Carbon nanotube fiber terahertz polarizer

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Conventional, commercially available terahertz (THz) polarizers are made of uniformly and precisely spaced metallic wires. They are fragile and expensive, with performance characteristics highly reliant on wire diameters and spacings. Here, we report a simple and highly error-tolerant method for fabricating a freestanding THz polarizer with nearly ideal performance, reliant on the intrinsically one-dimensional character of conduction electrons in well-aligned carbon nanotubes (CNTs). The polarizer was constructed on a mechanical frame over which we manually wound acid-doped CNT fibers with ultrahigh electrical conductivity. We demonstrated that the polarizer has an extinction ratio of $\sim -30\,\mathrm{dB}$ with a low insertion loss ($<0.5\,\mathrm{dB}$) throughout a frequency range of 0.2-1.1 THz. In addition, we used a THz ellipsometer to measure the Müller matrix of the CNT-fiber polarizer and found comparable attenuation to a commercial metallic wire-grid polarizer. Furthermore, based on the classical theory of light transmission through an array of metallic wires we demonstrated the most striking difference between the CNT-fiber and metallic wire-grid polarizers: the latter fails to work in the zero-spacing limit, where it acts as a simple mirror, while the former continues to work as an excellent polarizer even in that limit due to the one-dimensional conductivity of individual CNTs.

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Unique properties of electromagnetic waves in the terahertz (THz) frequency range are expected to lead to new applications in diverse areas,[1–3] including wireless communications, chemical detection, and medical imaging. Recent advances in the generation, manipulation, and detection of THz waves have brought these anticipated applications closer to realization. However, THz technologies are still immature as compared to those available in different spectral ranges, and more sophisticated schemes and architectures as well as novel materials are being sought for improving operation performance and for making devices more compact and easier to fabricate.

Polarizers are essential components in THz imaging, communications, and spectroscopy. THz polarizers made of various materials have been reported,[4–9] but most commercially available THz polarizers are metallic wire-grid polarizers, whose extinction ratios and insertion losses sensitively depend on the wire widths and spacings. Carbon nanotubes (CNTs) are emerging optoelectronic materials[10] that have unique ultrabroadband anisotropic optical absorption properties. In particular, they exhibit essentially perfect polarization anisotropy in the THz frequency range,[7–9,11] ideally suited for polarizer applications. Multifunctional architectures of highly aligned CNTs, such as fibers with ultrahigh conductivity[12] and current-carrying capacity[13] synthesized by wet processing methods, are now available and promising as new polarizer wires.

Here, we describe a simple and robust method for fabricating a THz polarizer with nearly ideal performance, made of a hand-wound array of conductive fibers of well-aligned CNTs. The polarizer exhibited an extinction ratio (ER) of ~ -30 dB in a frequency range of 0.2-1.1 THz. We measured spectra of Müller matrix elements for the polarizer using a frequency-domain THz ellipsometer, which showed that this polarizer has properties comparable to a commercial wire-grid polarizer. Being freestanding, this polarizer has a small insertion loss (< 0.5 dB), as compared to previously reported THz polarizers based on thin films of aligned CNTs on substrates[7,9] or on aligned multiwall CNT areogel sheets.[8] In addition, the current method does not involve any complicated transfer and/or stacking processes that are time consuming and require careful alignment.

Figure 1 shows images of our THz polarizer. The polarizer was fabricated by manually winding a continuous, uniform, and ultralong ($>$20 m) CNT fiber[12] with an average diameter of 12.6 μm over a copper frame (Fig. 1a) to form two parallel layers with a suspended area of 5×10 mm^2 (Fig. 1b) and a layer spacing of 1 mm. Each layer consisted of a dense array of

