Abstract: We numerically investigate the polarization characteristics of photonic crystal fibers selectively filled with metal wires into cladding air holes, through a full-vector modal solver based on the finite-element method (FEM). Firstly, we investigate the fundamental coupling properties between the core guided light and surface plasmon polaritons (SPPs) excited on the surface of metal wire. Secondly, we show that we can obtain highly polarization-dependent transmission characteristics in PCFs by introducing several metal wires closely aligned into the cladding, and reveal the strongly polarization-dependent coupling properties between the core guided modes and the SPP supermodes, which consist of discrete SPP modes. Finally, we show the importance of arranging the metal wires close to each other for high polarization-dependence.

OCIS codes: (060.2310) Fiber optics; (060.5295) Photonic crystal fibers; (240.6680) Surface plasmons.

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1. Introduction

Photonic crystal fibers (PCFs) [1], also called holey fibers (HFs) or microstructured optical fibers (MOFs), basically composed of two-dimensional triangular lattice arrays of air holes running along the entire length and confine light in the defects of the periodic structure, have extraordinary properties not achievable in conventional optical fibers such as endlessly single-mode operation, unusual chromatic dispersion, high birefringence, high or low non-linearity, etc. Additionally, optical properties of silica-air PCFs can be extended by filling the cladding air holes with materials such as liquid crystal [2], semiconductor [3], or metal [4], etc. In metal-filled PCFs, surface plasmon polaritons (SPPs) can form on the metal wires [5], and the core guided light can be coupled with SPPs when the phases of them match. Metal-filled PCFs have strongly wavelength-dependent transmissions because the core guided light couples to leaky SPPs at particular frequencies. Selective filling of individual air holes with metal bring polarization-dependent transmission [6–8]. Lee et al. have reported polarization-dependent characteristics of polarization-maintaining PCFs with a gold wire [7], and Zhang et al. have demonstrated selective silver coating in PCFs, expected to be applicable as absorptive polarizers [8]. H. K. Tyagi et al. have reported step-index fibers with a gold wire adjacent to the core [9]. However, these reported fibers do not have sufficient performance for polarizers. Moreover, there have not been any reports of concrete design methods for polarizers based on metal-filled PCFs.

In this work, we investigate the polarization characteristics of PCFs selectively filled with metal wires into cladding air holes through a full-vector modal solver based on the finite element method (FEM) [10]. We show that it is possible to achieve highly polarization-dependent transmission properties in metal-filled PCFs by arranging several metal wires close to each other.

2. Fundamental properties of metal-filled PCFs

Firstly, we show the polarization characteristics of PCFs with a metal wire into cladding air holes, in order to understand the fundamental property of metal-filled PCFs. Figure 1 illustrates the schematic of a PCF with a metal wire, whose cladding is composed of a triangular lattice of air holes with the parameters of lattice constant Λ and the hole diameters d, with four layers of air holes. The background material is pure silica. A metal wire is introduced into the cladding air hole. In the numerical calculation, the material dispersion of both silica and metal are included, and refractive index of air is 1. We have used Sellmeier equation for the dispersion of silica [11], and Drude-Lorentz model for metal [12] defined as

\[
\varepsilon_m = \varepsilon_\infty - \frac{\omega_0^2}{\omega(\omega - j\gamma_D)} - \frac{\Delta \varepsilon \cdot \Omega_m^2}{(\omega^2 - \Omega_m^2) - j\Gamma_m \omega}
\]
where $\varepsilon_m$ is the permittivity of the metal, $\varepsilon_e$ is the permittivity in the high frequency, $\Delta \varepsilon$ can be interpreted as a weighting factor, and $\omega$ is the angular frequency of guided light, $\omega_D$, and $\gamma_D$ are the plasma frequency and damping frequency, $\Omega_L$ and $\Gamma_L$ represent the frequency and the spectral width of the Lorentz oscillator. In this report, we assume metal as gold, using the parameters presented in Table 1, which gives good agreement with measured values at optical frequencies [12].

