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Low loss porous terahertz fibers containing multiple subwavelength holes

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We propose a porous polymer terahertz fiber with a core composed of a hexagonal array of subwavelength air holes. Numerical simulations show that the larger part of guided power propagates inside the air holes within the fiber core, resulting in suppression of the bulk absorption losses of the core material by a factor of ~10–20. Confinement of terahertz power in the subwavelength holes greatly reduces effective refractive index of the guided mode but not as much as to considerably increase modal radiation losses due to bending. As a result, tight bends of several centimeter bending radii can be tolerated. © *2008 American Institute of Physics*.
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Terahertz wavelengths, covering the range of 30–3000 μm, have strong potential for applications in biomedical sensing, noninvasive imaging, and spectroscopy. Terahertz sources are generally bulky; thus, designing efficient terahertz waveguides for remote delivery and collection of broadband terahertz radiation is a priority for many practical applications of this technology.

The main complexity in designing terahertz waveguides is the fact that almost all materials are highly absorbent in the terahertz region. Since the lowest absorption loss occurs in dry air, an efficient waveguide design must maximize the fraction of power guided in the air. For instance, hollow core metallic waveguides, such as those conventionally used to guide microwaves, were shown to have 5 dB/cm loss at 1 THz.[1] However, metals, such as stainless steel, are not efficient reflectors in the terahertz regime because of their finite conductivity, thus leading to appreciable waveguide losses. Nevertheless, plasmon mediated guidance along metal wires was proven to have a very low absorption loss of about 6–20 dB/m at 1 THz.[2] However, not only is it difficult to excite the plasmon (large coupling loss) but also the majority of the field is guided outside the metallic wire, resulting in a too strong coupling to the environment and high bending losses.[3] On the other hand, many groups have studied a wide variety of dielectric waveguides, such as plastic solid core holey fibers,[4,5] Bragg bandgap fibers,[6] subwavelength plastic fibers,[7] and low index discontinuity waveguides.[8] These studies have again shown that, even when using relatively low absorption loss plastics or glasses, the waveguide absorption loss remains substantial unless a considerable fraction of power is guided in the air.

This work is motivated by two recently reported high air fraction waveguide designs[7,8] operating on the principle of total internal reflection. Particularly, Chen *et al.*[7] report a step index plastic fiber, in which a subwavelength polyethylene rod acts as a fiber core, while the surrounding air acts as a cladding. The field of the guided mode extends far into the surrounding air cladding, resulting in low absorption loss; however, the fiber suffers from strong coupling to the environment and high bending losses. The other design is by Nagel *et al.*;[8] it reports a subwavelength air hole placed in the center of a glass rod. To satisfy Maxwell's equations, the displacement field component D_{norm} normal to the air-glass interface must be continuous across the boundary of a hole. Large refractive index difference between the air and glass causes strong discontinuity in the amplitude of the electrical field at the boundary, resulting also in the high electric field concentration in the lower refractive index material (air hole). For a given refractive index, the sizes of the rod and air hole can be optimized to maximize the concentration of modal power in the air hole. However, even in the optimal designs, a considerable amount of modal power is still present inside the absorbing material.

In this letter, we present a design of a low loss fiber consisting of a highly porous polymer core containing a hexagonal array of subwavelength holes separated by subwavelength material veins. The fiber core is surrounded by the air cladding, and the core diameter is comparable to the wavelength of transmitted light. Due to the subwavelength size of the material veins in the fiber core, modal fields are pushed into the air regions both inside and outside the fiber core, thus allowing significant reduction of the modal absorption losses. Furthermore, fiber geometry parameters can be chosen in such a way as to ensure that the modal effective refractive index is small enough for efficient suppression of the fiber material absorption losses, yet not too small as to cause significant bending loss or significant penetration into the fiber cladding.

Figure 1 shows the schematic of the cross section of the proposed porous terahertz fiber. The structure consists of a

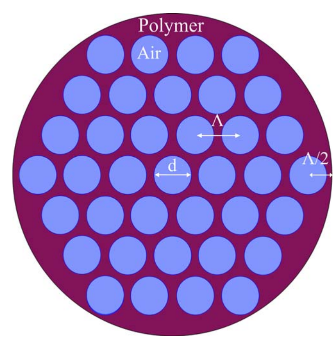

FIG. 1. (Color online) Schematic of the cross section of a porous terahertz fiber with subwavelength air holes.

