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Electromagnetic analysis and characterization of photonic crystal fibers with slit-like geometry

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ABSTRACT

We propose a rigorous electromagnetic analysis for a Photonic Crystal Fiber (PCF) geometry consisting of multiple hollow slits that go across the fiber core along the propagation axis z . The slits are regarded as invariant along the transverse dimension x but exhibit multiple sinusoidal bends in the y - z plane, which prevents the transversal profile being constant along the z axis. To analyze and characterize the electromagnetic behavior of the considered PCF geometry, we use a 2D Finite-Difference Time-Domain (FDTD) scheme assuming an ultrashort incident pulse with a polarization angle of 45 degrees as the excitation source. Our analysis focuses on three key aspects for the ultrashort pulse propagation through the slit array: pulse shaping and delay, spatiotemporal dispersion and birefringence features. Numerical FDTD simulations illustrate the effect of the slit array parameters on the previous magnitudes. Our results demonstrate that the proposed structure provides with a wide and deep control over the pulse propagation and wavefront.

Keywords: Photonic Crystal Fibers, Pulse Shaping, Spatiotemporal Dispersion, Birefringence, Electromagnetic Optics.

1. INTRODUCTION

Since the publication of the seminal paper of Knight et al¹ in 1996, the analysis and fabrication of Photonic Crystal Fibers (PCFs) has attracted much attention in the optical fiber community. Photonic Crystal Fibers are optical fibers with a periodic transverse microstructure² that provides with two basic ways of guiding light different to the Total Internal Reflection (TIR) mechanism in conventional index-step fibers³: index guiding and photonic bandgaps. On one hand, an index-guiding PCF consists of a solid core surrounded by a microstructured cladding in which the presence of air holes reduces its effective refractive index respect to the core and therefore allows light guidance^{4,5}. On the other hand, photonic bandgap PCFs have a hollow core and the light guidance mechanism is based on the presence of a photonic bandgap (at certain wavelengths) in the cladding that arises from its structure of microscopic holes^{6,7}. Beyond the aforementioned light guidance features, PCFs exhibit other important properties such as birefringence induced by an asymmetric transverse hole structure or the possibility of engineering dispersion in combination with nonlinear phenomena among many others^{8,9}.

The typical PCF structures are characterized by a series of micro-holes that cross the entire fiber in the direction of light propagation, which gives rise to an invariant transverse profile. In contrast with this standard structure, in this paper we explore a new kind PCF geometry in which the core is formed by an array of hollow slits (filled with air) that cross the fiber along the light propagation axis z . Such slits are invariant in the transverse direction x but exhibit multiple bends along the y - z plane, as depicted in figure 1 (a). The multiple bends of the slits are modelled as a sinusoidal profile, and taking into account the invariance along the x axis, the structure can be analyzed in the framework of a two-dimensional scheme as shown in figure 1 (b). The key parameters of the sinusoidal slit array are (figure 1 (b)):

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- Input plane $z = z_{in}$ and output plane $z = z_{out}$ of the slit array, which are the boundaries of the structure in the z axis. The core contains all the slits of the array, and its total width shall be denoted by W .
- Refractive indexes n_{core} and $n_{cladding}$ of the core and cladding respectively. It is assumed that the incident pulse is generated in a medium with refractive index n_{core} , whereas the hollow slits (black thick curves in figure 1 (b)) have refractive index $n_{air} = 1$.
- Slit thickness l : it is the width of each hollow slit and can be regarded as an analogous parameter to the fill factor in standard PCFs.
- Longitudinal period Λ : it is the period of the sinusoidal slits along the propagation axis z .
- Transversal period Γ : it is the period of the slit array along the y axis and can be regarded as an analogous parameter to the pitch in standard PCFs.
- Slit phase ϕ : it is the phase difference between two consecutive hollow slits defined as $\phi = 360^\circ \cdot \Delta/\Lambda$ (in degrees), being Δ the distance between two consecutive maximums (or minimums) of two adjacent slits along the z axis.
- Amplitude A : it is the amplitude that each slit would have in the extreme case that $l = 0$. Consequently, the total transverse size of a single hollow slit is $2A + l$ (figure 1 (b)).