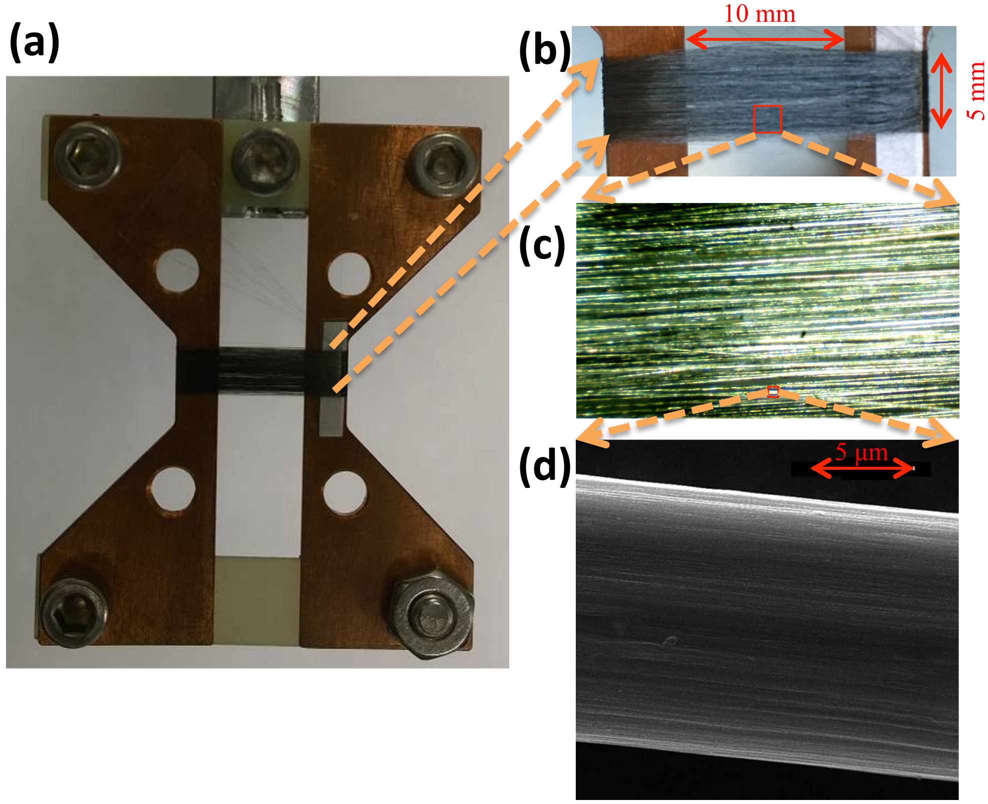

FIG. 1. Optical and scanning electron microscopy images of CNT-fiber THz polarizer. (a) Copper frame over which the fiber was wound. (b) The suspended area of the polarizer consisting of two parallel layers, each containing ∼400 parallel CNT fibers. (c) Magnified view of the suspended area, showing densely packed fibers. (d) High magnification scanning electron microscopy image of a CNT fiber, showing excellent alignment of nanotubes.

∼400 parallel CNT fibers; i.e., each layer was designed to be a monolayer of parallel fibers *with zero average spacing*. Because the fiber was manually wound, it was impossible to keep the structure perfect (Fig. 1c); however, the structural imperfections did not negatively impact the performance of the fabricated polarizer, as detailed below. The CNT fibers had high electrical conductivity (∼0.1 that of copper) because they consist of highly aligned (Fig. 1d), densely-packed, low-defect acid-doped CNTs.[12,14]

We performed THz transmission measurements through the suspended area of the polarizer with a normal incident THz beam.[14] Figure 2a shows time-domain waveforms for THz pulses transmitted through the polarizer for parallel, perpendicular, and 45° polarizations as well as for dry air (reference). For the perpendicular polarization, the transmitted THz