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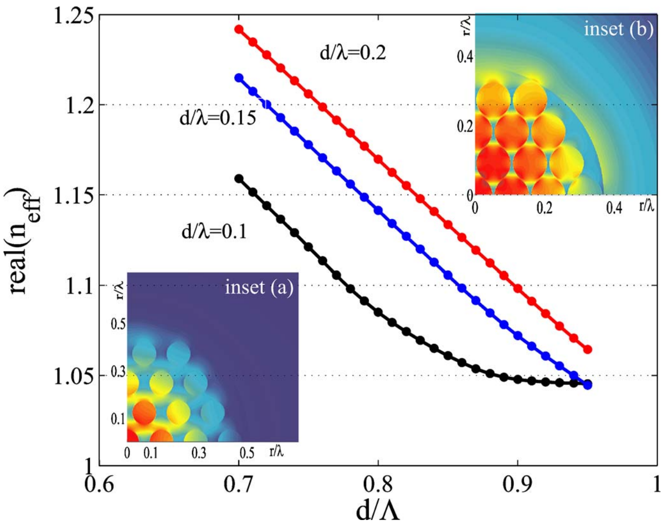

FIG. 2. (Color online) Effective refractive index of the fiber core mode vs d/Λ for the three fiber designs having hole diameters of $d=0.10\lambda$, 0.15λ, and 0.20λ. For the fiber with $d/\lambda=0.1$, inset (a) shows the S_z energy flux distribution in the case of $\Lambda=d/0.7$; inset (b) shows the S_z energy flux distribution in the case of $\Lambda=d/0.95$.

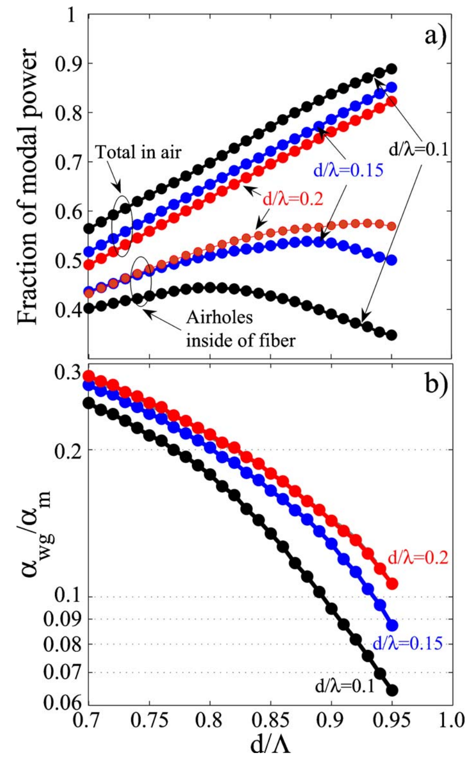

FIG. 3. (Color online) (a) Three upper curves show the total fraction of the modal power guided in the air (air holes plus air cladding) as a function of d/Λ parameter. Three lower curves indicate the modal power fraction guided in the air holes only (inside the fiber). (b) Normalized absorption loss coefficient.

polymer rod having a hexagonal array of air holes. Note that periodicity in the hole arrangement is not strictly necessary as the guiding mechanism is total internal reflection and not the photonic bandgap guidance. For the polymer we assume a refractive index of 1.5 (which is a typical value for most polymers at 1 THz), while the refractive index of air is 1. The fiber in Fig. 1 has three layers of holes and for the size of the holes we consider three different designs: $d=0.1\lambda$, 0.15λ, and 0.2λ, where d is the hole diameter and λ is the operating wavelength. The center to center distance between two neighboring holes is called the pitch Λ. The fiber diameter used in the simulations is 7Λ. To study the effect of the thickness of material veins on the absorption and bending losses of a porous fiber, we vary the diameter to pitch ratio d/Λ from 0.7 to 0.95, with the larger values of d/Λ corresponding to thinner material veins.

