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Fresnel Reflection Spectra at Multimode Optical Fiber Ends with Heterodyne Detection

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The Fresnel reflection (FR) spectra at the ends of a step-index (SI-) multimode fiber (MMF) and a graded-index (GI-) MMF were investigated with heterodyne detection, and compared with that of a standard single-mode fiber (SMF). The FR spectra of the MMFs were found to spread broader than that of the SMF, and the FR spectrum of the SI-MMF was even broader than that of the GI-MMF. It was also demonstrated that the observation of the Brillouin gain spectrum in a polymer optical fiber (POF) is severely influenced by the FR spectrum. We believe that this information will provide a guideline for the design of robust Brillouin sensing systems using MMFs including POFs.

Optical fiber sensors based on Brillouin scattering have been widely studied as a promising technology for smart materials and structures, due to the capability of distributed measurement of strain and/or temperature along an optical fiber. They are classified into two types: "analysis systems",[1–5] in which two light beams need to be injected into both ends of the fiber under test (FUT), and "reflectometers",[6–10] in which one light beam is injected into only one end of the FUT. Several kinds of analysis systems have been proposed so far, such as Brillouin optical time-domain analysis (BOTDA)[1–3] and Brillouin optical correlation-domain analysis (BOCDA).[4,5] Since these methods are based on stimulated Brillouin scattering (SBS), we can obtain relatively large signals. However, they need two-end access, which is often not feasible in long-range applications, and cannot work properly when the FUT has even one breakage point. Therefore, one-end-access reflectometers, such as Brillouin optical time-domain reflectometry (BOTDR)[6,7] and Brillouin optical correlation-domain reflectometry (BOCDR) systems,[8–11] are more favorable in this sense, even though the signals are weaker because they are based on spontaneous Brillouin scattering.

Recently, in BOTDR employing a single-mode fiber (SMF) as the FUT, it has been reported that the measurement sensitivity is deteriorated by the Fresnel reflection (FR) spectra at the end of the FUT.[12] Meanwhile, fiber-optic sensors using multimode fibers (MMFs),[13–16] including polymer optical fibers (POFs),[17–20] have also been extensively studied, because their fracture toughness and flexibility can make the systems much simpler to handle in field applications. However, there have been no reports on the observation of the FR spectra at the end of MMFs.

In this work, we investigate the FR spectra at the ends of a step-index (SI-) MMF and a graded-index (GI-) MMF, and compare them with that of an SMF. It is experimentally shown that the FR spectra of the MMFs spread broader than that of the SMF, and that the FR spectrum of the SI-MMF spreads broader than that of the GI-MMF. We also show that the FR spectrum in a POF has a great influence on the observation of the Brillouin signal.

An SI-MMF and a GI-MMF, manufactured by Newport Corporation, and a standard SMF were used as the FUTs. Their physical properties are summarized in Table I. The experimental setup is shown in Fig. 1, which is based on self-heterodyne detection and has been used to study the Brillouin scattering in a POF.[21,22] A distributed-feedback laser diode (DFB-LD) at 1552 nm with a linewidth of about 10 MHz was used as a light source. A 1-km-long delay fiber was inserted in the Brillouin pump path, which ensures that this measurement is well beyond the coherence length (several tens to 100 m) regardless of the FUT length. The power of the incident light at the end of each FUT was fixed at 17 dBm, and the polarization state was adjusted to minimize the FR using a polarization controller (PC).

The spectra of the light beams reflected at the ends of the SI-MMF, GI-MMF, and SMF within the range from DC to 3 GHz are shown in Figs. 2–4, respectively. The two curves in each figure represent the spectra without and with index-matching oil ($n = 1.46$) applied to the fiber ends, and the spectra were drastically decreased by applying matching oil for all three fibers. After applying matching oil, the spectrum in Fig. 2 was almost the same as that in Fig. 3. Since the spectra with matching oil applied were in good agreement with those when a large bending loss was applied near the fiber ends, it is reasonable to think that the FR can be almost completely suppressed by applying matching oil and that the reflected spectra with matching oil applied correspond to

Table I. Physical properties of the SI-MMF, GI-MMF, and SMF. d, core diameter; n_{eff}, core effective refractive index; NA, numerical aperture; α, propagation loss; L, fiber length.

