DGD and PDL reduction in twisted FBGs

V. García-Muñoz(1), C. Caucheteur(2), S. Bette(2), M. Wuilpart(2), M. A. Muriel(1), P. Mégret(2)

(1) Photonics Technology Department, Universidad Politécnica de Madrid, Spain

(2) Service d'Electromagnétisme et de Télécommunications, Faculté Polytechnique de Mons, Belgium.

A fabrication process for Fiber Bragg Gratings (FBGs) for the reduction of polarization dependent properties is proposed in this paper. The fiber is twisted, illuminated, and finally relaxed. The maximum of the transversal refractive index profile describes a spiral along the optical axis. This produces a change of the polarization axes orientation along the grating length. This change causes Polarization Mode Coupling (PMC) that leads to the reduction of the Differential Group Delay (DGD) and the Polarization Dependent Loss (PDL). We theoretically demonstrate that the higher the number of twist, the greater the reduction of both DGD and PDL.

The electrical field in a single mode optical fiber is characterized by two degenerated modes HE_{11}^{x} and HE_{11}^{y}. If the optical fiber is not ideal (due to geometrical or material variations), the degeneration is broken. Consequently, the field is composed by two orthogonal modes that propagate with different velocity as they experience different refractive index. The refractive index difference of the modes is called birefringence. The birefringence value and the polarization axes orientation can vary along the optical axis of the fiber. In this case, the optical fiber can be modeled as a concatenation of dielectric layers, with each layer having its own polarization axes and birefringence values. We define the discretization length L_d as the length in which the former two characteristics can be considered as constant, Consequently, a fiber with length L can be modeled as a concatenation of L/L_d segments (see Fig.1). When the light passes through one layer to another the field is projected on the new polarization axes, this phenomenon is known as Polarization Mode Coupling (PMC).

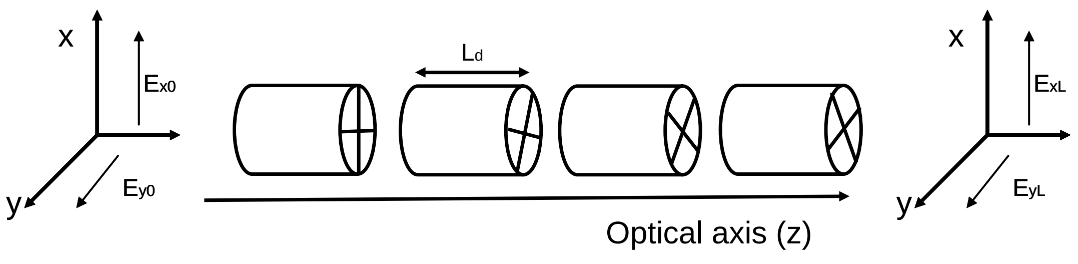


Figure 1 Diagram of the polarization axes variation along the fiber optical axis. The fields at the beginning and at the end are also shown.

In the case of Fiber Bragg Gratings (FBGs), the birefringence induced during its fabrication has two main causes: the polarization of the UV laser that illuminates the optical fiber and the asymmetry in the refractive index profile (RIP) in the plane transversal to the optical axis due to the side written fabrication process. Erdogan *et al* [1] demonstrated that when the UV laser has a polarization parallel to the direction of the optical axis the induced birefringence is reduced by a magnitude factor compared to the birefringence induced when the UV laser is polarized in the transversal direction.

Vengsarkar [2] demonstrated that the induced asymmetry in the RIP leads to a birefringence that is not negligible. This small quantity of birefringence is not easily detectable into the grating amplitude response, but it induces significant wavelength dependent DGD and PDL in FBGs [3].

Due to the increasing bit-rate, lightwave transmissions are less and less tolerant to polarization effects. Using FBGs in the frame of high-speed communication systems implies to know their polarization properties and to develop techniques to reduce their effects. Several techniques for the reduction of the PDL and the DGD have been proposed. The PMC can be used to decrease the DGD of the FBG as in [4], where FBGs are constructed in spun fibers. In this type of fibers, the core of the fiber is twisted during the fabrication process in a way that the induced PMC is designed to reduce the DGD of the fiber. The FBG is simply manufactured in the spun fiber by lateral illumination. The main drawback of the use of spun fibers for the fabrication of FBGs is that the cost of spun fibers is higher than the cost of standard fibers. Another method for the reduction of the DGD and the PDL is the use of High birefringence (Hi-Bi) FBGs, but a very accurate alignment of the input state of polarization with one of the principal axes of the Hi-Bi FBG is needed. A third method was presented by Vengsarkar [2] and extended by the authors to Superimposed FBGs [5]. This method provides symmetrization of the refractive index profile by multiple illuminations of the fiber with different angles. In the case of single FBGs the same grating has to be written twice. If the second illumination is not in phase with the first one, the resulting FBG response will be distorted. Owing to the constraints presented by spun FBGs, Hi-Bi FBGs, and symmetrized FBGs, it is desirable to find solutions to decrease the DGD and the PDL induced in the fabrication process of FBGs written into standard fiber, but avoiding to do multiple illuminations. In this paper we present a fabrication process in which the fiber is twisted before the illumination and then relaxed. These actions lead to a spiral like refractive index profile along the FBG optical axis that will lead to PMC which produces a reduction of the DGD and the PDL in the same way as spun fibers do. The main advantage over the spun fibers based FBGs is that in our case the fabrication is done in a standard fiber, which is much more interesting in terms of production costs.

