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Experimental characterization of a tuneable all-fiber mode converter device for mode-division multiplexing systems

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Abstract. In this work, we present a novel scheme to make a controllable, stable, and versatile all-fiber mode converter device. The converter consists of a few modes polarization-maintaining fiber, which is laterally stressed using an electrical actuator. The electrical actuator provides a simple mechanism to control the refractive index changes in the optical fiber thought the elasto-optic phenomena. Thus, it is possible obtain a platform to make mode conversion between the HE_{11} mode and the TE_{01}, TM_{01} and HE_{21} modes. Likewise, the proposed methodology allows controlling the modal conversion trough the variation of the applied force. The results reveal that the performance of the converter depends on the input light polarization, the analyzer angle and the applied force. In addition, the device presents a compact size of 8 cm and shows an excellent performance when is analyzed at 980 nm. Thereby, it is suitable to be implemented for future optical fiber communication systems that employs mode-division multiplexing.

1. Introduction

Mode-division multiplexing (MDM) has attracted attention as a promising way to upgrade the transmission and reception capacity of the incoming telecommunication devices since it increases the transmission channels by exploiting the transverse spatial dimension of the optical fiber [1,2]. The MDM technique has achieved high spectral efficiencies of 32 bits/s/Hz, which is larger than the achieved by a single mode fiber (SMF). However, the development of high-resolution selective spatial multiplexers (mode converters) is one of the main challenges for this technique, due it requires selectively launch and detect each core mode. The mode converters offers the possibility to use each of the orthogonal polarization states of the spatial modes as a transmission channel and the energy coupling from the fundamental core mode to higher order modes [3,4].

Many alternatives have been explored to create and manipulate the propagation modes using few mode fibers (FMFs) , some of them are based on long period fiber grating (LPFG), fiber bragg gratings (FBG), dual-core fibers and tapers [5–7]. However, these methods are limited since, in general, they offer passive alternatives. For this reason, more promissory alternatives use external perturbations over the fibers in order to modify and control the propagating modes [8–10]. For example, McGloin, *et al.* proposed in 1998 a simple method to generate a phase difference by inducing mechanical stress over the used fiber with rectangular lead weights [11]. Li, *et al.* in 2015 presented a novel method that employs mechanical devices to deform a two-mode fiber to control all-fiber orbital momentums [12]. In 2015, Schulze, *et al.* presented a comparative study where an FMF is mechanically stressed using homogeneous and irregular slabs. Thus, they demonstrated that the coupling between degenerated and non-degenerated modes depend on the induced phase and the geometry of the used mechanical slabs

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[13]. Finally, Zhang, *et al*. proposed a method to generate high-order optical vortex mode conversion using acusto-optic phenomena in 2016 [14]. However, in all cases, the mode conversion was only analyzed using conventional optical fibers. Therefore, the implementation of high-birefringent (Hi-Bi) optical fibers could open new possibilities in this research area.

In this work, we propose a simple scheme to make a mode conversion device based on the use of a few mode polarization maintaining optical fiber (FM-PMF). To evidence the feasibility of this methodology an experimental setup was carry out. Here, we test the performance of the proposed device under different condition. So, the mode conversion is evaluated as function of the polarization of the injected beam, the magnitude of the applied force and the analyzer angle, when an electrical actuator is employed to induce perturbations in the phase birefringence of the FM-PMF.

2. Experimental setup

The proposed mode converter device is based on a FM-PMF (PANDA-type optical fiber). To demonstrate the capability of this optical fiber as a platform to create a tuneable mode converter device, the experimental setup depicted in Figure 1 was proposed. In this setup, an electrical actuator (Newport AD30) was employed to apply a controllable lateral force. In this case, the lateral force was applied parallel to the stress applying parts (SAPs). To guarantee this condition, the cladding region was illumined with the fabry-perot (FP) laser diode at 980 nm, thus an image of the entire structure is projected on the charge-coupled device (CCD) camera. To adjust the correct position of the fiber under test with respect the orientation of the force, a rotational stage was employed in both extremes of the testing optical fiber.

