Bend-insensitive distributed sensing in singlemode-multimode-singlemode optical fiber structure by using Brillouin optical time-domain analysis

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ABSTRACT

We propose a bend-insensitive distributed Brillouin optical fiber sensing by using a singlemode-multimode-singlemode optical fiber structure for the first time to the best of our knowledge. The sensing fiber is a graded-index multimode fiber (GI-MMF) sandwiched by two standard single-mode fibers (SMFs) with centrally alignment splicing at the interface between GI-MMF and SMF to excite the fundamental mode only in GI-MMF. The sensing system can resist a minimal bend radius of 1.25mm while maintaining the measurement performance, with which the measured coefficient of strain is 421.6MHz/%. We also demonstrate that the higher-order modes exciting in GI-MMF can be easily influenced by bending, so that the fundamental mode exciting is essential for bend-insensitive distributed sensing.

Keywords: Bend-insensitive distributed sensing, singlemode-multimode-singlemode structure, BOTDA.

1. INTRODUCTION

Recent years, distributed sensing system based on Brillouin scattering in single mode fiber (SMF) has been widely studied in the research field of Structural Health Monitoring (SHM) of civil infrastructures such as buildings, bridges, highway pavements and dams [1]. So far, several distributed measurement techniques based on Brillouin scattering in standard single mode optical fibers have been proposed, including Brillouin optical time-, frequency-, and correlation-domain techniques, which can be classified into two categories: "reflectometry" and "analysis." In reflectometry systems, a relatively weak signal and a low signal noise ratio (SNR) is produced due to spontaneous Brillouin scattering , resulting in a low accuracy and small measurement scale of the distributed sensing system. Brillouin optical time-domain analysis (BOTDA), a two-end access of analysis system, features high SNR and accuracy and can solve these problems effectively by virtue of stimulated Brillouin scattering (SBS).

Several techniques have been developed to improve the performance of BOTDA sensing system, such as pulse code technique [2], Raman amplification [3] and differential pulse pair (DPP) [4]. However, in practical SHM engineering application, a real big concern is that, due to harsh construction environment, it may introduce a huge deformation and subsequently a large loss at a local point of the sensing fiber so that the Brillouin signal after the point would be sharply reduced, hence shortening the sensing range dramatically [5].

In this paper, we propose a configuration of singlemode-multimode-singlemode (SMS) fiber structure to achieve a bend-insensitive distributed sensing in BOTDA system for the first time to be best of our knowledge, which features low cost, simple structure, and suitable for long distance. The proposed SMS structure is formed by sandwiching a silica-based graded index multimode fiber (GI-MMF) by two standard single mode fibers (SMFs) with centrally alignment splicing at the interface between GI-MMF and SMF to excite fundamental mode only. The limit bend radius investigated is as low as 1.25mm, with which the measured strain coefficient of the GI-MMF is 421.6MHz/%. In addition, we also demonstrate that higher order modes exciting in the GI-MMF of the SMS structure are easily influenced by bending, so that fundamental mode exciting is essential for bend-insensitive distributed sensing.

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2. EXPERIMENTAL SETUP

The experimental setup is illustrated in Fig. 1. The output of an optical fiber laser is split into two arms by a 50/50 coupler providing two waves, i.e. pump and probe. An arbitrary function generator is used to drive a high extinction ratio (>45dB) electro-optic modulators to generate the pump pulse. A polarization scrambler is used to randomly change the polarization state of the pump pulse to reduce polarization-fading induced fluctuation on the signal by averaging a large number of signal traces, where 5000 times averaging is used in our experiment. Before launched into SMS structure, the pump pulse is amplified by an Erbium doped fiber amplifier (EDFA 1). For the probe beam, the output of laser is modulated by an EOM drived by a microwave generator to acquire carrier-suppressed two sidebands modulation by adjusting the bias voltage of the modulator; after amplified by EDFA 2, the probe beam is launched into the SMS structure. The lower sideband of the probe beam is extracted by a narrowband FBG filter and then is converted into an electrical signal with a photo detector and monitored by an oscilloscope, and then a BGS can be obtained by scanning frequency offset between the pump and the probe in the vicinity of BFS. All the optical paths are composed of silica SMFs except for GI-MMF (Yangtze Ltd.) in SMS structure, of which numerical aperture, length, core size and core refractive index is 0.275, 50m, 62.5μm and ~1.4841, respectively. Noted that the width of pump pulse used in the experiment is 10ns corresponding to a 1-m spatial resolution in a silica fiber. The peak power of pulse pump is 1.5W and the power of probe is 100mW, which lead to a relative high signal intensity. As is shown in the inset 1 of Fig. 1, both ends of GI-MMF are centrally spliced to a standard single mode fiber by arc fusion to excite the fundamental mode in the GI-MMF and inset 2 shows the photo of the SMS structure under a bend radius of 1.25mm in the experiment.

