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Low loss, low dispersion and highly birefringent terahertz porous fibers

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ABSTRACT

We demonstrate that porous fibers in addition to low loss and high confinement, have near zero dispersion for 0.5–1 THz resulting in reduced terahertz signal degradation compared to microwires. We also show for the first time that these new fibers can be designed, introducing asymmetrical sub-wavelength air-holes within the core, to achieve high birefringence ≈0.026. This opens up the potential for realization of novel polarization preserving fibers in the terahertz regime.

1. Introduction

Bulk optics are used to transport terahertz (THz) radiation in almost all terahertz spectroscopy and imaging systems. However, this limits the integration of THz techniques with infrared and optical systems. Although THz waveguides promise to overcome these hurdles, results to date have been limited by the high loss and dispersion. A number of waveguide solutions based on technologies from both electronics and photonics, as reviewed in detail in Refs. [1,2], have been studied among which solid-core sub-wavelength fibers [3] (called THz microwires [4,5]), air-core microstructure fibers [6], and Ag/PS-coated hollow glass fibers [7] have the lowest loss reported in the literature for dielectric based waveguides. These fibers are only suitable for relatively narrow band applications.

Recently, a novel class of porous fibers for the THz range was suggested independently by two research groups [1,2,8]. Porous fibers are air-clad fibers with a pattern of sub-wavelength air-holes in the core. Such fibers allow low loss THz propagation and a better confinement of the field relative to microwires.

In this paper, we demonstrate that in addition to low loss and high confinement, porous fibers provide a significant improvement in the group velocity dispersion in comparison to THz microwires. We also propose new designs of porous fibers, introducing asymmetrical discontinuities, which lead to a strong birefringence avoiding distortion due to polarization mode dispersion. The low distortion (loss and dispersion) and high polarization preserving characteristic of the novel designed porous fibers, using asymmetrical shaped air-holes, expand the possibility range of applications to polarization preserving systems, e.g. coherent heterodyne time-domain spectrometry [9].

The porous fibers studied herein are air-clad and have a pattern of sub-wavelength air-holes within the core. The distribution, shape, and size of the air holes determine the porosity of the structure, which is defined as the fraction of the air-hole area to core area. Field enhancement and localization, occur within these sub-wavelength air-holes as demonstrated in Ref. [2] and the references therein. In THz porous fibers, the discontinuities are chosen to be air because firstly air is transparent at THz frequencies, has negligible loss, and secondly it gives the highest refractive index contrast, resulting in an increased enhancement of the field. Previously only circular air-holes have been considered [8,1,2], as shown in Fig. 1a. However, other shapes can also be introduced into the core of these fibers. The degree of enhancement at the air-hole interface depends on the normal component of the electric field, thus in order to have well separated propagation constants for the two polarizations of the fundamental mode, we choose rectangular and slot-shaped sub-wavelength air-holes with the sides of the rectangles aligned with the two polarizations. The best

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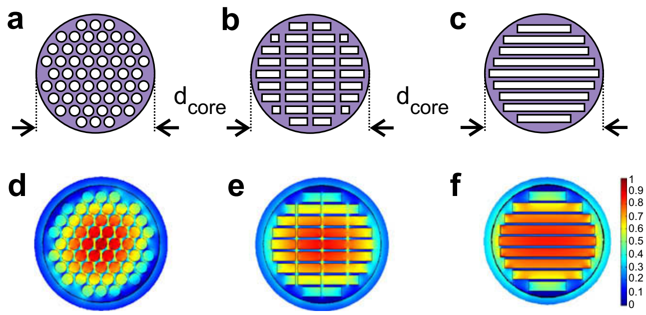

Fig. 1. Cross-section of porous fibers with (a) circular, (b) rectangular, and (c) slot-shaped air-holes. The 2D view of normalized S_z for (d) circular shaped air-holes, 57% porosity and $d_{core} = 560\ \mu m$, (e) rectangular shaped air-holes, 57% porosity and $d_{core} = 570\ \mu m$, and (f) slot-shaped air-holes, 61% porosity and $d_{core} = 600\ \mu m$, at 0.4 THz.

arrangement for achieving high porosity values for circular, rectangular, and slot-shaped air-holes are demonstrated in the Fig. 1a–c, respectively. Fig. 1 shows all the three cross-sections and the two-dimensional view of normalized z-component of the Poynting vector, S_z, at 0.4 THz.