As indicated in figure 1 (b), we shall consider an ultrashort incident pulse that will reach the slit array at $z = z_{in}$ and then will propagate through the slit array until it leaves such structure crossing the output plane $z = z_{out}$. The main goal of this manuscript consists of studying the propagation features of such ultrashort incident pulse through the slit array by analyzing the transmitted pulse at the output region $z \geq z_{out}$. For this purpose, we shall apply the FDTD algorithm¹⁰ to analyze three key aspects for the transmitted pulses: shaping and delay, spatiotemporal dispersion and birefringence features. It should be remarked that our birefringence analysis shall focus on the FDTD simulation results and not on modal theories, so the expected results will provide features that are closely related to the time-domain behavior of the structure rather than with the modal features.

2. FINITE-DIFFERENCE TIME-DOMAIN FORMULATION

The starting point of our analysis are Maxwell equations for the electromagnetic field $(\vec{E}(\mathbf{r}, t), \vec{H}(\mathbf{r}, t))$ in a non-magnetic medium ($\mu(\mathbf{r}) \equiv 1$) with relative permittivity $\epsilon(\mathbf{r})$, which are given by¹¹ :

$$\nabla \times \vec{E}(\mathbf{r}, t) = -\mu_0 \frac{\partial \vec{H}(\mathbf{r}, t)}{\partial t} \quad (1)$$

$$\nabla \times \vec{H}(\mathbf{r}, t) = \epsilon_0 \epsilon(\mathbf{r}) \frac{\partial \vec{E}(\mathbf{r}, t)}{\partial t} \quad (2)$$

where $\mu_0 = 4\pi \cdot 10^{-7} \frac{H}{m}$ and $\epsilon_0 = 8.82 \cdot 10^{-12} \frac{F}{m}$ are the vacuum permeability and permittivity respectively. According to the scheme depicted in figure 1, we can work in the context of a two-dimensional geometry for which all the magnitudes are invariant respect to x . This assumption allows to rewrite equations 1 and 2 in terms of the (scalar) field components $\vec{E}(y, z, t) = (E_x(y, z, t), E_y(y, z, t), E_z(y, z, t))$ and $\vec{H}(y, z, t) = (H_x(y, z, t), H_y(y, z, t), H_z(y, z, t))$ as two separate set of equations given by:

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0} \frac{\partial E_x}{\partial z} \quad (3)$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu_0} \frac{\partial E_x}{\partial y} \quad (4)$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\epsilon_0 \epsilon(y, z)} \left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \right) \quad (5)$$

Figure 1. (a) Three-dimensional view of the sinusoidal slit array. The hollow slits (black curves) are invariant respect to the x coordinate and cross the fiber along the z axis with multiple bends in the y - z plane. (b) Two-dimensional view (vertical sight) of the slit array showing its fundamental parameters and dimensions. An incident ultrashort pulse travels along the z axis until it reaches the core of the slit array (at normal incidence) at its input plane $z = z_{in}$.

and:

$$\frac{\partial E_y}{\partial t} = \frac{1}{\epsilon_0 \epsilon(y, z)} \frac{\partial H_x}{\partial z} \quad (6)$$

$$\frac{\partial E_z}{\partial t} = -\frac{1}{\epsilon_0 \epsilon(y, z)} \frac{\partial H_x}{\partial y} \quad (7)$$

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu_0} \left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \right) \quad (8)$$

