Porous Fibre: A Novel THz Waveguide

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Abstract - We propose a novel class of fibre with a porous core transverse cross-section that can offer a combination of low transmission loss and high mode confinement in the THz regime.

Introduction

The terahertz (THz) or T-ray region of electromagnetic spectrum, located between millimeter wave and infrared frequencies, has attracted much interest over the last decade. The frequency range is loosely defined as 0.1-10 THz [1]. Terahertz spectroscopic techniques have many applications, as for example in detection of biological and chemical materials [2, 3]. Many of these preliminary proof-of-principle studies have been carried out in spectroscopy systems, where terahertz radiation propagates in free space. For biomedical applications, however, these systems have limitations such as large diffraction limited focal spot size leading to the need for inconveniently large biosamples [4], and the systems are quite large thus not easy to integrate with optical and infrared techniques. Terahertz waveguides are a promising approach for overcoming these hurdles and potentially provide low-cost and robust THz integrated systems. However, efficient low-loss transmission of THz radiation within waveguides is still a challenge.

Waveguide solutions based on technologies from both electronics and photonics have been studied in literature [5-10]. Bare metal wires and sub-wavelength plastic fibres (described as THz microwires [11] in analogy with optical nanowires) with attenuation constants less than 0.03 cm^{-1} [12] and 0.01 cm^{-1} [13], have the lowest loss reported in the literature. Low losses are achieved in these waveguides, because almost all the field propagates in the medium surrounding the structure. This, however, results in weak confinement of the guided field within the structure that makes the guided field susceptible to any small perturbation on the surface or vicinity of the structure, since a large portion of the guided power can be readily coupled into radiation modes. Furthermore, as a result of weak confinement, the guided modes within these structures suffer strong bend loss [14].

An approach to improve the field confinement in the structure has been demonstrated by Nagel et al. [15]. They have shown that a low index discontinuity in dielectric waveguides (split rectangular and tube waveguides) has increased field in the low-index central region and reduced field in the high-index surrounding region results in increased confinement. The split rectangular waveguide is difficult to handle because it needs another structure to keep the slabs together and the tube waveguide is not a promising low-loss waveguide structure for terahertz.

Here, we propose a novel class of fibre for the THz, porous fibre, based on introducing sub-wavelength low index discontinuities within air-clad fibres. Instead of having one sub-wavelength air-hole in the core of the fibre [16, 17], we consider a pattern of sub-wavelength air-holes in the core, which leads to a better confinement of the field to the structure while still allowing THz propagation in the sub-wavelength holes.

Porous fibre

Porous fibres can be created by including a distribution of sub-wavelength air holes within the core of an air-clad fibre. A typical example is shown in Fig. 1. The distribution, shape, and size of the holes determine the porosity of the structure, which is defined as the fraction of the air holes to core area. The structure shown in Fig. 1. has a triangular lattice of circular holes with radii of 20 μm, core radius of 200 μm, which results in a porosity of 37 %. The arrangement of the holes within the core of porous fibre can be based on different varieties of lattice structures. We chose a triangular lattice because it leads to higher porosity when compared to a rectangular lattice of circular holes.

Polymethyl methacrylate, PMMA, is considered as the host material because of its low material absorption in THz and we use the THz optical properties of PMMA (refractive index and attenuation constant) [18] measured by THz time-domain spectroscopy for the calculations. To find the propagation constant and field distributions for the porous fibres, we solve the full vectorial form of

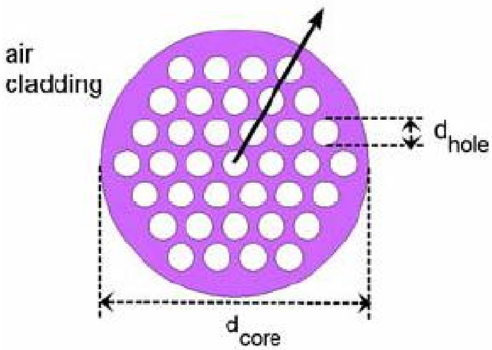

Fig. 1. Cross section and geometrical definitions of the triangular lattice porous fibre.

(FEM) technique instantiated in the commercial FEM package COMSOL 3.2. The calculated propagation constant of the fibre is accurate to five significant figures.

