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Brillouin scattering effect in the multicore optical fiber applied to fiber optic shape sensing

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ABSTRACT

A shape sensor exploiting Brillouin scattering measurements in multicore fibers is presented. Based on previous reports[1], the shape sensor's principle of operation is firstly described. The presented idea is realized through Brillouin Frequency Shift (BFS) measurements in the time domain along the entire multicore fiber. The BFS value is related to the strain value in each core and the differential inter-core strains lead to the bend radius and orientation. Authors present an experimental demonstration of the shape sensor using a 7-core microstructured optical fiber.

Keywords: Shape senor, Multicore optical fiber technology, Brillouin scattering in multicore optical fibers, Distributed sensing

1. INTRODUCTION

Distributed sensors utilizing the Brillouin scattering effect are widely used to measure temperature and strain[2–4]. Recently there is a huge interest in beating the range limits, improving spatial resolution and reducing the measurement time[5]. In the high-range systems used for distributed measurement of temperature and strain, standard optical fibers are most commonly applied[2–5].

On the other hand, microstructured multicore optical fibers, which possess the diversity and possibility of changing the light propagation properties, are applied for various sensing applications, such as temperature[6], strain[7] and bend measurements[8]. Additionally, multicore fibers are suitable for inscription of fiber Bragg gratings (FBG)[9], which can be useful for shape sensing[10,11]. Recently, observations of Brillouin scattering effect in multicore fibers were reported[12] and the effect was successfully applied for shape sensing[1]. Unlike in previous report[1], here authors used multicore fiber with air-hole isolation.

Shape sensing is a subject which has drawn much interest in the past few years. There are various optical fiber sensing architectures, but in general, shape sensing is possible if the exact bend radius, its location and orientation can be

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measured. To this end, authors take advantage of distributed sensing using Brillouin scattering in multicore optical fibers.

2. PRINCIPLE

As mentioned above, shape can be calculated once having information about a bend radius, orientation and location. The exact bend radius is deduced from the measurement of strain induced in lateral cores, which impacts on the BFS. Additionally, the comparison of the differential strain between cores enables to distinguish the bending orientation. The bending location is identified by performing an optical time-domain measurement, such as the Brillouin Optical Time Domain Analysis (BOTDA).

The presented sensor is based on a 7-core microstructured fiber (MCF7) designed for telecommunication applications (Fig. 1) [13–15]. The MCF7 structure consists of a central core and 6 lateral cores arranged hexagonally and it is optimized to ensure low attenuation and low optical cross-talk[16] (less than −30 dB @ 1550 nm). The MCF7's cores diameter and doping is comparable with the ITU-T G.652 recommendations hence optical properties of each MCF7's core are similar as in the standard single-mode fibers.

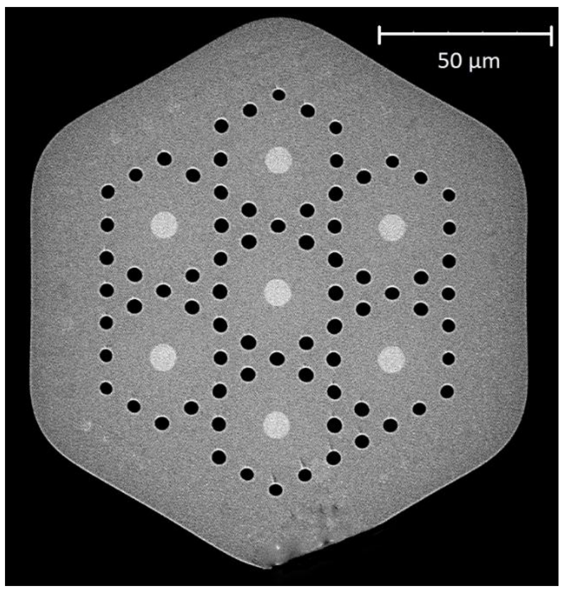

Fig. 1 Scanning electron microscope image of MCF7.

