Experimental observation of spontaneous depolarized guided acoustic-wave Brillouin scattering in side cores of a multicore fiber

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Spontaneous depolarized guided acoustic-wave Brillouin scattering (GAWBS) was experimentally observed in one of the side cores of an uncoated multicore fiber (MCF). The frequency bandwidth in the side core was up to ∼400 MHz, which is 0.5 times that in the central core. The GAWBS spectrum of the side core of the MCF included intrinsic peaks, which had different acoustic resonance frequencies from those of the central core. In addition, the spontaneous depolarized GAWBS in the central/side core was unaffected by that in the other core. These results will lead to the development of polarization/phase modulators using an MCF. © 2018 The Japan Society of Applied Physics

Nonlinear optical phenomena in optical fibers have been used extensively for sensing and nonsensing applications, such as distributed temperature and strain sensors and radio-frequency (RF) generators. This is because optical fibers have high electromagnetic tolerance and a compact and simple structure.[1–12] Fiber-optic guided acoustic-wave Brillouin scattering (GAWBS), one of such nonlinear optical phenomena,[8–20] is caused by the interaction of incident light and acoustic waves in the core of the optical fiber. It occurs as either depolarized or polarized GAWBS.[8] Owing to the high signal-to-noise ratio (SNR) of depolarized GAWBS compared with that of polarized GAWBS,[8] the former is often used in applications such as temperature,[13] strain,[14] and optomechanical sensing.[15,16] The depolarized GAWBS can be categorized as either spontaneous or stimulated. Stimulated depolarized GAWBS has been observed in dual-mode single-core fibers[17] and small-core (2-µm-diameter) photonic crystal fibers (PCFs).[18] Recently, stimulated depolarized GAWBS in multicore fibers (MCFs) has been observed by the pulse excitation method.[10] The observed spectrum in the central MCF core was almost the same as that of a silica single-mode fiber (SMF). The spectrum in the side core was observed in the frequency range up to ∼400 MHz, which did not agree with theoretical calculations, assuming the use of a CW light source, because the stimulated backward Brillouin scattering was generated by the pulse excitation method.[10] An interaction occurs between stimulated depolarized GAWBSs in both the central and side cores, which act as the cross-phase modulation (XPM).[10] On the other hand, spontaneous depolarized GAWBS has been observed in various optical fibers, such as silica SMFs,[8] polarization-maintaining fibers,[19] and few-mode fibers.[20] In the MCF, the spontaneous depolarized GAWBS has been observed in the central core, but not in the side cores of the MCF, because the SNR is significantly reduced by acoustic wave dumping in the polymer coat.[8–10,20]

In this study, we successfully observe spontaneous depolarized GAWBS in one of the side cores of an MCF with its polymer coat removed. The spectrum in the side core is observed in the low frequency range up to ∼400 MHz, which is different from that of stimulated depolarized GAWBS in MCFs because stimulated backward Brillouin scattering does not appear as noise with the use of a continuous-wave (CW) light source. The spontaneous depolarized GAWBS in the side core contains peaks with the same central frequencies as that in the central core (which we call "intrinsic peaks") and peaks with central frequencies different from those in the center core (which we call "shear peaks"). We then measure the interaction of the spontaneous depolarized GAWBS between the center and side cores, with the result of no interaction detected. These findings will be useful in the development of various optical devices, including strain, temperature, and acoustic impedance sensors, phase/polarization modulators, and RF oscillators.

Several acoustic waves that have their origin in thermal fluctuations can exist in optical fibers.[8,9] Among these acoustic waves, the torsional-radial acoustic mode ($TR_{2,m}$, where m is the acoustic resonance mode), which induces displacements not only in the radial direction but also in the torsional direction, perturbs the refractive index and birefringence in the fiber.[8,9] The optical scattering caused by this acoustic mode is termed depolarized GAWBS. In this case, multiple spectral peaks of up to several GHz are observed. The central frequency (GAWBS-induced frequency shift) of the m-th acoustic mode ($\nu_{GB,m}$) is given by[8]

$$\nu_{GB,m} = \frac{v y_m}{\pi d},\tag{1}$$

where d is the fiber outer diameter and v_s is the velocity of the shear acoustic waves for depolarized GAWBS. The symbol y_m is the value derived from the following equation:[8]

$$\begin{vmatrix} \left(3 - \dfrac{y_m^2}{2}\right)J_2(\alpha y_m) & \left(6 - \dfrac{y_m^2}{2}\right)J_2(y_m) - 3y_m J_3(y_m) \\ J_2(\alpha y_m) - \alpha y_m J_3(\alpha y_m) & \left(2 - \dfrac{y_m^2}{2}\right)J_2(y_m) - y_m J_3(y_m) \end{vmatrix}$$
$$= 0,\tag{2}$$

where α is v_s/v_L (= 0.624[15]) and J_2 and J_3 are the second- and third-order Bessel functions, respectively. The central frequency is known to depend on strain and temperature with dependence coefficients ($m = 5$) of 1.9 MHz/%[14] and 11 kHz/K,[13] respectively.