### Table 1. Values of the optimized parameters to fit the experimental data of bulk gold [12].

| $\varepsilon_e$ | $\omega_D/2\pi$ (THz) | $\gamma_D/2\pi$ (THz) | $\Omega_L/2\pi$ (THz) | $\Gamma_L/2\pi$ (THz) | $\Delta \varepsilon$ |
|----------------|------------------------|-----------------------|----------------------|---------------------|-------------------|
| 5.9673         | 2113.6                 | 15.92                 | 650.07               | 104.86              | 1.09              |

To investigate the polarization characteristics, we calculate the dispersion property and modal attenuation of the horizontally polarized ($x$-polarized) and vertically polarized ($y$-polarized) modes guided in the core of metal-filled PCFs. Figure 2 shows the effective index and the loss dependence on the operating wavelength $\lambda$ of the $x$-polarized and $y$-polarized core modes in the PCFs for $d=1.0$ μm, $\Lambda=2.0$ μm with a gold wire into (a) the first air hole layer and (b) the second air hole layer as the schematic illustrations in each loss diagrams represent. In order to understand the coupling properties, dispersion curves of the relevant modes are also plotted in both dispersion diagrams of Fig. 2(a) and Fig. 2(b). The green curves represent the specific SPP modes of the five mode orders excited on an isolated gold wire embedded in silica surrounded by air hole lattice, and the dashed black line represents the fundamental core mode guided in unfilled PCF. Extremely high losses of the $x$-polarized and $y$-polarized core modes are observed at particular wavelengths where the curves of the unfilled PCF core mode and each SPP modes cross. That is, these high losses are observed at the phase matching points and caused by resonant coupling to SPP modes on the surface of gold wire. Figure 3 shows the dominant component of the electric field distributions of the $x$-polarized and $y$-polarized core modes at the peak wavelengths with plasmonic resonances as shown in the loss diagram of Fig. 2(a). It is also evident from the figures that the extremely high losses of the core modes are caused by strong coupling to SPP modes on the wire. These results suggest that the metal-filled PCFs have the potential to be in-fiber filter. The fundamental and 1$^{\text{st}}$ order modes, correspond to so-called short-range and long-range SPP modes, have much higher effective indices than the core modes, and can never couple to the core modes. Only the modes higher than 1$^{\text{st}}$ order can be phase matched with the core modes [5]. The dispersion curves of the $x$-polarized and $y$-polarized core modes are continuous at the regions where the core mode couples to each SPP mode, except the region where the coupling to the 2$^{\text{nd}}$-order SPP mode occurs in Fig. 2(a). This phenomenon can be explained by the leaky mode coupling [13]. The dispersion curve of a core mode splits into another two modes where the complete coupling happens, such as the anti-crossing region where the coupling to the 2$^{\text{nd}}$-order SPP mode occurs in Fig. 2(a). At this point, the two coupled modes (upper-branch and lower-branch modes) have dissimilar value of effective index, and have same value of loss. In addition, the core modes couple to SPP modes in opposite phase (Fig. 3(b) and Fig. 3 (e)) on the lower branch, while in coordinate phase (Fig. 3(c) and Fig. 3 (f)) on the upper branch. On the other hand, where the incomplete coupling happens, the dispersion curves of the core modes are continuous and cross with that of the SPP mode at phase matching point. At this point, the core modes and the SPP mode have equal value of effective index while they have much different value of loss, resulting in the incomplete coupling. As for the location of the gold wire, the coupling strength becomes weaker as the gold wire becomes farther from the core region, that is apparent from loss values of Fig. 2(a) and Fig. 2(b). Besides, these PCFs,
Fig. 2. Wavelength dependence of effective indices and losses of the $x$-polarized and $y$-polarized core modes in the PCFs for $d=1.0 \mu m$, $\Lambda=2.0 \mu m$, filled with a gold wire into the hole of (a) first air hole layer and (b) second air hole layer. The solid green lines represent SPP modes of the specific mode orders excited on an isolated gold wire embedded in silica surrounded by air hole lattice, and the dashed black line is the core mode index of the unfilled PCF with the same structural parameters, and the dotted line is the cladding mode index, and the dashed-dotted line is the silica index. The insets on dispersion diagrams represent the magnitude of electric field of the relevant modes. The shaded regions denote the resonance points of the core guided modes and SPP modes.

Fig. 3. (a)-(c) $x$-component of the electric field distributions of the $x$-polarized core mode and (d)-(f) $y$-component of the electric field distributions of the $y$-polarized core mode at the peak wavelengths with plasmonic resonance achieved in Fig. 2(a).
with only a gold wire, do not achieve highly polarization-dependent loss characteristics.