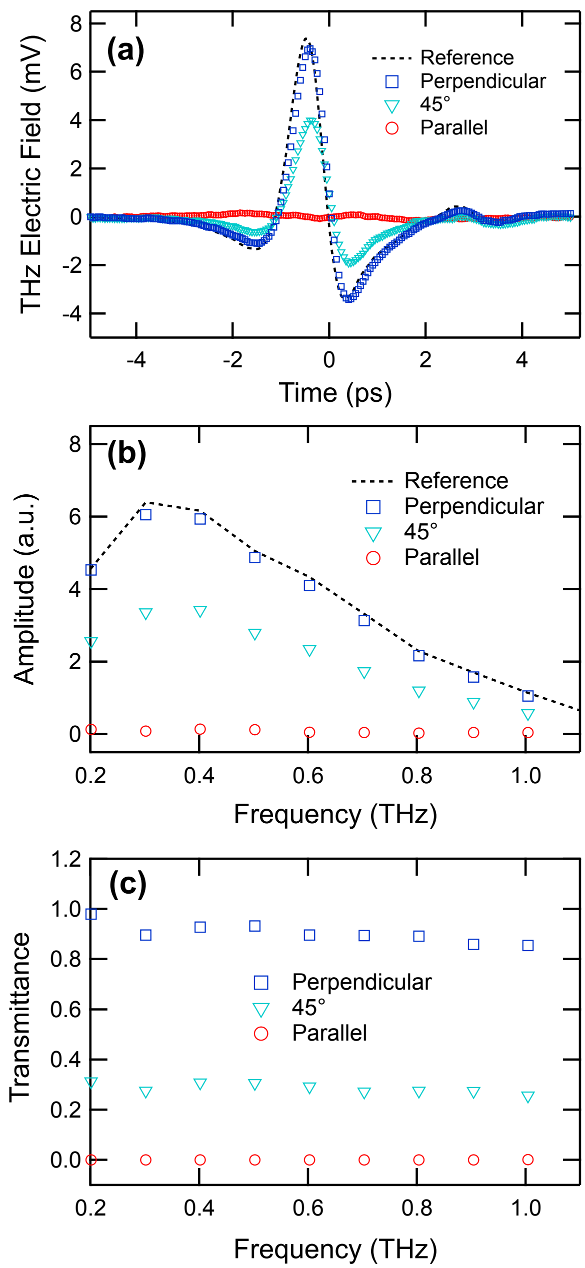

FIG. 2. (a) Time-domain waveforms for THz radiation transmitted through the CNT-fiber polarizer for parallel polarization (red circles), 45° polarization (green triangles), and perpendicular polarization (blue squares), together with the waveform transmitted through dry air (black dashes). (b) Frequency-domain signal spectra for the dry-air reference (black dashes), parallel polarization (red circles), 45° polarization (green triangles), and perpendicular polarization (blue squares). (c) Transmittance spectra for parallel polarization (red circles), 45° polarization (green triangles), and perpendicular polarization (blue squares).

signal is close to that for the reference, indicating that there is little attenuation. On the other hand, transmission is completely suppressed for the case of parallel polarization. The same trends can be seen in the frequency domain after Fourier transformation, as shown in the amplitude spectra (Fig. 2b) and transmittance spectra (Fig. 2c).

Figure 3a shows the attenuation spectra of the polarizer for parallel polarization (red circles) and perpendicular polarization (blue squares). The attenuation is defined as $A = -\log_{10} T$, where T is the transmittance. Figure 3b shows the degree of polarization, $DOP = \frac{T_{\parallel}-T_{\perp}}{T_{\parallel}+T_{\perp}}$, as well as the extinction ratio, $ER = \frac{T_{\parallel}}{T_{\perp}}$, where $T_{\parallel}$ ($T_{\perp}$) is the transmittance for the parallel (perpendicular) polarization. The DOP value is almost 100% throughout the entire frequency range. The ER value is less than 10^{-3} (or -30 dB), with the minimum and average values -37.1 dB and -33.3 dB, respectively. The average value for $T_{\perp}$ in this spectral range is 90% (Fig. 2c), so the average insertion loss ($-\log_{10} T_{\perp}$) is 0.45 dB, a value two or six times smaller than that reported by Ren *et al.*[9] or Kyoung *et al.*[8], respectively.

For a more complete characterization of the polarizer, we further performed continuous-wave transmission measurements using a solid-state frequency-domain THz source and super-heterodyne detector system based on the frequency multiplication of a 13-20 GHz microwave local oscillator.[15] Polarimetric transmission was measured in a frequency range of 0.2-0.8 THz, and the ER was computed. As can be seen in Fig. 3c, this experiment also showed ER values of ~ -30 dB for the CNT fiber polarizer (red crosses). Also shown in Fig. 3c are data taken for a reference commercial free-standing metallic wire-grid polarizer (black solid circles). The expected -35 dB ER of the reference polarizer was obtained at 0.8 THz, thereby validating the calibration of the ellipsometer and demonstrating that the CNT polarizer has comparable performance to the commercial polarizer.