The fiber under test (FUT) was a 20-m-long standard MCF uncoated with a heater, which has a central core, and six side cores that are equally spaced on a hexagonal grid as shown in Fig. 1. The outer diameter was 142.4 µm and the centers of the side cores are 40.4 µm away from the fiber center. The mode field diameter in all the cores is 7.4 µm at 1550 nm. The optical power coupling between any pair of cores, in the fiber itself,
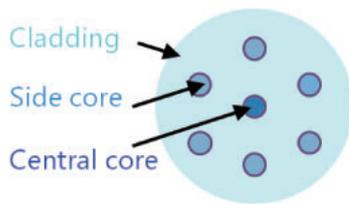
Fig. 1.   Cross section of the multicore fiber under test.

Fig. 2.   Schematic setup for observing spontaneous depolarized GAWBS. EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FUT, fiber under test; MCF, multicore fiber; PC, polarization controller; PD, photodetector; PL, polarizer; PSCR, polarization scrambler.

and in the fan-out units (maximum input power: 20 dBm CW) at both fiber ends was verified as lower than −40 dB.

A schematic of the setup for observing the spontaneous depolarized GAWBS spectrum in the MCF is depicted in Fig. 2; this is basically the same as that previously reported,[10] except that a CW source was used. The output of a distributed-feedback laser diode (wavelength: 1550 nm; linewidth: 15 kHz; maximum output power: 15 dBm) was divided using a 70/30 optical coupler. One output component was used as the probe source and the other as the pump. The probe signal was directly injected into the core of the FUT, where the measured core was arbitrarily selected. The pump light was injected into the core through an erbium doped optical fiber amplifier (EDFA) and an optical switch, and the measured core was also arbitrarily selected. Subsequently, the optical beat signal of the GAWBS forward-scattered light and pump light was guided to a polarizer (PL), and then to a photodetector (PD) for optical-to-electrical conversion. All the optical paths excluding the FUT consisted of silica SMFs. The signal was finally monitored as a spontaneous depolarized GAWBS spectrum using an electrical spectrum analyzer (ESA) with 100 kHz frequency resolution and 100 kHz video bandwidth. Averaging was performed 1000 times. The peak power of the spontaneous depolarized GAWBS spectrum was maximized using polarization controllers (PCs), indicating that the light beam can be regarded as a depolarized beam.[3,4]

In this investigation, we performed noise-floor compensation using the following procedure: (i) the raw data of the spontaneous depolarized GAWBS spectrum was obtained using the ESA, (ii) the noise floor (the spectrum when the FUT was removed from the experimental setup) was separately obtained, and (iii) the noise floor was subtracted from the raw data. The vertical axis of the spectrum calculated in this manner is defined as an SNR in this paper. The measurement temperature was 26 °C. The spontaneous depolarized GAWBS spectrum in the uncoated MCF is shown in Fig. 3. The green curve represents the measured GAWBS spectrum in the central core. A blue curve shows the spectrum of the GAWBS in a side core. The frequency range of the spectrum extended to ∼400 MHz, which was 0.5 times larger than the frequency range for the same phenomenon in a silica SMF because the spectrum in the higher frequency range has a low SNR compared with that in the lower frequency range.[1] The maximum SNR in the center core was 8 dB at 105 MHz. The spectrum of the side core included some intrinsic and sheared GAWBS peaks (note that no significant difference was observed among different side cores). An accurate calculation of the theoretical center frequency of each peak might be possible using the combination of $TR_{m,n}$ ($m = 2, 3, 4, \ldots,\ n = 1, 2, 3, \ldots$).[11] The maximum SNR in the side core was 2 dB at 30 MHz,
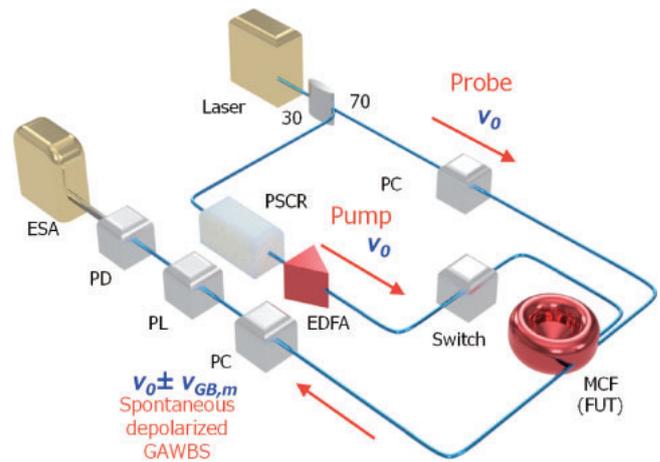
which was smaller than that in the central core owing to the unsymmetrical structure around the side core.[11] If we use these intrinsic peaks for acoustic impedance sensing, we can expect a more accurate acoustic frequency response. The spontaneous depolarized GAWBS spectrum of the central core is the same as that of this nonlinear event in silica SMFs, which can be calculated using Eq. (1), assuming that the longitudinal acoustic velocity in the MCF is 5998 m/s and the ratio of the transverse acoustic velocity to the longitudinal acoustic velocity in the MCF is 0.624.

