Role Of Optical Fiber Technology In Grating Mechanical And Biochemical Sensors

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Abstract:
The current research investigates the role of grating mechanical and biochemical seniors. fiber Bragg grating (TFBG) has a grating period similar to that of a regular fiber Bragg grating (FBG), i.e. roughly one third of the wavelength (in glass fibers) but grating planes that are weakly tilted relative to the fiber axis. Similar to LPGs, this tilt enables strong coupling between the core mode and select cladding modes but the phase matching condition is different, as the resonance wavelength depends on the SUM of the effective indices (the corresponding theory was developed by Erdogan et al. at Roche-ster University in the US [39–41] and in many other follow up papers [42–53]). This makes resonance positions much less sen-sitive to perturbations but much more controllable in real appli-cations.

Introduction: The field of optical fiber technology has experienced an inter-esting return towards its sources over the past few years. Because of the need for ever increasing communication capacity, trans-mission systems based on mult,˘¿.imode optical fibers are being de-veloped for mode multiplexing applications [1–4]. The same is true for optical fiber sensors where there is a growing interest in using the simultaneous but differential response of optical fiber modes to perturbations as a means of increasing the sensitivity, capacity, or limits of detection (LOD) in sensing systems [5,6]. In order to access these improved functionalities however, some form of mode control is require
“ile complex mode launching instrumentation based on free space optics can be used in tele-communications, such complexity is prohibitively expensive in sensing. In optical fiber sensors, mode control is most easily achieved from a fiber with single mode core by using a grating to couple from this well-defined starting point to higher order modes at specific wavelengths determined by the phase matching con-dition of the grating [7–15]. Polarization control is also useful and often necessary, especially in sensing applications involving sur-face plasmon resonance (SPR) or other “plasmonic” effects [16–19]. The first widespread grating-assisted multimodal optical fiber sensors relied on long period gratings (LPGs) that couple core guided light to forward propagating cladding modes of the same fiber. It is with LPGs that the wide range of sensing modalities that are possible with cladding modes was discovered [12]. Unlike the core mode, cladding modes properties are sensitive to bending and to the surrounding refractive index for instance. Furthermore these sensitivities vary widely from mode to mode, as mode field shape, effective index and polarization depend strongly on mode order and launching conditions. The final great advantage is that conventional single mode fibers (of any kind, including low cost telecommunication fibers and plastic optical fibers) inherently guide hundreds of cladding modes without further modification because of the large size of the cladding diameter relative to wavelength.

sensitive to select perturbations, and this is considered very good for sensing applications. However, by the same principle such cladding mode resonances are sensitive to everything and it is nearly im-possible to eliminate cross-talk between the desired measurand and other effects, most notably temperature or small bends.

The present paper describes a structure that is apparently si-milar to a LPG but differs in many important aspects. A tilted fiber Bragg grating (TFBG) has a grating period similar to that of a regular fiber Bragg grating (FBG), i.e. roughly one third of the wavelength (in glass fibers) but grating planes that are weakly tilted relative to the fiber axis. Similar to LPGs, this tilt enables strong coupling between the core mode and select cladding modes but the phase matching condition is different, as the resonance wavelength depends on the SUM of the effective indices (the corresponding theory was developed by Erdogan et al. at Roche-ster University in the US [39–41] and in many other follow up papers [42–53]). This makes resonance positions much less sen-sitive to perturbations but much more controllable in real appli-cations [54–60]. Furthermore, the phase matching condition also implies that the linewidth of resonances is orders of magnitude smaller than LPGs and that the spacing between individual re-sonances is much smaller, meaning that hundreds of resonances can be measured simultaneously and compared using a spectral range of less than 100 nm. In the remainder of this paper, the fabrication and properties of TFBGs and their transmission/re-flection spectra will be described, followed by a review of their sensing applications, with special emphasis on mechanical sensing for structural health monitoring and biochemical sensing for in-situ medical detections.

