Curvature and shape distributed sensing using Brillouin scattering in multi-core fibers

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Abstract: Distributed curvature and shape sensing using Brillouin scattering in multi-core fiber (MCF) is presented for the first time to the best of our knowledge, by exploiting bend-dependent Brillouin frequency shift (BFS) in off-center cores.
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1. Introduction

Among the numerous fiber sensing technologies, distributed optical fiber sensing, particularly Brillouin scattering based sensors, have been intensively investigated over the last three decades for distributed temperature and/or strain sensing, based on the mechanism that the Brillouin frequency shift (BFS) is dependent on both temperature and strain [1]. However, by now, Brillouin scattering based sensors are just mainly performed in normal single mode fiber, and has recently been extended to photonic crystal fiber [2], polymer optical fiber [3], few mode fiber [4], and micro-/nano-fiber [5], among others.

On the other hand, multi-core fibers (MCF), which contain several separate cores within one common cladding, can provide sufficient flexibility to implement spatial independent transmission in distinct cores along the whole fiber length. However, the cores may undergo identical and differential responses with quantifiable difference with respect to environmental perturbations. This offers a new platform for optical fiber sensing technology. So far, some "point" sensors based on Bragg gratings inscribed in a MCF have been reported for special sensing applications, such as bending measurement [6], accelerometer [7], and shape sensor [8]. But fully distributed sensing using the specific response observed in MCFs is still untouched [9].

In this paper we show, for the first time to the best of our knowledge, the bending dependence of BFS in off-center cores of MCF. Essentially, this bending sensitive feature is due to the local tangential strain over the bent segment, so that distributed curvature measurement is achievable in off-center cores by interrogating the BFS along the fiber. We have theoretically studied the dependence of BFS on geometric parameters, and the curvature responsivity was carefully experimentally calibrated. We have also experimentally validated the feasibility of Brillouin distributed optical fiber sensing for curvature measurement in MCF and shown the potential for distributed three dimensional (3-D) shape sensing.

2. Principle

In standard fibers, Brillouin distributed fiber sensors can normally just monitor temperature and strain. However, the BFS in off-center cores of a multi-core fiber are sensitive to bending, as shown in Fig. 1(a). The figure presents the typical distribution of Brillouin gain spectrum in an off-center core, when the fiber is coiled in a spool with a diameter of ~15 cm. As a result of coiling and the random azimuthal orientation of the core under test, large BFS excursion can be observed. A 57/55 ns differential pulse pair (DPP) technique [10] has been employed in this case to obtain a spatial resolution of 20 cm. The bending dependence of BFS in off-center cores is essentially resulting from the local tangential strain when the fiber is under flexure. In particular, the BFS experiences a down-shift when the off-center core is compressed and an up-shift when being stretched. Fig. 1 (b) sketches the geometrical distribution of the 7-core fiber used in our experiment. The bending-induced strain of core i at any point along the MCF is given by:

$$\varepsilon_i = -\frac{d_i}{R}\cos(\theta_b - \theta_i) \tag{1}$$

where, ε_i is the local strain in core *i*, d_i is the distance of core *i* to the fiber center, R is the bending radius, θ_b and θ_i are respectively the bending direction and the angular position of core *i*, where θ_b is defined to be the angle between the local x-axis and the local direction of the center of curvature, and θ_i is the angle from the local x-axis to core *i*, as depicted in Fig. 1(b). In theory, the central core does not suffer from bending-induced strain since it is always co-located with the neutral flexure line, which in turn provides a perfect reference to compensate the temperature variation of the system. The variation of BFS as a function of strain ε_i is given by:

$$\Delta \nu_{Bi} = \alpha \cdot \nu_B \cdot \varepsilon_i \quad (2)$$

where $\Delta \nu_{Bi}$ is the variation of BFS of core *i*, α is a curvature-induced strain response coefficient to be determined, ν_B is the rest BFS of a straight fiber section.

