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Direct Accurate Determination of the Spatial Refractive Index Profile in Bragg gratings

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Abstract

We show that by measuring the temporal phase of the pulse response of a fibre Bragg grating with a current-induced phase-shift, the magnitude of the phase-shift and the corresponding refractive index distribution can be accurately determined.

1. Introduction

Fibre Bragg gratings (FBG's) with one or more phase shifts along their length are called phase-shifted gratings [1]. Typically, the grating phase shift is introduced by imposing a spatial gap between two gratings during fabrication, or by introducing an additional variation of the effective refractive index n_{eff} along the fibre through post-exposure/processing [2]. Assuming that the distribution of the effective refractive index variation along the fibre is $\Delta n_{eff}(x)$ from point x_1 to point x_2, the resultant phase shift becomes $\phi = \frac{4\pi}{\lambda_B}\int_{x_1}^{x_2}\Delta n_{eff}(x)dx$, where λ_B is the Bragg wavelength of the grating.

Typically, the phase shift produced by an effective refractive index change is distributed. An example of how to achieve this is shown in Fig.1. A fine tungsten wire is put in contact with a uniform FBG and an electric current is passed through the wire. The heat produced by this will affect the grating because the temperature increase causes an increase in the refractive index in the fibre, which consequently will produce a phase shift in the grating. If the electrical current is tuned, different temperatures and hence different current-induced phase shifts can be obtained. This principle forms the basis of the OCDMA (optical code division multiple access) encode/decoders with multiple tunable phase shifts that we have demonstrated in the past [3].

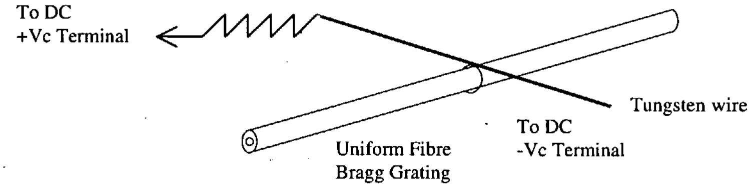

Fig.1 An FBG with a wire induced distributed phase shift

In the design and application of FBG's with tunable and distributed phase-shifts, it is essential to know two features of the grating [3]. One is the relationship between the applied electric current to the wire and the resulting induced phase-shift, and the other is the spatial distribution/extension of this.

Some insight to the index-distribution can be gained by measuring the spectral response of the grating and comparing it with a theoretical spectrum of assumed phase-value and distribution. However, this method is indirect and many parameters affect the reflection spectra and so it becomes difficult to obtain accurate results. Another possibility is to use inverse scattering characterisation methods [4].

In this paper, we propose a new simple method to directly measure the current-induced phase shift and spatial refractive index distribution in a Bragg grating. This method is based on the measurement of the pulse response of the grating. We derive a direct relationship between the refractive index distribution and the temporal phase of its pulse response. With this method, we experimentally characterise a tunable phase-shift grating with different applied values of electrical currents.

2. Characterisation principle

The characterisation is based on measuring the impulse response of the FBG. A short optical pulse is reflected from the phase shifted FBG. This reflected pulse is the convolution of the input pulse and the impulse response of the grating. If the input pulse is short compared to the length of the grating, the reflected pulse can be approximated by the impulse response of the grating.

If the measured FBG is weak, the spatial phase of the grating will cause an equivalent temporal phase in its impulse response due to the time-space conversion relationship [5]. Thus, the magnitude of the temporal phase in its impulse response relates directly to the magnitude of the spatial phase shift of the grating.

