Polarization Beat Length Distribution Measurement in Single-Mode Optical Fibers with Brillouin Optical Correlation-Domain Reflectometry

Yosuke Mizuno, Zuyuan He, and Kazuo Hotate

Department of Electrical Engineering and Information Systems, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan

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The polarization beat length distribution along a single-mode optical fiber (SMF) is measured with a Brillouin optical correlation-domain reflectometry. The beat lengths of SMFs wound on mandrels with radii 10.0, 7.4, and 3.1 cm were measured to be 25.4, 12.1, and 2.56 m, respectively, which agreed well with the theoretical calculations. A distributed measurement was also successfully performed using an SMF comprising two sections with different mandrel radii.

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For high-speed fiber-optic communication systems, such as those with transmission rate of 40 Gbps and above, polarization mode dispersion (PMD), that is, the differential group delay (DGD) between the two polarization mode propagation in the single-mode fiber (SMF), is one of the most serious effects that reduce the transmission capacity of the fibers. Therefore, the knowledge of DGD is of high interest. Various methods have been used for the PMD measurement,[1] but these methods give us no distributed information about DGD along the fiber but only the overall DGD of the link. A simple method based on Rayleigh reflectometry using polarized light, which is called polarization-sensitive optical time-domain reflectometry (POTDR), has been proposed,[2] and demonstrated its potential to measure local birefringence (the beat length) over a long distance, but with low spatial resolution and long integration time.[3] The beat length measurements with very high resolution have been achieved by polarization-sensitive optical frequency-domain reflectometry (POFDR),[4] but over a short distance. Recently, as an alternative approach, the polarization dependence of stimulated Brillouin scattering (SBS) has been used to measure the beat length distribution along the fiber.[5,6] One of the methods is based on Brillouin optical correlation-domain analysis (BOCDA),[7] and has obtained a spatial resolution as high as 2.7 cm.[5] However, these methods need to access both ends of the fiber under test (FUT), which is often not feasible in long-range application, and cannot work completely when the FUT has even one breakage point. In most long-range practical applications, one-end access reflectometries are more favorable.

In this paper, we propose a new method to measure the distribution of beat length based on Brillouin optical correlation-domain reflectometry (BOCDR),[8,9] which was originally proposed to measure the distribution of strain and/or temperature along an FUT by controlling the interference of continuous lightwaves. The method shows unique features such as one-end access, random access to measuring positions, high spatial resolution, and high speed measurement. In our previous experiments, 13-mm spatial resolution and 50-Hz sampling rate were simultaneously achieved with the measurement accuracy of $\pm 100\,\mu\varepsilon$,[9] which can be improved, for example, to $\pm 50\,\mu\varepsilon$ by 5-times averaging.

The experimental setup of BOCDR is shown in Fig. 1. The Stokes light due to the spontaneous Brillouin scattering of the pump light in the FUT is heterodyned with the

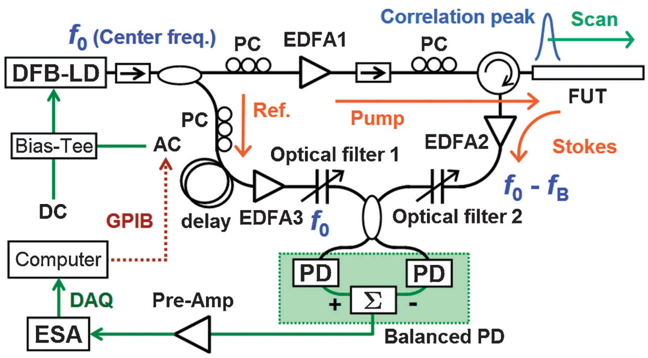

Fig. 1. Experimental setup of BOCDR system: AC, alternating current; DAQ, data acquisition; DC, direct current; DFB-LD, distributed-feedback laser diode; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FUT, fiber under test; GPIB, general-purpose interface bus; PC, polarization controller; PD, photo-diode.

reference light (self-heterodyne scheme). In order to get the distribution of the Stokes light along the FUT, the pump light and the reference light are sinusoidally frequency-modulated, producing periodical correlation peaks along the FUT. The measurement range of BOCDR, that is, the interval of the correlation peaks is given by

$$d_m = \frac{V_g}{2 f_m}, \tag{1}$$

where V_g is the group velocity of light and f_m the modulation frequency. We limit the length of the FUT shorter than d_m to include only one non-0th correlation peak (where the 0th peak is defined at the position of zero optical-path difference), so that the Stokes light scattered at the correlation peak position can be detected. The position of the correlation peak can be moved along the FUT by changing f_m. Hence, the distribution of the Stokes light can be obtained by controlling f_m. The spatial resolution Δz is given by

$$\Delta z = \frac{V_g \Delta \nu_B}{2\pi f_m \Delta f}, \tag{2}$$

where $\Delta \nu_B$ is the intrinsic linewidth of the Brillouin gain spectrum (BGS), and Δf is the modulation amplitude of the light source, which is limited to a half of the Brillouin frequency shift (BFS), i.e., about 5.4 GHz in BOCDR with standard SMF at 1550-nm wavelength.[8)] In BOCDR, the peak power P of the BGS observed by the electrical spectrum analyzer (ESA) is given as:

