Fiber-optic vector vibroscope

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A directional vibration sensor based on polarization-controlled cladding-to-core recoupling is demonstrated. A compact structure in which a short section of multi-mode fiber (MMF) stub containing a weakly tilted fiber Bragg grating (TFBG) is spliced to another single-mode fiber without any lateral offset. Multiple core modes of the MMF are coupled at the junction and appear as well defined resonances in reflection from the TFBG. Some of those resonances exhibit a strong polarization and bending dependence. Both the orientation and the amplitude of the vibrations can be determined unambiguously via dual-path power detection of the orthogonal-polarimetric lowest order LP_{1n} modes. Meanwhile, the unwanted power fluctuations and temperature perturbations can be referenced out by monitoring the fundamental LP_{01} mode resonance. © 2012 Optical Society of America

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The tilted fiber Bragg grating (TFBG) is a new kind of sensor that possesses all the advantages of well-established Bragg grating technology in addition to being able to excite cladding modes resonantly. This grating tilt has the effect of locally breaking the cylindrical symmetry of the fiber in a way that allows strong coupling between the core guides light and a large number of (hundreds of) cladding modes. Since the cladding modes each have a unique mode field shape and effective index, they react differently to perturbations inside and outside of the fiber (temperature and strain, bending and lateral force, vibration, acceleration, inclination, and refractive index, *et al.*). This device opens up a multitude of opportunities for single-point sensing in hard-to-reach spaces [1], with very controllable cross-sensitivities, absolute and relative measurements of various parameters, and an extreme sensitivity to metal particles and coatings (surface plasmon resonance excitations), without requiring the fiber to be etched or tapered in order to get core guided light to interact with a material external to the fiber.

For TFBGs in single mode fibers (SMF), the high-order cladding modes—whose resonances occur at short wavelengths that are far from the Bragg resonance—do appear to be very strongly polarization-dependent [2–4]. This is because higher order cladding mode resonances actually come in pairs made up of nearly degenerate orthogonally polarized modes (the EH and HE vector modes of the cladding) and the TFBG automatically selects one or the other polarization when core mode light is linearly polarized either in the plane of the tilt (*P*-polarization) or perpendicular to it (*S*-polarization), respectively. The polarization dependency of high-order modes in TFBGs has important consequences for sensing. Polarization control allows the users to select only EH modes (oriented radially at the cladding boundary) or HE modes (oriented tangentially at the cladding boundary) across large portions of the spectrum. Therefore, any sensing modality that depends strongly on the polarization state of the light near the cladding boundary can be controlled very effectively with TFBGs.

How to transfer such strong polarization dependence from high-order cladding modes to low-order modes (strongly guided and influenced by core perturbations, but little by contact with the cladding boundary)? A TFBG inscribed in multi-mode fiber (MMF) provides a potential solution due to the physically "enlarged" fiber core. Compared to our recent papers on SMF-based TFBG sensors that used an offset splicing [5] or an abrupt biconical fused taper [6,7] to couple light from the core to cladding modes for vibration and inclination measurement, and the reports from other groups of using a core-diameter mismatched fiber section as cladding mode coupler [8,9]. Here we use the multiple guided modes of a MMF generated at a spliced junction between a SMF and MMF upstream of the tilted grating (Fig. 1). The mode mismatch at the junction generates several core guided modes in the MMF that reflect off the TFBG and return towards the junction where they recouple some power into the core of the interrogating fiber (each at a different wavelength as shown in Fig. 2). We will show here that for linearly polarized input light, the coupling of the LP_{1n} modes of the MMF depends strongly on the polarization orientation relative to the grating tilt plane while the coupling of the LP_{0n} modes does not. Therefore, it is possible to excite separate LP_{1n} modes with S and P polarized input light. Furthermore, those individual S and P LP_{1n} resonances only change when the fiber is bent along a specific direction relative to the tilt plane (i.e., for bend along the S and P planes, respectively). The other resonances are relatively insensitive to bending and can be used as power references. These features allow the construction of a very simple vector vibroscope that can determine the orientation,

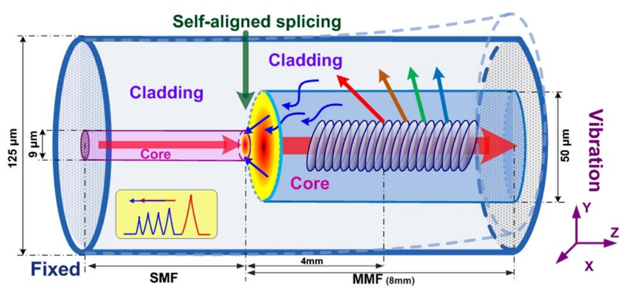

Fig. 1. (Color online) Schematic diagram of MMF-TFBG vector vibroscope.