The first set of Maxwell equations 3-5 corresponds to the Transverse Electric (TE) mode consisting of the scalar components $E_x(y, z, t)$, $H_y(y, z, t)$ and $H_z(y, z, t)$, whereas equations 6-8 correspond to the Transverse Magnetic (TM) mode consisting of the scalar components $H_x(y, z, t)$, $E_y(y, z, t)$ and $E_z(y, z, t)$. It should be noticed that both set of equations can be treated independently, which is due to the well-known fact that the modes TE and TM are orthogonal and therefore they do not interfere. Furthermore, the (unique) solution for both set of equations is determined by imposing TE and TM field excitations $s(y, t)$ and $p(y, t)$ on a fixed source plane $z = z_0$ for which:

$$E_x(y, z = z_0, t) = s(y, t) \quad (9)$$

$$H_x(y, z = z_0, t) = p(y, t) \quad (10)$$

Equations 3-5 and 9 constitute the full set of FDTD equations for the TE polarization mode, whereas equations 6-8 and 10 constitute the full set of FDTD equations for the TM polarization mode. In the following section, both sets of FDTD equations shall be solved by applying the standard Yee's algorithm¹⁰.

3. NUMERICAL RESULTS

We shall apply the FDTD methodology described through equations 3-10 to analyze behavior of the electromagnetic field when it interacts with the slit arrays depicted in figure 1. For this purpose, we shall assume an

ultrashort incident field upon the input plane of the slit array $z = z_{in}$, whose different propagation features through the slit array shall be analyzed. The ultrashort incident pulse will be generated at a certain (source) plane $z = z_0 < z_{in}$ with a polarization angle of 45° degrees through the following equations:

$$s(y, t) = A' \exp \left[- \left(\frac{y - y_0}{w_y} \right)^2 - \left(\frac{z_0 - vt}{w_z} \right)^2 \right] \cos(\omega_0 t) \quad (11)$$

$$p(y, t) = -\frac{A'}{\eta} \exp \left[- \left(\frac{y - y_0}{w_y} \right)^2 - \left(\frac{z_0 - vt}{w_z} \right)^2 \right] \cos(\omega_0 t) \quad (12)$$

where A' is the amplitude, y_0 is the transversal position of the maximum pulse intensity, w_y is the transversal pulse width at $z = z_0$, w_z is the longitudinal pulse width, $v = c/n_{core}$ is the pulse speed at the source plane, $\eta = \eta_0/n_{core}$ is the intrinsic impedance at the source plane and $\omega_0 = \frac{2\pi c}{\lambda_0}$ is the optical carrier frequency. Once the incident pulse has been generated at $z = z_0$, it will propagate until it reaches the input plane of the slit array $z = z_{in}$ and then interaction between the incident pulse and the slit array will begin. In the sequel we shall assume the following constant simulation parameters:

$$\lambda_0 = 1.3 \mu m, n_{core} = 1.5, n_{cladding} = 1.2, A = 0.2\lambda_0, z_{in} = -\lambda_0, z_0 = -5\lambda_0 \\ W = 16\lambda_0, z_{out} = 6\lambda_0, \Gamma = \lambda_0, y_0 = 0, w_y = 3.5\lambda_0, w_z = 1.5\lambda_0, A' = 1 \quad (13)$$

The rest of parameters shall be varied in order to analyze their influence on the ultrashort pulse propagation through the considered slit array. As previously indicated, our analysis shall focus on three key aspects to be discussed in the following subsections: pulse shaping and delay, spatiotemporal dispersion and birefringence features.

3.1 Ultrashort pulse shaping

The electric field intensity distributions $I_{TE}(y, z, t)$ and $I_{TM}(y, z, t)$ for the TE and TM modes are respectively given by:

$$I_{TE}(y, z, t) = \epsilon_0 \epsilon(y, z) E_x^2(y, z, t) \quad (14)$$

$$I_{TM}(y, z, t) = \epsilon_0 \epsilon(y, z) (E_y^2(y, z, t) + E_z^2(y, z, t)) \quad (15)$$

Applying our FDTD methodology to the scheme of figure 1 (b), equations 14 and 15 provide with the TE and TM spatial intensity distributions of the transmitted pulses through the slit arrays for different slit phases ϕ and longitudinal periods Λ as well as different slit thickness l (figure 1 (b)). As it can be appreciated in figures 2-6, the transmitted pulses split into several lobes with different intensities and relative delays, for which we shall focus our attention on the central lobe and its two adjacent ones.

