Fabrication of high reflectivity chirped fiber Bragg gratings and its sensing applications

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In this paper we present the fabrication technology of high reflectivity chirped fiber Bragg gratings (CFBGs) using the phase mask technique. In order to achieve gratings with high reflectivity, the optical fibers were hydrogen loaded prior photo-inscription process. We fabricated gratings having different chirps using phase masks with different chirp rates. The obtained chirped gratings had reflectivity of over 93% and they were rigorously tested. Particularly, the temperature and strain sensitivity of the chirped fiber Bragg gratings was derived. The CFBGs are attractive as intrinsic sensor elements, as fiber components for dispersion compensation, and as in fiber laser reflectors with an additional option of wavelength tunability, e.g. by temperature change.

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1. Introduction

During the last twenty years passive and active optoelectronics devices have been subject of great development, mainly thanks to the miniaturization possibilities of devices and also to the multiple advantages such as: flexibility, low optical power losses and low fabrication cost, brought by the new information transmission medium – the optical fiber. Among these, the fiber Bragg gratings (FBGs) are quietly revolutionizing modern telecommunication systems and are introducing a new optical fiber sensor [1].

A fiber Bragg grating consists of a periodic change in the refractive index of a fiber core caused by exposure of an interference pattern of an UV laser beam [2].

There are a several distinct types of fiber Bragg grating structures such as: the uniform Bragg grating characterized by a constant grating pitch (spacing between grating planes), the blazed Bragg grating which has the grating planes tilted with respect to the fiber axis, and the chirped Bragg grating (CFBG) that has a non-periodic pitch, displaying a linear variation in the grating pitch, called a chirp [3, 4].

The Bragg grating acts as a stop–band filter, i.e. when excited by a broadband source it reflects particular wavelength of light, called Bragg wavelength and transmits all other wavelengths. The Bragg wavelength is directly related to fiber grating parameters such as pitch and refractive index modulation. These parameters can be varied with the environmental changes of the fiber grating (i.e. temperature, strain applied along the fiber, vibrations) which leads to a corresponding Bragg wavelength shift. Therefore, a fiber Bragg grating has been used as an in-fiber optical filter to block certain wavelengths, such as a wavelength-specific reflector, or as a sensor (intrinsic sensing element) [1]. Furthermore, in the case of the chirped Bragg grating the reflected wavelength changes with the grating pitch, broadening the reflected spectrum and adding a new property called dispersion, because different wavelengths reflected from the grating will be subject to different delays. This property has been intensively used in the development of dispersion compensation in optical fiber communication systems.

There are mainly two fabrication techniques for the chirped gratings based on the axial change either of the grating pitch or of the refractive index of the core along the grating length [1, 5, 6]. Both techniques employee a phase mask placed closely behind a fiber core in order to obtain the UV interference photo-imprinted pattern. In the first case a phase mask having a chirped period is employed in fiber core photo-inscribed process, while in the second case a uniform phase mask is placed closed to the transition region of a tapered optical fiber [5, 6]. The first method has the advantages over the second one presented above due to its simpler writing process and more reproducible characteristics.

In this paper we report on strong CBFGs photo-written in a standard single mode fiber (OFS) using a conventional phase-mask technique [7] and 248 nm KrF excimer laser. This technique was combined with the hydrogen loading of the optical fibers prior the inscription process [8], in order to obtain chirped gratings with high reflectivity. We have fabricated CFBGs by employing chirped phase masks in the writing setup.

We used phase masks with different rates of the chirped pitch. We have also determined the temperature and the strain sensitivity of the Bragg wavelength for gratings with different chirps. The CFBGs are attractive as in-fiber sensing elements [6, 9, 10], as fiber components for dispersion compensation [11], and as in fiber laser reflectors with an additional option of wavelength tunability, e.g. by temperature change [12].

