A Wide Range Tunable Fiber Bragg Grating Using Fast Changeable Electromagnetic Force

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ABATRACT

We demonstrate a silica-based tunable fiber Bragg grating (TFBG) filter with a wavelength tuning range over 60 nm. A magnetically TFBG package is employed to obtain a wide wavelength tuning range from 1540 to 1602 nm which covers the entire C band and most of the L-band. TFBG is achieved by varying an input current to a solenoid, resulting in an electromagnetic force, used as a strain (tension and compression) on the FBG. This approach is fast, has a broad band of tuning wavelengths and achieves a power reduction as no continuous supply of power is needed to maintain the set shift, due to the latch system used. This novel TFBG device can have a variety of applications in optical fiber communication systems such as programmable optical add/drop multiplexers (OADMs), dispersion compensators and tunable lasers.

Keywords: tunable fiber Bragg grating, electromagnetic force, strain.

1. INTRODUCTION

With the increasing use of dense wavelength division multiplexing (DWDM) in today's telecommunication industry, fiber Bragg gratings (FBGs) are widely used in various telecommunication and sensing applications due to the tunable properties of Bragg wavelength [1], flat top spectral response, narrow line-width and low insertion loss that makes FBG attractive for filtering and routing of different closely spaced wavelengths of light. The Bragg wavelength of a FBG can be tuned by changing the temperature [2] or by applying mechanical strain [3-5]. Changing the temperature of the FBG results in a slow wavelength shift; hence, a small tuning range is achieved (1.4 nm/100 ^{o}C at 1550 nm). Mechanical tuning of the FBG results in a faster and large response in terms of wavelength shift (12 nm/1% strain at 1550 nm).

Recently, several mechanical tuning setups have been reported. One of the methods is that a FBG is mounted on a flexible beam where the beam was applied by an axial compressive strain [6]. The tuning range of 90 nm was achieved, but it has many problems related to the FBG bending [7]. FBG embedded in a triangular beam of carbon-fiber material showed a tuning range of 2 nm and a repeatability of less than 0.4%. Based on the principle of a trapezoidal beam of uniform strength, a tuning range of 12.52 nm was achieved [8]. It has been demonstrated that, large wavelength shifts up to 45 nm can be achieved by using piezoelectric actuators along with the beam bending method [9]. However, such devices were usually bulky and costly, due to the need of high voltage amplifiers (1000 V, 100 W) and two piezoelectric actuators.

In this paper, a simple magnetically tunable FBG device for tuning the Bragg wavelength is proposed. The device description is presented in Section 2. The principle of operation is discussed in Section 3. Results and discussions are presented in Section 4, followed by a conclusion in Section 5.

Photonics North 2010, edited by Henry P. Schriemer, Rafael N. Kleiman, Proc. of SPIE Vol. 7750,
77501R · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.871527

2. DEVICE DESCRIPTION

A schematic diagram of the magnetically TFBG device is shown in Fig. 1. The device consists of two steel closely spaced programmable magnets (solenoids), with dimensions of L = 10 cm long and 2 cm in diameter. The solenoids have 5000 turns and could produce a magnetic flux density of B = 0.754 T with a current of 120 mA at the initial separation between the two magnets x = 1.85 cm. One of the programmable magnets is fixed and the other is movable. The movable programmable magnet is attached to the fiber cable which includes a 10 mm FBG. Its other end is attached to a lockable system as will be shown in Section 3.

