Analysis of Different Writing Techniques for Chirped Fibre Bragg Gratings

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***Abstract* — Writing techniques for chirped fibre Bragg grating with a linear chirp profile are compared. Larger bandwidths are achieved when small subgrating lengths are used in stitching technique. Values of bandwidth and group delay for each technique are presented, as well as its inherent complexities.**

I. INTRODUCTION

Gratings in fibre optics where the Bragg wavelength changes linearly or nonlinearly along the grating length are known as chirped fibre Bragg gratings (CFBG). In long haul optical communication systems, fibre dispersion (about 17 ps/nm · km for standard fibres) degrades system performance [1]. An alternative to the dispersion compensating fibres are CFBG, which are of particular interest since they are compact, low-loss, and polarization insensitive devices.

Nowadays, the two main approaches for grating fabrication are the holographic method [2] and phase mask technique [3]. The use of phase masks for producing fibre Bragg gratings (FBG) is more attractive because of its repeatability. Several techniques have been developed to fabricate CFBG; one method involves the use of a chirped phase mask. However, a chirped phase mask is expensive, and the fabricated gratings exhibit fixed group delay characteristics. To overcome this deficiency, other methods have been proposed. In this work, different methods to produce CFBG are implemented and analyzed.

II. THEORY

A fibre Bragg grating is a periodic modulation of the refractive index in the core of an optical fibre. When the FBG is illuminated with a broadband light it will reflect a narrowband portion of this electromagnetic spectrum, consisting of a coherent scattering from the index variations. The strongest interaction or mode-coupling occurs at the Bragg wavelength λ_B given by

$$\lambda_B = 2 n_{eff} \Lambda \ , \qquad (1)$$

where n_{eff} is the modal index and Λ is the grating period.

A CFBG is an FBG where there is a dependence of λ_B with the axial position along the FBG. Therefore a CFBG can be seen as an FBG in which a specific injected wavelength is reflected at a characteristic position of the grating. The simplest CFBG is obtained when the variation on the period is linear,

$$\Lambda(z) = \Lambda_0 + \Lambda_1 z \ , \qquad (2)$$

where Λ_0 is the initial period and Λ_1 is the linear variation along of the grating length (z).

There are two different alternatives in order to modify the λ_B along the grating. One option is to longitudinally change the refractive index of the fibre core [4] and the other is to create an axial variation of the period of the grating [5].

In this paper, we present the inscription of chirped FBG with an arbitrary group delay response using a uniform phase mask, based on three different techniques. The first one is the stitching method [6]. The second method makes use of two exposures to create an axial change in the refractive index of the fibre core. The last one is based on an axial change of the mean refractive index with a single exposure, but with a different exposure time along the grating length.

All techniques are employed with a photosensitive optical fibre and an excimer UV laser (248 nm, *BraggStar S-Industrial LN*). The reflectivity and group delay were measured using the Agilent 86038B Photonic Dispersion and Loss Analyzer (ONA). The simulations were carried out with the commercial software *Optiwave Gratings*.

III. IMPLEMENTATION

A. Stitching Method

With this method, it is possible to write an FBG with a length higher than the length of the phase mask. The fibre is kept static, while the set composed by the mirror, slit, lens, phase mask and the UV beam is moved longitudinally along the fibre (Fig.1). This recording method depends on the *S* (exposure length): lower *S*-values result in higher precision at the expense of a slower recording speed. This process evolves according to a file that establishes the steps which correspond to the values of displacement of the stage. Each exposition writes the pattern defined by the phase mask onto the fibre; when the first exposition is completed, the set moves and then another exposition is performed after the first one. This process continues until the desired length is obtained. At the end of the process, the FBG is composed by various sections (subgratings) stitched together in phase.

In the CFBG each stitching process presents a phase shift that increases or decreases with grating length. The resultant grating will show a delay response that is dependent of the evolution of the induced phase shifts. The exposure time in each point is the same, maintaining the mean refractive index.

