Virtual Long Period Fiber Gratings

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ABSTRACT

In this paper a theoretical prediction of a new kind of in-fiber devices is presented. They behave essentially like long-period Bragg gratings except for the fact that they are not permanent but volatile. This is because these devices are not formed by the UV-induced increment of the refractive index but by the twisting of a pristine HiBi fiber. This way, a long period fiber grating whose characteristics can be modified by changing the polarization of the incoming light is obtained.

Keywords: Long period fiber Bragg grating, HiBi fiber, twisted fiber.

1. INTRODUCTION

In the last years a great effort has been devoted to developing the Fiber Bragg Grating (FBG) technology to the degree of maturity of the present moment. As a result, several devices, based on these FBG structures (both short and long period), have been created. Among them: sensors [1], gain equalizers [2], mode converters [3], or filters [4]. The fabrication of such gratings is made by the side-exposure of a hydrogen loaded fiber to a UV beam [5]. This beam can go through a phase mask and, thus, being turned into a diffraction pattern for the writing of short-period FBGs; or the fiber can be directly exposed to an spatially filtered beam for the point-to-point fabrication process which result is the Long Period Fiber Gratings (LPG). In one case or the other a permanent UV-induced refractive index increment in the core of the fiber is provoked. This implies that, once the gratings are written, their characteristics cannot be modified, that is, they are static. This fact, obtained as a result of the fabrication process, means a lack of flexibility in the operation of these devices. Moreover, there are many applications in which dynamic elements, that is, elements whose characteristics change in time in a controlled way, are required; the best example of such devices is the tunable filter. The most common practice for making FBGs tunable is attaching them to a piezoelectric transducer. But this approach is more a patch than a real solution. This is because there is a rather big limitation in the tuning range (usually not exceeding a few nanometers) and because the frequency response is poor. Ideally, the best solution would come from controlling the FBG characteristics with another electromagnetic radiation (light as the best choice). This will greatly improve the frequency response of the device since no mechanical parts will be involved. Moreover, if more than one parameter (the Bragg wavelength) could be modified the potential applications of the device will be multiplied. In that sense very little work has been done so far. The most remarkable ones are a volatile tunable Bragg filter formed by applying a voltage to liquid-crystal plates [6] and a soon to be commercialized adaptative filter based on a Digital Light Processing™ chip [7].

In this paper the theoretical prediction of a new device that behaves like a LPG is reported. It can be fabricated by heavily twisting a pristine High Birefringence (HiBi) fiber. In this structure the polarized light that propagates through the twisted fiber sees periodic index increments that create a LPG. These are due to the ever changing state of polarization (SOP) of the light as a result of the combined effects of the linear and circular birefringences. In case the SOP of the incident light changes, so will the index increments and, therefore, the characteristics of the LPG. Thus, these index increments are not real but virtual since they depend on the state of polarization of the light. This is the reason that justify that these structures are given the name of Virtual Long Period Fiber Gratings (VLPG).

In the next paragraphs the theoretical basis of the VLPG will be outlined (section II) and the results of several simulations will be presented and discussed. These will show that the VLPGs are light-controlled devices. Finally several conclusions will be extracted.

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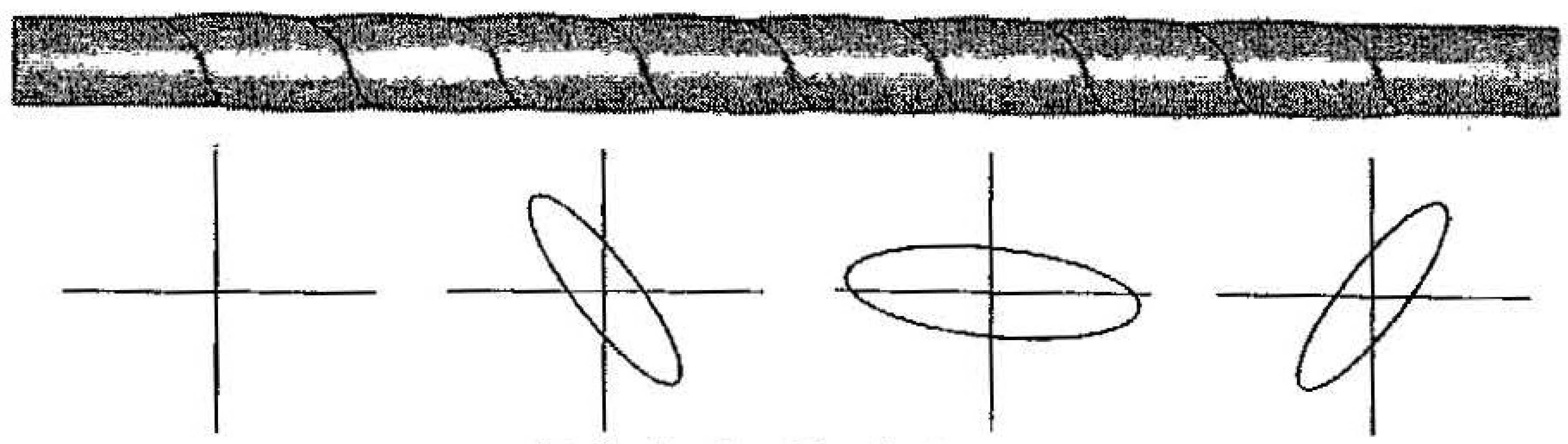
2. THEORETICAL ANALYSIS

