Effect of a dielectric coating on terahertz surface plasmon polaritons on metal wires

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The authors present measurements and calculations on the effect of thin dielectric coatings on the propagation of terahertz pulses along the surface of metal wires. Our measurements show that propagation over only a few centimeters of wire having a thin dielectric coating, strongly distorts the terahertz pulse, which results in a several tens of picoseconds long chirped signal. We demonstrate that the terahertz pulses propagate along the wire as surface waves, and show how a thin coating of a nondispersive material makes this propagation strongly dispersive, giving rise to the chirped signal observed in the measurements. Our results show the potential of terahertz surface plasmon polaritons on metal wires for the sensitive detection of thin dielectric layers. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2011773]

Recently, there has been an increased interest in the search for a good waveguide for the transportation of terahertz radiation.[1–6] The latest development in this field is the propagation of terahertz waves along bare metal wires with very little absorption and dispersion.[7,8] Indeed, measurements were shown in which two metal wires were combined to form what could eventually become a medical probe. Many metal wires, however, are not bare. Thin dielectric layers can often be found on the surface of metal wires, applied intentionally or unintentionally through oxidation or contamination, and the effects of these layers on the propagation of terahertz pulses along the wire are not wellknown.

Here we show measurements and calculations on the propagation of terahertz pulses over copper wires with and without a thin polyurethane coating. Our time-domain measurements of a terahertz pulse propagating along a 4 cm long wire show that a coating of tens of micrometers thickness strongly distorts the terahertz pulse resulting in a chirped terahertz signal that lasts tens of picoseconds. A comparison with calculations based on Maxwell's equations shows that the terahertz pulses propagate along the wire as surface plasmon polaritons, and that the distortion of the terahertz pulse originates from the dispersive propagation of these waves along the coated wire. Remarkably, the propagation is dispersive, although we assume that the coating material itself has a frequency-independent refractive index. Our work indicates that thin coatings can seriously distort terahertz pulses propagating along metal wires. At the same time, however, this offers the possibility of using metal wires as sensitive detectors of thin layers.

Figure 1 shows a schematic drawing of our setup. The terahertz pulses from our emitter are focused onto one of two types of metal wires. The first wire is a bare copper wire with a diameter of 1 mm. The second wire is a copper wire with a diameter of 1 mm having a polyurethane coating, specified to be about 34 μm thick.[9] A sharp copper needle is used to couple the terahertz radiation onto the wire.[8] The terahertz surface plasmon polariton propagates over the wire toward the detection crystal, which is a 1 mm thick ⟨110⟩-oriented ZnTe crystal and is held close to the end of the wire. For both the coated and the uncoated wire, the propagation distance from the detection crystal to the point where the terahertz pulse is coupled onto the wire is 4 cm. In the detection crystal, a birefringence is induced proportional to the instantaneous strength of the electric field of the terahertz wave. The induced birefringence is measured by a probe beam, which enters the detection crystal from the back and back-reflects at the front face. The terahertz-induced polarization change of the probe beam is then measured by a conventional electro-optic detection setup. We note that large variations in the spectral content of the measured terahertz electric fields were observed for small changes in the exact position of the needle used to couple the terahertz pulses onto the system. This is not altogether unexpected, since moving the needle changes its position with respect to the frequency-dependent focus of the incident terahertz beam. In our measurements we optimized the position of this wire to maximize the measured spectral bandwidth.

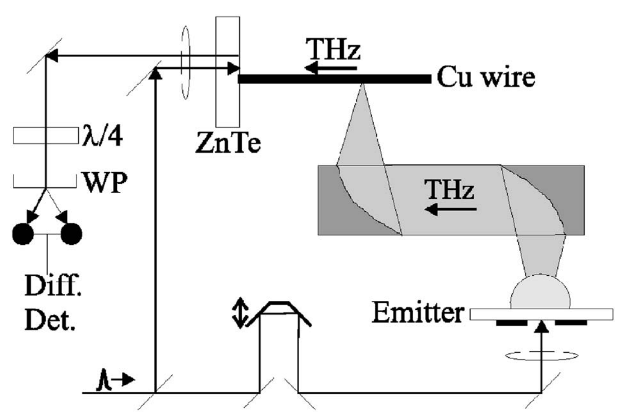

FIG. 1. Schematic of the setup. A time-delayed pump pulse is focused onto the biased GaAs emitter. The terahertz pulses generated by the emitter are focussed and coupled onto the copper wire by a sharp copper needle, placed underneath the wire. The pulses then propagate over the wire to the ZnTe detection crystal. The electric field of the terahertz pulses in the detection crystal is then measured with a synchronized probe pulse, using a conventional electro-optic detection setup, consisting of a quarter-wave plate ($\lambda/4$), a wollaston prism (WP), and a differential detector (Diff. Det.).

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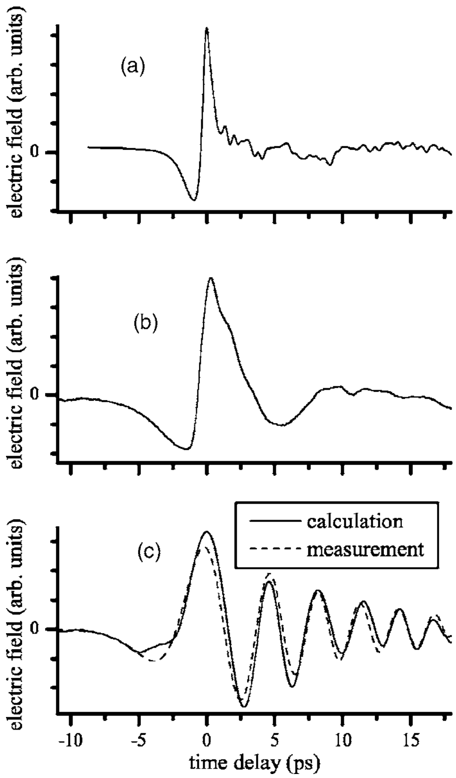

FIG. 2. Measured electric fields as a function of time of the terahertz pulse incident on the wire (a) and of the pulse after propagating over 4 cm of the bare wire (b). (c) shows the measured and the calculated pulse after propagation over the coated wire.