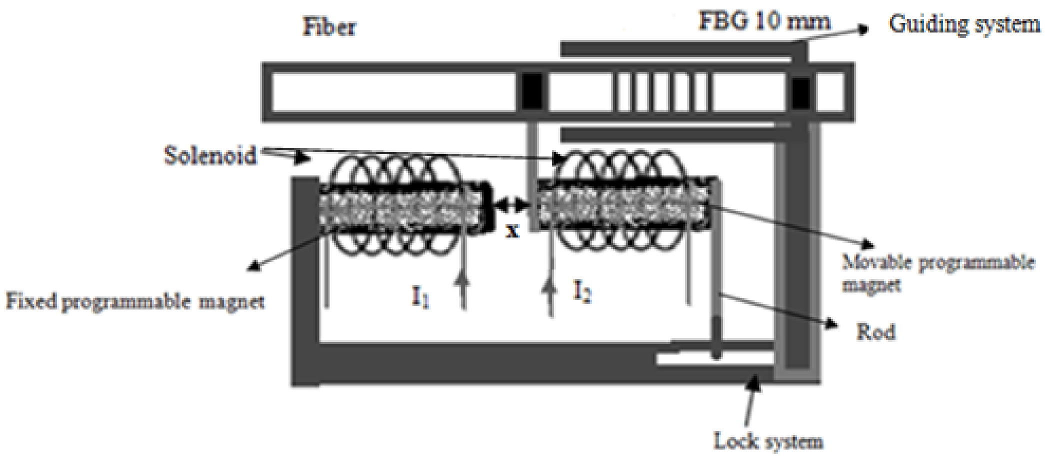

Fig. 1 Schematic of magnetically-tunable fiber Bragg grating device.

The fiber containing the Bragg grating is epoxy bonded on one side of the grating to the movable magnet and on the other side is fixed as shown in Fig. 1. It is inserted in a guiding system to avoid buckling. The programmable magnets are then magnetized in a controllable manner using input currents I_1, I_2 such that the two magnets are magnetically attracted or repulsive and move closer or away from each other. This, in turn, strains the FBG by tension or compression respectively and shifts the Bragg grating wavelength. A key advantage of this approach is that once the programmable magnets are magnetized, no continuous supply of power to achieve the set shift. This is due to the lock system, as the movable magnet is bounded by a rod, this rod moves freely when current is applied (tuning the wavelength shift) and stuck (hold its place) when there is no current. This reserves the shift gained in the TFBG system when no current is applied.

3. PRINCIPLE OF OPERATION

The TFBG depends on the input current which produces an electromagnetic force; this force is used to apply a strain on the FBG as tension or compression. The Bragg grating wavelength shift, $\Delta\lambda_B$, depends on the magnitude of this induced force. The force between two identical magnet solenoids placed end to end is given by [10]

$$F = \left[\frac{B^2 A^2 (L^2 + r^2)}{\pi \mu_0 L^2}\right]\left[\frac{1}{x^2} + \frac{1}{(x+2L)^2} - \frac{2}{(x+L)^2}\right] \quad (1)$$

where A is the cross-sectional area of each pole (= πr^2), r is the radius of each magnet, L is the length of each magnet, x is the separation between the two magnets and μ_o is the free space permeability. B is the magnetic flux density of solenoid which depends on the effective length, L, with a current, I, through, N, loops and a relative permeability, μ_r, as

$$B = \mu_o \mu_r NI/L \tag{2}$$

Substituting Eq. (2) in Eq. (1), one can get the electromagnetic force that depends on the current I as

$$F = \left[\frac{I^2 N^2 \mu_r^2 \mu_o A^2 (L^2 + r^2)}{\pi L^4}\right]\left[\frac{1}{x^2} + \frac{1}{(x+2L)^2} - \frac{2}{(x+L)^2}\right] \tag{3}$$

Controlling the strength of the applied magnetic field (by changing the solenoid current) alters the magnetization in the two magnets; thus affecting the magnetic force and hence, the fiber grating wavelength shift, $\Delta\lambda_B$, which is given by [11]

$$\Delta\lambda_B = \lambda_B.(1-P_e).\ \varepsilon \tag{4}$$

where $\varepsilon = \Delta L/ L$ is the axial strain (tensile or compressive) imposed on the FBG and P_e is the effective strain-optic constant, defined as [11]

$$P_e = \frac{n_{eff}^{\ 2}}{2}.\{P_{12} - \nu(P_{11} + P_{12})) \tag{5}$$

where P_{11} and P_{12} are components of the strain-optic tensor, and ν is the Poisson's ratio. For a typical silica optical fiber $P_{11} = 0.153$, $P_{12} = 0.273$, $\nu = 0.17$ and $n_{eff} = 1.5$ [7, 8]. This results in $P_e = 0.22$ and for a wavelength shift of -49.608 nm, the required axial compression strain change, ε, is ~ 4 %.