Figures 2 and 3 illustrate the effect of the slit phase and longitudinal period on the transmitted pulse shape assuming a fixed slit thickness $l = 0.5\lambda_0$. In the case of TE polarization, figures 2 (a), (d) and (g) indicate that a slit phase $\phi = 0$ gives rise to a very weak central lobe that vanishes slightly *before* the two significant adjacent ones do, regardless the value for the longitudinal period. For $\phi = 90^\circ$, figures 2 (b), (e) and (h) show that the central lobe is still weak for $\Lambda = \lambda_0$, but it becomes more significant and vanishes *after* the two adjacent ones do for $\Lambda = 1.5\lambda_0$ and $\Lambda = 2\lambda_0$. Finally, for a slit phase $\phi = 180^\circ$, figures 2 (f) and (i) indicate that the central lobe becomes as significant as the adjacent ones and vanishes after them when $\Lambda = 1.5\lambda_0$ and $\Lambda = 2\lambda_0$, whereas it is still weak when $\Lambda = \lambda_0$ (figure 2 (c)). Consequently, *the longitudinal period plays an important role in determining the intensity of the TE polarized central lobe, whereas the slit phase allows to modify its relative delay with respect to the two adjacent lobes*. In the case of TM polarization, figure 3 shows that the central lobe is very weak in all cases except for $\phi = 180^\circ$ and $\Lambda = 1.5\lambda_0$, for which figure 3 (f) shows that the delay between the central lobe and the adjacent ones is completely different with respect to the corresponding one for the TE mode depicted in figure 2 (f). Furthermore, for $\phi = 180^\circ$ and $\Lambda = 2\lambda_0$, figure 3 (i) shows that the central lobe vanishes slightly before the adjacent ones do (likewise in the case analyzed in figure 2 (a)), which is just the opposite behavior to the one for the TE mode described in figure 2 (i). Consequently, *the delay between*

Figure 2. Spatial intensity distribution $I_{TE}(y, z, t)$ for the TE mode at $t = 97.5 fs$, i.e. once the ultrashort incident pulse has passed through the sinusoidal slit array. A constant slit width $l = 0.5\lambda_0$ is assumed for: (a) $(\phi, \Lambda) = (0^\circ, \lambda_0)$; (b) $(\phi, \Lambda) = (90^\circ, \lambda_0)$; (c) $(\phi, \Lambda) = (180^\circ, \lambda_0)$; (d) $(\phi, \Lambda) = (0^\circ, 1.5\lambda_0)$; (e) $(\phi, \Lambda) = (90^\circ, 1.5\lambda_0)$; (f) $(\phi, \Lambda) = (180^\circ, 1.5\lambda_0)$; (g) $(\phi, \Lambda) = (0^\circ, 2\lambda_0)$; (h) $(\phi, \Lambda) = (90^\circ, 2\lambda_0)$; (i) $(\phi, \Lambda) = (180^\circ, 2\lambda_0)$.

Figure 3. Spatial intensity distribution $I_{TM}(y, z, t)$ for the TM mode at $t = 97.5 fs$, i.e. once the ultrashort incident pulse has passed through the sinusoidal slit array. The parameters (ϕ, Λ, l) are the same as in figure 2 for each case.

Figure 4. Spatial intensity distribution $I_{TE}(y, z, t)$ for the TE mode at $t = 97.5 fs$, i.e. once the ultrashort incident pulse has passed through the sinusoidal slit array. A constant longitudinal period $\Lambda = 1.5\lambda_0$ is assumed for: (a) $(\phi, l) = (0^\circ, 0.25\lambda_0)$; (b) $(\phi, l) = (90^\circ, 0.25\lambda_0)$; (c) $(\phi, l) = (180^\circ, 0.25\lambda_0)$; (d) $(\phi, l) = (0^\circ, \lambda_0)$; (e) $(\phi, l) = (90^\circ, \lambda_0)$; (f) $(\phi, l) = (180^\circ, \lambda_0)$.

