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2004 Jpn. J. Appl. Phys. 43 L317

(http://iopscience.iop.org/1347-4065/43/2B/L317)

Japanese Journal of Applied Physics
Vol. 43, No. 2B, 2004, pp. L317–L319

Express Letter

Teflon Photonic Crystal Fiber as Terahertz Waveguide

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(Received January 7, 2004; accepted January 11, 2004; published February 6, 2004)

We demonstrate the construction of reasonably long and non-polarization changing photonic fiber waveguide using Teflon which is a readily available and highly flexible material. Due to its relatively low loss coefficient, the possibility of preparing longer photonic fiber waveguide, which has the potential of guiding intense THz radiation, can be easily attained.
[DOI: 10.1143/JJAP.43.L317]

KEYWORDS: terahertz radiation, waveguide, photonic crystal fiber, polarization

The terahertz (THz) region that lies between the electronic and optical region in the electromagnetic spectrum, with frequencies ranging from 100 GHz to 10 THz, is an important region. This is because various characteristic parameters of materials, such as phonons, excitons, and cooper pairs exist in this region. As a result, much interest has been given in the generation and detection of THz radiation. To date, progress in THz spectroscopy has been enormous. Several THz-radiation emitters, such as photoconductive switch,[1)] semiconductor surface,[2)] and nonlinear optical process,[3)] have been reported as a result of the development of ultrafast optical pulses. With these devices, THz spectroscopy can be applied to virtually all kinds of samples, including chemical and organic materials. At present, THz spectroscopic techniques uses mainly free space propagation of this far-infrared electromagnetic (EM) wave and it is to some extent difficult to control and guide. To overcome this difficulty, it is thus necessary to develop and utilize waveguides that are transparent in the THz region. Several works on THz waveguides using various materials such as metal tube,[4)] plastic ribbon,[5)] and photonic crystal fiber (PCF)[6)] have been reported. These waveguides show low absorption coefficient with values less than 1 cm^{-1}.

The potential of using photonic crystals, both 2D and 3D, in manipulating and controlling EM waves have been reported by several groups.[7–10)] Photonic crystals molded into fibers are very attractive from the scientific and technological point of view due mainly to its single-mode propagating characteristic.[11)] A common PCF is made of waveguiding parts with a solid core and cladding layers consisting of spatially periodic air holes. The effective refractive index of the cladding region relative to the core is reduced due to the presence of these air holes. Confinement and guiding of light in this PCF with relatively high core index would then occur via total internal reflection.[12,13)] Single-mode propagation is dependent of the ratio between the core radius and wavelength; as a result, it is not difficult to construct PCFs waveguide for THz radiation because of its long wavelength compared to the wavelength used in conventional PCF application system. Silica is commonly used in fabricating optical fiber. However, this material is not transparent in the THz region. Alternative plastic materials such as Apel and Tpx have been found to be transparent to THz radiation[14)] and are good candidates for the construction of PCF. The main advantage of using plastics is because of their flexibility.

Most plastic THz waveguide uses high-density polyethylene as material. In this study, we propose an alternative PCF material for THz waveguide. Utilizing readily and commercially available material, highly flexible PCFs are assembled. The PCFs are made of polytetrafluorethylene, which is commonly known as Teflon. A solid rod of this material is used as core and hollow tubes as air clad. The PCFs are fused together without the need of furnace heating thereby making it simple and easy to fabricate. Moreover, the PCFs showed effective waveguiding of THz radiation and are found to have efficient polarization preserving property.

The experimental setup used is shown in Fig. 1. THz radiation from an undoped bulk InAs with (100) surface immersed in a magnetic field provided by a 2.5-T permanent magnet and excited by a mode-locked Ti:Sapphire laser with an average power of 1-W was used. The excitation laser delivered 100-fs optical pulses with center wavelength of 800 nm at a repetition rate of 82-MHz. The spot size of the THz beam on the InAs surface was approximated to be 2 mm. The emitted THz radiation was collimated and focused using paraboloidal mirrors. A silicon hyper-hemispherical lens was used to focus the THz beam into the waveguides. A liquid-He cooled Si-bolometer was used for detecting the THz radiation. The PCFs samples were constructed using Teflon rods as core and Teflon tubes for the periodic cladding. The periodic cladding mounted in the

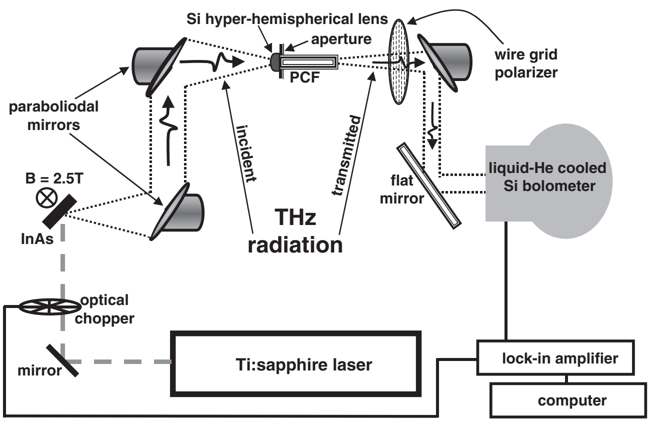

Fig. 1. The experimental setup used in characterizing the waveguides. A Si hyper-hemispherical lens is placed at one end of the waveguide and both (lens and waveguide) are placed at the beam waist of the THz radiation. A wire grid polarizer is used to determine the polarization of the emitted THz radiation.