Fig. 2 compares the calculated effective material loss of the new designed porous fibers with rectangular and slot-shaped air-holes to the porous fibers with circular shaped air-holes and microwires proposed in Ref. [2]. Effective material loss is a measure of the loss that a guided mode with a certain mode field distribution experiences when it propagates along a fiber with an inhomogeneous loss coefficient profile in transverse direction. The effective material loss, α_{eff}, of a guided mode is defined as [10]:

$$\alpha_{eff} = \frac{(\epsilon_0/\mu_0)^{1/2} \int_{A_\infty} n(r)\alpha_m(r)|E|^2 dA}{\left|\int_{A_\infty} S_z dA\right|}, \qquad (1)$$

where $\alpha_m(r)$ is the material absorption loss, $n(r)$ is the refractive index, ϵ_0 and μ_0 are the permittivity and permeability of free space, respectively. Since air is a transparent medium for THz (negligible absorption coefficient $\alpha_m = 0$), the integration in the numerator of the Eq. (1) is performed only over the solid core area. Note that in Fig. 2 the curves stop where the single mode operation ceases (that is also the case for Figs. 3 and 4). As defined in Ref. [2], beyond this point the fibers either become multi-mode, or for the case of the porous fibers, the material begins to act as an array of independent sub-wavelength fibers.

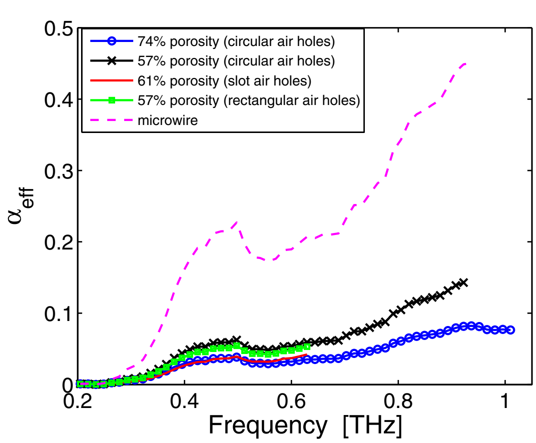

Fig. 2. Effective material loss, α_{eff}, versus frequency of porous fibers with circular shaped air-holes and 74% porosity and 57% porosity, porous fibers with rectangular and slot-shaped air-holes and 57% porosity and 61% porosity, respectively; and a microwire.

The geometrical parameters of the fibers in Fig. 2 are as follows: a porous fiber with rectangular shaped air-hole, 57% porosity and $d_{core} = 570\ \mu m$, a porous fiber with slot shaped air-hole, 61% porosity and $d_{core} = 600\ \mu m$, a microwire with $d_{core} = 375\ \mu m$, two porous fibers with circular shaped air-hole, 57% and 74% porosities and $d_{core} = 560\ \mu m$ and $d_{core} = 760\ \mu m$, respectively. The dimension of the fibers are chosen in a way that they have the same amount of loss at 0.2 THz, 0.007 cm^{-1}. Cyclic olefin copolymer (TOPAS) is considered as the host material for all of the simulations here. We use the THz properties of TOPAS (refractive index and absorption coefficient as a function of frequency) measured by THz time-domain spectroscopy (THz-TDS) [11]. As expected the effective material loss depends on the porosity of the porous fibers and not the air-hole shapes. This can clearly be seen in Fig. 2, where the effective material losses of porous fiber with different shaped air-holes but same 57% porosity are comparable. It should be noted that the single mode operating bandwidth is lower for the porous fibers with rectangular and slot-shaped air-holes.

Dispersion is the other mechanism for signal degradation in broadband applications. This occurs when the propagation constant of the guided modes varies with frequency. The frequency dependency of the propagation constant arises from refractive index variation of the host material (material dispersion) or/and waveguide structure (waveguide dispersion) with frequency. The group velocity of the host material, TOPAS, is calculated from the measured refractive index of the bulk material. As shown in Fig. 3, the almost flat feature indicates that the host material has negligible material dispersion. However, for the fibers used here, the waveguide dispersion, which depends on the structure of the fiber, plays an important role. In order to compare the dispersion of the fibers, the group velocity, $v_g = \partial\omega/\partial\beta_{eff}$, is calculated and compared for porous fibers and microwire.

Fig. 3 shows the group velocity normalized to the speed of light in free space as a function of frequency. For lower frequencies, where the dimension of the fiber is less than the operating wavelength and almost all the power is in the air, the group velocity of the propagating mode in all the structures approaches the velocity of light in free space. By increasing the frequency, the group velocity drops to that of the bulk TOPAS for microwire with a turning point around 0.6 THz (corresponding to zero dispersion), while it drops very slowly to 0.9 and 0.83 for porous fibers with circular shaped air-holes and 71% and 56% porosity, respectively, and 0.87 and 0.85 for porous fibers with slot and rectangular shaped air-holes and 61% and 56% porosity, respectively, without a turning point. The dispersion of porous fibers, with circular shaped air-holes, plateaus after 0.5 THz indicating that all the frequency components propagate with constant v_g, i.e. that dispersion is negligible. Thus a terahertz pulse propagating along porous fibers encounters small normal dispersion at lower frequencies, corresponding to a positive chirp in the time domain, and zero dispersion at higher frequencies. In the case of microwires, Fig. 3, the terahertz pulse encounters strong normal and anomalous dispersion corresponding to a positive and a negative chirp in the time domain, respectively.

