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Investigation of the Influence of Temperature on the Characteristics of Fibre Bragg Gratings

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ABSTRACT The article presents the results of a fibre Bragg grating (FBG) investigation. Two types of FBGs, uniform and tilted, were fabricated. They were inscribed in the cores of fibres using a UV excimer laser KrF Coherent Bragg Star M and the phase mask method. Photosensitive optical fibres GF1 were chosen for FBG fabrication. The properties and characteristics of the fabricated FBGs were investigated in order to design fibre-optic bending sensors. In this case, the analysis of FBG spectral characteristics and temperature sensitivity dependencies is crucial. The setup including a climatic chamber, an AQ6370D Optical Spectrum Analyser, an S5FC1550S-A2 SM Benchtop SLD Source and a computer was used for FBG spectral characteristics and temperature sensitivity measurement. Spectral characteristics of uniform and tilted FBGs were investigated within the temperature range from -40.6°C to 181.8°C . The following peaks in the spectral characteristics in the above-mentioned temperature range were chosen for analysis: the Bragg peak for uniform FBGs and such peaks as Bragg peak, Ghost peak and three peaks of certain wavelengths for tilted FBGs. The shifts of the analysed peaks in the spectral characteristics with temperature were observed. Temperature dependencies of wavelengths of the analysed peaks were obtained. It was shown that there is an approximately linear temperature dependence of the Bragg wavelength and other above-mentioned analysed peaks of certain wavelengths. The linear character of the investigated temperature dependencies of the fabricated FBGs allows for their use in sensor application. It was shown that temperature sensitivities of uniform and tilted FBGs were dependent on the temperature range chosen. Temperature sensitivities approximately equal to $11.1 - 11.4 \text{ pm} / ^{\circ}\text{C}$ in a temperature range of $120.8 - 181.8^{\circ}\text{C}$ and approximately equal to $8.5 - 8.9 \text{ pm} / ^{\circ}\text{C}$ in a temperature range of $-40.6 - 20.7^{\circ}\text{C}$ for uniform and tilted FBGs were determined. Temperature sensitivities were dependent on certain wavelength and changed from $8.4 \text{ pm} / ^{\circ}\text{C}$ to $10.1 \text{ pm} / ^{\circ}\text{C}$ for particular wavelengths.

KEYWORDS fibre Bragg grating (FBG), uniform FBG, tilted FBG, spectral characteristics, temperature sensitivity.

I. INTRODUCTION

In recent years, different sensing structures of bending sensors based on fibre Bragg gratings (FBGs) have been proposed [1-2]. Fibre optic cable can be bent at a radius of less than 1 cm (microbending) or more than 1 cm (macro-bending). Microbending can cause signal loss and reduced transmission in the fibre. The macrobending can result in spectral changes in FBGs, e. g. Bragg wavelength shift (mainly to shorter wavelengths), reflectivity decrease and widening the FBG spectrum. Investigations have shown that spectral properties of FBGs depend on fibre type and bend radius. The examples of transmission spectra for low bend loss fibres F-SBC and F-SBD are given in Fig. 1. In Fig. 1a the trend in wavelength shift is depicted: the wavelength shift to lower wavelengths is observed with bend diameter decrease. The arrow indicates the trend in wavelength shift as bend diameter decreases, shifts its Bragg wavelength (usually shorter), reduces reflectivity and broadens its spectrum.

Analysis and considering the changes in FBG spectra due to bending should be taken into account at sensor design. The aim of the work was to fabricate the uniform and tilted FBGs and investigate their properties and characteristics in order to design the fibre-optic bending sensors.

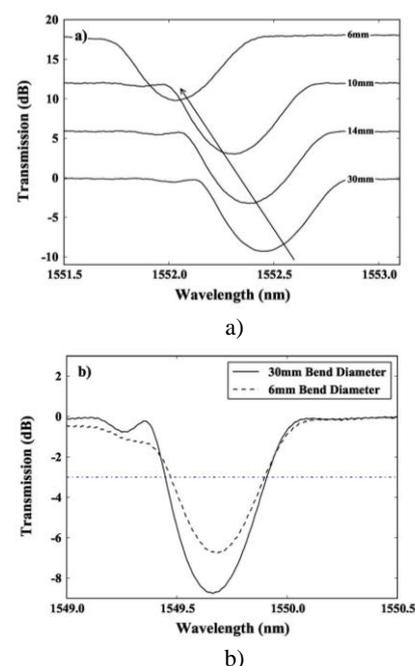


FIG. 1. (a) Example of shifts in spectra of F-SBC fibre ($125 \mu\text{m}$ fibre diameter) for various bend diameters; (b) the spectra of F-SBD fibre ($80 \mu\text{m}$ fibre diameter) for various bend diameters [3].

