Enhanced Coupling Property using a Conical Metal Wire Waveguide in the Terahertz Frequency Range

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***Abstract*— We investigated the coupling properties of a metal wire waveguide in the terahertz (THz) frequency range using theoretical simulations and experiments. Because a conical wire tip has a smaller tip diameter than a cylindrical wire tip, it has a greater THz field density than a cylindrical wire tip. After the coupling of the THz pulse to the receiver (Rx) using a 1-µm-diameter conical-wire tip, the detected THz pulse increased 5.3 times compared with when the 500-µm-diameter cylindrical-wire tip was used. This result agrees with that of theoretical simulations using high-frequency structure simulation (HFSS).**

I. Introduction And Background

RECENTLY there has been increasing interest on a surface wave propagation on a cylindrical conductor in the terahertz (THz) frequency range. The propagation wave along the single metal wire is known as the Sommerfeld wave, which is caused by surface plasmon polaritons [1]. The single metal wire has low attenuation and low group velocity dispersion. But, wave propagation has a weak guidance property due to the small electric field in the metal wire [1]. When the generated THz pulses were coupled with the cylindrical conductor (wire), only the dominant transverse-magnetic surface wave mode (TM_{01}: the Sommerfeld wave) was propagated along the wire. Because all the higher modes had very high attenuations, they vanished almost immediately after they were coupled with the wire. The wire diameter was an important factor in the characterization of the THz propagation [2,3]. A conical wire tip has a smaller tip diameter than a cylindrical wire tip, it has a greater THz field density than a cylindrical tip. We have studied a 30µm-diameter conical copper wire [4] and a 1µm-diameter conical tungsten wire waveguides to enhance the detection of the propagated THz field.

II. Experimental Setup

As shown in Fig. 1, the conical tungsten wires W_1 and W_3 were made to come in contact with the Tx chip and the Rx chip, respectively. Each wire consisted of a 2.5-cm-long cylindrical part with a 500-µm-diameter tip, and of a 0.5-cm-long conical part with a 1-µm-diameter tip. The wire tips were located near the dipole antennas of the Tx and Rx chips. The direction of the dipole antennas was parallel to the Sommerfeld field direction. The 12.5-cm-long and 500-µm-diameter-tip cylindrical tungsten wire (W_2) was connected with the conical wires (W_1 and W_3), and the separations (air gaps) between the wires were 150 µm wide. Since the separations were very small, the THz pulses were able to easily propagate and couple with the other

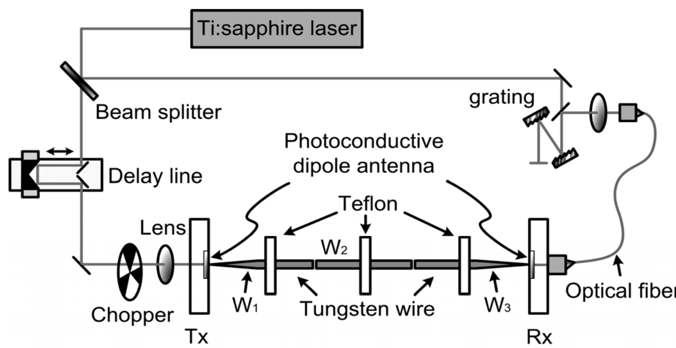

Fig. 1. Experiment setup: Two conical-wire tips, W_1 and W_3, were made to come in contact with an SOS transmitter (Tx) and a receiver (Rx) chip, respectively.

wire. The THz pulse that was generated from the Tx chip was coupled at the W_1 tip and was propagated along W_2 and W_3. Three Teflon disks were used to support each wire and to enable the adjustment of their position for optimal coupling.

III. Simulations And Measurements

Fig. 2(a) and (b) show the magnitude of the field distribution of 500µm-diameter cylindrical wire and the 1µm-diameter conical wire. The diameter of the conical wire was reduced from 500 µm to 1 µm. Therefore, the guided THz Sommerfeld wave along the wire was concentrated around the conical tip. The amplitude of the THz field of the conical wire tip was much stronger than that of the cylindrical wire tip. The field amplitude increased by about 4.9 and 4.2 times for the tips with diameters from 1 to 30 µm, as opposed to the field amplitude for the 500-µm-diameter tip.

The tips of conical wires W_1 and W_3 came in contact at 30 µm away from the dipole-antenna gap of Tx and Rx chips. The THz pulses were in turn propagated on W_1, W_2, and W_3 and reached the dipole antenna on the Rx chip. The two different shapes of W_3 with fixed Tx, Rx, W_1, and W_2 states were compared. W_3 was a cylindrical tungsten wire that was made to

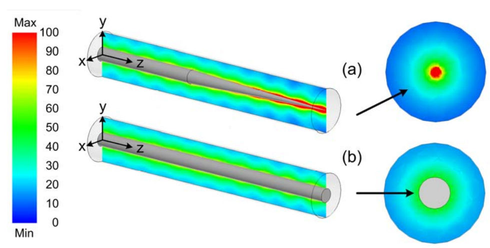

Fig. 2. Calculated electrical field distribution on the conical wire and the cylindrical wire using 0.15 THz.

