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doi:10.15199/48.2019.04.34

Spectral properties of Tilted Bragg Gratings with different tilt angles and variable surrounding conditions

***Abstract**. This paper presents a differences in spectral characteristics of Tilted Fiber Bragg Gratings (TFBG) with variable angle of refractive index fringes and spectral response of this structures influenced by different surroundings. The light-guiding mechanism of fiber periodic structures with angled fluctuations of refractive index allow to modulate their spectral characteristics in wide range. It also makes them sensitive to refractive index of medium surrounding the fiber where this structure is inscribed.*

***Streszczenie.** W tej publikacji autorzy pokazują zależności parametrów widmowych struktur zwanych Skośnymi Światłowodowymi Siatkami Bragga dla różnych wartości kąta nachylenia zmian współczynnika załamania w rdzeniu światłowodu oraz ich odpowiedź spektralną dla różnych mediów otaczających. Mechanizm prowadzenia światła w strukturach z nachyloną płaszczyzną zmian w rdzeniu pozwala na zmiany ich parametrów widmowych w szerokim zakresie jednocześnie sprawia, że są one wrażliwe na określone zmiany w otoczeniu światłowodu. (**Właściwości widmowe Skośnych Światłowodowych Siatek Bragga dla różnych kątów nachylenia oraz zmiennych warunków otoczenia**).*

Keywords: tilted Bragg gratings, optoelectronics, special fiber structures.
Słowa kluczowe: skośne siatki Bragga, optoelektronika, specjalne struktury światłowodowe.

Introduction

Fiber Bragg Gratings (FBGs) have become as an important field in technology of optical sensing due to their advantages in comparison to electronic counterparts. Most important advantages of this structures used as sensing elements are extremely small size, immunity to electromagnetic interference and ability to multiplexing of many structures in single fiber. They are generally very sensitive to temperature[1] changes and elongation of fiber with inscribed grating [2-4]. An important feature of FBGs used as sensing structures is that they are sensitive to many physical quantities which could lead to undesirable cross-sensitivity which occur in the same spectral response for changes of different quantities affecting the FBG. This property generally leads to requirement of temperature compensation. Scheme of internal structure and spectral characteristics of FBGs are presented in Fig. 1. The inconveniences resulting from spectral properties of conventional FBGs could be solved by performing a technological modifications e.g. by creating a chirp (variable period of internal refractive index perturbations in fiber core) to obtain desirable spectral properties.

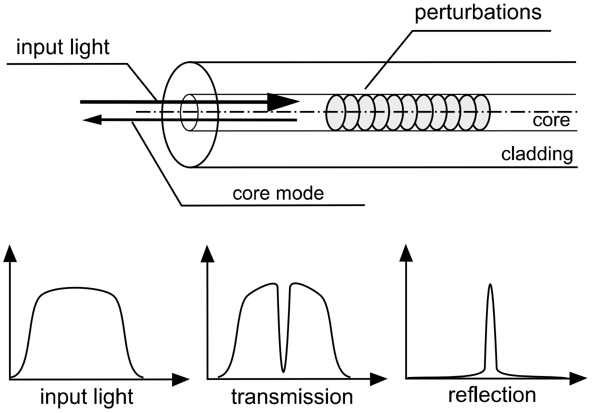

Fig.1. Scheme of internal refractive index structure in fiber core with inscribed Conventional FBG and spectral response in transmitted and reflected light

Another possibility to change the spectral behaviour of gratings is creating the structure with introduced particular angle between planes of fiber core periodic fringes and fiber cross-section plane. In case of conventional gratings, planes of refractive index perturbations are parallel to cross-section plane of fiber while in tilted grating structure planes of internal fringes are angled in relation to cross-section plane with Θ_{TFBG} angle [5,6]. Tilted fiber Bragg gratings (TFBGs) stand out by enhancement of resonances of backward-propagating cladding modes which is most evident effect of tilt angle introducing. It could be observed as a series of dips in optical power of transmission spectrum. Fig. 2. presents the scheme of internal structure of TFBG – grating perturbations orientation in fiber core.