II. CHARACTERISTICS OF FIBRE BRAGG GRATINGS

In order to inscribe FBGs (uniform and tilted) the authors have chosen single mode fibres. Single mode fibre consists of core and cladding (typically 125 μm) surrounded by a coating (protective layer). In order to support only one light mode in the single-mode fibre optic core the following conditions should be met: the core diameter should be small (typically 9 μm), the cladding material should have slightly lower refractive index than the core to eliminate modal dispersion and the operating wavelength should be longer than the cut-off wavelength. This is caused by the condition for attenuation of higher-order modes (for single mode operation):

$$V = \frac{2\pi a \sqrt{n_1^2 - n_2^2}}{\lambda} < 2.405 . \quad (1)$$

V – V parameter (normalised frequency) which determines the number of modes a fibre can support; a – the core diameter, μm ; n_1 – the core refractive index; n_2 – the cladding refractive index; λ – the free-space wavelength, μm ; the V parameter decreases with wavelength increase.

Due to this, reflection in the core occurs less frequently and attenuation is minimised. But the small core diameter can lead to difficulties in coupling losses. In single-mode fibres, splice loss less than 0.1 dB is acceptable. Commonly light sources such as laser or laser diodes working at 1310 nm (lowest dispersion) and 1550 nm (lowest attenuation) are used in single-mode fibre cables.

Single mode photosensitive optical fibres GF1 were chosen for FBGs recording (Fig. 2).

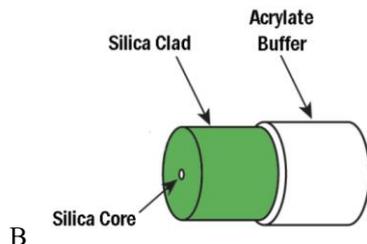


FIG. 2. Fiber construction [4].

The use of these fibres allows to reduce FBG-writing time, simplify splicing and achieve low attenuation. Shorter grating writing time is achieved by enhanced photosensitivity of the fibre. The enhanced photosensitivity is achieved by Ge doping of fibre cores resulting in high Ge concentration and yielding a larger effective refractive index change. Mode-matching to transmission fibres allows to minimise signal loss and distortions. The main specifications of GF1 optical fibres are as follows: clad diameter 125 \pm 1.5 μm , coating diameter 250 \pm 20 μm , core diameter 9.0 μm , operating temperature -55 $^{\circ}\text{C}$ to 85 $^{\circ}\text{C}$, numerical aperture (nominal) 0.13, operating wavelength (nominal) 1500 – 1600 nm [5]. Optical fibres GF1 are Restriction of Hazardous Substances (RoHS) compliant.

FBGs inscribed in single-mode fibres have been intensively investigated and widely employed in different types of sensors, including bending sensors, the designs of which often contain single-mode optical fibres [6]. The advantages of the sensors based on single-mode FBGs are reliability, wavelength encoded measurements, immunity

to electromagnetic interference and multiplexing ability [7]. But their sensitivity to temperature and strain complicates their usage and requires development of additional methods for temperature or strain compensation.

Typical spectral characteristics for uniform and tilted FBGs are given in Fig. 3.

For analysis of spectral characteristics of FBGs the following parameters can be used: Bragg wavelength (λ_B , wavelength of highest reflection), reflectivity, Full Width at Half Maximum (FWHM), side lobe suppression ratio (SLSR), and FBG reflection spectra shape asymmetry ratio (A_s). FWHM for FBG spectrum is measured at 50% of its maximum reflectivity. For sensor applications it is better to obtain the higher reflection peaks. As FWHM changes, e. g. with temperature or bending, it can be used for temperature and bending sensor applications [10]. The sharper the reflection spectra, the smaller the FWHM. The grating length and refractive index modulation influence the FWHM.