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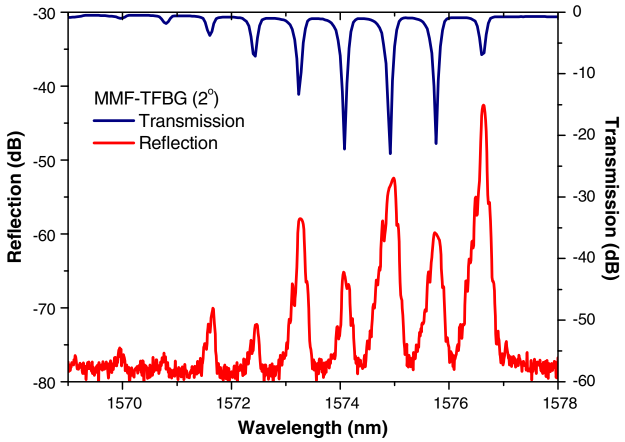

Fig. 2. (Color online) Transmission and reflection spectra of 2 deg MMF-TFBG.

frequency, and amplitude of vibrations. The proposed sensing configuration also provides temperature immunity, better reproducibility, as well as a compact size (works in reflection) for applications requiring embedding into structures.

As shown in Fig. 2, the transmission spectrum of the SMF-MMF (TFBG) configuration shows several clear resonances with approximately equal spectral spacing that are well reproduced in the reflection spectrum. Here, an excellent alignment of the splicing between the SMF and MMF is necessary to maintain the polarization and symmetry of the modes across the junction. Modelling of the MMF-TFBG with Optigrating (from Optiwave) is shown in Fig. 3, using the following parameters for the MMF (Δ2% graded index profile with core/cladding diameters of 62.5/125 μm) and the TFBG (2 deg tilted grating with pitch period of 0.5368 nm over 10 mm). Excellent agreement is obtained and allows for the identification of the LP_{0n} and LP_{1n} resonances. The mode field profiles associated with these resonances clearly show that the LP_{1n} modes do not possess cylindrical symmetry and their coupling response to changes in input polarization and bending will be greatest.

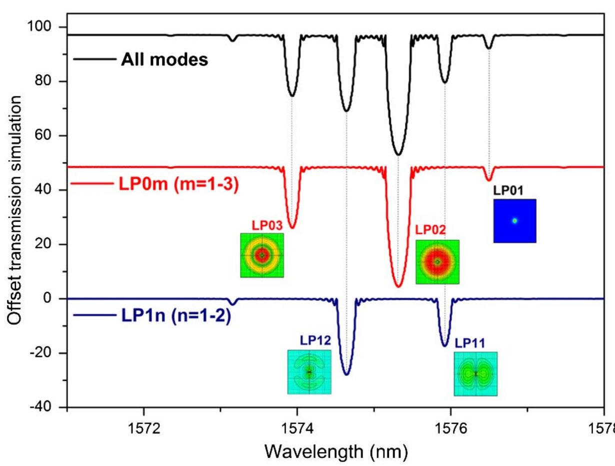

Fig. 3. (Color online) Simulation spectrum of MMF-TFBG and its component azimuthal mode families LP_{0m} and LP_{1n} (with Y-offsets). Insets show the transverse electric field amplitude distributions of each mode.

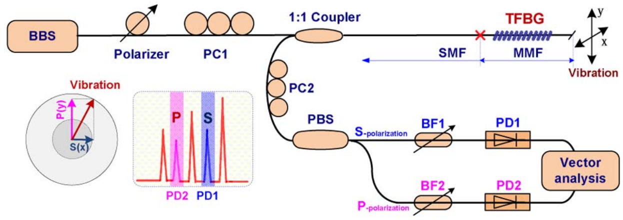

Fig. 4. (Color online) Schematic diagram of vibration sensing system. Insets show the dual-path power detection of the orthogonal-polarimetric odd cladding modes (LP_{11} mode in S-polarization and LP_{12} mode in P-polarization) for vector vibration measurement.

Figure 4 shows the schematic diagram of the vibration sensing system. TFBGs (5 mm in length) with an internal tilt angle of 2 deg are inscribed in a Corning MMF (Δ2% graded index, 62.5/125 μm) using a pulsed KrF excimer laser and the phase-mask technique. A 8 mm long segment of MMF containing the TFBG was spliced back to a 1 m long piece of SMF using a commercial Corning compact fusion splicer. The gap distance between the splice and the grating center was 4 mm. The fiber length downstream from the grating should be carefully selected as it works as the inertial mass which dominates the sensor resonance frequency and amplitude-frequency response. Meanwhile, care must be taken to eliminate reflections from the end surface of fiber tip, since such reflections will return part of broadband light to the interrogation system and reduce the dynamic range of the measurement. The initial characterization of the sensor was carried out by launching light from an erbium amplified spontaneous emission broadband source (BBS) into the sensing fiber through a 3 dB coupler, and the reflected spectrum with an polarization beam splitter (PBS) following by two bandpass filters (BFs) and two power detectors (PDs) for vector analysis. Polarization control is essential for this system. Here, one polarizer and two polarization controllers (PCs) are used to line up the launch light (via PC1) and the PBS axes (via PC2) along the orthogonal orientation defined by the tilt plane of the TFBG, then the two PDs will measure the "pure" polarized S and P modes.