Figure 5. Spatial intensity distribution $I_{TM}(y, z, t)$ for the TM mode at $t = 97.5 fs$, i.e. once the ultrashort incident pulse has passed through the sinusoidal slit array. The parameters (ϕ, l, Λ) are the same as in figure 4 for each case.

the central and adjacent lobes exhibits a strong dependence on the slit phase and polarization mode but it is less sensitive to variations in the longitudinal period.

Figures 4 and 5 illustrate the effect of the slit thickness l on the transmitted pulse shape for different slit phases and a constant longitudinal period $\Lambda = 1.5\lambda_0$ assuming TE and TM polarizations respectively. In the case of TE polarization, figures 4 (a)-(c) show that a small slit thickness $l = 0.25\lambda_0$ and phase $\phi = 0$ give rise to a dominant central lobe, although the adjacent lobes gain energy as the slit phase increases. Conversely, figures 4 (d)-(f) show that a large slit thickness $l = \lambda_0$ gives rise to an almost complete removal of the central lobe. In the case of TM polarization, figures 5 (a)-(c) show that the adjacent lobes are more significant than the corresponding ones with TE polarization for a small slit thickness $l = 0.25\lambda_0$. On the other hand, figures 5 (d)-(f) illustrate that the central lobe is not completely suppressed for $l = \lambda_0$, which is the opposite behavior to the one for the TE mode described in figures 4 (d) and (f). This feature enables the interesting possibility of polarization discrimination for the central lobe.

Figure 6. Results for a planar slit array without bendings along the y-z plane. Spatial intensity distribution $I_{TE}(y, z, t)$ for the TE mode at $t = 97.7 fs$ for: (a) $l = 0.25\lambda_0$; (b) $l = 0.5\lambda_0$; (c) $l = \lambda_0$. Spatial intensity distribution $I_{TM}(y, z, t)$ for the TM mode at $t = 97.5 fs$ for: (d) $l = 0.25\lambda_0$; (e) $l = 0.5\lambda_0$; (f) $l = \lambda_0$.

To conclude this section, we shall compare the performance of the considered sinusoidal slit array with a planar slit array without bends. For this purpose, figure 6 shows the transmitted pulses through such a planar slit array for different slit thicknesses and polarization modes (TE and TM). In the case of a TE polarization mode, figures 6 (a)-(c) show that the central lobe is dominant over the adjacent ones for small slit thicknesses, whereas this behavior reverses as the slit thickness increases. This result is in total accordance with the pulse shapes shown in figures 4 and 5, but it also evidences that the slit phase and longitudinal period provide with a much wider control over the intensity and relative delay of the central lobe. Finally, as shown in figures 6 (d)-(f), the previous conclusion can be extended to the case of a TM polarization mode: in comparison with the effect caused by a variation of the thickness l in a planar slit array, the variation of the parameters ϕ and Λ offer a much wider control over the intensity and relative delay of the central lobe.

3.2 Spatiotemporal dispersion

Once the FDTD equations 3-10 have been applied to compute the electromagnetic fields in the space-time domain (y, z, t) , the following step in our analysis consists of determining the spatiotemporal frequency-domain fields at the output plane $z = z_{out}$ (eq. 13) through the Fourier transforms given by:

$$E_x(y, z_{out}, \omega) = \int_{-\infty}^{+\infty} E_x(y, z_{out}, t) \exp(i\omega t) dt \quad (16)$$

$$E_y(y, z_{out}, \omega) = \int_{-\infty}^{+\infty} E_y(y, z_{out}, t) \exp(i\omega t) dt \quad (17)$$

$$E_x(k_y, z_{out}, \omega) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} E_x(y, z_{out}, t) \exp[i(k_y y + \omega t)] dy dt \quad (18)$$

$$E_y(k_y, z_{out}, \omega) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} E_y(y, z_{out}, t) \exp[i(k_y y + \omega t)] dy dt \quad (19)$$

The resulting modulus of the (complex) components obtained through equations 16-19 for different slit phases, thicknesses, longitudinal periods and polarization modes are depicted in figures 7-12. As it can be observed, the transmission of ultrashort pulses through the slit arrays gives rise to a series of diffracted orders with different intensities and bandwidths. On one hand, the central order has only the transverse components carried by the incident pulse, which are all of them in a small neighbourhood around $k_y = 0$. On the other hand, the rest of adjacent orders carry transverse components that are completely different to the ones of the input pulse because of diffraction at the slit array.

