An azimuthally polarizing photonic crystal fibre with a central gold nanowire

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Abstract. An air–silica photonic crystal fibre with a gold nanowire at core centre is shown to support a low-loss azimuthally polarized mode. Since all the other modes have very high attenuation, the fibre effectively supports only this mode, acting as a single-polarization fibre with an extinction ratio $> 20 \text{ dB cm}^{-1}$ over a broad range of wavelengths (550–1650 nm in the device reported). It can be used as an effective azimuthal mode filter.

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1. Introduction

Cylindrically (i.e. azimuthally or radially) polarized laser beams have many uses. Radially polarized beams can be focused to spot sizes significantly smaller than the Rayleigh resolution

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Figure 1. (a) Working principle and structure of the azimuthal mode polarizer. A hexagonal array of hollow channels surrounds a silica core containing a central gold nanowire. The gold wire is depicted in yellow and the hollow channels in grey, and the blue background represents fused silica. The green and blue arrows indicate the input and output light. The three lower sketches indicate linear (LP), circular (CP) and unpolarized (UP) light, and the upper sketch represents azimuthal polarization (AP). (b) Scanning electron micrograph of the first ring of hollow channels, polished by focused ion beam etching (hole radius: 1.0 µm; wire radius: 310 nm; pitch: 3.2 µm). The inset shows the entire holey region.

When focused, an azimuthally polarized beam maintains perfect zero intensity at the focal point, permitting a higher spatial resolution to be reached in stimulated emission depletion (STED) microscopy [4, 5]. Fibre-based scanning near-field optical tips require a radially polarized mode to excite the fundamental plasmon mode on a tapered metallic nanowire attached to the core of a nanofibre [6, 7]. In nanobore photonic crystal fibres, quantum squeezing of cylindrically polarized modes has been used to generate continuous variable states through entanglement between spatial and polarization degrees of freedom [8]. Cylindrically polarized modes have also found applications in optical particle trapping and guidance experiments [9–12]. Charged particles can be accelerated in the focus of a radially polarized laser beam, where a strong axial electric field component exists [13]. Cylindrically polarized laser beams have been proposed for generating azimuthally polarized spatial dark solitons [14].

Cylindrically polarized beams can be synthesized by using liquid–crystal-based spatial light modulators [15] or holographic phase-masks [16] or by extracavity generation [17]. In all these cases, a precise (usually linear) input polarization state is required if the cylindrical polarization state is to be produced with high fidelity. Doughnut-shaped modes with cylindrical polarization can also be guided in optical fibres, where they are designated as TM_{01} (radially polarized) and TE_{01} (azimuthally polarized) [18]. High-fidelity conversion, over a ~30 nm bandwidth, from a linearly polarized fundamental mode to a cylindrically polarized mode has been demonstrated recently in fibre [19].
In this paper, we present a novel structure consisting of a photonic crystal fibre (PCF) with a gold nanowire running axially through the centre of its solid glass core. This structure has the property of transmitting only the azimuthally polarized mode, with all other guided modes being strongly absorbed. It thus acts as an effective broadband transmission filter for azimuthal modes (depicted in figure 1(a)).

2. Experiment

2.1. Fabrication

The samples were fabricated in a two-step process. First, an empty PCF was produced using the stack-and-draw technique [20]. The PCF cladding was a hexagonal array of hollow channels (radius 1.0 \( \mu \)m; inter-hole spacing 3.2 \( \mu \)m) and its core had a central nano-channel of radius 310 nm. The cladding channels were then masked by splicing to an appropriate thick-walled silica capillary and the central hole was filled by pumping in molten gold. The temperature and the applied pressure during the filling process were 1100 °C (well below the transition temperature of fused silica) and 200 bar, respectively. Filling lengths, which are limited by the length of the hot zone of the furnace, of approximately 20 cm were routinely achieved. Fibres with longer gold wires (100 m and more) can be fabricated using a recently reported technique [21] where a gold-filled cane is directly drawn to the fibre. The pressure-assisted filling procedure is highly reproducible and relatively simple to implement, having previously been used to fabricate hybrid PCFs for the excitation of guided surface plasmon polaritons (SPP) both on single nanowires and in two-dimensional arrays of metallic nanowires [22–24]. Figure 1(b) shows a scanning electron micrograph (SEM) of the PCF with its central channel filled with gold. Lengths of a few cm were used in the experiments. Optical inspection revealed that the wires were not continuous, but displayed narrow breaks \( \sim 1 \mu \)m wide at intervals of \( \sim 50 \mu \)m. These discontinuities were not, however, found to affect the optical transmission or the polarization sensitivity.

