Three layer fiber with high stimulated Brillouin scattering threshold

M.M. Khudyakov[1,2*] , M.E. Likhachev[1] , M.M. Bubnov[1] , D.S. Lipatov[3], A.S. Lobanov[3] , A.N. Guryanov[3]

[1] Fiber Optics Research Center, Russian Academy of Sciences, 38 Vavilova street, 119333 Moscow, Russia; [2]Moscow Institute of Physics and Technology (State University), Institutskii per. 9,141700 Dolgoprudnyi, Moscow region, Russia; [3]G.G. Devyatykh Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, 49 Tropinina street, 603950 Nizhnii Novgorod, Russia

ABSTRACT

Simple method to increase stimulated Brillouin scattering (SBS) threshold in MCVD fiber based on design with few concentric layers having different compound has been proposed. Two sets of fibers with core consisting of three layers with different alumina and germania concentrations have been fabricated. First set of fibers was designed for Raman amplifiers and had a relatively small mode field area of 23-28 μm^2. The second set of fibers was designed for high peak power pulse delivery and had mode area of 225-325 μm^2. SBS suppression (as compared to the Ge-doped fibers) was estimated from SBS gain spectra and direct observation of SBS threshold to be more than 6 dB and 3.3 dB for the first and the second type of fibers correspondingly.

Keywords: Stimulated Brillouin Scattering, SBS, SBS suppression, optical fiber, MCVD.

1. INTRODUCTION

Stimulated Brillouin scattering (SRS) is the major factor limiting maximal power of narrow-band (less than 100MHz in linewidth) fiber lasers. It is especially crucial in applications, which require small mode field diameter (MFD), i.e. Raman amplifiers. In recent years, considerable attention has been paid for developments of new methods allowing SBS suppression. One of the promising approaches is fabrication of acoustically antiguiding fiber structures. Dragic et al. [1] proposed to create an acoustically guiding layer outside the light guiding core. Such layer has acoustic refractive index higher than that of the core and in this way reduces overlap between electric and acoustic fields. The design proposed in [1] resulted in suppression of SBS by 3.5 dB in comparison to SMF-28 fiber. Li et al. [2] improved this design by creating ramp shaped acoustic profile via codoping it with aluminum oxide (the only dopant that reduces acoustic refractive index) and germanium oxide. Suppression of 6 dB has been achieved in this work. Further increase of acoustic index difference of the fiber structure has allowed Mermelstein et al. [3] to achieve SBS suppression of 11.2 dB relative to a fiber with similar waveguide parameters. It should be noted that necessity to create additional acoustically guided layer outside the core has many disadvantageous, in particular F-doped layer [1] has limitation in term of maximum acoustic index that could be fabricated Fiber design and triple clad fibers [2-3] are not very convenient in utilization due to additional waveguide structure. Moreover, fabrication of a huge outer cladding complicates the fabrication process and makes it to be very expensive. From many points of view, it is preferable to create SBS-suppressed fiber without outer acoustic guiding layer. As was shown in our previous study, it is possible with ramp-like acoustic profile matched to the SiO_2 level and gives SBS suppression up to 4.4 dB in comparison to a standard SMF-28 fiber. Disadvantage of this method is sensitivity to the fiber core diameter - efficient SBS suppression has been achieved only at cutoff wavelength much smaller (by 1.5 times) than operating wavelength [4]. Such fiber design is not acceptable for large mode area fiber (LMA) and strongly constraints the ability to control fiber parameters. An alternative approach is introduction into the fiber core segments with a different compound. SBS spectrum of such fiber would consist of several peaks. Robin C. et al. [5] produced a fiber with the core made of hexagonal rods with three different compounds. Disadvantages of suggested approach are the difficulty of control relative amplitudes of SBS peaks (one of SBS peaks in [5] is twice smaller than the highest one) and complicated technology that requires composing final preform from rods (etched preforms) produced by MCVD technique.

