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Photonic-crystal-fiber pigtail device integrated with lens-duct optics for terahertz radiation coupling

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An integrated optics called terahertz (THz) pigtail, which is comprised of an emitter, an optically transparent launching media, and a waveguide, is devised and fabricated. The InAs emitter under a 1 T magnetic field is coupled to the launching media using silicone grease, an index matching liquid. The launching media, a lens duct made from a polymer based on poly 4-methyl pentene-1 (commonly known as TPX), is designed based on the concept of guiding THz radiation into Teflon photonic crystal fiber (PCF) waveguide by means of total internal reflection. It is found that the constructed THz lens duct is able to channel and couple the THz radiation into the PCF waveguide with a loss of <1 dB. The results here show that the idea of using the THz pigtail can be a potential means of effectively directing THz radiation. © *2005 American Institute of Physics*.

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Since the successful generation and detection of terahertz (THz) radiation using photoconductive antenna,[1] several schemes such as semiconductor surfaces under magnetic field[2] and nonlinear optical process[3] have been reported as a result of the development of ultrafast optical pulses. Among these techniques, using a semiconductor wafer is widely accepted. In particular, InAs under magnetic field is considered to be the practical THz radiation source since it provides intense THz radiation and without the need for any chemical process or microfabrication technique in the sample preparation.[4] With these devices, THz spectroscopy and imaging can be applied to virtually all kinds of samples, including chemicals,[5–7] polymers,[8] and biomolecules.[9–11] At present, THz spectroscopic techniques uses free space propagation of this far-infrared electromagnetic wave and it is to some extent difficult to control and guide. This then led to the development of THz waveguides using various materials such as plastic ribbon,[12] sapphire fibers,[13] photonic crystal fiber (PCF),[14] and metal wires[15] in order to overcome this difficulty. Recently, we developed a PCF waveguide for THz radiation utilizing readily available and highly flexible material.[16] The material used was Teflon and the fibers were fused together without the need of furnace heating thereby making the Teflon PCF simple and easy to fabricate. Moreover, the Teflon PCF showed effective waveguiding of THz radiation and were found to have efficient polarization maintaining property. In a recent report, Nakajima *et al.* used an MgO hemispherical lens coupler to enhance THz radiation power from InAs surfaces excited by ultrashort laser pulses.[17] Such enhancement was explained by the increase of the transmission efficiency of the THz wave from InAs to free space. Although these waveguides and lens coupler have in part provided a solution to control and guide THz radiation, still the problem of effectively launching THz wave into the waveguide remains. In most cases, THz radiation is guided into the waveguide using a paraboloidal mirror coupled with a hemispherical lens at the entry point of the waveguide. Using these optical devices, one has to consider the coupling between air and hemispherical lens and between hemispherical lens and waveguide. More often than not, this trivial problem leads to an enormous amount of signal loss.

In this letter, a lens duct is designed using a transparent optical medium to facilitate the launching of THz radiation from an InAs emitter into Teflon PCF waveguides. The fabricated lens duct is found to channel and focus the THz radiation thereby ably transmitting the radiation from emitter to the core of the waveguide with a coupling loss of ~ 0.7 dB. By coupling an InAs emitter to the lens duct, which in turn is juxtapose to a Teflon PCF waveguide, a kind of integrated THz optics is constructed. Such concept is here put forth and the results prove that the assembled integrated optics can be a potential means of effectively channeling and directing THz radiation.

A lens duct is a simple optical device that has found application in the coupling of pump radiation from a semiconductor laser diode into a solid-state laser gain medium.[18] Basically, this device relies on the combined effects of lensing at the input surface, channeling by means of total internal reflection and focusing to its apex. With this in mind, a lens duct for THz radiation is devised and fabricated and the material used is a polymer based on poly 4-methyl pentene-1, commonly known as TPX. This material is chosen due to its high transparency in the visible, near-infrared and THz frequency regions. Reports have shown that the absorption coefficient of TPX at 800 nm and at 0.3 mm wavelengths is <2.17 dB/cm.[19,20] In constructing the lens duct, three important aspects are considered. These are, an input surface for the excitation laser, a coupling surface for the InAs emitter and a provision to guide and channel the THz radiation into the core of the PCF waveguide. The input surface with dimension 10 mm×5 mm is oriented in such a way that the incidence of the horizontally polarized excitation laser is at Brewster's angle (θ_1) with respect to the input-surface nor-