Furthermore, we used a third THz measurement system, a frequency-domain THz ellipsometer,[16] which allowed us to measure the Müller matrix[17] of the CNT-fiber polarizer. The Müller matrix of an optical sample is a real-valued 4×4 matrix that completely describes the polarization properties of a material by the way it transforms the four-element polarimetric Stokes vector of the incident beam to the Stokes vector after its interaction

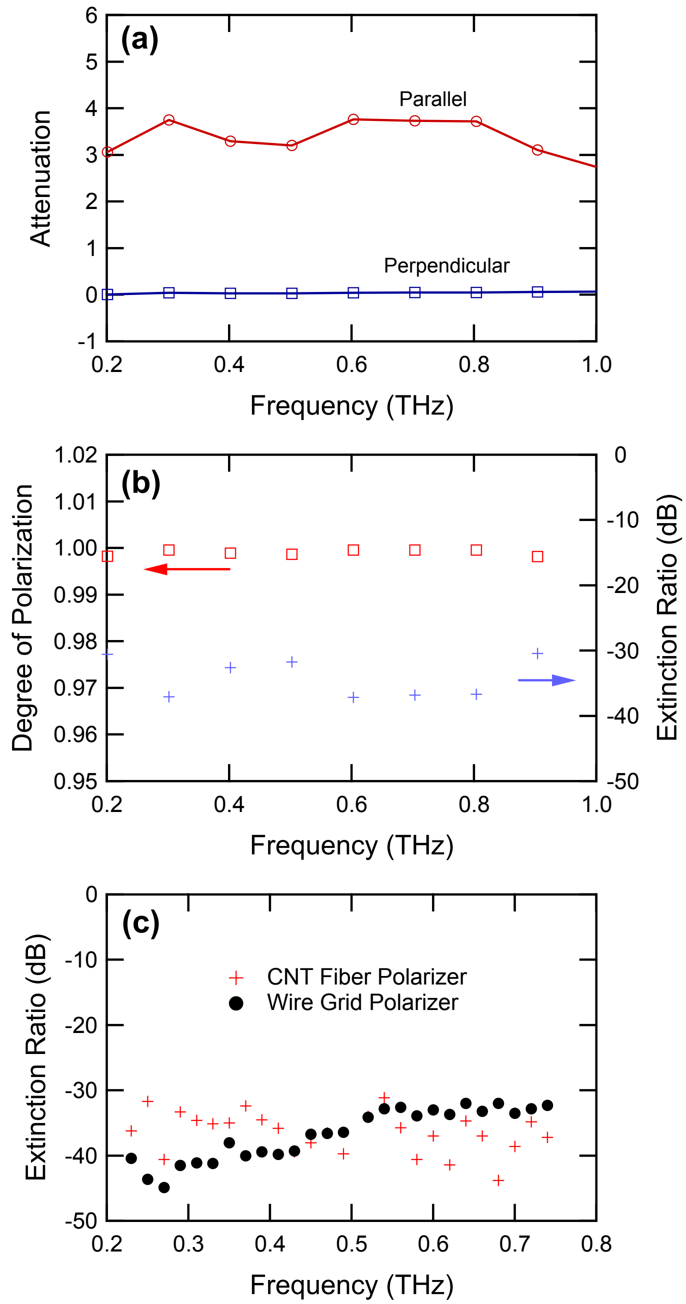

FIG. 3. (a) Attenuation spectra of the CNT-fiber polarizer for parallel polarization (red circles) and for perpendicular polarization (blue squares) in a frequency range of 0.2-1.1 THz. (b) Degree of polarization and extinction ratio of the polarizer in the 0.2-1.1 THz range. The degree of polarization is basically 100%, and the average extinction ratio in this frequency range is -33.5 dB. (c) Extinction ratio of the CNT-fiber polarizer (red crosses) and a commercial metallic wire-grid polarizer (black solid circles) in in a frequency range of 0.2-0.8 THz, taken with a frequency-domain THz ellipsometer.