Furthermore, the distribution of the current-induced refractive index change can be derived from the temporal phase distribution of its impulse response. By differentiating the temporal phase ϕ with respect to time t, and considering that the differentiation of the temporal phase with respect to the time is a frequency shift [6],

$$\Delta\omega = -\frac{\Delta\phi}{\Delta t} \tag{1}$$

Then, simply by substituting the formulae $\Delta\omega = -\frac{2\pi c}{\lambda^2}\cdot\Delta\lambda$ and $\Delta\lambda_B = 2\cdot\Lambda\cdot\Delta n_{eff}$ into (1), we can obtain a relationship between the temporal phase distribution and the current-induced refractive index distribution as

$$\Delta n_{eff} = \frac{\lambda\cdot n_{eff}}{2\pi c}\frac{\Delta\phi}{\Delta t} \tag{2}$$

3. Experimental results

To characterise a grating with a tunable temperature-induced phase-shift, we fabricated a 17mm long uniform grating in a standard photosensitive fibre, and placed a $19\mu m$ diameter tungsten wire, 8mm from one end, in direct contact with the grating. The coupling coefficient of the grating is ~67m^{-1}, its peak reflectivity and bandwidth is 66% and 0.1nm respectively. A 23-ps pulse generated by an electro-absorption modulator (EAM) is reflected from the grating, and the reflected pulse is measured by the EAM frequency-resolved optical gating (EAM-FROG) technique [7]. A current of 70mA then is applied to the wire yielding a net temperature increase of 20-25 °C. In the experiment, the centre wavelength of the 23-ps input pulse is matched to that of peak reflection wavelength of the grating ~1550nm.

The measured intensity and phase profiles of the reflected pulses are shown in Fig.2a. These show that the measured temporal phase-shift for the applied wire current is $\sim 0.96\pi$. The corresponding refractive index distribution calculated using Equation 2 is plotted in Fig.2b.

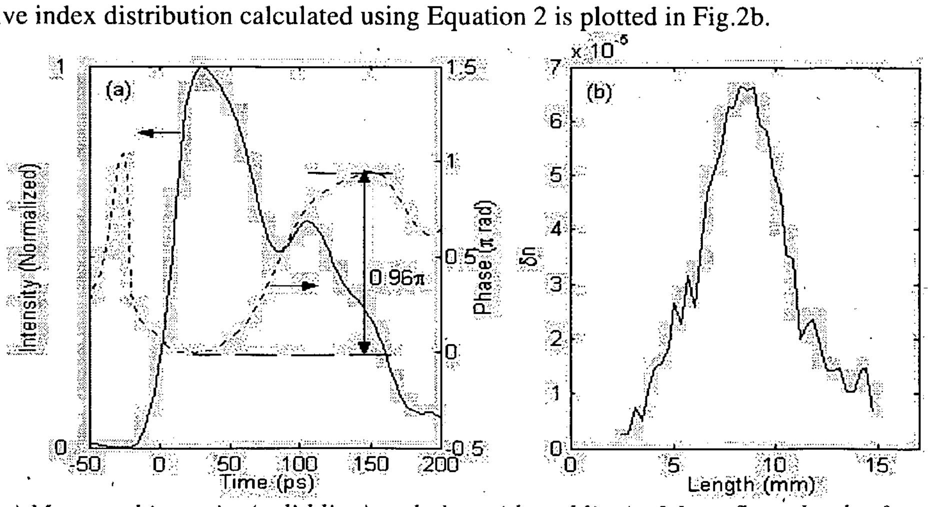

Fig.2 (a) Measured intensity (solid line) and phase (dotted line) of the reflected pulse from the grating with a wire-current of 70mA. (b) Corresponding retrieved effective refractive index change.

Phase-shifts and refractive index distributions for applied currents of 52mA, and 84mA were also measured, and these were found to be roughly 0.47π and 1.45π respectively. The details of these measurements will be presented at the conference.

4. Discussion

As mentioned above, the measurement is based on two basic principles. Firstly, the input pulse is very short so its impulse response is approximated by its pulse response. Secondly, the reflectivity of the measured grating is relatively weak so the temporal phase of the grating impulse response directly gives the grating structure. The following simulation is used to assess the accuracy of these two basic assumptions.