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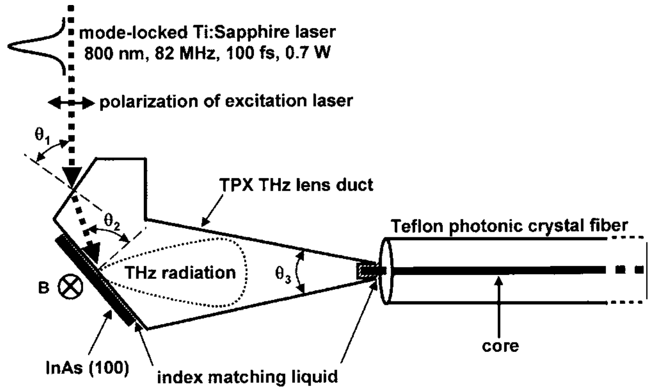

FIG. 1. Schematic diagram of the THz pigtail.

mal. By considering the indices of refraction of air and TPX, which was found to be highly transparent at 800 nm,[21] θ_1 for the air-TPX interface is determined to be 55°. As for the coupling surface, with dimension 5 mm × 9 mm, its orientation is adjusted so that the excitation laser is incident at Brewster's angle (θ_2) on the InAs emitter. Taking into account the indices of refraction of TPX (Ref. 21) and InAs (Ref. 22) at 800 nm, the obtained value of θ_2 at the TPX-InAs interface is 69°. The generated THz radiation from the InAs emitter is then contained in a provision for channeling and focusing the radiation into the waveguide. The containment provision is shaped into a conelike structure with its apex formed to accommodate the core of the PCF waveguide. This conical portion of the lens duct has a conic angle $\theta_3=8°$ and a conic length of 30 mm. Such specifications are devised to ensure that the reflection angle inside the lens duct is greater than the TPX-air critical angle of 46°. Although total internal reflection is maintained inside the conical portion of the lens duct, its outside surface is painted with metal paint so as to preserve its reflectivity and for easy handling. The emitter used here is an undoped slightly *n*-type InAs (100) wafer with carrier concentration of about $2.0 \times 10^{16}\ \mathrm{cm}^{-3}$. Using a very thin layer of silicone grease, the InAs wafer is attached at the coupling surface of the lens duct. To readily facilitate the entry of THz radiation into the waveguide, a small portion of the core was allowed to protrude. This overhang portion of the core was inserted into the apex of the lens duct. To aid the coupling of the lens duct and core, a small amount of silicone grease was applied on the outer surface of the protruding portion of the waveguide core. Silicone grease, with a refractive index of 2.7 in the THz region,[23] is used since it is a good low-loss refractive index matching liquid. The assembly comprised of emitter, channeling agent, and waveguide for THz radiation is here termed as THz pigtail which can be utilized for THz optics. Figure 1 shows a schematic diagram of the THz pigtail.

As for the experimental setup, a mode-locked Ti-sapphire laser system, which delivered 100 fs optical pulses at a center wavelength of 800 nm, was used as excitation source. The laser provided 0.7 W average-power at a repetition rate of 82 MHz. The horizontally polarized excitation laser was focused on the input surface of the lens duct by a cylindrical lens with 50-mm focal length at Brewster's angle incidence and the laser spot size on the input surface was about 1 mm × 2 mm. The magnetic field was provided by a 1 T permanent magnet and was applied parallel to the surface of the InAs emitter. The THz pigtails were constructed using the previously reported Teflon PCF waveguide.[16] A liquid-helium-cooled Ge bolometer and a polarizing Michelson interferometer were used to determine the THz radiation power and spectrum of the THz pigtail, respectively. For comparison, the THz radiation power and spectrum of bare InAs were also measured.

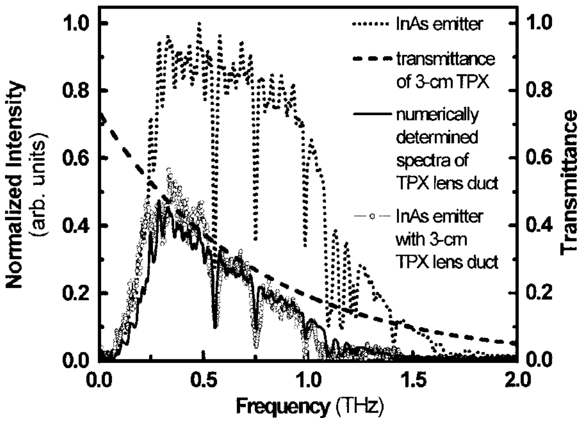

FIG. 2. The dotted line and open circles represent the experimentally obtained spectra (normalized values) of bare InAs emitter and the InAs emitter coupled to the TPX lens duct, respectively. The dashed line designates the transmittance of a 3-cm thick TPX slab while the solid line denotes the numerically calculated spectrum of the emitter-lens duct assembly.

