Low-loss single-mode terahertz waveguiding using Cytop

Glenda de los Reyes, Alex Quema,[a] Carlito Ponseca, Jr., Romeric Pobre,[b] and Reuben Quiroga[b]
Institute for Molecular Science, Myodaiji, Okazaki, Aichi 444-8585, Japan

Shingo Ono
Nagoya Institute of Technology, Gokiso, Showa, Nagoya, Aichi 466-8555, Japan

Hidetoshi Murakami,[c] Elmer Estacio, and Nobuhiko Sarukura
Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka 565-0871, Japan

Ko Aosaki, Yoshihiko Sakane, and Hideki Sato
Asahi Glass Co., Ltd., Kanagawa-ku, Yokohama 221-8755, Japan

(Received 15 June 2006; accepted 13 October 2006; published online 22 November 2006)

A polymer-based, Cytop planar photonic crystal waveguide (PPCW) was designed for guiding terahertz radiation. Results indicate that the propagation and coupling losses in the 0.2–1.1 THz range are relatively small for a sheetlike thickness design. Spectral analysis of the transmission data reveals frequency selectivity of the PPCW. Calculations of the spatial distribution of the terahertz electric field through the waveguide show evidence of single-mode propagation at a 0.45 THz central frequency. The highly transparent nature of Cytop from deep ultraviolet to the far infrared region indicates its potential use as an integral component in hybrid optics. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2392990]

The spectroscopic applications of terahertz radiation extend to the characterization of chemicals,[1–3] biological samples,[4,5] and polymers.[6] However, terahertz radiation today relies mainly on free space propagation. As such, several workers have recently reported the use of quasioptical techniques and low-loss waveguides, such as plastic ribbons[7] and metal wires.[8] The demand for broader bandwidth and higher terahertz coupling efficiency to single dominant-mode waveguides has resulted in the development of plastic photonic crystal fibers (PCFs).[9–11] Although integrated terahertz optics using a lens duct and a Teflon PCF has been demonstrated, fiber loss is relatively high.[12] Moreover, the applications of PCF are rather limited. On the other hand, planar photonic crystal waveguides (PPCWs) offer compactness and highly tunable optical properties.[13] They can have a variety of functions such as high-quality resonators,[14] miniaturized wavelength multiplexing devices,[15] and more importantly, they play a big role in photonic integrated circuits.[16]

In this work, experimental characterization and finite difference time-domain (FDTD) simulations for the terahertz transmission of a PPCW patterned on a plastic material, Cytop, are presented. Cytop is a cyclized fluoropolymer prepared by copolymerization of alkenyl vinyl ethers. Previous work on the optical properties of this material shows that it has >95% transmittance from 2 μm down to 200 nm wavelength.[17] This characteristic makes Cytop highly attractive for simultaneous optical and terahertz spectroscopy of wide band gap semiconductors. Its high transparency is attributed to the absence of a lossy carbon-hydrogen bond which is present in most plastics.[18] This material is mainly composed of carbon-flourine, carbon-oxygen, and carbon-carbon bonds wherein the absorption band occurs betweeen 7.7 and 10.0 μm.[19] As shown in Fig. 1, terahertz absorption spectrum from the transmission spectroscopy of a bare Cytop slab exhibited an absorption coefficient not exceeding 1 cm^{-1} (4 dB/cm) at 1 THz. The terahertz radiation source was a surface-irradiated InAs wafer under magnetic field, producing transients centered at ~0.6 THz ranging from 0.2 to 1.2 THz. A typical terahertz spectrum of the source may be seen in Ref. 12. The periodic oscillations in the absorption spectrum are due to interference fringes from the front and back surfaces of the slab. The fringe spacing was used to deduce an average refractive index of 1.4. This value was then used to fit the absorption spectrum from the original transmission data.[20] Note that the poor fitting at the edge regions are due to the limited bandwidth of the terahertz source and the dips in the experimental data are due to water vapor absorption.