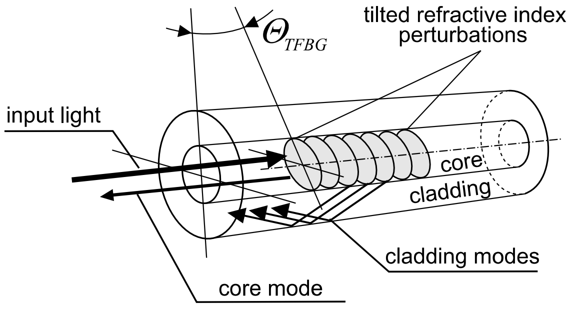

Fig.2. Scheme of internal structure of Tilted Bragg Grating with marked planes which designate TFBG tilt angle

A tilt in orientation of index perturbations planes favors the coupling of light to modes which are guided by cladding. The parameter of tilt angle is very important and can be used to choose which cladding modes will be excited. Cladding modes could appear over the range from tens to more than one hundred nanometers. Analysis of tilted gratings transmission spectra leads to distinguish three types of appeared modes. The mechanism of core mode coupling is similar in case of FBGs and TFBGs so it could be observed both in reflection and transmission. It could be used as a reference for strain or temperature and its is sensitive only to quantities which influences on the fiber core. The so-called ghost mode appears in the close wavelength proximity of the core mode as a result of light propagation in cladding zone close to core. The other cladding modes appears only in spectrum of transmission because light transferred to cladding has weak conditions for propagation. They are propagating backwards in relation to direction of input light. This properties and geometrical asymmetry of tilted grating internal structure makes them useful as a sensors of physical quantities neutral to conventional gratings such as RI of surrounding medium [7], bending of fiber [8] and polarization of input light [9]. These sensitivities are strongly related with order of exact cladding mode. Control of polarization is often necessary in sensing applications using plasmonic resonance (SPR) [10]. The dependency of particular spectrum areas on polarization angle of linearly polarized input light could be used in e.g. twist measurement instruments while spectral response of core mode resonances is nearly insensitive to changes in polarization angle of input light. Temperature and strain measurements using TFBGs are most generally based on core mode wavelength shift. Sensitivity for temperature in this structures approximately equals 10 pm/°C which is similar to sensitivity of conventional gratings.

Principles and fabrication of TFBG

The spectral properties of radiation transmitted through TFBG is highly dependent on tilt angle introduced to its internal structure. Spectral width of dips related with cladding resonances observed in transmission is getting wider with growth of Θ_{TFBG} angle. The Bragg wavelength of core mode and the i-th order cladding mode resonance wavelength could be expressed as [11]

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

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

where $\Delta\lambda^{core}$ is a core mode wavelength, $\Delta\lambda_i^{clad}$ is the wavelength difference between core and i-th mode, n_{eff}^{core} is effective index of the single mode guided by core at wavelength that resonance is observed, $n_{eff\_i}^{clad}$ is effective index of mode i at the same wavelength and Λ is the period of refractive index perturbations in fiber core. Reflectivity of particular resonant mode depends on the modulation amplitude of refractive index in fiber core perturbations. The reflectivity of individual cladding resonant mode R_i^{cl} could be estimated by following expression:

$$\kappa = C\int\int_{-\infty}^{\infty} \vec{E}^{*}_{core}\cdot\vec{E}_{r}\Delta n\left(x,y\right)dxdy \tag{3}$$

where C is constant related to the normalization of the transverse mode fields, E is a transverse component of the electric fields if the modes, L is the longitude of grating and Δn is a function which describes variation of refractive index due to the grating cross-section in fiber.

TFBGs could be fabricated using similar tools and techniques as in case of conventional FBGs. Examples of appropriate method are inducing of permanent refractive index perturbations in doped fibers by creating an interference patters by two intense laser beams [12] or point by point approach [13]. However most widely used method for manufacturing FBGs and TFBGs is diffractive phase mask technique with keeping phase mask in close proximity to the fiber. Period of grating is fixed by phase mask interval and because of small distances between elements low coherent light source can be used. Creating of tilt can be done by rotating the phase mask and fiber consistently around an axis perpendicular to the writing beam, or by keeping the phase mask and fiber perpendicular to laser beam but rotating the phase mask around the axis of writing beam.