Through E, the modulus of elasticity, and A, the fiber outer cross-sectional area, the strain, ε, is defined as

$$\varepsilon = F/E.A \tag{6}$$

Therefore, the grating wavelength shift can be written as

$$\Delta\lambda_B = \frac{\lambda_B (1-P_e)}{E.A}\left[\frac{I^2 N^2 \mu_r^2 \mu_o A^2 (L^2 + r^2)}{\pi L^4}\right]\left[\frac{1}{x^2} + \frac{1}{(x+2L)^2} - \frac{2}{(x+L)^2}\right] \tag{7}$$

For a typical silica based fiber, E = 72.5 GPa and the outer fiber diameter is 125 µm.

Figure 2 displays the electromagnetic force as well as the grating wavelength shift against the solenoid current. The electromagnetic force depends on the direction of currents. If I_1 and I_2 are at the same direction, this causes a repulsive force resulting in the compression on FBG which achieves negative wavelength shift. On the other hand, if I_1 and I_2 are at opposite directions, an attractive force is obtained, resulting in the stretching of FBG and a positive wavelength shift. For example, when applying a current (at the same direction) $I_1 = I_2 = 113$ mA, a magnetic flux density B = 0.709 T is achieved. In this case, the electromagnetic force F = -35.583 N (repulsive force) giving a compressive strain ε = 4% and a wavelength shift, $\Delta\lambda_B$ = - 49.608 nm.

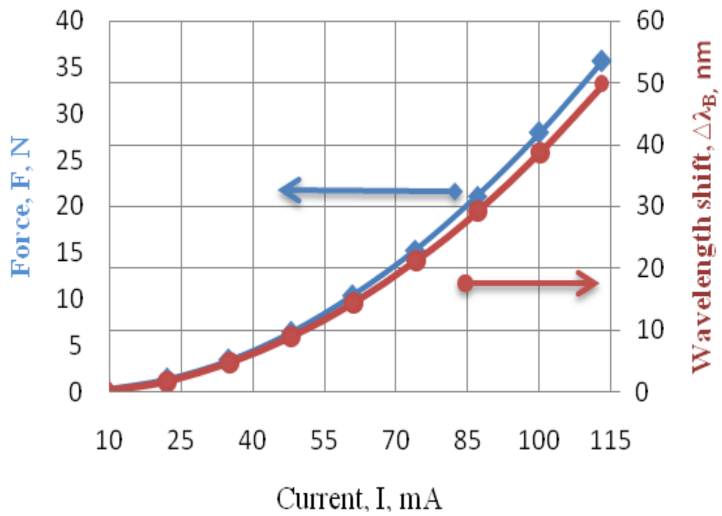

Fig. 2 The electromagnetic force and grating wavelength shift against solenoid current.

3.1 FBG Strain Ranges

Typical mechanical properties of a FBG are indicated in Fig. 3. Although a tensile breaking strength of an optical fiber without writing the grating is up to 6000 MPa, it drops to about 700 MPa during the grating process [11]. The tensile strength is reduced by the fiber's exposure to high intensity ultraviolet radiations during manufacturing using the phase mask technique, which is being widely used to manufacture FBGs due to its simplicity. The 700 MPa tensile strength gives a strain of only around 1 % in tension strain, which can theoretically give a wavelength shift of about 12 nm according to Eq.(4).

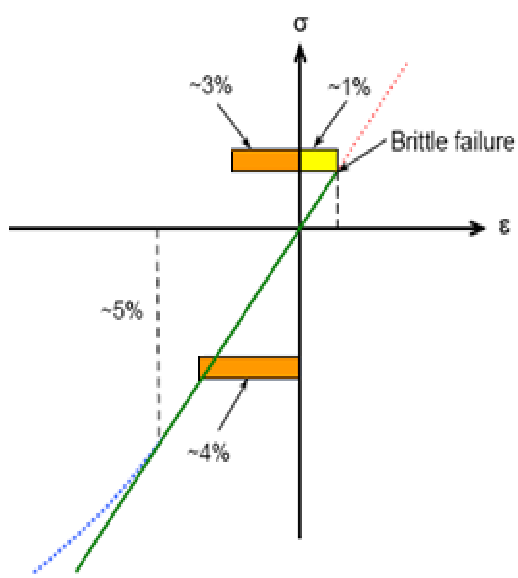

Fig. 3 Stress-strain relationship for an optical fiber [12].