Figure 2 shows the effective refractive index of the proposed fibers as a function of d/Λ for the three cases $d/\lambda=[0.1,0.15,0.2]$. From the figure one can see that, even though the refractive index of a core material is 1.5, the effective refractive index of a guided mode can be as low as 1.05 for the high diameter to pitch ratios $d/\Lambda\sim0.95$. Generally, when the modal effective refractive index is significantly smaller than that of a polymer material, the overlap between the terahertz waves and the absorptive polymer is greatly reduced. Moreover, to achieve the same value of modal refractive index, the fibers featuring larger holes d/λ have to have thinner material veins (higher d/Λ ratios). Insets (a) and (b) in Fig. 2 show the S_z energy flux distributions in the fundamental core modes of the fibers with $d=0.1\lambda$, $\Lambda=d/0.7$ and $d=0.1\lambda$, $\Lambda=d/0.95$, respectively. In both cases the field distributions exhibit an overall Gaussian-like envelope modulated with field discontinuities at the air-material interfaces. Note that it is the subwavelength size of the material veins, and not the size of the air holes, which is essential for the creation of smooth modal field envelopes. Finally, as it follows from the data in Fig. 2, the effective refractive index of the mode shown in inset (a) is larger than that of the mode shown in inset (b), and, as a consequence, the mode of inset (a) is localized stronger inside the fiber than the mode of inset (b).

We now quantify the fraction of modal power propagating in the air as a function of various fiber parameters. Defining the Poynting vector in the direction of propagation as S_z, the fraction of modal power guided in the air η is given by

$$\eta=\int_{\mathrm{air}} S_z dA \Big/ \int_{\mathrm{all}} S_z dA, \tag{1}$$

where "air" and "all" are the integrals over the air filled fiber region versus the entire fiber cross section. Figure 3(a) shows the fraction of the modal power in the air as a function of d/Λ for the three choices of air hole sizes. The upper three curves show the total power fraction in the air (air holes plus cladding), while the lower three curves indicate the fraction of the power which is confined solely within the air holes of the fiber core. Note that the fraction of power guided outside the fiber can be easily ascertained from Fig. 3(a) and is given by the difference between the upper and the lower curves. For the fiber with $d=0.1\lambda$, for example, as the vein thickness decreases (larger values of d/Λ), the total modal power fraction in the air monotonically increases. In contrast, the modal power fraction in the air holes inside the fiber core achieves its maximum $\Lambda\simeq d/0.8$. This behavior is easy to rationalize. Indeed, thinning of the material veins beyond their optimal size leads to the reduction of the modal effective refractive index and stronger expulsion of the modal fields into the fiber air cladding, eventually resulting in the smaller modal power fraction in the air holes of the fiber core. On the other hand, thickening of the material veins beyond their optimal size leads to higher concentration of modal fields inside the polymer veins, eventually resulting also in the smaller modal power fraction in the air holes of the fiber core.

We now characterize the modal absorption loss of a fiber by using the results of a perturbation theory found in Ref. 9. Particularly, the normalized propagation loss of a guided mode due to fiber material absorption is given by

$$f = \frac{\alpha_{\mathrm{wg}}}{\alpha_{\mathrm{mat}}} = \left[\frac{\displaystyle\int_{\mathrm{polymer}} n_r |\mathbf{E}|^2 dA}{\mathrm{Re}\left(\displaystyle\int_{\mathrm{tot}} \mathbf{E} \times \mathbf{H}^* \cdot \hat{z} dA \right)} \right], \quad (2)$$

where α_{wg} is the modal propagation loss due to material absorption, while α_{mat} is the bulk absorption loss of the fiber material. $\mathbf{E}$ and $\mathbf{H}$ are, respectively, the electric and magnetic fields of the fiber mode, while n_r is a real part of the fiber material refractive index. Figure 3(b) presents normalized modal propagation losses due to material absorption as a function of the d/Λ parameter. Not surprisingly, fibers featuring smaller air holes (smaller d/λ values) and thinner veins (higher d/Λ values) exhibit smaller modal losses. As an example, consider a representative porous fiber with geometrical parameters $d/\lambda = 0.1$ and $d/\Lambda = 0.95$ made of a Teflon material with bulk absorption loss of 0.3 cm^{-1}.[5] The fundamental mode propagation loss due to material absorption in such a fiber is 0.018 cm^{-1}, which is 15 times smaller than the bulk absorption loss of a fiber material. Note that this loss value is among the lowest loss values of the currently available terahertz waveguides.

