Subwavelength plastic wire terahertz time-domain spectroscopy

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This work demonstrates the feasibility of a terahertz time-domain spectrometer based on a subwavelength-diameter plastic wire (SPW) for sensing applications. The dispersion property of the SPW is experimentally and theoretically studied. The SPW exhibits a low and controllable waveguide dispersion, which can be engineered by changing the core diameter, the core index, and the cladding index of the wire. Two white powders, tryptophan and polyethylene, deposited on the bottom of the wire can be successfully distinguished based on the waveguide dispersion of SPW. The SPW would be a promising candidate for combination with biochips for sensing minute molecules. © *2010 American Institute of Physics*. [doi:10.1063/1.3279154]

Various terahertz (THz) waveguides have been developed for efficient transmission of THz waves and successfully applied in numerous fields, such as spectroscopy,[1,2] sensing,[3,4] and near field imaging.[5] However, the proposed waveguides either have low coupling efficiency or high propagation loss and high dispersion, subsequently shortening the THz propagation distance and reducing the capability for detecting strongly absorbed materials. Among the merits of the simple THz subwavelength plastic wire (THz-SPW) include single mode sustentation, a high coupling efficiency, a low propagation loss[6] (on the order of 0.01 cm^{-1}), as well as theoretically low dispersion in the transmission band.[7] THz-SPW has been successfully adopted in directional couplers,[8] endoscopic imaging,[9] and microscopy.[10] To our knowledge, the dispersion feature of THz-SPW has not been experimentally measured or analyzed. Because the core has a low index of refraction, the extended electric field of an evanescent wave on a THz-SPW[6] is enhanced much more than an optical nanowire,[11] causing THz waves on the SPW to interfere easily with the surrounding medium, supporting remote sensing and the detection of molecules in biochips or microfluidic channels. Dispersion shifts in optical nanowires with thin dielectric coatings have been theoretically demonstrated,[12] revealing that the waveguide dispersion of a weakly guiding fiber is very sensitive to the refraction index of cladding. In this letter, the dispersion property of THz-SPW is experimentally and theoretically investigated and the feasibility of integrating SPW with a THz time-domain spectroscopy system for molecular sensing applications is demonstrated. Transmission spectroscopy indicated that the SPW exhibits low and controllable waveguide dispersions, which can be tuned by changing the core diameter, the core index, and the cladding index of the wire. This fact is consistent with theoretical predictions. By measuring the variation in the waveguide dispersion of an SPW with various molecules deposited in the wire cladding region, the demonstrated SPW-based THz time-domain spectrometer can identify two similar white powders. These results imply that SPWs can potentially be applied in future THz communication and the sensing of minute molecules.

In this study, we used two SPWs, whose cores were made of polyethylene (PE) and polystyrene (PS) with refractive indices[13] of 1.5 and 1.59, respectively, and an air cladding, were adopted. Dispersion in a THz-SPW is dominated by material dispersion and waveguide dispersion. The modal dispersion can be neglected because SPW is associated with the single-mode wave-guiding. Since the refractive indices of both PE and PS are almost constant at THz frequencies,[14] the material dispersion in SPW can also be neglected. The main contribution of dispersion in a THz-SPW is waveguide dispersion. In this experiment, the waveguide dispersion in an SPW was measured using a transmission-type THz time-domain spectrometer, which is schematically depicted in Fig. 1, and consists of a pair of low-temperature (LT)-grown-GaAs-based photoconductive antennas[15] as the THz emitter and receiver. The THz emitter was optically excited using a mode-locked Ti:sapphire laser with a central wavelength of 800 nm, a pulse width of 100 fs, and a repetition rate of 82 MHz. The generated THz pulse was collected and directly coupled into the SPW using a pair of parabolic mirrors. By means of direct optical coupling, a 300 μm diameter PE wire delivers over 60% of the THz energy (including the

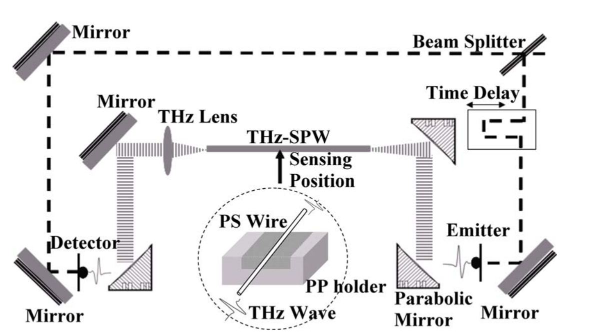

FIG. 1. (Color online) THz time-domain spectrometer based on subwavelength-diameter plastic wire (SPW). Inset shows THz pulse on an SPW propagated through powder materials in the PP channel.