In distributed measurements based on the Brillouin scattering effect, backcoupled light with shifted frequency is observed. This frequency shift, called Brillouin Frequency Shift (BFS), is a value which is constant in unchanged external conditions for a given fiber and is defined as[1,2]

$$\nu_B = \frac{2\, n_{eff}\, V_a}{\lambda}$$

where n_{eff} is the effective refractive index, V_a is the acoustic wave velocity and λ is the incident wavelength.

For a bended fiber the BFS value in each core is different, as it depends on the induced strain, as shown in Fig. 2. Cross-section of the bended multicore fiber shows that each core localized in a bending plane will experience differential strains. Comparing to the central core, the strain experienced by the lateral core, which is on the inside of the bend, is negative, as this core is actually compressed. On the other side, the core outside of the bend experiences positive strain, as this core is actually elongated. The central core is located on the neutral bending line and therefore experiences no strain, providing a zero-bending reference value. This corresponds to the BFS presented in the graph (Fig. 2).

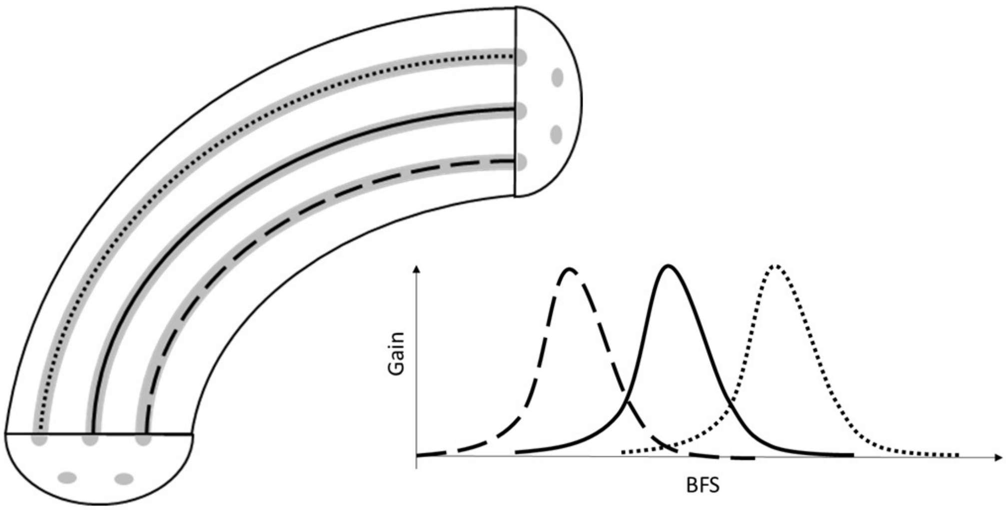

Fig. 2 BFS in the bended multicore fiber. On the left the cross-section along bended multicore fiber, on the right, the graph with corresponding BFS values for three cores is shown. BFS is smaller for the compressed core and greater for the elongated core.

Strain in an arbitrary lateral core depends on the bend radius and bend orientation, which can be expressed as[1]:

$$\varepsilon_i = -\frac{d_i}{R}\cos\left(\theta_b - \theta_i\right)$$

where ε_i is strain of the i-th core, d_i is the distance between the i-th core and the center of the fiber, R is the bend radius, θ_b is the bend orientation and θ_i is the angular position of the i-th core. For the sake of clarity d_i, θ_b θ_i are shown in Fig. 3.

