Highly tunable optically switched time delay line for transversal filtering

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A novel tunable dispersion device, based on two chirped fibre gratings subjected to non-uniform magnetic fields, is presented. A large degree of tunability is achieved from 250 to 750 ps/nm. This is used to demonstrate RF filtering in the 3–11 GHz range.

Introduction: Variable dispersion lines are very attractive due to their many applications in optical fibre systems, such as dispersion compensation, optical beamforming in phased-array antennas, microwave and millimetre wave signal generation, and radiofrequency filtering [1–5]. Chirped fibre Bragg gratings are dispersive elements that are suitable for these types of applications and can be tuned by using different mechanical techniques. Several approaches have been demonstrated to achieve dispersion tunability by applying temperature [1] or strain gradients [2] or by using piezoelectric transducers [3]. In this Letter, a new tunable dispersive system based on the cascade of two switched tunable stages is proposed. Each one includes a tapered fibre Bragg grating subjected to the non-uniform magnetic field created inside an electrical coil. Among the advantages of such a device are its very large tuning range, fast response and easy implementation. To show the viability of this technique, this tunable dispersion device has been used to implement widely tunable radiofrequency filters [6].

System setup: Two tapered fibre Bragg gratings (TFBG) were used as dispersive elements. The tapers were fabricated by heating and elongating the fibres. The diameter profile was quasi-linear, with a variation between 125 and 85 µm. The Bragg gratings were written on the taper length (5 cm long) by using a uniform period phase mask [6]. Inset *b* of Fig. 1 shows the response of one of the gratings, centred at 1543.56 nm, with a 3 dB bandwidth of $\Delta\lambda_{3\ \mathrm{dB}} = 1.4$ nm; the other TFBG showed a similar reflection bandpass centred at 1543.41 nm with $\Delta\lambda_{3\ \mathrm{dB}} = 1.3$ nm.

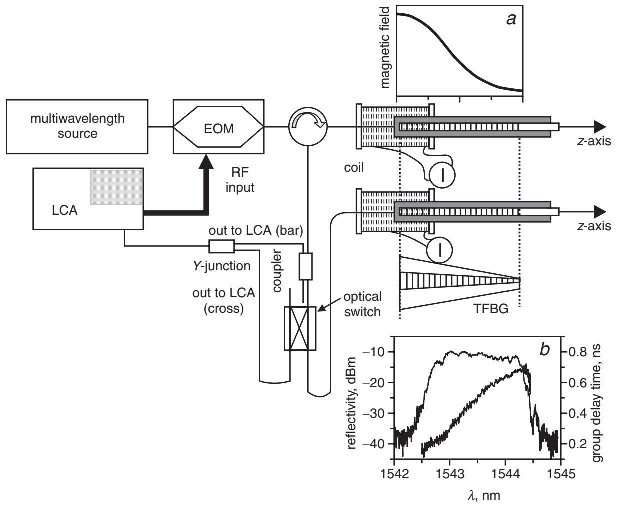

Fig. 1 *Schematic diagram of dispersion tunable device*

Insets: *a* Dependence of magnetic field on the *z*-axis along grating
b Reflectivity and time delay response of one of chirped fibre gratings

Each TFBG was fixed on a magnetostrictive rod and located at the axial region of a 4 cm long magnetic solenoid (see Fig. 1). In this application, two coils having 800 turns and an equivalent radius of 1.58 cm were employed. The magnetic field, created at the edge of the coils, showed a quasi-linear variation (see inset *a* of Fig. 1) having a slope of 17 mT/A cm and a time response of around 0.35 ms. In this way, when an electrical current is applied to the coil, the TFBG subjected to the magnetostrictive rod modifies its dispersion depending on the current intensity [6]. In our setup, the electrical current applied to both coils had the same value ($I_1 = I_2$), so both tunable subsystems had, independently, a similar tuning range.

Fig. 1 shows a schematic diagram of the tunable dispersion system. A laser source is amplitude modulated and launched into the first TFBG through a circulator. The optical signal reflected goes through a 50–50 coupler, and then to an optical switch with a time response of 8 ms. When the optical switch is in the bar state (BS) the optical signal is launched into the second TFBG, and therefore the response of the global system is given by the cascade of both subsystems. After reflection in the second grating, the signal is measured at one of the input ports of the coupler by using a lightwave components analyser (LCA). Alternatively, when the optical switch is in the cross state (CS), the signal is driven to the LCA through the output port of the switch.

Experimental results: Measurements of the amplitude and time delay response of the whole system were performed with the optical switch in CS and BS. The first state led to dispersion slopes from 230 to 351 ps/nm, whereas a range between 420 and 715 ps/nm was obtained in the second state. Therefore, as shown in Table 1, the global tuning range of the system is 230–715 ps/nm, which is significantly larger than compared to others previously published [6].

Table 1: Measured dispersion slope when state of optical switch is bar and cross ($I = 0$, 2 and 4 A).

