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Higher-Order Core Mode Resonances in a Mechanically Induced Long-Period Holey Fiber Grating

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We present the spectral analysis of higher-order core mode resonances in a long period holey fiber grating induced mechanically in an asymmetric holey fiber. Calculations based on a fast-Fourier transform mode solver shows that the mode resonances obtained experimentally correspond to the odd- and even-$LP_{1,1}$ core modes. Additionally, we analyze the twist and polarization response of these mode resonances in the long period holey fiber grating. The results obtained in this work are of great importance in the design of new all-fiber optical devices that involve couplings of higher order core modes in asymmetric holey fibers.

Keywords: holey fiber, core modes, long-period fiber gratings, mechanically induced gratings

1. Introduction

Long-period fiber gratings (LPFGs) consist of a periodic perturbation of the refraction index of the fiber core that couples energy between two copropagating modes, typically the fundamental mode and a higher order mode of the core or cladding. For their fabrication, different techniques like UV radiation, thermal and press-induced have been developed.[1–3] LPFGs formed by press-induced technique have generated great interest due to its versatility in the process of fabrication. In these gratings the fiber is subject to periodical stress, which results in alternated regions under compression and stretching that modulate the refractive index via the photoelastic effect. Also, these LPFGs can be implemented in almost any type of fiber; they show an erasable and reconfigurable behavior and allow a wide tuning and bandwidth control.[3–5] These characteristics present mechanically induced LPFGs like an attractive option for many applications such as broadly tunable nonreflecting band-rejection filters, dynamical gain equalizers in fiber amplifiers or lasers, and optical fiber sensors.[6–9]

An important parameter to consider in a mechanically induced LPFG is the type of optical fiber used. In this matter, holey fibers have been demonstrated to be an adequate medium to implement LPFGs.[3,5,10] Compared with gratings written in standard communication fibers, holey fibers, which incorporate numerous air holes in the cladding, offer more stable performance against changes in temperature, strain, and the refractive index of the medium that surrounds the cladding.[11,12] One of the principal features observed in holey fibers is that when they show a perfect hexagonal arrangement of holes, the first higher order core modes $TM_{0,1}$, $TE_{0,1}$, and $HE_{2,1}$ are degenerated and resemble the $LP_{1,1}$ core modes observed in standard communications fibers.[13,14] Nevertheless, any slight disorder in the inner air-hole lattice can make them split into the odd- and even-$LP_{1,1}$ modes.[15,16] These modal changes can modify the behavior of the resonances in a mechanical LPFG. As result, multiple peaks can appear or disappear in the spectral transmission of the grating modifying its resonance wavelength range. The control of these spectral characteristics is of great importance in the design of all holey-fiber devices based on mechanical LPFGs. In this case, a characterization of the higher-order $LP_{1,1}$ core mode resonances in these kinds of gratings is required, principally in holey fibers that do not show a perfect arrangement of holes, which is the case of the great majority of microstructure fibers.

In this paper, we characterize the higher-order core modes resonances in a mechanically induced long-period holey fiber grating (LPHFG). Calculations based on a fast-Fourier transform (FFT) mode solver indicate that the resonances obtained in this work correspond to the odd- and even-$LP_{1,1}$ higher order core modes. On the other hand, our experimental results show that the resonances of these modes have a strong fiber-orientation dependency. This dependency can be used to modulate the amplitude of the odd- and even-$LP_{1,1}$ resonances according to the initial orientation of the holey fiber on the mechanical LPFG. In addition, an analysis of the twist response of both mode resonances is realized. Finally, the results obtained in this work can be generalized to other holey fibers that allow the coupling of the odd- and even-$LP_{1,1}$ core modes in mechanically induced LPFGs.