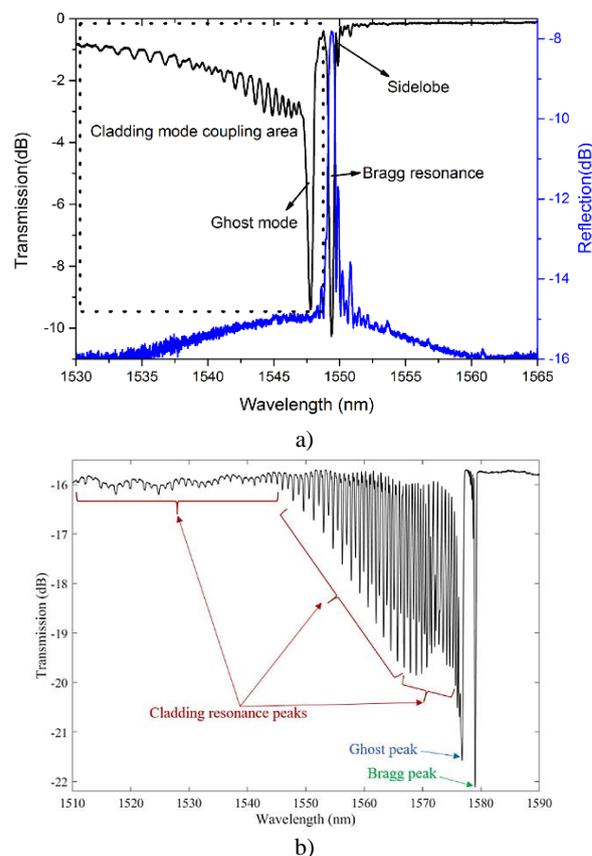


FIG. 3. Spectral characteristics for uniform FBG (a) [8] and tilted FBG (b) [9].

The relationship between reflectivity and grating length is dependent on FBG profile, e. g. for uniform FBGs 100% reflectivity is achieved at much lower grating lengths as compared with apodised (Gaussian or raised sine) FBG profiles. Reflectivity increases with index modulation increase. For uniform FBGs 100% reflectivity is achieved at much lower index modulation as compared with e. g. apodised (Gaussian or raised sine) FBG profiles. The bandwidth decreases with grating length and increases with index modulation. Side lobe suppression ratio (SLSR, the ratio between the FBG main lobe peak and the highest secondary neighbour peak) should be the highest to ensure

only the main reflection peak. The side lobe intensity increases with grating length and index modulation [11-12]. FBG reflection spectrum asymmetry ratio factor A_s (A_s 50% / A_s 10%) characterises the asymmetry of the spectrum peaks. In the case of full symmetry of the peak the A_s factor equals 1. According to the above-mentioned relationships between the main FBG parameters, the optimal grating parameters should be chosen depending on the sensor application.

Temperature sensitivity of FBGs is used in sensor applications [13]. Temperature changes cause changes in refractive indexes resulting in Bragg wavelength shift.

III. FBG FABRICATION AND INVESTIGATION

Uniform and tilted FBGs were inscribed in the cores of photosensitive optical fibres GF1 using UV excimer laser KrF (wavelength 248 nm) Coherent Bragg Star M and phase mask method. A uniform FBG has been inscribed with a pulse energy of 75 mJ and repetition rate of 20 Hz in 60 s. A tilted FBG has been inscribed with a pulse energy of 71 mJ and repetition rate of 50 Hz in 40 min. The phase mask method was used for FBG fabrication [14]. The phase masks of 1075.86 nm and 1080 nm pitch were used to fabricate the uniform and tilted FBGs, respectively. The length of the uniform and tilted FBGs were, accordingly, 6 mm and 10 mm.

