Distributed Brillouin measurement in graded index multimode optical fiber

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ABSTRACT

We present distributed Brillouin measurements realized in a commercially available graded-index few mode optical fiber. The measurements were performed using a Brillouin Optical Time Domain Reflectometer instrument coupled with an industrial multiplexer designed for the multimode fiber, enabling the characterization of 15 Hermite-Gaussian modes of the multimode fiber. The low intermodal crosstalk observed allowed for reliable measurements even in the absence of the multiplexer. Preliminary results of temperature Brillouin frequency coefficient are also presented.

Keywords: Distributed fiber sensor, Brillouin measurement, Multimode optical fiber

1. INTRODUCTION

Optical fiber sensors based on multimode fibers (MMF) are predominantly utilized as point sensors, such as in multimode interference or absorption-based sensors.[1] These configurations capitalize on the impact of environment fluctuations on the propagation of different optical modes to provide localized measurements with high sensitivity. For distributed temperature measurements, intensity-based techniques leveraging anti-Stokes Raman scattering have successfully employed multimode fibers to enhance the signal-to-noise ratio (SNR). In contrast, distributed sensing methods that rely on frequency detection, such as Brillouin or Rayleigh scattering, tend to experience significant noise levels due to optical mode crosstalk when implemented with multimode fibers.

Nevertheless, recent advancements with few-mode optical fibers have demonstrated improved SNR, particularly for distributed acoustic sensing (DAS) applications.[2] In addition, temperature and curvature sensing in few mode fibers was demonstrated with Brillouin Optical Time Domain Reflectometer (BOTDR).[3]

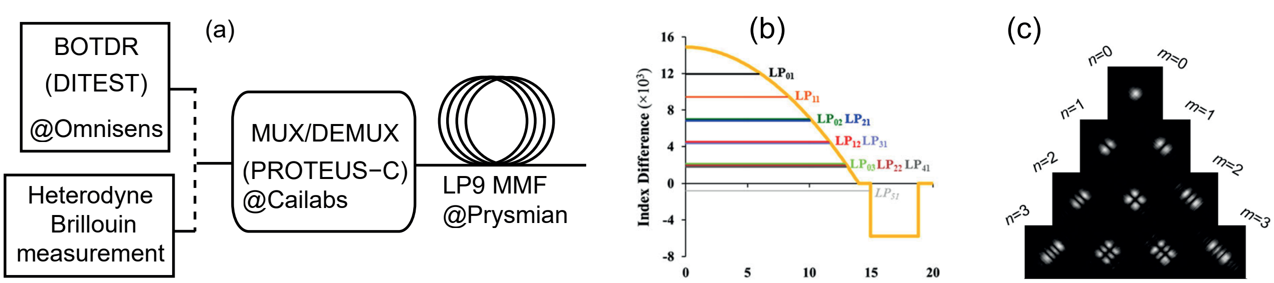

Figure 1. (a) Experimental setup. The length of optical fiber is 4.5 km. (b) Refractive index profile of LP9 multimode optical fiber from reference.[4] (c) Theoretical representation of optical spatial mode from cailabs.com.

Furthermore, there has been growing interest in exploring multimode fibers for distributed Brillouin sensing due to their ability to differentiate the effects of temperature and strain.[5,6] Multimode optical fibers offer the capability to achieve simultaneous measurements of temperature and strain through the use of optical mode multiplexers.[7,8] In this case, the reduction of optical intermodal crosstalk is the key parameter.

2. EXPERIMENTAL SETUP AND MEASUREMENTS

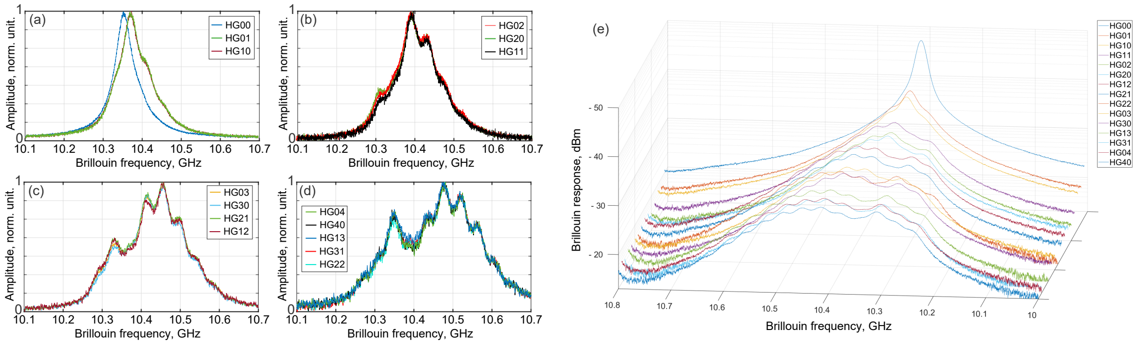

Figure 2. Spontaneous Brillouin measurement obtain with heterodyne detection and Multiplexer for injection in different optical mode. (a) normalized Brillouin spectrum for the different family of optical mode. (b) Waterfall of spontaneous Brillouin spectrum for the same input power. The Brillouin efficiency decrease when the number of spatial mode increases.