*DAngeL.74@gmail.com;

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2. SMALL MODE FIELD AREA FIBER

2.1 Fiber design

We have developed fiber design compatible with conventional MCVD technique, which allows superior control of SBS spectra. The idea based on utilization of few ring layers with different dopants concentrations. In this case, the control over relative amplitude of SBS gain peak of any area is achieved by simply changing its width. In the first approximation, it is sufficient to choose these areas to have equal part of light power going through them. To prove the concept we have manufactured preform for small mode field area fiber. Figure 1 shows electric field distribution, refractive index, doping and acoustic refractive index profiles of fiber with outer diameter of 125 μm drawn from the fabricated preform. Here we define acoustic index as $1-(\frac{V_{Sio_2}}{V})$, where V_{Sio_2} is the speed of sound in the silica cladding and V is the speed of sound in a certain point of the core. The width of each segment with different compound was chosen to guide the same part of light power at wavelength of 1550 nm in the fiber with outer diameter of 125 μm and cut-off wavelength near 1500 nm. Four fibers with outer diameter of 80 μm, 100 μm, 125 μm and 135 μm were drawn from the preform. MFD at wavelength of 1550 nm was 6.0 μm, 5.44 μm, 5.53 μm and 5.66 μm respectively. Cut-off wavelengths were 930 nm, 1160 nm, 1450 nm and 1560 nm correspondingly.

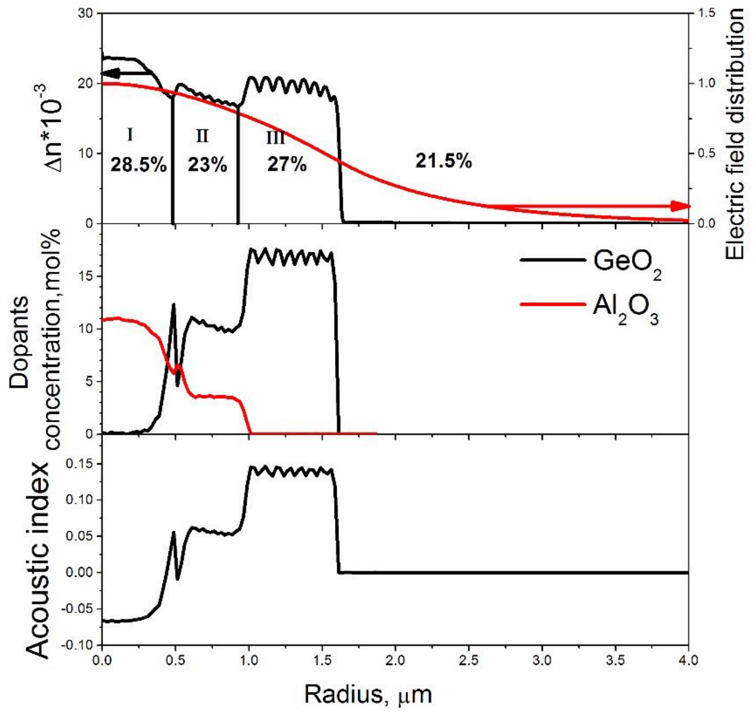

Figure 1. From top to bottom: electric field distribution (red) and refractive index profile (black), doping profile, calculated acoustic refractive index profile in the fiber with outer diameter of 125 μm drawn from the produced preform