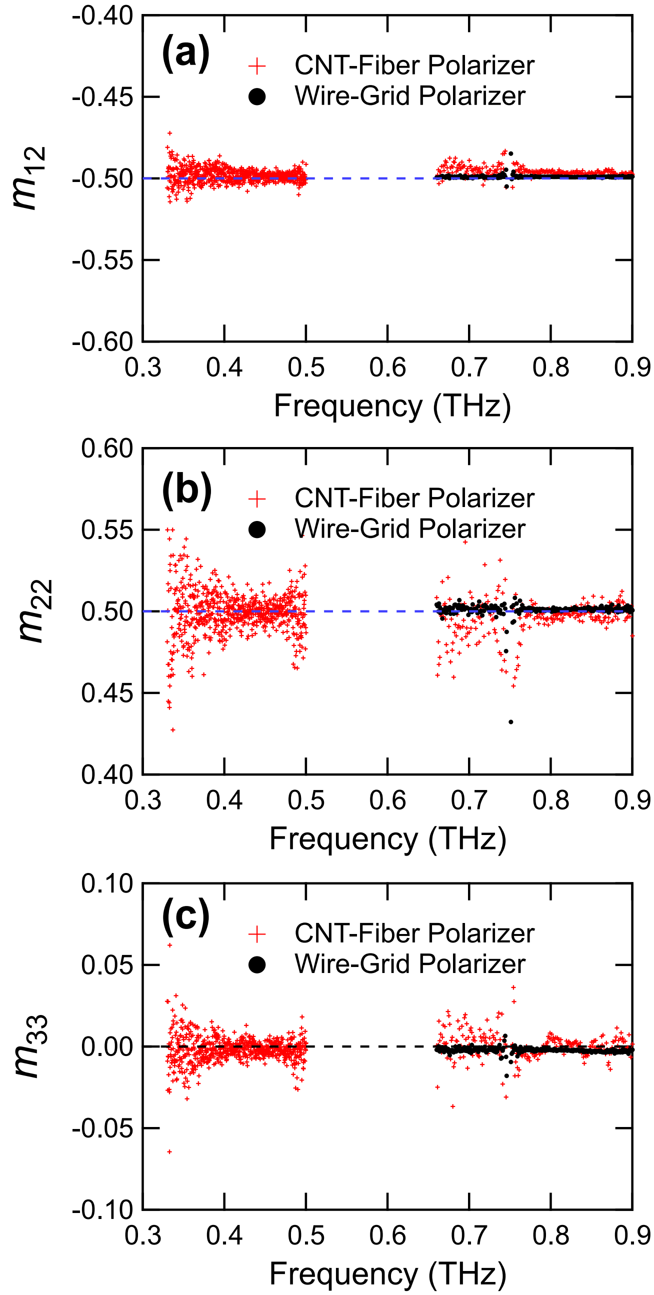

FIG. 4. Significant Müller matrix elements, (a) m_{12}, (b) m_{22}, and (c) m_{33}, measured for the CNT-fiber polarizer (red crosses) and a commercial metallic wire-grid polarizer (black solid circles) as a function of frequency using a frequency-domain THz ellipsometer.

with the material.[14] Figure 4 shows the significant elements of the Müller matrix given by[17]

$$m_{12} = \frac{T_\parallel^2 - T_\perp^2}{2} \quad (1)$$

$$m_{22} = \frac{T_\parallel^2 + T_\perp^2}{2} \quad (2)$$

$$m_{33} = T_\parallel T_\perp \quad (3)$$

where m_{ij} is the ij-th element of the Müller matrix, i (j) being the row (column) number. For an ideal polarizer, $T_\parallel = 0$ and $T_\perp = 1$, and therefore, $m_{12} = -0.5$, $m_{22} = 0.5$, and $m_{33} = 0$. As shown in Fig. 4, the CNT polarizer exhibits these ideal values.

Finally, we emphasize that the CNT fibers in our polarizer are disordered with irregularities and that the average spacing between adjacent fibers is zero. These facts are striking in light of the nearly ideal polarizer characteristics we demonstrated above. In the case of a metallic wire-grid polarizer, such irregularities and zero spacing would be detrimental to its performance. To further demonstrate this point (particularly, the zero-spacing limit), we performed simulations of transmission of polarized light through an array of metallic wires with varying spacings.[14] Figure 5a shows the calculated transmittance values, $T_\parallel$ and $T_\perp$, at 0.5, 1, and 2 THz as a function of spacing. At all frequencies, the value of $T_\perp$ rapidly decreases to zero as the spacing approaches zero, while $T_\parallel \approx 0$ for all spacings. The corresponding insertion loss, $-\log_{10} T_\perp$, is plotted in Fig. 5b, which increases with decreasing spacing and becomes infinite in the zero spacing limit. These results highlight the uniqueness of the CNT-fiber polarizer, as compared to conventional wire-grid polarizers: the latter's working principle is based on the structural anisotropy of wires, whereas the former is reliant on the intrinsically one-dimensional character of conduction electrons in CNTs. For THz and infrared measurements of optical conductivity of CNTs, see, e.g., Ref.[18].