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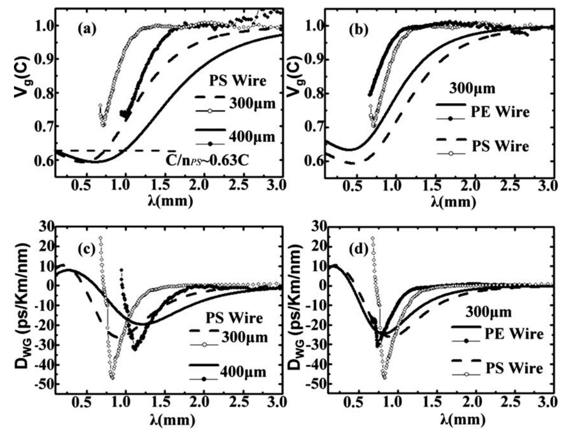

FIG. 2. (a) Measured and theoretical group velocities, V_g, of the THz pulse on the PS wire with various core diameters. At short wavelengths, V_g approaches 0.63C for a PS wire. (b) Measured and theoretical group velocities of THz pulse on 300 μm thick PS and PE wires. (c) Measured and theoretical waveguide dispersions, D_{wg}, of THz pulse on PS wire with various core diameters. (d) Measured and theoretical waveguide dispersions of THz pulse on 300 μm thick PS and PE wires.

coupling loss and the propagation loss) along a 30 cm long wire, with a THz transmission spectrum centered at the wavelength of 1 mm ($\lambda = 1$ mm). To measure the THz waveguide dispersion and propagation loss in an SPW, a standard cutback method was employed with a fixed input coupling efficiency. In the sensing experiment, a sample holder that was made of polypropylene (PP) on which was a 6 mm wide and 0.5 mm deep channel, filled with the test sample, was placed on the bottom of a THz-SPW oriented parallel to the length direction of a PP holder, as presented in the inset in Fig. 1. Two PP holders with lengths of 5 and 8 mm were adopted to determine the phase difference between the THz pulses transmitted through the sample for dispersion calculation. The SPW was slightly in contact with the sample to ensure overlap between the THz evanescent wave and the sample. As demonstrated, two white powders, with similar appearances, tryptophan (T8941 L-tryptophan, Sigma-Aldrich Inc.) and PE (434272 Polyethylene, Sigma-Aldrich Inc.), were employed as test samples. THz waves on the SPW, transmitted through the powder sample and propagated to the output end of the plastic wire, were collected and focused onto a photoconductive switch receiver using a PE lens (f=6 cm) and a parabolic mirror. From the optical time-delay between the THz pump and the probe beams, we can obtain the time-domain waveform of the THz pulse propagated through an SPW, and information on both the phase and amplitude of the transmitted THz pulse could also be thus extracted. Typically, the signal-to-noise-ratio of an SPW-based THz time-domain spectrometer exceeds 10^5.

Maxwell's equations are used to determine the theoretical group velocity V_g and the waveguide dispersion D_{wg} of THz-SPW. In Figs. 2(a) and 2(b), the theoretical group velocities, V_g, (solid and dashed lines) of PS and PE wires approach to the speed of light (C) in a vacuum at long wavelengths since a large fraction of the THz waves are propagated in air. As the wavelength becomes shorter, more THz energy enters the wire core and thus declines V_g to a value C/n_{core}, which is the group velocity of THz waves in the bulk material. At a particular wavelength, a thinner SPW has a larger V_g because the THz energy is less confined, as displayed in Fig. 2(a). In contrast, the V_g of PS wire is less than that of PE wire, as shown in Fig. 2(b) since the higher core index of the wire causes the THz wave to be strongly confined within the wire core. The theoretical waveguide dispersion, D_{wg}, (solid and dashed lines) of SPW reaches a minimum value at the curve in Figs. 2(c) and 2(d), and slowly approaches zero as the wavelength increases. For a weakly guiding wire waveguide, a smaller diameter or a lower core index causes the deep of the theoretical D_{wg} curve to shift to the short wavelengths, as shown in both Figs. 2(c) and 2(d). The minimum of D_{wg} is more negative in a thinner SPW (PS wire with a 300 μm diameter core), as shown in Fig. 2(c), and becomes less negative as the core index decreases (PE wire), as plotted in Fig. 2(d).

By comparing the two measured THz waveforms that pass through SPWs of different lengths, we can obtain the THz effective index n_{eff} of SPW by the relation, $n_{eff} = 1 + \lambda\varphi/(2\pi L)$, where L and φ are the length and phase differences between two SPWs, and λ is the THz wavelength. The measured group velocity,[11] $V_g = -2\pi C(d\beta/d\lambda)/(\lambda^2)$, and the measured waveguide dispersion,[11] $D_{wg} = d(1/V_g)/d\lambda$, can thus be calculated in an SPW, where C is speed of light in a vacuum and β is the effective propagation constant given by $\beta = 2\pi n_{eff}/\lambda$. The waveguide dispersion D_{wg}, group velocity V_g, propagation constant β, and effective index of SPW n_{eff} are all functions of THz wavelength. In Figs. 2(a) and 2(b), the measured wavelength-dependent V_g of THz-SPWs follows a trend that is consistent with theory. As described above, at a particular wavelength, the measured group velocities in a weakly guiding wire waveguide, the 300 μm thick PS wire shown in Fig. 2(a) and the 300 μm thick PE wire shown in Fig. 2(b), exceed that of 400 μm thick PS and 300 μm thick PS wires, respectively. The measured wavelength-dependent D_{wg} of the THz-SPWs exhibits a trend that is consistent with the theoretical result, as shown in Figs. 2(c) and 2(d), indicating the D_{wg} can be positive, zero, or negative at a particular wavelength as determined by the chosen wire diameter and core index. Manipulating waveguide dispersion to control the properties of THz wave propagation is important in many fields, including communication and nonlinear optics.