3. Polarization characteristics of PCFs with several metal wires

There have been some reports of PCFs which have polarization-dependent properties by metal-filling or metal-coating of the air holes [6–8], but their filling or coating is only for one hole or isolated holes, resulting in insufficient polarization-dependent losses as shown in the previous section. Next, we investigate the coupling properties of PCFs selectively filled with several gold wires into air holes, and reveal that it is possible to achieve strong polarization-dependent coupling characteristics in PCFs with closely-aligned metal wires. Figure 4(a) shows the effective index and loss dependence on the operating wavelength $\lambda$ of the $x$-polarized and $y$-polarized core modes in the PCFs for $d=1.0 \, \mu m$, $\Lambda=2.0 \, \mu m$, with two gold wires into the second and third air hole layer as the schematic illustration in the loss diagram represents. There is a major difference between the loss characteristics of Fig. 4 and Fig. 2. The peak wavelengths of the $x$-polarized and $y$-polarized core mode at resonant point in Fig. 2 are almost the same, whereas those of Fig. 4 are different from each other at several resonant regions. This difference of the peak wavelength is caused by resonance with SPP supermodes. By introducing more than one of gold wires aligned, discrete SPP modes interact each other, forming SPP supermodes, and each supermode has different phase constant at a same wavelength. Figure 5 shows the transverse electric field vector distributions of SPP supermodes excited on the surfaces of two gold wires embedded in silica. Each of the mode in Fig. 5 consists of (a),(b) fundamental, (c)-(f) $1^{st}$-order, (g)-(j) $2^{nd}$-order SPP modes, respectively. Furthermore, the figures in Fig. 5 are arranged according to the value of the phase constant (the value of Fig. 5(a) is the highest, and of Fig. 5(j) is the lowest). All the electric field distributions in Fig. 5 are different from each other. In the PCFs with several gold wires such as the case of Fig. 4, either of the two-polarized core modes only couples to

![Fig. 4. (a) Wavelength dependence of effective indices and losses of the x-polarized and y-polarized core modes in the PCF for $d=1.0 \, \mu m$, $\Lambda=2.0 \, \mu m$, filled with two gold wires into cladding air hole of second and third air hole layer. The solid green lines represent SPP supermodes consisting of the two isolated SPP modes, and the dotted black line is the cladding mode index, and the dashed-dotted line is the silica index. (b) x-component of the electric field distributions of the x-polarized core mode and (c) y-component of the electric field distributions of the y-polarized core mode at wavelength 1.822 $\mu m$.](image-url)
Fig. 5. Transverse electric field vector distributions of SPP supermodes. Each SPP supermode consists of isolated SPP modes of (a),(b) fundamental, (c)-(f) 1<sup>st</sup> order, (g)-(j) 2<sup>nd</sup> order.
particular SPP supermode whose parity matches, and the another does not couple. In Fig. 4, high polarization extinction ratio is achieved at wavelength 1.822 μm, where the losses of x-polarized and y-polarized modes are 296.57 dB/cm and 1.58 dB/cm, respectively. This is caused by the phase matching of the x-polarized mode to the SPP supermode which has the electric field distributions of Fig. 5(f), consists of two isolated 1st-order SPP modes. Surprisingly, 1st-order SPP modes can be coupled to the PCF core modes when the SPP modes become supermodes and get as lower effective index as the core modes have, whereas isolated 1st-order SPP modes can be never coupled as discussed in the Section 2. The electric field distributions of the two polarized core modes at wavelength 1.822 μm are shown in Fig. 4(b) and (c). It is evident from the figures that the x-polarized mode strongly couples to the SPP supermode, whereas the y-polarized mode is strongly confined into the central core. Thus, it is possible to realize a polarizer by metal-filled PCFs with sufficient extinction ratio.

Next, we show the importance of arranging the gold wires close to each other for high polarization-dependence. Figure 6 shows the loss characteristics of PCFs selectively filled

![Graphs showing modal losses of core modes](image)

**Fig. 6.** Wavelength dependence of modal losses of the x-polarized and y-polarized core modes in the PCF for \(d=1.0\ \mu m, \Lambda=2.0\ \mu m\), selectively filled with gold wires into cladding air hole. The insets show the schematic representation of PCFs filled with gold wire in different arrangement.

