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Design of Low-loss and Highly BirefringentPorous-Core Photonic Crystal Fiber and Its Application to a Novel Terahertz Polarization Beam Splitter

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Design of Low-loss and Highly Birefringent Porous-Core Photonic Crystal Fiber and Its Application to a Novel Terahertz Polarization Beam Splitter

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Abstract: The design of a novel porous photonic crystal fiber (PCF) optical waveguide is presented, that demonstrated high birefringence and low losses for wavelengths in the terahertz range. Using the finite element method (FEM), waveguide birefringence, dispersion, and signal attenuation were simulated for the given design. The maximum birefringence, occurring at the maximum porosity value and the highest measured frequency, was measured to be 1.32×10^{-2}. Based on the designed waveguide, a dual core polarization beam-splitter was designed, with strong polarization-dependent coupling behavior. Its effective material loss, optimized using a symmetric fiber structure, was found to be sufficient to allow transmission at THz frequencies.

1. INTRODUCTION

Terahertz radiation, forming part of the electromagnetic spectrum with frequencies between 0.1 and 10 THz, is of interest in scientific and engineering fields due to its broad applicability. Terahertz radiation has found uses in medical imaging and chemical spectroscopy, by use of interferometric techniques to living tissues and biochemical molecules. It has also been used with significant success in high-speed data transmission, sub-millimeter astronomy, and manufacturing and quality control applications. Most applications of terahertz radiation involve transmission across air, which is sub-optimal due to scattering, diffraction, and signal strength attenuation.

To decrease the effect of these phenomena on optical signal transmission, optical waveguides, physical structures that aid in the transmission of electromagnetic radiation, have been developed using first parallel plates, bare metal wires, and later photonic crystal fibers, which offer greater flexibility in controlling material and transmission properties such as dispersion, birefringence, and confinement loss. This paper presents a summary of a novel design of such a photonic crystal fiber porous waveguide with elliptical holes, showing high birefringence. Then, based on the design of this waveguide, two polarization beam-splitters were developed, which demonstrate polarization-dependent coupling behavior.

2. MATERIALS & METHODS

A. Design and Performance of Photonic Crystal Fiber (PCF) Optical Waveguide

Photonic-crystal fibers (PCFs) are a class of optical fiber with approximately wavelength-sized holes running along the optical axis, and are generally constructed with one or more cores surrounded by a periodic lattice structure of one or two materials. PCFs are effective in controlling various properties of optical transmission, and generally report low signal attenuation; for a solid core PCF, attenuation of optical signals has been found to be as low as 0.37 dB/km. The lattice structure of the PCF waveguide also usually causes strong birefringence, the property of having a refractive index dependent on the polarization and propagation direction of light.

The proposed THz PCF waveguide is based on the following design: the entire fibrous structure is made of Cyclin Olefin Copolymer (COC), colloquially known as Topas. The air-filling fraction, defined as the ratio of the diameter of each air hole to the distance between adjacent holes and shown in Fig. 1, was defined to be 0.95. The core diameter was varied and the performance of the waveguide measured, in order to ascertain its optimal value. The core is porous, with elliptical holes of major axis length b and semimajor axis length a. The proposed waveguide had an overall refractive index of 1.53 with losses of about 1 dB/cm in the direction of optical propagation.

The performance of the porous-core PCF waveguide was measured by determining the birefringence for different values of the core diameter, D_{core} and core porosity. It is observed that PCFs with higher core porosity had universally higher birefringence. For a given porosity, the birefringence seemed to increase with core diameter sharply until a threshold value, at which it remained approximately constant. The maximum overall birefringence for this design was 1.32×10^{-2}. The dependence of birefringence on transmitted signal frequency was also measured, and it was found to increase with porosity as well. The previously mentioned maximum of 1.32×10^{-2} was sustained from frequencies of about 0.75 THz to 1.5 THz.

