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Damian Harasim, Akmaral Tolegenova, Aliya Tergeusizova, "The spectral properties of bended tilted fiber Bragg gratings," Proc. SPIE 11045, Optical Fibers and Their Applications 2018, 110450B (15 March 2019); doi: 10.1117/12.2522409

Event: 18th Conference on Optical Fibers and Their Applications, 2018, Naleczow, Poland

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[a]*Damian Harasim, [b]Akmaral Tolegenova, [b]Aliya Tergeusizova
[a]Lublin University of Technology, Institute of Electronics and Information Technology, Nadbystrzycka Str. 38D, 20-648 Lublin, Poland
[b]Al-Farabi Kazakh National University, Almaty, Kazakhstan

ABSTRACT

This paper presents the introduction about fiber periodic structures which have a ability to coupling light from fiber core to cladding, their principles and applications. Paper also presents the detail description of particular example of TFBG spectral response for changes of fiber bending in range of curvature radius from 30 to 7 mm. The area of observed cladding mode resonances is changing due to strengthening of fiber curve with simultaneous core mode independence for this quantity. The ghost mode which is resonance closest to Bragg mode wavelength also stands out with transmission loss dependency from fiber bending which is also described.

Keywords: optics, fiber sensors, tilted Bragg grating

1. INTRODUCTION

Over the past few years the optical fiber technology is experiencing an increasing development and interest. Optical fiber sensors are one of the fields with greater development with interest in using the differential but simultaneous response of modes transmitted in optical fiber[1,2] to different perturbations as means of increasing capacity, sensitivity or reducing the limits of detection in optical sensing systems[3,4,5]. One of the promising field of optical sensors technology development are fiber Bragg gratings (FBGs) which are manufactured by inscribing periodic zones of increased refractive index in core of fiber. Optical sensors based on gratings have a great advantages such as extremely small size[6], high sensitivity, ability for multiplexing many sensors in single fiber and immunity to electromagnetic interference[7,8]. The first widespread grating-assisted multimodal fiber sensors relied on LPGs (long period gratings) which couples lights guided by core to cladding modes which are forward propagating in the same fiber. The wide range of sensing potentialities that are possible with using cladding modes were discovered thanks to research of LPGs and their spectral properties. Properties of cladding modes are sensitive to surrounding refractive index and bending for instance in opposite to core mode which is sensitive to quantities which have direct influence on core of fiber[9,10]. Otherwise described sensitivities varies strongly from mode to mode. Effective index, field shape and polarization depends strongly on mode order and initial conditions. The conventional single mode optical fibers in this applications has another great advantage which is inherently guiding of hundreds of cladding modes without additional modifications because of the large cladding diameter in relation to guided wavelength. The tilted fiber Bragg grating (TFBG) has a grating period similar to conventional fiber Bragg grating (FBG) which is around one third of the wavelength but in opposite to regular gratings, TFBG has refractive index perturbations planes tilted relative to fiber cross-section plane[11,12]. This particular tilt enables strong coupling between the core mode and selected cladding modes which is similar to LPGs but different conditions of phase matching makes TFBG resonances much less sensitive but also much more controllable in manufacturing and applications[13,14]. Moreover, this conditions also implicates that the wavelength range of appeared resonances is much smaller for tilted gratings than LPGs. It means that tens of resonances can be simultaneously compared and inspected using equipment with spectral range about or less than 100 nm. Dependencies between cladding mode resonances and input light polarization direction related to spatial structure of TFBGs makes them useful for creation of structural condition sensors[15,16]. However in some applications this properties are undesirable and there are few propositions for new kinds of structures[17].

The result of introducing tilt between grating refractive index perturbations planes relative to fiber cross-section plane is the interaction of grating periods with the light guided in core achieves greatly different properties from conventional

*d.harasim@pollub.pl; +48 81 538 43 13; pollub.pl

Optical Fibers and Their Applications 2018, edited by Ryszard S. Romaniuk,
Waldemar Wójcik, Andrzej Smolarz, Proc. of SPIE Vol. 11045, 110450B

"straight" grating. The light from the core could be coupled to specified forms: a subset contains the high number of modes that are transmitted by the fiber cladding; modes that are leaking from cladding; high directional light beams transferred outside the fiber[18,19]. The fact that transfer function of spectral parameters can be distinguished using volume manufacturing systems and ability to inscribing structures in many kinds of optical fiber including standard telecommunication SMF.