samples had two layers, wherein the first and second layers had 8 and 16 Teflon tubes, respectively. The diameter of the core used was 1 mm while the clad had an outer diameter of 0.75 mm and an inner diameter of 0.25 mm. For comparison purposes, a metal tube (inner diameter of 0.25 mm, outer diameter of 5 mm) and a solid Teflon rod whose diameter is the same as that of the PCF was also used. Teflon is chosen for this study due to the fact that several reports have shown that this material is highly transparent in the THz frequency region.[15,16] These reports were verified by our group and the absorption coefficient plot of a 5 cm solid Teflon rod is shown in Fig. 2. It can be seen that the Teflon material used in the PCF has low absorption for the THz radiation with an absorption coefficient of approximately $0.3\,\mathrm{cm}^{-1}$ at 1 THz.

A photograph of the constructed PCFs is shown in Fig. 3. The upper right-hand corner inset shows the cross-section of the PCF. The cladding layers and the core are fused together without any furnace heating. Holding the 1st cladding layer and the core together is ordinary plastic tube, which is placed between the 1st and 2nd cladding layers. Another thin plastic tube is placed on the outer portion to envelop the whole PCF thereby fusing together the core, 1st and 2nd layers into one fiber. To test the confinement of the incident THz wave inside and to confirm that the wave propagation is mainly in the core of the constructed PCF, knife-edge measurements at the exit point are conducted. The intensity profile of the beam in one of the PCFs is shown in the lower left-hand corner of Fig. 3. From the plot shown, it can be seen that the data is well described via Gaussian fitting. This clearly indicates that almost all the beam is confined within a diameter of 1 mm thereby confirming that almost all the THz radiation propagate in the core.

Figure 4 shows the length dependence of the transmitted intensity through the waveguides. The dotted line indicates the incident THz radiation while the best-fit lines for the metal tube and PCF are designated by solid and dashed lines, respectively. It can be inferred that the intensity is fitted by an exponential function of length. This indicates that by extrapolating the best-fit lines, the coupling loss at the waveguide-hyper-hemispherical lens interface can be extracted. It can be deduced that at the PCF-hyper-hemispherical lens interface 10% of the total radiation propagates into the PCF while 30% transmits through the metal tube. From the best-fit lines, it can be determined that the loss coefficient for the PCF and the metal are approximately $0.12\,\mathrm{cm}^{-1}$ and $0.10\,\mathrm{cm}^{-1}$, respectively. Based on the relatively low loss coefficient of the PCFs, the possibility of constructing long PCFs for potential THz waveguide can be easily attained. The inset shows the spectra of the PCFs with various lengths. The reference is the based on the emitted THz pulses from a single hyper-hemispherical lens placed at the beam waist of the radiation. High frequency cut-off is observed for each PCF and such cut-off shifts toward low frequency with increasing PCF length. This implies absorption of the PCF material as its length increases. Further modifications are currently being done

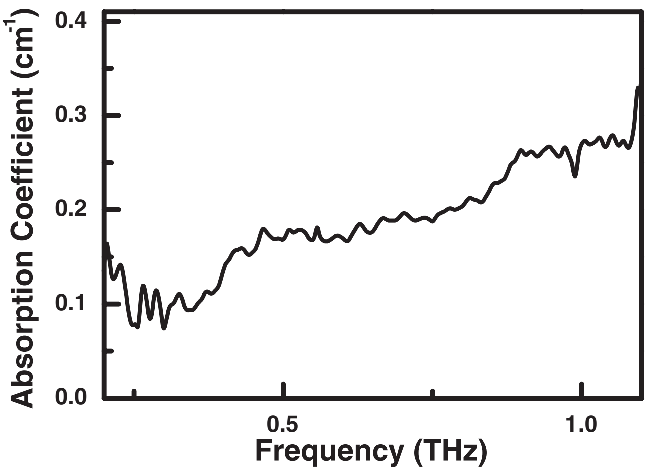

Fig. 2. Absorption coefficient versus frequency plot of the 5 cm solid Teflon rod with a diameter similar to that of the PCF. The absorption coefficient at 1 THz is found to be approximately $0.3\,\mathrm{cm}^{-1}$.