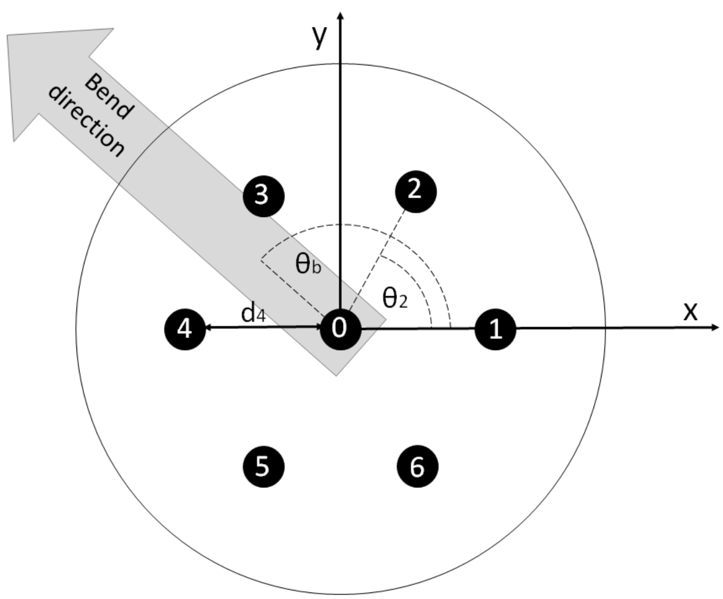

Fig. 3 The XY-plane cross-section of the bended fiber with outer cores (marked from 1 to 6) and central core (marked as 0).

The BFS is linearly proportional to any signed strain variations. The proportionality constant is called strain sensitivity α. Hence, the BFS can be expressed using the mentioned relation for strain

$$\frac{\Delta\nu_{Bi}}{\nu_B} = \varepsilon_i \alpha = -\frac{\alpha d_i}{R}\cos(\theta_b - \theta_i)$$

where $\Delta\nu_{Bi}$ is a variation of the BFS in the i-th core and ν_B is an initial BFS value in reference conditions (in the case of the MCF7 the BFS for central core can be used). Based on this relation and acquiring BFS measurements for at least 3 lateral cores, it is possible to determine the bend radius and orientation at each point along the fiber in the 3D space [1,17].

3. EXPERIMENTAL SETUP

The BFS in each core of the MCF7 was measured using the set-up presented in Fig. 4 using Brillouin Optical Time Domain Analysis (BOTDA). The optical-time domain method enables to distinguish BFS for each point along the fiber and hence strain localization along the fiber. The tested MCF7 sample was 26 m long. Both ends of the MCF7 were spliced to tapered multicore fiber connectors (TMC)[18], which enable light injection and detection into and from each core separately.

