs for C- and L-bands (solid lines). Optical loss spectrum of a single-mode telecom fiber of SMF-28 (dashed line).

Table 4. Main summarized parameters of BDFAs

Band	Range, nm	Bandwidth, nm	Gain, dB	NF, dB	Flatness, dB	Efficiency	Ref.
O/E/S	1325–1475	120	>25	5	<2	<1%	[58]
E/S	1425–1475	50	21	6	<1	0.065 dB/mW	[59]
E	1415–1435	20	39	4.7	<2	32.6%	[3]
S/C	1431–1521	90	>27	<7	<10	8.7%	[62]
U	1680–1750	40	>20	<7	<3	0.1 dB/mW	[63]

5. Conclusions

Thus, the review outlined the main and most promising results obtained in the development of bismuth-doped fibers with improved characteristics and the creation of advanced devices based on them. It is important to emphasize that current trends in the research area are predominantly focused on fabrication of highly concentrated BDFs, where the main progress so far is associated with germanosilicate core BDFs, where a gain of 3–4 dB/m can be achieved. Strategically important tasks also include the production of BDFs with an ultra-wideband gain spectrum, especially for the O+E band and E+S-band to expand erbium amplifiers operating wavelengths, i.e., outside conventional C+L band. In parallel with the development of BDFs, the possibilities of practical application of such materials for obtaining lasing in various spectral regions are being investigated using various approaches, including the creation of single-mode watt-level sources with multimode diode pumping. In such a dynamically developing area, important results are constantly appearing, giving new impetus to the further research and developments in this area, many of which were not included in this review. For example, in the process of finalizing the manuscript, new information appeared on the applicability of BDFAs for the O-band in coherent data transmission over a record distance of 1200 km [64]. This reinforces the belief that such BDFAs might become an indispensable basis for future telecommunication systems. The review demonstrated that BDFs have shown impressive progress in the pursuit of improved optical amplifiers parameters, which are rapidly gaining popularity. Of course, there are still unresolved issues, in particular, the production of fibers with higher Bi concentrations and the nature of BACs; however, BDFs now are an efficient medium from the point of view a variety of practical applications. A noticeable number of scientific groups and companies have started to work on these issues, which gives hope for potential near-future breakthroughs and revolutionary discoveries in this direction leading to the next generation of BDFLs and BDFAs.

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