Experimental analysis and TFBG spectral properties

A structures used in following spectral analysis were inscribed in single core hydrogen loaded optical fiber with using phase mask rotation technique and BraggStar KrF excimer pulse laser. Longitude of fabricated gratings were established as 12 mm. Figure 3 presents the transmission spectra of three tilted gratings fabricated with different angles of index perturbations planes: 2°, 4° and 6°. Characteristics of manufactured structures were measured using Optical Spectrum Analyser (OSA) and SLED light source with 1550 nm central wavelength.

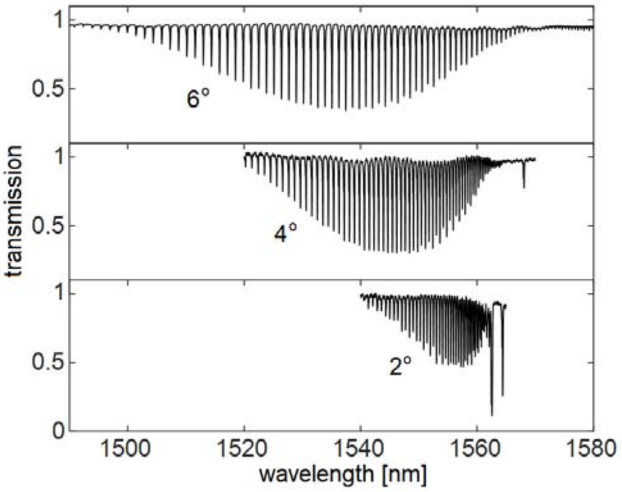

Fig.3. Transmission spectra of TFBGs with increasing of tilt angle for: 2, 4 and 6 degrees

Plots presented in Fig. 3. shows, that changes of grating tilt influences on coupling series of cladding modes. Increase of TFBG angle results with appearance of transmission dips in wider range of spectrum, especially in shorter wavelengths. At the same time the coupling in fiber core is getting weaker and finally for 6° TFBG Bragg core mode disappears. Similar behaviour could be observed in case of ghost mode which is strongest in gratings with weak tilt angle. The wavelength of core resonance is longer with increase with tilt angle which is related with geometric of refractive index fringes in fiber. The area created between line of source power reference and contour line created by dips in transmission related with strong cladding modes coupling is increasing with growth of tilt angle which is presented in Fig. 4. Spectral areas shown in below figure were shifted to provide their boundary–longest wavelength in the same point.

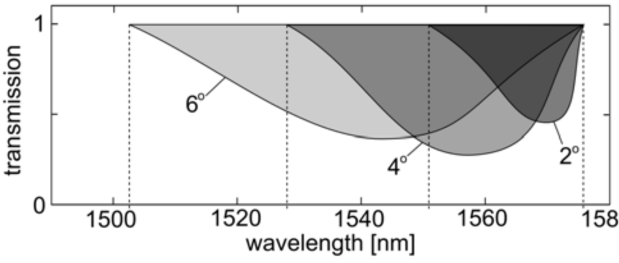

Fig.4. Areas plotted between top and contour line of TFBGs transmission spectra

The areas designated by transmission spectra of TFBGs with 2, 4 and 6 degrees shows, that their wavelength range increases almost linearly with increase of tilt angle. For 2° there is 24 nm, for 4° is 48 nm and for 6° there is 70 nm. It have to be noticed, that estimating of boundary wavelengths of spectral area is burdened by the adopted method. The small dips (few %) related with weak coupling are present in much wider spectrum, especially in shorter side. This phenomena has strong influence on properties of created structure.

Another phenomenon which occurs while tilt angle is going greater is increasing of wavelength spacing between sequential dips which is presented in Fig. 5.