In the simulation, we utilise similar grating and input pulse characteristics as in the experiment. An effective refractive index variation distribution corresponding to a distributed spatial phase-shift of π, plotted in Fig.3a, is added to a uniform grating with a coupling coefficient of $67m^{-1}$. The theoretical temporal phase of its 23-ps pulse response is plotted in Fig.3b. As demonstrated the calculated amplitude of the temporal phase-shift is 0.93π. The deviation between the assumed spatial phase-shift of π and the theoretically recovered temporal phase-shift of 0.93π we believed to be caused by the relatively high peak reflectivity of 66% of the grating. Using Equation 2, the retrieved refractive index distribution is calculated from Fig.3b and shown in the solid line of Fig.3c. Comparing the initial (dotted line) and the retrieved (solid line) refractive index variation distribution, we can find that the distribution is slightly smeared near its maximum, which might be due to the input pulse width of 23ps. It is worth noting that this type of simulation can give an indication to the experimental accuracy of the retrieved results.

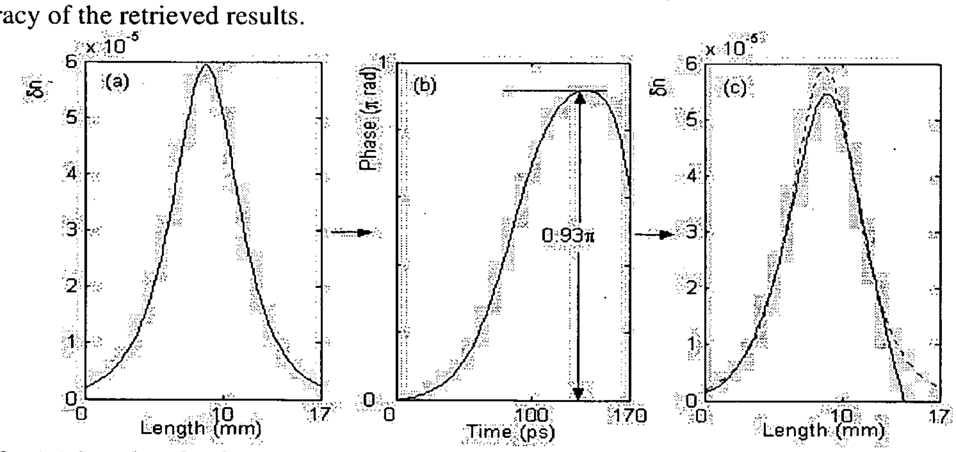

Fig. 3 (a) Simulated refractive index variation distribution of an FBG with a π phase shift.
(b) Temporal phase distribution of the reflected pulse from the grating (23ps input pulse)
(c) Retrieved (solid line) and assumed (dotted line) refractive index variation

5. Conclusion

In conclusion, we have proposed and experimentally demonstrated a new method to directly measure the current-induced phase shift and refractive index distribution in a tunable phase-shift Bragg grating. An advantage of the reported method is that the local effective refractive index distribution only depends on the temporal phase of the impulse response. We believe that this method will be useful when characterising complex super structure profiled Bragg gratings.

References

[1] T. Erdogan, *Journal of Lightwave Technology*, **15**, pp. 1277-1294, (1997).
[2] J. Canning *et al.*, *Electronic Letters* **30**, pp. 1344-1345, (1994).
[3] M. R. Mokhtar *et al.*, *IEEE Photonics Technology Letters* **15**, pp. 431-433, (2003).
[4] J. Skaar *et al.*, *IEEE Journal of Quantum Electronics* **39**, pp. 1238-1245, (2003).
[5] P. C. Teh *et al.*, *Journal of Lightwave Technology* **19**, pp. 1352-1365, (2001).
[6] R. Trebino *et al.*, *Review of Scientific Instruments* **68**, pp. 3277-3295, (1997).
[7] C. Dorrer and I. Kang, *IEEE Photonics Technology Letters* **16**, pp. 858-860, (2004).