2.2 SBS spectra measurements

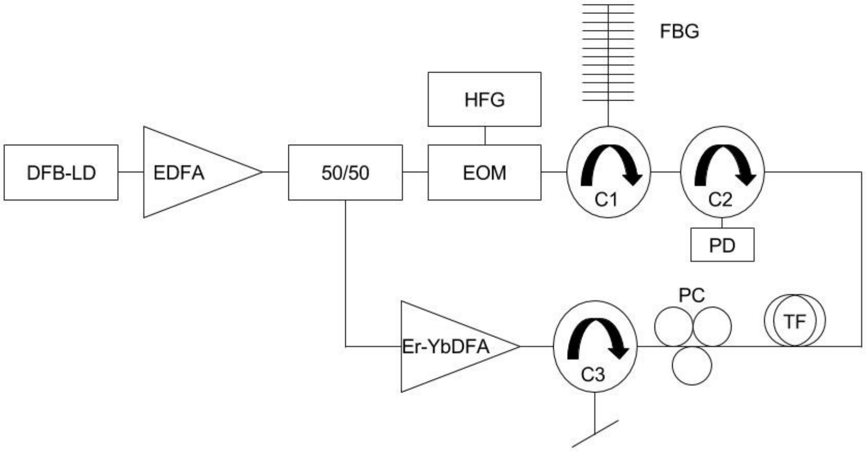

Figure 2. SBS spectrum measurement setup

To measure SBS spectrum of the produced fibers, we used well-known pump-probe technique. The scheme of the setup is presented in figure 2. The setup consists of semiconductor narrowband distributed feedback laser diode (DFB-LD) with wavelength of 1554 nm and output power of 2-3 mW. It was amplified by erbium-doped fiber amplifier (EDFA) to average power of 100 mW. The signal was divided by 50/50 coupler and sent to two arms. The first arm was used to generate a seed with a frequency shifted by 8-12 GHz. For this aim signal was passed through electro-optic modulator (EOM) driven by high frequency generator (HFG) operated in range of 8-12 GHz. As a result, two additional signals with frequency down- and up-shifted relative to the central line at 1554 nm were generated. A single spectral component with positive shift was filtered by a circulator (C1) combined with a narrow-band (<0.1nm) fiber Bragg grating (FBG). Resulted "probe" signal with power of about 2 mW and up-shifted frequency by 8-12 GHz was coupled through high power circulator (C2) into the test fiber (TF). Second arm was used to generate a high power "pump" signal. For this purpose, the signal after 50/50 coupler was amplified by Er-Yb fiber amplifier (Er-YbDFA) to 600 mW and coupled into opposite end of the test fiber through high power circulator (C3). The "probe" signal was amplified in the test fiber by SBS if its frequency shift matches fiber's own SBS shift. The power of the amplified "probe" signal was registered by photodetector connected to oscilloscope (PD). Scanning of the frequency offset between "probe" and "pump" signals allowed us to obtain SBS gain coefficient spectrum ($g_b(f)$) of the test fiber.

It should be noted that g_b depends on relative pump and probe signals polarization state. Thus, we utilized polarization controller (PC) to measure the lowest g_b when polarizations of pump and probe are "orthogonal" to each other and highest g_b when they are "collinear". For an ideal fiber which maintains polarization state of light along its length (PM fiber) the lowest gb is exactly zero and highest is its actual g_b. For non-PM fibers lowest g_b is one third of actual g_b and highest is two thirds [6]. Therefore, an actual g_b for both cases is a sum of lowest highest measured coefficients.