Another important parameter to consider in designing highly porous fiber is bending induced radiation loss. As the core/clad refractive index in such fibers is relatively small, guided mode can be considerably delocalized beyond the core region and, therefore, is sensitive to fiber bending. Even though direct calculation of bending losses for a porous microstructured fiber is not an easy task, we can use an approximate analytical method detailed in Ref. 10. In the framework of this method, microstructured fiber is approximated as a step index core/air clad fiber with a core region having the effective refractive index n_{eff} equal to that of a corresponding guided mode. Bending loss is then obtained by

$$\alpha \simeq \frac{1}{8}\sqrt{\frac{2\pi}{3}}\frac{1}{A_{\mathrm{eff}}}\frac{1}{\beta}F\left[\frac{2}{3}R\frac{(\beta^2-\beta_{\mathrm{cl}}^2)^{3/2}}{\beta^2}\right], \quad (3)$$

where $F(x) = x^{-1/2}\exp(-x)$, the propagation constant β is defined by $\beta = 2\pi n_{\mathrm{eff}}/\lambda$, and R is the bending radius. Also, A_{eff} is the effective area defined by[11]

$$A_{\mathrm{eff}} = \left[\int I(r) r dr\right]^2 \Big/ \left[\int I^2(r) r dr\right], \quad (4)$$

where $I(r)$ is the transverse field intensity distribution in the cross section of a fiber. As an example, consider the fiber with $d/\lambda = 0.1$, operating at 0.5 THz. In Figure 4 various loss curves are shown as a function of d/Λ. A thin solid black curve corresponds to the modal transmission loss due to material absorption; the bulk material loss of the core material is assumed to be that of a Teflon polymer 0.3 cm^{-1}. The thin dotted curves show bending losses for the various values of the bending radius R ranging from 1 to 3 cm. Finally, the thick solid curves show the net of bending and absorption losses for the given values of the bending radius R. Interestingly, for the tight bends (bending radii smaller than ~2.5 cm), there exists an optimal design that minimizes the total transmission loss. For the bends of larger bending radii, the minimal transmission loss design is that with the highest air filling fraction d/Λ. Generally, for moderate air filling fractions $0.7 < d/\Lambda < 0.8$, the dominant loss mechanism is the absorption loss due to the field penetration into the material core, whereas for higher air filling fractions $0.85 < d/\Lambda$, bending loss dominates due to strong delocalization of a core guided mode outside the porous fiber core.

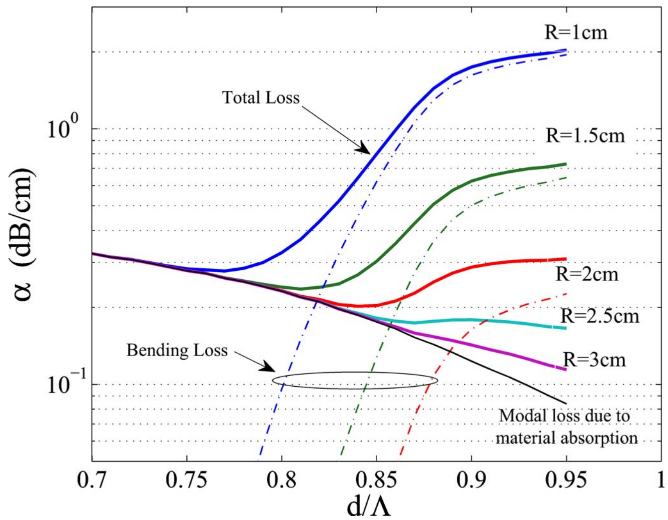

FIG. 4. (Color online) Total modal transmission loss due to fiber bending and material absorption as a function of the air filling fraction d/Λ. Example of a terahertz fiber with $d/\lambda = 0.1$, and a core material loss of 0.3 cm^{-1}.

In conclusion, we have proposed a microstructured polymer terahertz fiber composed of a porous polymer core containing a hexagonal array of subwavelength air holes and subwavelength material veins. In such fiber, a large fraction of the modal power propagates inside the fiber air holes. As a result, low modal transmission loss can be achieved with a typical bulk absorption loss suppression factor of 10–20. Using approximate analytical expression for the radiation loss due to fiber bending, we conclude that, even in the presence of tight bends (bending radii ~3 cm), modal radiation loss is comparable to the modal absorption losses, thus making such fiber highly tolerant to bending.

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