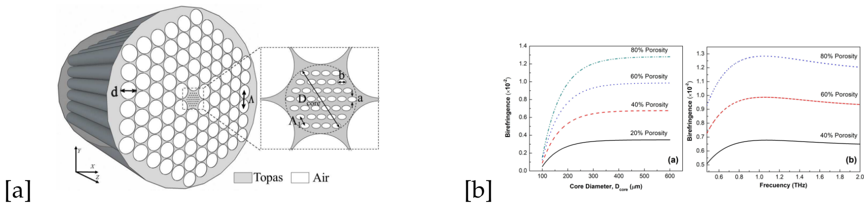

Fig. S1. The design of the Topas PCF optical waveguide, [a], shown left with enlarged porous core parameterized by diameter and elliptical axes lengths. On the right, (b), characterization of waveguide birefringence with respect to core diameter and frequency is shown.

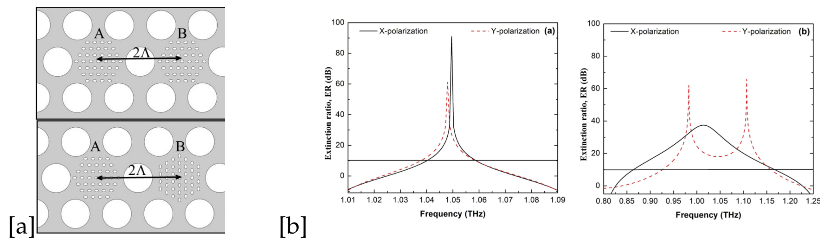

Fig. S2. The dual-core beam splitter design is shown left in (a), with cores A and B separated by a distance 2Λ. In (b), the extinction ratio as a function of frequency is shown for each polarization direction, demonstrating a peak at around 1.00 THz for both.

B. Design and Performance of Beam Splitter

A polarization beam-splitter is a device that, using optical and metallic properties, splits a beam of electromagnetic radiation into S and P polarizations for use in interferometry, and more recently high-speed fiber-optic communications. Based on the previously described PCF optical waveguide, a THz polarization beam splitter was constructed with a symmetric dual-core fiber and parameterized by $D_{core} = 400\mu m$, porosity equal to 80%, $\Lambda = 380.95\mu m$, $\dfrac{d}{\Lambda} = 0.95$, and the distance between cores as 2Λ. This design is shown in Fig. 2(a) above.

Highly important to optical transmission is the fact that due physical proximity between cores, power transfer occurs between the propagating electric fields travelling in each core. To this end, mode theory provides a mathematical framework to model the interaction of strongly coupled propagating optical radiation, like that of a beam splitter. These coupled modes are termed supermodes, and we may define a coupling length at which complete power transfer occurs between the two cores: $L = \frac{\lambda}{2(n_{even} - n_{odd})}$, where λ is the wavelength of the propagating optical radiation, and n_{even} and n_{odd} are the nominal refractive indices of even and odd supermodes of the propagating electromagnetic wave for each polarization direction.

The performance of the beam-splitter was judged based on its extinction ratio, which measures the ratio between the output powers of the unintended and intended polarization directions; that is, for $x-$ polarized waves, $ER_x = 10 \log \frac{P_{out,y}}{P_{out_x}}$ and for y-polarized waves, $ER_y = 10 \log \frac{P_{out,x}}{P_{out_y}}$. The extinction ratio of the beam-splitter was measured across varying input frequencies, and plotted in Fig. 2(b).

3. CONCLUSION

The proposed design of an optical waveguide based on a porous-core photonic crystal Topas fiber was designed and its optical properties analyzed and optimized based on a simulation-based FEM analysis. As is desired, with appropriate parameter configurations, such as core diameter and cladding pore axes lengths, a high-birefringence, low-loss, low-dispersion waveguide could be achieved in the frequency range from 0.5 to 2 THz. The designed fiber was then used to propose a dual-core polarization beam-splitter, whose extinction ratio was measured against input signal frequency for a given set of parameters.

REFERENCES

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