TFBGs are fabricated using the same tools and techniques as standard FBGs, i. e. from a permanent refractive index change in-duced in doped glasses by an interference pattern between two intense ultraviolet laser beams [61], or a point by point approach [62]. In general however, the phase mask technique [63–66] is preferred for mass produced FBGs. In this case, the interference pattern is generated by a diffractive phase mask located in close proximity to the fiber. The period of the grating is fixed by the phase mask and because of the proximity of the fiber, low co-herence ultraviolet sources can be used, such as high energy pulsed excimer lasers. With a phase mask, tilting can be done in two ways: rotating the phase mask and fiber consistently around an axis perpendicular to the laser beam (phase mask and fiber are kept parallel), or keeping the fiber and phase mask perpendicular to the incident writing beam but rotating the phase mask around the axis of the writing beam. We have found by experience that rotating the fiber phase mask assembly by the former technique (inset of Fig. 1) provides the best spectral responses for strong TFBGs with tilt angles between

2.3.2. Ghost modes

The ghost modes of TFBG are a group of strongly guided clad-ding modes which interact much with core–cladding interface but little with the outside fiber boundary [68]. It is because their re-sonances are adjacent to the core mode (approximately 2 nm away on the shorter wavelength side) and most often form a single re-sonance that is spectrally similar (in amplitude and width) with that of core mode, that they are named “ghost” modes.

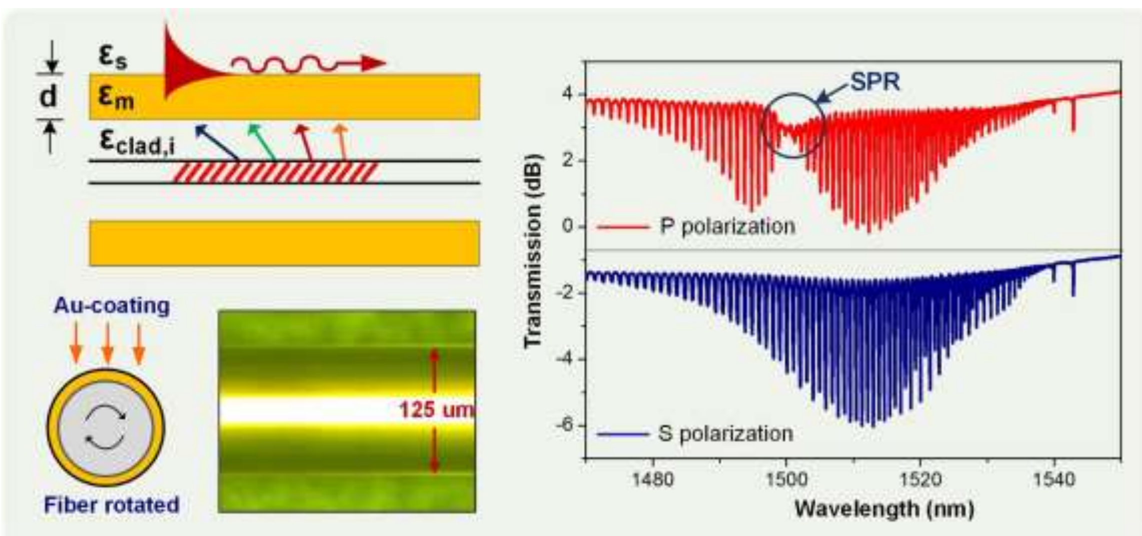
To gain a better understanding of the characteristics of the ghost modes we used numerical mode simulation (OptiGrating) to analyze the composition of the ghost resonance and the transverse electric field amplitude distributions of its constituent modes [69]. We model the modes of a TFBG with a 4° tilt angle and Bragg resonance centered at 1550 nm. Among low order LP_{nm} modes (n¼0–3) we found that the first order odd LP_{1m} modes with m¼1–4 contribute most to the ghost resonance. Fig. 5 shows the amplitude distributions and transmission spectra of the basic low order cladding LP_{nm} modes and the first-order odd LP_{1m} modes which contribute most to the ghost resonance (the red curves of the inset in Fig. 5). Because these first-order odd modes are ad-jacent to the core–cladding interface with an asymmetrical dis-tribution, any slight fiber bending may induce a change in their transverse electric field amplitude distributions. With help from a discontinuity in the core (like off-set splicing, taper or core-dia-meter mismatching [13]), such ghost modes can be recaptured back to the fiber core with high efficiency. And the recoupling

point” (evidenced by reduced amplitude of the cladding mode resonance, as indicated by the red stars in Fig. 6a) and the last guided mode before this point has the maximum extent of eva-nescent field penetration in the external medium (and hence the largest sensitivity). The operating point (i.e. the range of wave-lengths where modes have maximum sensitivity, near the “cut-off point” for instance) determines the choice of tilt angle: increasing the tilt angle shifts the maximum of the resonance amplitudes towards lower wavelengths.

Moreover, a further mode selection mechanism (i.e. polariza-tion) can be used to refine the sensing capabilities of the TFBG [72–74]. By launching linearly polarized light in the core (polar-ization rotated from 0° to 90° relative to the tilt plane), cladding-guided resonances with strong polarization dependence have been obtained.