Jones matrix formalism relates two input ports, corresponding to the two components of the input field propagating in the optical axis direction, with two output ports, corresponding to the two components of the output field propagating in the optical axis direction. In this scheme, the reflections that occur inside the device are neglected. FBGs are wavelength selective reflective filters, hence reflection can not be avoided. In order to describe multilayer devices such as FBGs or thin film filters in which reflection and polarization are taken into account, a 4x4 matrix formalism is needed [6]. The *M* matrix relates the input electrical field components of the device with the output components.

$$\begin{pmatrix} E_{x0}^{+} \\ E_{x0}^{-} \\ E_{y0}^{+} \\ E_{y0}^{-} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{pmatrix} E_{xL}^{+} \\ E_{xL}^{-} \\ E_{yL}^{+} \\ E_{yL}^{-} \end{pmatrix} \quad (1)$$

where E_{x0}^{+} and E_{y0}^{+} are respectively the *x* and *y* components of the electrical field at the input of the optical device that propagates in the direction of the optical axis. E_{x0}^{-} and E_{y0}^{-} are the components of the reflected field. E_{xL}^{+} and E_{yL}^{+} are the components

transmitted by the device , finally E_{xL}^{-} and E_{yL}^{-} are the components of the field entering in the device in the negative direction. If the matrix of each layer, M_j, is known, the total M matrix that describes the FBG can be calculated by multiplication of the M_j matrices in the correct order. In our case, we consider that the layers forming the twisted FBG are uniform FBGs with constant birefringence and polarization axes, but varying from layer to layer. The *j-th* layer matrix M_j was calculated with respect to its eigenaxes, and then rotated by the angle θ_j that it forms with the fixed coordinate system. In this approximation we consider that PMC occurs in the interface between the layers and coupling between forward and counter propagating modes is produced inside each uniform FBG layer that forms the whole FBG. Obviously, when the spin period decreases, more PMC is produced along the twisted FBG.
At the end of the whole FBG, there is no counter propagating field. If we simplify the null entries and take E_{xL}^{+} , E_{yL}^{+}, E_{x0}^{-} and E_{y0}^{-} as dependent variables, we can obtain a matrix relationship that relates two input ports (input field polarization components) with four output ports (transmission and reflection field components) [7] which corresponds with the Jones matrix in transmission and in reflection.

$$\begin{pmatrix} E_{xL}^{+} \\ E_{yL}^{+} \\ E_{x0}^{-} \\ E_{y0}^{-} \end{pmatrix} = M' \begin{pmatrix} E_{x0}^{+} \\ E_{y0}^{+} \end{pmatrix} = \frac{1}{M_{DEN}} \begin{pmatrix} -M_{33} & M_{13} \\ M_{31} & -M_{11} \\ M_{23}M_{31} - M_{21}M_{33} & M_{13}M_{21} - M_{11}M_{23} \\ M_{31}M_{43} - M_{33}M_{41} & M_{13}M_{41} - M_{11}M_{43} \end{pmatrix} \begin{pmatrix} E_{x0}^{+} \\ E_{y0}^{+} \end{pmatrix} \quad (2)$$

$$M' = \begin{pmatrix} \frac{1}{M_{DEN}} \begin{pmatrix} -M_{33} & M_{13} \\ M_{31} & -M_{11} \end{pmatrix} \\ \hline \frac{1}{M_{DEN}} \begin{pmatrix} M_{23}M_{31} - M_{21}M_{33} & M_{13}M_{21} - M_{11}M_{23} \\ M_{31}M_{43} - M_{33}M_{41} & M_{13}M_{41} - M_{11}M_{43} \end{pmatrix} \end{pmatrix} = \begin{pmatrix} J_T \\ J_R \end{pmatrix} \quad (3)$$

where $M_{DEN} = M_{13}M_{31} - M_{11}M_{33}$. It is worth noting that the Jones matrices of the twisted FBG (J_T and J_R) are calculated from the *M'* matrix, not by multiplication of partial Jones matrices.
Using the formalism showed above, and the relationships between the Jones matrices and the DGD and the PDL given by Heffner [7], we have simulated the evolution of the PDL and the DGD in transmission for a uniform twisted FBG as a function of the twist angle. The characteristics of the FBG are: effective index $n_0 = 1.4514$, index modulation $\delta n = 8\times10^{-5}$, birefringence $\Delta n = 8\times10^{-6}$, length $L = 1\ cm$ and grating pitch $\Lambda = 535.08\ nm$. We can see from Fig. 2 that as the twist angle increases, i.e. as the spinning period decreases, the DGD reduces its maximum value from 7.6 ps to 2.8 ps and the PDL from 1.33 dB to 0.44 dB when the total twist angle goes form 0° to 180° (spin period=2cm). We can also observe in Fig. 3 that as the number of turns increases, the induced PDL and DGD reduce to marginal values.