Typically, an optical fiber is up to 20 times stronger in compression than that in tension. Also, a compression strain up to 5% is linear (no deformation in the fiber when relaxed) as shown in Fig. 3. In this system, to achieve the 5% needed strain that gives an overall shift in Bragg wavelength of 62 nm, only 1 % of tension can be applied as shown in Fig. 3. Therefore, the reaming 4% is achieved from the compression strain. The only technical problem is that it is very difficult to compress a thin optical fiber because of buckling, so, one adds a guiding system to avoid buckling.

3.2 FBG and Tuning System Parameters

The FBG used in this system has a length of 10 mm with Δn, the modulation of the refractive index, of 0.00022, Λ, the Bragg grating period of 0.53µm and n_{eff} = 1.5. These FBG parameters gives the proposed TFBG system a Bragg wavelength of 1590 nm at ε = 0%. This gives a full wavelength half maximum (FWHM) bandwidth of 0.3 nm and a reflectivity of about 98.4%.

4. RESULTS AND DISCUSSIONS

4.1 Stretching a 10 mm FBG

Figure 4-a displays the FBG under stretching. The grating period, Λ, will increase from 0.530 to 0.534 µm to achieve the required strain ε = 1%. Figure 4-b shows a sample of the reflectivity of the FBG during stretching. Any desired Bragg wavelength shift can be achieved in this range just by changing the applied current. The maximum wavelength shift achieved is $\Delta\lambda_B$ = 12 nm, corresponding to ε ~ 1%.

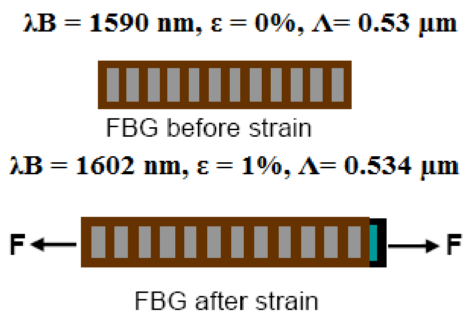

Fig. 4-a. Tension strain on FBG.

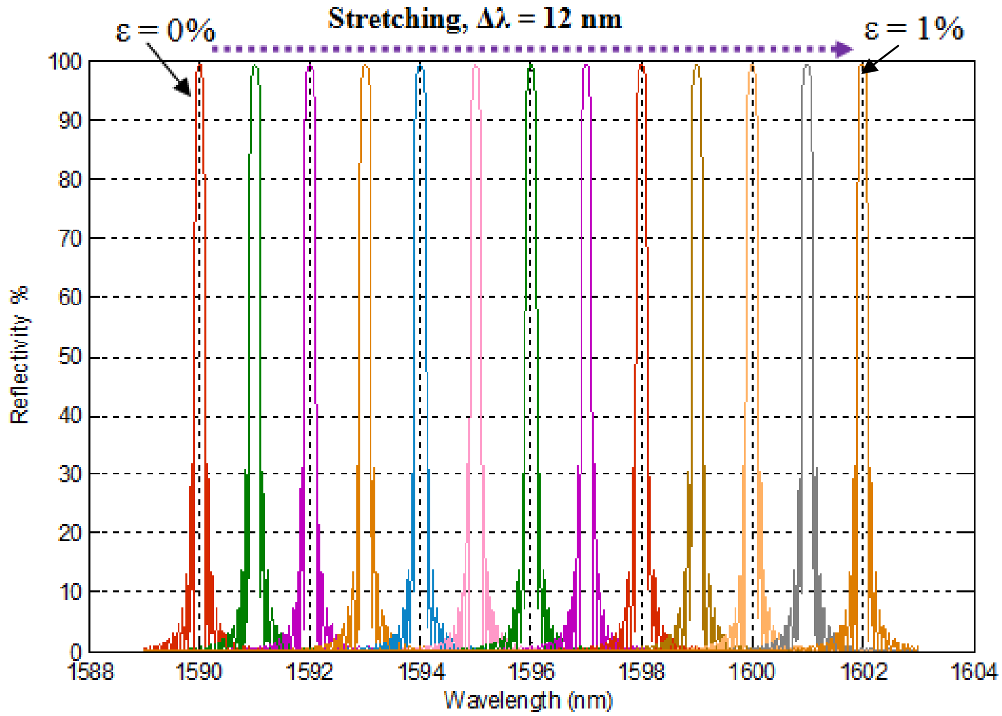

Fig. 4-b. Reflectivity of a 10 mm FBG during stretching.