2.2. Optical measurements

For optical characterization (figure 2) we used a PCF-based supercontinuum source [25] emitting unpolarized (time-averaged) light in the range 500–1700 nm. The input polarization state was continuously monitored using a polarimeter.
Figure 3. Theoretical (first column) and experimental images of the mode patterns of the azimuthal mode. The black arrows in the first column indicate the local polarization orientation and their lengths are proportional to the magnitude of the transverse electric field components. The white arrows in the last five columns indicate the transmission axis of the polarizer. The wavelengths are (a) 600 nm and (b) 1400 nm.

The light was launched into the fibre core with a 20× microscope objective (MO 1; NA 0.4), and a flip mirror (FM) was used to deliver the transmitted light to either a camera or an optical spectrum analyzer (OSA). A linear polarizer (LP) was placed in front of the camera so as to ensure that only the light polarized in one desired direction was detected.

The last five columns of figure 3 show optical near-field images of the azimuthal mode at two representative wavelengths: (a) 600 nm and (b) 1400 nm. In the absence of a polarizer (the second column from the left), the mode is not perfectly sixfold symmetric but rather shows two intensity maxima. These arise from distortions in the fibre structure—two of the channels in the first ring are approximately 4% smaller in diameter than the others. At shorter wavelengths (<900 nm), the field maxima are located between the central nanowire and the smaller-diameter holes, as confirmed by finite-element (FE) simulations using dielectric functions from the literature [26, 27] (leftmost image in figure 3). At longer wavelengths the maxima are located between the nanowire and the inter-hole glass strands, again as predicted by FE calculations. Even though the output light does not show perfect sixfold symmetry (as in an ideal PCF, see figure 4(c)), the experimentally observed two-lobe output pattern is completely azimuthally polarized and the small structural irregularity does not influence the overall performance of the polarizer. The four rightmost columns in figure 3 show the mode patterns obtained when a polarizer is inserted between the fibre end-face and the camera (the white arrows indicate the electric field polarization). The mode splits into two distinct lobes that rotate with the polarizer, shifted by 90°, as expected of an azimuthally polarized beam.

The azimuthal mode loss was measured by cutting back the original 4 cm-long gold-filled fibre to 2.5 cm in four successive steps. After each cut-back the transmitted spectrum was recorded using the setup in figure 2. The measurements yielded a loss of 1 dB mm$^{-1}$ at 600 nm and 0.7 dB mm$^{-1}$ at 1400 nm. Note that both the linear and the radial modes have very high attenuation (>22 dB cm$^{-1}$) and so do not significantly affect the measurement. Although the experimental values approximately follow theory, they are overall somewhat higher, perhaps due to scattering at imperfections on the surface of the gold nanowire (see the next section).

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![Figure 3](http://www.njp.org/)

![Figure 2](http://www.njp.org/)
Figure 4. Modal characteristics of a perfect PCF structure with circular holes (FE simulation). (a) The difference $\Delta n = \text{Re}(n_{\text{eff}}) - n_{\text{silica}}$ between the refractive index of the modes and that of bulk silica. The blue dashed line represents the dispersion of the $m = 3$ guided SPP mode of the nanowire, which phase matches to the azimuthal mode within a narrow wavelength range around 650 nm. Higher-order guided SPP modes do not cross the dispersion of the hybrid core modes. In the grey area, the azimuthal mode has the highest effective index of all modes. The inset defines the radial, axial and azimuthal magnetic field components. (b) Upper panel: theoretical loss spectra of the three modes, together with the imaginary part of the dielectric function of gold \[26\] (dashed line). Lower panel: experimental cut-back loss of the azimuthal mode compared with theory. (c) Transverse distributions of the axial Poynting vector (over a $6.5 \times 6.5 \mu m^2$ region centred on the nanowire) of the guided modes at 600 nm (white arrows indicate the instantaneous electric field orientation): the linear mode (left), azimuthal mode (middle) and radial mode (right).