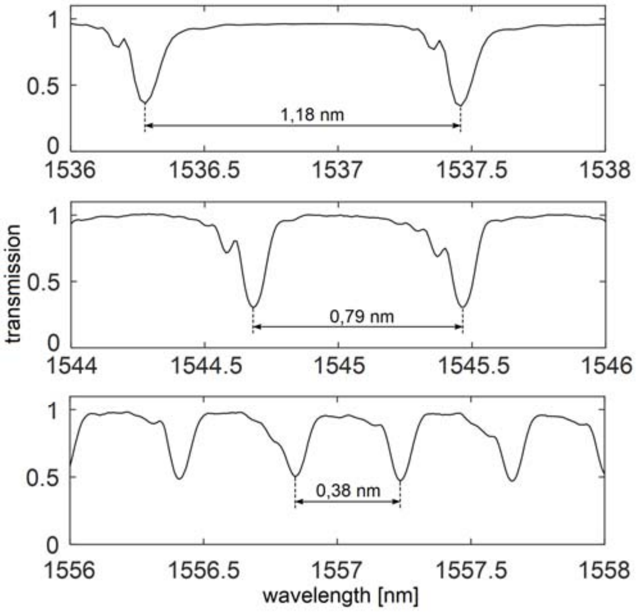

Fig.5. Presentation of transmission dips related with cladding resonances for gratings with 2°, 4°, and 6° tilt

Figure 5. shows fragments of spectra measured for the same TFBGs as in case of characteristics in Fig.3, presented in 2 nm spectral range. Wavelength range is chosen to show transmission dips of modes with highest loss (highest amplitude). All of plots shown on Fig.5 presents characteristics in 2 nm range so differences in spacing between neighbouring dips are clearly visible. This property of gratings can be useful when spectral response (for particular perturbation) of TFBGs with different tilts are similar but spacing between utilized modes is critical.

Sensing properties of TFBG spectra

One of the unique properties of tilted gratings is their spectral behaviour related with refractive index of ambient medium. Figure 6. presents spectral characteristics of TFBG with tilt angle 5° immersed in solutions with RI: 1.384, 1.407, 1.432. Resonances observed at decreasing wavelengths correspond to modes guided by cladding with increase of evanescent fields extending outside the cladding. In further decreasing wavelengths could be distinguished the point where grating couples much weaker modes guided by cladding called "leaky modes". The boundary between modes which are strongly coupled and guided and modes which are no more coupled is generally called cut off. When the refractive index of immediate environment (ambient medium) increases, the coupling of subsequent modes from shortest wavelengths is getting weaker so the wavelength of cut off is shifted which is presented in Fig. 6.

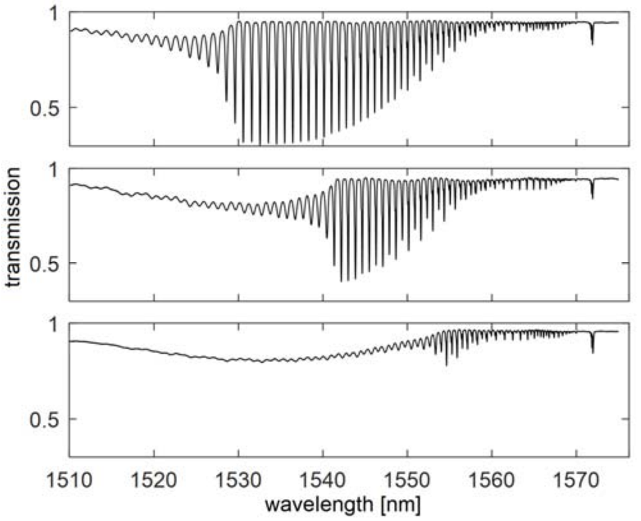

Fig.6. Transmission spectra of TFBG with 6° tilt angle immersed in solutions with increasing RI: 1.384, 1.407, 1.432

Actually the tilt angle of intrinsic fiber refractive index perturbations planes has strongest influence on TFBGs spectral properties interaction with ambient medium. Increasing of angle causes widening of wavelength range with observable transmission dips which is related with boundary surrounding indices that can make any reaction with TFBG spectrum. When the spectral range of cladding modes resonances is wider, the lower refractive index of surrounding medium can cause leaking of "outer" mode.
However, in contrast to cladding mode resonances, coupling of core mode is practically independent of changes of ambient refractive index. It can be observed because the radiation responsible for Bragg mode coupling is transmitted only in core of optical fiber and have no interaction with cladding-surrounding medium boundary. The core resonance transmission characteristics of examined tilted grating immersed in prepared media with assumed RI's are presented in Fig.7.