Figure 7. Map for $|E_x(k_y, z_{out}, \omega)|$ (TE mode). The parameters (ϕ, Λ, l) are the same as in figure 2 for each case.

Figures 7 and 8 illustrate the effect of the slit phase and longitudinal period on the (transmitted) TE and TM diffracted orders assuming a constant slit thickness $l = 0.5\lambda_0$. In the case of TE polarization, figures 7 (a), (d) and (g) show that a slit phase $\phi = 0$ gives rise to significant adjacent orders compared to the central one, while the energy of such adjacent orders increases as the longitudinal period Λ does. However, figures 7 (b), (e) and (h) show that the energy of the adjacent orders decreases significantly by changing the slit phase to $\phi = 90^\circ$. Furthermore, figures 7 (c), (f) and (i) show that the energy of the adjacent orders decreases considerably for a slit phase $\phi = 180^\circ$. We can therefore deduce that *for a TE polarization mode with constant slit width $l = 0.5\lambda_0$, increasing ϕ allows to reduce significantly the energy of the adjacent orders*. In the case of TM polarization, figures 8 (a), (d) and (g) show that *for $\phi = 0$ the energy of the adjacent orders is much smaller than in the case of TE polarization* depicted in figures 7 (a), (d) and (g), regardless the value for Λ . When slit phases $\phi = 90^\circ$ and $\phi = 180^\circ$ are assumed, figures 8 (b), (e), (h), (c), (f) and (i) show that the adjacent orders are still weaker than the corresponding ones for the TE polarization, although such effect is less significant than in the previous case. However, it can be clearly appreciated that, *in all cases, there are less visible adjacent orders for the TM polarization than for the TE polarization*. This behavior can be explained as follows: internal reflections and scattering inside the slit array for the TM mode are weaker than for the TE mode due to incidence angles (at interfaces vacuum-core) close to the Brewster angle, at which reflections tend to disappear for a TM polarization mode -but not for a TE polarization mode-. Therefore, a TM polarized beam will tend to cross the slit array

Figure 8. Map for $|E_y(k_y, z_{out}, \omega)|$ (TM mode). The parameters (ϕ, Λ, l) are the same as in figure 2 for each case.

Figure 9. Map for: (a) $|E_x(y, z_{out}, \omega)|$ (TE mode); (b) $|E_y(y, z_{out}, \omega)|$ (TM mode). Slit parameters $\phi = 0^\circ$, $\Lambda = \lambda_0$ and $l = 0.5\lambda_0$.

with less scattering than an analogous beam with TE polarization. This effect which can be clearly observed through the maps for $|E_x(y, z_{out}, \omega)|$ and $|E_y(y, z_{out}, \omega)|$ depicted in figures 9 (a) and (b) respectively. Whereas the TE polarized transmitted beam shown in figure 9 (a) does not spread to the zone of the slits anywhere in its (temporal) spectrum (and thus remains guided through the cores), the TM polarized transmitted beam shown in figure 9 (b) spreads to the slit zones in almost its whole spectrum, which makes such slits visible as vertical fringes.

Figure 10. Map for $|E_x(k_y, z_{out}, \omega)|$ (TE mode). The parameters (ϕ, l, Λ) are the same as in figure 4 for each case.

Figure 11. Map for $|E_y(k_y, z_{out}, \omega)|$ (TM mode). The parameters (ϕ, l, Λ) are the same as in figure 4 for each case.