The standard, straight FBG have only one, strong resonance which could be observed as a dip in transmission and peak in reflected spectrum that is corresponding to the Bragg condition for period and parameters of specified optical fiber. Spectrum of light transmitted by TFBG is highly dependent on tilt angle introduced into internal structure of grating.

The specified cladding mode wavelength is settled by grating tilt angle and effective refractive indices of fiber according to the following expressions[20]:

$$\lambda^{core} = \frac{2 n_{eff}^{core} \Lambda}{\cos\theta_{TFBG}} \tag{1}$$

$$\lambda_i^{clad} = \frac{\left(n_{eff}^{core} + n_{eff\ i}^{clad}\right)\Lambda}{\cos\theta_{TFBG}} \tag{2}$$

where: λ^{core} is a wavelength of core mode, λ_i^{clad} is the wavelength resonance between the core mode and another "*i*" labeled, $n^{core}{}_{eff}$ is the effective refractive index if the single mode transmitted by core at wavelength where the resonance appears, $n^{cl}{}_{eff\,i}$ is the effective index of *i*-th mode at certain wavelength, Λ is the grating constant (period of pattern used to create grating) and Θ_{TFBG} is the angle of periodic perturbations in fiber core. The individual resonant mode reflection factor $R_i^{core,\ clad}$ could be expressed by following formula which takes into account the modulation of refractive index of TFBG:

$$R_i^{co,cl} = \tanh^2\left\{ LC \int \int_{-\infty}^{+\infty} \vec{E}^{co} * \vec{E}^{cl} \Delta n \cos\left(\frac{4\pi}{\Lambda} z \cos\left(\theta_{TFBG}\right) + y \sin\left(\theta_{TFBG}\right)\right) dxdy \right\} \tag{2}$$

where L is a grating longitude, C is the proportional constant related to the normalization of the transverse mode fields, E is a transverse component of modes electric fields and Δn describes the variation of refractive index along fiber cross-section with inscribed grating. The individual resonant modes amplitude and wavelength could be affected by refractive index changes, polarization state of input light and curvature of fiber section with inscribed TFBG.

2. EXPERIMENTAL SETUP AND RESULTS

The TFBG used in experimental studies described in following paper was inscribed on standard single mode SMF-28 fiber which was loaded by hydrogen by 10 days.

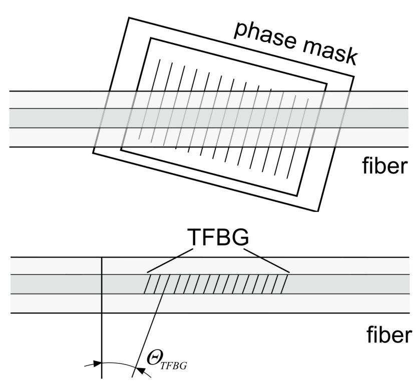

Figure 1. Schematic presentation of introducing tilt angle to inscribed gratings periods using phase mask technique with keeping fiber and mask perpendicular to laser beam and rotation of phase mask around axis.

Operation of hydrogen-loading enhances fiber sensitivity to high power ultraviolet radiation which able to change the refractive index of fiber core. The grating was inscribed using phase mask method by keeping the mask and fiber perpendicular to the incident writing laser beam but rotating the mask around axis of this beam. Figure 1 schematically presents a process of introducing tilt angle between created grating periods and cross-section plane of fiber. Tilt angle of TFBG used in curvature measurement described below was 2 degrees. The spectral characteristics of TFBG subjected to different curvature radiuses were measured with using Optical Spectrum Analyzer Yokogawa AQ6370D, broadband light source was SLED with 1550 nm center wavelength and 80 nm FWHM. Spectra were measured in transmission configuration because of desire to observe the behavior of cladding modes. Figure 2. presents a transmission measurement setup, where inset a) shows in detail a method of changing of fiber curvature in section with inscribed 2° TFBG. Grey zones on the bended part of fiber represents section with inscribed tilted grating.

