Mode Transition During Deposition of Nanoscale ITO Coatings on Tilted Fiber Bragg Gratings

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Abstract: The mode transition phenomenon is experimentally demonstrated in tilted fiber Bragg gratings (TFBG) through the deposition of an indium tin oxide (ITO) thin film employing a DC sputtering machine. © 2022 The Author(s)

The term mode transition was first employed in 2006 [1] to describe the gradual transfer of energy from a cladding mode to a leaky mode of a high refractive index thin film deposited on a long period fiber grating (LPFG) as the nanocoating becomes thicker. It had been previously demonstrated that this phenomenon produced a wavelength shift of the attenuation bands in the LPFG transmission spectra [2]. Simultaneously to this shift, there is an apparent fiber mode loss (a decrease of the amplitude of the grating resonance) since the power transfer from the fiber core to the coating reduces the power density in the fiber core and consequently the coupling coefficient of the grating. The term "Lossy Mode Resonance" (LMR) can be used to describe such effects [3]. Furthermore, the sensitivity of the LPFG resonances to the thin-film thickness, thin-film refractive index and surrounding medium refractive index increases in the vicinity of LMR conditions [4]. Initially, these properties could not be fully studied because the attenuation bands faded in the region of highest sensitivity due to deposition techniques used (Langmuir Blodgett and Layer by Layer self-assembly), which resulted in lossy coatings [2,5]. This problem was solved by employing the dip coating technique instead [6]. The mode transition phenomenon has also been observed in single-mode multimode single-mode (SMS) [7]. While mode transitions on TFBGs with a high refractive index coating (indium tin oxide, ITO) have been predicted and analyzed theoretically, no experimental evidence was provided [8]. The purpose of current work is to fill in this gap by studying this phenomenon experimentally during the deposition of ~400 nm-thick ITO film over a TFBG with a DC sputtering machine.

The employed TFBG was inscribed over a length of 1 cm on a standard single mode fiber (Corning® SMF-28) with a cladding/core diameter of 125/8 µm. A pulsed KrF excimer laser (PM-800, Light Machinery) was used to fabricate the grating by the phase mask technique and hydrogen loading of the fiber to enhance its photosensitivity. The FBG peak was located at 1610 nm, the grating period along the fiber axial direction was 554 nm and the tilt angle was 9.5º. The thin film was deposited over the TFBG employing a DC sputtering machine (Emitech K675X, Quorum Technologies Ltd.) with an ITO target (90% In_2O_3, 10% SnO_2) from Loyal target Technology Co. During the deposition, one end of the fiber was connected to a multi-SLD source (FJORD-X3, Pyroistech S.L.) through an in-line polarizer and a polarization controller (Phoenix Photonics Ltd), which enabled selecting a P or S linearly polarized state (relative to the tilt plane) for the core-guided light incident on the TFBG. The other end of the fiber was connected to an optical spectrum analyzer (MS9740A, Anritsu) to monitor the spectrum (see Fig. 1).

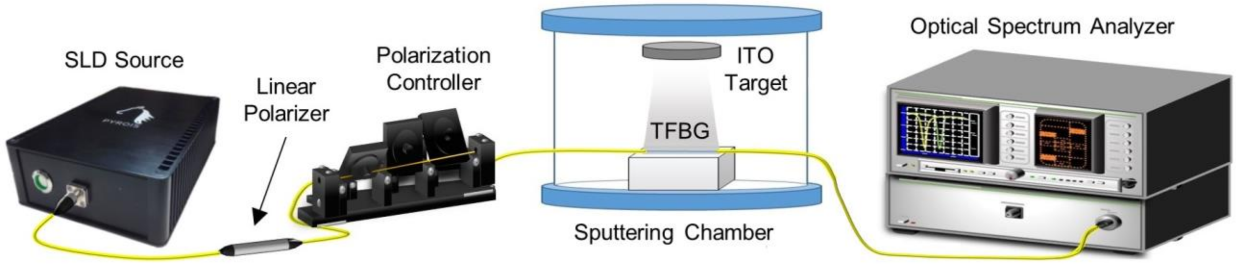

Fig. 1. Schematic of the employed setup for the mode transition monitoring in the TFBG while depositing an ITO thin film.