Due to the tension strain, the FBG length is increased. This will result in the change of the peak reflectivity of Bragg wavelength and FWHM. Figure 5 shows the evolution of the peak reflectivity of the Bragg wavelength during stretching. The variation in peak reflectivity is around 0.11 dB. Also, the evolution of the FWHM (-3dB), bandwidth during stretching, is presented in Fig. 5. The variation in bandwidth is around 0.002 nm. Both variations are well below the Bellcore standards requirement of ± 0.5 dB for peak reflectivity variation and ± 0.1 nm for bandwidth variation [11].

4.2 Compressing of 10 mm FBG

Figure 6-a shows the FBG under compressing. Λ will decrease from 0.530 to 0.513 µm to achieve the required strain $\varepsilon = -4\%$. Figure 6-b shows the FBG reflectivity during compressing. Similar to the stretching condition, any desired Bragg wavelength shift can be achieved in this range just by changing the applied current. The maximum wavelength shift achieved is $\Delta\lambda = -50$ nm, corresponding to $\varepsilon \approx 4\%$.

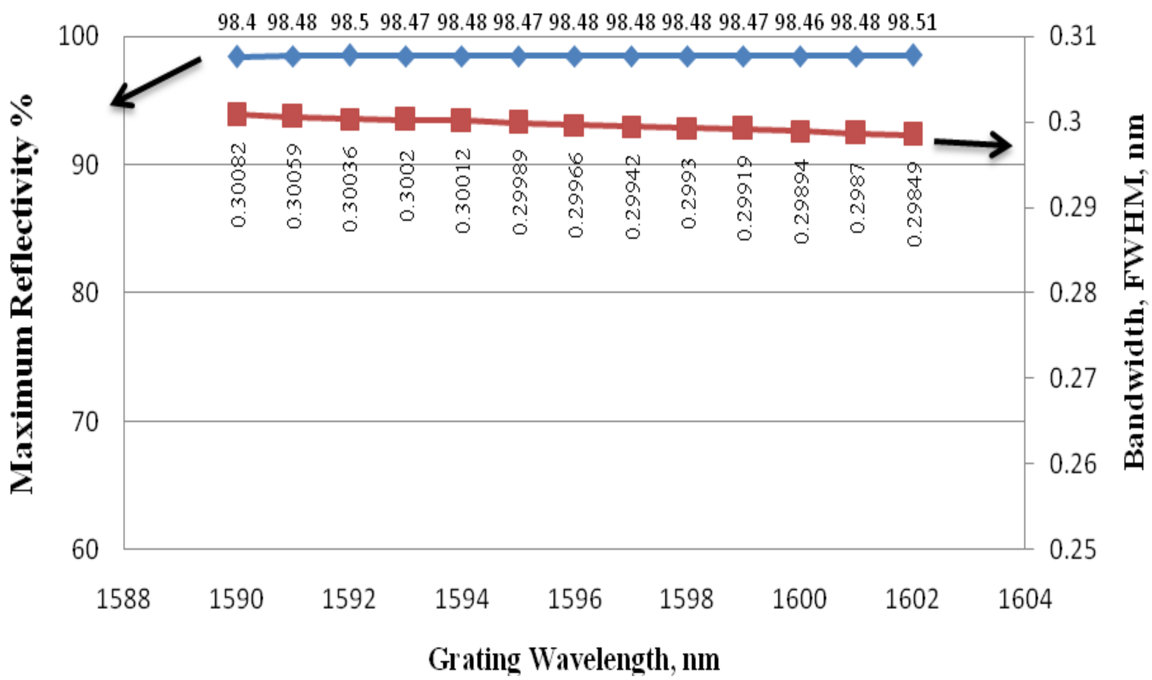

Fig. 5. FBG peak reflectivity and (FWHM) bandwidth variation during stretching.