As has been previously said, the VLPGs are fabricated by heavily twisting a High Birefringence fiber. Under these circumstances a circular birefringence appears and adds up to the inherent linear one of the fiber. The combined effect of these two different birefringences, in the way that will be explained in the following, leads to the appearance of periodic refractive index changes observed by the polarized propagating light. In order to qualitatively understand this phenomenon, it must be remembered that HiBi fibers have a core's refractive index whose value varies with the spatial direction within the cross-section of the fiber. It is also known that these fibers support two main or principal linear polarization states (SOP eigenstates) that propagate unperturbed along the fiber (reason for what they are also called polarization maintaining fibers). But these two main polarization states propagate at different speeds, that is, see two different refractive indexes. This implies that the effective index seen by the light guided by a HiBi fiber depends upon its SOP. On the other hand, the effect of the linear birefringence on the SOP of the light is to change the delay between the two main polarization states, this means that a linear SOP would be turned into elliptical and then into circular, etc. But the most important thing is that no exchange of energy between the two SOP eigenstates occurs, what ultimately implies that there is no change in the effective index of the propagating light. However, the effect of the circular birefringence is much different: it provokes the rotation of the SOP and, thus, the exchange of energy between the main polarization states and, therefore, the change of the effective refractive index seen by the light. Moreover, the rate of change of the index depends on the "circularity" of the SOP, and thus on the effect of the linear birefringence. This has been schematically sketched in Fig.1, where the evolution of the state of polarization of the light can be seen. Both the effects of the linear (changes in the SOP ellipticity) and circular (rotation of the SOP) birefringences are illustrated.

Twisted Optical Fiber



Polarization Evolution

Fig.1. Diagram of the twisted HiBi fiber (above) and schematic representation of the polarization evolution of the light as it propagates along the fiber.

To simulate and study these VLPG structures the first step is to obtain the effective index observed by this light of ever-changing SOP as it propagates along the twisted fiber. This can be done simply by obtaining the state of polarization of the light at every point along the fiber and decomposing it into the two eigenstates. Thus, provided the effective indexes of the two principal SOP are known, the effective index of any arbitrary SOP can be calculated as a weighed average of those of the two main SOP. By repeating this procedure all along the fiber length an average index profile is obtained. This profile is periodic (depending its period upon the twist ratio and linear birefringence of the fiber) and changes with the light's incident SOP as will be shown by the simulations. In order to calculate the state of polarization of the light at any arbitrary point along the fiber, and assuming a constant twist ratio, the general Jones matrix for any optical fiber of evenly distributed retardations can be used [8]:

$$T=\begin{bmatrix}P & -Q^*\\ Q & P^*\end{bmatrix};\ \text{where}\ \begin{array}{l} P=\cos\lambda_T - j\dfrac{\delta l}{2}\dfrac{\sin\lambda_T}{\lambda_T}\\ Q=\left(\tau\cdot z+\dfrac{\delta_c}{2}\right)\dfrac{\sin\lambda_T}{\lambda_T}\end{array} \qquad (1)$$

In this last expression $\delta l = 2\pi\cdot\Delta n\cdot z/\lambda$ is the cumulative linear birefringence, with Δn is the index difference between the two principal SOP, λ is the wavelength of the light, z is the position along the fiber. On the other hand

$\delta_c = -2 \cdot g \cdot \tau \cdot z$ is the cumulative circular birefringence, being g a factor which value ranges from 0.065 to 0.08 for most fibers, and τ the twist ratio (rad per unit length). Besides, $\lambda_T = \sqrt{\left(\delta_l/2\right)^2 + \left(\tau \cdot z + \delta_c/2\right)^2}$.