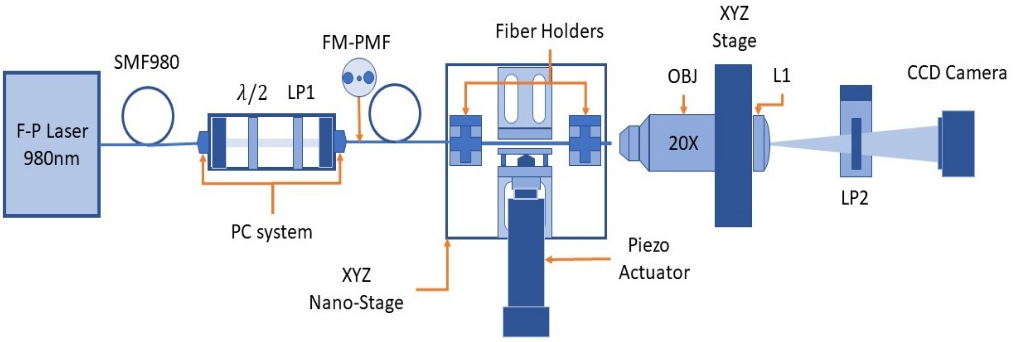

Figure 1. Schematic of the proposed experimental setup. The first polarizer LP1 defines the angular orientation of the injected modes into a FM-PMF and the second LP2 (analyzer) is employed to distinguish the polarization components of the output beam.

As is illustrated in Figure 1, the F-P laser diode at 980 nm (Optilab, FP-B-980-150) is used to inject light into the system. The input polarization of the beam was controlled with help of polarization control (PC) system. It was created using a linear polarizer (LP1), thus it is possible to regulate the input polarization of the light with respect the principal birefringent axis of the FM-PMF. Likewise, to ensure that the input mode is the fundamental mode, the light was injected using a pigtail of SMF-28e, this fiber acts as mode filter to avoid the excitation of high order modes at 980 nm. Therefore, the input mode in the first extreme of the FM-PMF is the HE_{11}. As mentioned before, in order to couple energy between the HE_{11} to high order modes, we apply a controlled lateral force using the electrical actuator. Then, elasto-optic effect induces a variation in the phase birefringence of the fiber, and consequently, modify the propagating modes into the FM-PMF [12]. Therefore, the propagating modes are coupled, and the energy can be transferred between them. Finally, the light at the rear end of the FM-PMF is collected using a 20X objective lens and the beam intensity is recorded in real time using a CCD camera (WiDy SWIR 640V-S). The second linear polarizer (LP2) is introduced before the CCD camera to discriminate the output mode. Here, it is important to highlight that the two extremes of the PMF were fixed using fiber holders to avoid vibrations and displacements of the fiber under test.

3. Results and discussion

The proposed experimental setup was used to characterize the capability of FM-PMF as platform to make mode conversion between the HE_{11} mode and TE_{01}, TM_{01} and HE_{21}. In this case, the electrical actuator with help of two flat slabs were employed to uniformly apply lateral force over 8-cm piece of FM-PMF. The actuator induced controlled linear birefringence changes and spatial modal transitions over the propagating modes. The employed actuator allows the variation of the force between 0 N and 400 N with steps of 53.4 N.