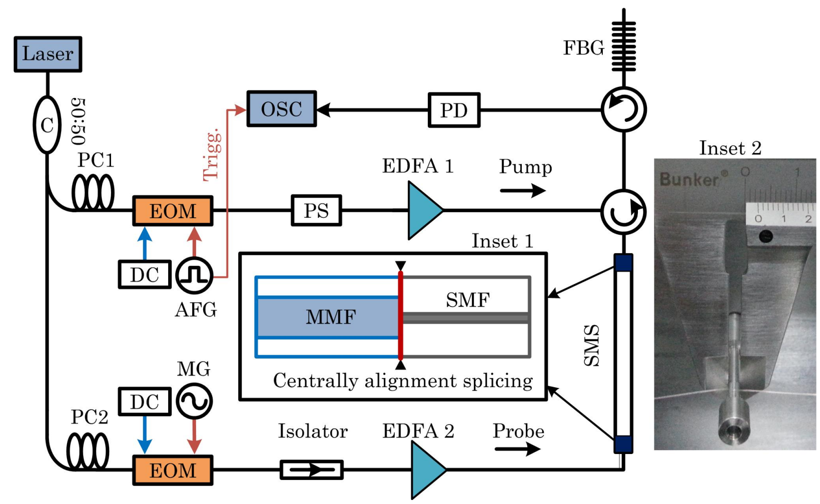

Figure 1. Experimental setup. C, coupler; PC, polarization controller; EOM, electro-optic modulator; DC, direct current; AFG, arbitrary function generator; MG, microwave generator; PS, polarization scrambler; EDFA, erbium-doped fiber amplifier; SMS, singlemode-multimode-singlemode fiber; FBG, fiber Bragg grating; PD, photo detector; OSC, Oscilloscope.
Inset 1, centrally alignment splicing at the interface of SMF and GI-MMF of the SMS structure by arc fusion to excite the fundamental mode in GI-MMF; Inset 2, the photo of SMS structure under a bend radius of 1.25mm.

3. RESULTS AND DISCUSSION

We stimulate the practical conditions by purposely introducing a single loop to the GI-MMF of SMS structure at the position of ~26m with different radii varying from 1.25mm to 12.5mm with a step of 0.5mm. The frequency offset between the pump and probe is set at 9.846GHz, which is the BFS of the GI-MMF at room temperature. The measured Brillouin signals with bend radii of 1.25mm, 2.5mm, 5mm, 7.5mm, 10mm, 12.5mm are shown in Fig. 2(a). It can be seen that the Brillouin signals have little loss for all of the bend radii, even at the minimal bend radius of 1.25mm, illustrating that the proposed SMS structure can effectively resist signal loss induced by extremely bending. The weak intensity variation of the whole Brillouin signals for different bend radii is induced by the power fluctuation of the pump and probe. For comparison, we also introduce a single loop to a 50-m SMF at the position of ~ 30m with the same conditions as that of GI-MMF to illustrate how macro bend radius shortens the sensing range of SMF. The frequency offset between the pump and probe is set at 10.866GHz, which is the BFS of SMF at room temperature. As shown in Fig.

2(b), several typical Brillouin signals with bend radii at 12.5mm, 10mm, 7.5mm, 6.5mm, 5.5mm, 4.5mm and 3mm are chosen for analysis, where the sensing signal of SMF begins to decrease from the radius of 12.5mm and exhibits an obvious signal loss at the radius of 10mm; with further reducing bend radius, the signal considerably decreases and completely disappears at the bend radius of 3mm. This result indicates that the SMF is easily influenced by bending, which would produce a huge loss on Brillouin signal at the bending point and shorten the sensing range of long distributed system of BOTDA. The comparison indicates that the proposed SMS structure can effectively resist macro bending which would considerably reduce the Brillouin signal in SMF.

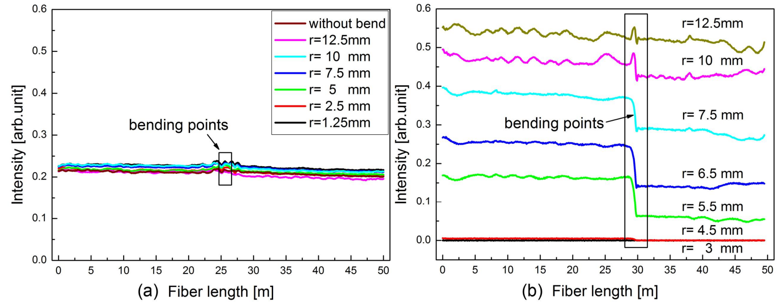

Figure 2. Measured Brillouin signals with different bend radii for (a) GI-MMF of the SMS structure and (b) SMF.

Under the condition of applying the bend radius of 1.25mm at the position of ~25m as shown in Fig. 3(a), the strain was applied to a 2.06m-long GI-MMF of SMS structure at the room temperature. The measured distributed BFS curves are shown in Fig. 3(a), where the stretched step is 2mm corresponding to a strain step of 0.097% and the maximum strain is 1.165%. Fig. 3(b) shows the excellent linear relationship between BFS and strain. The BFS variation sensitivity to strain is 421.6MHz/%, which is slightly smaller than that of SMF. The three-dimensional diagram of BFS of applying the maximal strain of 1.165% with bend radius of 1.25mm is shown in Fig. 3(c), it can be see that after the strain region, the signal experience a small loss but still relative high intensity for detection. These results indicate that the proposed SMS structure can effectively measure stain under the condition of extremely bending. The Brillouin gain spectra at point A, B and C in Fig. 3(a) are plotted in Fig. 3(d), and the bending point is between point A and B. The solid curves show the Lorentzian fits.

