Spectral filtering using fibre Bragg grating embedded Sagnac loop mirror

L. Men, P. Lu and Q. Chen

An approach to achieve spectral filtering is proposed, using a fibre Bragg grating (FBG) embedded polarisation maintaining fibre Sagnac loop mirror (SLM) through temperature tuning. The opposite temperature sensitivities of the FBG Bragg resonance wavelengths and the interferometric peaks of the fibre SLM, as well as their pronounced difference in bandwidth, provide an opportunity to realise spectral filtering.

Introduction: Fibre Sagnac loop mirrors (SLMs) attract considerable interest for their applications in optical communications, optical test and measurement, with the merits of low insertion loss, broad useful spectral bandwidth and high resistance to environmental changes [1]. In applications such as multi-wavelength fibre lasers, wavelength tunability is required, which is accomplished through a wavelength-selective comb filter. A wavelength-selective comb filter incorporating a fibre SLM shows significant advantages over other reported techniques with regard to the wavelength control capability. Most of the reported filters lack flexibility, except that some of them are tunable in the absolute position of the output or the channel spacing in which more complicated configurations such as figure-eight shaped loop devices are adopted [2]. To achieve polarisation-independent laser output, polarisation maintaining fibre (PMF) Sagnac loop mirrors incorporating specialty fibres have been reported recently, such as erbium-ytterbium codoped PMF [3], elliptical core side-hole fibre with elliptical or circular shape cladding [4], or PM photonic crystal fibre [5].

In this Letter, we propose and demonstrate a tunable SLM incorporating a fibre Bragg grating (FBG) embedded polarisation maintaining fibre (FBG-PMF) to achieve spectral filtering by temperature tuning. To the best of our knowledge, the proposed scheme is the first to combine the advantages of the Bragg resonance peak of the FBG and the interferometric pattern of the SLM for wavelength control, which renders FBG with more functionalities in wavelength control in addition to the wavelength locking [6]. As shown in Fig. 1, the experiment was carried out on a fibre SLM with a broadband light source (EBS-7210, MPB Communications, Inc.) incident on a singlemode 50:50 fibre coupler and the detection of the transmission spectra was achieved by an optical spectrum analyser (OSA, Ando AQ6315E) after the two light beams passing through a polarisation controller (HP 11896A) and a 10 cm FBG embedded 210 cm PMF (PANDA, Thorlabs), for which a section of 35 cm containing the grating section was placed in a heating tube with a temperature resolution of 0.1°C. The two light beams share the same physical path by passing through the fibre Bragg grating and the polarisation maintaining fibre (PMF) in counterpropagating directions and form the Sagnac interferometer when they re-enter the fibre coupler. Details on the fabrication of the FBG can be found elsewhere [7]. The fast-axis Bragg resonance wavelength of the FBG is 1546.013 nm with a reflection of 3.30 dB and the slow-axis Bragg resonance wavelength is 1546.385 nm with a reflection of 4.39 dB.

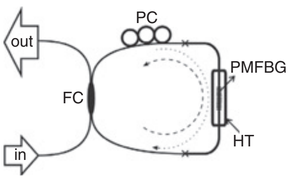

Fig. 1 *Schematic illustration of experimental setup*

PC: polarisation controller; FC: fibre coupler; HT: heating tube

Results and discussion: The optical intensity transmission spectrum $T(\lambda)$ of the SLM can be calculated using the Jones matrix representation with an expression [5]

$$T(\lambda) = \sin^2\left(\frac{\pi LB}{\lambda}\right) \tag{1}$$

where L and B are the length and the birefringence of the PMF, respectively, and λ is the operation wavelength. When the temperature changes along a length l of the PMF containing the FBG, a second-order Taylor series expansion around an initial temperature T_0 can be deduced from (1):

$$T(\lambda) = \sin^2\left(\frac{\pi L}{\lambda}B(T_0) + \frac{\pi l}{\lambda}\frac{dB(T)}{dT}(T - T_0)\right) \tag{2}$$

An SLM interferometric peak occurs when the phase of the sine function in (2) equals $k\pi$, where k is an integer. The corresponding SLM interferometric peak wavelength is

$$\lambda_k = \frac{LB(T_0)}{k} + \frac{l}{k}\frac{dB}{dT}(T - T_0) \tag{3}$$

Thus the gradient of the SLM peak wavelength due to the changes in the environmental temperature and the birefringence is

$$\frac{d\lambda_k}{dT} = \frac{l}{k}\frac{dB}{dT} + \frac{l}{k}\frac{d^2B}{dT^2}\Delta T \tag{4}$$

The birefringence B of a PMF can be expressed as $B = n_s - n_F$, where n_S and n_F are the effective refractive indices corresponding to the slow-axis and the fast-axis of the PMF, respectively. The Bragg resonance wavelengths of an FBG in a PMF, λ_i, in which the subscript i stands for the slow axis ($i = s$) or fast axis ($i = f$), correspond to the centre wavelength of the light back-reflected from the grating along the slow- and fast-axis, which depends on the effective index of refraction of the core (n_i) and the periodic spacing of the grating ($\Lambda_{\text{FBG-PMF}}$) through the relationship $\lambda_i = 2n_i\,\Lambda_{\text{FBG-PMF}}$. Parameters such as n_i and $\Lambda_{\text{FBG-PMF}}$ are both sensitive to a change in strain or temperature. Fig. 2 shows the transmission spectra of the FBG embedded SLM with the environmental temperature varying from 20 to 60°C, and the enlarged curves indicate the redshifted transmission spectra of the FBG at the two temperatures. The SLM interferometric pattern indicates a relatively broad bandwidth with a 3 dB bandwidth of 2.10 nm; however, the FBG exhibits a narrow 3 dB bandwidth (0.13 nm) in its Bragg resonance wavelength. The birefringence B of a PMF is given by $B = B_G + Bs_o + B_S$ [8], where B_G is the geometrical component, B_{So} is the self-stress component, and B_S is the outer stress-component. In the PANDA fibre the modal birefringence components B_G and B_{So} are zero. B_S can be expressed as