$$P = \kappa \langle \boldsymbol{E}_{\mathrm{ref}} \cdot \boldsymbol{E}^{*}{}_{\mathrm{Stokes}} \rangle, \tag{3}$$

where $\boldsymbol{E}_{\mathrm{ref}}$ and $\boldsymbol{E}_{\mathrm{Stokes}}$ are the electrical fields of the reference light and the Stokes light, respectively, at the heterodyne receiver, κ is a proportionality coefficient, and $\langle \cdots \rangle$ stands for time-averaging operation. When f_m is changed to perform a distributed measurement, $\boldsymbol{E}_{\mathrm{ref}}$ is kept constant but $\boldsymbol{E}_{\mathrm{Stokes}}$ changes according to the birefringence distribution along the FUT. As a consequence, P varies reflecting the distribution of the birefringence. Thus, by measuring the distribution of the peak power P of the BGS by use of BOCDR, we can obtain distributed information of birefringence and estimate the distribution of polarization beat length. Here, due to roundtrip of backscattered Stokes light, the beat length L_B is obtained as twice as the observed spatial period of P variation.[10)]

The experimental setup is shown in Fig. 1. A distributed-feedback laser diode (DFB-LD) at frequency f_0 (1552 nm) was used as a light source, and a sinusoidal frequency modulation was applied to generate a correlation peak within an FUT. The output from the LD was divided into two light beams by a coupler. One of the beams was directly used as the reference light of self-heterodyne detection, after passing a 2-km delay fiber for controlling the order of the correlation peak, an Er-doped fiber amplifier (EDFA) for enhancing the heterodyne beat signal, and an optical filter composed of fiber Bragg grating (FBG) with a 3-dB bandwidth of about 10 GHz for suppressing the amplified spontaneous emission (ASE) noise. The other beam was injected into the FUT as the pump light, after being amplified by a high-power EDFA to 28 dBm. The weak Stokes light at frequency $f_0 - f_B$ backscattered from the FUT was amplified again by an EDFA. An optical filter was inserted after the EDFA in order to suppress the Rayleigh scattering from the FUT at frequency f_0. The optical beat signal of the reference light and the Stokes light was converted by balanced photodiodes (PDs) to an electrical signal. After 15-dB amplification from an electrical pre-amplifier, the signal was monitored by an ESA.

A 1-km SMF was employed as an FUT, which was wound on a mandrel with radius $R = 10.0$ cm to induce birefringence intentionally. One end of the FUT was spliced to a circulator, and the other end was kept open. The sampling rate was set to about 20 Hz, which is higher than that of POTDR.[3)] The 400-m position from the circulator was defined as the relative position 0 m. A measurement of the BGS peak power was performed at every 1 m from the relative position 0 to 100 m. The modulation frequency f_m was changed from 98.19 to 103.09 kHz, and the modulation amplitude Δf was set to 5.4 GHz, which corresponds to the spatial resolution Δz of about 1.8 m and the measurement range d_m of about 1 km by eqs. (1) and (2). The measured distribution of the Stokes light is shown in Fig. 2, where periodical fluctuation was observed. In order to estimate its spatial period, the power spectral density (PSD) was calculated using fast Fourier transformation (FFT), and is shown in Fig. 3. The peak of the PSD appeared at 0.079/m, which corresponds to the spatial period of 12.7 m. Therefore,

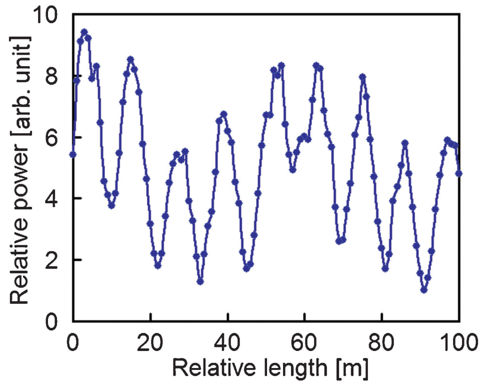

Fig. 2. Measured distribution of the BGS peak power when the mandrel radius R was 10.0 cm.

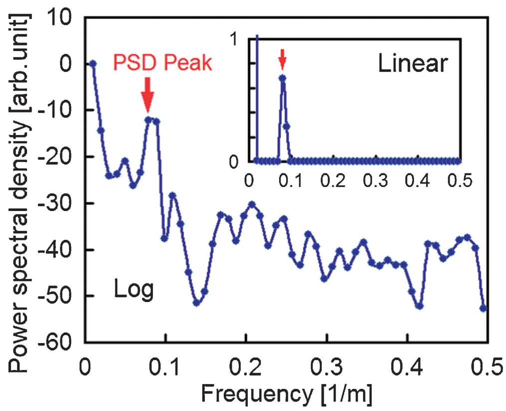

Fig. 3. Calculated PSD of the BGS peak power distribution in log scale when the mandrel radius R was 10.0 cm. The inset shows the same graph in linear scale.

