All-fiber tunable dispersion and polarization mode dispersion compensator based on enhanced thermal tuning

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Abstract — **An all-fiber device that is suitable for tunable second and third order dispersion compensation is presented. It can also be used for PMD compensation with a wide tuning range. The device is also transparent to bit format and bit-rate since it has no electronic processing.**

I. INTRODUCTION

Optical fiber communication systems are primarily operated at wavelengths near the 1550 nm window, in order to coincide with the minimum loss point of silica fiber and thereby, maximise transmission distance. However, at this wavelength, the group velocity dispersion (GVD) limits the achievable propagation distance. For a system that operates at a data rate greater than 10 Gbit/s, the maximum distance is on the order of kilometres. Beyond this distance, GVD induces signal pulse broadening that causes significant overlap of neighbouring pulses and results in signal corruption. This problem can be solved by inserting an element that imposes GVD on the optical signal that is opposite to that imposed by the fiber, thereby compensating for the naturally occurring GVD. Moreover, polarization mode dispersion (PMD) has recently appeared as one of the next critical hurdles in achieving high-performance optical transmission systems. This situation is due to the deployment of many fiber segments throughout the 1980's that have a PMD parameter that is as much as 100–1000 times greater than the current optimized fibers. Therefore, it is highly desirable for 10-Gb/s transmission systems using old embedded fiber to compensate for possible PMD. In this work we present an all-fiber device that is suitable for implementation in a second and third order GVD or PMD compensation. It is tunable over a wide range and is transparent to bit format and bit-rate since it has no electronic processing.

II – DISPERSION COMPENSATION

A. Introduction

Chirped fiber gratings are becoming a key element for dispersion compensation [1]. It induces different time delays for different wavelengths. This rechirping can be designed to reshape a pulse that was broadened by GVD and compress it back to its original width. Chirped gratings can be made to affect a broad-band of optical signals or a narrow-band, depending on the application. In addition, they are compact, passive, and have low insertion loss, in opposition to the highly loss dispersion compensation techniques, such as dispersion compensating fibers and mid-span inversion [2]. A method for achieving tunable dispersion compensation, based on induced thermal chirping in uniform fiber Bragg gratings, will be presented in the following subsections.

B. Theory

A uniform fiber Bragg grating has a peak reflection wavelength centered at

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

where n_{eff} is the effective refraction index of the fiber and Λ is the period of the index modulation of the grating. Any temperature perturbation (ΔT) in the grating, induces a shift in the Bragg wavelength, given by

$$\Delta\lambda_B = \lambda_B\left(\alpha_\Lambda + \alpha_n\right)\Delta T \qquad (2)$$

where α_Λ and α_n are the thermal expansion and thermo-optic coefficients of the fiber, respectively. The value $S = \lambda_B(\alpha_\Lambda + \alpha_n)$ is the fiber's temperature sensitivity and is approximately equal to 13.7 pm / ºC for a grating written at 1550 nm in a germania-doped silica-core fiber [3]. By applying a linear temperature gradient to a uniform fiber Bragg grating, an induced chirp will be generated. The group delay dispersion for the induced chirped can be calculated using the following expression

$$d \approx \frac{2n_{eff}L}{c\lambda_B S\Delta T} \qquad (3)$$

where L is the grating's length and c is the light velocity in the vacuum. In the expression above, the grating was approximated to a Dirac's delta in the wavelength, which means that the expression is not valid for ΔT near 0º C, since the grating has a residual bandwidth.

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C. Experimental

A uniform fiber Bragg grating was written at 1546 nm with 24 mm length using a scanning beam from an Ar-ion laser frequency-doubled to 244 nm [4]. The grating was glued in a zinc substrate. This procedure greatly enhances the grating sensibility, since the thermal expansion coefficient of the system zinc+fiber is significantly higher than the fiber's. The thermal sensitivity of the system was measured to be 84.5 ps / ºC. On each side of the Zn channel, a peltier forces a constant temperature. With this, different temperature gradients can be achieved by changing the individual temperatures on the peltiers. Since the substrate has a constant width and height along its length, the temperature gradient is linear, therefore, it induces a linear chirp on the grating which depends on the difference of temperature, ΔT, between the two peltiers. The grating was isolated from the air to avoid temperature deviations and heat loss due to convection. The reflection spectra of the grating for different temperature differences on the peltiers are shown in Fig. 1. The temperature in the middle of the thermal channel was 35º C, which means that for a difference of 40º C , the peltiers are at a temperature of 15 and 55º C respectively.

