O+E Band BDFA with Flattop 116 nm Gain Bandwidth Pumped with 250 mW at 1256 nm

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Abstract: We present highly efficient bismuth-doped fiber amplifier covering almost all O- and E-bands. Using 250 mW single wavelength pumping at 1256 nm and low OH bismuth-doped fiber, we managed to achieve 26dB peak gain with -3dB bandwidth of 116 nm.

1. Introduction

From year to year, data transmission in the global network is continuously growing. Today, long distance communication is provided by means of EDFAs through C and L spectral bands. To maintain increasing needs of the digital society existing network systems are becoming more and more sophisticated, and are moving to new complex mathematical algorithms and coding approaches speeding up data transmission through fixed spectral band. The capacity of C+L bands is finite and sooner or later a limit of EDFA-based networks will be achieved. A significant increase in capacity can be achieved with the development of Multi-band transmission (MBT) systems. These systems can potentially occupy the whole transparency window of silica-based fiber from 1250 to 1700 nm where optical losses are low enough to allow data transmission for tens or hundreds of kilometers. Except for the PDFA [1] or EDFA there are few active fiber media that are capable of amplifying the signal in this region. One of the most promising amplifiers which may help to cover this window is based on bismuth-doped active fibers. In fact, several types of bismuth-doped fibers can provide optical amplification in the stated spectral range. These are phosphosilicate fibers mainly containing bismuth active centers associated with phosphorus (BACs-P) and operating in the O-band [2], low Ge-doped fibers with BACs-Si suitable for amplification in E-band [3] and highly-germanium-doped fibers with BACs-Ge operating in L and U bands. P-doped and low-Ge doped fibers with bismuth showed applicability for data transmission [4–6]. In this work, we combined amplification properties of both P-doped and low-Ge-doped fibers with bismuth within one fiber and developed a highly efficient O+E-band amplifier. Similar approach was demonstrated in several earlier works [7, 8]. Here, we concentrated on improving of efficiency and gain spectral bandwidth and flatness.

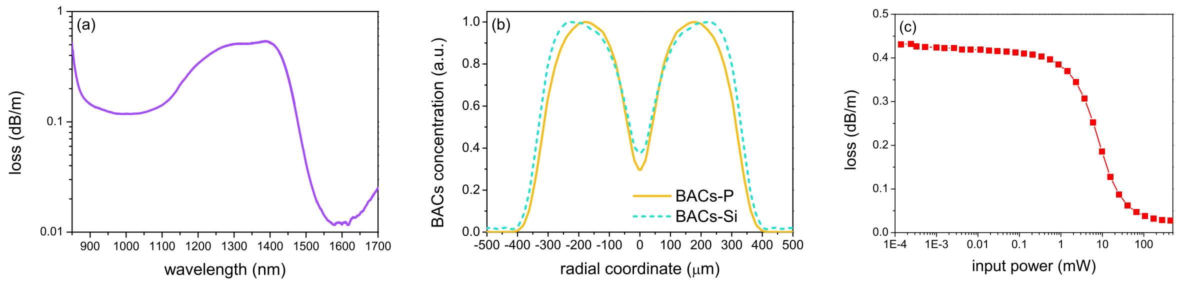

Fig. 1. Absorption spectra of bismuth-doped phosphosilicate fiber (a). Relative distribution of BACs-P and BACs-Si (b). Dependence of absorption at 1256 nm versus pump power (c)

2. Active medium and experimental setup

In the framework of the study, a bismuth-doped phosphosilicate fiber, containing substantial concentration of both bismuth active centers associated with phosphorus (BAC-P) and silicon (BAC-Si) was fabricated. The spectrum of optical losses in the fiber developed is shown in Fig. 1(a). Absorption in the region about 1240 nm is caused by BAC-P while absorption at 1430 nm is mainly due to the presence of BAC-Si. The bismuth-doped fiber was produced using the standard MCVD process. Importantly, in this fiber we managed to significantly decrease the undesired for gain spectrum flatness OH-group absorption peak at 1.38 μm, the band spoiling the flatness of gain spectrum. The cut-off wavelength of the first higher mode in the drawn fiber was at ∼1150 nm. Using the spectroscopic method described in [9], we measured the relative distribution of BAC-P and BAC-Si in the fiber preform. The result is presented in Fig. 1(b). As a relative measure of BACs-P, we took luminescence intensity at 1280 nm that is simultaneously nearby the BAC-P luminescence peak at 1320 nm and away from the luminescence peak of BACs-Si at 1430 nm when pumped at 798 nm. For the same reason the luminescence at 1480 nm was used to characterize the BACs-Si content. As one can see, in general, the shape of both distributions is similar. However, there are some features that are specific to each line. For instance, the peak of BACs-Si is farther from the core center than that of BACs-P, additionally, the BACs-Si distribution is slightly wider and its central dip is less pronounced. The differences in BACs-P and BACs-Si distributions listed could be explained by the reduction of phosphorus amount at the edge between the core and the cladding due to silica diffusion from the cladding and in the core center because of phosphorus evaporation during the preform collapsing stage. In general, based on results on BACs distribution measurements one can conclude that both types of active centers are well distributed along the core cross-section that should provide high enough gain and low level of unsaturable loss. We measured the dependence of absorption at 1256 nm on the pump power that is shown in Fig. 1(c). Unsaturable loss in the sample under study was ∼0.028 dB/m. Thus, the ratio of small-signal absorption to unsaturable losses was equal to ∼15.