2. Experiment and Results

The experimental configuration shown in Fig. 1 was used to produce the LPHFG. The grating was formed by pressing a section of a holey fiber between two corrugated grooved plates (CGP's). The dimensions of both grooved plates were 70 mm long and 24 mm wide and each one had a square groove pattern with 460 µm of period (Λ). The holey fiber was placed between the CGP's by two rotational holders H1 and H2. Both holders can be turned clockwise or anticlockwise, and their separation (L_τ) is 22.5 mm. When both holders are simultaneously turned in the same direction the holey fiber is rotated by an angle (θ) from a relative initial position in respect to the lateral stress axis generated by the

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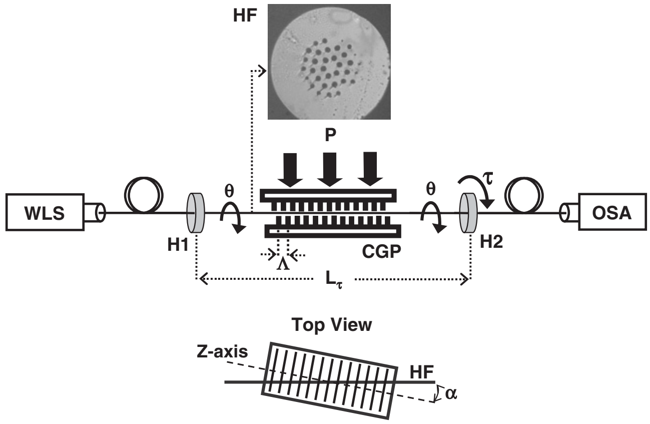

Fig. 1. Schematic of the experimental mechanically induced LPHFG setup.

CGP's. Additionally, the holey fiber can be twisted an angle (τ) if holder H1 is fixed and holder H2 is turned in a clockwise or counterclockwise direction, whereas the resonance wavelengths can be tuned changing the period (Λ) of the LPHFG by adjusting the angle (α) of the z-axis of the CGP in respect to the fiber as is shown in Fig. 1. A white light source (WLS) and an optical spectral analyzer (OSA) were used for the spectral measurements. The inset in Fig. 1 shows a photograph of the holey fiber transverse section. This fiber has a core/cladding diameter of 11/125 µm, with 5 µm hole diameter and lattice pitch of 11 µm and shows an imperfect hexagonal cladding structure.

In the experiment, we adjusted the period of the grating to 482 µm. Two rejection bands were obtained at 1121 and 1527 nm as is shown in Fig. 2. In this part, the holey fiber was rotated at different angles and, for each selected angle, it was pressed between the two corrugated grooved plates. As can be seen, both rejection bands depend strongly on the rotation angle of the fiber. In this experimental stage, we chose the initial position ($\theta = 0°$) when only the rejection band at 1527 nm is observed. To analyze the tuning of the LPHFG, both rejection bands are plotted in Fig. 3 for different values of Λ maintaining $\theta = 45°$. In this case we always observed simultaneously both rejection bands over a tuning range of 100 nm, meaning that the grating period does not affect the behavior of the two mode couplings in the LPHFG.

To describe the modes associated with both rejection bands, a numerical simulation was performed. Figure 4 shows the resonance curves of the LPHFG obtained by simulation based on a FFT-mode solver.[17,18] The solid lines are the theoretical resonant wavelength behaviors for the odd- and even-$LP_{1,1}$ core modes according to the calculation of the effective index of the modes, while the circles are experimental data that correspond to the resonance wavelength tuning of each rejection band shown in Fig. 3. According to these results, the modal coupling of the $LP_{0,1}$ fundamental mode with the odd and even $LP_{1,1}$ core modes of the holey fiber correspond to both rejection bands obtained at 1121 and 1527 nm, respectively. As is mentioned

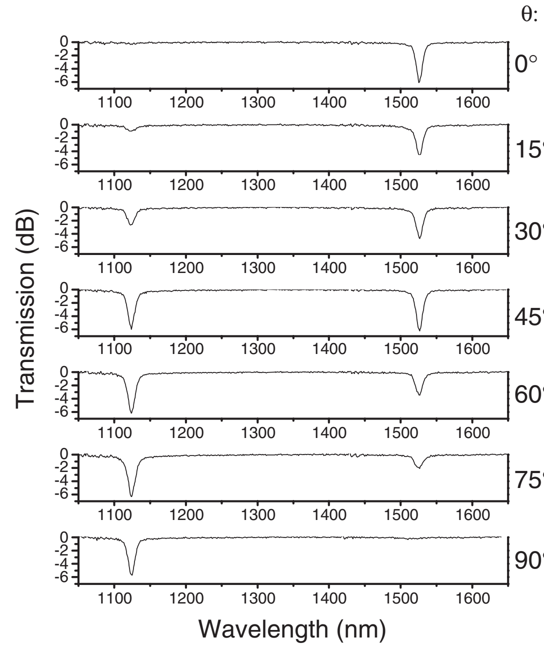

Fig. 2. Transmission spectra of the LPHFG for different rotation angles θ at $\Lambda = 482$ µm.

