Quantum Electronics **51** (3) 228–231 (2021)

FIBRE OPTICS

https://doi.org/10.1070/QEL17429

Optical fibre with an offset core for SBS suppression

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Abstract. **To raise the stimulated Brillouin scattering (SBS) threshold, we have fabricated an optical fibre having a core heavily doped with germanium oxide and displaced from the fibre axis. A method has been proposed for broadening the SBS gain spectrum of the fibre by winding it onto a small-diameter spool, and a broadening of the spectrum by 5.4 dB has been demonstrated, which indicates an increase in SBS threshold by 4.1 dB.**

Keywords: *SBS, optical fibre, offset core.*

1. Introduction

Fibre Raman lasers and amplifiers are widely used as light sources in spectral regions inaccessible to rare-earth-doped emitters. At the same time, a number of applications, such as detection of low gas concentrations [1], lidar measurements of gas concentrations in the atmosphere [2], and creation of laser guide stars [3], require a small spectral bandwidth. However, if use is made of long fibre sources having a heavily doped small-diameter core, this makes stimulated Brillouin scattering (SBS) the main nonlinear effect, limiting their output power.

The SBS gain coefficient is inversely proportional to the SBS gain bandwidth at an emission linewidth far smaller than the SBS bandwidth. There are a number of approaches for broadening the SBS gain spectrum of optical fibre (OF): modification of the acoustic profile (sound velocity distribution in the fibre core) [4–10] and generation of a temperature [11], tension [12], or dopant concentration [13, 14] gradient in the core along the length of the fibre. In the first approach, the sound velocity distribution in the fibre core is modified via codoping with a few additives, one of which raises the sound velocity (aluminium oxide) and the others reduce it (germanium and phosphorus oxides and fluorine). As a result, the SBS gain spectrum of the fibre acquires a complex structure having a few peaks comparable in height, which leads to an increase in SBS threshold by 6.4 dB for passive fibre [4] and 11.2 dB for active fibre [5] in comparison with the SBS threshold of standard fibre with similar optical parameters. However, this method requires precise control over dopant concentrations to significantly raise the SBS threshold, which makes it technologically impractical and leads to a high cost of such fibre. A temperature gradient allows one to vary the frequency of the SBS peak along the fibre length, thereby broadening the SBS gain spectrum. Because of this, the SBS signal from one part of fibre can only be amplified where the spectra still overlap, which reduces the effective interaction length of SBS signals from different parts of the fibre. The use of temperature [11], tension [12], and dopant concentration [14] gradients has made it possible to raise the SBS threshold by 4.8, 15.3, and 6 dB, respectively. The cause of the large scatter in results is that the highest temperature of the fibre in Ref. [11] was limited by the failure temperature of the polymer coating (140 °C), which allowed for a shift of the SBS gain spectrum by just 180 MHz. The largest dopant concentration gradient is determined by the necessity to maintain guidance properties of the fibre. The best result so far [12] is due to the fact that the highest tension of fibre, limited by its mechanical strength, allows one to reach an order of magnitude larger change in the frequency of the SBS peak: 1.7 GHz at a tensile strain $\varepsilon = \Delta l/l = 3.1\%$ (where l is the initial fibre length and Δl is the tension-induced length change). Unfortunately, these methods are difficult to use in practice because it is necessary to produce a uniform gradient for achieving the best result. Moreover, high temperature or high tensile strain dramatically impairs the long-term reliability of the fibre.

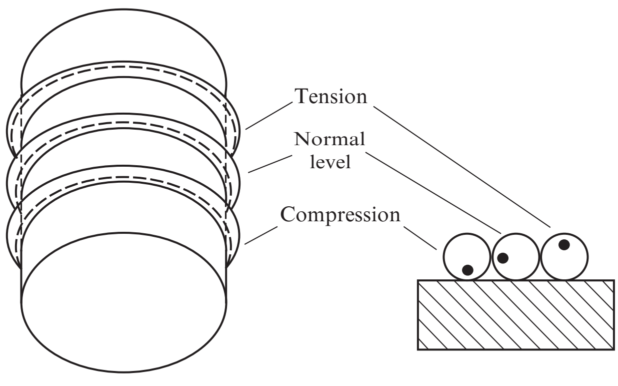

Figure 1. Schematic of the offset core fibre winding process.