Figures 10 and 11 illustrate the effect of the slit thickness l on the TE and TM diffracted orders for different slit phases assuming a constant longitudinal period $\Lambda = 1.5\lambda_0$. Both figures show that the number of visible orders increases as the slit thickness l does regardless the polarization mode, which is a direct consequence of diffraction. Furthermore, the number of visible orders in the case of TE polarization (figure 10) is greater than the one for TM polarization (figure 11) regardless the value for l , which is in accordance with the previously discussed effect in figure 9. On the other hand, both figures show that the effect of the slit phase is not very

significant for slit thickness $l = 0.25\lambda_0$ (figures 10 and 11 (a), (b), (c)) or $l = \lambda_0$ (figures 10 and 11 (d), (e), (f)), so the feature of reducing the energy of the adjacent orders by increasing ϕ only holds for TE polarization and $l = 0.5\lambda_0$. Moreover, figures 11 (d), (e) and (f) show another interesting property: contrary to the case of TE polarization, for a TM polarized beam and slit thickness $l = \lambda_0$, the central order is partially suppressed in a spectral region around $\omega = \omega_0$ regardless the slit phase. Once again, we find that a geometric parameter such as the slit thickness enables the possibility of discriminating both polarization modes.

Figure 12. Results for a planar slit array without bendings along the y-z plane. Map of $|E_x(k_y, z_{out}, \omega)|$ (TE mode) for: (a) $l = 0.25\lambda_0$; (b) $l = 0.5\lambda_0$; (c) $l = \lambda_0$. Map of $|E_y(k_y, z_{out}, \omega)|$ (TM mode) for: (d) $l = 0.25\lambda_0$; (e) $l = 0.5\lambda_0$; (f) $l = \lambda_0$.

To conclude this section, figure 12 shows the spatio-temporal dispersion for planar slit arrays with different slit thicknesses with the purpose of comparing the performance of both structures. The results shown in figures 12 (a)-(f) are in accordance with all the previous reasonings but also evidence that the slit array parameters ϕ and Λ offer the possibility of a much deeper control for the spatiotemporal dispersion features.

3.3 Birefringence features

All the results obtained in the previous sections show evident differences between the behaviors for the TE and TM polarization modes. In order to quantify such differences, we shall define the parameter $P(\omega)$ on the basis of equations 18 and 19 as:

$$P(\omega) = \frac{E_y(k_y = 0, z_{out}, \omega)}{E_x(k_y = 0, z_{out}, \omega)} \quad (20)$$

The parameter $P(\omega)$ defined in equation 20 is a complex number that relates the TM and TE transmitted transverse component $k_y = 0$ (which is the main component present in the incident pulse that is transmitted through the slit array) at the output plane of the slit array $z = z_{out}$. The square modulus $|P(\omega)|^2$ and the phase $\arg[P(\omega)]$ respectively provide with the energy ratio and phase delay between the TM and TE modes for the main transmitted component $k_y = 0$ at each frequency ω . Such magnitudes allow themselves to define a polarization ellipse¹¹ at each frequency ω , so we shall regard $P(\omega)$ as the essential parameter that quantifies the birefringence in the framework of the FDTD scheme developed through equations 3-10 (as remarked in the introduction, a rigorous measure of the birefringence would require a modal analysis out of the scope of this paper). The resulting parameters $|P(\omega)|^2$ and $\arg[P(\omega)]$ obtained from equation 20 for different slit thicknesses, phases and longitudinal periods are depicted through figures 13-16, in which a strong dependence with respect to the frequency ω can be appreciated.

Figures 13 and 14 respectively illustrate the behavior of the squared modulus and phase of $P(\omega)$ for different slit phases and longitudinal periods assuming a constant slit thickness $l = 0.5\lambda_0$. In the graphics shown in figure

Figure 13. TM-TE energy ratio $|P(\omega)|^2$. The parameters (ϕ, Λ, l) are the same as in figure 2 for each case.

