Temperature-independent tilted fiber grating vibration sensor based on cladding-core recoupling

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A novel structure in which a short optical fiber stub containing a weakly tilted Bragg grating is spliced to another slightly offset fiber. The total power reflected from this structure is independent of temperature and occurs in two well-defined wavelength bands, only one of which reflects a different amount of power as the fiber stub bends or vibrates. The smart sensing structure presents an extremely high sensitivity for microbending, and its frequency response has been tested to higher than 2 kHz so far in temperature-immune vibration measurements via cost-effective power detection. © 2008 Optical Society of America

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Tilted fiber Bragg gratings (TFBGs) belong to the short-period gratings family, but the grating planes are slanted or blazed with respect to the fiber axis. In this respect, they benefit from the same well-established technological base (fabrication, characterization, reliability), and favorable low temperature sensitivity (relative to long-period gratings in particular) [1,2]. The tilt of the grating planes enhances the coupling of the light from the forward-propagating core mode to backward-propagating cladding modes at shorter wavelengths. Since the core mode and the cladding modes respond differently to external perturbations (strain, temperature, bending, refractive index, etc.), TFBGs can be applied in many important sensing applications, ranging from traditional mechanical monitoring to modern biological analysis [3–8].

In most applications of TFBG sensors, the sensing modalities rely on the analysis of the insertion loss spectrum through the amplitude and positions of the resonances, either individually [3–6] or globally [7,8]. In this Letter, we propose a novel configuration for TFBG sensors and demonstrate how a simple power measurement can be used to detect bending or vibration of the fiber, which shows several interesting improvements over conventional approaches. The scheme is based on the recoupling into the core of a subset of the cladding modes excited by the TFBG. The recoupling occurs at a fiber discontinuity (an offset fusion splice upstream from the grating), and the amount of recoupling strongly varies with curvature, thus providing the sensing mechanism. Simultaneously, the core-mode reflection from the same weakly tilted FBG remains unaffected by curvature (lying on the neutral strain axis of pure bending), and the power reflected in this band of the reflection spectrum can be used as a reference to cancel out light source power level fluctuations from the sensor. Finally, the total reflected spectrum (core-mode reflection and recoupled cladding modes) shifts globally with temperature at a rate of 10 pm/°C (same as conventional FBGs). As a result, a relatively coarse bandpass filtering of the reflected light is sufficient to render the sensor temperature immune (for temperature variations of a few tens of degrees at least). The frequency response of the sensor is currently limited by the acoustic resonances of the fiber stub used: Vibrations with frequency higher than 2 kHz have been measured so far.

As shown schematically in Fig. 1, the basic idea behind this configuration is to recapture backward-propagating low-order cladding modes into the fiber core via a misaligned fused cross section located a short distance upstream of the TFBG. In general, the backward transmitted cladding modes emitted from the tilted grating planes cannot propagate for a long distance along the fiber cladding owing to the absorption of the high-index jacket material. However, when the fiber is kept straight and the cladding is not covered by absorbing material, such modes can propagate for several centimeters without much loss,

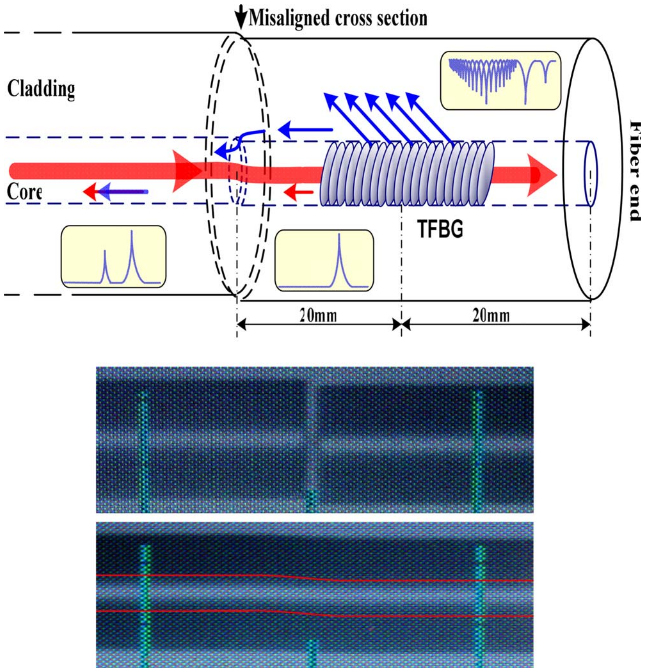

Fig. 1. (Color online) Schematic diagram of a TFBG with a misaligned fusion for vibration measurement and before and after photographs of the fusion splice.

