Tunable Dispersion Device Based on a Tapered Fiber Bragg Grating and Nonuniform Magnetic Fields

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***Abstract*—We present a new variable dispersion device based on tuning the chirp of a tapered fiber Bragg grating by means of a magnetic transducer. By using a nonuniform magnetic field, we demonstrate a 188–472-ps/nm dispersion tuning range, suitable for tunable radio-frequency filters and dispersion compensation, among others.**

***Index Terms*—Bragg gratings, dispersion, magnetostrictive, microwave filters.**

I. Introduction

VARIABLE time-delay lines, i.e., dispersive elements, are needed in many communication systems, such as high-bit-rate and long-haul transmission systems. Currently, the dispersive devices must operate dynamically because they have to adapt to temporal variations of the system. We focus on radio-frequency (RF) systems, which have applications such as optical beamforming for phased array antenna, microwave and millimeter wave signal generation, or the implementation of reconfigurable transversal notch filters, [1], [2].

Chirped fiber Bragg gratings (CFBGs) have been proposed to obtain tunable dispersion-slope gratings showing suitable optical bandwidth for RF applications. By acting on them, it is possible to vary the time delay of each optical wavelength carrier. Temperature and strain gradients on the CFBG [3] or the use of piezoelectric transducer (PZT) [4] are some of the most extended approaches. Recently, we demonstrated the dynamic chirp of an original uniform fiber Bragg grating based on a grating fixed to a magnetostrictive rod, which could be disturbed with a tapered magnetic circuit [5]. The piezoelectric and magnetostrictive transducers are interesting for dynamic applications because their time responses ($< 100\ \mu$s) could be higher than the temperature or strain methods (~1 s). Magnetostrictive materials have a relative expansion of 1800 ppm and bulk material rods up to 20 cm long are available; these rods can expand 360 μm in less than 1 ms. This performance can be only achieved with PZT stacks mounted with a lever but they usually have a time response of the order of 10 ms.

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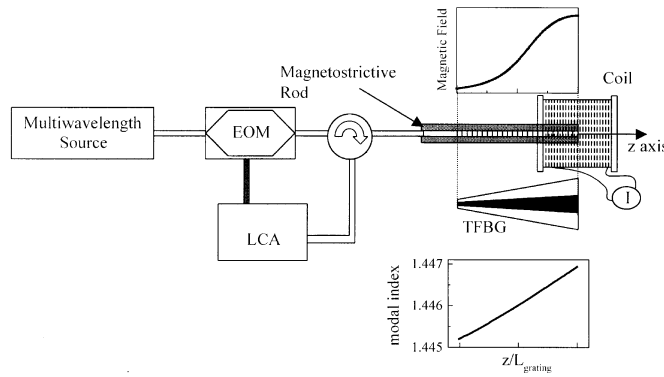

Fig. 1. Schematic diagram of the tunable device for RF filtering implementation purposes. Inset: calculated modal index.

In this letter, we show a new device for tuning the phase response of a tapered fiber Bragg grating (TFBG) by using a magnetostrictive transducer and the magnetic field inside a simple coil. We also demonstrate the suitability of our tunable dispersion device to obtain variable transversal filters by tuning the dispersion with a variable current in the solenoid. This magnetic device shows advantages such as good dynamic response, large tuning range, and easy implementation.

II. Experimental Setup

An FBG, which length was $L_{\mathrm{FBG}} = 5$ cm, was written in a tapered fiber by using a uniform period phase mask. The taper was fabricated by heating and elongating a fiber, with a numerical aperture NA $= 0.14$, to achieve a diameter profile [6] given by $d(z) = d_o \cdot \exp(-z/L_o)$, where z is the axial distance, between $z = 0$ and $z = L_{\mathrm{FBG}}$. The initial diameter is $d_o = 125\ \mu$m, and L_o is the length that determines the end diameter. In this way, L_o was 12.0 cm to obtain an end diameter of 82.4 μm. Due to the selected parameters of fabrication, the initial chirp of the TFBG was quasi-linear as shown in the inset of Fig. 1.