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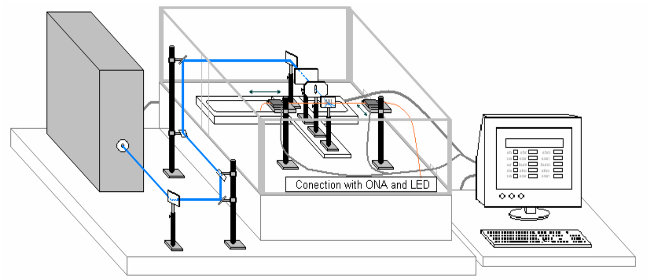

Fig. 1.Schematic diagram of CFBG fabrication setup.

B. Double Exposure

In the double exposure method, we start by inscribing a uniform FBG. This grating is written using a uniform phase mask, scanned by a UV beam at constant speed. After writing the FBG, the phase mask is removed and a post-exposure is made in order to obtain a change in the mean refractive index along the fibre (Fig. 2). Afterwards the uniform FBG is transformed in a CFBG as the scan speed for the post-exposure process changes with the position along the grating, inducing a variable mean refractive index profile.

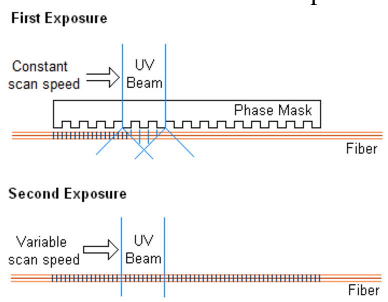

Fig. 2. Schematic diagram of CFBG fabrication with double exposure.

C. Phase Mask with Variable Scan Speed

This method is the simpler among the three used ones, because the UV beam moves with variable scan speed directly over the phase mask (Fig. 3). In this case, besides the periodic modulation in the refractive index along the fibre, also the amplitude average profile changes along the grating.

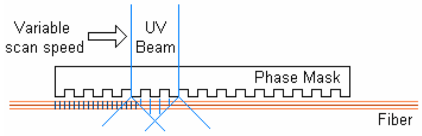

Fig. 3. Schematic diagram of CFBG fabrication with phase mask technique with variable scan speed.

IV. RESULTS

A. Stitching Method

Before obtaining a CFBG we started to simulate the dependence of the wavelength shift ($\Delta\lambda_B$) due to a constant phase shift between each subgrating $\phi(z)$. The simulations were repeated for different subgrating lengths (S), where S is a multiple of the grating period, keeping constant the length of all gratings (15 mm). The grating simulated with S = 50 µm presents 300 sections and the other grating with S = 250 µm has only 60 sections. The Figure 4 shows the dependence of $\Delta\lambda_B$ as a function of the normalised phase shift ($\phi(z)/\Lambda$), when the period of each subgrating is Λ = 532.5nm.

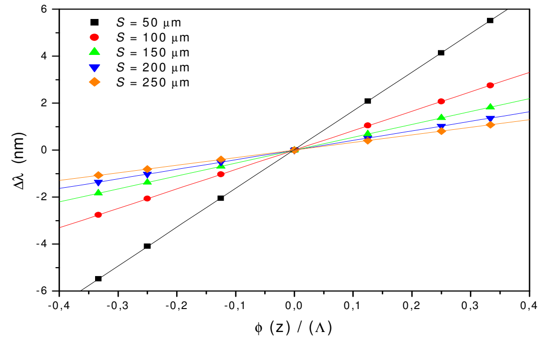

Fig. 4. Shift wavelength $\Delta\lambda_B$ as function of $\phi(z)/\Lambda$ for different subgrating lengths (S).