Subsequently, we measured the interaction between spontaneous depolarized GAWBSs in the side and center cores as shown in Fig. 4. The depolarized GAWBS spectra in the side core, central core, and side core in the vicinity of the first were measured as shown in Figs. 4(a)–4(c), respectively, when the optical switch was OFF; such spectra were almost the same as those in Fig. 3. The pump power was 20 dBm, which was the maximum input power of the splitter of the MCF for avoiding the cross talk between cores to other cores. First, we injected the pump signal into the central core and the probe light into the side core, but there was no observed interaction [Fig. 4(d)]. When the pump light was injected into the side core and the probe light into the center core, we still did not observe any interactions [Fig. 4(e)]. Finally, the pump signal was injected into the side core and the probe light was injected into a separate side core in the vicinity of the first. This did not yield any observable interactions [Fig. 4(f)]. These results are consistent with the basic principle of active phase modulation using GAWBS.

Finally, we discuss how we can potentially implement (i) active phase modulators, (ii) RF oscillators, and (iii) multiparameter sensors, using the spontaneous depolarized GAWBS in an MCF. As for (ii) and (iii), the explanations are relatively simple. The GAWBS signal can be simply converted into an electrical signal (RF signal) using a photodetector, which can be regarded as an RF oscillator. In the meantime, the GAWBS signal is dependent on the ambient acoustic impedance, for instance, and thus, discriminative sensing of multiple physical parameters will be feasible if we combine the dependence of standard Brillouin
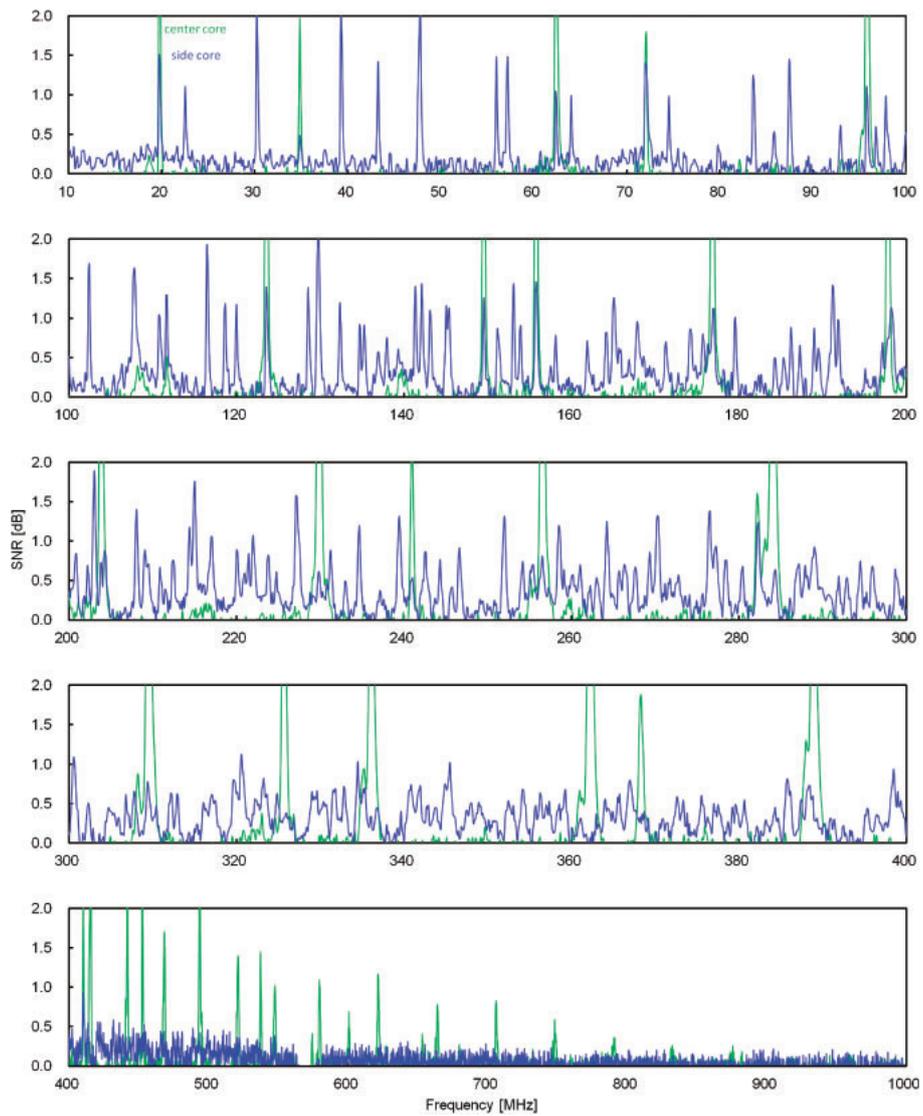
Fig. 3. Measured spontaneous depolarized GAWBS: spectra in side (blue) and center (green) cores.
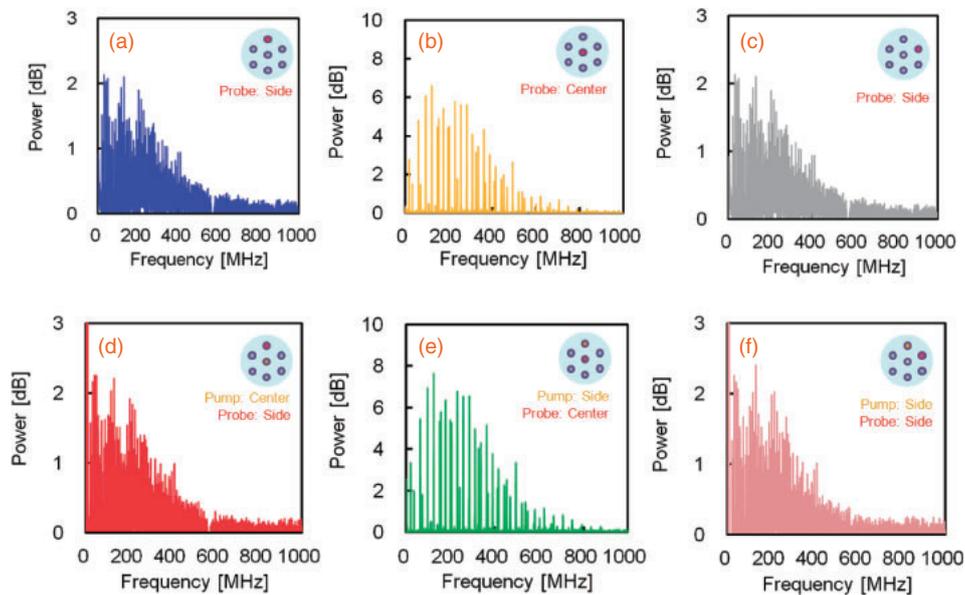