We start the trials of this mode converter at room temperature and a lateral force of 0 N, as initial condition, *i.e.*, the behavior of the proposed mode converter without an external perturbation. Then, an initial HE_{11} mode is injected into the fiber under test along the horizontal axis with respect to the position of the SAPs (it was alignment with respect to the slow axis). After, traveling into the FM-PMF, the light was recorder with the CCD camera while the analyzer (LP2) is rotated from 0° to 180° with steps of 10°. The recorded images under these conditions are presented in Figure 2. The recorded images show the normalized intensity obtained with the CCD camera, where the dark blue region indicates low intensity and the red color indicates high intensity. The results reveal that when the analyzer is oriented at $\theta = 70°$ with respect the orientation of LP1, only the fundamental mode arrives to CCD camera and the other modes are filtered. Otherwise, when the analyzer is rotated other 90°, *i.e.*, to reach 160° only the pass of the TE_{01} mode is allowed [15–17].

Now, we insert a $\lambda/2$ plate between the laser and the LP1 to rotate the input polarization 90°, thus, we can inject the light on the fast axis of the FM-PMF and interrogate the behavior of the proposed structure as function of input polarization. The obtained results under these conditions are illustrated in the second row of Figure 2. In this case, we proof that the results are complementary compared with the obtained when LP1 is oriented at 0° since in this case the fundamental mode is recorded at $\theta = 160°$, while at $\theta = 70°$ only is possible the pass of the TM_{01} mode. These results probe that this mode converter is suitable to be employed in mode division multiplexing and polarization division multiplexing techniques, simultaneously. Owing to the proposed mode converter could send at least two independent modes on each birefringent axis. In addition, each axis allows the propagation of at least two different modes and the excitation of each mode depends of the induced phase birefringence. For this reason, we evaluate the behavior of this mode converter when the birefringence is modulated using an external lateral force.

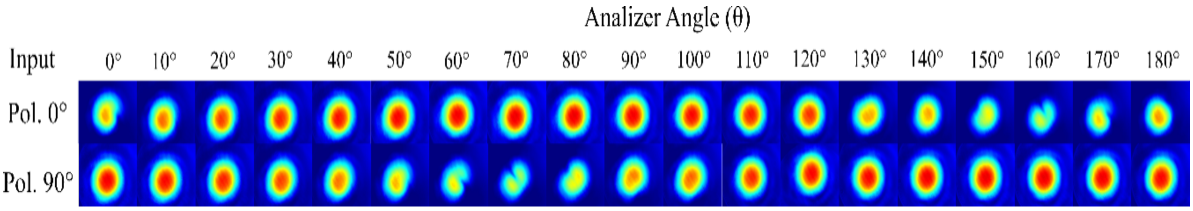

Figure 2. Experimental recorder modal images at different analyzer (LP2) angles. These results illustrate the obtained modes when the polarization of the laser light is along the slow axis (first row) and the fast axis (second row). These results were obtained at room temperature and F = 0 N. The dark blue and red color regions indicate low and high intensity respectively.

Then, the effects of the lateral force on the mode response of the proposed mode converter device was experimental analyzed. In this case, the last experiment was carried out for seven different forces, which were controlled using the electrical actuator.

Figure 3 illustrates the experimental recorders when the light was injected along the slow axis of the FM-PMF. From these results, we can observe that the mode converter device does not operate when the analyzer is placed at 90° with respect the input polarization. Nowadays, at these conditions only the HE_{11y} mode could be propagate. On the other hand, the best results were obtained when the analyzer turned at 160° regarding the input polarization. In that case, we obtain the TE_{01} mode when the applied force is 26.7 N and it couples the energy to the fundamental mode when the force increases to reach

133.5 N. After that, the mode continues with the transformation until it returns to TE_{01} mode when the force is 347.1 N. Otherwise, weak coupling between the HE_{11x} mode and the HE_{21} mode is obtained when the analyzer was placed at 0°.

