Low Loss THz Fibers with Multiple Subwavelength Holes

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Abstract: We propose the design of a THz Fiber that is composed of a polymer rod containing a hexagonal array of subwavelength air holes. A high air fraction gives an absorption loss of 0.018 cm^{-1}.

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Terahertz wavelengths, covering the range of 30-3000 micron, have big potential for applications such as biomedical sensing, noninvasive imaging and spectroscopy. Terahertz sources are generally bulky and designing efficient THz waveguides, in order to remotely deliver the broadband THz radiation, would be a big step towards commercialization of compact and robust THz systems for these applications. On the other hand, almost all materials are highly absorbent in the THz region. Since the lowest absorption loss occurs in dry air, an efficient waveguide design must maximize the fraction of power guided in the air.

The challenges of guiding THz radiation require creative waveguide design because the typical waveguides that are used to guide visible or microwave light are no longer sufficient. 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]. Thus metals, like stainless steel, are not proper reflectors in the THz regime because their finite conductivity leads to appreciable 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, but the majority of the field is guided outside of the metallic wire resulting in coupling to other waveguides and large 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], Bragg bandgap fibers [5], subwavelength plastic fibers [6], and low index discontinuity waveguides [7]. These studies have shown that, even when using plastics or glasses, the absorption losses remain substantial unless a considerable fraction of power is guided in the air. In the case of the subwavelength plastic fiber [6], a subwavelength polyethylene rod acts as a high refractive index core and the surrounding air acts as a lower refractive index cladding. The field of the guided mode extends far into the surrounding air resulting in low absorption loss, but this fiber also suffers from cross-talk and large bending losses. Interestingly, in the case of the low index discontinuity waveguide [7] a subwavelength air hole is placed at the center of a glass rod that acts as a subwavelength waveguide. To satisfy Maxwell's equations the electric flux density $\mathrm{D}_{\mathrm{norm}}$ that is normal to the air-polymer interface must be continuous across the boundary of the hole. The large refractive index difference between air and glass therefore causes a large discontinuity in the amplitude of the electrical field at this boundary, resulting in a proportionally high field concentration in the lower refractive index part (air hole). However a considerable amount of power can nevertheless exist in the material.

Here, we present the design of a low loss waveguide consisting of a porous wavelength-size polymer rod containing a hexagonal array of subwavelength holes. Again the THz field is guided by a high-index polymer core that is surrounded by an air cladding, but the presence of several subwavelength air holes provides a greater opportunity for the field to be confined in the air holes instead of the material or the outside air.

Figure 1-a) shows the schematic of the cross-section of our proposed microstructured THz fiber. The structure consists of a polymer rod having a hexagonal array of air holes. This fiber has 3 layers of holes and for the size of the holes we consider three different designs: $d = 0.1\lambda, 0.15\lambda$, and 0.2λ, where d is the hole diameter, λ is the operating wavelength, and Λ indicates the pitch. Figure 1-b) shows the effective index of the proposed fibers versus d/Λ for the three cases $d/\lambda = [0.1, 0.15, 0.2]$. Even though the refractive index of polymer is considered to be 1.5, the effective index of the fiber can reach below 1.05 by decreasing the pitch size to $\Lambda = d/0.95$ while the air hole size remains constant. As a result, the interaction between the THz

waves and the absorptive polymer is greatly reduced. The presence of a multitude of holes in the proposed design increases the number of air regions where the THz radiation can be concentrated. Inset (a) and (b) in Fig. 1-b) show the S_z field distribution of the fiber with $d = 0.1\lambda$ for the cases $\Lambda = d/0.75$ and $\Lambda = d/0.95$, respectively. In both cases the field distribution corresponds to the superposition of the Gaussian-like field distribution of a rod suspended in air, with an effective refractive index n_{eff}, and the field distribution of the individual subwavelength holes. Because of this, more power is concentrated in the air holes near the center of the fiber, resulting in reducing the bending loss of the fiber considerably [8].