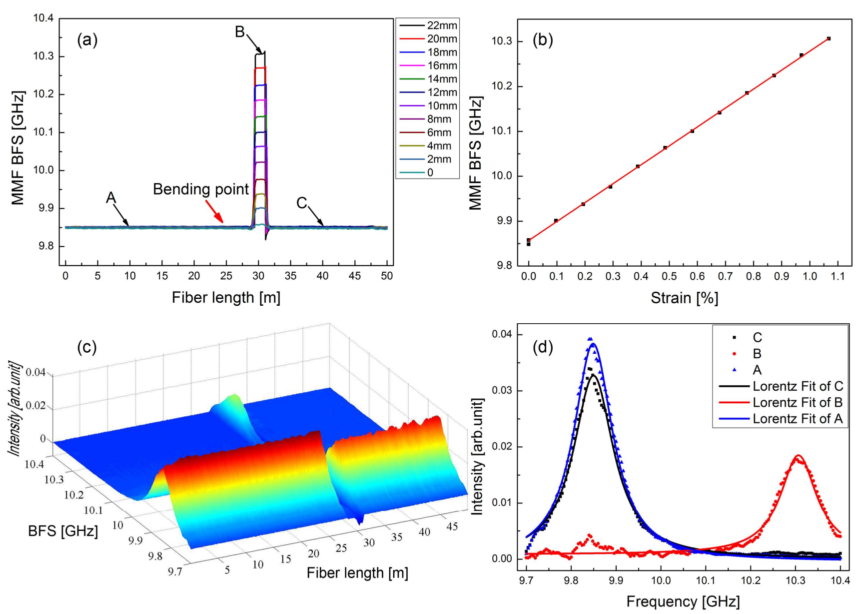

Figure 3. Measured results of a stretched 2.06m-long segment of a 50-m GI-MMF while a bend radius of 1.25mm is applied at the position of ~25m: (a) distributed BFS curves for different strain, (b) linear relationship between BFS and strain, (c) 3D BGS with a strain of 1.165%, (d) Brillouin gain spectra at point A, B and C in (a).

In order to investigate the influence of higher-order mode of the proposed SMS structure on the sensing performance, offset splicing with 10um and 15um were introduced at the interface of SMF and MMF in the SMS structure to purposely excite higher order modes [6] and the BFS of GI-MMF of SMS structure was measured for 10 times, respectively, as shown in Fig. 4. Fig. 4(a) shows the measured BFS curves with an offset of 10um, where the BFSs have a variation of 20MHz, indicating that there are a few higher-order modes excited in the fiber; while for the 20μm offset as shown in Fig 4(b), the variation of the BFSs is as high as 100MHz, indicating more higher-order modes are excited in the GI-MMF. Note that the higher-order modes are unstable and more likely to couple to other modes, which cause the fluctuation of the BFS along the fiber and subsequently inducing the measurement error for sensing. For the proposed SMS structure to achieve bend-insensitive sensing, it is highly important to make central alignment splicing at both interfaces between SMF and GI-MMF to excite fundamental mode only, which can effectively alleviate the loss induced by bending and maintain the sensing performance.

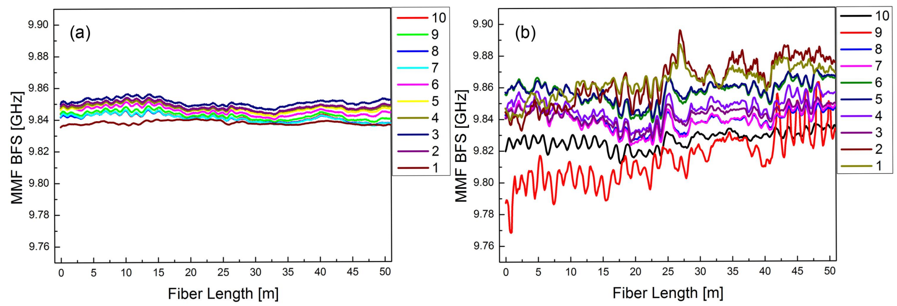

Figure 4. BFSs of the GI-MMF with offset splicing at the interface of SMF and MMF for (a) 10um and (b) 15um

4. CONCLUSION

In conclusion, we reported a bend-insensitive distributed Brillouin sensor by using Brillouin optical time-domain analysis (BOTDA). The sensor is formed by sandwiching a silica graded index multimode fibers (GI-MMF) by two standard single mode fibers (SMFs) with centrally alignment splicing at the interface between GI-MMF and SMF to excite fundamental mode only. The limit bend radius has been investigated, with which the measured strain coefficient is 421.6MHz/%. We also demonstrated that higher order modes exciting in the GI-MMF of the SMS structure are easily influenced by bending, so that fundamental mode exciting is essential for bend insensitive-distributed sensing.

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