Fiber	d (μm)	n_{eff}	NA	α (dB/km)	L (m)
SI-MMF	50	~1.46	0.2	~1.0	100
GI-MMF	50	~1.46	0.2	~1.0	100
SMF	9	~1.47	0.13	~0.5	1

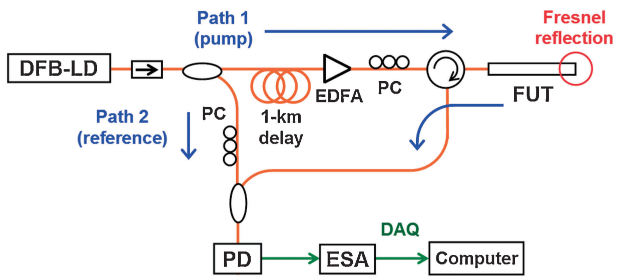

Fig. 1. Experimental setup for characterizing the Fresnel reflection spectra. DAQ, data acquisition; DFB-LD, distributed-feedback laser diode; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FUT, fiber under test; PC, polarization controller; PD, photodetector.

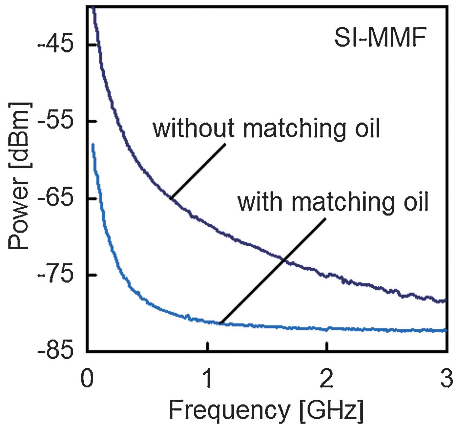

Fig. 2. Spectra of the light reflected from the SI-MMF with and without index-matching oil applied to the fiber end.

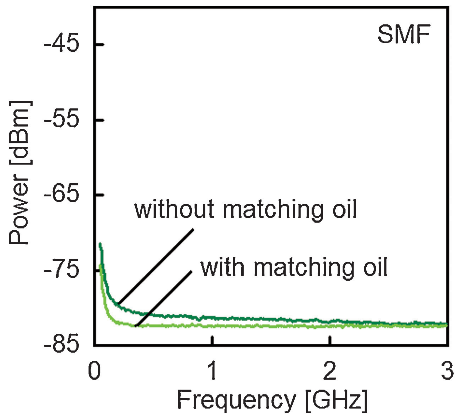

Fig. 4. Spectra of the light reflected from the SMF with and without matching oil applied.

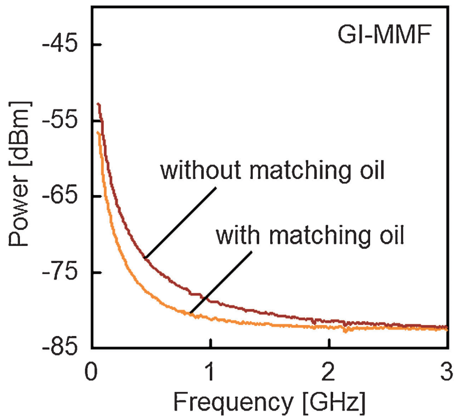

Fig. 3. Spectra of the light reflected from the GI-MMF with and without matching oil applied.

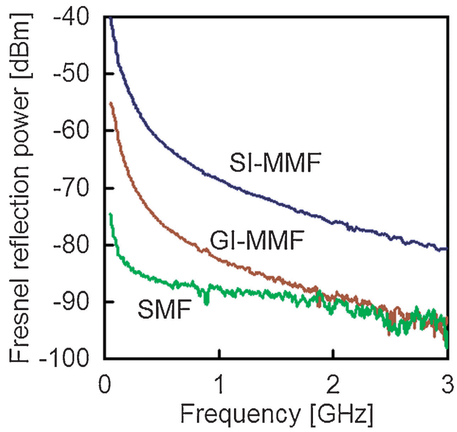

Fig. 5. Fresnel reflection spectra at the ends of the SI-MMF, GI-MMF, and SMF.

Rayleigh scattering and $1/f$ noise. Therefore, the net FR spectrum excluding Rayleigh scattering and $1/f$ noise can be simply calculated as the difference between the spectra with and without matching oil applied.