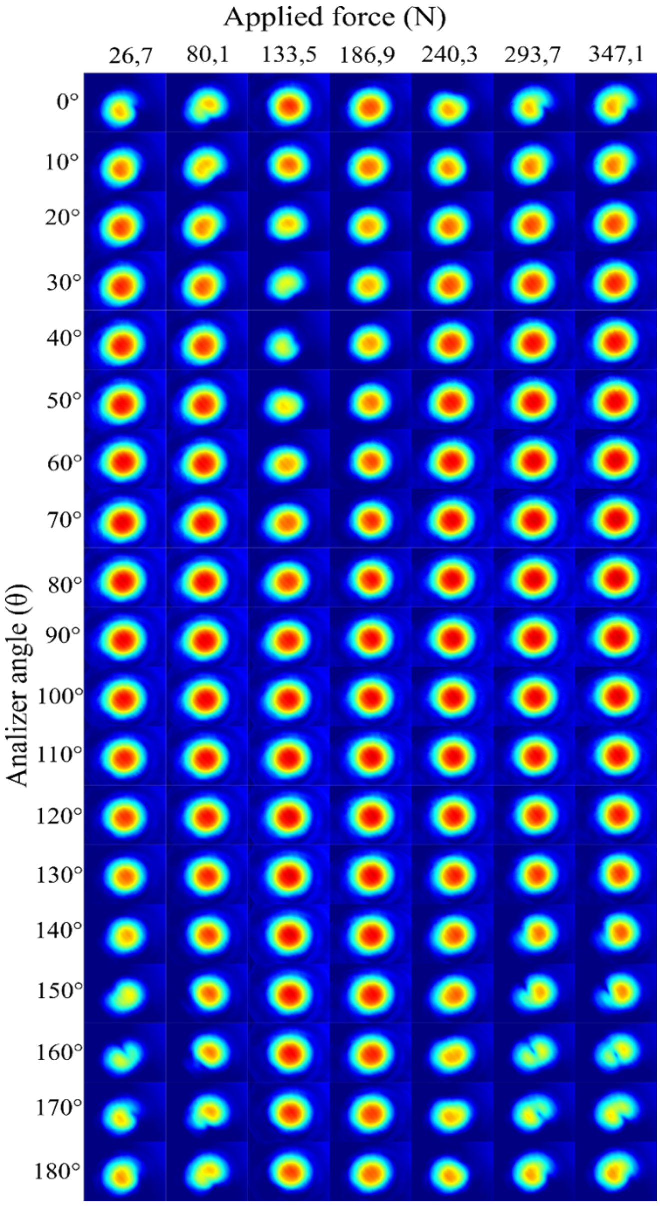

Figure 3. Near-field experimental patterns obtained at the output end of the mode converter based on FM-PMF as a function of the applied lateral force and analyzer angle, when the laser light at the input end of the device is aligned along slow axis. These results were obtained for a wavelength of 980 nm. The dark blue and red color regions indicate low and high intensity respectively.

Figure 4 shows the obtained results when the light was injected parallel to fast axis of the FM-PMF. The first row presents the results obtained when the applied force increases from 26.7 N to 347.1 N, while the analyzed is fixed at 0°. The results show an opposite behavior compared when the light was injected along the slow axis since at these conditions does not occur mode conversion, *i.e.*, only the HE_{11x} mode arrive to the CCD. Nevertheless, if the analyzer (LP2) is oriented at 70° with respect the orientation of LP1, the transition from the TM_{01} mode at F = 26.7 N to HE_{11} mode at F = 133.5 N is observed. As well, when the force continues to increase to reach 347.1 N, we obtain the best TM_{01} mode. It means that at these conditions the required birefringence to obtain a maximum energy coupling between these pair of modes. Similar results were obtained when the analyzer was oriented at 60°, 80° and 90°, while in other analyzer angles the mode conversion is not given. As it is evident, the results obtained in Figure 3 and Figure 4 are complementary between them.