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especially for low-order cladding modes. We want to recouple the light from these low-order cladding modes into the core of the fiber so that this light can propagate back to the interrogation system with low loss. The recoupling is achieved with a fusion splice that is very slightly misaligned (few micrometers) to provide some overlap between the core mode and low-order cladding modes at the junction. As seen in Fig. 2, the final reflection spectrum of the TFBG then consists of a slightly weakened Bragg resonance at the longest wavelengths and a strong group of resonances at shorter wavelengths, the so-called "ghost" resonance. The ghost resonance corresponds to a group of low-order strongly guided cladding modes that interact much with the fiber core but little with the cladding boundary [6–8]. The Bragg resonance is weaker by 3 dB, as the core light goes through the "bad" splice twice. Once this configuration is achieved, bending or deflecting the fiber introduces refractive index variations across the fiber that influence the reflection spectrum in several ways: the core-to-cladding mode coupling by the TFBG changes, the propagation loss of the cladding modes towards the junction changes (bend loss), and finally the cladding-to-core recoupling efficiency at the junction may change as well (mostly owing to the stress-induced refractive index variation changes along the fiber cross section, which would compensate or increase the mode offsets at the junction [9,10]). The sensor works in reflection, and the sensor "head" can be as small as the sum of the grating length (typ. 2–10 mm) plus the distance between the grating and the junction.

One-centimeter-long TFBGs with an internal tilt angle of 4° are inscribed in hydrogen-loaded Corning SMF-28 fibers using a pulsed KrF excimer laser and the phase-mask technique. As indicated in Fig. 1, a 40 mm long segment of the sensor head containing the TFBG was cleaved with the grating center at a point 20 mm away from the outer end, and the other end of the fiber segment was then spliced back to a 1 m long piece of fiber using a Corning Compact fusion splicer. The distance between the misaligned cross section and the grating center was 20 mm. Note that the fiber length downstream from the grating serves no purpose and can be eliminated. However, care must be taken to eliminate reflections from this segment, since such reflections will return broadband light to the interrogation system and reduce the dynamic range of the measurement. The sensor head was clamped on a translation stage configured to allow transverse deflections of the end of the fiber stub that contains the grating, and a Peltier heater was positioned 1 mm below the stub in order to allow simultaneous bending and temperature tests.

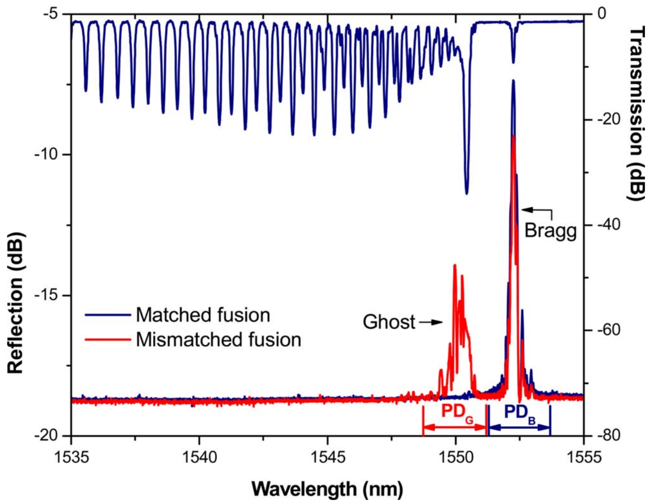

Fig. 2. (Color online) TFBG spectra before and after misaligned junction.

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 measuring the reflected spectrum with an ANDO AQ6317B spectrum analyzer using a wavelength resolution of 0.05 nm. Figure 3 shows how the reflection spectra change under bending and temperature perturbations. Apart from a 10 pm/°C shift (not detectable on this scale), the spectra are invariant with temperature (as expected [3]). However, changing the bend radius from infinity to 50 mm results in more than 6 dB of reduction of the recoupled ghost mode but no visible change in the core mode reflection. In all cases, the spectrum returns to its initial state when the perturbation is removed.

We use this bending-induced power loss as a measure of curvature in the following implementation.