The net FR spectra calculated from Figs. 2–4 are shown in Fig. 5. It is known that the FR spectrum depends on the phase noise of the light source,[12] and that its 3-dB bandwidth with heterodyne detection is twice as broad as the linewidth of the light source.[12,23] Therefore, the shapes of the FR spectra are the same in principle regardless of the fiber type. Considering that the noise floor in Fig. 5 is roughly estimated to be about −90 dBm, the three spectra have similar shapes but with quite large differences in magnitude. The FR spectra of both the MMFs are over 20 dB higher and spread much broader than that of the SMF. The physical reason can be understood from the approximate expression of the FR coefficient $F(\theta)$ on the fiber-end surface:[24]

$$F(\theta) = F(0) + (1 - F(0))(1 - \cos\theta)^5, \qquad (1)$$

where θ is the incidence angle on the fiber-end surface, and $F(0)$ is the FR coefficient when $\theta = 0$, i.e., when an SMF is employed. Since the light beams in the MMFs reach the fiber ends not only vertically but also at different angles due to their multimode nature, the FR magnitude of MMFs is larger than that of SMF. On the other hand, the FR spectrum of the GI-MMF is about 15 dB lower than that of the SI-MMF. This is because the light beams in the GI-MMF are more concentrated inside the center of the core and reach the fiber end at deeper incidence angles (i.e., $\theta_{\text{GI-MMF}} < \theta_{\text{SI-MMF}}$).

Finally, we demonstrate that, when a POF with low Brillouin frequency shift (BFS) is employed as the FUT, the observation of the Brillouin gain spectrum (BGS) is severely influenced by the FR spectrum. Since the coupling loss between the POF and the SMF devices (such as the optical isolator) is over 10 dB, and the optical propagation loss of the POF is much higher than that of silica-based fibers, it is difficult to fairly estimate the net FR spectrum of the light reflected at the end of the POF. However, we can experimentally show the influence of the FR spectrum, with Rayleigh scattering and $1/f$ noise included, on the BGS observation in the POF. The POF used in the experiment was a 5-m perfluorinated graded-index (PFGI-) POF with 0.185 in numerical aperture (NA), 120 µm in core diameter, ~1.35 in core refractive index, and ~150 dB/km in propagation loss at 1.55-µm wavelength. The experimental setup was the same as that depicted in Fig. 1, except that a 23-dB electrical pre-amplifier was inserted before the electrical spectrum analyzer (ESA) to enhance the weak BGS of the POF. The spectra of the light beams reflected at the end of the PFGI-POF within the range from DC to 3 GHz are shown in Fig. 6. The incident power was set to 19 dBm, and the measurement

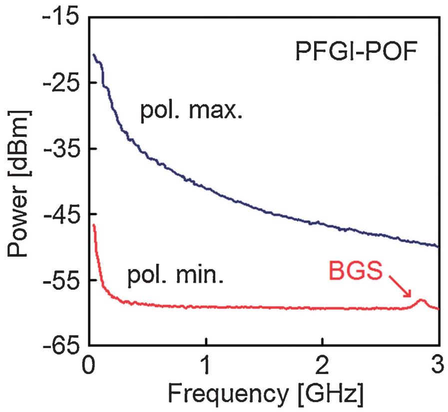

Fig. 6. Spectra of the light reflected from the PFGI-POF with two polarization states.

was performed with two polarization states, where the FR spectral power became minimal and maximal. When the FR power was minimal, the BGS was clearly observed at 2.83 GHz with no overlap of the FR spectrum. In contrast, when the FR power was maximal, the BGS was completely overlapped by the FR spectrum and was not observed. Thus, it was shown that the BGS observation in the PFGI-POF is greatly influenced by the FR spectra.

In conclusion, we investigated the net FR spectra at the ends of an SI-MMF, a GI-MMF, and an SMF with heterodyne detection. The FR spectra of the MMFs spread broader than that of the SMF, and the FR spectrum of the SI-MMF was even broader than that of the GI-MMF. We also showed an example where the Brillouin measurement based on MMFs, especially POFs, is more severely influenced by the FR spectra than that based on SMFs. One of the methods to suppress this influence is to taper the open ends of the MMFs. We believe this paper is of great assistance in developing robust one-end-access Brillouin sensing systems based on MMFs including POFs.

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