Figure 5 shows the orthogonal-polarimetric MMF-TFBG reflections for S and P polarizations, respectively. Via the PBS and BF, perfect "0" and "1" spectral response have been achieved over LP_{11} and LP_{12} narrow bands, which agrees well with the theoretical considerations provided earlier. More importantly, these two individual LP_{1n} resonances only change when the fiber is bent along a specific direction relative to the S and P planes respectively, providing their potentials for directional vibration measurement. The polarization selectivity of the recoupled resonances is not due to birefringence arising from the side inscription process because otherwise all resonances would split as the polarization rotates (Fig. 5 clearly shows that this is not the case). We have also shown in [1] that our TFBG process does not lead to measurable birefringence, as confirmed by the absence of polarization loss of the fundamental mode coupling.

Figure 6 demonstrates that the orientation of the applied vibrations can be recognized simply with dual-path power detection of the orthogonal-polarimetric S and

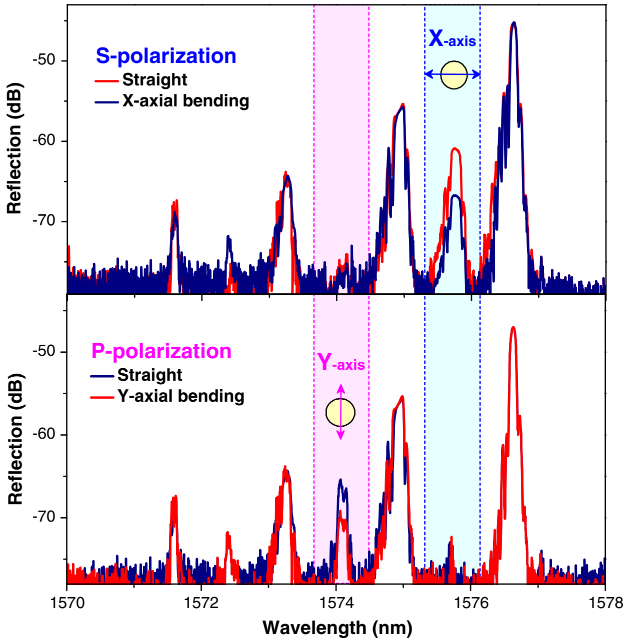

Fig. 5. (Color online) Spectral comparison of two orthogonal polarimetric reflections (*S*- and *P*-polarizations) of MMF-TFBG via the PBS, and their response to orthogonal-polarimetric bending (*X*- and *Y*-axis).

P modes (LP_{11} and LP_{12}). The correct polarization is most easily found by maximizing the power detected by PD1 when the fiber is kept straight and the input polarization rotated. The *P*-polarization can be found similarly but is always found with the polarizer at 90 deg from the *S* state. For vibration with an orientation at 45 deg, both PDs get the same power output. For vibration orientations over the full range from 0 deg to 360 deg, response repeats in every quadrant. Meanwhile, the LP_{0m} modes are really insensitive to the fiber bending and can be used as references to remove the power fluctuations, regardless of the orientation of the vibrations.

A compact fiber-optic sensor for orientation-recognized vibration measurement has been presented and experimentally demonstrated. The interrogation of the sensor only requires a PBS, two relatively coarse BFs and two PDs. Since the pass band of the filters is near 1 nm, the sensor response is immune to temperature fluctuations of several tens of degrees Celsius. The sensor comprises a weakly tilted, but otherwise very ordinary FBG, that is inscribed in a short section of MMF, fusion spliced to an additional piece of SMF. The whole sensor can be as short as 10 mm (possibly less) and does not require precise fabrication tolerances (in terms of Bragg wavelength, grating strength or splicing alignment). In addition, when the fiber stub sensor is vibrating freely an additional BF and PD combination can be used to monitor the core mode reflection

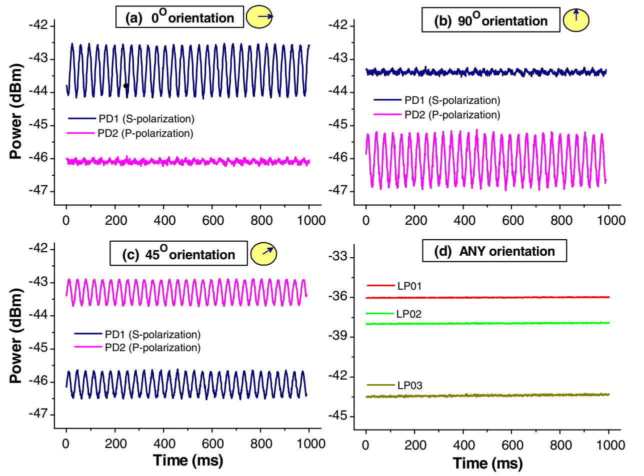

Fig. 6. (Color online) Real-time power output of PD1 (LP_{11} mode) and PD2 (LP_{12} mode) under a given vibration (29 Hz) with different orientations of 0 deg (a), 90 deg (b) and 45 deg (c), and (d) the stable power references of fundamental core mode (LP_{01}) and higher order even modes (LP_{02}–LP_{03}) under vibrations with arbitrary orientations.

(insensitive to bending), and hence, to provide a normalization signal that is proportional to the light source power and its fluctuations.

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