The paper is organized as follows: in Sect. 2 we present some theoretical considerations concerning the CFBG characteristics, in Sect. 3 we show the experimental setup together with relevant results and in Sect. 4 we draw the conclusions of this work.

2. Theoretical considerations

The center wavelength, λ_B, of the back-reflected light from a uniform FBG is called Bragg wavelength and is defined by [13]:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of the unperturbed mode in the fibre and Λ represents the grating pitch. Any physical influence on the optical fiber, such as strain or temperature, leads to the variation of the refractive index or of the grating pitch with subsequent change in the Bragg wavelength.

By differentiating Eq. (1), the dependence of the Bragg grating wavelength on strain and temperature, can be expressed as:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial\Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T \tag{2}$$

where $\Delta\lambda_B$ is the Bragg grating wavelength shift corresponding to a temperature variation ΔT and to a variation of FBG lenght Δl due to applied strain. In Eq. (2), the first term represents the strain effect, while the second one represents the temperature effect on the Bragg grating wavelength shift. By maintaining one of these parameters constant and by changing the other one, the temperature and strain sensitivity of the Bragg grating wavelength can be determined.

A chirped Bragg grating structure has a monotonically varying pitch, as illustrated schematically in Fig. 1. In this case the Eq. (1) becomes [1]:

$$\lambda_B(z) = 2n_{eff}(z)\Lambda(z) \tag{3}$$

Where z is considered along the fiber axis direction.

Considering a linearly chirped grating structure, the variation in the grating pitch is described by [1]:

$$\Lambda(z) = \Lambda_0 + \Lambda_c z \tag{4}$$

Where Λ_0 is the starting pitch (at $z = 0$), and Λ_c is the linear change along the lenght of the grating. The chirped grating can be understood if it is thought of as a series of smaller length uniform Bragg gratings with increasing pitch. A linearly CFBG has typically asociated with it a chirp given by a chirped value per unit length (Λ_c) and starting pitch (Λ_0).

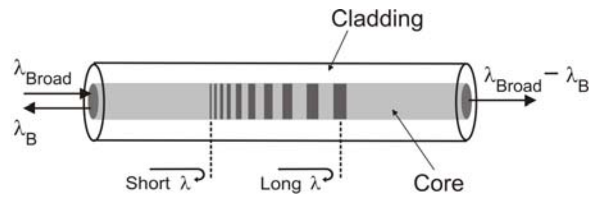


Fig. 1. A schematical representation of a chirped grating with an unperiodic pitch.

In our work, we fabricated chirped Bragg gratings varying the pitch of the gratings, by UV photo-imprinted phase mask technique. This method is based on the diffraction of UV light by a phase mask placed closely to the fiber. A phase mask with linearly varying pitch was employed in the UV writing set-up in order to expose the fiber core to a chirped light interference pattern, and consequently to obtain a linearly chirped Bragg grating having the start pitch and the chirp given by the phase mask characteristics.

3. Experimental setup and results

3.1 Fabrication of the CFBGs

The chirped Bragg gratings were imprinted into a core of standard single mode fiber (OFS) using phase-mask technique. An UV beam scanning system was implemented in order to get high quality gratings. The photo-printed process was carried out using a 248 nm KrF excimer laser COMPex by Lamda Physik GmbH. The UV laser beam was focused by the beam scanning system over a perpendicular direction to the phase-mask surface. The beam scanning system consists of a linear air-bearing scanning stage which supports the mounts of mirror, of cylindrical lens, and of a precision optical slit. This system allows to perform multiple scans over the fiber length during the photo-printing operation, and to control the width of the focused laser beam which determines the amount of light that illuminates the phase-mask. The mounts of mirror and of cylindrical lens can be moved in order to adjust beam orientation over the phase mask pitch.

Table 1. The phase masks characteristics.