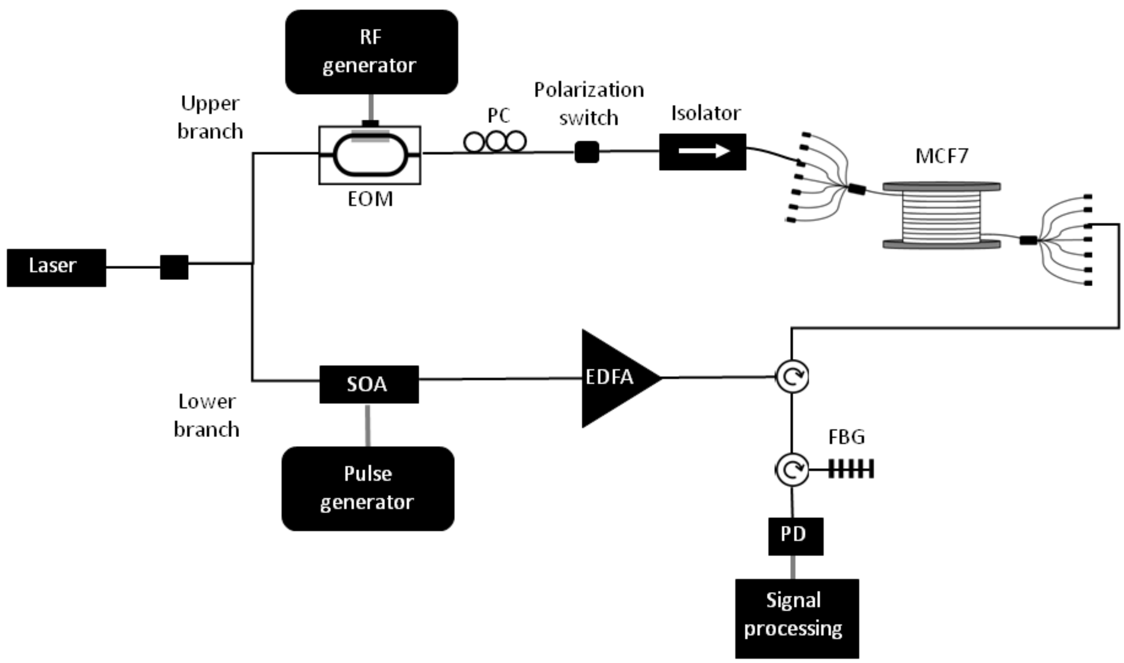

Fig. 5 Experimental setup: EOM: electro-optic intensity modulators, PC: polarization controller, SOA: semiconductor optical amplifier, EDFA: erbium-doped fiber amplifier, FBG: fiber Bragg grating, PD: photodetector.

The measurement is performed with 1 m spatial resolution using a standard distributed feedback laser operating at 1551 nm as a light source. Light from the laser is divided into two branches. In the upper branch a probe signal with two sideband frequencies is created. Sideband frequencies are generated using an electro-optic intensity modulator driven by tunable radio frequencies from a RF generator[2]. Then the signal propagates through a polarization switch where the polarization state of the probe signal can be switched between orthogonal states during the measurement. Polarization switching is necessary to avoid the effect of polarization-induced fading and it is performed by summing up the response for two orthogonal polarizations. Then, through the TMC, the probe signal is launched into a specific core of the MCF7. In the lower branch the pump signal is generated. Light from the laser propagates through a semiconductor optical amplifier where light pulses are shaped. Next, pulses are amplified using an erbium-doped fiber amplifier, and the pump signal goes via a circulator through the TMC to the tested MCF7. The probe signal and the light backcoupled in the MCF7 propagate to the receiver unit where one sideband frequency is filtered out using a fiber Bragg grating (FBG). Afterwards the signal is detected on the photodetector (PD) and analyzed to distinguish BFS at each location along the fiber.

4. EXPERIMENTAL DEMONSTRATION

BOTDA provides a measurement of the Brillouin Gain Spectrum (BGS) which is a 3-dimensional plot representing the probe signal gain for each frequency shift and each location along the tested fiber. The maximum gain of the probe signal corresponds to the situation when the difference between the probe signal and the pump signal is equal to the BFS. In Fig. 6 the Brillouin Gain Spectra for the central core and one of the lateral cores are shown.