Ec. 1 as written above is always referred to the same reference system, to the same axes, that corresponding to the principal SOP at the beginning of the twisted fiber. But these axes, that constitute the valid reference system for determining the energy exchange between the main SOP, rotate with the fiber twist. Therefore, an static reference is no longer appropriate for this problem, but one that evolves with the twist is required instead. Thus, the transfer matrix of ec. 1 must be modified for including a rotation term that accounts for the axes change. This way the modified matrix, that serve as the basis for the simulations, is:

$$T_\tau = \begin{bmatrix} P \cdot \cos(\tau \cdot z) + Q \cdot \sin(\tau \cdot z) & P^* \cdot \sin(\tau \cdot z) - Q^* \cdot \cos(\tau \cdot z) \\ -P \cdot \sin(\tau \cdot z) + Q \cdot \cos(\tau \cdot z) & P^* \cdot \cos(\tau \cdot z) + Q^* \cdot \sin(\tau \cdot z) \end{bmatrix} \qquad (2)$$

3. SIMULATION RESULTS AND DISCUSSION

Using the index profiles obtained by evaluating ec. 2 at different points of the fiber, and then employing the commercial program IFO_GRATINGS from Optiwave for the calculation of the spectra, several VLPGs were simulated. All of them have in common the host fiber (a HiBi fiber of Δn =6e-4, 1.447 average core index, 1.4424 cladding index, 4.5 μm core radius, 62.5 μm cladding radius, 20 cm long and surrounded by air), and a twist ratio of 1000 turns per meter (far beyond of what the authors were able to achieve in the lab for a standard HiBi fiber. Because of this only simulation results are presented in this paper. Nevertheless, with higher birefringence levels the twist ratio will decrease to more manageable values). In the spectrum calculations the fiber has been taken as a normal single mode fiber. Therefore, since the cladding modes of a real HiBi fiber can differ substantially from those of a normal fiber, the resonances will be at different wavelengths in the real case. However, the behavior with the SOP is expected to remain the same as that obtained in the simulations. In these circumstances the simulations consisted in sweeping the polarization state of the incident light. This causes changes in the refractive index profile and, therefore, in the spectrum of the VLPG as shown in Fig.2.