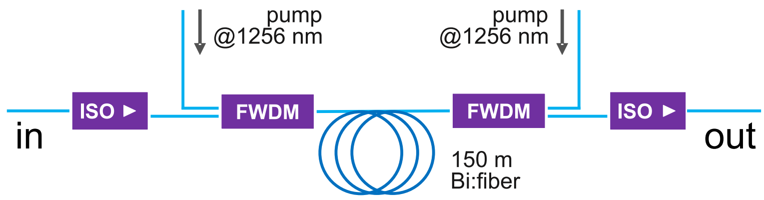

Fig. 2. Absorption spectra of bismuth-doped phosphosilicate fiber (a). Relative distribution of BACs-P and BACs-Si (b). Dependence of absorption at 1256 nm versus pump power (c)

The schematic of the bi-directionally pumped amplifier based on the fiber described is in Fig. 2. To eliminate gain spectrum distortion, we did not use fused WDMs, instead of such multiplexers a pair of filter WDMs (FWDM in the figure) were applied. Raman laser with 500 mW maximum output power at 1256 nm was used as a pump source. A 150 m long piece of the Bi-doped phosphosilicate fiber act as an active medium of the amplifier.

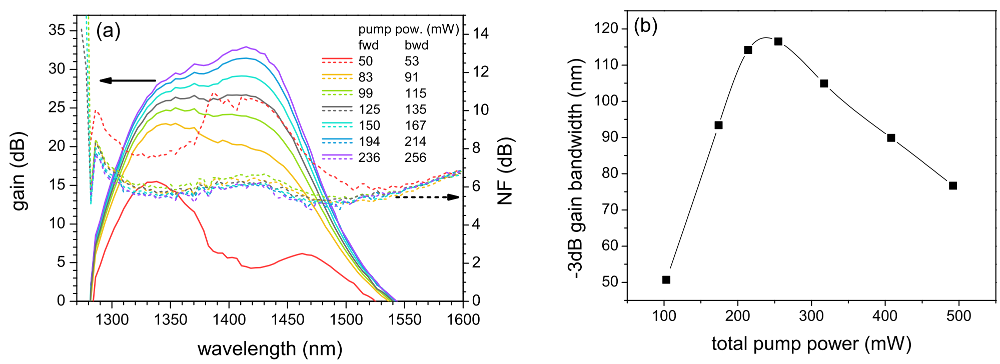

Fig. 3. Gain and noise figure spectra at different pump powers (a). The dependence of -3dB gain bandwidth on total pump power at 1256 nm (b).

3. Results

Fig. 3(a) shows the gain and noise figure spectra at various pump powers. A single wavelength tunable signal source with power $\lesssim$-20 dBm was used in gain experiments. As one can see, since the gain spectra are formed by simultaneous contribution of two independent and spectrally separated active centers, the shape of the spectral envelope changes nonuniformly with the pump power. Accordingly, BACs-P are responsible for gain at shorter wavelengths while BACs-Si provide gain at longer ones. As expected, at a lower pumping level, more effective pumping of BACs-P is observed that is due to higher absorption of BACs-P, while at higher pump powers contribution of BACs-Si increases. Adjusting pump level, one can achieve a wide flattop gain spectrum. It should be noted, that in contrast to earlier works on wideband Bi-doped fiber amplifiers [7, 8], to obtain broadband amplification over 23 dB a pump power level of ∼250 mW is enough. Fig. 3(b) shows the dependence of gain width at a level of -3dB from the maximum. The widest spectrum of 116 nm corresponds to the case when both BACs-P and BACs-Si contribute equally to the total curve.

Unlike the gain spectra, except for the spectrum corresponding to ∼100 mW total pump power, the spectra of the noise figure are almost the same for all the cases presented. The average value of noise in the operating spectral range is 5÷6 dB. Nonetheless, one should pay attention to the fact that while in the spectral region about 1.32 μm a slight decrease of the noise factor with an increase in gain coefficient is observed, in the region about 1.41 μm we have a reversed dependence.

Thus, we developed an effective amplifier based on bismuth-doped phosphosilicate fiber. A pump power as low as ∼250 mW at 1256 nm was sufficient to obtain over 23 dB wide flattop gain spectrum with 116 nm at -3dB level. The gain spectrum covers almost the whole O+E telecommunication band.

Acknowledgements

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