![Schematics of PCFs](image)

**Fig. 7.** (a) x-component of the electric field distributions of the x-polarized core mode and (b),(c) y-component of the electric field distributions of the y-polarized core mode at the peak wavelengths with plasmonic resonance achieved in Fig. 6(c).
with (a), (b) two or (c), (d) three gold wires. High polarization-dependence can be achieved in the cases of Fig. 6(c) and Fig. 6(d) where the gold wires in the cladding is closely arranged, and low polarization-dependence in Fig. 6(a) and Fig. 6(b) where the two gold wires are separated. Briefly, to form SPP supermodes for high polarization characteristics, close-arranging of the gold wires is needed. Figure 7 shows the dominant component of the electric field distributions of the \(x\)-polarized and \(y\)-polarized core modes at the peak wavelengths in Fig. 6(c), achieved by coupling to SPP supermodes consist of 2\(^{nd}\) order SPP modes. The three electric distributions of Fig. 7(a)-(c) are different from each other. In the meantime, loss values of Fig. 6(b) and Fig. 2(b) are almost the same, which is to say that the outer gold wire of the inset in Fig. 6(b) has slight influence for resonant coupling. In the case of Fig. 6(d), the \(x\)-polarized core mode has much larger losses than \(y\)-polarized core mode at longer wavelength region.

So far, we have shown the importance of arranging the several gold wires close to each other for high polarization-dependence. Finally, we show the influence of varying the value of the wire diameter \(d_m\). Figure 8 shows the schematic of a PCF whose location of gold wires is the same as represented in Fig. 6(d), and the effective index and loss dependence on the operating wavelength of the \(x\)-polarized and \(y\)-polarized core modes in the PCFs for \(d=1.0\) \(\mu\)m, \(\Lambda=2.0\) \(\mu\)m, \(d_m=\) (a) 1.0 \(\mu\)m, (b) 1.4 \(\mu\)m are plotted in Fig. 9(a) and (b), respectively. The SPP supermodes consisting of 1\(^{st}\)-order SPP modes are represented by the green curves, and their transverse electric field vector distributions are shown in Fig. 10 for \(d_m=1.0\) \(\mu\)m. The figures in Fig. 10 are arranged according to the value of the effective index, and their effective indices are (a) 1.475422, (b) 1.467014, (c) 1.464523, (d) 1.461778, (e) 1.461643, (f) 1.446053, at wavelength 1.3 \(\mu\)m. There are six SPP supermodes consisted of isolated SPP modes of 1\(^{st}\) order, and the two-polarized core modes can only couple to particular SPP supermode whose parity matches, as we discussed the coupling characteristics in Fig. 4. In the PCF represented in Fig. 8, the \(x\)-polarized core mode couples to SPP supermodes (a), (e), (f) in Fig. 10, whereas the \(y\)-polarized core mode couples to SPP supermodes (b), (c), (d) in Fig. 10. The dashed green lines in Fig. 9 represent the dispersion curves of SPP supermodes which couple to the \(x\)-polarized core mode [(a), (e), (f) in Fig. 10], and solid green lines in Fig. 9 represent the curves of SPP supermodes which couple to the \(y\)-polarized core mode [(b), (c), (d) in Fig. 10]. The dashed green curves are separated from each other, whereas the solid green curves are closer to each other. In addition, when the value of \(d_m\) become larger, the dashed green curves become more separated from each other, but the solid green curves do not shift so much. As a consequence, we can achieve larger extinction ratio over wide range of wavelengths as shown in Fig. 9(b), expect to operate as a polarizer at communication wavelength.

![Fig. 8. Schematic representation of a PCF filled with three gold wires.](image)
Fig. 9. Wavelength dependence of effective indices and losses of the $x$-polarized and $y$-polarized core modes in the PCF for $d=1.0 \ \mu m$, $\Lambda=2.0 \ \mu m$, $d_m=(a) \ 1.0 \ \mu m$, (b) $1.4 \ \mu m$, filled with three gold wires into cladding air hole as shown in Fig. 8. The dotted black line is the cladding mode index, and the solid green lines represent SPP supermodes consist of three isolated SPP modes of 1$^{st}$ order.

Fig. 10. Transverse electric field vector distributions of SPP supermodes consist of isolated SPP modes of 1st order in the PCF shown in Fig. 8 ($d=1.0 \ \mu m$, $\Lambda=2.0 \ \mu m$, $d_m=1.0 \ \mu m$).
4. Conclusion

We have shown the polarization characteristics of PCFs selectively filled with gold wires into the cladding air holes by investigating the coupling properties between the $x$-polarized and $y$-polarized core modes and SPP modes, through a full-vector modal solver based on FEM. We have revealed that we can obtain large polarization extinction ratio in the PCFs filled with several gold wires aligned into its cladding, and shown the importance of arranging the metal wires close to each other for high polarization-dependence. As discussed in ref [4], the resonant wavelengths of fabricated metal-filled fibers shift to shorter wavelength than simulated results, because of air gaps between the metal wires and the silica glass caused by the higher thermal expansion coefficient of the metal. We should consider it when fabricating the metal-filled PCFs.