The spectral properties of gratings were measured in a transmission, using setup including a climatic chamber, an AQ6370D Optical Spectrum Analyser, an S5FC1550S-A2 SM Benchtop SLD Source and a computer. In the case of measurements performed in transmitted mode the light from the SLD source was injected into an FBG, which reflected the Bragg wavelength λ_B back to the source. The light of other wavelengths passed through the FBG and was measured allowing the determination of the dip (notch) at the Bragg wavelength λ_B . The climatic chamber allowed to provide precise temperature measurements and determine temperature dependencies of FBG wavelengths. The temperature range of the measurements was from -40.6 °C up to 181.8 °C. The setup for measurement of FBG characteristics is given in Fig. 4.



FIG. 4. Setup for measurement of FBG characteristics.

The measured spectral characteristics of uniform and tilted FBGs at different temperatures are depicted in Figs. 5a and 5b, respectively. For the uniform FBG one can see the shift of the Bragg wavelength λ_B relative to the temperature. For the tilted FBG the transmitted wavelength of each particular peak is also shifted with the temperature. The analysed peaks for tilted FBG are depicted in Fig. 5b.

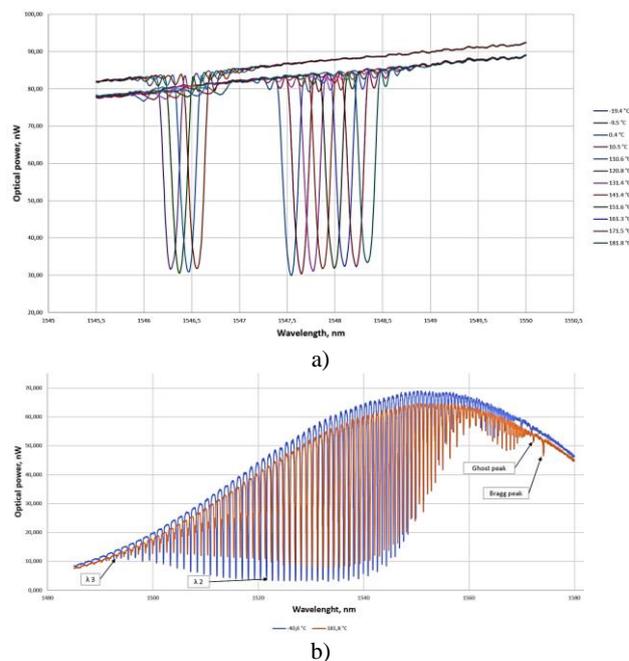


FIG. 5. Spectral characteristics of uniform (a) and tilted FBGs (b) at different temperatures (curve colours are assigned to different temperatures).

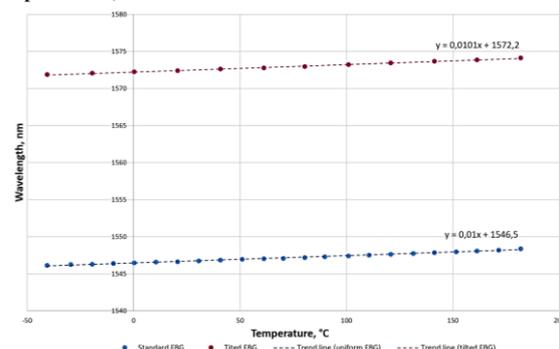


FIG. 6. Temperature dependencies of the Bragg line wavelength for uniform and tilted FBGs.

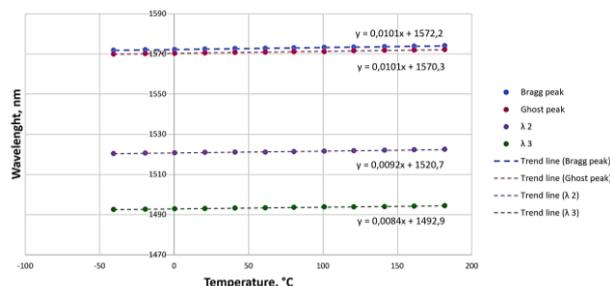


FIG. 7. Temperature dependencies of the peak wavelength (Bragg, Ghost, λ_2 , and λ_3) for tilted FBGs.