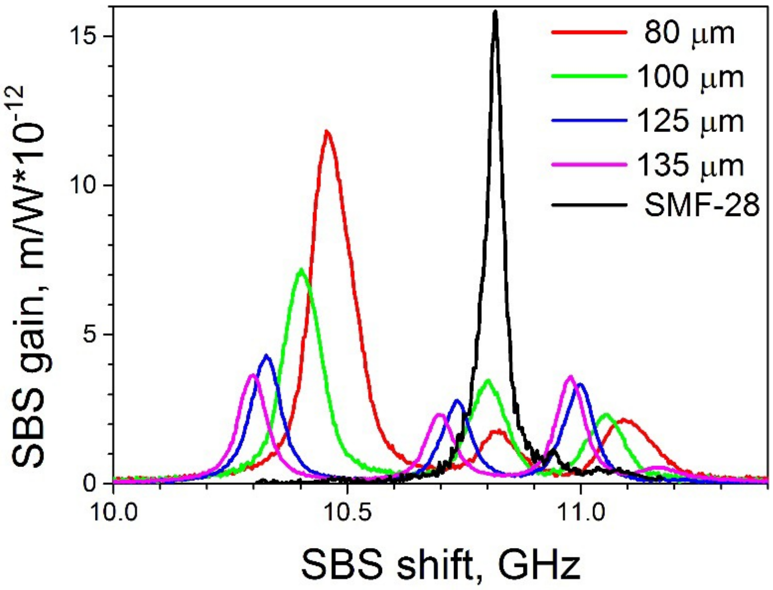

Figure 3. Measured SBS spectra

The results of measurements are shown in figure 3. We also measured spectrum of conventional Ge-doped Corning SMF-28 fiber to compare our results. For every fiber except SMF-28 there are three gain peaks: the leftmost corresponds to the Ge-doped outer layer of the core, middle one corresponds to Al and Ge-doped middle layer, the rightmost one corresponds to Al-doped layer at the fiber axis. As expected amplitudes of peaks match for the fiber with outer diameter of 125 µm, however there is an additional peak in the fiber with outer diameter of 135 µm corresponding to the second leaking mode of central layer, which leads to a further increase in SBS threshold power.

2.3 SBS threshold measurements

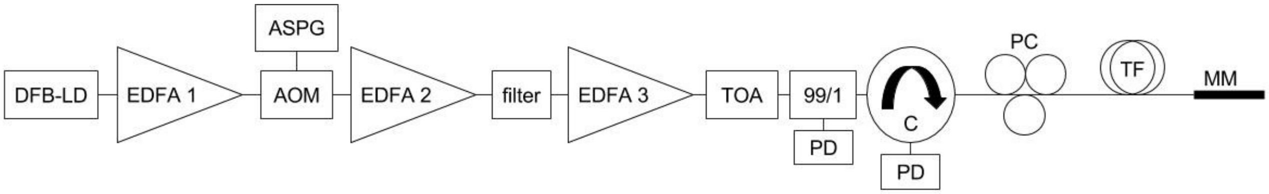

Figure 4. SBS threshold measurement setup for low mode area fibers. PD - photodetector

We also measured SBS threshold power for all fibers by launching high peak power pulses into the test fibers and measuring part of the launched power that was reflected back due to SBS. The scheme of the experimental setup is shown in figure 4. We used acousto-optic modulator (AOM) driven by arbitrary shape pulse generator (ASPG) to create 500 ns pulses with repetition rate of 2kHz from narrowband DFB-LD(DFB-LD) with wavelength of 1555nm amplified by EDFA (EDFA1). Resulting pulses were further amplified by double stage EDFA (EDFA2, EDFA3) with narrowband filter (filter) between them with spectral width at half maximum of ~0.8 nm. In this way, we achieved 30W of peak power in rectangular 500 ns pulses. It is worth noting that maintaining rectangular shape of the pulses while varying output peak power is a difficult task for manual shaping method. Therefore, instead of varying output power we used tunable optical attenuator (TOA) to couple resulting signal into the test fiber. Additional 1% coupler (99/1), polarization controller (PC) and circulator (C) were used to control the signal power, its polarization state and the SBS reflected signal power correspondingly. Output end of the fiber was spliced with 60/125 µm multimode fiber (MM) to prevent backward reflection. The length of all the test fibers was kept to be 50 meters which is almost twice as short as pulse length. In this way the SBS threshold was measured in a quasi-CW regime. SBS threshold also depends on the polarization state of light being minimum for linearly polarized light and by the factor of 1.5 higher for circular polarized light [6].

The results are shown on figure 5. These are deduced results for linearly polarized signal and one meter of test fiber. To compare fibers with different mode areas we plot reflectivity (backscattered power divided by coupled power) against light intensity in the fiber core. Our criteria for SBS threshold was reflectivity being more than 0.001. Thresholds for SMF-28 and fibers with outer diameter of 80 µm, 100 µm, 125 µm and 135 µm are 0.88, 1.19, 1.96, 3.25 and 3.88 W*µm^{-2} respectively. This shows SBS suppression of 6.4 dB for fiber with outer diameter of 135 µm compared to SMF-28.