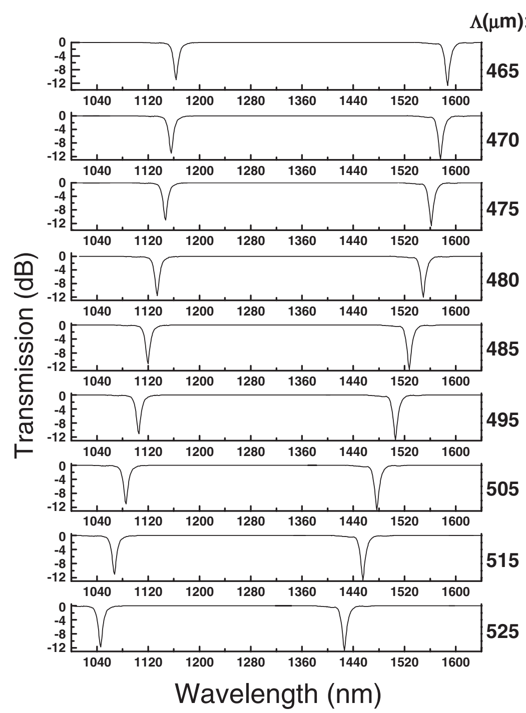

Fig. 3. Tuning of the rejection bands by adjusting the period Λ at $\theta = 45°$.

above, the even- and odd-$LP_{1,1}$ modes can be guided in holey fibers with low hexagonal symmetry. Figure 5 depicts the electric fields and intensity distributions of the $LP_{0,1}$ mode and the $LP_{1,1}$ modes. In this figure, each LP mode has two eigen-polarization states and a birefringence with a numerical error of 1×10^{-6}. Additionally, one can observe that the $LP_{1,1}$ modes have a set of symmetrical axes called

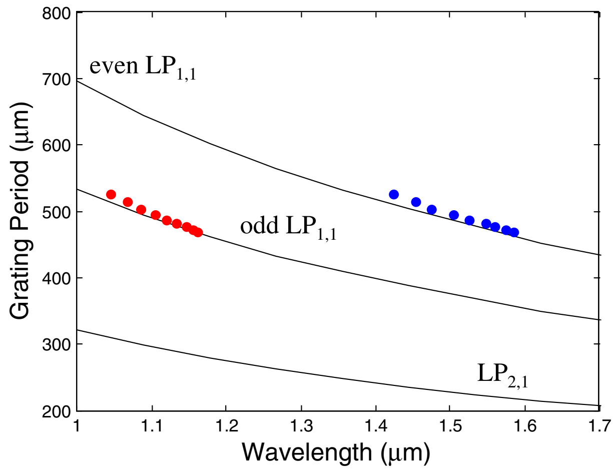

Fig. 4. (Color online) Calculated and measured resonant wavelengths of the mode coupling between the fundamental $LP_{0,1}$ mode and odd $LP_{1,1}$ or even $LP_{1,1}$ core modes. Solid lines are simulation and circles indicate measured data.

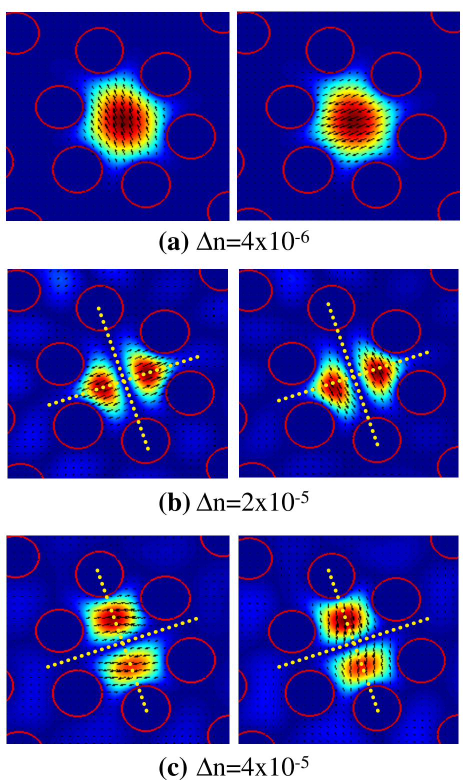

Fig. 5. (Color online) Calculated electric field distributions and birefringence Δn of (a) the $LP_{0,1}$, (b) the even $LP_{1,1}$, and (c) the odd $LP_{1,1}$ core modes. Dashed lines indicate the eigen-axes of the $LP_{1,1}$ modes.