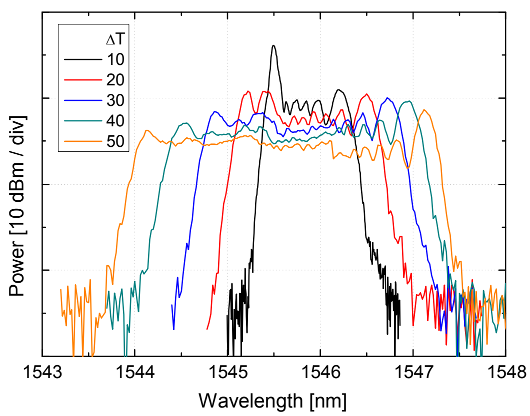

Fig. 1. Reflection spectra of the grating for different temperature gradients.

As should be expected, a wider bandwidth is related to a wider temperature difference, since more wavelengths are reflected at the grating. For a temperature difference of 50º C, the peak power reflection is 5 dB lower than in the uniform temperature situation. This is due to the reduction of the mode coupling for each wavelength, however, a minimum rejection of 20 dB is still evident.

In Fig. 2, the group delay for a ΔT of -50 (60 and 10º C) and 50º C (10 and 60º C) is displayed. The group delay variation is quite smooth and straight. For ΔT=-50º C, the slight bending around 1544.5 nm means that the system was not totally stable when the measurements were made. It should be stressed that that the glue needs some time to stabilize in a new position.

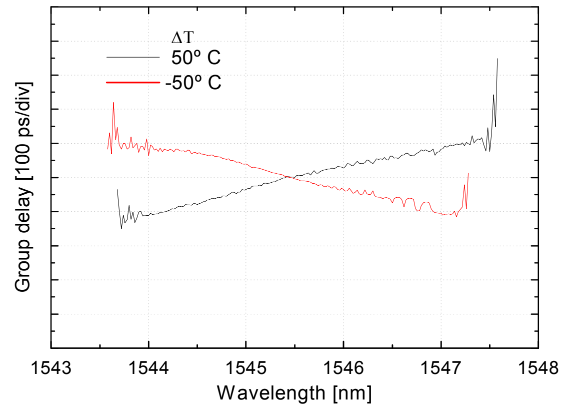

Fig. 2. Group delay for the induced chirped fiber Bragg grating for different temperature gradients.

The dispersion measured for different temperature gradients as well as the theoretical values calculated with the expression (3) is shown in Fig. 3

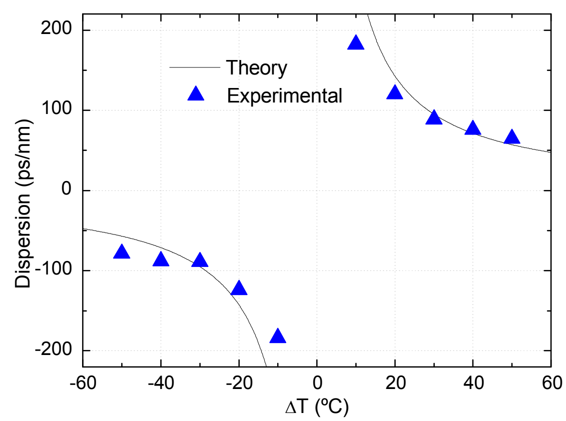

Fig. 3. Group delay dispersion for different temperature gradients.

The results are quite near the theoretical values. The small deviation between the experimental values and the theoretical ones, as ΔT is near 0º C is due to the approximation used in expression (3).

D. 3rd order dispersion compensation

The concept presented before for second order dispersion compensation can also be used for third order dispersion compensation. However, a quadratic temperature gradient must be generated in order to induce a quadratic group delay. That can be done by using a substrate with linear width variation along its length. It can be proven that with this shape, a quadratic gradient is generated if two different temperatures are on each side of the substrate. So, a uniform fiber Bragg grating with 24mm length was glued in a zinc substrate with a linear width variation from 3 mm to 10 mm.