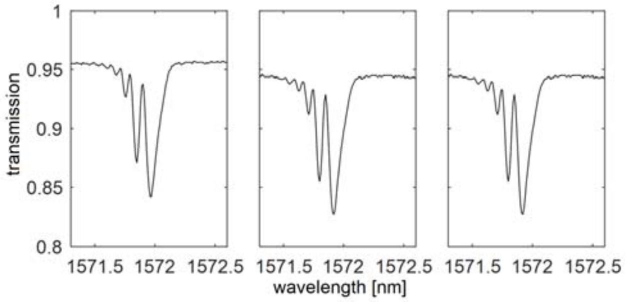

Fig.7. Transmission spectra of core mode resonance of tilted Bragg grating for different surrounding refractive indices

The property of dual character of light coupling and propagation makes TFBGs an interesting sensing elements for applications as transducers of many physical quantities simultaneously. Described above properties related with leaking of cladding modes could be also observed in case of surrounding medium with refractive index value close to cladding of optical fiber. For this instance, there is no border between fiber and surrounding environment and transmission spectrum of TFBG is smoothed from all of dips characteristic for cladding mode resonances which is presented in Fig.8 with example of 2° grating. It is also visible that there is no lowering of transmission loss of Bragg and ghost modes.

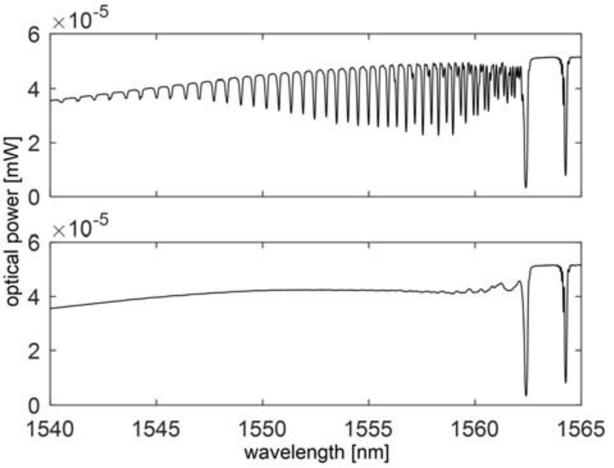

Fig.8. Transmission spectra of TFBG with 2° tilt angle in air and immersed in solution with RI value close to cladding of fiber

The utilization of intrinsic capacity of TFBG makes them applicable as a passive element to forming of transmission or reflection optical filter. The angle of grating tilt and spectral width of cladding modes dips has crucial meaning in forming of smoothed spectral characteristics. However the amplitude of refractive index modulation in fiber grating also can be used for obtaining desirable slopes. Increasing of modulation amplitude will cause higher transmission loss for TFBG with smoothed characteristics.

Conclusions

Titled fiber Bragg gratings are promising structures in applications in many fields of measurement. Their properties that distinguish them from conventional gratings with straight internal perturbations are the result of dual character of light coupling – core mode and series of cladding modes transferred in core-cladding border. Most important parameter which determines spectral properties of TFBG is angle of refractive index fringes tilt in relation to fiber cross-section plane. This modification of grating internal structure cause partial transferring of coupled light to core-cladding boarder as a cladding modes which makes them sensitive to refractive index of medium surrounding fiber with inscribed TFBG. However, part of coupled light still remains as core mode and is independent from this quantity and has sensitivities similar as in case of conventional "straight" gratings. Increasing of tilt angle causes widening of transmission dips observable in spectral characteristics related with stronger coupling of cladding modes with lower effective refractive index. This property also determines the wavelength spacing between consecutive cladding resonance dips observed in transmission. This angle has also influence on acceptable range of surrounding refractive index which can make the reaction with light coupled in TFBG structure. For higher tilt angles, the coupling of lower-order cladding modes is going stronger and the interaction between spectral characteristics can be performed with lower "initial" value of ambient medium refractive index. Increase of surrounding index in acceptable range causes leaking of consecutive cladding modes which could be observed as weakening of cut-off mode transmission loss. In this case core mode could be used as reference because it is sensitive only to quantities which influences directly fiber core: temperature and strain. Properties of this light propagation are preserved even when all of cladding modes disappears. The ability of TFBG for creating a smoothed wide spectral characteristics opens a widespread application opportunities for using in optical filters forming.

Acknowledgement: *This work is supported by grant from the Ministry of Education and Science of the Republic of Kazakhstan within the framework of the Project № AP05132778 "Research and development of signals interrogation system with fiber-optic refractometer in telecommunication networks".*

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