Figure 1(a) depicts the experimental setup used to test the 4.5 km of fiber under test. Two instruments are used to characterize Brillouin scattering in multimode fiber. The distributed Brillouin measurement is realized with a commercial BOTDR (Ditest, Omnisens), while the spontaneous Brillouin spectrum is achieved with homemade heterodyne detection. The optical fiber is provided by Prysmian and designed to propagate 9-LP-mode (15-spatial-mode) with low DMGDs ($\leq$155 ps/km), low attenuation ($\leq$0.22 dB/km) and large effective areas (95 μm^2).[4] The index profile is represented in figure 1(b). For information, optical mode classification is depicted in fig 1(c) An optical mode MUX/DEMUX was specially designed for this fiber, allowing us to inject light specifically on a chosen mode, with an average intermodal crosstalk coupling of 25 dB.

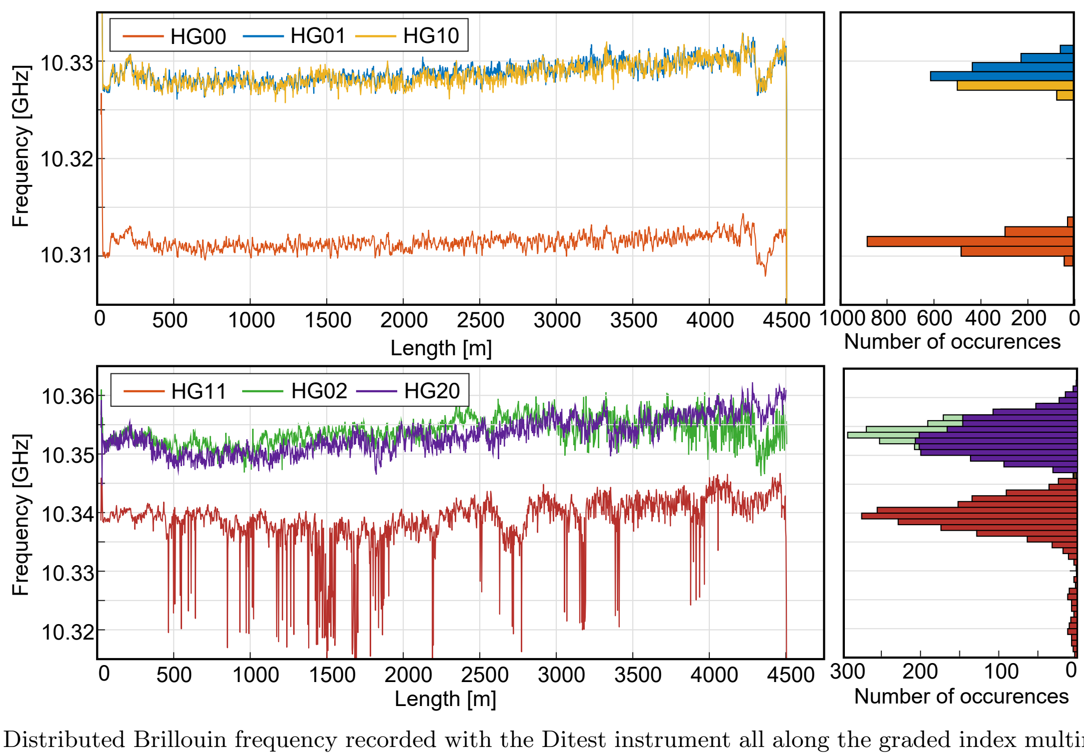

Figure 3. Distributed Brillouin frequency recorded with the Ditest instrument all along the graded index multimode fiber for injection in the first six different optical modes. The experimental parameter were : frequency step 1 MHZ, sampling 2.5 m, spatial resolution 10 m, 5000 average. At the right, integrated Brillouin frequency calculation for the different tested optical modes.