optical eigen-axes,[15] as indicated by dashed lines in Figs. 2(b) and 2(c). The presence of these eigen-axes explains the behavior of the two rejection bands shown in Fig. 2. According to this figure, we can obtain only one or simultaneously the two rejection bands if the eigen-axes are or are not aligned with the pressing direction of both grooved plates.

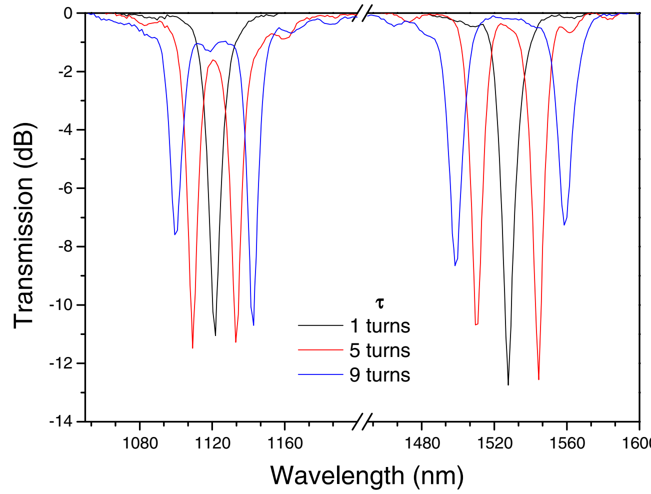

Fig. 6. (Color online) Splitting evolution for both rejection bands centered at 1121 and 1527 nm with $\tau = 1$, 2, and 3 turns per 22.5 mm.

Once the modal characterization of both rejection bands was realized, we analyzed the twist effect in the spectral transmission of the LPHFG. In this case, we first placed the holey fiber at $\theta = 0°$ in such way that we only obtained the resonant peak at 1527 nm as is indicated in Fig. 2(a). Then, the holey fiber was clockwise twisted along 22.5 cm length and was pressed between the two corrugated grooved plates. This process was repeated for different values of twist. The result is the spectral transmission illustrated in Fig. 6 where the holey fiber is twisted with $\tau = 1$, 5, and 9 turns. One can observe that under twist both rejection bands at 1121 and 1527 nm are always obtained. These results indicate that the effect of the fiber rotation angle is reduced. This behavior is due to the fact that when the holey fiber is under twist there is not a preferential orientation of the fiber with respect to the pressure direction of the two grooved plates. Also, one can observe that, after $\tau = 1$ turn, both rejection bands split into two shifted peaks that move symmetrically further apart as the twist is increased. This result does not depend on whether the fiber is twisted in a clockwise or counter-clockwise direction. For higher values of twist no further measurements were made since the fiber was usually broken. Additionally, the pressure between the corrugated plates did not affect the splitting observed in Fig. 6. The coupling strength was reduced or increased when a lower or higher pressure was applied and the rejection bands only decreased or increased in depth. Therefore, the twist is the origin of the splitting.

Figure 7 shows the resonance wavelength evolution under twist from $\tau = 0$ to 9 turns for each rejection band observed in Fig. 2(d) with $\theta = 45°$. One can observe that with a twisting angle between 0 and 1 turn both rejection bands are obtained practically without change, and after 1 turn each band is split into two resonant peaks. For values lower than 1 turn we did not observe a splitting of the resonant peaks within the resolution of the OSA. In this case, the twist perturbation is not sufficient to clearly split each rejection