The group delay measured for different temperature gradients is displayed in figure 4.

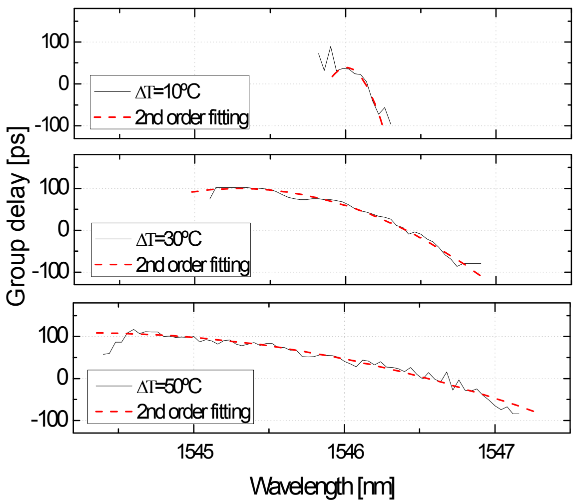

Fig. 4. Group delay for different temperature gradients (solid line) and the respective quadratic fit (dashed).

The linear and quadratic coefficients for the fitting curves are shown in Table 1.

Induced gradient	*Linear coefficient*	*Quadratic coefficient*
ΔT=10 º C (T1=30 ºC T2=40 º C)	-357 ± 87 ps / nm	-2408 ± 320 ps / nm^2
ΔT=30 º C (T1=20 ºC T2=50 º C)	-104.4 ± 5.9 ps / nm	-80.3 ± 5.2 ps / nm^2
ΔT=50 º C (T1=10 ºC T2=60 º C)	-64.0 ± 2.3 ps / nm	-21.0 ± 2.3 ps / nm^2

Table 1. Linear and quadratic coefficients for the curves fitted in the experimental results

The results show that a third order compensation is only suitable for temperature gradients ΔT ≥ 30ºC. For gradients bellow that, the error associated is not appropriated.

III – PMD COMPENSATION

A. Introduction

The dynamic PMD compensation in the optical domain is always based on the same principle: inducing a relative delay of one transversal polarization component of the fundamental propagation mode in relation to the orthogonal one. One of the approaches for optical PMD compensation is based on free-space optics. The concept is based on the separation of the two polarization components by a polarization-beam splitter in free-space optics. Before getting combined again in the fiber, each polarization component travels a different path, which induces different delays for each one. The tuning process is made by changing one of the optical paths. However this method has all the inherent difficulties of free-space optics such has alignments or reflections. Other approaches use the temperature tuning of small lengths of highly birefringent (HiBi) fibers [5], but the process lacks speed and flexibility.

B. Theory

The proposed technique for dynamic compensation of the PMD is based on chirped fiber Bragg gratings written in HiBi fibers. In these fibers, the x- and y-components of the degenerated LP_{01} mode have different refractive indexes. Therefore, due to (1), a HiBi FBG will reflect two different wavelengths with orthogonal polarization. The wavelength difference between the two peaks is dependent on the birefringence of the fiber (B) and can be given by

$$\Delta\lambda_{HB} = 2B\Lambda \tag{4}$$

In a linearly chirped grating, written in a HiBi fiber, each position in the grating will reflect two wavelengths at orthogonal polarizations. This means that the group delay of these gratings is a combination of two linear functions, one for each polarization, with the same dispersion slope (d) and shifted by $\Delta\lambda_{HB}$:

$$\begin{aligned} \tau_y(\lambda) &= d\lambda + b \\ \tau_x(\lambda) &= d(\lambda - \Delta\lambda_{HB}) + b \end{aligned} \tag{5}$$

Here, it is assumed that the $-y$ polarization is the fast axis, so the reflection spectrum corresponding to $-y$ polarization is at lower wavelengths than the one corresponding to $-x$ polarization. So, the relative group delay induced by a linearly CFBG written in a HiBi fiber ($\Delta\tau = \tau_x - \tau_y$) is calculated using the following expression

$$\begin{aligned} \Delta\tau &= -d\Delta\lambda_{HB} \\ &= -2dB\Lambda \end{aligned} \tag{6}$$

The expression (6) shows that the dynamic tuning of the induced PMD can be made by adjusting the birefringence of the fiber [6] or by adjusting the dispersion slope of the grating.