Additional degradation in transmission is associated with birefringence, which can arise from structural and environmental perturbations. This occurs because of different group delays between polarization states, which leads to pulse broadening through polarization mode dispersion. It is well known from optics that the solution to this problem is the use of polarization maintaining (PM) fibers, which introduce modal birefringence into the fiber [12–14]. Modal birefringence arises from effective refractive index differences between x and y polarization modes, $|n_x - n_y|$. Modal birefringence can be introduced using either stress-applying parts in the cladding [12] or/and asymmetry in the core/cladding geometry

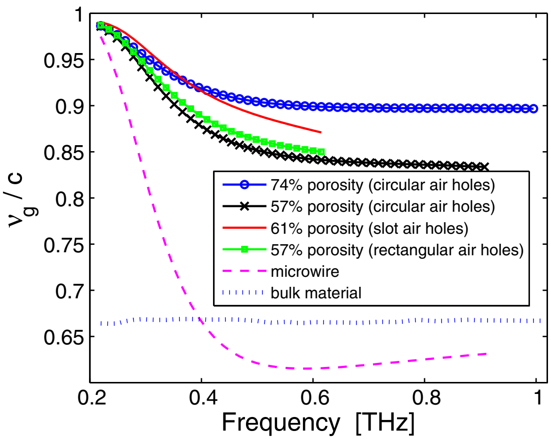

Fig. 3. Waveguide dispersion versus frequency of porous fibers with circular shaped air-holes and 74% porosity and 57% porosity, porous fibers with rectangular and slot-shaped air-holes and 57% porosity and 61% porosity, respectively; and a microwire.

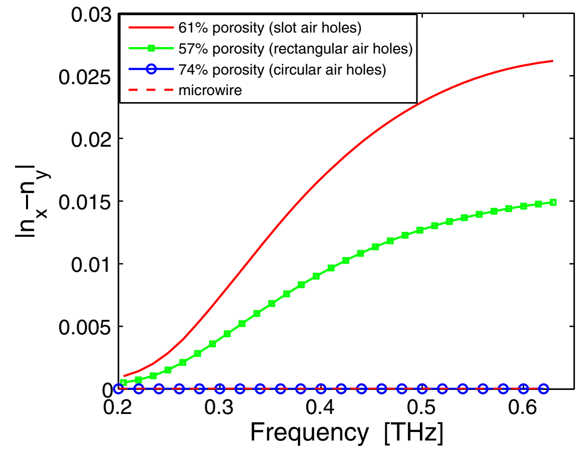

Fig. 4. Modal birefringence versus frequency of porous fiber with circular shaped air-holes and 74% porosity, porous fibers with rectangular and slot-shaped air-holes and 57% porosity and 61% porosity, respectively; and a microwire.

of the fibers [15]. Thus light launched onto one of the principle axes of a PM fiber remains in this polarization in the presence of any environmental perturbations.

Fig. 4 shows the modal birefringence, $|n_x - n_y|$ as a function of frequency. As expected, for symmetrical fibers the birefringence is zero. However, for porous fibers with circular shaped air-holes the calculated birefringence is at the order of 10^{-5}, nearly zero as shown in Fig. 4. This non-physical residual birefringence provides a guide to accuracy of the calculation [2]. In contrast for porous fibers with slot and rectangular shaped air-holes, asymmetrical discontinuities in the *x*- and *y*-direction, there is a noticeable birefringence for the fundamental mode. The value of birefringence depends on the shape and arrangement of the holes; the porous fibers with slot and rectangular shaped air-holes proposed in this paper provides a birefringence of 0.026 and 0.015, respectively at 0.6 THz. These values are comparable to recently achieved high birefringence (≈0.025) in photonic crystals fibers [16]. These high birefringence porous structures have lower single mode operating bandwidth relative to porous fibers with circular shaped air-holes because there is a considerable amount of material between the air-holes and the edge of the core. Recently it has been shown that it is possible to fabricate non-circular air-holes in microstructure optical fibers made up of polymer and soft glasses through extrusion technique [17,18], indicating that the fabrication of the proposed structures are feasible.

To conclude, we have shown that the effective material loss and group velocity of porous fibers are independent of the air-hole shapes and a flatter function of frequency compared to microwires. We have also demonstrated that introducing asymmetrical, slot and rectangular shaped, sub-wavelength air-hoes in the core of porous fibers leads to a birefringence ≈0.026. Maintaining the polarization of the propagating field in THz waveguides makes these fibers a good substitute for free space THz propagation, where the polarization state of the THz field is always preserved.

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