Figure 2 shows the experimentally obtained spectra (normalized values) of the bare InAs emitter (dotted line) and the InAs emitter coupled to the TPX lens duct (open circles), both of which are under a 1 T magnetic field. The dashed line represents the transmittance (T) of a 3 cm thick TPX slab. Considering that absorption is the only source of attenuation, T is obtained using the equation[24]

$$T=\exp-(\alpha l), \tag{1}$$

where α is the absorption coefficient and l is the thickness of the specimen. Here it should be pointed that the experimentally obtained absorption coefficient of the TPX material used for the lens duct in the region $\omega=0.1-1.5$ THz is frequency dependent and its behavior is best described by the relation $\alpha=[0.43+1.95(\omega)]$ dB/cm. Using Lambert's Law, the spectrum of the TPX lens duct is obtained and is denoted by the solid line. It can be seen that the experimentally obtained and the numerically calculated spectra of the emitter-lens duct assembly are in reasonable agreement. At the apex of the lens duct, the THz radiation is focused and coupled to the Teflon PCF waveguide. Figure 3 presents the experimentally obtained spectra (normalized values) from the lens duct (open circles) and from the THz pigtail using a 5-cm waveguide (filled circles). Using Eq. (1), the transmittance of Teflon is determined and is designated here by the broken line. In this case, the absorption coefficient of Teflon is experimentally determined to be $\alpha=[0.09+0.91(\omega)]$ dB/cm. The solid line is the numerically determined spectrum of the THz pigtail with a 5-cm waveguide calculated using Lambert's Law and it is found that the experimental data is well-described by such line.

The THz radiation power as a function of length is shown in Fig. 4 The plot is divided into two regions; Region I (0–3 cm) and Region II (3–18 cm). The THz radiation power of the lens duct is in region I while that of the pigtail is in region II. The data points represent the calculated integrated intensities of the spectra obtained from

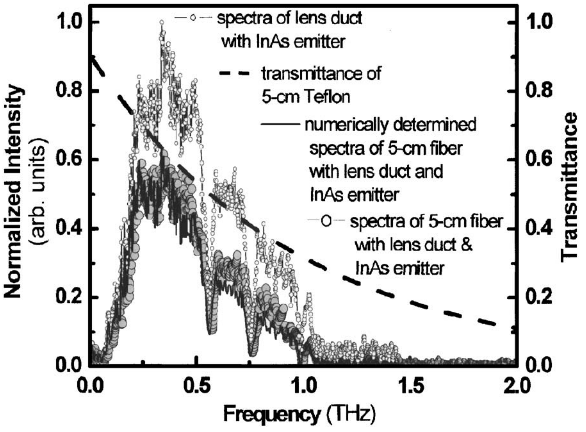

FIG. 3. The experimentally obtained spectra (normalized values) of the lens duct and the THz pigtail with a 5-cm waveguide are indicated by the open circles and the filled circles, respectively. The transmittance of Teflon is symbolized by the broken line while numerically determined spectrum of the THz pigtail with a 5-cm waveguide is signified by the solid line.

0.1 to 1.5 THz. These values are found to be comparable to those obtained via direct THz radiation power measurements using the bolometer. The solid line in region II is a linear fit of the data. It can be seen that at the 3-cm mark, the linear fit and the data point do not coincide. This connotes a certain loss due to coupling at the interface between lens duct and waveguide and is estimated to be ~0.7 dB. Although a rather large amount of THz radiation dissipated upon propagating through the lens duct, which can be attributted to large index mismatch between InAs (3.8) (Ref. 22) and TPX (1.45),[20] this assembly is able to minimize the insertion loss between lens duct and waveguide.

In summary, the design and fabrication of an integrated optics called THz pigtail is discussed. Using the THz lens duct, it is found that THz radiation can be effectively coupled into the Teflon PCF waveguide with minimum loss (<1 dB). Based on the results obtained here, the THz pigtail can be a means of guiding THz radiation without the need of using expensive optical devices. To lessen the dissipation of THz radiation, improvement in the design and survey of other materials with higher refractive index to reduce the index mismatch are currently being under taken.