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have a length of 3 cm and a 500-µm-diameter tip so that it would have reference THz pulses. After the reference THz pulses had been obtained, W_3 was replaced with a 3-cm-long conical tungsten wire with a 1-µm-diameter tip. The measured peak-to-peak current was 648 pA. Since the Rx part was connected with the optical fibers, the other optical and mechanical components were fixed. The THz pulses that were obtained on the time domain are shown in Fig. 3(a). The dashed and solid lines indicate the THz pulses when the 500-µm-diameter cylindrical wire and the 1-µm-diameter conical wire were used, respectively. The amplitude increased 5.3 times compared with the reference THz pulse, which was bigger than that of the 30-µm-diameter conical-wire tip (4.5 times) in [4]. The inset shows a comparison of the 500-µm-diameter cylindrical wire and the 30-µm-diameter conical wire. The full widths at half maximum of the dashed and solid THz pulses were 1.58 ps (pico-second) and 2.09 ps, respectively. The pulse width of the conical-wire tip was broader than that of the cylindrical-wire tip. This means that for the conical-wire tip, the low-frequency part of the signal was strong and the center frequency moved to a low-frequency range, as shown in Fig. 3(b). There was a slight difference in the simulation result of 4.9 times. The 8% deviation was caused by the location of the wire tip on the dipole antenna. The amplitude of the electric field around the 1-µm-diameter conical-wire tip was very sensitive due to the radial distance from the wire tip's surface. An exact 30 µm separation between the tip surface and the detection source, as in the field simulation, could not be maintained for reference purposes. The 8% deviation was similar, however, to the results of [4].

Fig. 4 shows the definitions of the radial distance (R) and tip diameter (D) as well as the calculations of the field distribution for the tungsten conical wire. Fig. 4(a) shows the field amplitude with different tip diameters, from 1 to 500 µm. As the meshes in the simulation were limited, the field amplitudes that were calculated around the radial distance were not uniform. The error bar shows the limitation of the field margin, and the dots indicate the average of the calculated field distribution. The field amplitude increased by about 4.9 and 4.2 times for the tips with diameters from 1 to 30 µm, as opposed to the field amplitude for the 500-µm-diameter tip. The amplified ratio of the different tip diameters to the 500 µm tip diameter is

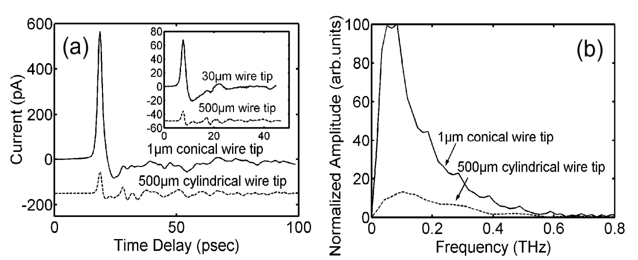

Fig. 3. (a) Measured THz pulses (in the time domain). The dashed line indicates the 500-µm-diameter cylindrical-wire tip, and the solid line indicates the 1-µm-diameter conical-wire tip. The inset shows the measured data for the 500-µm-diameter cylindrical-wire tip and the 30-µm-diameter conical-wire tip in [4]. (b) Comparison of the THz pulse spectra (in the frequency domain).

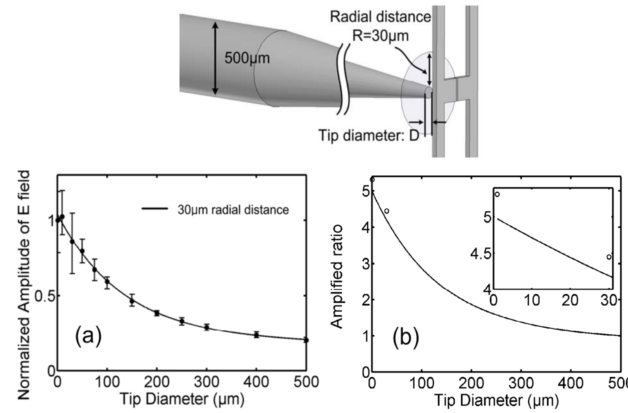

Fig. 4. (a) Calculated field intensities for different tip diameters, with 30 µm radial distances. (b) Field amplitude ratio compared with the 500 µm tip diameter. The circles indicate the measured data for the 1- and 30-µm-diameter conical-wire tips, respectively.

shown in Fig. 4(b). The inset shows the expanded curve from 1 to 30 µm, and the two circles show the results of the measurements of the 30-µm-diameter tip [18] and the 1-µm-diameter tip. The results of the simulation coincided with the results of the measurements.

IV. Conclusions

The improvement of the detection of the THz field through the use of a 1-µm-diameter tungsten conical-wire tip in the THz waveguide system was reported in this study. The measured amplitude of the THz pulse was increased 5.3 times compared with the THz pulse when a 500-µm-diameter cylindrical-wire tip was used, because the THz Sommerfeld field was concentrated at the end of the conical-wire tip. The results of the measurements coincided with the results of the simulation, where an HFSS software was used.

Acknowledgments

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