The results show a shift in the wavelength with $\phi(z)/\Lambda$ and S, as expected. Furthermore, $\Delta\lambda_{B\ 50} = 2 \times \Delta\lambda_{B\ 100} = 3 \times \Delta\lambda_{B\ 150} = 4 \times \Delta\lambda_{B\ 200} = 5 \times \Delta\lambda_{B\ 250}$, where the subscript 50, 100, 150, 200 and 250 refers to the subgrating lengths multiple of the grating period (S) and the simulation points are consequence of the phase shift introduced in each stitching process ($S+\phi(z)$). This study was realized to make possible the project of CFBG with an arbitrary bandwidth. The Figure 4 makes possible to establish a relation for the bandwidth $\Delta\lambda_{B\,i,f}$ for any value of S.

$$\Delta\lambda_{B\,i,f} = \left[0.00571 + 16.51817\frac{\phi(z)_{i,f}}{\Lambda}\right]\frac{50.40985}{S}\ , \qquad (3)$$

where the resulting bandwidth is obtained by adding the initial and final wavelength shifts, $\Delta\lambda_{B\,i,f} = \Delta\lambda_{Bi} + \Delta\lambda_{Bf}$.

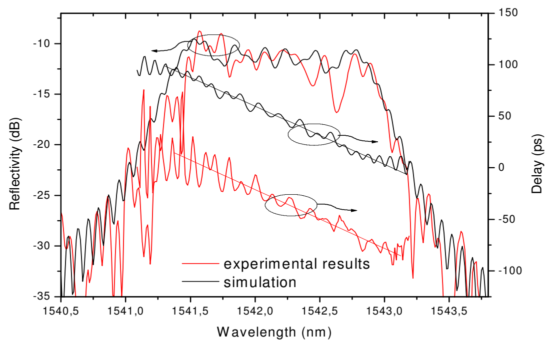

Fig. 5. Reflectivity and group delay of the resultant CFBG with a linear chirp profile.

The Figure 5 shows a CFBG projected with the use of Equation 3, with bandwidth of 1.6 nm, using S = 150.165 µm, initial phase shift of $\phi_i(z)/\Lambda$ = -0.1455Λ and final phase shift of $\phi_f(z)/\Lambda$ = +0.1435Λ. The CFBG presents a total length of

10 mm and it was written and simulated with 66 subgratings, showing that the experimental and simulation results are in good accordance. The measured bandwidth and dispersion are 1.63 nm and -56.32 ps/nm for simulated grating and 1.50 nm and -57.05 ps/nm for recorded grating.

In order to demonstrate that it is possible to achieve CFBG with higher bandwidths by using the stitching method, Fig. 6 shows the reflection spectra and the group delay of two CFBG simulated with S = 100 µm and S = 150 µm, with a linear chirp profile, resulting in a bandwidth of 8.3 nm and 5.5 nm, respectively. The phase shift introduced in each stitching process increases from (-0.5Λ) up to (0.5Λ).

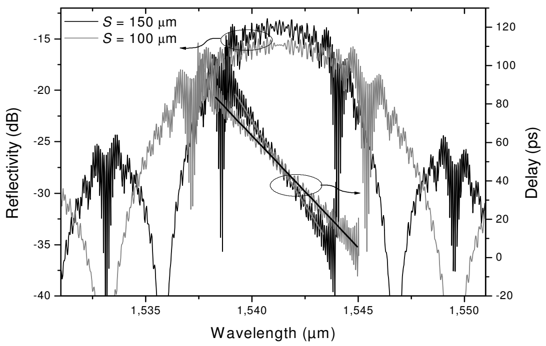

Fig. 6. Spectra of two CFBG with a linear chirp profile.

The spectral shape in the Fig. 6 is due to the fact that the CFBG are simulated with the maximum value of ϕ(z)/Λ, resulting in destructive interference in the grating's extremities. The dispersion is indirectly proportional to the bandwidth.

In order to achieve satisfactory results with this method, the precision in the positioning of the set phase mask/UV beam is critical, presenting a relative error bellow 10 nm. With higher errors, undesired phase shifts between sections will degrade the spectrum.

