Holistic Excitation of a Grating-coupled Waveguide at the Inner Wall of a Glass Tube

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Abstract: This study presents a miniaturized silica tube, coated with a dielectric TiO_2 sol-gel layer and a complementary positive photo resist periodically patterned in its inner walls. A cylindrical subwavelength diffraction grating is printed, after being light exposed by a specially designed radial phase mask that projects solely the ±1 diffractive orders transversally to the central tube axis. A first demonstration of the excitation of the mode in the microstructure is achieved by the holistic phenomenon and through a centred reflective conical mirror able to transpose plane to cylindrical waves and conversely. A fine spectral resonance in reflection in the near-infrared range is measured and subsequently analyzed by optical spectroscopic means. The design, fabrication, characterization of this structure are described as well as the first results of experimental resonant TE/TM reflection pick spectrum.

1 INTRODUCTION

Under the need of miniaturization and reduction of the optical system complexity (Zhou et al., 2016) new technologies for submicron diffraction grating pattering in small surfaces are developed. Optical components destined for filtering tend to shrink increasingly in order to render less bulky and easily integrated in optical circuits. Planar Diffractive Optical Elements (DOEs), mostly related to Micro-optics, are usually fabricated with conventional etching techniques. For exploiting though a light beam that is often circular, more appropriate stand the diffractive structures with a circular symmetricity. Within this study, we demonstrate a cylindrical based waveguide resonant grating photoengraved in inside the walls of an 8 mm of diameter of a silica tube that can fulfill the previous demand. The fabrication of this grating employs a radial phase mask, which involves the optical transform of a 2D planar ring grating to a 3D periodical structure by means of ± 1 orders projection in air. This optical set-up creates an interferogram in the cavity of the tube by a single step exposure, providing a double integer number of N grooves compared to these of mask and possessing a constant Λ period in length units equal to Λ_φ angular period of the mask in radians multiplied with the R radius of tube ($\Lambda = 2\pi R/N = R\ \Lambda_\varphi$). Previous attempts and propositions for fabricating such cylindrical optical microstructures have already held out (Tonchev et al., 2012) , (Hirshy et al., 2014), (Berthod et al., 2017) without though yielding any resonance estimation. This study manufactures a well-formed cylindrical diffraction grating in the walls of a tube able to give rise to a wavelength resonance in reflection in the range of the near infrared using a holistic and homogenous illumination of the grating. The functionality lies to the coupling and decoupling of a mode by TiO_2 solgel based waveguide with an upper photo sensitive engraved layer suitable for light trapping. The holistic mode excitation is thus allowed by the reflective cone of 90° apex angle which converts plane waves to cylindrical and conversely when impinged to its accentuated surface. The control of the resonance can lead therefore to applications of a high-resolution shaft encoders with a reinforced interference contrast (Parriaux et al., 2013). New resonance phenomena can also be exploited by cylindrical resonators of a micro-gear type arising potentially a perfect monomode structure (Huy et al., 2005). Finally, the above technology combined with the Sagnac effect could create new generation gyroscopes and rotational sensing components.

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2 STRUCTURE DESIGN

2.1 Modeling of the Structure

Cylindrical structures request rigorous design and modelling before proceeding to fabrication. Even if one claims that cylindrical morphology presents a complexity, the holistic effect simplifies the structure by simulating it as a planar one. Hence, our structure is simulated with the commercial software (”MC Gratings”) which applies the RCWA (Rigorous Coupled Wave Analysis) or the True modes method on planar surfaces. For obtaining narrow resonant peak with a significant efficiency and maximum power in the structure only a single mode, the fundamental one, propagates in the waveguide layer. The thickness of the waveguide must be accurately calculated by the dispersion equation with the cut-off width to the wavelength of our interest. As it is requested for every waveguide medium, the effective refractive index has to be included between the substrate refractive index and the one of the waveguide for total internal reflection. The aspect ratio and the line space of the grating must be properly adjusted for better light trapping while the period is fixed at 960 nm to reach a resonance in the near IR spectral range. The grating period is fixed by the period of the phase mask and the inner diameter of the tube. For a mode excitation, the normal incidence (θ=0°) and two polarizations (TE and TM) are calculated. The structure is simulated as rectangular grating profile and the resonance wavelengths are at 1437 nm for TE polarization and at 1407 nm for TM according to the structural parameters (Figure 1). Simulated TE/TM resonant reflection spectrum is illustrated in Fig.5