State	*I* (A)		
	0 A	2 A	4 A
bar, ps/nm	351	297	230
cross, ps/nm	715	580	420

To show the performance of the new system, three-tap RF filters were implemented for CS and BS through which different electrical currents are injected to the solenoid (0, 2 and 4 A). The multiwavelength was set to emit light at three different optical wavelengths, given by $\lambda_n = \lambda_0 + n\Delta\lambda$ ($n = 0$, 1 and 2), where $\lambda_0 = 1543.02$ nm and $\Delta\lambda = 0.41$ nm is the spectral spacing between them. The dispersion provided by the system, *D*, gives the differential delay between adjacent optical taps: $\Delta\tau = D\Delta\lambda$. Fig. 2 shows the free spectral range (FSR) of the measured RF filters for different electric currents. CS led to achieved FSRs between 7 and 10.6 GHz and BS led to a tuning range from 3.5 to 5.8 GHz. The inset of Fig. 2 shows the group time delay against wavelength when no electric current is applied to the coils. Note the increase of the dispersion when BS was set instead of CS.

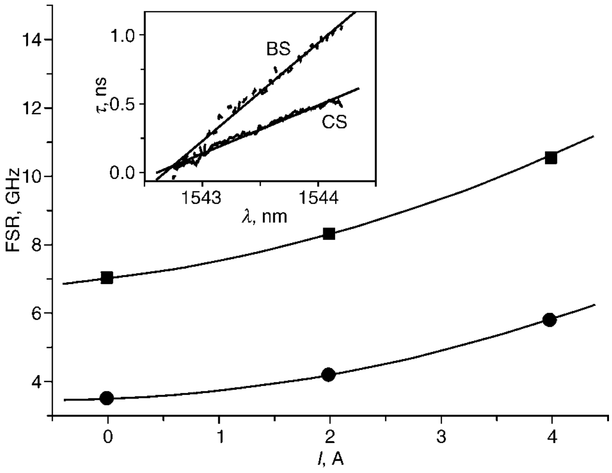

Fig. 2 *Free spectral range of RF filters against current intensity*

Cross (■) and bar (●) states of switch
Inset: Group delay time for cross state (351 ps/nm; solid line) and bar state (712 ps/nm; dotted line) when no current is applied to solenoids

Fig. 3 shows the RF filter response within the tuning range. When the system is operating under CS, the filters show FSRs of 7.0, 8.3 and 10.6 GHz (Fig. 3*a*) with a 3 dB bandwidth of the main lobe of 2.2, 2.8 and 3.4 GHz and a main to side lobe ratio of 9.9, 16.9 and 14 dB, respectively. Furthermore, when BS is active, FSRs of 3.5, 4.2 and 5.8 GHz were measured with a 3 dB bandwidth of the main lobe of 1.4, 1.5 and 2.1 GHz, respectively and a main to side lobe ratio lower than 15 dB (Fig. 3*b*). All the measurements fit well with theoretical predictions corresponding to the analysis of the response of a transversal filter, so the following equation is satisfied [5]:

$$\mathrm{FSR} = \frac{1}{\Delta\tau} = \frac{1}{D\Delta\lambda} \qquad (1)$$

according to the dispersion slopes shown in Table 1.

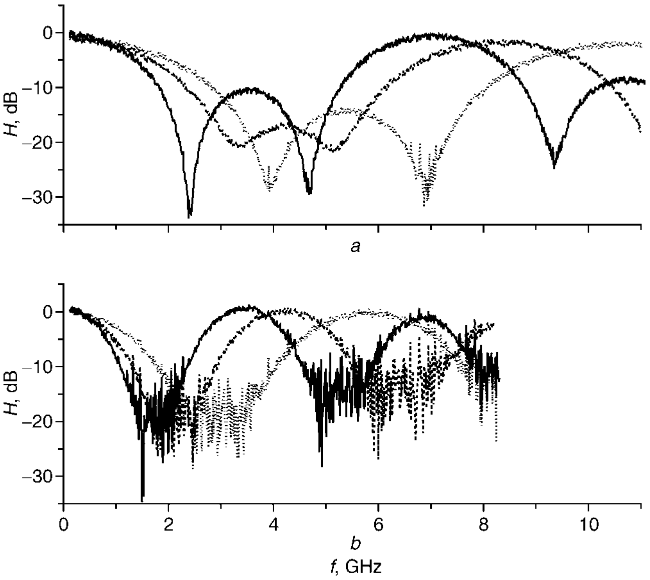

Fig. 3 *Three-tap RF filter responses for different current values*
a Second TFBG off (cross state)
b Second TFBG on (bar state)
——— $I = 0$ A – – – – $I = 2$ A · · · · · $I = 4$ A

Conclusions: A novel tunable optical delay line based on the magnetic control of the dispersion of two optically switched TFBGs has been presented. The system offers larger tuning range (230–750 ps/nm) and other advantages, compared to other alternatives, such us simpler design, easier control and faster response. In this way, our proposal is suitable for RF filtering in the range 3.5–10.6 GHz and can also be proposed for dynamic dispersion compensation and the control of phased-array antennas.

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