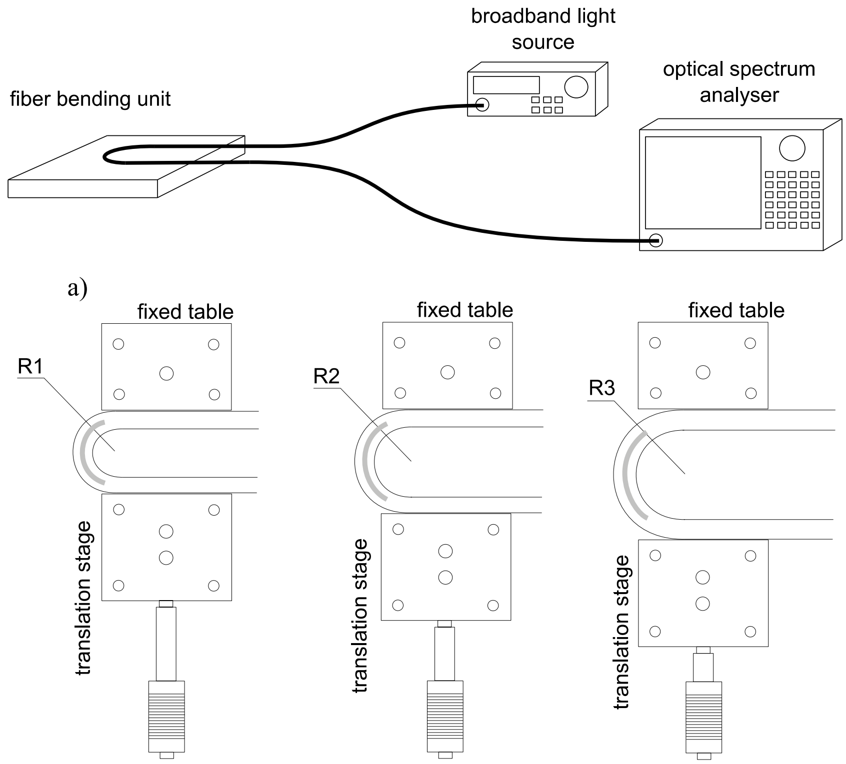

Figure 2. Scheme of transmission spectrum measurement setup and a) method for changing the curvature radius of fiber section with inscribed TBFG (marked as grey zone)

The fiber was mounted between two stages – one fixed which was the base and second translation stage which allows to control the distance between stages. Decreasing of distance between two edges where fiber was mount, caused strengthened of curvature – decreasing of radius. Optical fiber was leaned against the walls of stages which protects fiber against warping. Warping of fiber could have the strong influence on distinguishing of radius and the shape of curvature will be not round. Figure 3 presents a bending on internal structure of TFBG with directions of caused strain. In experimental setup fiber was prevented from rotating around its longitudinal axis.

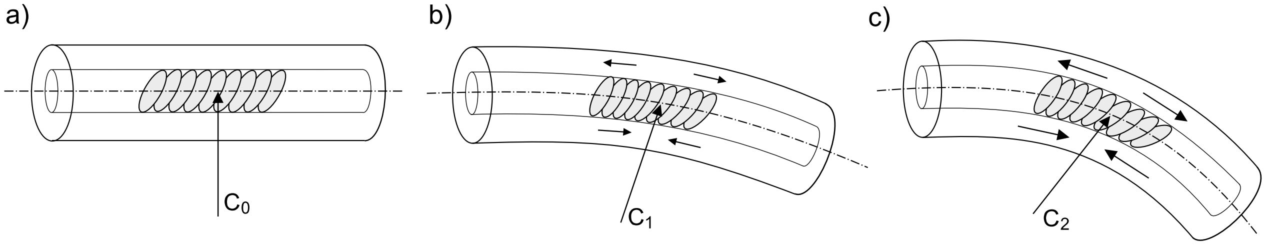

Figure 3. The presentation of internal structure of tilted periodic refractive index perturbations in case of bended optical fiber in its section with TFBG

Bending of structure with tilted refractive index perturbations have an influence on its internal organization. The main changes of spectral characteristics comes from fact, that bending introduces non-uniform stress across the fiber which have the result in shifting the mode field profiles in relation to the center of fiber core. Figure 4 presents the transmission spectra of 2° tilted grating subjected to bending with decreasing curvatures with 60, 45, 30 and 15 mm radiuses.