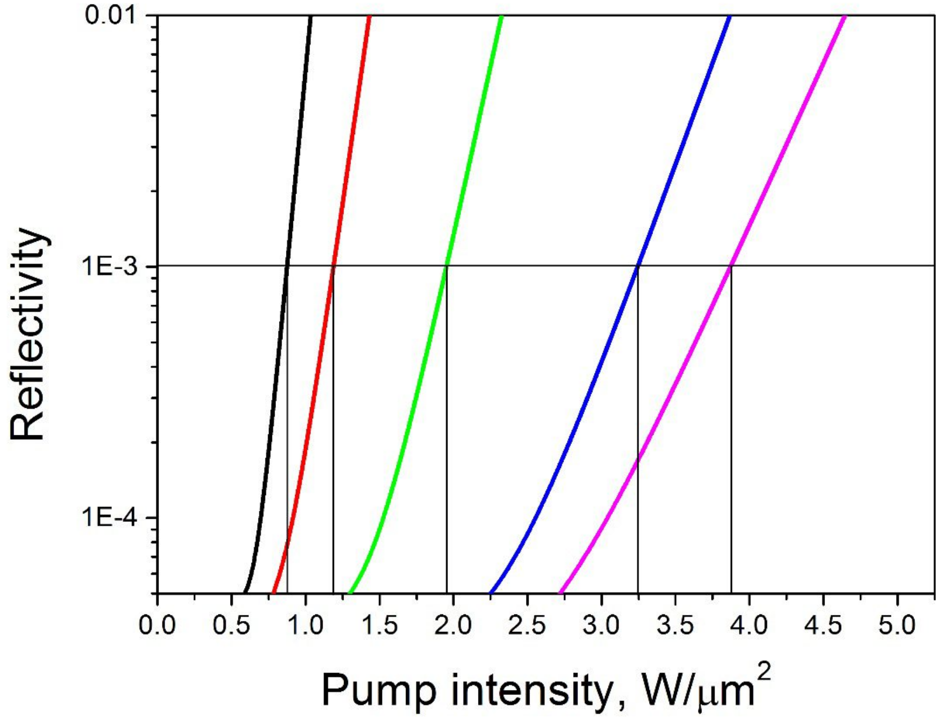

Figure 5. Reflectivity against intensity. Threshold is 0.001.

Table 1. SBS thresholds for small mode field area fiber. Pth in W*m corresponds to threshold power for 1 meter of a fiber.

Name	MFD, µm /Aeff, µm^2	Pth, W*m	Ith, W·µm^{-2}
SMF-28	10.4/84.95	74.8	0.88
135 µm	5.66/25.16	97.6	3.88
125 µm	5.53/24.02	78.1	3.25
100 µm	5.44/23.24	45.6	1.96
80 µm	5.99/28.18	33.5	1.19

3. LARGE MODE FIELD AREA FIBER

3.1 Fiber design

High peak power single-frequency pulsed fiber laser systems have drawn a significant interest in recent year. One of the promising application of such systems is wind LIDAR (Light Detection And Ranging). As it was shown in our previous work [7] in the case of all-fiber systems it is the passive fibers at the amplifier output (used in fiber components like isolators, circulators, pigtails) limits the maximum SBS threshold. Thus, development of large mode area passive fibers with increased SBS threshold become an important task. To test the proposed approach for SBS suppression we have manufactured fiber preform with reduced dopant concentration and core numerical aperture (NA). Similar to that in previous paragraph, the preform has three layers those width was chosen to have equal part of light power propagating in each layer (was designed for the fiber with core and clad diameters of 20 and 125 µm). From this preform, four fibers were drawn with outer diameter of 100 µm, 110 µm, 125 µm and 150 µm. MFD at wavelength of 1550 nm was 16.9 µm, 17.5 µm, 18.5 µm and 20.4 µm respectively. Cut-off wavelengths were 1434 nm, 1579 nm, 1786nm, 2174nm respectively. Single-mode propagation regime in the fibers with cut-off larger than 1550 nm was achieved by bending the fibers and optimization of splicing condition (to avoid excitation of the high order modes). It's worth noting that since these fibers have larger mode area theirs refractive index difference (and therefore acoustic index difference) was almost 10 times smaller as compared to the fiber described in previous section.