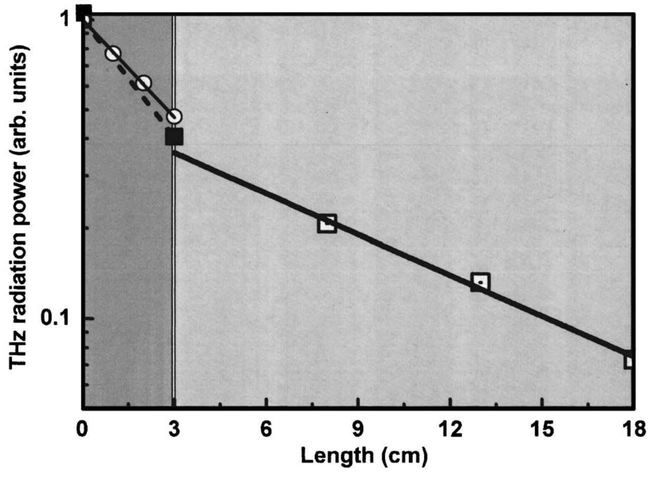

FIG. 4. THz radiation power as a function of length. This plot is divided into two regions; region I (0–3 cm) and region II (3–18 cm). Region I is that of the lens duct while region II is that of the pigtail. The solid square in region I at the 3-cm mark represents the THz radiation power from the lens duct itself as measured directly by the bolometer. In this region also, the open circles represents the calculated values of the THz radiation power from TPX with thicknesses of 1 cm, 2 cm, and 3 cm, which are obtained based on the absorption coefficient $\alpha = [0.43 + 1.95(\omega)]$ dB/cm of TPX. The loss due to coupling based on the calculated THz power from the TPX of various thicknesses is estimated to be ~1.4 dB.

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[1] D. Auston, K. Cheung, and P. Smith, Appl. Phys. Lett. **45**, 284 (1984).
[2] X. C. Zhang, B. Hu, J. Darrow, and D. Auston, Appl. Phys. Lett. **56**, 1011 (1990).
[3] K. Kawase, M. Sato, and H. Itoh, Appl. Phys. Lett. **68**, 2483 (1996).
[4] N. Sarukura, H. Ohtake, S. Izumida, and Z. Liu, J. Appl. Phys. **84**, 654 (1998).
[5] K. Kawase, Y. Ogawa, Y. Watanabe, and H. Inoue, Opt. Express **11**, 2549 (2003).
[6] A. Quema, H. Takahashi, M. Sakai, M. Goto, S. Ono, N. Sarukura, R. Shioda, and N. Yamada, Jpn. J. Appl. Phys., Part 1 **42**, L932 (2003).
[7] A. Quema, M. Goto, M. Sakai, G. Janairo, R. El Ouenzerfi, H. Takahashi, H. Murakami, S. Ono, and N. Sarukura, Appl. Phys. Lett. **85**, 3914 (2004).
[8] K. Yamamoto, M. Yamaguchi, M. Tani, M. Hangyo, S. Teramura, T. Isu, and N. Tomita, Appl. Phys. Lett. **85**, 5194 (2004).
[9] Y. Shen, P. Upadhya, E. Linfield, and A. Davies, Appl. Phys. Lett. **82**, 2350 (2003).
[10] M. Walter, B. Fischer, and P. Uhd Jepsen, Chem. Phys. **288**, 261 (2003).
[11] M. Johnston, L. Herz, A. Khan, A. Kohler, A. Davies, and E. Linfield, Chem. Phys. **377**, 256 (2003).
[12] R. Mendis and D. Grischkowsky, J. Appl. Phys. **88**, 4449 (2000).
[13] S. Jamison, R. McGowan, and D. Grischkowsky, Appl. Phys. Lett. **76**, 1987 (2000).
[14] H. Han, H. Park, M. Cho, and J. Kim, Appl. Phys. Lett. **80**, 2634 (2002).
[15] K. Wang and D. Mittleman, Nature (London) **432**, 376 (2004).
[16] M. Goto, A. Quema, H. Takahashi, S. Ono, and N. Sarukura, Jpn. J. Appl. Phys., Part 1 **43**, L317 (2004).
[17] M. Nakajima, K. Uchida, M. Tani, and M. Hangyo, Appl. Phys. Lett. **85**, 191 (2004).
[18] R. Beach, Appl. Opt. **35**, 2005 (1996).
[19] G. Chantry, J. Fleming, and P. Smith, Chem. Phys. Lett. **10**, 473 (1971).
[20] J. Birch, J. Dromey, and J. Lesurf, Infrared Phys. **21**, 225 (1981).
[21] A. Quema, M. Goto, H. Takahashi, S. Ono, N. Sarukura, R. Shioda, and N. Yamada, in *The Japan Society of Applied Physics 64th Autumn Meeting Extended Abstracts*, Fukuoka University, Fukuoka, Japan, 2003, Session No. 2a-ZD, p. 84.
[22] E. Palik and R. Holm, *Handbook of Optical Constants of Solids*, edited by E. Palik (Academic, New York, 1985), pp. 479–489.
[23] Spectroscopy of freestanding silicone grease was conducted and its refractive index in the THz region was determined using the concept of the etalon effect as discussed in P. Milonni and J. Eberly, *Lasers* (Wiley, New York, 1988), pp. 356–364.
[24] J. Fleming and G. Chantry, IEEE Trans. Instrum. Meas. **IM-23**, 473 (1974).