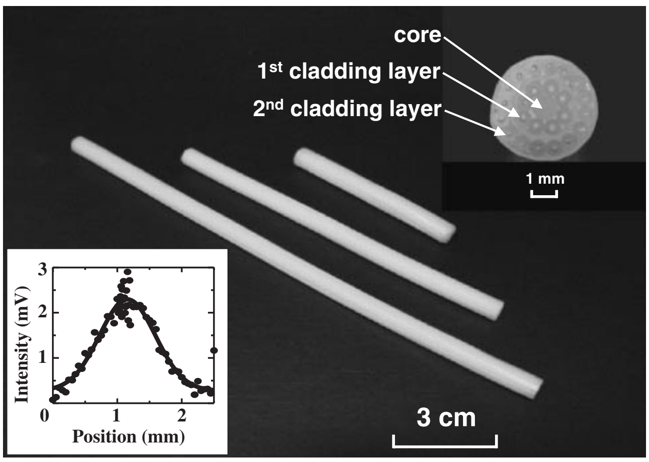

Fig. 3. Photograph showing the PCFs constructed. Upper right-hand corner inset shows the cross-section of the PCF where the core (solid rod) and cladding (hollow tubes) are both made of Teflon. Thin ordinary plastic tubes are used to hold the 1st cladding layer and core and also as an envelop of the outer most part thereby fusing the together the core, 1st and 2nd layers into one fiber. The lower left-hand inset shows the intensity profile of the emitted radiation, which is well described via Gaussian fitting (solid line).

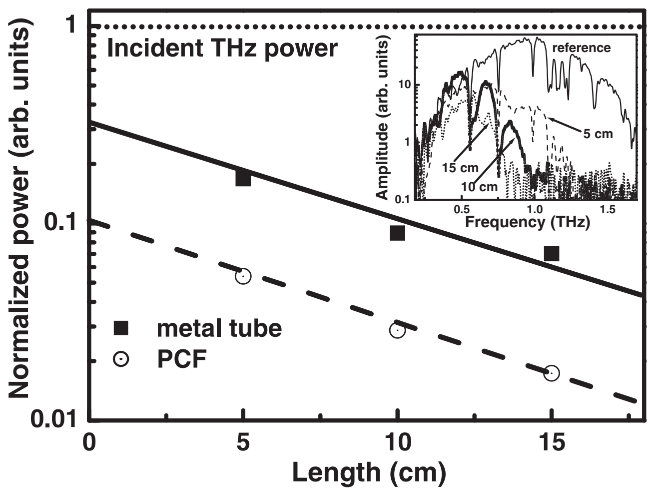

Fig. 4. Length dependence of the transmitted intensity through the waveguides. The dotted line indicates the incident THz radiation while the solid and dashed lines denote the best-fit lines for the metal and PCFs, respectively. Inset shows the spectra of the PCFs with various lengths.

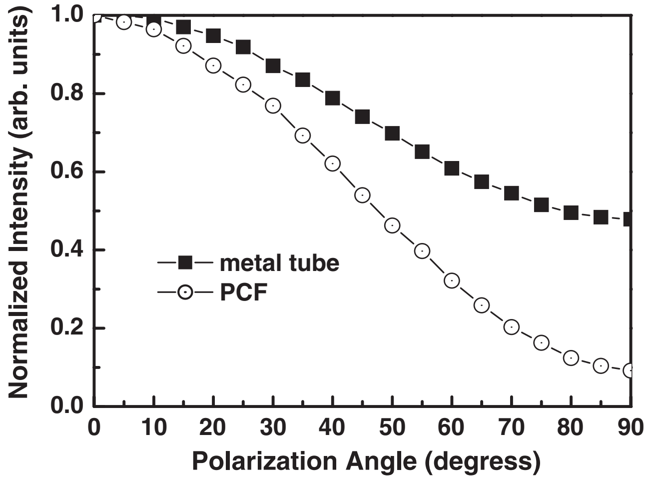

Fig. 5. Polarization angle dependence of various waveguides. The PCF is found to be highly polarization preserving while the metal tube depicts non-polarization preserving property.

to improve the efficiency of the PCF, which has the potential for the propagation and guiding of intense THz radiation.

By placing a wire grid polarizer in front of the bolometer and rotating it at increments of 5 degrees, the polarization angle dependence of the various waveguides are determined as shown in Fig. 5. In this plot, a polarization angle of 90 degrees means that orientation of the transmitted wave is normal and lies on the plane of the wire grid. As seen in Fig. 5, the metal tube is found to be non-polarization preserving. This is possibly due to multiple reflections inside the metal tube, which tends to rotate the wave polarization. On the other hand, all of the constructed PCF show good polarization conservation. Considering the characteristics of the PCFs, i.e. intensity profile well fitted via Gaussian function with high polarization preserving quality, and the initial polarization of the incident THz pulse, it is likely that the PCFs have single-mode propagation. To confirm this, thorough mode propagation analysis is required.

In summary, we have demonstrated the construction of reasonably long, easily-prepared and non-polarization changing photonic fiber waveguide using readily/commercially available and highly flexible material. Based on the relatively low loss coefficient obtained from the PCFs, the possibility of constructing long PCFs for potential THz waveguide can be easily achieved. Modifications are now being done to improve the efficiency of the PCF.

This research was partially supported by a Grant-in-Aid for Scientific Research on Priority Areas (11231204), and a Grant-in-Aid for Scientific Research (B) (13555015) from the Ministry of Education, Culture, Sports, Science and Technology, the Creative and Fundamental R & D Program for SMEs, "Research for the Future (RFTF)" of the Japan Society for the Promotion of Science (JSPS-RFTF 99P01201) and the Research Foundation for Opto-Science and Technology.

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