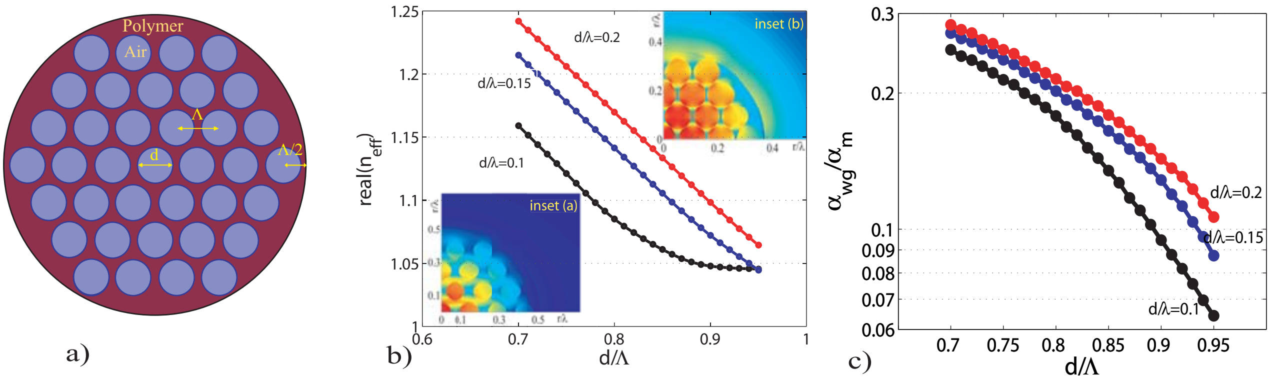

Fig. 1. Schematization of the cross-section of the proposed subwavelength THz polymer fiber, b)The effective index of the fiber versus d/Λ for the three fiber designs having hole diameters of $d = 0.10\lambda$, 0.15λ, and 0.20λ respectively, for the fiber with $d/\lambda = 0.1$, inset (a) shows the S_z field distribution in the case where $\Lambda = d/0.75$ and inset (b) shows the S_z field distribution in the case where $\Lambda = d/0.95$, c)Normalized absorption loss coefficient versus d/Λ for the three proposed fibers.

To calculate the modal absorption loss of the fiber, as a result of material absorption, we calculate the following field fraction corresponding to the loss of the waveguide normalized with respect to the material loss $f = \frac{\alpha_{\mathrm{wg}}}{\alpha_{\mathrm{mat}}} = \left[\frac{\sqrt{\epsilon_0/\mu_0}\int_{\mathrm{polymer}} n_r|E|^2 dA}{Re\{\int_{\mathrm{total}} \vec{E}\times\vec{H}^*\cdot\hat{z}dA\}}\right]$, where α_{wg} and α_{mat} are the absorption coefficients of the THz waveguide and the bulk material (polymer), respectively. $\vec{E}$ and $\vec{H}$ are respectively the electric and magnetic fields, and n_r is the real part of the refractive index of the absorbent material (polymer). Figure 1-c) presents the normalized absorption loss as a function of d/Λ. The $d/\lambda = 0.1$ case gives a minimum normalized absorption loss of about 0.06 as a result of having the higher power fraction in the air. Considering the absorption loss of a low-loss material such as Teflon, 0.3 cm^{-1} [4], one can obtain a fiber absorption loss of 0.018 cm^{-1} for this case ($d/\Lambda = 0.95$). Note that even in the $d/\lambda = 0.2$ case the minimum of absorption loss would be 0.03 cm^{-1} which is among the current lowest loss THz waveguides.

In conclusion, we have proposed a microstructured polymer THz fiber composed of a polymer rod containing hexagonal array of subwavelength air holes. The major portion of THz power launched into the fiber propagates inside of the air holes and the air surrounding the fiber. As a result, The presence of subwavelength holes as a THz power confiner reduces the large bending loss that normally accompanies a small bending radius.

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