At any interface between two materials, there is a discontinuity in the electric-field strength; i.e., the electric-field enhances on the low refractive index side. The enhanced electric field is stronger, if the discontinuity in material occurs within a region of a waveguide structure where the electric field is stronger. The enhanced electric field rapidly decays away from the interface; however, if the dimension of the low index discontinuity is at the sub-wavelength scale, the decay of the evanescent field within the discontinuity is minimal. Thus a localized intensity enhancement can be achieved throughout the discontinuity region [16, 17].

Fig. 2. shows the normalized *z*-component of the Poynting vector (S_z) profile of the fundamental mode of the porous fibre along the arrow shown in Fig. 1. The refractive index profile along the same axis is also shown, demonstrating where the sub-wavelength air-holes are located. The refractive indices n_1 and n_0 refer to material (PMMA) and air refractive indices, respectively. The field is enhanced at the each air-material interface and stays localized in the sub-wavelength air-holes.

Fig. 3. shows the power fractions versus fibre diameter of three porous fibres with fixed porosities, 61%, 70% and 74%. For comparison, the power fractions of a THz microwire have also been evaluated and sketched in red. For large fibre diameters ($d_{core} \geq \lambda$), most of the guided power of the THz microwire is located in the solid core, while the power fraction residing in the sub-wavelength air-hole region of the porous fibre is dominant. Although the diameter increase in the porous fibre does not have a significant effect on the power fraction in the core material, it transfers most of the power in the air-clad region to the sub-wavelength

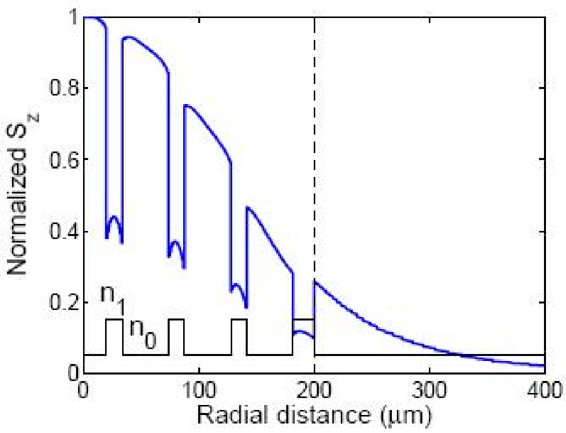

Fig. 2. The normalized Poynting vector, S_z, profile along the cross-section shown in Fig. 1., of the fundamental mode of a polymer porous fibre with core radius of $d_{core}/2$ = 200 µm, hole radii of $d_{core}/2$ = 20 µm and 37% porosity at f = 0.5 THz (λ = 600 µm). The dashed line represents the core to cladding interface and the lower solid line represents the refractive index profile.

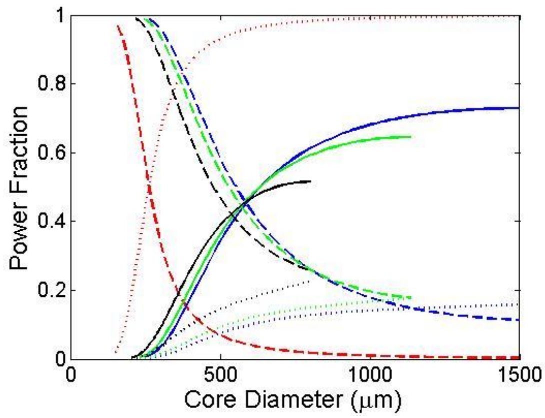

Fig. 3. Power fraction in the air holes (solid lines), core material (dotted lines) and air-clad (dashed lines) versus fibre diameter of a THz microwire (red lines) and porous fibres of 61% (black lines), 70% (green lines) and 74% (blue lines) porosity at f = 0.5 THz (λ= 600 µm).

air-holes. Unsurprisingly, for sub-wavelength diameters (d_{core} <<λ), the power fractions in the core of both waveguides decrease as the diameter decreases and most of the power is transferred to the air-clad region. Owing to porosity of the core and transparency of air in THz, for similar diameters the effective material loss of these fibres is less than that of the THz microwire.

Moreover, the power in the sub-wavelength air-holes of the porous fibre improves the confinement of the field to the structure when compared to that of the THz microwire. This is confirmed by showing that the power in the tail of the mode, for similar effective loss values, of the porous fibre is less than that of the microwire. The full details of the results will be presented and discussed.

Conclusions

In conclusion, we propose a new fibre structure for the THz regime, a porous fibre that improves the effective material loss and confinement in comparison to the THz microwire.

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