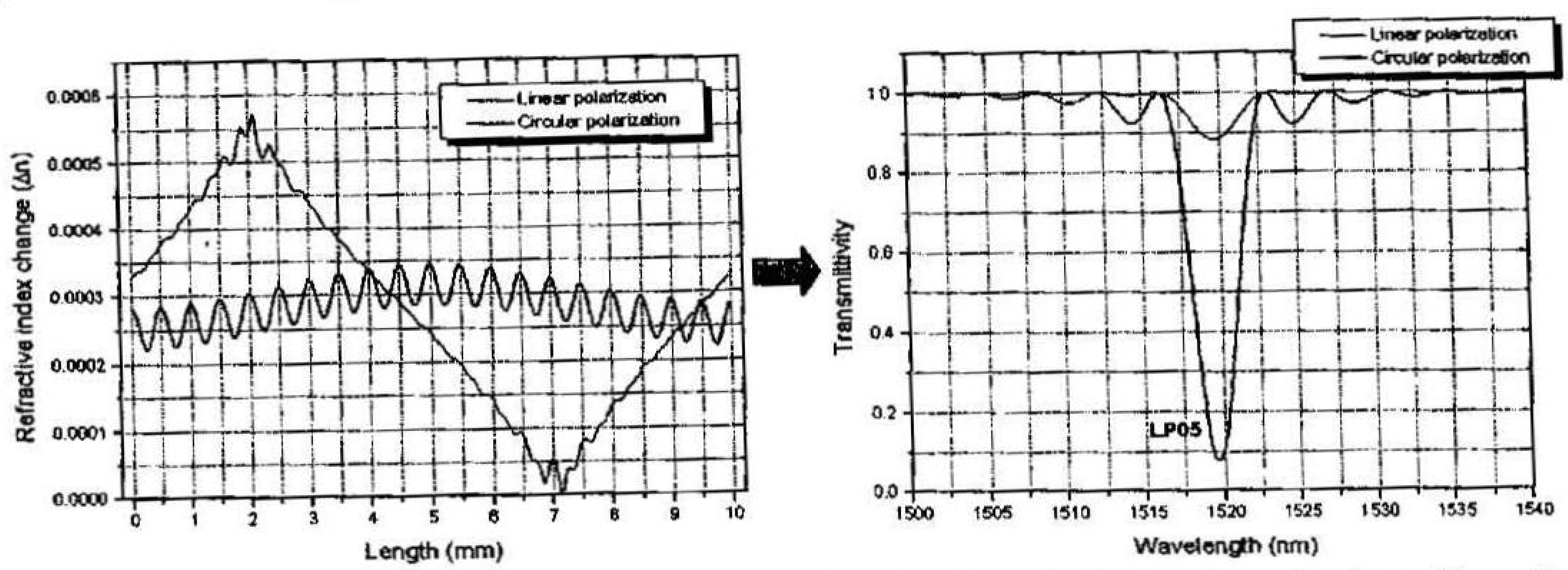


Fig.2. Different index profiles of a VLPG obtained by changing the polarization from circular to linear (left graph), and their corresponding spectra (right graph).

These graphs have been obtained for a circular polarization whose Jones vector is [1,j], and for a linear polarization of [1,0.75]. As can be seen, a 500μm-period VLPG is obtained in both cases, but both the apodization and the modulation depth differ considerably from one situation to the other. This means that the wavelength of the resonance will not shift by changing the polarization, but the attenuation will change. This fact can is shown in the right graph of Fig.2, where the two spectra corresponding to the index profiles can be seen. In both cases there is a coupling to the same cladding mode (LP05) at the same wavelength, but the strength of that coupling is much weaker for the linear case. Therefore, by changing the SOP of the light the attenuation of the VLPG spectrum can be controlled, but not the wavelength. The latter can be achieved simply by changing the twist ratio.

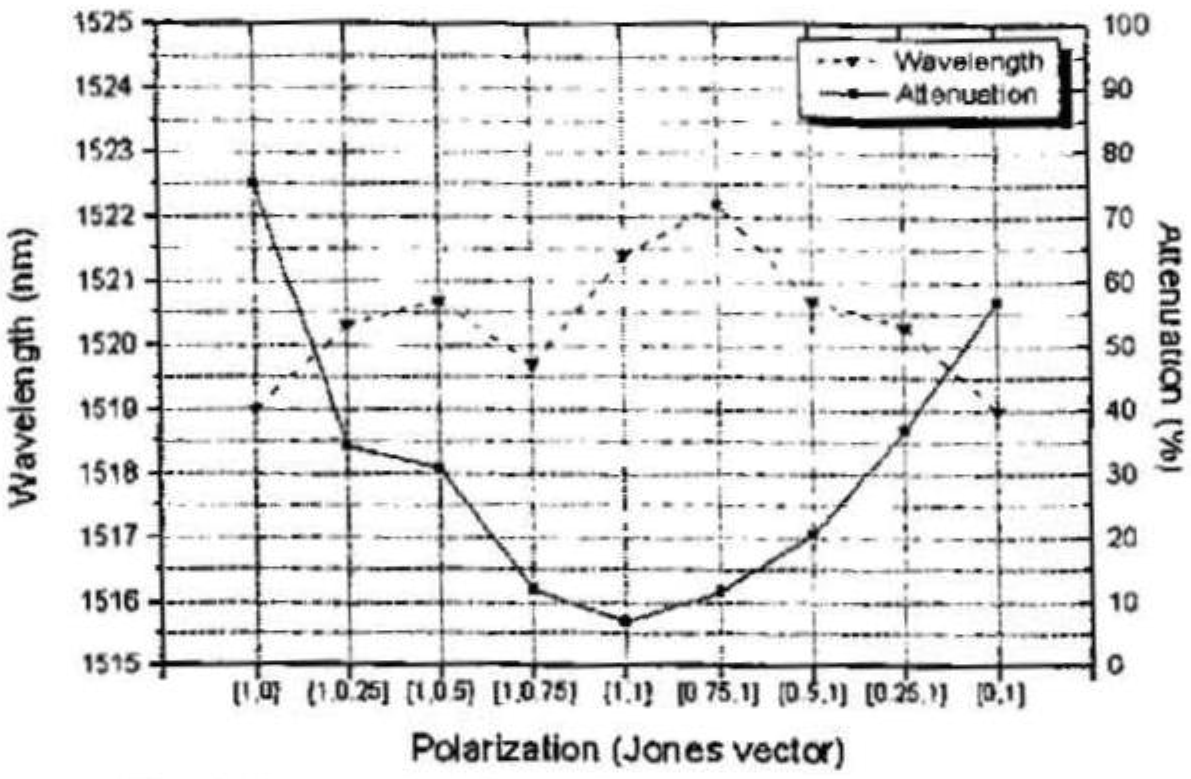


Fig.3. Evolution of the attenuation and resonance wavelength for linear polarization.