L_B was calculated to be 25.4 m. The same measurements were performed in the cases of $R = 7.4$ cm and $R = 3.1$ cm with $\Delta z = 55$ cm and $\Delta z = 25$ cm, resulting in $L_B = 12.1$ m and $L_B = 2.56$ m, respectively.

In theory, the beat length L_B (m) can be calculated as[11)]

$$L_B(\mathrm{m}) = \left| \frac{4\lambda R^2}{n^3 p(1+\nu) r^2} \right|, \tag{4}$$

where λ (μm) is the wavelength of the light, R (cm) the radius of the mandrel, n the refractive index, p the strain-optical coefficient, ν the Poisson's ratio, and r (μm) the radius of the fiber cladding. Figure 4 depicts the measured and theoretical beat length against the mandrel radius. The theoretical values were calculated by inserting into eq. (4) parameters: $\lambda = 1.55$ μm, $n = 1.46$, $p = -0.15$, $\nu = 0.17$,[12)] and $r = 63$ μm. The experimental results seem to agree well with the theory, although some discrepancy exists. This is thought to have come from the following three factors: (i) The number of sampling points of the PSD is not sufficient. (ii) When a long optical fiber is wound on a mandrel, small strain will remain. As a consequence, the BGS shifts toward the upper frequency, and so the detected power changes even if the polarization state does not change. (iii) Some parameters such as p and ν, which are difficult to measure, may slightly vary among fibers, and their accurate values are unknown.

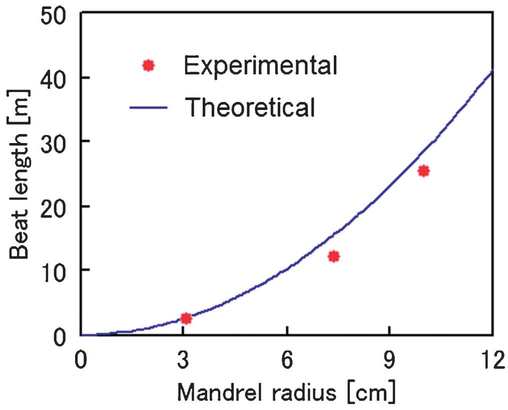

Fig. 4. Polarization beat length as a function of the mandrel radius. The curve shows the theoretical values.

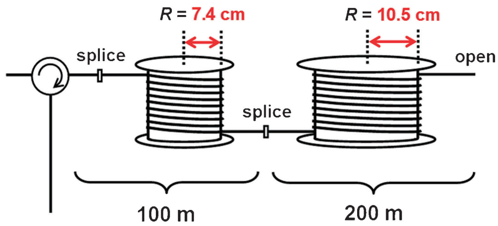

Fig. 5. Structure of the FUT.

Finally, a distributed beat length measurement was performed using an FUT comprising two SMFs with different mandrel radii. The schematic structure of the FUT is shown in Fig. 5. A 200-m SMF wound on a mandrel with radius $R = 10.5$ cm was spliced to a 100-m SMF wound on a mandrel with radius $R = 7.4$ cm. The 60-m position from the circulator was defined as the relative position 0 m, and consequently, the mandrel radius changes at the relative position 40 m. The measurement of the BGS peak power was performed at every 50 cm from the relative position 0 to 100 m. The modulation frequency f_m was changed from 125.64 to 130.95 kHz, and the modulation amplitude Δf was set to 5.4 GHz, which corresponds to the spatial resolution Δz of about 1.4 m and the measurement range d_m of about 800 m. The experimental result is shown in Fig. 6. The spatial period of the fluctuation certainly changes at the relative position 40 m. The calculated PSDs within the range of 0–40 and 40–100 m became maximal at frequency 0.17 and 0.067/m, which correspond to the beat lengths L_B of 11.76 and 29.8 m, respectively. Their theoretical values are 15.6 and 31.5 m, respectively. Considering the error causes discussed above, these experimental values are valid.

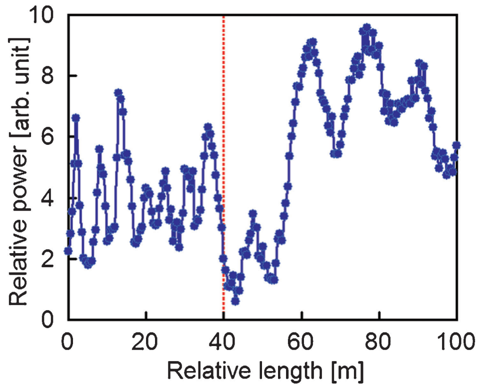

Fig. 6. Measured distribution of the BGS peak power. The mandrel radii were 7.4 and 10.5 cm corresponding to the ranges of 0–40 and 40–100 m, respectively.

In conclusion, we have presented that the BOCDR system can be applied to a distributed measurement of polarization beat length in single-mode optical fibers. The measurement was successfully performed with unique features such as one-end access, 25-cm spatial resolution, and 20-Hz sampling rate.

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