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Received 1 September 2020; revision received 7 December 2020
Kvantovaya Elektronika **51** (3) 228–231 (2021)
Translated by O.M.Tsarev

In this work, we propose and implement a new method for SBS suppression in OF: via core offset to the edge of the cladding and subsequent winding of the fibre onto a small-diameter spool. This allows a periodic strain gradient to be produced in the fibre core without a complex system such as was used by Engelbrecht et al. [12]. Note that, in our configuration, the fibre core experiences periodic stretching and compression (Fig. 1), which allows the change in the frequency of the SBS peak at a given strain to be doubled in comparison with the configuration that ensures only fibre stretching. Thus, the highest strain needed to reach a given broadening of the SBS gain spectrum decreases twofold, which has an advantageous effect on the long-term reliability of the fibre.

2. Fibre design

A fibre preform was produced by the MCVD process. Doping the core with germanium oxide (24 mol% GeO_2) ensured a core–cladding index difference $\Delta n = 0.035$. The core to cladding diameter ratio was ~1/4. To reduce this ratio, the preform was then jacketed in a few silica tubes. The resultant preform was asymmetrically polished so that its core was strongly displaced to the edge of the cladding. The fibre drawn out from this preform had cladding and core diameters of 125 and 8 μm, and the axis of its core was 13 μm from the edge of the cladding (Fig.2a). The calculated mode field diameter at a wavelength of 1550 nm was 6.7 μm, and the second mode cutoff wavelength was 1750 nm. The fibre is not strictly single-mode at the operating wavelength (1555 nm), but its strong bending as a result of the winding onto a small-diameter spool leads to large higher order mode losses and ensures essentially single-mode operation. To improve its strength and long-term reliability, an airtight carbon coating was produced directly on the fibre, in addition to a polymer coating [15]. This allowed the fibre to be wound onto a spool 28 mm in outer diameter, with no risk of breakage during its service life.

The principal difficulty in using offset core fibre is presented by fusion splicing with standard fibre. For this purpose, it is necessary to align the offset fibre core with the centred core of the standard fibre. In the case of non-coaxial fibre fusion splicing, surface tension forces tend to displace the materials of the two fibres toward a common axis. To reduce the displacement, fusion splicing was performed at a low arc current for a short time. Since this did not preclude displacement of the fibre core material, additional displacement compensation before fusion splicing was needed. The two fibres were aligned using the amplitude of a signal that was launched into the standard fibre and detected at the other end of the offset core fibre. Translating the latter along the axis passing through its centre and the centre of the core (the x-axis in Fig. 2b), we found the maximum of the signal and then, continuing to translate it away from the axis of the standard fibre, we stopped when the signal decreased to a level of 80%–90% of its maximum. The particular signal level depended on the viscosity of the fibre cores during the fusion splicing process and the splicer arc duration and power. Optimising the process, we were able to reach a loss per fusion splice under 0.5 dB.

3. SBS gain spectrum

Figure 3 shows a schematic of the setup used to measure the SBS gain spectrum. Light from a distributed feedback cw laser diode (LD) (wavelength of 1555 nm, linewidth under 2 MHz) was amplified to 20 mW by a core-pumped erbium-doped fibre amplifier (EDFA1). The amplified beam was split into two equal parts. One part was used to pump the test fibre (TF) during the SBS process and was modulated by an electro-optical modulator (EOM1) at a frequency from 8 to 12 GHz. Its central and low-frequency components were filtered off using a circulator (C1) and fibre Bragg grating (FBG) with a reflection bandwidth of 0.08 nm (FWHM). The remaining, high-frequency component was amplified to 100 mW by a fibre amplifier (EDFA2) and launched into the TF through a circulator (C3) and polarisation controller (PC). The other part of the LD beam was used as a ‘signal’ at the centre frequency. It was modulated at a frequency of 1 kHz by an electro-optical modulator (EOM2) and launched into the TF through a circulator (C2). The amplified SBS signal was detected by a synchronous detector (SD).

