O-band bismuth-doped fiber amplifier with 67 nm bandwidth

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Abstract: We present 30 dB Bi-P-doped fiber amplifier from 1287 to 1354 nm. The wider bandwidth was achieved using inhomogeneous broadening of bismuth active centers (BAC-P). Blue shifted BAC-P were pumped at 1178 nm and generated laser radiation at 1276 nm which serves as a pump source for red shifted BAC-P.

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1. Introduction

The Coarse Wavelength Division Multiplexing (CWDM) technology is widely used for short distance data transmission. Although, the wavelengths grid of CWDM is in the range from 1270 to 1610 nm, the O-band of optical communications that is in-between 1260-1360 nm suits best for local networks. First of all, it is due to the fact that standard telecom fibers have a zero-dispersion point in the stated wavelength range, so there is no need in additional dispersion compensation modules during operation. To provide higher transmission rates or longer distances one should use some optical amplifiers. In fact, there are few fiber media capable to amplify signal in this region. In particular, those are praseodymium-doped fluoride fibers [1] and bismuth-doped phosphosilicate fibers [2]. Although, the latter ones is still under investigation, it has already had a number of advantages including silica-based glass host, wide amplification band, and high efficiency. Recently, a successful data transmission over 50 km via 8 channels in 1270-1310 nm region [3] and one over 100 km via 6 channels in the range 1320-1370 nm [4] using bismuth-doped phosphosilicate fiber amplifiers was demonstrated. In [5] it was shown that due to inhomogeneous broadening the spectral position of gain band in bismuth-doped phosphosilicate fibers is significantly affected by the wavelength of pump source used. In particular, it reflected in [3] and [4] operation regions where pump source at 1195 nm and dual pump at 1240 and 1267 nm correspondingly were used. In both cases, gain bandwidth of the amplifier did not exceed ∼45 nm at a 3-dB level. Since both amplifiers based on similar fibers, there is a question, is it possible to expand the gain bandwidth to whole O-band using single amplifier? In this work, we investigated the possibility to increase the gain bandwidth of the bismuth-doped fiber amplifier by means of various approaches of dual-wavelength pumping.

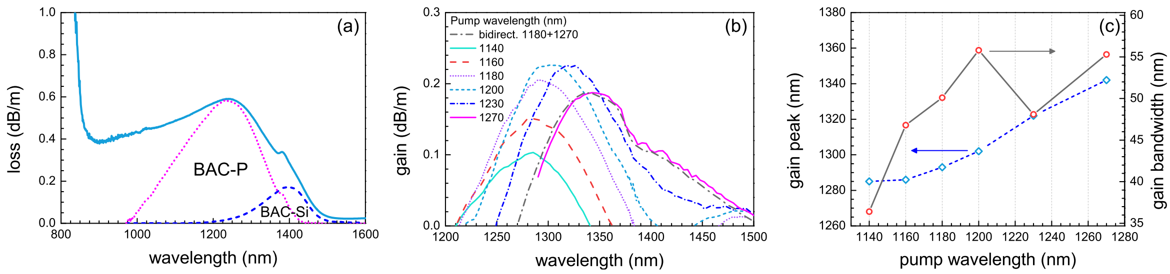

Fig. 1. Absorption spectrum (a) and gain spectra for pump wavelengths in the range 1140 – 1270 nm of bismuth-doped phosphosilicate fiber (a). Dependence of gain peak and bandwidth (at a level of 85% from maximum) on wavelength of pump (b).