Temperature dependencies of the Bragg peak for uniform and tilted FBGs are given in Fig. 6. Temperature dependencies of different peaks in spectral characteristics, e. g. Bragg peak, Ghost peak, certain wavelength peaks (marked in Fig. 5b) for tilted FBG are shown in Fig. 7. As can be seen from Figs. 6 – 7, for fabricated uniform and uniform FBGs there is an approximately linear temperature dependence of the Bragg wavelength which simplifies calibration, not requiring complex electronic corrections. Temperature sensitivity of the FBG is determined by the slope of the line of temperature dependence of wavelength

(Figs. 5 – 6). For uniform FBG and tilted FBG, temperature sensitivities are dependent on temperature range: the highest temperature sensitivity (approximately equal to 11.1 – 11.4 pm / °C) was determined in a temperature range of 120.8 – 181.8 °C and the lowest temperature sensitivity (approximately equal to 8.5 – 8.9 pm / °C) was determined in a temperature range of -40.6 – 20.7 °C. For the above-mentioned FBGs, temperature sensitivities are also dependent on certain wavelength. As can be seen in Fig. 7, there are temperature sensitivity changes from 8.4 pm / °C for λ_2 to 10.1 pm / °C for the Bragg wavelength.

IV. CONCLUSION

The article describes fabrication of uniform and tilted FBGs and investigation of their spectral characteristics and temperature sensitivity dependencies. Analysis of the parameters and characteristics of fabricated FBGs has shown that the investigated uniform and tilted FBGs can be used in fibre-optic bending sensors. This guides the direction of our ongoing study.

AUTHOR CONTRIBUTIONS

L.H. – conceptualization, methodology, investigation, writing-original draft preparation, writing-review and editing, visualization; J.K. – methodology, investigation, writing-review and editing; I.H. – conceptualization, writing-review and editing, supervision.

COMPETING INTERESTS

The authors declare no conflicts of interest.

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Дослідження впливу температури на характеристики волоконної брегівської ґратки

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АНОТАЦІЯ У статті представлені результати дослідження волоконної брегівської ґратки (ВБґ). Було виготовлено два типи ВБР: однорідну та похилу. Вони були вписані в сердцевини волокон за допомогою УФ-ексимерного лазера KrF Coherent Bragg Star M та методу фазової маски. Для виготовлення ВБґ було обрано фоточутливі оптичні волокна GF1. Властивості та характеристики виготовлених ВБґ досліджувалися з метою розробки волоконно-оптичних сенсорів вигину. У цьому випадку вирішальним є аналіз спектральних характеристик ВБґ та залежностей температурної чутливості. Для вимірювання спектральних характеристик ВБґ та температурної чутливості використовувалася установка, що включає кліматичну камеру, оптичний спектральний аналізатор AQ6370D, настільне джерело SLD S5FC1550S-A2 SM та комп'ютер. Спектральні характеристики однорідних та похилих ВБР досліджувалися в діапазоні температур від -40,6°C до 181,8°C. Для аналізу було обрано наступні піки спектральних характеристик у вищезгаданому температурному діапазоні: пік Бреґга для однорідної ВБґ та такі піки, як пік Бреґга, побічний резонансний пік та три піки певної довжини хвилі для похилої ВБґ. Спостерігалися зміщення аналізованих піків спектральних характеристик з температурою. Були отримані температурні залежності довжин хвиль аналізованих піків. Було показано, що існує приблизно лінійна температурна залежність довжини хвилі Бреґга та інших згаданих вище аналізованих піків певної довжини хвилі. Лінійний характер досліджуваних температурних залежностей виготовлених ВБґ дозволяє їх використовувати в сенсорних застосуваннях. Було показано, що температурна чутливість однорідних та похилих ВБР залежить від обраного температурного діапазону. Було визначено температурну чутливість, що приблизно дорівнює 11,1 – 11,4 пм/°C у температурному діапазоні 120,8 – 181,8 °C та приблизно дорівнює 8,5 – 8,9 пм/°C у температурному діапазоні -40,6 – 20,7 °C для однорідної та похилої ВБР. Температурна чутливість залежала від певної довжини хвилі та змінювалася від 8,4 пм/°C до 10,1 пм/°C для досліджуваних довжин хвиль.

КЛЮЧОВІ СЛОВА волоконна брегівська ґратка (ВБґ), рівномірна ВБґ, похилена ВБґ, спектральні характеристики, температурна чутливість.



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