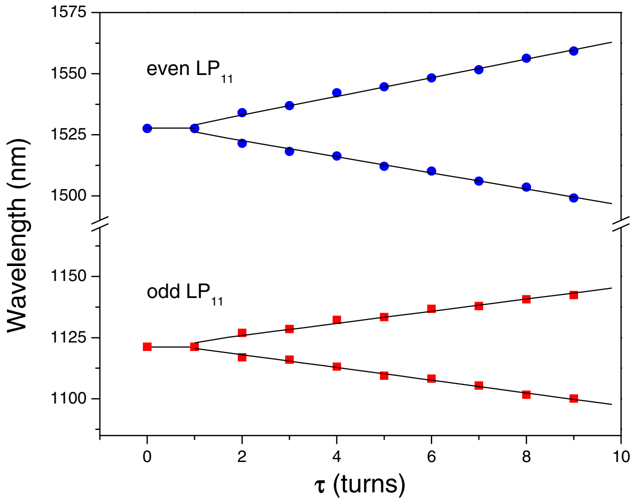

Fig. 7. (Color online) Wavelength shift of each resonant peak of the LPHFG under twist. Solid circles indicate measured data and solid lines are linear fitting.

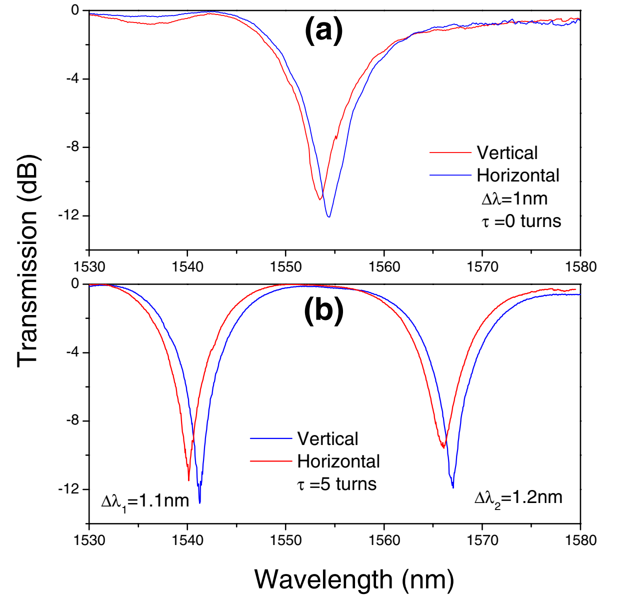

Fig. 8. (Color online) Polarization response of the even $LP_{1,1}$ resonance: (a) without twist, and (b) under twist.

band. These results change slightly for different values of θ. The upper and lower resonance wavelengths of the split resonance peak at 1527 nm show wavelength shift rates of 3.8 and −3.3 nm/turn. On the other hand, wavelength shift rates of 2.4 and −2.6 nm/turn were obtained for the split resonance peak at 1121 nm. These wavelength shift rates were calculated by linear regression of the data points shown in Fig. 7. In this figure one can observe that the wavelength shift of both peaks of the split rejection band at 1527 nm show higher shift values that those in the split rejection band at 1121 nm. These differences are attributed principally to the fact that the odd- and even-$LP_{1,1}$ modes associated with both split resonant peaks have different field distribution in the transverse direction of the holey fiber and they respond in different forms with respect to the twist perturbation.

Finally, to characterize the polarization response of the grating peaks, we analyzed the rejection band of the LPHFG centered at 1555 nm that corresponds to the even $LP_{1,1}$ mode resonance. In this part, the white light source in the setup of Fig. 1 was changed by a polarized light source. We used a polarimeter-synthetizer that works in the 1500–1600 nm wavelength range. The spectral transmission of the LPHFG for both vertical and horizontal polarized inputs is shown in Fig. 8(a), where one can observe that due to the polarization dependence of the grating without twist, the localization of the resonant peak is changed 1 nm. Also, we measured the polarization response of the rejection band under twist. In this case, the holey fiber was twisted 5 turns in 22.5 cm length. In Fig. 8(b), it can be observed that the localization of the two peaks of the split rejection band is changed 1 and 1.2 nm, respectively. These values are modified slightly for different values of twist. According to the birefringence of the LP modes obtained by simulation, we can expect wavelength shift values between 3 and 6 nm. These results do not agree with our measurements. In this case, we have to additionally consider the circular birefringence induced by twist and the linear birefringence caused by the directional pressure of the mechanical LPFG; nevertheless these effects are not analyzed in this work.