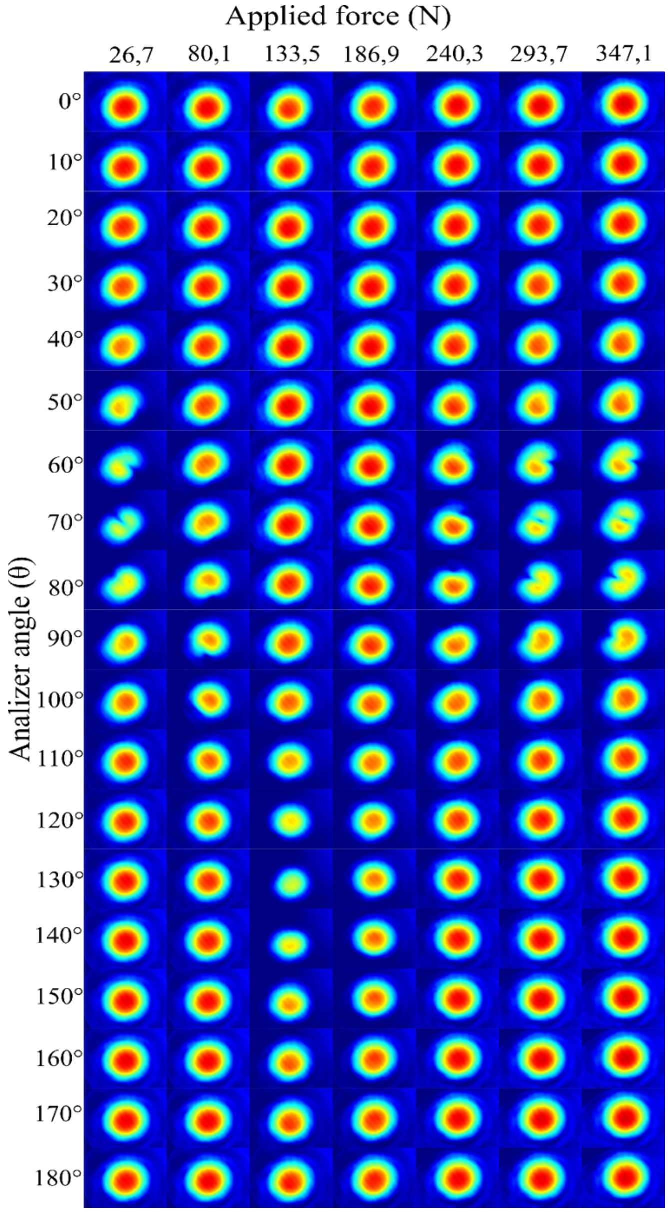

Figure 4. Near-field experimental patterns obtained at the output end of the mode converter based on FM-PMF as a function of the applied lateral force and analyzer angle, when the laser light at the input end of the device is aligned along fast axis. These results were obtained for a wavelength of 980 nm. The dark blue and red color regions indicate low and high intensity respectively.

From the above results, it is evident that the mode conversion in this kind of devices depends of many factors such as applied force, polarization and the analyzer position. This last factor plays an important role due that, the analyzer acts like a filter. Then, it allowing or inhibiting the passage of light, depending on the orientation of the electric field vector of the propagating modes as explained in detail in [15,18]. On the other hand, the obtained results suggest that this platform could be used in polarization division multiplexing systems because the response on either perpendicular axis is complementary, *i.e.*, when the mode converter propagate the HE_{11} mode on the fast axis, the slow axis propagates a two-lobe mode (TE_{01}, TM_{01} and HE_{21}).

4. Conclusions

In this work, a simple and tuneable modal converter based on a FM-PMF was experimentally analyzed at 980 nm. For the modal characterization, we evaluated the performance of the mode converter device as a function of the polarization of the input beam, the applied lateral force and the analyzer angle. Thus, the experiment demonstrated the capability to tune the excitation modes through the control of the induced phase birefringence as consequence of elasto-optic phenomena. Thereby, a scalable, controllable, low-cost, and versatile all-fiber mode converter was demonstrated by deforming a FM-PMF with a simple mechanical method. Finally, the proposed mode converter device is suitable to be used as tuneable mode generator and it has a great potential to be integrated in mode-division multiplexing, optical manipulation and polarization division multiplexing systems.