Due to the compression strain the FBG length is decreased, resulting in a change of the peak reflectivity of Bragg wavelength and FWHM. Figure 7 shows a sample of the evolution of the peak reflectivity of the Bragg wavelength during compression as well as the FWHM bandwidth. The variation in peak reflectivity is around 0.46 dB and in bandwidth is around 0.02 nm. Like the tensile case, both variations are well below the Bellcore standards requirement of ± 0.5 dB for peak reflectivity variation and ± 0.1 nm for bandwidth variation [11].

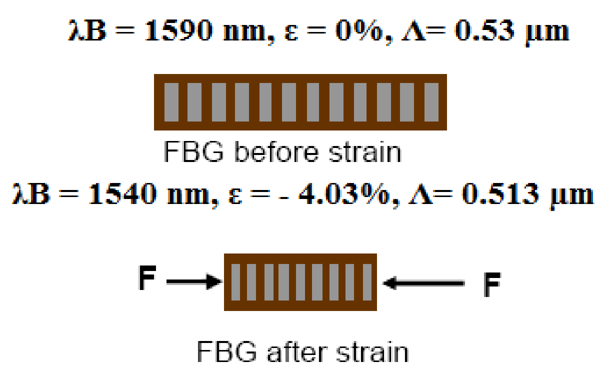

Fig. 6-a. Compression strain on FBG.

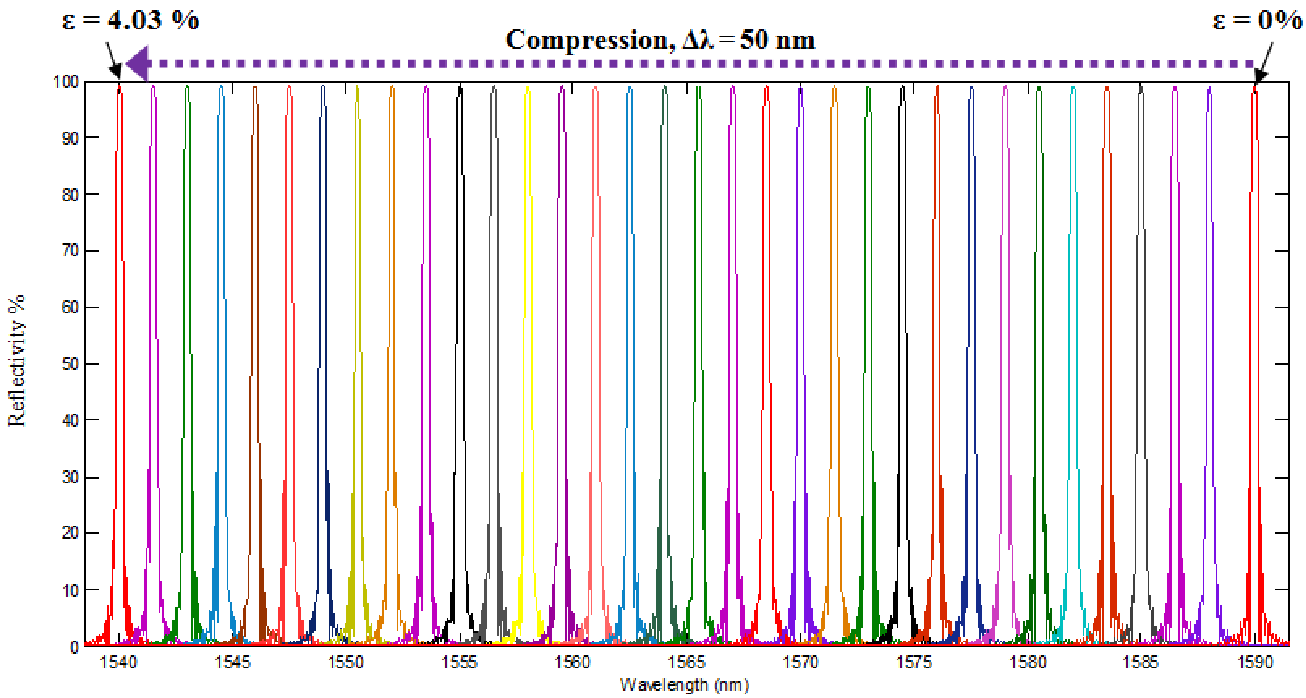

Fig. 6-b. Reflectivity of a 10 mm FBG during compression.