Figure 2 illustrates the design details of the PPCW. The perforations comprise of a triangular array of air holes. The 1.732-mm-wide line defect is the center row that was intentionally devoid of holes. The hole radius a is 0.25 mm with a lattice constant of 4a. In this work, 10-, 20-, and 30-mm-long PPCW samples were studied, each in three thickness versions: 0.5, 1, and 2 mm. The terahertz transmission experiments were carried out similarly as in Ref. 12. Two Si hyperhemispherical lenses were placed at both ends of the PPCW to improve terahertz radiation coupling and collection. The terahertz transmission spectrum was taken using a Michelson interferometer. A Ge bolometer was used to detect the terahertz signal in either the spectroscopy or broadband terahertz power measurements.

Figure 3 shows the plot of the transmitted broadband terahertz radiation power as a function of propagation distance (i.e., the PPCW length) for different thickness values.

[a] Also at Department of Physics, De La Salle University, Taft Avenue, Manila 1004, Philippines.
[b] Permanent address: Department of Physics, De La Salle University, Taft Avenue, Manila 1004, Philippines.
[c] Author to whom correspondence should be addressed; electronic mail: murakami-hide@ile.osaka-u.ac.jp

0003-6951/2006/89(21)/211119/3/$23.00

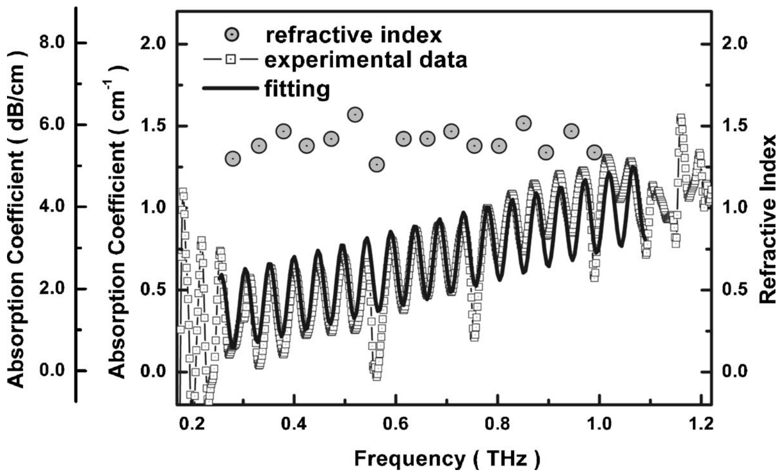

FIG. 1. Plot of the calculated absorption coeficient and refractive index of an unfabricated Cytop slab that were derived from terahertz transmission data. In the 0.2–1.1 THz region, the absorption coefficient does not exceed 1 cm^{-1} and the calculated refractive index is 1.4.

The continuous lines are fits to a linearized, semilog plot to estimate the propagation loss. The coupling loss between the PPCW and the Si lens was obtained by extrapolating the linear fits. On the other hand, the propagation loss in the PPCW-Si lens system was found from the slope of the best fit line according to propagation loss$=10(\log I_2/I_1)/\Delta L$, expressed in dB/mm. The inset summarizes the results and it can be observed that the broadband coupling loss increases with thickness and the propagation loss decreases. While having an acceptable broadband propagation loss value of ~0.36 dB/mm, the 0.5-mm-thick waveguide possesses the lowest coupling loss of 1.2 dB compared with the thicker samples.

The terahertz transmission spectra of 0.5-mm-thick, 1- and 3-cm-long PPCW's are shown in Fig. 4. The transmission peak occurs at ~0.45 THz for both samples. The transmittance for higher frequencies is damped for increased lengths. For longer propagation distances, the stronger absorption of Cytop at higher frequencies becomes more evident as in Fig. 1. Moreover, it can be surmised that the frequency-selective transmittance cannot be attributed to material absorption alone. In the absence of photonic band gap calculations, we tentatively attribute this apparent frequency selectivity to the presence of the microstructured air hole array. Note, however, that this transmission bandwidth is also limited by the frequency span of the terahertz radiation source. Finally, the spatial distribution of the propagating terahertz field was studied by FDTD calculations as shown by the dotted traces in the inset. The input was a 4.48-mm-diameter, TE-polarized Gaussian beam, with a frequency range of 0.3–1.1 THz centered at 0.45 THz. The beam diameter value was deduced from earlier knife-edge measurements of the incident terahertz radiation. This beam was made to propagate through a 0.5-mm-thick PPCW with real and imaginary indices of 1.4×10^{-3} and 1.85×10^{-3}, respectively. Although leaky modes were initially observed, the majority of the terahertz field has been confined to the line defect after a 30-mm-distance. Actual knife-edge measurements for the 10- and 30-mm-long PPCW's (continuous line traces) revealed that the width of the Gaussian profile is maintained even after 30 mm of propagation although the simulation seemed to underestimate the actual propagation loss.