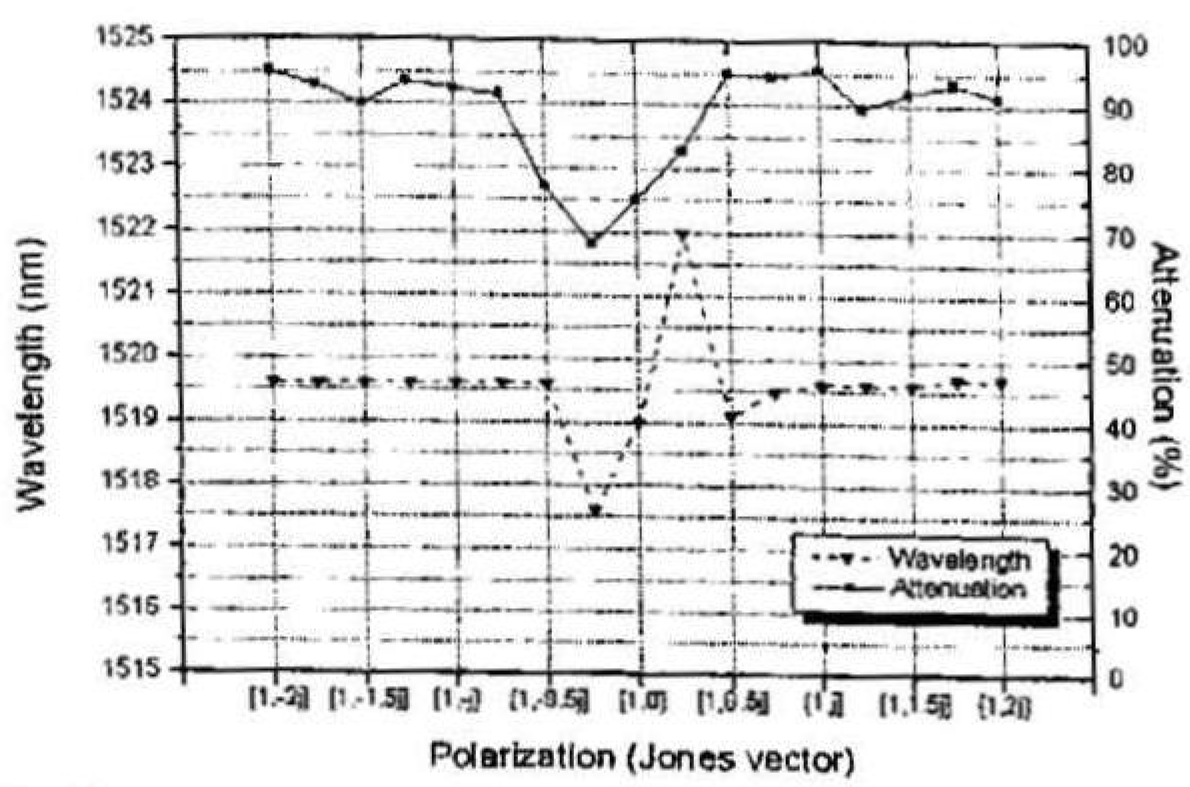


Fig.4. Evolution of the attenuation and wavelength of the resonance for circular polarization.

In order to study in more detail the behavior of these devices with the initial state of polarization of the light two sweeps (one for linear SOP and another for circular SOP) were performed. During the sweeps both the attenuation and wavelength of the spectral peak were recorded. The results are shown in Fig.3 and Fig.4 respectively. In both cases it can be observed that the wavelength doesn't change very much, being the deviations from one polarization to another more a result of the approximations in the simulation process than actual wavelength shifts. However the attenuation changes are highly polarization dependant. Moreover, with linear polarizations attenuations ranging from 70% to 5% can be obtained meanwhile with circular polarizations this range goes from 70% to 100%. Therefore with one polarization or the other the attenuation can be set to the desired value without affecting in a substantial way to the wavelength.

4. CONCLUSIONS

The theoretical prediction of a novel device whose behavior is similar to a LPG has been presented: the VLPG. It is based on illuminating a heavily twisted HiBi fiber with polarized light. In that structure the combined action of the linear and circular birefringences generate a periodic virtual index change that gives rise to a LPG. This index change is virtual since it is not permanent and depends on the polarization changes of the light. Therefore changing the polarization of the light will change the characteristics of the VLPG. Particularly, as has been demonstrated with simulations, the parameter that can be tuned with the SOP of the incident light is the spectral attenuation.

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