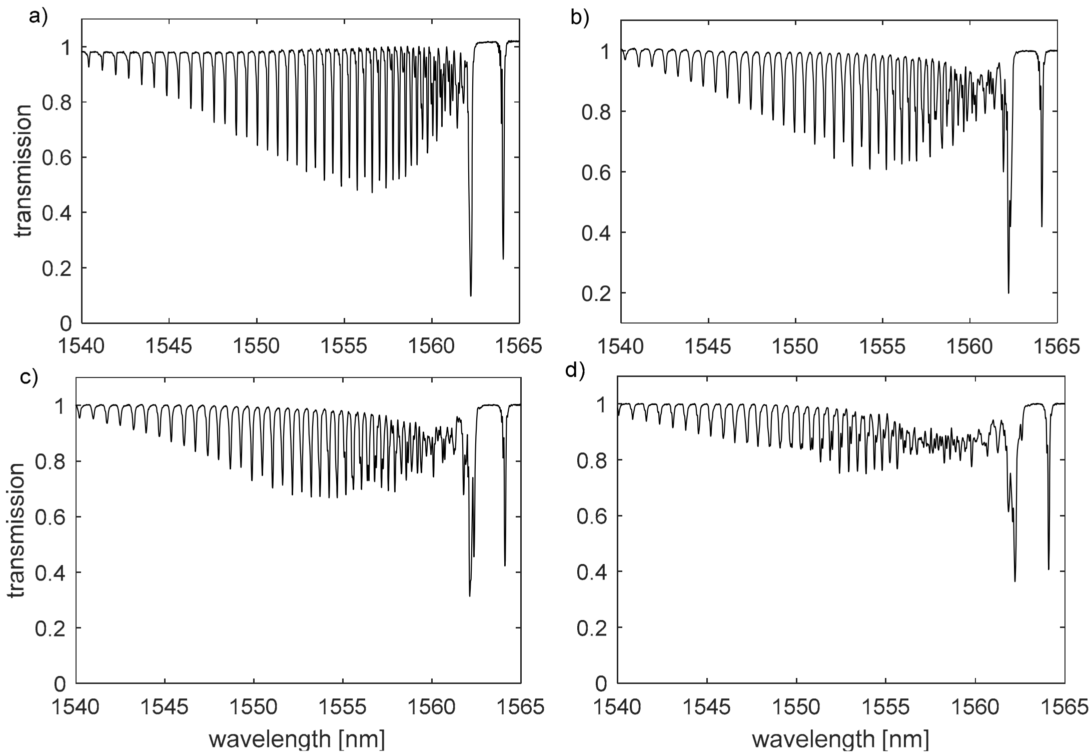

Figure 4. Transmission spectra of TFBG with 2° tilt angle subjected to strengthened curvature radiuses: a) 60 mm, b) 45 mm, c) 30 mm, d) 15 mm.

Spectra shown on figure 4 representing the spectral response of weak tilted grating inscribed in single mode fiber which was suspected to bending. The Bragg resonance is insensitive to this quantity because there is no strain induced by curvature within the core. Also effective refractive index of fiber core is constant. However bending have a strong influence on actually every other spectral parameter. Figure 5. presents schematically spectral areas outlined between top and bottom envelopes.

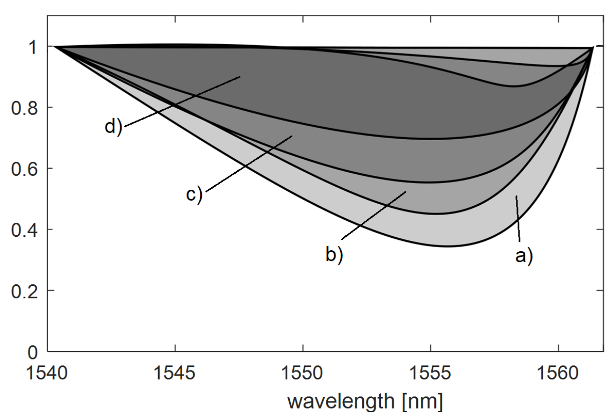

Figure 5. The schematically outlined and imposed on each other areas of transmission spectra of TFBG with 2° tilt angle subjected to strengthened curvature radiuses: a) 60 mm, b) 45 mm, c) 30 mm, d) 15 mm.