2. Bismuth-doped phosphosilicate fiber gain characteristics

In our experiments we used a phosphosilicate fiber doped with bismuth with a core diameter of 125 µm and cutoff wavelength at around 1.1 µm manufactured by the standard MCVD technique. The absorption spectrum of the examined fiber is shown in Fig. 1(a). We have also measured a small-signal gain spectra of the fiber for pump wavelengths in the range from 1140 to 1270 nm. One can see that variation of pump wavelength provides wide tuning of the gain peak position (Fig. 1(b)), but for pump wavelengths shorter than 1180 nm the gain dramatically decreases. Additionally, at these wavelengths unsaturable absorption is significantly higher than that at 1200 nm or longer, therefore, efficiency of the pump is also reduced. A dependence of gain peak position and bandwidth on the pump source wavelength is depicted in Fig. 1(c) . According to the data, the widest gain spectrum of $\sim$ 55 nm can be achieved using single pump at 1.2 and 1.27 µm. In the case of the pump at 1.2 µm, the result is due to the excitation of most of inhomogeneously broadened bismuth active centers (BACs) associated with phosphorus (BAC-P), while the gain spectrum for pump at 1.27 µm is mainly broadened by a significant contribution of BACs associated with silica (BAC-Si), that are more efficiently excited at longer wavelength. The bandwidth in Fig. 1(b) is a bit wider than that in the works mentioned above because the spectra presented here correspond directly to active fiber itself and are not distorted by the fused WDM coupler transmission function. Further, to increase the width of the gain spectrum we investigated a dual pump at 1.18 and 1.27 µm.

3. Direct 1.18+1.27 µm pumping

We measured gain spectra in a 36 m-long phosphosilicate fiber doped with bismuth using bidirectional pump at 1.18 and 1.27 µm. The experimental scheme is in Fig. 2(a). Since we do not have appropriate WDM coupler at 1.18 µm, pumping at this wavelength was arranged through a 50:50 wideband fused coupler. Note that gain was measured between the active fiber ends. Pumping at 1.27 µm was carried out using a standard filter WDM coupler passing a narrow 10 nm spectral band centered at 1.271 µm (FWDM in figures). The pump power at both wavelengths was chosen so that the unabsorbed part at the opposite end of the active fiber was $\sim$80 mW which is enough to maintain high level of inversion population if the signal is small or absent. The resulting gain spectrum is presented in Fig. 1(b), one can see that peak value as well as position and bandwidth of the spectrum are close to that in the case of pumping at only 1.27 µm. Actually, the result is expected since radiation at 1.27 µm significantly depletes the signal at 1.18 µm and depopulate the upper level of blue-shifted BAC-P. The reason for that is comparable power of signals at 1.18 and 1.27 µm and gain clamping with small coefficient of gain at 1.27 µm. Thus, bidirectional pumping in this case does not provide any benefits in broadening gain bandwidth.

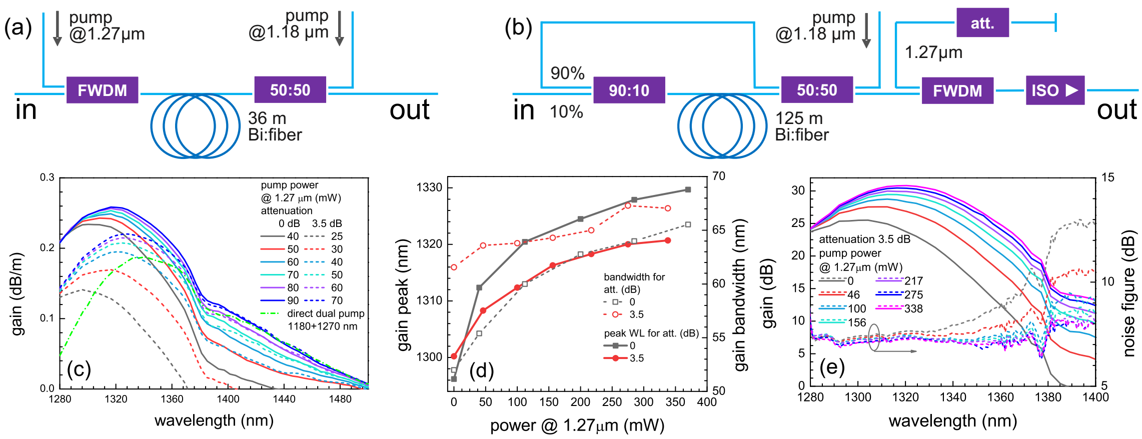

Fig. 2. Schematic of the bismuth-doped fiber amplifier bidirectionally pumped at 1.18 and 1.27 µm (a). Experimental scheme of the bismuth-doped fiber amplifier bidirectionally pumped by the source at 1.18 µm with gain clamping at 1.27 µm using intracavity lasing (b). Gain coefficient (c), gain peak wavelength and bandwidth (at a level of 85% from maximum) (d) in the bismuth-doped fiber amplifier with laser at 1.27 µm inside for different attenuation at the 1.27 µm end of FWDM. Net gain and noise figure at different powers of the laser at 1.27 µm in the case of 3.5 dB attenuation (e).