In summary, we have demonstrated a terahertz PPCW fabricated from Cytop. Transmission power measurements in the 0.2–1.1 THz region revealed that a low coupling loss, with a comparably low propagation loss value, is achieved for a thin, sheetlike waveguide design. The PPCW transmission spectra exhibit frequency selectivity with a 0.15 THz wide, high-transmission band centered at 0.45 THz. Simulations and knife-edge data show evidence of single-mode propagation for a sufficiently long propagation distance at a center frequency of 0.45 THz. The high transparency of Cytop over a wide range of frequencies, i.e., from the ultraviolet

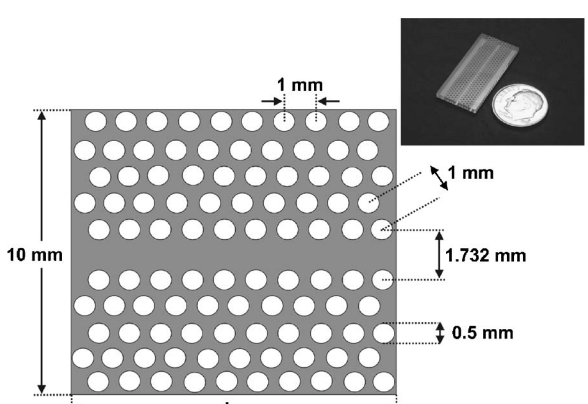

FIG. 2. Design details of the Cytop PPCW. Nine samples were studied with lengths of 10, 20, and 30 mm, each of which had three versions with thicknesses of 0.5, 1.0, and 2.0 mm. The inset shows the photograph of a 30-mm-long, 2-mm-thick PPCW.

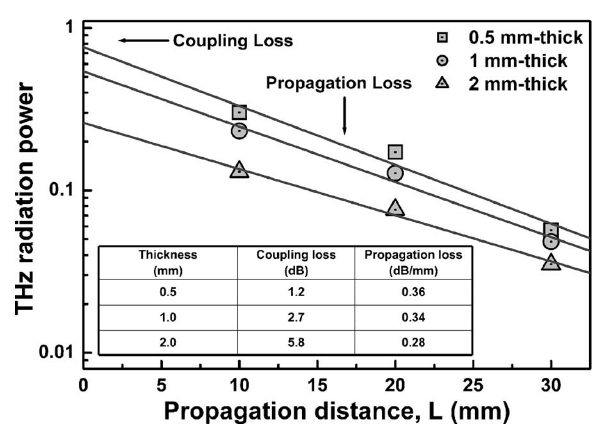

FIG. 3. Semilog plot of the transmitted broadband terahertz radiation power as a function of propagation distance. The linear fit to the data was used to estimate the broadband propagation loss and to deduce the coupling loss for the PPCW-Si lens system.