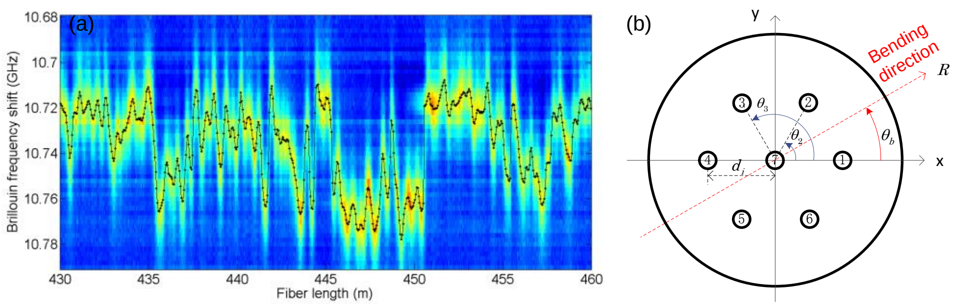

Fig. 1. (a) Brillouin gain spectrum in an off-center core of the MCF showing bound random variations resulting from bending due to coiling, and (b) the geometrical distribution of the 7-core fiber.

By interrogating the BFS, we can get the continuous variations of BFS of every core, and subsequently the strain from equation (2) at every point along the whole fiber. It must be mentioned that the BFS from multiple cores can be obtained in a single measurement, by serially connecting different cores and making light propagate back and forth along distinct cores. When strain information from more than three cores has been obtained, distributed curvature measurement is realizable [8]. Furthermore, the 3-D spatial trajectory of the fiber can be retrieved by solving a set of Frenet-Serret equations: this is possible once the curvature and torsion functions are derived, obtained from distributed Brillouin fiber sensing in more than three cores forming an opened triangle.

3. Experimental setup, results and discussion

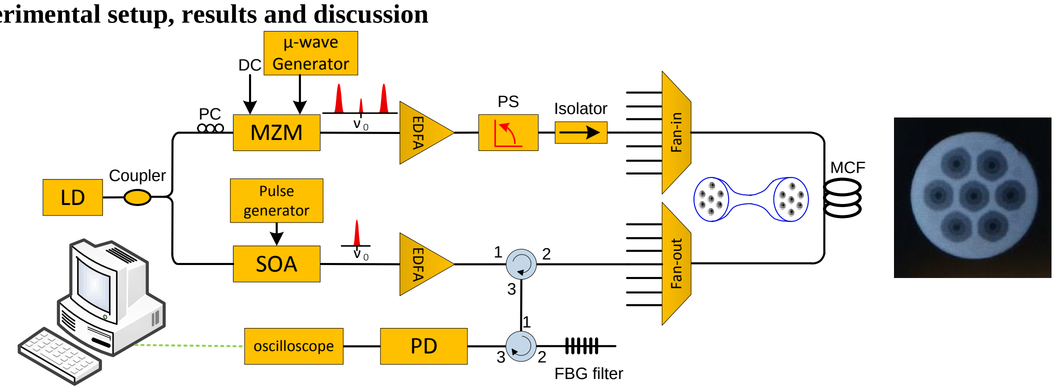

Fig. 2. Experimental setup. LD: Laser diode; PC: polarization controller; MZM: Mach-Zehnder modulator; SOA: semiconductor optical amplifier; EDFA: erbium-doped fiber amplifier; PS: polarization switch; FBG: fiber Bragg grating; PD: photodetector.

A 1012 meter long multi-core fiber with 7-cores in a hexagonal array is used in our proof-of-concept experiment. The nominal cladding diameter of the MCF is 150µm and the core pitch is ~40µm, respectively. The MCF is spliced to fan-in/out spatial Mux/De-Mux couplers at its two ends, which enables a flexible assembling of different system configurations. Using the setup shown in Fig. 2, a BOTDA profiling performed in one outer core has been carried out to determine the curvature response coefficient of BFS, namely α . In order to provide a flat BFS reference on both sides of the curved section, we uncoiled ~31 m at the fiber far end from the spool and placed them loosely straight, and the curved section was positioned in its middle region. The MCF cores in the ~1.5 m curved segment have to be azimuthally positioned before measurement, which is done by injecting visible light into a given core and simultaneously observing the scattered light under a microscope to check the real time orientation of the fiber, by rotating and taping it from point to point. Extreme care has been taken to prevent the fiber from any twist when forming the curved segment that was shaped along a perfect circular trajectory of constant length, but varying radius.