3. Discussion

We reported the analysis of higher-order core mode resonances in a LPHFG induced mechanically in an asymmetric holey fiber. These higher-order core mode resonances are similar to those obtained in LPHFGs inscribed with an electric arc.[10] Nevertheless, the mode resonances obtained in our work correspond to the odd- and even-$LP_{1,1}$ core modes. According to simulations based on a FFT-mode solver, these core modes can be propagated in the imperfect hexagonal structure of the holey fiber used in the experiment. One principal feature of these modes is that they show two perpendicular optical eigen-axes as is indicated in Fig. 4. These eigen-axes modify the resonance behavior of the LPHFG according to the rotation angle of the holey fiber in respect to the lateral stress axis. In this case, only one rejection band corresponding to the odd- or even-$LP_{1,1}$ mode can be obtained if the eigen-axes of the odd- or even-$LP_{1,1}$ mode is aligned with the pressure direction of the two grooved plates, respectively. On the other hand, if the holey fiber is rotated 45 degrees from the above position, both mode resonances with similar depth can be obtained simultaneously. This behavior is attributed to the fact that the effective pressure of the grooved plates is distributed equally in both eigen-axes of the $LP_{1,1}$ core modes. These characteristics are of great utility in the alignment of fiber devices; for example, the odd- and even-$LP_{1,1}$ core modes can also propagate in polarization-maintaining holey fibers (PMHF's). In these fibers it is very important to know the direction of the birefringence axes. These axes can be associated with the eigen-axes of the odd- and even-$LP_{1,1}$ modes. In this way, if one uses a mechanical LPFG with an adequate grating period, one can determine according to the presence of the odd- or even-$LP_{1,1}$ mode resonances whether the axes are or are not aligned with respect to the pressure direction of the two grooved plates. This scheme to determine the orientation of the birefringence axes of a holey fiber using a mechanical LPFG is of great interest due to the simplicity and low cost of the device.

We found that when the holey fiber is twisted slightly prior pressure application in the LPHFG, the odd- and even-$LP_{1,1}$ mode resonances were obtained simultaneously. This behavior is attributed to the fact that when the holey fiber is twisted, there is not a preferential orientation of the fiber in respect to the pressure direction of the two grooved plates. In this way, the fiber rotation angle dependency of the $LP_{1,1}$ mode resonances is reduced. However, for strong twist, both $LP_{1,1}$ mode resonances split in two peaks that move symmetrically further apart as the twist is increased. To explain qualitatively the splitting observed in this work we have to consider that the odd- and even-$LP_{1,1}$ core modes in holey fibers are degenerated by $HE_{2,1}$, $TM_{0,1}$, and $TE_{0,1}$ modes. Then, if a certain level of twist is applied to the fiber, this modal degeneration is broken. Consequently, the removal of the modal degeneracy modifies the mode coupling between the fundamental $LP_{0,1}$ mode and the $LP_{1,1}$ higher-order core modes and two rejection bands are formed instead of one.[19] Also, the polarization response of the even-$LP_{1,1}$ mode resonance under twist has been measured. The results show that both peaks of the split rejection band are shifted in the same direction for vertical and horizontal polarized inputs maintaining the splitting of the mode resonance. It is worth to mention that the splitting observed in both rejection bands shows a near linear behavior within a wide range of twist and it does not depend on the induced pressure. These splitting characteristics of the odd- and even-$LP_{1,1}$ core mode resonances are of great interest in the design of band pass filters with high tunability.[20] With these devices, one can modify the gain spectrum of an ytterbium doped fiber in order to improve the generation of three-wavelength Raman fiber lasers. Additionally, these characteristics can be used to sense twist-deformations in material structures based on LPFGs induced mechanically in holey fibers.[21]

4. Conclusions

We have presented a theoretical and experimental study of higher-order $LP_{1,1}$ core mode resonances in a mechanically induced long period holey fiber grating. We found that these resonances depend strongly on the fiber rotation angle with respect to the lateral press-direction of the mechanical LPFG. This dependency disappears when the holey fiber is slightly twisted because the effective pressure of the grooved plates is distributed in both directions of the eigen-axes of the odd- and even-$LP_{1,1}$ modes. However, for strong twist a splitting of both mode resonances is presented. This splitting is near linear within a wide twist range and does not depend on the twist direction or the initial orientation of the holey fiber. The splitting of both rejection bands is generated by removal of modal degeneracy. Also, higher values of splitting are obtained for the odd $LP_{1,1}$ mode resonance. These results are of great importance in the design of new all-fiber optical devices that involve couplings of odd- and even-$LP_{1,1}$ core modes in asymmetric holey fibers.

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