Phase mask	Supplier	Central pitch (nm)	Chirp (nm/cm)	Illumwave (nm)
PM # 1	Ibsen	744.69	0.5	244
PM #2	Ibsen	714.00	1.4	248
PM # 3	Ibsen	715.00	7	244

The phase-mask was fixed into a support that provides reliably mount and position to it. The phase mask support includes a tilt platform that allows high precision two-axis angular alignment of the phase mask, and a high reliability motorized stage for phase mask positioning respect to optical fiber. The hydrogen loaded optical fiber was placed in close proximity behind the phase mask with the distance between the phase mask and the fiber at few micrometers level. The optical fiber was fixed, between two computer controlled motorized translation stages which moved parallel to the phase mask. During the alignment and photo-printing processes, the optical fiber was tensioned by applying a constant strain along the fiber axis. The fiber alignment was carried out by means of a high resolution camera equipped with a high magnification objective placed into structural rail gantry translation stage. The entire alignment components were precisely controlled by a computer, through a LabView program.

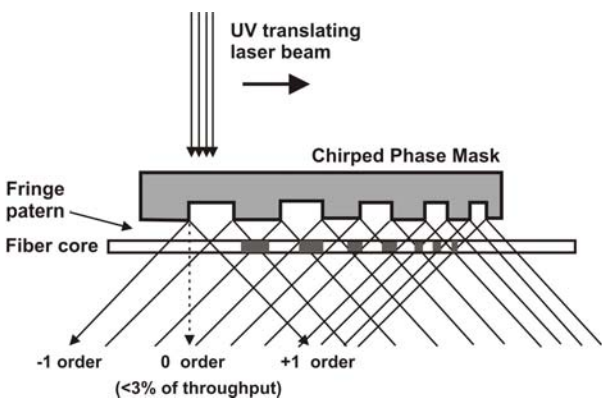


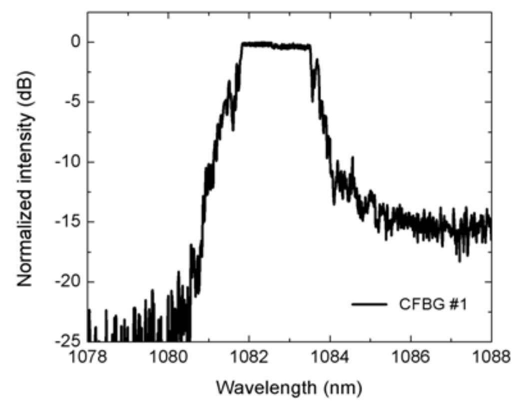
Fig. 2. A schematic diagram for UV laser beam diffracted through a chirped phase mask.

The phase mask consists of one-dimensional corrugation structure fabricated in a high fused silica flat transparent to the KrF excimer laser radiation (Fig. 2). The grating corrugation structure is designed to suppress the zero-order diffracted beam down to less than 3 % and to equally maximize plus- and minus-first orders (typically more than 35 %). The interference between the two orders (+1st and -1st) creates an interference pattern having half the phase mask period. During the writing process the interference pattern imprints a refractive-index modulation in the core of the photosensitive optical fiber, which was connected to a broadband light source and to an optical spectrum analyzer (OSA) in order to monitor the grating growth.

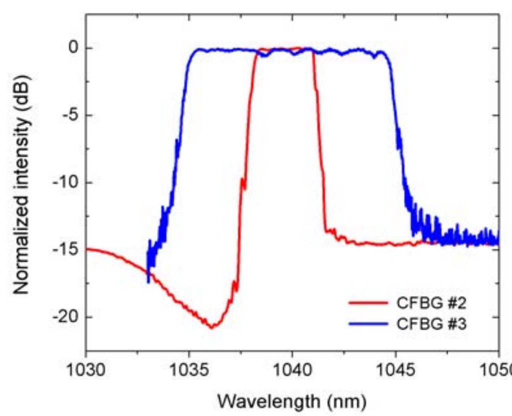
After the fabrication, the chirped Bragg grating can not be used immediately due to a high hydrogen concentration in the fiber which leads to an increased optical signal loss. Therefore, removing of the hydrogen from fiber grating is a necessary procedure known as fiber annealing.