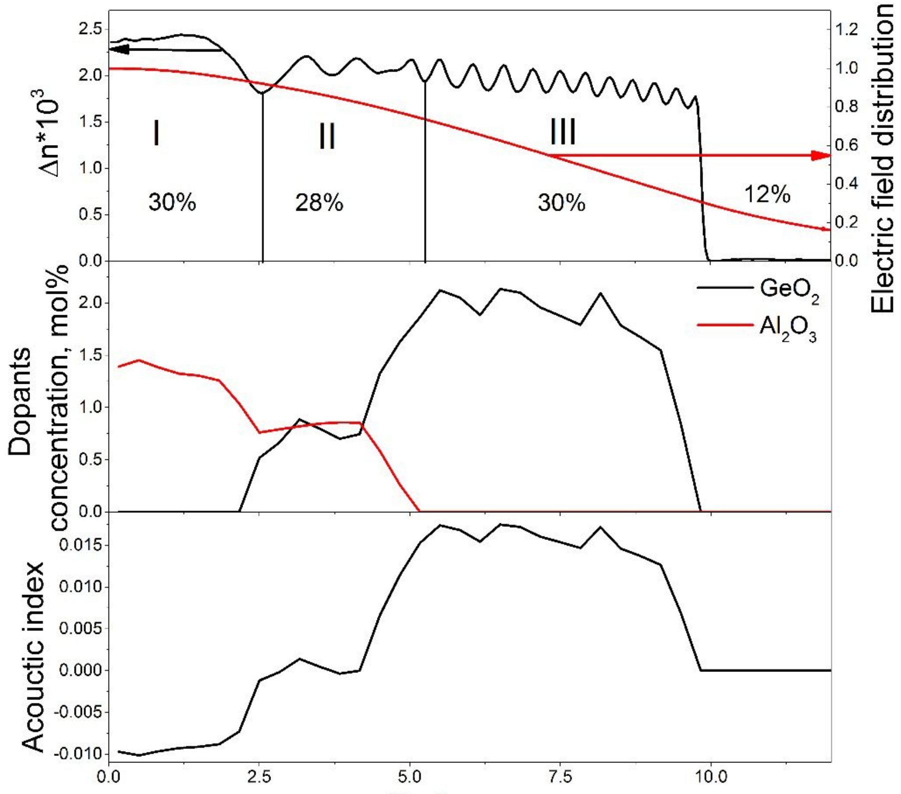

Figure 6. From top to bottom: electric field distribution (red) and refractive index profile (black), doping profile, calculated acoustic refractive index profile in the fiber with outer diameter of 125 µm drawn from the produced preform.

3.2 SBS spectra

To measure SBS spectra in the developed fibers we used the setup described in the previous paragraph. For comparison we took Ge-doped LMA fiber with 20 µm core, MFD of 20.4 µm and cut-off wavelength of 1831 nm. Measured SBS gain spectra for all the fibers are shown in figure 7.