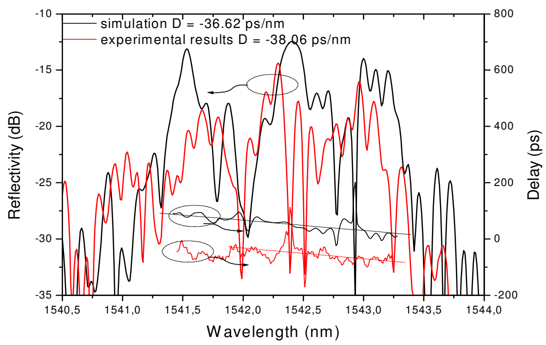

Fig. 7. Reflectivity and group delay of the resultant CFBG with random phase shift errors between sections.

The grating shown in Fig. 7 was simulated and recorded with the same parameters of grating in Fig. 5, but with an added random phase shift fluctuation between sections within the range -60 nm < ϕ(z) < 60 nm, where the spectral degradation can be observed.

B. Double Exposure

The key point of the technique relies on determining the correct speed of the post-exposure scan along the FBG axis.

This in turn leads to the designated chirp profile that dependent of the average increase of the refractive index along the FBG, and it depends on the UV exposition energy at each exposed point.

The Fig. 8 depicts the wavelength shift and increment of the refractive index with increasing writing energy of a uniform FBG.

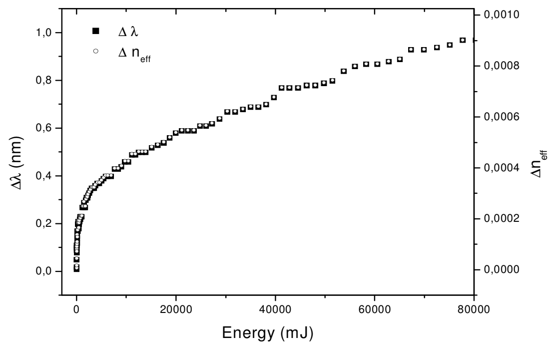

Fig. 8. Increment of the refractive index UV-induced and wavelength change as function of the accumulated energy.

After the first exposure a uniform modulation in the refractive index of fibre is obtained, producing a uniform FBG. With the second exposure which employs a non-linear scan-speed profile (right axis in Fig. 9), the average index along the fibre increases linearly with the grating length (left axis in Fig. 9), resulting in the CFBG with linear chirp.

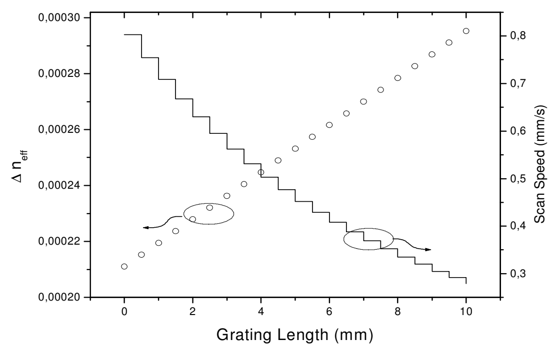

Fig. 9. Scan speed for a linear function of the refractive index increment.

The minimum and the maximum speeds are calculated to provide the energy necessary to increment of the refractive index along the grating, according to Fig. 8. The overall effect is that the wavelength reflected at each point of CFBG will be slightly different, provoking a broadening of the spectral width and a shift in the central wavelength. This effect can be seen in the Fig. 10, where are shown three spectra (left axis): a uniform FBG, a chirped grating obtained after a post-exposure with non-constant exposition time and a simulated CFBG with the same parameters.