C. Experimental

The tunable PMD compensator is based on dynamic tuning of the dispersion slope used for the second order dispersion compensator. A uniform fiber Bragg grating was written in a HiBi fiber with 24 mm length. The grating was inserted in a uniform zinc substrate without glue. On each side of the zinc channel, a peltier forces a constant temperature, inducing a linear gradient. Once again, the grating was isolated from the air to avoid temperature deviations and heat loss due to convection. Figure 5 shows the reflection spectra of the grating under different temperature gradients. It is quite visible the spectrum broadening due to the induced chirp as the temperature difference increases. At ΔT = 10º C, the two peaks, at orthogonal polarizations, are still separated. When ΔT is increased to ΔT = 30º C the two peaks start to overlap.

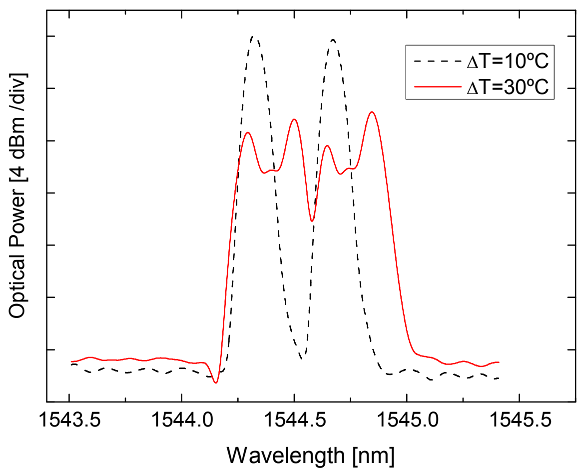

Fig. 5 – Reflection spectra of a FBG written in a HiBi fiber with two induced temperature gradients: ΔT=10ºC and ΔT=30ºC.

The delay between -*x* and -*y* polarizations can be tuned for any wavelength in the overlap region, by adjusting the dispersion slope (which depends on ΔT). In the experiments, we have measured the group delay for both polarizations at 1544.75 nm for different temperature differences. The results are displayed in figure 6.

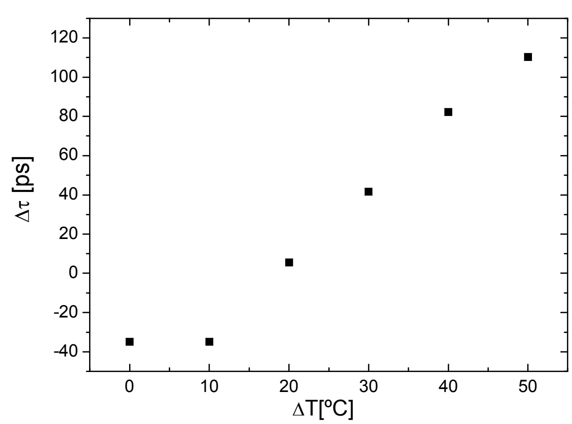

Fig. 6 – Difference in the group delay between the two orthogonal polarizations for different applied temperature gradients.

The results show that the group delay between the two orthogonal polarizations was tuned between -35 to 110 ps for temperature gradients between 0 and 50ºC respectively. After ΔT=10ºC, the two orthogonal peaks start to overlap, increasing the group delay between *x* and *y* polarizations. It is also possible to see that the evolution is quite linear with the temperature gradient increase, which simplifies the implementation in a prototype with feedback architectures. The results show that it is possible to compensate the PMD with an induced temperature gradient in a uniform fiber Bragg grating written in a HiBi fiber.

IV – CONCLUSION

In this work, a technique for inducing linear and nonlinear chirp in uniform fiber Bragg gratings has been presented. The method was able to generate a chirped grating with dispersions between -185 to 185 ps / nm. This amplitude makes the device suitable to be integrated with a fixed second order dispersion compensator with higher dispersion values in order to obtain a flexible tunable dispersion compensator. It also showed its ability to be used for third order dispersion compensation with a second order group delay coefficient between -21 and -80 ps/nm^2. PMD compensation capacity was also demonstrated with Δτ varying between -35 to 110 ps. Further improvements are under study in order to use it in real time environment.

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