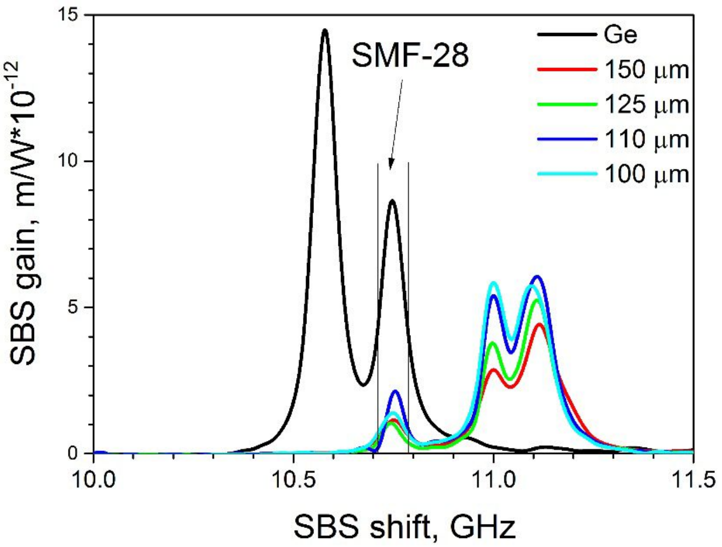

Figure 7. Measured SBS spectra of LMA fibers

It should be noted that the developed fibers have a rather low SBS gain, which is few times less than that of SMF28 fiber. In this case, fake peak at 10.75 GHz, related to SMF-28 fiber from which circulators and buffer fibers were made, was appeared in the measured SBS spectra. All the measured fibers have SBS shifts different to that of SMF28 and therefore the peak at 10.75 GHz was omitted from consideration. The Ge-doped fibers has single peak. LMA SBS suppressed fibers have only two peaks unlike the SBS suppressed fibers with a small mode filed area (see previous paragraph): the right one corresponding to 1'st leaking core acoustic mode and the left one corresponding to 2'nd acoustic leaking mode. The right peak corresponds to Al-doped center region and left peak corresponds to shared leaking mode from the other two Al and Ge codoped and Ge-doped regions. The acoustic index of Ge-doped layer in case of LMA fiber was not enough to guide few acoustic modes, which limits number of peak in the SBS spectra by two. According to these measurements SBS gain coefficients is 14.5 m/W*10^{-12} for Ge-doped fiber; 4.4, 5.2, 6.1 and 5.8 m/W*10^{-12} for SBS-suppressed LMA fibers having outer diameters of 150 μm, 125μm, 110μm and 100μm correspondingly. Achieved SBS suppression (as compared to the purely Ge-doped fiber) was about 5.2 dB for the fiber with outer diameter of 150 μm.

3.3 SBS threshold measurement

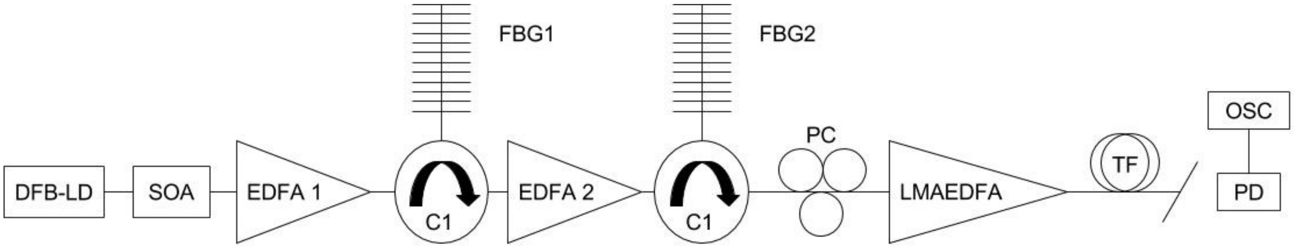

Figure 8. Setup for measuring SBS threshold in LMA fibers.

Setup used to measure SBS threshold developed in the previous paragraph does not suffice to measure threshold in LMA fiber, as it is at least 10 times higher compared to the small mode filed area SBS-suppressed fibers. Therefore, we used measurements of pulse instability threshold [8] to characterize the developed LMA fibers. Similar to our previous work [8] we used LMA Er-doped cladding pumped amplifier (LMAEDFA) to amplify 80ns pulses up to peak power of 4 kW (no pulse instability in active fiber was observed up to this power). The experimental setup consist of DFB-LD with wavelength of 1550.9 nm and output power <1 mW, semiconductor optic amplifier (SOA), which was modulated to produce 80ns pulses at repetition rate of 2.45 kHz, and two stages EDFA (EDFA1, EDFA2) with circulators (C1, C2) and a narrow-band (spectral width of less than 0.1nm) fiber Bragg gratings (FBG1, FBG2) to suppress amplified spontaneous emission. We obtain output average power of 2 mW (peak power of about 10W) which was enough to seed LMA EDFA. Seed pulses were coupled into LMA EDFA through polarization controller (PC). We measured output power and pulse shape from the output end of test fiber (TF) by power meter and photodetector (PD) connected to oscilloscope (OSC). Criteria for SBS threshold was observing impulse instability caused by test fiber. In order to prevent reflection from output end test fiber was angle-cleaved.