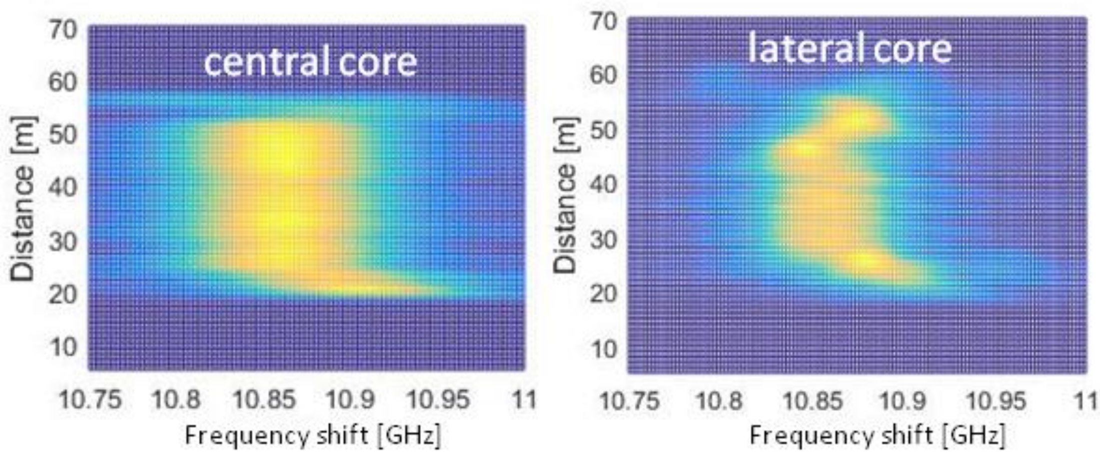

Fig. 6 Brillouin gain spectrum for central core (graph on the left) and one of the lateral cores (graph on the right). X-axis represents the frequency shift, which is equal to the frequency difference for the probe and pump signals, Y-axis represents the distance along the fiber. The MCF7 fiber is localized from the 25^{th} m till 51^{st} m of the measured optical path. The probe signal gain is represented in a color scale, where maximum is colored in orange and minimum in blue.

To introduce a specific shape of the MCF7, the fiber was coiled on a spool. That means that fiber was bended with a constant radius and randomly twisted. Experimental results were consistent with expectations, since in the central core of the MCF7 the measured BFS was constant along the whole fiber. In the same time, in the lateral core BFS varied along the fiber. The BFS variation in the lateral core was influenced by the random twist of the fiber. The observed core was once in the inside of the bend and once in the outside, that is, it was elongated and compressed alternatively. These variations of BFS along the MCF7 are clearly visible in Fig. 7.

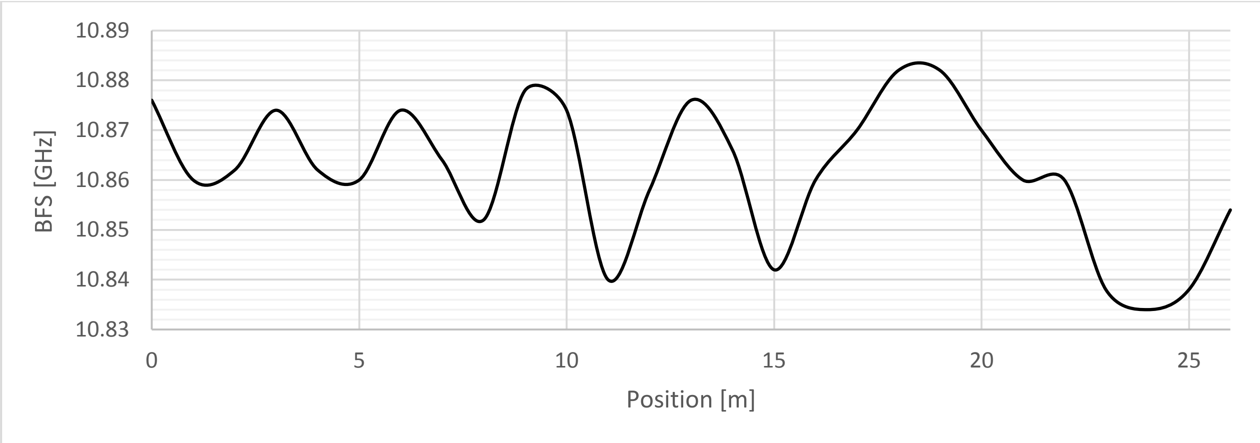

Fig. 7 Brillouin frequency shift variations for one of the lateral cores along the 26 m-long MCF7.

5. CONCLUSIONS

Authors discussed the idea of shape sensing based on Brillouin Frequency Shift measurement in a multicore fiber, firstly reported by Z. Zhao at al.[1]. According to this idea, the BFS values measured at a given point for at least 3 lateral cores carry enough information to determine the bend radius and its orientation. This theory was confronted with the experimental demonstration, where the Brillouin gain spectrum along a 26 m-long 7-core microstructured fiber was measured. The results for the central core and one of the lateral cores are presented. BFS variations for the lateral core related to twists and bend along the MCF7 confirm that shape sensing in the proposed configuration is possible.

Presented results give promising conclusions for the future. After improving the spatial resolution of the bend localization and insertion losses of the sensing element, it will be possible to measure shape with high accuracy.

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