The OFS fibers used in the experiments were loaded with hydrogen before writing the fiber Bragg grating. This technique, called hydrogen treatment or hydrogenation can increase the photosensitivity of the standard optical fiber, and consequently allowing us to obtain stronger grating characterized by a high reflectivity. We placed the OFS fibers in a pressure controlled hydrogen chamber for 7 days, at room temperature under pressure of 130 atm.

In this research, we have chosen 3 phase masks having different characteristics (such as chirp and central pitch) for photo-inscribing the CFBGs. The characteristics of the phase masks employed in our experiment (labeled as PM #1, PM #2 and PM #3) are presented in Table 1.



a)



b)

Fig. 3. Reflectivity spectra of the obtained CFBGs: a) CFBG #1, b) CFBG #2 and CFBG #3.

Table 2. Characteristics of the fabricated CFBGs such as: length, reflectivity, and measured strain and temperature coefficients.

Sample	Phase mask	Length (mm)	Reflectivity (%)	Temperature coefficient (pm/°C)	Strain coefficient (nm/N)
CFBG #1	PM #1	10	99.99	5.03	1.12
CFBG #2	PM #2	10	95	4.71	0.98
CFBG #3	PM #3	10	93	3.80	0.92

The photo-printed process was carried out with KrF excimer laser set to a repetition rate of 30 Hz and beam energy of 35 mJ. The longitudinal tension applied to the fixed fiber was equal to 1 N. The relative position between the phase mask and the fiber was adjusted to a few microns using the alignment program control. During the UV inscribing process the laser beam scanned the phase-mask surface from long pitch side to short pitch side, along the fiber axis (Fig. 2). The beam scanning rate was of 2.5 μm/s. To interrogate the CFBG we have used a broadband spectrum of an Yb-doped fiber ASE source, while the spectral response from the CFBG was displayed and measured using an optical spectrum analyzer (ANDO AQ6317B) with the resolution of 0.01 nm.

After the writing process, the fiber gratings were annealed, placing them into an oven, for 48 hours at 60 °C to out-diffuse the hydrogen.

The measured spectra of the obtained CFBGs (labeled as CFBG #1, CFBG #2 and CFBG #3), when these were interrogated from short wavelength to long wavelength of their Bragg resonances are shown in Fig. 3 a) and b). It can be observed that the broadening of CFBG reflected spectrum is strongly related to its chirp magnitude. The reflected spectrum of the CFBG becomes broader when the grating chirp increases (see Table 2 for phase mask employed in writing of every CFBG sample).

After the hydrogen annealing process, the measured reflectivity of the obtained CFBG spectra was typically over 93%, reaching a value of 99.99% which was corresponded to CFBG #1.

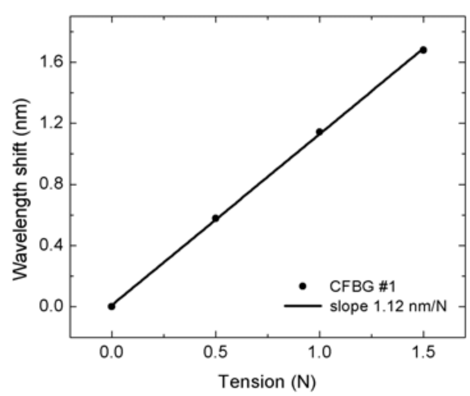
3.2 Sensing nature of the CFBGs

The characterization of the strain sensitivity of the obtained CFBGs was carried out by applying longitudinal tension to the grating using a fiber handling device and a computer control. The tension range was varied from 0 N to 1.5 N, or up to 4 N.