The figure 2 illustrates the spontaneous Brillouin spectrum measurement conducted in an all-optical mode using MUX/DEMUX. The Brillouin spectra display consistent shapes across different optical modes, which is attributed to low intermodal coupling.

However, only the first three optical modes HG00, HG01, and HG10 produce a Brillouin spectrum suitable for distributed Brillouin measurements (fig. 2(a)). As shown in Fig. 2(b), the measurement performed at the same input power reveals the Brillouin efficiency as a function of injection in different optical modes. The Brillouin efficiency for higher-order optical modes is significantly weaker. Additionally, the Brillouin gain spectrum associated with interactions involving higher-order optical modes exhibits spectral broadening. Distributed Brillouin frequency measurement is only feasible for the HG00, HG01 and HG10 optical mode as their spectra exhibit a single and quasi-symmetric resonance. To confirm this assumption, distributed Brillouin frequency measurement was conducted on the first six optical modes and depicted in figure 3. A clear distinction is observed between the two families of measurements. For the first three modes, a small frequency variation of 5 MHz is detected, whereas the higher-order optical modes induce a significantly larger frequency shift of 23 MHz.

3. DISCUSSION AND CONCLUSION

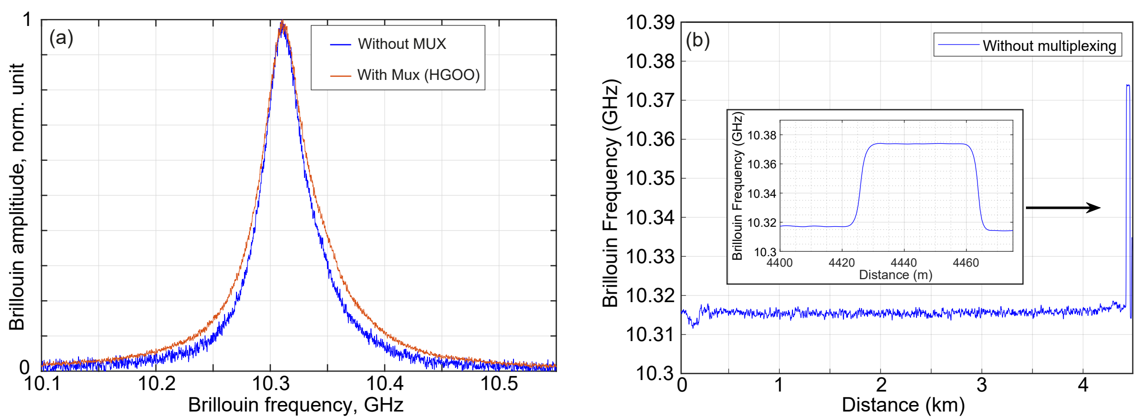

Figure 4. (a) Spontaneous Brillouin spectrum measurement with heterodyne detection along the 4.5 km of graded LP9 fiber direct measurement (blue) and injection on HG00 optical mode with multiplexer. (b) BOTDR measurement with DITEST in LP9 without multiplexing. A hot spot of 30 m with a temperature of 80°C is applied at this end of the fiber with spatial resolution of 5 m.

The figure 4(a) represents the spontaneous Brillouin measurement obtained by heterodyne detection without multiplexing and for injection in the fundamental spatial mode HG00. For this measurement, the multimode fiber was spliced to a single mode fiber. The splicing loss is 0.1 dB. Both spectra present a similar shape close to Lorentzian fit without broadening. Without multiplexing, most of the light is coupled in the fundamental optical mode HG00. The small broadening is linked to the coupling of different optical modes on different acoustic resonances.[9] The figure 4(b) shows the Brillouin frequency shift for the BOTDR measurement in LP9 fiber without multiplexing. The Brillouin frequency fluctuation along the fiber is small. We can deduce that the direct measurement without multiplexing shows a Brillouin measurement with a good signal-to-noise ratio available for distributed measurement.

A BOTDR measurement in the LP9 multimode fiber, without multiplexing, is represented in fig 4(b). A hot spot of 30 m with a temperature of 80°C is applied at this end of the LP9 fiber with a spatial resolution of 5 m. The Brillouin frequency at ambient temperature (20°C) and at the hot spot (80°C) are equal to 10.316 GHz and 10.374 GHz, respectively. We deduce a temperature Brillouin coefficient of 0.97 MHz/°C for direct measurement without injection on a specific optical mode. The work is on going to measure the repeatability and Brillouin coefficients of temperature and strain as a function of optical mode injection. This preliminary work demonstrates the potential of graded index fiber for distributed measurement.

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