Results are shown in figure 9. Threshold power was measured for different lengths L of the test fibers and aproximated by P_{th}/L dependence, where P_{th} has dimension of [W·m] and correspond to the SBS threshold of 1 meter length fiber. We obtained highest P_{th} of 620 W·m for the fiber with outer diameter of 150 µm. The P_{th} for Ge-doped fiber was 290 W·m. Since they have very close MFD, we can say that we achieved suppression by 3.3 dB. MFDs, effective mode areas, threshold power P_{th} and intensity of measured fibers are presented at table 1. SBS suppression value obtained by pulse instability measurements differs from values obtained by spectrum measurements. We believe that it is due to poor polarization state control. Another reason is different SBS peaks width and therefore different thresholds dependencies on pulse width (in the current measurements we were limited by the pulse width of about 80 ns).

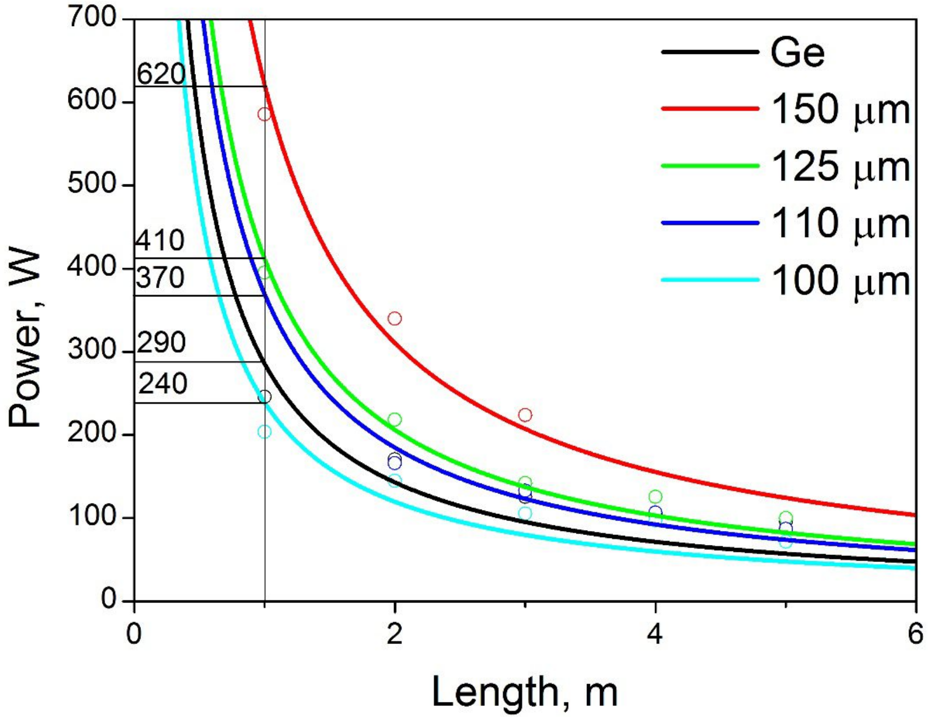

Figure 9. SBS threshold power against test fiber length.

Table 2.SBS thresholds for LMA fibers.

Name	MFD, µm /Aeff, µm^2	Pth, W·m	Ith, W·µm^{-2}
Ge	20.39/ 326.5	290	0.88
150 µm	20.37/325.9	620	1.90
125 µm	18.47/267.9	410	1.53
110 µm	17.46/239.4	370	1.54
100 µm	16.94/225.4	240	1.06

4. CONCLUSION

In conclusion, a new method of SBS suppression by management of fiber's acoustic profile has been proposed and tested. Two sets of Al/Ge co-doped fiber having three layers with different compound have been developed. SBS suppression was found to be 6.4 dB and 3.3 dB for fibers with mode field area of 25 μm^2 and 326 μm^2 correspondingly. SBS spectrum of fiber with a small mode field area has 4 peaks and spectrum of the fibers with large mode area has 2 peaks. This feature might be caused by a small dopants concentration in the LMA fiber and therefore lower acoustic index difference and reduced number of the acoustic modes.

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