This TFBG was fixed on a magnetostrictive rod and placed inside of a 4-cm-long magnetic coil consisting of 800 turns of an equivalent radius of 1.58 cm (see Fig. 1). The magnetostrictive material suffers a local lengthening, which is proportional to the intensity of the applied magnetic field, with a time response of 0.35 ms. The TFBG is located at the axial region where the magnetic-field variation is quasi-linear [7] with a slope of 7 mT/(A $\times$ cm) and central value of 18.8 mT/A. Therefore, when an electrical current of a given intensity is injected to the solenoid, the magnetic field applied to the TFBG leads to different dispersions depending on the intensity current. The magnetostrictive

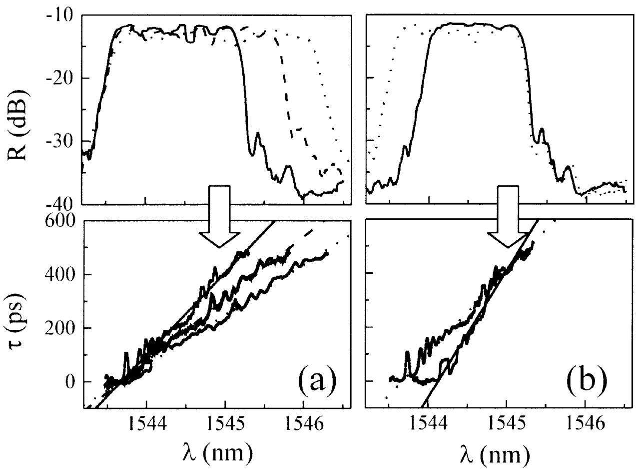

Fig. 2. Optical (upper) and time-delay (lower) response when different magnetic gradients are applied. (a) Positive magnetic gradient: solid line $I = 0$ A, dashed line $I = 3$ A, and dotted line $I = 5$ A. (b) Negative magnetic gradient: solid line $I = 5$ A and dotted line $I = 0$ A.

rod shows a hysteresis around 15% of the distance traveled. It can be reduced to less than 5% by loading the material with a constant mechanical force. Additionally, for high accuracy applications, a closed feedback loop (as used with PZT translators) would control the expansion to 0.2% of the nominal travel.

When no current is applied, the TFBG has a linear dispersion due to the design of the taper profile [6]. It has a flat reflectivity and a 3-dB bandwidth of 1.58 nm.

III. Dispersion Measurements

Fig. 2 shows the reflectivity and the time-delay characterization of the TFBG when different currents are applied to the coil. Fig. 2(a) shows the reflectivity (upper) and time-delay (lower) responses when electric currents are 0, 3, and 5 A, whose corresponding magnetic-field gradients are 0, 21, and 35 mT/cm. The 3-dB bandwidths of the gratings are 1.58, 2.05, and 2.51 nm, respectively. In this case, the centre of the coil is located in the section of the taper that has a 125-μm radius (positive magnetic gradient). Results plotted in Fig. 2(b) are obtained when the tapered section with a 82.5-μm radius has been subjected to the maximum field intensity. Thus, the magnetic gradient is opposite to the previous case, i.e., negative. In this case, the solenoid was fed with currents of 0 and 5 A, giving a magnetic-field slope of 0 and -35 mT/cm. The 3-dB bandwidths of the gratings were 1.58 and 1.06 nm, respectively.

The power consumption of the coil is close to 200 W for a current of 5 A, so the device was air cooled to stabilize the grating temperature. This high power level can be reduced making a smaller coil. If the coil has the same number of turns and its diameter is reduced by a factor of 1/3, the same magnetostriction would be reached with a current of 1.7 A. The inductance would be three times lower and keeping constant the wire thickness; the time response of the solenoid would improve by a factor of 3. Such a coil would consume less than 10 W.

As shown in Fig. 3, we can achieve dispersion variations from 188 to 472 ps/nm with linear dependence on the magnetic-field gradient. The overall useful bandwidth is $\Delta\lambda_o = 1.06$ nm and increases to 1.58 nm for positive gradients. We can see that the

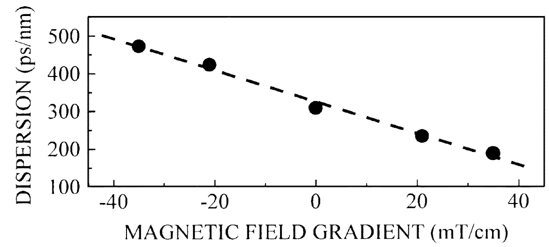

Fig. 3. Dispersion of the TFBG as a function of the magnetic-field gradient along the axis, when electrical current is applied to the solenoid.