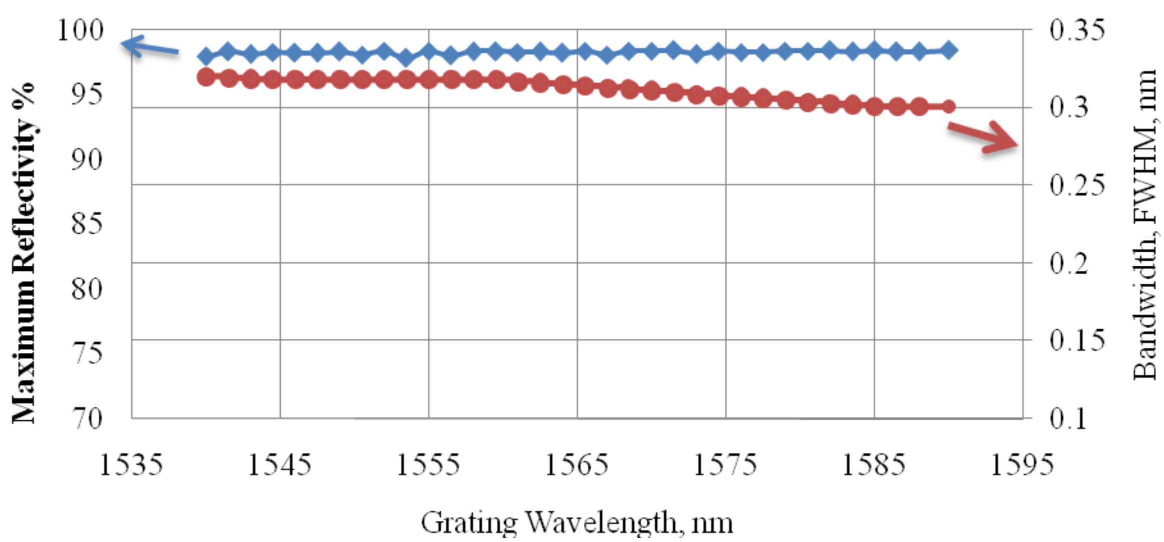

Fig.7. FBG peak reflectivity and (FWHM) bandwidth variation during compression.

Using the results of Figs. 5 and 7, it is clear that, a wavelength shift about 50 nm (from 1540 nm to 1590 nm) can be obtained by compression and a wavelength shift about 12 nm (from 1590 nm to 1602 nm) can be obtained by tension.

This gives a total range 62 nm of wavelength shift. This shift would correspond to about 155 channels (each channel has bandwidth around 0.4 nm to avoid cross talk) in DWDM systems.

4.3 Some numerical results

Table 1 summarizes some results at different values and directions of current. For example, the FBG maximum reflectivity at an initial wavelength 1590 nm after applying current 57 mA in two solenoids I_1 and I_2 in the same direction, the grating wavelength is shifted by -12.402 nm (1577.598 nm).

Table 1 Relation between current and its produced electromagnetic force and its effect on wavelength shift

Current, I (mA)	Magnetic flux density, B (T)	Separation between two magnets, x (cm)	Electromagnetic force, F (N)	Axial strain (tensile or compressive), ε	Wavelength shift, $\Delta\lambda_B$ (nm)	Shifted wavelength, λ_{BS} (nm)	Maximum reflactivity, R_{max} (%)
0	0	1.85	0	0	0	1590	98.4
57(same direction)	0.357	1.86	-8.89575	-0.01	-12.402	1577.598	98.37
81(same direction)	0.507	1.87	-17.7915	-0.02	-24.804	1565.196	98.36
110(same direction)	0.69	1.88	-26.68725	-0.03	-37.206	1552.794	98.37
57(different direction)	0.357	1.84	8.89575	0.01	12.402	1602.402	98.51

