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Review

Tilted fiber grating mechanical and biochemical sensors

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ABSTRACT

The tilted fiber Bragg grating (TFBG) is a new kind of fiber-optic sensor that possesses all the advantages of well-established Bragg grating technology in addition to being able to excite cladding modes resonantly. This device opens up a multitude of opportunities for single-point sensing in hard-to-reach spaces with very controllable cross-sensitivities, absolute and relative measurements of various parameters, and an extreme sensitivity to materials external to the fiber without requiring the fiber to be etched or tapered. Over the past five years, our research group has been developing multimodal fiber-optic sensors based on TFBG in various shapes and forms, always keeping the device itself simple to fabricate and compatible with low-cost manufacturing. This paper presents a brief review of the principle, fabrication, characterization, and implementation of TFBGs, followed by our progress in TFBG sensors for mechanical and biochemical applications, including one-dimensional TFBG vibroscopes, accelerometers and micro-displacement sensors; two-dimensional TFBG vector vibroscopes and vector rotation sensors; reflective TFBG refractometers with in-fiber and fiber-to-fiber configurations; polarimetric and plasmonic TFBG biochemical sensors for *in-situ* detection of cell, protein and glucose.

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1. Introduction

The field of optical fiber technology has experienced an interesting return towards its sources over the past few years. Because of the need for ever increasing communication capacity, transmission systems based on multimode optical fibers are being developed 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 required. While complex mode launching instrumentation based on free space optics can be used in telecommunications, 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 condition of the grating [7–15]. Polarization control is also useful and often necessary, especially in sensing applications involving surface 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.

LPGs for sensing have limitations however. In "normal" LPGs with grating induced index change that is azimuthally symmetric in the fiber cross section, only modes with the same azimuthal symmetry as the incoming core mode can be excited and polarization control is difficult if not impossible. In polarization selective applications, it means that half the light is "wasted", i.e. not participating in the sensing mechanism and thus contributing to a high background signal (and reduced signal to noise ratio). This can be improved upon however by using the "excessively tilted" grating structures developed by Zhou and Zhang et al. at Aston University in the UK [20–22], where LPGs with tilted grating planes are used, thereby breaking the azimuthal symmetry and allowing the excitation of polarization distinct cladding modes in many important applications, including in-fiber polarizers [23–25], lasers [26–28], sensors [29–31] and spectral interrogators [32–38]. The main drawback of LPGs however comes from their perceived advantage: the grating phase match condition between an incident core mode and the cladding modes depends on the DIFFERENCE between the effective indices of the two modes being coupled. Because of the relative dispersion of the two modes, the resonance wavelength of these couplings can be made extremely 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 impossible 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 similar 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 Rochester University in the US [39–41] and in many other follow up papers [42–53]). This makes resonance positions much less sensitive to perturbations but much more controllable in real applications [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 resonances 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/reflection 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.

2. TFBG fabrication and sensing principle

2.1. Fabrication

TFBGs are fabricated using the same tools and techniques as standard FBGs, i. e. from a permanent refractive index change induced 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 coherence 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 4° and 30°. We use an excimer laser operating at 193 nm wavelength to make TFBGs in standard single mode fibers that have been hydrogen-loaded to enhance their photosensitive response.