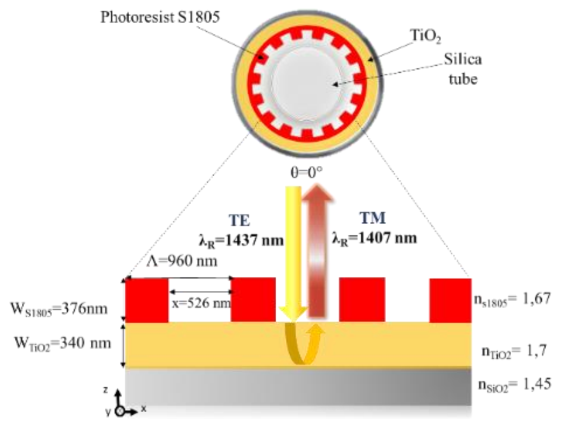

Figure 1: Diffractive structure for zero order reflection resonance in normal incidence.

2.2 Resonant Grating Printing

2.2.1 Tio$_2$ based Sol-gel Layer Deposition

The TiO_2 layer is a photo polymerized negative resist, and is suitably exploited for waveguide interests (Berthod et al., 2016). Fabricated via the solgel method, the TiO_2 solution employs a succession of hydrolysis-condensation reaction in molecular state. It derives from the mixture of a mother solution of TIPT (Sigma-Aldrich, 97%) (Tetraisopropoxide of Titan- metallic precursor)/ H_2O/ HCl /and butanol (BuOH, Fisher, 99%) with a molar composition of 1 / 0.82 / 0.13 / 23 and a daughter solution of a chelating agent of BzAc/ TIPT/and methanol (MeOH, de Sigma-Aldrich, 99, 9%) in a proportion of 1 / 0.75 / 20.4 moles. The presence of the chelating agent BzAc (Sigma-Aldrich, 99,9%) in the solution prevents further TIPT metal precursor polymerization and renders the solution stable (Sanchez et al., 2010) .
The sol gel layer is deposited on the tube in clean room environment by dip coating. Our dip-coating apparatus functions with a descent rate of 7 cm/min starting by a distance of 10 mm away from the sample until its partial immersion in the sol during 1 min. The obtained layer undergoes a heat treatment at 110°C during 3 hours after being naturally dried in ambient temperature. The post-baked stabilized layer is a xerogel layer in amorphous phase. During our experiments, we assume that the solgel layer is deposited equally on the outer wall and on the inner wall of tube. The thickness is measured on the outer wall with the profilometer Dektak resulting to 340 nm thick Above the TiO_2 coating, 50% positive photoresist of S1805 diluted with 50% ethyl lactate is similarly deposited and baked at 60°C during 1 min. The photoresist layer leads to a thickness of 376 nm.

2.2.2 Diffraction Grating Patterning

For the cylindrical diffraction patterning, the photolithography technique is proposed. The set-up encloses a low number of optical elements emphasizing mostly to the radial phase mask. The “MC gratings” software based on the RCWA method has calculated the phase mask parameters yielding to an angular period of $\Lambda\varphi_m$= 480 µrad, depth of 400 nm and line space ratio of 0.538 (Berthod et al., 2017). This angular period, closely dependent on the phase mask radius, is reported to be the half of the grating angular period, which results to a spatial period Λ of 960 nm for a tube of a radius of 4 mm.
As depicted in fig. 2, the optical bench integrates properly the phase mask adapted to diffract only the

TE polarized ±1 orders while extinguishing the zero order that propagates parallel to the central axis. This returns a high contrasted interferogram since no overlap of the 0^{th} transmitted order is issued with the other two orders interfering in the walls. Therefore, a linear polarized 355 nm laser source with an axial beam in normal incidence illuminates the glass tube, already coated for structuration, passing through the radial mask (as described in the previous section). A beam expander is aligned before the mask to enlarge the light spot uniformly with the sole conservation of the Gaussian center of the beam. Special substrate holders with angular and planar displacements enable to align accurately the phase mask and the substrate, furnishing a high angular resolution around 0.01°. This optical set-up provides a fine alignment with the laser source and with the others optical components helping to diffract symmetrically the projected lines in the inner walls of the tube and parallel to the cylindrical axis. Supplementary control for a high quality alignment is added with a computer screen at the end of the optical bench that checks the relative positions between the sample and the phase mask. After the alignment, the tube is enlightened by the UV source and a uniform interferogram with an integer number of submicron periods and no overlay is ensured. The illumination on the photoresist layer lasts only 5 sec using a beam power of 50 mW. The final pattern on the tube is revealed after a development treatment in a basic solution.