Acknowledgments

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References

[1] Reyes-Vera E, Senior D E, Luna-Rivera J M and López-Giraldo F E 2018 Advances in electromagnetic applications and communications *TecnoLógicas* **21** 9
[2] Richardson D J, Fini J M and Nelson L E 2013 Space-division multiplexing in optical fibres *Nature Photonics* **7** 354
[3] Reyes-Vera E, Úsuga J, Acevedo-Echeverry J, Gómez-Cardona N and Varón M 2017 Performance analysis of a modal converter based on an asymmetric dual-core photonic crystal fiber *Optica Pura y Aplicada* **50** 251
[4] Tkach R W 2010 Scaling optical communications for the next decade and beyond *Bell Labs Techincal Journal* **14(4)** 3
[5] Zhang X, Liu Y, Wang Z, Yu J and Zhang H 2018 LP 01 LP 11a mode converters based on long-period fiber gratings in a two-mode polarization-maintaining photonic crystal fiber *Optics Express* **26** 7013
[6] Ali M M, Jung Y, Lim K-S, Islam M R, Alam S-U, Richardson D J and Ahmad H 2015 Characterization of mode coupling in few-mode FBG with selective mode excitation *IEEE Photonics Technology Letters* **27** 1713
[7] Vera E R, Restrepo J Ú, Varon M and Torres P 2018 Dual-Core transversally chirped microstructured optical fiber for mode-converter device and sensing application *Selected Topics on Optical Fiber Technologies and Applications* Eds F Xu and C Mou (Croatia: InTech)
[8] Reyes Vera E E, Usuga Restrepo J E, Gómez Cardona N E and Varón M 2016 Mode selective coupler based in a dual-core photonic crystal fiber with non-identical cores for spatial mode conversion *Latin America Optics and Photonics Conference* (Medellin: Optical Society of America)
[9] Montoya Cardona J A, Gomez Cardona N D, Gonzalez Valencia E, Torres Trujillo P and Reyes Vera E 2019 Tunable mode converter device based on photonic crystal fiber with a thermo-responsive liquid crystal core *Photonics* **7** 3
[10] Sakata H, Sano H and Harada T 2014 Tunable mode converter using electromagnet-induced long-period grating in two-mode fiber *Optical Fiber Technology* **20** 224
[11] McGloin D, Simpson N B and Padgett M J 1998 Transfer of orbital angular momentum from a stressed fiber-optic waveguide to a light beam *Applied Optics* **37** 469
[12] Li S, Mo Q, Hu X, Du C and Wang J 2015 Controllable all-fiber orbital angular momentum mode converter *Optics Letters* **40** 4376
[13] Schulze C, Bruning R, Schroter S and Duparre M 2015 Mode coupling in few-mode fibers induced by mechanical stress *Journal of Lightwave Technology* **33** 4488
[14] Zhang W, Huang L, Wei K, Li P, Jiang B, Mao D, Gao F, Mei T, Zhang G and Zhao J 2016 High-order optical vortex generation in a few-mode fiber via cascaded acoustically driven vector mode conversion *Optics Lett*ers **41** 5082
[15] Khan S N, Chatterjee S K and Chaudhuri P R 2015 Polarization and propagation characteristics of switchable first-order azimuthally asymmetric beam generated in dual-mode fiber *Applied Optics* **54** 1528
[16] Mo Q, Hong Z, Yu D, Fu S, Wang L, Oh K, Tang M and Liu D 2017 All-fiber spatial rotation manipulation for radially asymmetric modes *Scientific Reports* **7** 1
[17] Snyder A W and Love J D 1984 *Optical Waveguide Theory* (Boston: Springer)
[18] Reyes Vera E 2019 *Few-Mode Photonic Crystal Fibers for Mode-Converter Devices and Sensing Applications* (Bogota: Universidad Nacional de Colombia)