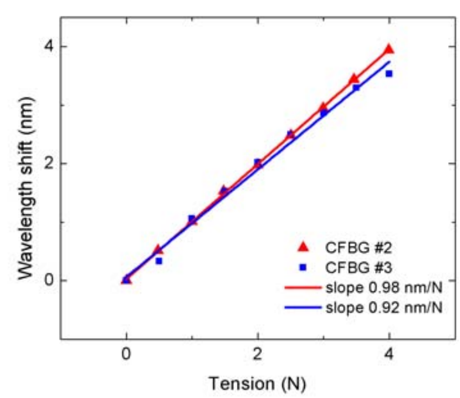
The temperature sensitivity measurements were made using an oven with a temperature accuracy of 0.1 °C. The gratings were fixed inside the oven and the temperature range was varied from 30 °C to 150 °C.

In both cases, the CFBGs under test were interrogated by connected them to the Yb-doped fiber ASE source, while the central Bragg wavelengths of their reflected spectra were measured using the OSA.

The central Bragg wavelength shifts of the reflected spectra of the three CFBG samples under tension versus the applied tension are presented in Fig. 4 a) and b).



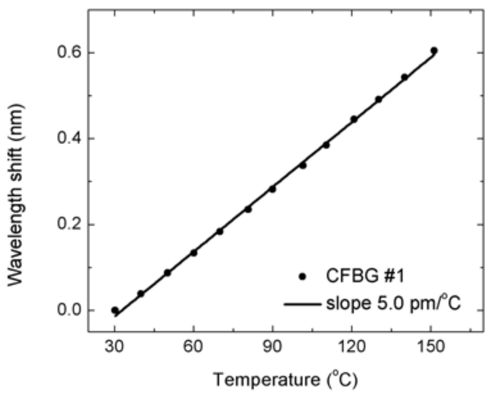
a)



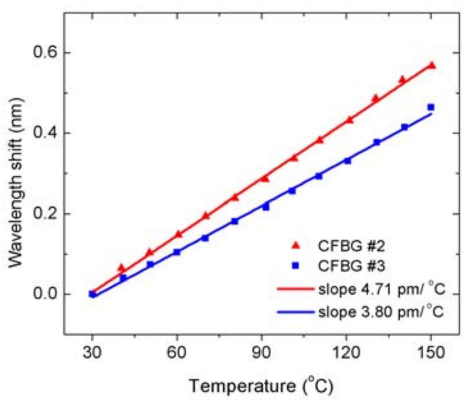
b)

Fig. 4. Dependence of the wavelength shift on applied tension corresponding to a) CFBG #1, b) CFBG #2 and CFBG #3.

In Fig. 5 a) and b) are represented the Bragg wavelength shifts with the temperature change for the obtained CFBG samples. Characteristics of the fabricated CFBGs such as: length, reflectivity, measured strain and temperature coefficients are summarized in Table 2. As it is seen in Table 2 the temperature sensitivity coefficients were different for different grating chirps, but their values were within the sensitivity range of a few pm/^{o}C. The sensitivity of CFBGs under tension was around 1 nm/N with slight variation respect to the grating chirp value.



a)



b)

Fig. 5. Dependence of the wavelength shift on temperature corresponding to a) CFBG #1, b) CFBG #2 and CFBG #3.

4. Conclusions

Strong CFBGs were fabricated into a core of standard optical fiber, by UV photo-imprinting using phase mask technique. The fibers were highly hydrogen loaded prior to the photo-inscription process in order to increase the photosensitivity. We have fabricated three samples of chirped fiber Bragg gratings using phase masks having different chirp rates. We have obtained chirped fiber Bragg gratings having high reflectivity of over 93% after the hydrogen annealing process. We have also measured the temperature and the strain sensitivity of the Bragg wavelength. It was observed that the period structure has effect on the broadening spectrum of the CFBG and on the Bragg wavelength shift corresponding to temperature and applied strain changes. The fabricated CFBGs could be used as temperature and strain sensors, and in fiber laser reflectors having high reflectivity, with an additional option of wavelength tunability, e.g. by temperature change.

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