3. Numerical simulations

FE simulations were used to analyse the modal properties of the nanowire PCF used in the experiments (figure 1), with the approximation that the hollow channels are perfectly circular with a diameter of $2.0 \mu m$. Figure 4(a) plots the difference between the real part of the modal refractive indices and the index of bulk silica glass, $\Delta n = \text{Re}(n_{\text{eff}}) - n_{\text{silica}}$, for the TM$01$ (radial), TE$01$ (azimuthal) and HE$11$ (linearly polarized or ‘linear’) modes. For wavelengths greater than $\sim 990 \text{ nm}$ the azimuthal mode has an index higher than that of the HE$11$ mode (grey area in figure 4(a)), i.e. it becomes the fundamental guided mode.

The attenuation of the azimuthal mode (figure 4(b)) is at least one order of magnitude lower than the radial mode and follows approximately the imaginary part of the dielectric function of gold \[26\]. The decrease in radial mode loss at long wavelengths is a consequence of the field spreading out into the dielectric cladding. The transverse profiles of the axial Poynting vector for each of the three modes are plotted in figure 4(c), the instantaneous electric field directions...
being marked with white arrows. Although above $\sim 800 \text{ nm}$ only the three hybrid modes shown in figure 4(c) are supported, an additional higher-order mode appears at shorter wavelengths. This mode has an even higher loss than the HE$_{11}$ mode and hence is not shown in figure 4.

Although the TE$_{01}$ and HE$_{11}$ modes have identical indices at $\sim 990 \text{ nm}$, no coupling is expected since they are eigenmodes of the system, i.e. no anti-crossing forms. However, any axial variations in the structure (scattering points, surface imperfections) will couple light from the azimuthal to the highly lossy HE$_{11}$ mode at wavelengths close to 990 nm. This may explain the broad loss peak between 900 and 1150 nm seen in the experiments. The sharp increase in loss below 700 nm compared with theory can be explained in a similar manner by scattering to the high-loss $m = 3$ guided SPP mode on the wire.

The different modal losses can be explained by the fact that the optical absorption at the surface of a real (imperfect) conductor is approximately proportional to the square of the tangential magnetic field $|H_z|^2 + |H_\phi|^2$ (the inset in figure 4(a)) [21, 28]. Since the azimuthal (TE$_{01}$) mode has only a very small axial component of magnetic field its attenuation is small relative to all the other modes. The radial (TM$_{01}$) mode, on the other hand, has a very large azimuthal magnetic field and consequently experiences much higher attenuation. For the HE$_{11}$ mode all six field components are non-zero, giving it the highest attenuation. Since the azimuthal polarizer does not operate by resonant excitation of guided SPPs, it is intrinsically broadband. In the experiments, better than 80 dB discrimination was obtained (for a 4 cm-long sample) between radial and azimuthal polarization over almost the entire visible and near-IR regions (from 550 to 1650 nm), with an insertion loss better than 10 dB.

The use of a PCF, rather than a step-index fibre with a central nanowire, brings the advantage of a broader wavelength range of operation through the filtering away of unwanted higher-order modes by the photonic crystal cladding [29]. In a step-index fibre, the presence of low-loss higher-order modes will contaminate the output polarization state, especially at shorter wavelengths, reducing the effectiveness of the device. This is especially true for higher-order TE modes (e.g. TE$_{02}$), which will have loss values of the same order as the TE$_{01}$ mode.

4. Conclusions

A solid-core silica–air PCF with a central gold nanowire can act as an effective single-polarization fibre, providing low-loss transmission only for the azimuthally polarized TE$_{01}$ mode. The azimuthally polarized output beam can be converted into radial polarization using two half-wave plates placed at 45$^\circ$ relative to each other. Usable polarizing bandwidths greater than 1100 nm can be achieved for a discrimination of better than 20 dB cm$^{-1}$, which explains why the fibre is of interest in many of the applications discussed in the introduction. For example, by providing radially polarized white light it will allow multicolour super-resolution imaging. Radially polarized beams are also suitable for direct coupling to the zero-order radially polarized SPP mode guided on a metallic nanowire. This mode can then be focused to a nanoscale spot by tapering the wire down to a sharp tip [30]. This arrangement has the advantage that the excitation of the guided SPP mode does not rely on phase matching and hence can be broadband and highly efficient [6]. Broadband azimuthally polarized light has the potential to enhance the flexibility of STED microscopy, allowing simultaneous excitation of several different molecules. The ability to produce high-fidelity azimuthally polarized beams at any laser wavelength in the visible and near-IR regions may also be useful in laser tweezer experiments, where tunability is important if internal particle resonances are to be excited.

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