Fig. 4. Depolarized GAWBS spectra in the (a) side core, (b) central core, and (c) side core in the vicinity of the first. GAWBS spectra with the interaction between acoustic waves in the (d) side core and central core (pump light into the center core and probe light into the side core), (e) side core and central core (pump light into the side core and probe light into the central core), and (f) side core and another side core (in the vicinity).

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scattering on strain/temperature in another core of a single MCF. As for (i), the basic concept has been proposed by Zadok's group.[10] They have reported XPM in an MCF; when a strong optical pump is injected into the central core of an MCF, stimulated GAWBS is induced, generating the strong radial acoustic wave. This strong radial acoustic wave affects the birefringence of the side cores, and then the polarization state of the optical signal in the side cores is changed. In this paper, we have clarified that the XPM is not caused by using the spontaneous GAWBS. Thus, we speculate that the XPM can be controlled by switching stimulated/spontaneous GAWBS. In addition, if we define the generation of stimulated GAWBS as "1" and that of spontaneous GAWBS as "0", the modulator will potentially act as a communication device.

In conclusion, we successfully observed the spontaneous depolarized GAWBS in one of the side cores of an uncoated MCF. The spontaneous depolarized GAWBS spectrum in the side cores was observed to be in the low frequency range up to ∼400 MHz, which was different from the stimulated depolarized GAWBS in MCFs. We did not observe any interaction between spontaneous depolarized GAWBSs in the center and side cores. The physical aspects of these results are interesting and will be of great significance in the development of various optical devices such as multi-parameter sensors, active phase/polarization modulators, and RF oscillators.

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