Core 1 (see Fig. 1(b)) was selected to track the bending response, while the bending direction was set along the local x-axis, so that the two parameters $\theta_b = 0^o$ and $\theta_1 = 0^o$ are determined and equation (2) can be simplified as

$\Delta \nu_{B1} = -\alpha \cdot \nu_B \cdot d_1 / R$, assuming temperature does not change during the measurement. Additionally, ν_B is measured to be 10.735 ± 0.00083 GHz and d_1 is 39.252 ± 0.4062 μm. It should be pointed out that the azimuthal positioning of the cores cannot be perfect, but it shows the lowest sensitivity to positioning angular offset when $\theta_b = 0^o$ or $\theta_b = 180^o$, because the slope of the cosine function in equation (1) is zero at the maximum/minimum value points.

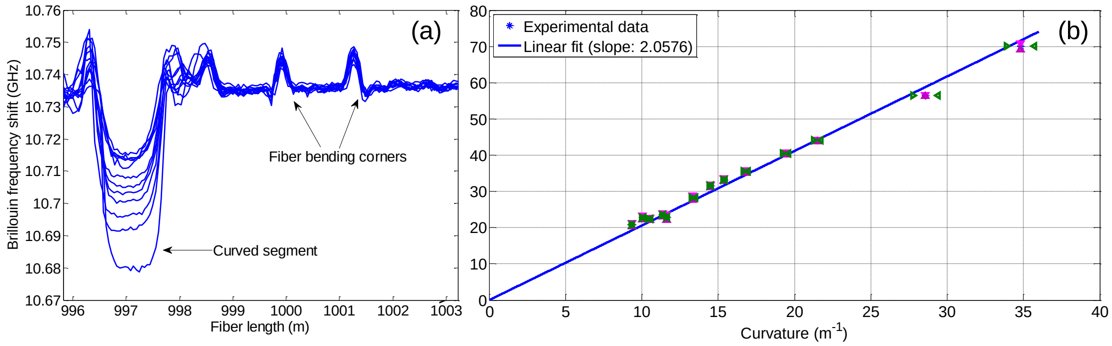

Fig. 3. (a) Extracted Brillouin frequency shift with different bending diameters; (b) measured dependence of the variation of BFS on curvature, the error bars on the curvature and the measured $\Delta \nu_{B1}$ have been marked with green and purple triangles, respectively.

For every circular bending that we made, we performed four measurements with pulse widths larger than 55 ns for a full acoustic response and a differential pulse width of 2 ns to obtain a 20 cm spatial resolution. The BFS traces with different bending radii of the curved segment are shown in Fig. 3(a) and the variation of BFS ($\Delta \nu_{B1}$) (averaged on 5 distinct measurements) as a function of curvature is given in Fig. 3(b) with a linear fitted slope of $\text{S} = 2.0576 \pm 0.02132$ MHz/m^{-1}. Note that here the standard deviation of the measurement at each curvature has been calculated using the 5 measurements.

From this calibration, the variation of BFS (namely $\Delta \nu_{B1}$) on curvature can be determined using $\Delta \nu_{B1} = S / R$; on the other hand $\Delta \nu_{B1} = \left| -\alpha \cdot \nu_B \cdot d_1 / R \right|$, thus $\alpha = S / (\nu_B \cdot d_1)$. Note that S , ν_B and d_1 are uncorrelated measured quantities and α is calculated to be $\alpha = 4.8831 \pm 0.0505$. Its positive value is consistent with a negative BFS change given by the theory and confirmed experimentally in Fig. 3(a). It is also fairly identical to the BFS longitudinal strain coefficient [1], supporting a solid consistency of the technique.

In conclusion, we have presented a detailed experimental investigation of Brillouin scattering in multi-core fibers. The good linearity on curvature shown by the Brillouin frequency shift in off-center cores demonstrates the excellent potentiality for distributed curvature sensing along the whole fiber by performing Brillouin distributed sensing in multi-core fibers, and its great potential for 3-D shape sensing [8]. The proposed technique provides some unique advantages in comparison with FBG-based schemes, including its simple implementation, while no post-fabrication fiber processing is needed at all. Due to the high sensing performance that can be achieved by Brillouin distributed sensing techniques, shaping and curvature sensing over much longer fiber ranges can be achieved, which can offer a new kind of sensing method for real applications. A specific drawback is related to the intrinsic lower sensitivity of Brillouin to strain when compared to FBG, so that an accuracy of 1 MHz on the BFS enables the measurement of curvatures with radii from 2 m down to the bending breaking point. This turns out to be more than sufficient for several structural monitoring applications.

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