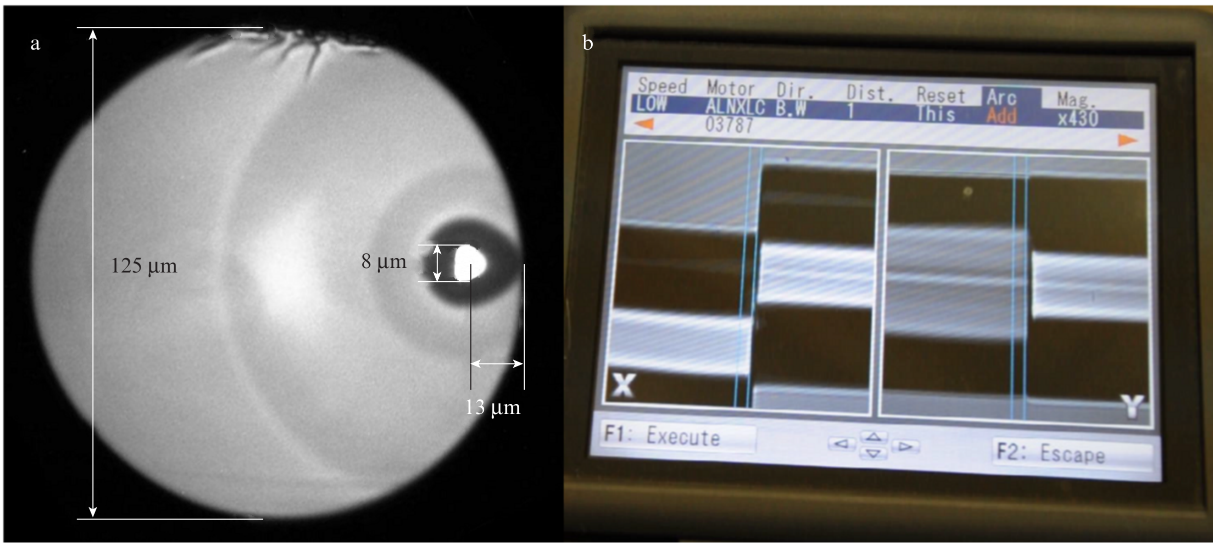

Figure 2. Photographs of (a) the end face of the offset core fibre and (b) fusion splicing of the offset core fibre with standard fibre.

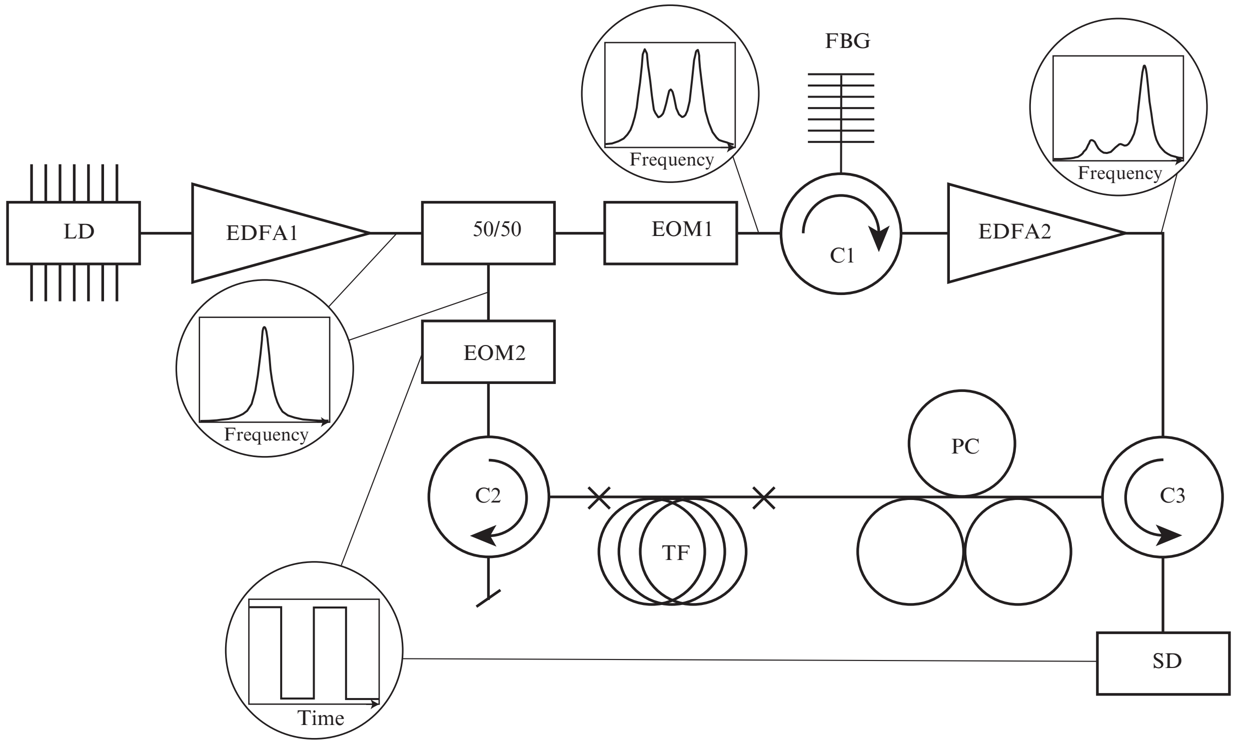

Figure 3. Schematic of the setup used to measure the SBS gain spectrum: (LD) laser diode; (EDFA1, EDFA2) erbium-doped fibre amplifiers; (TF) test fibre; (EOM1, EOM2) electro-optical modulators; (C1 – C3) circulators; (FBG) fibre Bragg grating; (PC) polarisation controller; (SD) synchronous detector.