Fig. 6b presents two very different families of cladding modes that can be selected: modes with radially polarized eva-nescent fields (hereafter named P-modes, as they are excited by
are hybrid waves that have intense field localization at the outer surface of a metal film deposited on a solid dielectric support (Fig. 7). When the SRI of the outer medium is smaller than that of the solid support, a propagating wave incident from the support side can be totally internally reflected at the support metal boundary but phase-matched to a quasi-plasmon excitation at the outer boundary of the metal. In order for this coupling to occur, the incident wave must be polarized in the plane of incidence (i. e. TM- or P-polarized) and the metal layer must be thin enough to let some light tunnel across. It is the tunneling wave that excites the quasi-plasmon and when this coupling occurs the reflected wave loses power and the corresponding cladding mode resonance loses amplitude (Fig. 7).

In order to effectively excite and accurately measure plasmon resonances and hence to achieve this optimum sensitivity, SPR based TFBG sensors have been developed and well-studied [77– 83]. There are two unique features of TFBGs: the strong polariza-tion selectivity (comes from the breaking of the cylindrical sym-metry of non-polarization-maintaining fibers) and the high-den-sity comb of narrowband spectral resonances. This makes it pos-sible to excite SPR and to measure their spectral location with quality factors between 10^3 and 10^4. Therefore, SPR based TFBG sensors open up a multitude of opportunities for single-point biochemical sensing in hard-to-reach spaces, and offer an ex-tremely improved LOD level to molecular interactions together with very controllable cross-sensitivities.



3.1.1. Accelerometer

Fig. 8 presents a fiber-optic accelerometer comprising a TFBG and an abrupt biconical taper, all encapsulated in a plastic tube using a rigid ultraviolet-cured acrylate epoxy [69]. The electric-arc-heating induced taper is located a short distance upstream from the TFBG and functions as a bridge to recouple the TFBG-excited lower-order cladding modes back into the fiber core. This recoupling is extremely sensitive to microbending (Fig. 8a, PD_G). We avoid complex wavelength interrogation by simply monitoring the power change in reflection, which we show to be proportional to acceleration (Fig. 8c). In addition, the Bragg resonance is vir-tually unaffected by fiber bending (Fig. 8a, PD_B) and can be used as a power reference to cancel out any light source fluctuations. The proposed accelerometer provides a constant linear response (nonlinearityo1%) over an acceleration range from 0.5 to 12.5 g, a flat amplitude sensitivity over a vibration frequency range from DC to 250 Hz and a adjustable resonance frequency by simply varying the sensor length. The composite structure is very stiff to ensure a good transfer of the vibrations from the tube to the TFBG and provides long term protection, even in harsh environments.

3.2. Two-dimensional TFBG vector mechanical sensors

Orientation information is essential in many branches of me-chanical measurement. For example, a precise identification of the orientation of a vibration is a key point to find the position an unknown or dynamically changing vibration source, in seismic detection for instance. Traditional methods normally use several separate sensors oriented orthogonally to measure two dimen-sional or three dimensional strain fields and waves. This results in sensors suffering from a complex configuration and unavoidable cross-talk between vibration or bending directions. The question is how to use a single detector to achieve an orientation-recognized mechanical measurement, i.e. a vector measurement. The polar-ization dependency of high-order modes in TFBGs provides a po-tential way for orientation-recognized sensing. Wavelength and polarization control allows the users to select only EH modes (oriented radially at the cladding boundary) or HE modes (or-iented tangentially at the cladding boundary), as well as modes with well-defined azimuthal power distributions across large portions of the spectrum. Therefore, any vector sensing modality that depends strongly on the polarization state and mode power distribution of the light near the cladding boundary can be observed.

5. Conclusions

A review of several of our group's recent and on-going devel-opments in TFBG-based optical fiber sensors has been presented as well as basic theoretical underpinnings of their properties, with reference to other technologies involving fiber cladding modes, i.e. LPGs and “excessively tilted” FBGs. Many of these advances require multidisciplinary teams of engineers, physicists, chemists and biologist because optics cannot “talk” to chemistry and biology without some translation. It is these efforts that are allowing the full potential of such fiber sensors to be reached, and in particular to be able to exploit the extraordinary figures of merit and signal to noise ratio reachable with fiber gratings in simple configura-tions. It has also been demonstrated that in many of the cases presented, the required instrumentation and protocols are

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