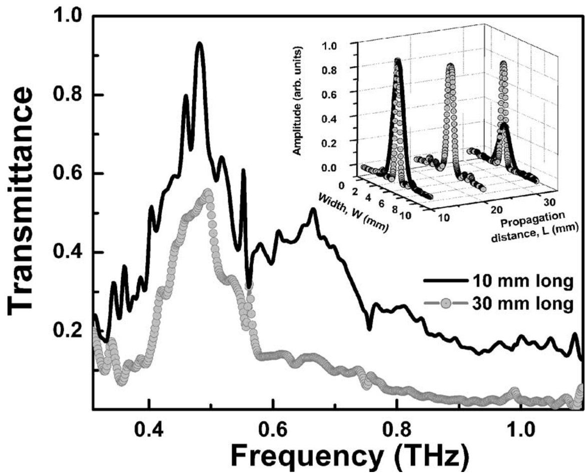

FIG. 4. Terahertz transmission spectra for the 10- and 30-mm-long, 0.5 -mm-thick PPCW samples. A high-transmission band centered at ~0.45 THz with a full width at half maximum of 0.15 THz is evident. The frequency-selective property of the PPCW is tentatively ascribed to the microstructured air holes. The inset shows the plot of the spatial distribution of the transmitted terahertz field derived from FDTD calculations and from actual knife-edge measurements. Single-mode waveguiding can be achieved after a 30-mm propagation distance.

to the terahertz region, indicates its potential use as an integral component in hybrid optics design.

Two of the authors (R.P. and R.Q.) are visiting associate professors in IMS.

[1] A. Quema, M. Goto, M. Sakai, G. Janairo, R. Quenzerfi, H. Takahashi, H. Murakami, S. Ono, and N. Sarukura, Appl. Phys. Lett. **85**, 3914 (2004).
[2] A. Quema, H. Takahashi, M. Sakai, M. Goto, S. Ono, N. Sarukura, R. Shioda, and N. Yamada, Jpn. J. Appl. Phys., Part 2 **42**, L932 (2003).
[3] K. Kawase, Y. Ogawa, Y. Watanabe, and H. Inoue, Opt. Express **11**, 2549 (2003).
[4] Y. Shen, P. Upadhya, E. Linfield, and A. Davies, Appl. Phys. Lett. **82**, 2350 (2003).
[5] M. Walter, B. Fischer, and P. Uhd Jepsen, Chem. Phys. **288**, 261 (2003).
[6] K. Yamamoto, M. Yamaguchi, M. Tani, M. Hangyo, S. Teramura, T. Isu, and N. Tomita, Appl. Phys. Lett. **85**, 5194 (2004).
[7] R. Mendis and D. Grischkowsky, J. Appl. Phys. **88**, 4449 (2000).
[8] K. Wang and D. Mittleman, J. Opt. Soc. Am. B **22**, 2001 (2005).
[9] H. Han, H. Park, M. Cho, and J. Kim, Appl. Phys. Lett. **80**, 2634 (2002).
[10] T. A. Birks, J. C. Knight, and P. St. J. Russell, Opt. Lett. **22**, 961 (1997).
[11] M. Goto, A. Quema, H. Takahashi, S. Ono, and N. Sarukura, Jpn. J. Appl. Phys., Part 2 **43**, L317 (2004).
[12] G. Diwa, A. Quema, E. Estacio, R. Pobre, H. Murakami, S. Ono, and N. Sarukura, Appl. Phys. Lett. **87**, 15114 (2005).
[13] *Photonic Crystals: Physics, Fabrication and Applications*, edited by K. Inoue and K. Ohtaka (Springer, Berlin, 2004), pp. 131–143.
[14] B. S. Song, S. Noda, T. Asano, and Y. Akahane, Nat. Mater. **4**, 207 (2005).
[15] M. Notomi, K. Yamada, A. Shinya, J. Takahashi, C. Takahashi, and I. Yokohama, Phys. Rev. Lett. **87**, 253902 (2001).
[16] *Photonic Crystals*, edited by K. Busch, S. Lolkes, R. B. Wehrspohn, and H. Föll (Wiley-VCH, Weinheim, 2004), pp. 289–305.
[17] Y.-G. Zhao, W.-K. Lu, Y. Ma, S.-S. Kim, S. Ho, and T. Marks, Appl. Phys. Lett. **77**, 2961 (2000).
[18] A. Bendada, Y. Simard, and M. Lamontagne, Polym. Eng. Sci. **44**, 955 (2004).
[19] H. Liu, G. Peng, and P. Chu, Opt. Commun. **204**, 151 (2002).
[20] M. Born and E. Wolf, *Principles of Optics* (Cambridge University Press, Cambridge, 1998), pp. 323–329.