The SBS gain coefficient depends on pump polarisation with respect to the signal at each point of the fibre. Accordingly, varying the position of the polarisation controller (PC) we were able to measure the maximum and minimum gains. If polarisation-maintaining fibre is used, the minimum gain is zero and the maximum gain corresponds to the SBS gain coefficient. In the case of non-polarisation-maintaining fibre, the minimum corresponds to one-third of the SBS gain coefficient, and the maximum, to two-thirds [16]. Accordingly, the spectral dependence of the SBS gain coefficient was obtained by adding up the minimum and maximum values.

SBS gain spectra were measured for a 50-m length of relatively undeformed fibre wound onto a 180-mm-diameter spool and for the same fibre segment after deformation by winding onto a 28-mm-diameter spool. At this winding diameter, the total tensile and compressive strain ε was 0.7%. Figure 4 shows the measured SBS gain spectra. The FWHM of the spectrum of the undeformed fibre was 78 MHz, with a peak gain coefficient of 24 pm W^{-1}. In the case of the fibre wound onto the 28-mm-diameter spool, the FWHM increased to 272 MHz and the peak gain coefficient dropped to 9.3 pm W^{-1}. It is worth noting that the increase in SBS frequency is proportional to the tensile strain of the fibre, and the decrease is proportional to the compressive strain. Thus, the two peaks in the spectrum of the fibre wound onto the 28-mm-diameter spool (Fig.4) correspond to the positions of the fibre on the spool in which the fibre core experiences the largest compression (left peak) and the largest stretching (right peak). Since rotation of the fibre about its axis during winding cannot be precisely controlled, in most of the fibre the offset core turned

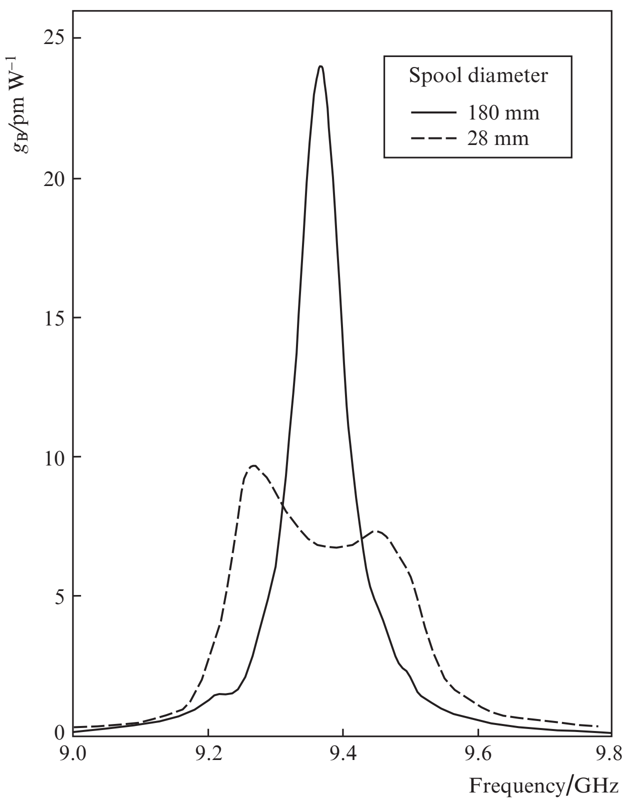

Figure 4. Measured spectral dependences of the SBS gain coefficient for fibre wound onto spools 180 and 28 mm in diameter.

out to be oriented towards the centre of the spool, which led to a 'skewness' of the gain spectrum and a reduction in maximum SBS suppression to 4.1 dB.

4. Conclusions

We have fabricated an OF with its core displaced from the fibre axis and doped with a high germanium oxide concentration. Measurements of SBS gain spectra of the fibre wound onto spools 180 and 28 mm in diameter indicated SBS suppression by 4.1 dB. It is worth noting that larger suppression can be reached at a smaller spool diameter, but the mechanical strength of the fibre limits the spool diameter. In particular, the long-term allowable bend diameter of a 10-m length of SMF-28 commercially available fibre is 16 mm [17]. At this winding diameter, the total strain of offset core fibre will be 1.2%, which will lead to broadening of the SBS gain spectrum by 7.7 dB in comparison with undeformed fibre.

Note also that the proposed method is attractive mainly because it can be combined with fibre acoustic profile modification. Using the latter approach, Khudyakov et al. [4] obtained an SBS gain spectrum in the form of three peaks spaced more than 200 MHz apart. In such a case, the use of offset core fibre will allow for an increase in SBS threshold by more than 8 dB without reducing the spool diameter.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 19-38-90281).

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