Given a geometry in which one portion of the THz evanescent field[6] interacts with the sample and the other portion leaks into the air, as shown in the inset in Fig. 1, the THz evanescent wave resembles to be immersed in a new cladding with an effective refractive index that differs from that of air. The effective refractive index of the new cladding is determined by both the air and the sample, and is given by $n_{clad} = n_{air}\sigma + n_{sample}(1-\sigma)$, where σ is the power percentage of the evanescent wave in the air. The index of air, n_{air}, equals 1 and n_{sample} is the refractive index of the sample in the THz frequency range. In this experiment, the average THz refractive index of tryptophan and PE powder are 1.17 and 1.50, respectively.[13,16] From the geometric parameters of the wire and the PP channel that contained powders, we can calculate that 60% of the THz energy was in the air while 40% was in the powder. From the above relation, the effective cladding indexes for PE and tryptophan powders are calculated as 1.2 and 1.068, respectively. Different cladding indices of the PS wire would differently affect the propagation characteristics of the THz evanescent wave, including effective index of refraction and propagation constant, thereby modifying the waveguide dispersion curve. Figure

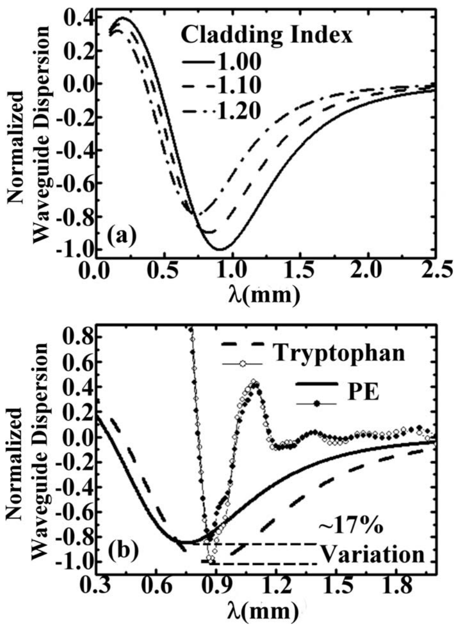

FIG. 3. (a) Theoretical normalized waveguide dispersions of 300 μm thick PS wire with various cladding indices. (b) Measured (solid and dashed lines) and simulated (solid and open circles) waveguide dispersions of PS wire with PE and tryptophan powders in wire cladding regions.

3(a) plots the theoretically normalized waveguide dispersion of THz-SPWs with different cladding indices, and indicates the deep of the waveguide dispersion curve shifts toward the short wavelength range and becomes less negative when an SPW turns into a weakly guiding waveguide with a small index difference between the core and the cladding. The trend plotted in Fig. 3(a) is similar to that in Fig. 2(d), suggesting that the waveguide dispersion of SPW can also be manipulated by changing the cladding index of the wire. Figure 3(b) plots the normalized measured wavelength-dependent waveguide dispersion curves of the THz pulse transmitted through PE and tryptophan powder, indicating that SPW immersed in PE powder has a smaller negative D_{wg} at the deep of curve, because the refractive index of the PE powder is higher than that of tryptophan powder, so the former less strongly confines THz waves that pass through it, the result is consistent with the simulated results, plotted in Fig. 3(a). Notably, a 17% variation in the measured waveguide dispersions between PE and tryptophan powders is observed at the deepest point, the finding is consistent with that estimated from the aforementioned effective cladding indices. The preliminary sensing result in Fig. 3(b) indicates that the THz-SPW can be used to identify two materials with similar appearances by characterizing their measured waveguide dispersions. The sensing scheme can potentially be applied for monitoring the quality of food, detection illicit drugs or explosives, and characterizing molecular dynamics in living cell specimens.

The dispersion property of an SPW was experimentally and theoretically investigated using transmission spectroscopy. The SPW has a low and controllable waveguide dispersion, which can be engineered by changing the core diameter, the core index, and the cladding index of the wire, in a manner consistent with theoretical predictions. Characterizing the waveguide dispersion variations in SPW reveals that the demonstrated SPW-based THz time-domain spectrometer can identify two similar white powders. These results imply that SPW has potential for use in communication applications and for combination with biochips or microfluidic channels for sensing minute molecules.

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