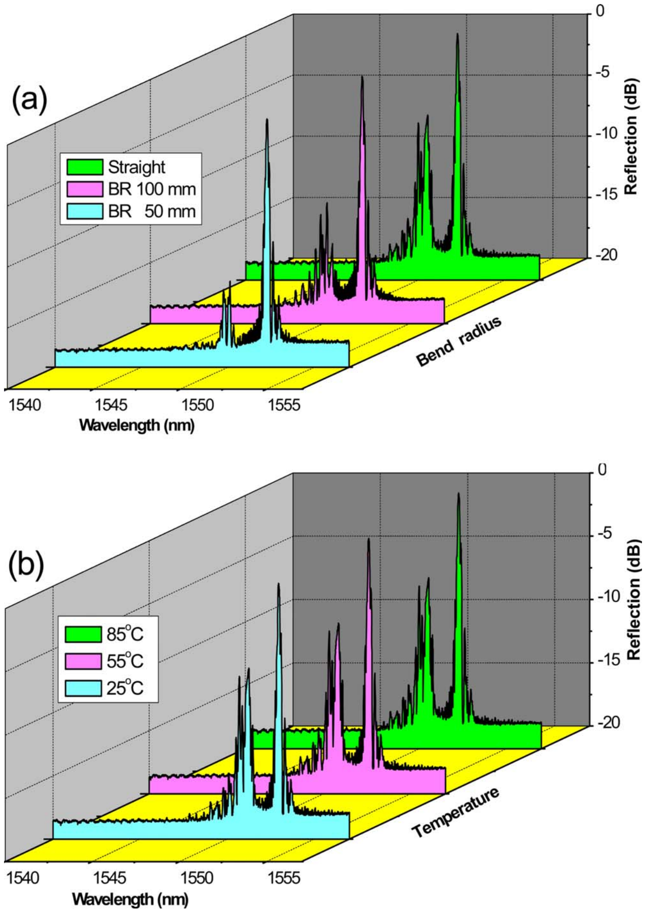

Fig. 3. (Color online) Spectral response of ghost and Bragg resonances versus (a) bending and (b) temperature.

Instead of using the optical spectrum analyzer (OSA) as a spectrum analyzer we use it as a bandpass filter, measuring the total power in a 2 nm wavelength interval (centered on the recoupled ghost mode), as a function of bending, or as a function of time for vibration measurements. To further replicate a "real" sensing environment, the stub (including both the splice and the grating) is bonded to a thin metal beam (100 mm free length, by 11.5 mm width and 0.45 mm thickness). Since only low-order cladding modes are recoupled at the junction, their coupling properties and propagation loss between the grating and the junction is not perturbed by the bonding medium. We show in Fig. 4 [gray curve (red online)] the ghost-mode reflected power measured following a step impulse given to the metal beam. The response time is limited by the acoustic resonances of the support beam used, as well as the frequency response of the OSA used in power measurement mode. Here, the time scale of the oscillations (1.6 ms rise time) indicates a frequency response exceeding 2 kHz. According to [5], the frequency response of a similar perturbation in a fiber can exceed the megahertz range when using an acousto-optic based rf amplifier. Simultaneously, the black curve in Fig. 4 shows how the bandpass filtered reflection of the Bragg resonance responds to vibration: The reflected power in this band remains quasi-constant (+/−0.1 dB instead of +/−1.5 dB). Finally, since the ghost-mode power occupies only ~1 nm of the filter's passband (2 nm), temperature fluctuations of +/−50 °C (corresponding to wavelength shifts of 0.5 nm) will not influence significantly the measured power from the sensor.

Of the three effects already mentioned above to explain the change in reflected ghost mode, the change in the cladding-to-core mode recoupling at the junction is thought to be dominant, especially in view of the fact that the recoupled power decreases and increases around its unbent stage (as shown in Fig. 4), and is not maximum when the fiber is straight. Separate experiments where the fiber is bent while either the TFBG or the junction are kept straight confirm this. The fact that the core-mode reflection changes little upon bending can be used to normalize the sensor's response with regard to power source fluctuations; however, such normalization will be strictly accurate only for pure bending since in that case the Bragg resonance is not expected to change as the core of the fiber lies on a neutral strain axis. However, when the stub is bonded to something, this condition is broken, and the core will experience some strain that will cause a Bragg wavelength shift and hence in a power variation past the bandpass filter, as seen in Fig. 4.

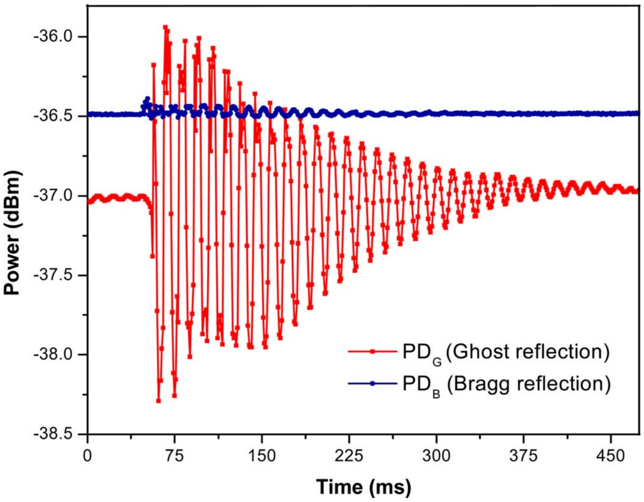

Fig. 4. (Color online) Harmonic oscillating response of the sensor system following an impulse excitation.

A novel, simple fiber grating–based bend and vibration sensing mechanism has been presented and demonstrated experimentally. The interrogation of the sensor requires only a 3 dB coupler, a relatively coarse bandpass filter and a power detector, and 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 fusion spliced to an additional piece of the same fiber. The whole sensor can be as small as 10 mm (possibly less) and does not require precise fabrication tolerances (in terms of Bragg wavelength or grating strength). In addition, when the fiber stub sensor is vibrating freely an additional passband filter and power detector combination can be used to monitor the core-mode reflection (insentive to bending) and hence to provide a normalization signal that is proportional to the light source power (and its fluctuations). In real applications, the proposed sensing device is expected to achieve a megahertz frequency response with proper packaging and high-frequency photodiode detector.

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