4. Pumping at 1.18 µm and gain clamping at 1.27 µm

To provide excitation at 1.27 µm and simultaneously keep population inversion for blue-shifted BAC-P we designed the scheme presented in Fig. 2(b). In fact, it is an amplifier which simultaneously generates at 1.27 um using short wavelength BAC-P and this radiation serves as a pump source for longer wavelength BAC-P. Since we intentionally choose the low level of feedback (34 dB roundtrip loss at 1.27 µm due to single Fresnel reflection from fiber right angle cleaved end-face and 50:50 widebend coupler), gain coefficient at this wavelength was fixed at high enough level after the threshold of lasing was achieved. Additionally, we placed a variable attenuator just before the end-face of the 1.27 μm channel of FWDM (att. in Fig. 2(b)) to control the laser feedback. Actually the gain at 1.27 μm was clamped at a certain level after the start of lasing. The level could be tuned by means of variable attenuator. With the aim to obtain enough gain for lasing at 1.27 μm, the length of bismuth-doped fiber was increased till 125 m. To pump the whole active fiber we arranged bidirectional pumping using wideband 50:50 and 90:10 fused couplers (the power of signal was decreased by 10dB at the input end and by 3 dB at the output). The gain was again measured between the active fiber ends so that attenuation introduced by couplers used was eliminated. Result of amplification tests in the case of different attenuation imposed is presented in Fig. 2(c) and (d). We have tested the amplifier at 0 and 3.5 dB of extra losses introduced by variable attenuator. Fig. 2(c) presents gain coefficients at different powers of lasing at 1.27 μm monitored using free end of FWDM coupler (values restored taking into account losses in attenuator). The pump power at 1.18 μm was varied from 500 mW (lasing threshold for 1.27 μm) to ∼3W in all cases presented, therefore we presume that variation of the power at this wavelength did not effect much on the amplifier operation. One can see that addition of attenuation leads to higher threshold of generation at 1.27 μm and, consequently, higher gain coefficient nearby wavelength of lasing. In addition, maximum value of gain coefficient observed for the 3.5 dB attenuation case also increased to 0.25 dB/m due to simultaneous operation of short- and long-wavelengths BAC-P. Noteworthy that this value of gain coefficient have never achieved in such fibers whichever pump powers and wavelengths were applied. Except for increase of gain coefficient, the amplifier showed similar behaviour at different values of feedback for laser at 1.27 μm that could be seen in Fig. 2(d). Thus, increase of power at 1.27 μm leads to spectral shift of the gain peak towards longer wavelengths and broadening of the spectrum bandwidth. The maximum width achieved in this experiment was 67 nm at a level of 85% from maximum of the spectrum, which is equal to 3dB bandwidth for 20 dB gain amplifier. For the case of 3.5 dB attenuation, we also measured spectral dependence of noise figure (NF) at different powers at 1.27 μm that is presented in Fig. 2(e) with a net gain of the amplifier. The NF level is about 7 dB for almost all cases where amplification is over 20 dB.

To summarize, we demonstrated 30 dB gain broadband bismuth-doped phosphosilicate fiber amplifier operating in almost all O-band from 1287 to 1354 nm using one pump source at 1.18 μm. Radiation generated at 1.27 μm inside the amplifier cavity clamp the gain and serves as additional pump source for long-wavelength BAC-P. Owing to the combined pumping we achieved 67 nm bandwidth of gain spectrum at a level of 85% from maximum.

Acknowledgements

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