In this paper, we have proposed a new fabrication technique for the reduction of the induced DGD and PDL. We have presented the theoretical foundations of the technique and demonstrated a reduction of the polarization characteristics with the twist angle via numerical simulations.

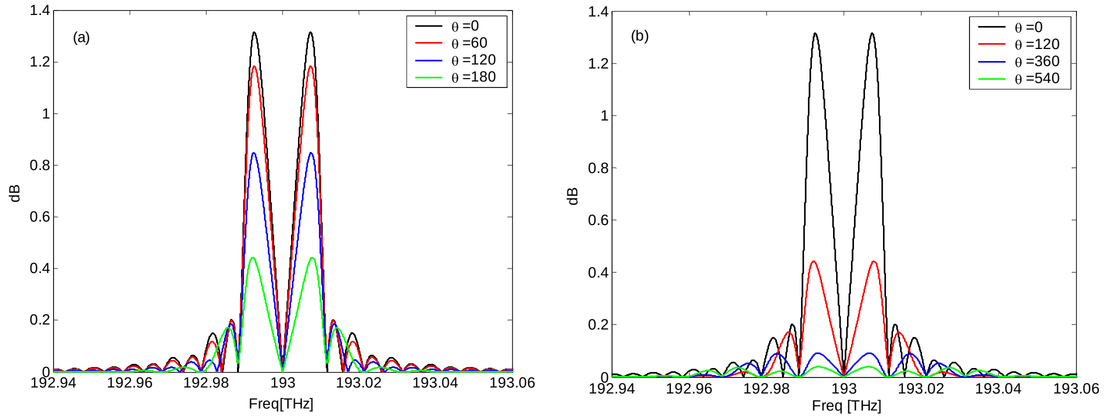
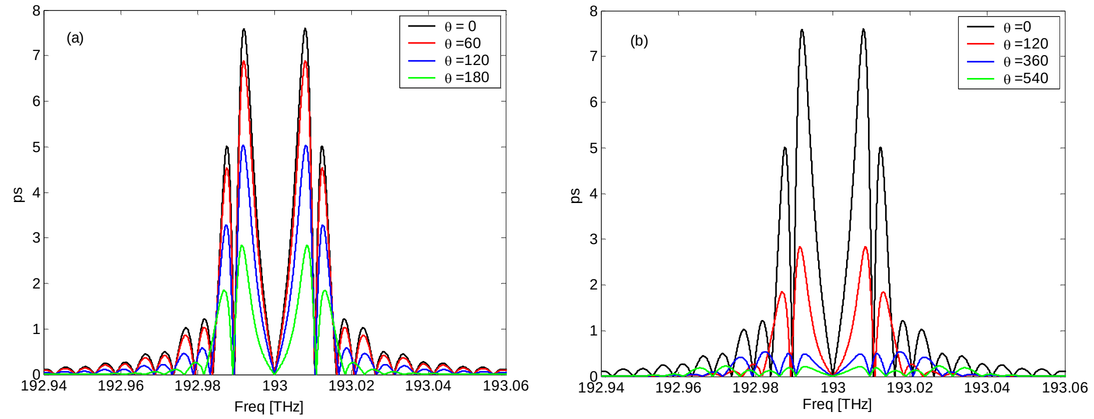


Figure 2 PDL evolution in function of the total twist angle. (a) From 0˚ to 180˚ (b) From 0˚ to 540˚.



***Fig**ure 2 DGD evolution in function of the total twist angle. (a) From 0˚ to 180˚ (b) From 0˚ to 540˚.*

The authors acknowledge the support of e-Photon/ONe+, the Belgian IAP and F.R.S.-FNRS, and the Spanish I+D+I TEC2004-04754-C03-02 and TEC2007-68065-C03-02.

References

[1] Erdogan *et al* “Characterization of UV-induced birefringence in photosensible Ge-doped silica optical fibers,” J. Opt. Soc. Am. B, vol. 11, pp. 2100-2105, 1994.

[2] A. M. Vengsarkar *et al*, “Birefringence reduction in side-written photoinduced fiber devices by a dual-exposure method,” Opt. Lett. vol. 19, pp. 1260-1262, 1994.

[3] S. Bette *et al*, “Spectral characterization of differential group delay in uniform fiber Bragg gratings”, Opt. Exp., vol. 13, pp. 9954-9960, 2005.

[4] Y. Wang, *et al*, “Bragg gratings in spun fibers,” IEEE PTL, vol. 17, pp. 1220–1222, 2005.

[5] V. García-Muñoz, *et al*, “Optimized Superimposed Fiber Bragg Gratings to Reduce Birefringence Effects in WDM Applications,” Conference on Optical Communications (ECOC), Berlin (G), 2007.

[6] P. Yeh, Optical Waves in Layered Media, John Wiley & Sons, New York, 1988.

[7] B. L. Heffner, “Automated Measurement of Polarization Mode Dispersion Using Jones Matrix Eigenanalysis,” IEEE PTL, vol. 4, pp. 451–453, 1992.