5. CONCLUSION

We have demonstrated a tunable FBG, which has over 60 nm transmission band coverage, using a simple compressive and tension technique. A TFBG system is used and an electromagnetic force controlled by applied current is used to achieve strain along the grating for tuning the Bragg wavelength. A wavelength shift of 50 nm (from 1540 to 1590 nm) is obtained by compression and the variation in peak reflectivity is ~ 0.46 dB and in FWHM bandwidth is ~0.02 nm. Also, a wavelength shift of 12 nm (from 1590 to 1602 nm) is obtained by tension. The variation in peak reflectivity is ~ 0.11 dB. Also and the variation in FWHM bandwidth during stretching is ~ 0.002 nm. Both variations are well below the Bellcore standards requirement of ± 0.5 dB for peak reflectivity and ± 0.1 nm for bandwidth. This gives a total range ofg 62 nm for the wavelength shift. The key advantages of this approach are: fast wavelength switching, broad achievable range of wavelength tuning, simple configuration, low cost and easy to operate, and no continuous power supply is needed to achieve the set shift due to used lock system. This system can be used in various optical components; such as tunable filters, tunable fiber lasers, dynamic add-drop demultiplexers, dispersion compensators and tunable lasers.

REFERENCES

[1] K. O. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," J. Lightwave Technol., vol. 15, pp. 1263–1276, 1997.

[2] A.A. Abramov, A. Hale, R.S. Windeler and T.A. Strasser, "Temperature-sensitive long-period fiber gratings for wideband tunable filters," Proceedings of OFC, Paper ThJ2, pp. 144-146, San Diego, USA, February 21-26, 1999.

[3] Iocco, H.G. Limberger, R.P. Salathé, L.A. Everall, K.E. Chisholm, J.A.R. Williams and I. Bennion, "Bragg grating fast tunable filter for wavelength division multiplexing," J. Lightwave Technol., vol. 17, no. 7, pp. 1217-1221, 1999.

[4] W.W. Morey, G. Meltz and W.H. Glenn, "Bragg grating temperature and strain sensors," Springer Proceedings of OFS'89, vol. 44, pp. 526-531, 1989.

[5] G.A. Ball and W.W. Morey, "Tunable Bragg grating fiber filters and their applications," Proceedings of CLEO'97, Baltimore, USA, pp. 108-109, 1997.

[6] A. Iocco, H. G. Limberger and R. P. Salathe, "Bragg grating fast tunable filter," Electron. Lett., vol. 33, pp. 2147–2148, 1997.
[7] Chee S. Goh, M. R. Mokhtar, S. A. Butler, Sze Y. Set, Kazuro Kikuchi and Morten Ibsen, "Wavelength tuning of fiber Bragg gratings over 90 nm using a simple tuning package," IEEE Photonics Technology Letters, vol. 15, no. 4, pp. 557-559, 2003.
[8] Y. Yu, H. Tam, S. Geng, M. S. Demokan, Z. Liu and W. Chung, "Chirp-free tuning of fiber Bragg grating using a cantilever beam,", Jpn. Journal of Applied Physics, vol. 38, Part 2, no. 9A/B, pp. 1032-1034, 1999.
[9] Z. Qin, Q. Zeng and X. Yag, "Bidirectional grating wavelength shifter with a broad range tunibility by using a beam of uniform strength", IEEE Photonics Technology Letters, vol. 13, no. 4, pp. 1041–1135, 2001.
[10] Raymond A. Serway, Physics for Scientists and Engineers with Modern Physics, 4th ed., Saunders College Publishing, USA, 1996.
[11] Monica L. Rocha, Flavio Borin, Hoan C.L. Monteiro, Mariza R. Horiuchi, Miriam R. X. de Barros, Maria Aparecida D. Santos, Flavia L. Oliveira, and Fabio D. Simoes, "Mechanical tuning of a fiber Bragg grating for optical network application" , Journal of Microwaves and Optoelectronics, Brazilian Microwaves and Optoelectronics Society-SBMO, vol. 4, no. 1, pp. 1516-1527, 2005.
[12] Jaroslav Mencik, "Strength and fracture of glass and ceramics," Elsevier, New York, pp.1041-1048, 1996.