Spectral areas shown on fig. 5 presents that in case of weak tilted grating the large number of cladding modes acts similar to ghost mode – transmission loss decreases while strengthening of bending curvature. It is promising to perform measurement of bending or other indirect quantities by application of envelope methods similar as in case of surrounding refractive index measurements with TFBG transducers. This methods needs to use optical spectrum analyzer because measurement results are calculated from spectrum measured in selected wavelength range. Another possibility is utilization of ghost mode resonance properties. The spectral characteristic of ghost mode is getting distorted and transmission loss in wavelength with strongest initial ghost coupling decreasing. The dependence between transmission loss and radius of fiber with inscribed TFBG curvature is presented in figure 6.

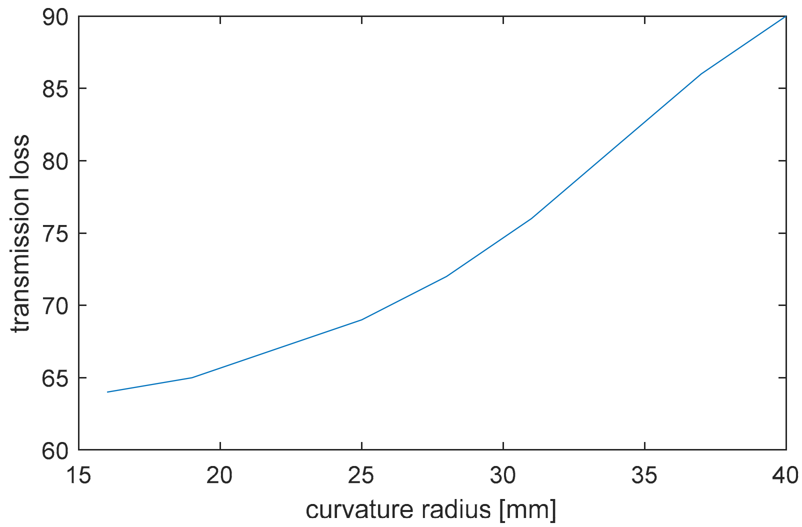

Figure 6. Transmission loss of ghost mode for 2° TFBG subjected to bending with different radius from 16 to 40 mm.

Transmission loss of ghost mode gives a strong response for changes of curvature in selected range of bending radiuses. Loosening of bending (increasing of curvature radius) causes increasing of transmission loss measured in transmission. Strengthening of fiber bending causes decrease of transmission loss which is unambiguous with decreasing of amplitude. The values shown in figure 6 were measured for wavelength where the transmission dip occurs for ghost mode of not bended TFBG.

3. CONCLUSIONS

Tilted Bragg gratings are promising structures for applications in many kinds of sensing systems as a transducers of wide spectrum of physical quantities. Their intrinsic ability to transfer light from core into cladding of optical fiber as a cladding mode resonances makes them useful in sensing fields inaccessible for conventional Bragg gratings. Except the measurements of surrounding refractive index, they are capable for distinguishing the radius of fiber bending in section with inscribed grating. This property differentiates TFBGs from traditional FBGs because of their spatial asymmetry. Transmission factor measured for ghost mode in wavelength with greatest initial reflectivity gives a good response for bending changes. Decreasing of tilt angle of used TFBG could increase the sensitivity by amplifying the ghost mode coupling. The behavior of whole area of cladding mode resonances varies with curvature changes. Bragg mode coupled and guided by core of fiber is inherently insensitive to this perturbations. However, ghost On the other hand, it could be important to keep the control about arrangement between bending plane and spatial organization of grating fringes planes. In presented case fiber was prevented from rotating around its longitudinal axis but without control about initial internal structure arrangement related to curvature plane.

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