$$B_S = \frac{\alpha_T(T - T_S)n_1^3(P_{11} - P_{12})(1 + \upsilon)}{(1 - \upsilon^2)}\frac{(r_2 - r_1)}{(r_2 + r_1)} \times \left\{1 - \frac{3}{b^4}(r_2 - r_1)^4\right\} \tag{5}$$

where T_S is the softening temperature of the optical fibre core (about 690°C), T is the environmental temperature surrounding the fibre, and all other parameters are constants as defined in [8]. Therefore, the birefringence B of a PANDA PMF can be simplified as $B = -aT + b$, where a and b are constants, calculated to be 4.4×10^{-7} °C^{-1} and 3.1×10^{-4}, respectively.

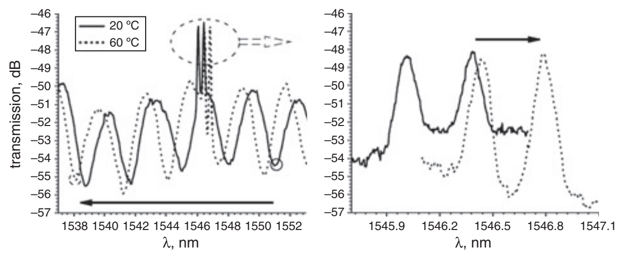

Fig. 2 *Transmission spectra of FBG-PMF Sagnac loop mirror at 20 and 60°C*

Enlarged curves show redshifts in Bragg wavelengths of FBG along both slow and fast axes

Fig. 2 indicates that the slow-axis and fast-axis Bragg resonance wavelengths of the FBG redshift with the increasing temperature from 1546.385 and 1546.013 to 1546.78 and 1546.43 nm, respectively. However, the difference between the two Bragg wavelengths decreases from 0.372 to 0.350 nm owing to the decrease of the birefringence with the increasing temperature, which is evident from the simplified expression of B and the relationship between the Bragg wavelength and the refractive index of the fibre. One SLM peak wavelength of 1550.900 nm at 20°C with the corresponding k value of 420 blueshifts to 1538.025 nm at 60°C, exhibiting a wavelength shift of 12.875 nm. For the interferometric peak wavelength of the FBG as a function of increasing temperature, the two

Bragg resonance wavelengths redshift linearly with the increase in temperature, as shown in Fig. 3. The temperature sensitivities of the Bragg resonance wavelengths along the slow axis and fast axis are 9.875×10^{-3} and 10.425×10^{-3} nm/°C, respectively. The SLM peak wavelength at $k = 420$ as a function of temperature shown in Fig. 3 indicates blueshift with a temperature sensitivity of 3.219×10^{-1} nm/°C. Equation (4) can thus be expressed as $d\lambda_k/dT = -a\frac{l}{k}$ and $d(d\lambda_k/dT)/dk = al/k^2$. The values of the fibre length or the interference order, which are experimentally selectable, can be used to change the output transmission properties, in which change of the fibre length is easier to achieve. The value of $d(d\lambda_k/dT)/dk$ here is 5.2 pm/°C, indicating that the wavelength difference of neighbouring maxima during a temperature change of 40°C can be resolved by the OSA (maximum wavelength resolution 50 pm). On the other hand, a short fibre can be adopted to tune the spectral characteristics as a whole without changing the wavelength difference between neighbouring transmission maxima during temperature change. If the fibre is shorter than 0.5 m in this case, the change in the wavelength difference will be negligible as it cannot be detected by the OSA. The possibility of adjusting the fibre length provides an opportunity to satisfy specific applications.

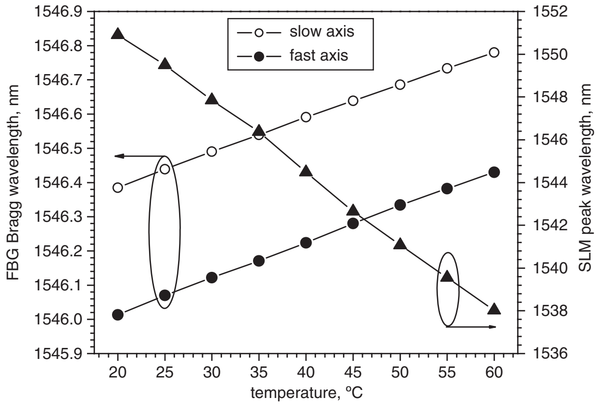

Fig. 3 *Temperature dependences of FBG-PMF Sagnac loop mirror*

Dots stand for Bragg resonance wavelengths of FBG along either slow axis or fast axis. Triangles represent interferometric peak wavelengths of SLM with $k = 420$

Conclusions: We present a tunable SLM incorporating an FBG embedded polarisation maintaining fibre to achieve spectral filtering by temperature tuning. In this scheme, the interferometric peaks of the SLM and the Bragg resonance wavelengths of the FBG exhibit opposite temperature sensitivities. The proposed SLM possesses comb-like transmission characteristics, where the spectral characteristics can be tuned as a whole through temperature adjustment and the wavelength differences between neighbouring transmission maxima during temperature change can be intentionally set to be constant or variable through judicious selection of fibre length or interference order.

Acknowledgments: This research has been supported by the Natural Sciences and Engineering Research Council of Canada, Canada Research Chairs Program, Canada Foundation for Innovation, the Province of Newfoundland and Labrador, and the Memorial University.

13 November 2008
doi: 10.1049/el.2009.3237

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