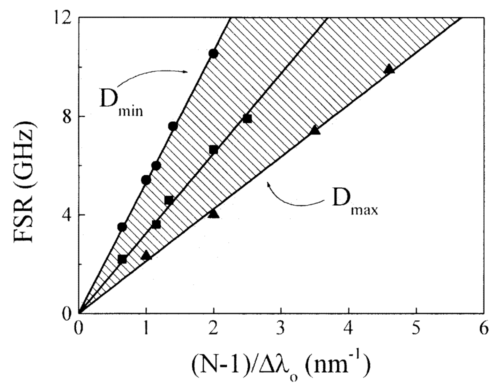

Fig. 4. FSR versus number of optical taps and optical bandwidth of the filter for different time-delay slopes obtained with a magnetic-field gradient of $+35$ (circle), 0 (square), and -35 mT/cm (triangle). The shaded region is the range of achievable FSR.

group delay time and the optical responses show ripples due to the lack of apodization of the TFBG. These ripples could be reduced by apodisating of the TFBG.

IV. Tunable RF Filters

The implementation of RF filters requires N optical carriers, equidistant by $\Delta\lambda_o/(N-1)$, which are provided by a multiwavelength tunable laser. They are amplitude modulated by an electrooptical modulator (EOM) and launched into the tunable TFBG, as shown in Fig. 1 [1]. The RF signal is supplied by the lightwave component analyzer (LCA). The dispersion of the TFBG gives the differential delay between adjacent optical taps. Because of the variation of the time-delay slope of the TFBG when we apply different magnetic gradients, transversal notch filters with tunable free-spectral range (FSR) are measured in the LCA.

To show the viability of this proposal, several filters have been implemented by changing the number of optical taps (N) and the total optical bandwidth ($\Delta\lambda_o$) of the filters for different magnetic-field gradients. Fig. 4 plots the FSR values that correspond to the microwave filters achieved with a magnetic-field slope of $+35$, 0, and -35 mT/cm. The shaded region represents the range of FSR that can be obtained with our device.

The transfer function of a filter implemented with two taps separated $\Delta\lambda_o = 1.0$ nm is presented in Fig. 5. The FSR of the filter can be modified with the current applied on the coil that changes the dispersion of the chirped grating. For a magnetic field of $+35$ mT/A, the grating dispersion is 188 ps/nm and results in an FSR of 5.4 GHz in the filter (solid line). The system was reconfigured to get a negative field gradient of -35 mT/A,

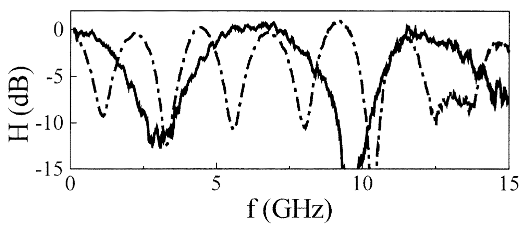

Fig. 5. Transfer function of a tuned RF filter for different magnetic-field gradients. (Dashed line: -35 mT/cm. Solid line: $I = +35$ mT/cm).

and the resulting grating dispersion was 472 ps/nm. Therefore, the FSR of the filter falls down to 2.3 GHz (dashed line). To avoid the system reconfiguration, the grating can be driven with two solenoids switching the current between them.

V. Conclusion

We have presented a new dynamic method for tuning the delay characteristic of a TFBG, offering many advantages, such as larger tuning range, simpler design, easier control, and lower response time than previous works. A TFBG held on a magnetostrictive rod subjected to a nonuniform magnetic field allows us to obtain time-delay slopes from 188 to 472 ps/nm. The dispersion characteristic can be adjusted by applying different electrical currents to a simple coil. Moreover, we have demonstrated the suitability of this device for tunable transversal filtering in RF systems, showing a significant tuning range.

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