In conclusion, we developed a very simple method for fabricating an ideal THz polarizer based on fibers of highly-conductive and well-aligned carbon nanotubes. Its performance was fully characterized through measurement of salient Müller matrix elements and shown to be comparable to commercial metallic wire-grid polarizers. Its performance characteristics are tolerant to structure imperfections introduced in the hand-winding process, making this a robust method for producing high-quality THz polarizers in a cost-effective manner. The intrinsic anisotropic optical properties of aligned CNTs are the reason for this ideal performance. This CNT-fiber polarizer will have important impact in emerging THz tech-

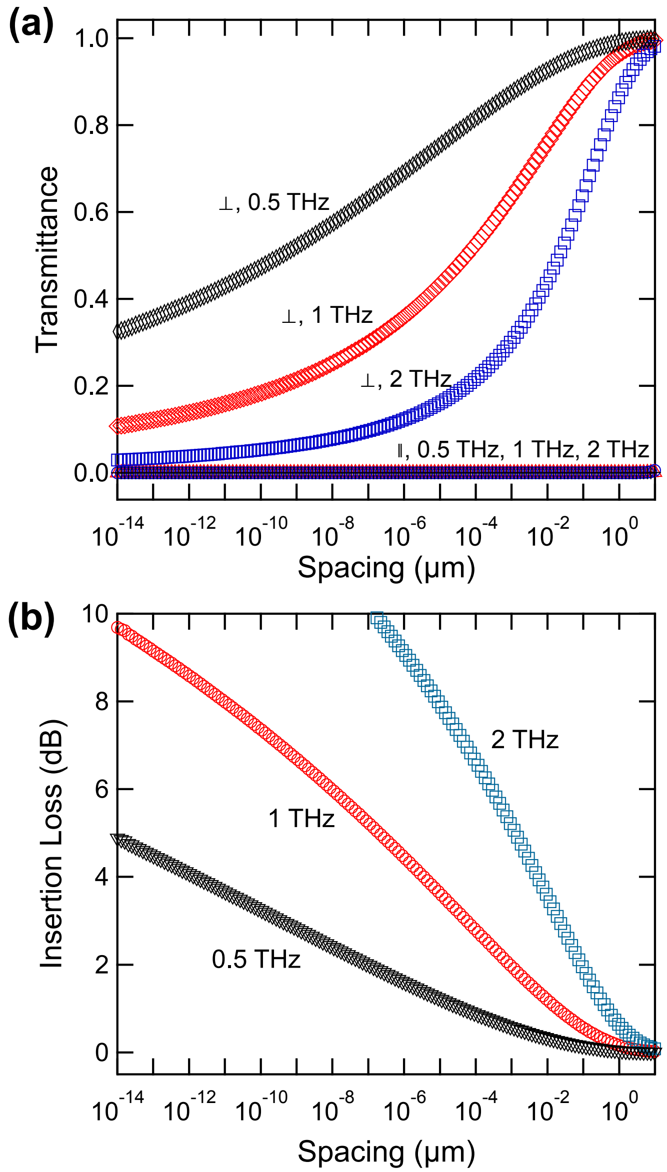

FIG. 5. (a) Calculated transmittance for polarized light with frequencies of 0.5, 1, and 2 THz through a periodic array of 12.6-μm-diameter metallic wires with infinite conductivity as a function of wire spacing. (b) Calculated insertion loss (in dB) as a function of wire spacing. In the limit where adjacent wires touch each other, the insertion loss becomes infinitely high, turning the polarizer into a mirror.

nological applications such as wireless communications, imaging, chemical detection, and astrophysics.

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