An ITO deposition was carried out with a duration of 8 minutes in the sputtering machine. The TFBG was measured employing S-polarized light (coupling to HE modes only) [9]. Fig. 2a shows the evolution of the central part of the transmission spectrum (1560 – 1570 nm). The experimental results were recorded for this wavelength window because the resonances are the narrowest and the deepest, making them easier to track. The deposition starts approximately at minute 2 and finishes around minute 10, corresponding to a thin film thickness of about 400 nm (see left y axis of Fig. 2a), measured with an ellipsometer

UVISEL 2 from Horiba Ltd. The effect of the mode transition caused by the LMR phenomenon can be observed in Fig. 2a as an acceleration of the wavelength shifts with time (and hence thickness). A fading phenomenon can also be observed in Fig. 2a. While the deposition takes place, the resonances become shallower until around minute 6, where the resonances start becoming deeper again, partially regaining the depth that they initially had. This phenomenon has been observed in LPFGs [2,6]. However, the particularity is that here, with a material with a non-negligible imaginary part, the resonances do not completely fade. This can be attributed to the fact that the studied resonances are due to higher order modes, located far from the mode that is guided in the thin-film. Hence, according to [10] the fading effect is diminished. In order to observe this fading phenomenon in detail, Fig. 2b and Fig. 2c show the resonances of the TFBG spectrum in the1564 – 1566 range. For example, for the resonance that starts at a wavelength of 1564 nm, the initial depth is around -21 dB, which starts progressively decreasing once the deposition begins, with -18 dB for t = 3 min and -15.7 dB for t = 4.5 min, until attaining a value of -15 dB for t = 6 min. The resonances maintain a similar depth until t = 9 min, becoming deeper afterwards, with a value around -16 dB for t = 10.5 min and -18 dB for t = 12 min.

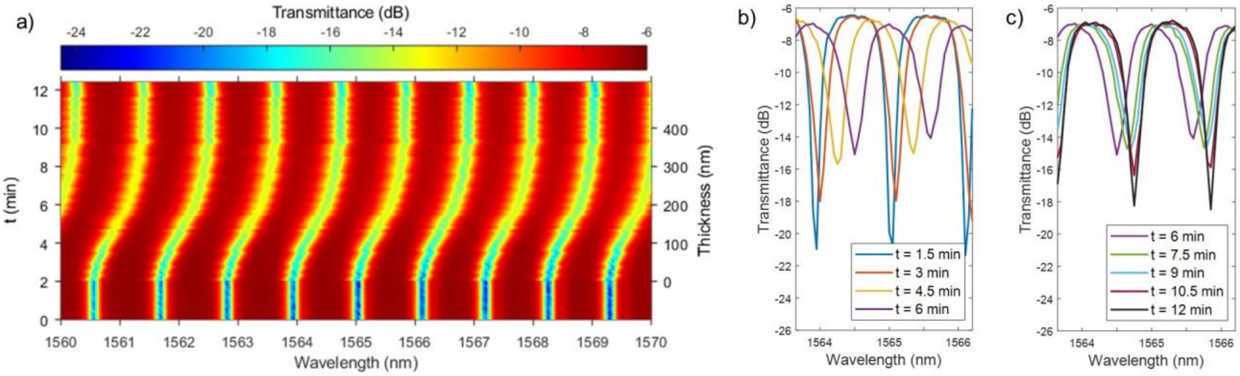

Fig. 2. a) Experimental ITO deposition with S-polarized input light in the 1560 – 1570 nm range. b) TFBG resonances between 1564 and 1566 nm during the mode transition, t = 1.5 - 6 min c) Same as b) but with t = 6 - 12 min.

In conclusion, the results presented here demonstrate experimentally that mode transitions produced by the LMR phenomenon can be observed in TFBGs during the deposition of a thin film with materials having a refractive index higher than that of the silica cladding, similarly with LPGs [11]. Moreover, in the domain of LPFGs, the mode transition is combined with other phenomena, like the dispersion turning point and the reduction of the cladding diameter [11,12]. The same approach could be applied in the case of TFBGs to reinforce the potential of this structure, combining the mode transition with other inherent properties of TFBGs, such as resonances that have much higher Q-factors than in LPGs or several "insensitive" resonances in the TFBG spectrum that can be used to improve accuracy by removing cross sensitivities.

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