Figure 14. Phase $\arg[P(\omega)]$ of $P(\omega)$. The parameters (ϕ, Λ, l) are the same as in figure 2 for each case.

13, the large values of $|P(\omega)|^2$ correspond to a low intensity for the TE mode compared to the one for the TM mode, and conversely, the small values of $|P(\omega)|^2$ correspond to a low intensity for the TM mode compared to the one for the TE mode. As it can be appreciated in figure 13 (e), *there is an almost complete removal of the TE mode for $\phi = 90^\circ$, $\Lambda = 1.5\lambda_0$ and a frequency $\omega = 0.685\omega_0$* , at which the energy of the TM mode is about two hundred times greater. We can also obtain considerable attenuation for the TE mode respect to the TM mode for the the cases in which the parameters $(\phi, \Lambda, \omega/\omega_0)$ are given by $(90^\circ, \lambda_0, 1.29)$ (figure 13 (b)) and $(180^\circ, \lambda_0, 0.725)$ (figure 13 (c)), whereas for $(\phi, \Lambda, \omega/\omega_0) = (0^\circ, \lambda_0, 0.682)$ or $(90^\circ, 2\lambda_0, 1.285)$ there is a considerable attenuation for the TM mode respect to the TE mode, as it can be observed in figures 13 (a) and (h). On the other hand, figure 14 shows another interesting result feature regarding $\arg[P(\omega)]$: for $(\phi, \Lambda, \omega/\omega_0) = (90^\circ, \lambda_0, 1.29)$ (figure 14 (b)) and $(\phi, \Lambda, \omega/\omega_0) = (0^\circ, 2\lambda_0, 1.265)$ (figure 14 (g)), there are small bandwidths around $\omega = 1.29\omega_0$ and $\omega = 1.265\omega_0$ at which $\arg[P(\omega)] \simeq \pi$ and $|P(\omega)| > 1$, i.e. *the TE mode is considerably removed respect to the TM mode but both modes have opposite signs in the bandwidth at which the attenuation for the TE mode occurs*.

Figure 15. TM-TE energy ratio $|P(\omega)|^2$. The parameters (ϕ, l, Λ) are the same as in figure 4 for each case.

Figure 16. Phase $\arg[P(\omega)]$ of $P(\omega)$. The parameters (ϕ, l, Λ) are the same as in figure 4 for each case.

To conclude this section, figures 15 and 16 respectively illustrate the behavior of the squared modulus and phase of $P(\omega)$ for different slit thicknesses and phases assuming a constant longitudinal period $\Lambda = 1.5\lambda_0$. Likewise in the cases analyzed in figure 13, in figure 15 we can find different frequencies at which the energy for the TE or TM mode is considerably smaller (or greater) than the energy for the other mode. The most significant result can be deduced from figures 15 (d), (e) and (f): *for a TM polarized beam and slit thickness $l = \lambda_0$, the central order is partially suppressed in a small spectral region around $\omega = 0.93\omega_0$ regardless the value for ϕ* , which corroborates the results shown in figures 11 (d), (e) and (f).

4. CONCLUSIONS

We have developed a rigorous 2D FDTD electromagnetic analysis for a PCF geometry consisting of multiple hollow slits that are invariant along the transverse dimension x and go across the fiber core (z axis) exhibiting multiple sinusoidal bends in the y - z plane. By assuming an ultrashort incident pulse upon the considered PCF structure with a polarization angle of 45 degrees, we have analyzed three key magnitudes: pulse shaping and delay, spatiotemporal dispersion and birefringence features. The FDTD simulation results have provided with a detailed picture describing the influence of the geometric parameters for the considered structure on the pulse propagation and wavefront. In particular, we have found that the slit periods and thicknesses as well as the relative phase delays between consecutive hollow slits provide with a wide and deep control of the pulse shaping, spatiotemporal dispersion and birefringence features. The analysis carried out in this manuscript suggests the possibility of extending our research to more general slit geometries with arbitrary bends and variable thicknesses along the fiber.

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