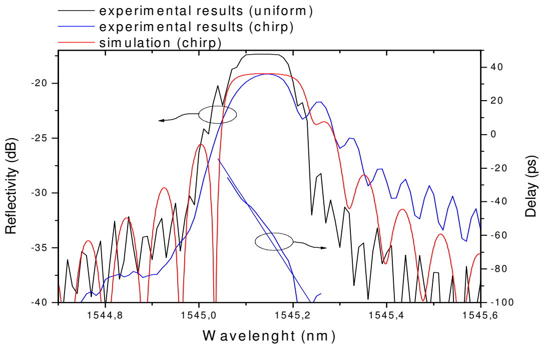

Fig. 10. Spectra of three gratings: a uniform FBG, a FBG with a non-uniform post-exposure and a simulated CFBG.

The uniform grating, with 10 mm length, was written with a scan speed of 0.81 mm/s with 3.5 mJ per pulse and 500 Hz of repetition rate. For the non-uniform post-exposure, the speed of scanning UV-beam changed between 0.279 mm/s to 0.803 mm/s, resulting in a CFBG with $\Delta\lambda = 0.2$ nm. As it was expected, the group delay obtained is a linear function, resulting in a dispersion of -432.37 ps/nm (right axis).

C. Phase Mask with Variable Scan Speed

In this method was used the data set of Fig. 8, but only with a single exposure with scan speed similar to the used in second step of the double exposure method (Fig. 9), resulting in a linear chirp profile. Energy of 3.5 mJ per pulse was used at 500 Hz repetition rate. The maximum scan speed was 2.876 mm/s and the minimum 0.033 mm/s, resulting in a CFBG with $\Delta\lambda = 0.5$ nm and 20 mm length (Fig. 11).

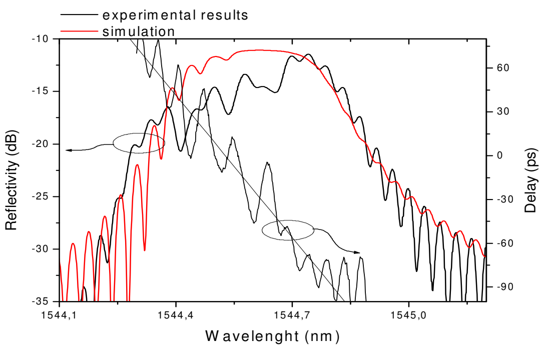

Fig. 11. Reflectivity and group delay of the CFBG written with phase mask technique with variable scan speed and a simulated CFBG.

V. COMPARISON BETWEEN THE THREE METHODS

In the stitching method, when small values of S are used, it is possible to achieve devices with larger bandwidths with higher precision, but more time is necessary. With this method it is possible to produce gratings with controllable chirp; presenting the additional advantage of maintaining constant the average refractive index along the device, but it is necessary a very high precision positioning system to avoid phase errors when various sections are stitched together.

The double exposure and the phase mask technique with variable scan speed are less sensitive to positioning errors, when compared to the stitching method. Nevertheless, these methods still require a positioning system with accurate speed control. The disadvantages of these methods are due to the facts that the average refractive index changes along the grating and the flexibility to produce gratings with arbitrary length is limited, depending on the size of the phase mask.

The phase mask technique with variable scan speed results in higher bandwidths when compared to the bandwidths obtained with the double exposure method. This is due to the fact that in this method, besides the change of the average refractive index due to a different writing energy, the visibility of interference fringes also changes along the grating. Therefore, this method can be used to obtain higher bandwidths, but with lower symmetry in the final device.

VI. CONCLUSION

We compared three different methods for the production of CFBG: the stitching method, when the necessary accuracy is attainable, is the most efficient; it allows obtaining gratings with higher bandwidths and high precision ($\Delta\lambda = 8.3$ nm $\leftrightarrow$ $S = 100$ μm). The other two methods, the double exposure and the phase mask technique with variable scan speed, are less sensitive to vibration and less demanding. The phase mask technique with variable scan speed allowed to reach bandwidths bigger (0.5 nm) than the double exposure technique ($\Delta\lambda = 0.2$ nm), however resulting in spectral asymmetric devices.

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