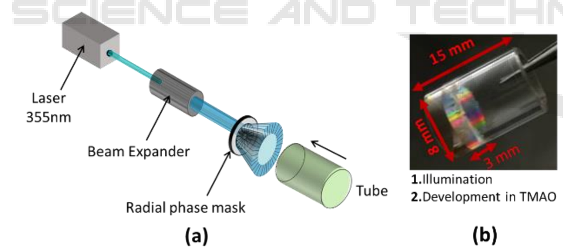

Figure 2: Optical bench for tube exposure (a) and diffraction grating in the tube after illumination and development (b).

2.3 Resonance Waveguide Grating Measurement

The measurement of the resonance waveguide excitation of the grating inside the inner tube is performed using a unique set-up. This optical set-up uses a centered 90°apex reflective cone that profits the holistic phenomenon by transforming the centered axial incident beam into a cylindrical wave and vice-versa. A linear polarized light emitted by a Supercontinuoum source (200 nm<λ<2400 nm) impinges on the conical mirror and undergoes a plane wave to radially polarized state conversion with the k-vector orthogonal to the plane of the incident beam axis as illustrated in Fig.3. After the mode coupling and decoupling by the grating, the resonant cylindrical wave is reflected by the cone. The reflected resonance arises in the IR wavelength bandwidth and gets photo detected after being splitted by the 45°blade. The signal propagates through an optical fiber connected to a NIR (900 nm - 2100 nm) spectrometer and is analyzed by the dedicated software on computer. (Figure 3)

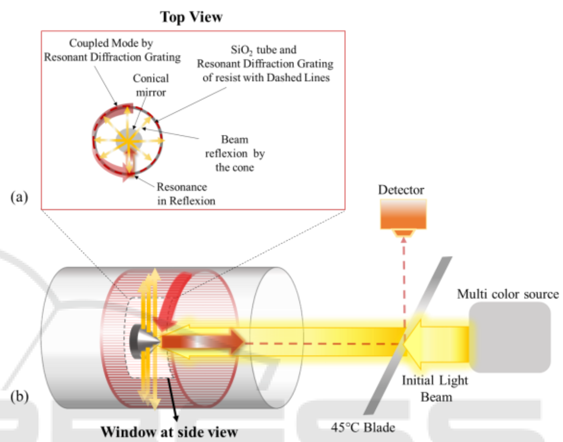

Figure 3: Spectroscopic set-up for resonance measurement in tubular structure a) top view, b) side view.

The resonant picks are curve fitted by a Lorentzian function to estimate their width and heights and they are assessed by the quality factor (λ/FWHM). The horizontal polarization demonstrates a 149.2 Q-factor while the vertical reaches at 61.3. Simulated resonances are superposed with the experimental and exhibit a good agreement almost for the two polarizations-horizontal and vertical. (Figure 4)

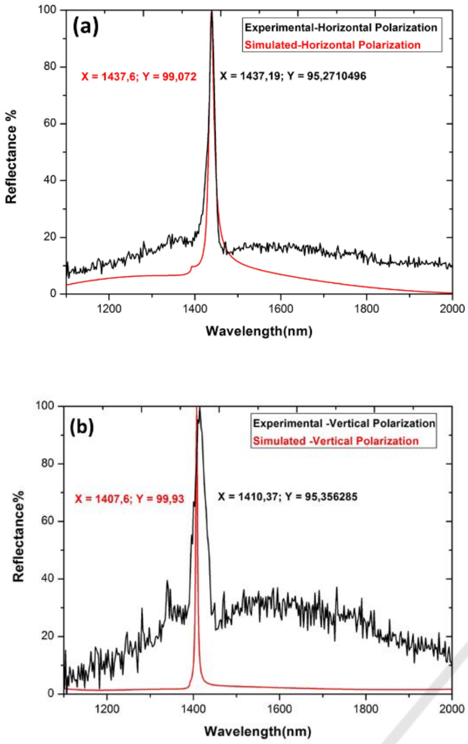

Figure 4: Experimental and Simulated spectra for horizontal (a) and vertical (b) polarization.

3 CONCLUSIONS

A demonstration of resonance grating waveguide inside a tube has been described and measured for the first time using a holistic illumination. Both TE and TM modes have been excited and measured since both polarizations have to be considered, with a linear polarized incident beam. The capability to estimate the resonance issued by the proposed geometries could open the horizons to applications of rotational micro sensors.

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