In Fig. 2(a), we plot a time-domain measurement of the electric field of the terahertz pulse incident on the wire. The terahertz pulse is characterized by a sharp peak, followed by many oscillations, which are caused by absorption and reemission of terahertz radiation by water vapor molecules in the atmosphere. Figure 2(b) shows the measured electric field versus time of the terahertz pulse after propagating over the 4 cm long bare copper wire. The striking differences between the pulse after propagation over the wire and the pulse incident on the wire are the difference in the pulse shape and the increase of the pulse duration; the duration of the first positive peak changes from 0.7 ps for the incident pulse to 2.3 ps after coupling onto and propagation over the bare wire. This difference is probably caused by the frequency-dependent coupling of the terahertz pulse to the wire.[10] The dotted line in Fig. 2(c) shows the measured electric field as a function of time after propagation along the 4 cm long coated wire. The figure shows that the terahertz pulse has acquired a remarkably long tail having a time-dependent frequency, which clearly contrasts with the result for the uncoated wire.

To investigate the physical origin of the long chirped tail, we have performed calculations of the propagation of terahertz pulses over the coated wire. We find that along the metal wire, the terahertz pulses propagate as surface waves, for which we can calculate the dispersion relation using a similar method as reported previously.[11,12] Due to the cylindrical symmetry, the solutions of Maxwell's equations for the magnetic and the electric fields are Bessel functions. We consider only the TM_{00} mode as it can be shown that for thin coatings this is the only mode with little absorption, which will survive after 4 cm of propagation.[11] For this mode, the nonzero components of the electric and magnetic fields are written as

$$B_\phi = [C_1 J_1(\kappa\rho) + C_2 Y_1(\kappa\rho)]\exp(i\psi), \qquad (1)$$

$$E_z = (i\omega\kappa/k^2)[C_1 J_0(\kappa\rho) + C_2 Y_0(\kappa\rho)]\exp(i\psi), \qquad (2)$$

$$E_\rho = (\omega k'/k^2)[C_1 J_1(\kappa\rho) + C_2 Y_1(\kappa\rho)]\exp(i\psi), \qquad (3)$$

where J_n and Y_n are Bessel functions of the nth order and of the first, respectively, second kind, and $\psi = k'z - \omega t$. The cylindrical coordinates are ρ for the radial distance, ϕ for the azimuth, and z for the direction parallel to the wire. B_ϕ is the magnetic field in the ϕ direction, and E_z and E_ρ are the electric fields in the z and the ρ directions. In the metal, in the coating, and in the surrounding air, the wave has the same radial frequency ω and the same z component of the wave vector k'. However, the constants C_1 and C_2, the wave number of the medium k, and $\kappa = \sqrt{k^2 - k'^2}$, are different for each region. From the appropriate boundary conditions, a dispersion relation is derived, which provides the phase velocity and the absorption length at each terahertz frequency. With this information, the influence of propagation over a coated wire on the temporal shape of a terahertz surface wave can be calculated.

In Fig. 2(c), we plot the calculated electric field of a terahertz surface wave after propagation over 4 cm of coated wire. Results of the uncoated wire are not shown, as in the calculation the pulse shape is not changed after propagation along this wire. In our calculations, we used a diameter of the copper wire of 1 mm and a coating thickness of 34 μm. We use 1.0 as the refractive index of air, and 2.5 as the refractive index of the coating, which is a reasonable value for polyurethane.[13] For the frequency-dependent refractive index of copper, we use the model from Ordal *et al.*[14] For the initial, undistorted, surface wave, we assume a temporal shape that corresponds to the time derivative of a Gaussian that has a duration of 2.1 ps. The results of the calculation are in remarkably good qualitative agreement with the measurement. The minor differences between calculation and measurement can easily be explained by the uncertainty in the exact shape of the input pulse or by the uncertainty in the refractive index of the polyurethane coating.

We can now understand the chirped terahertz signal as arising from the dispersion of the full system, consisting of the wire and the coating. To provide a physical picture for the origin of this dispersion, we calculated the electric and magnetic fields after 4 cm of propagation as a function of the radial distance ρ with Eqs. (1) and (3). The results are plotted in Fig. 3 for four different frequencies: 50 GHz, 0.2 THz, 0.5 THz, and 1.5 THz. The fields were normalized to unity at the metal-coating interface. Figure 3 clearly shows that for increasing frequency the decay of the fields with radial distance becomes faster. It is also shown that the strength of the electric and magnetic fields in the coating increases with frequency. Therefore, the fraction of the total terahertz energy that is transported within the coating increases with frequency. This means that the effective refractive index experienced by the surface wave increases with frequency, resulting in the dispersive pulse propagation seen in our measurements. The dispersion above is *not* an intrinsic property of the coating material itself, for which we have assumed a frequency-independent refractive index. In fact, the dispersion of the coating material plays only a small role in

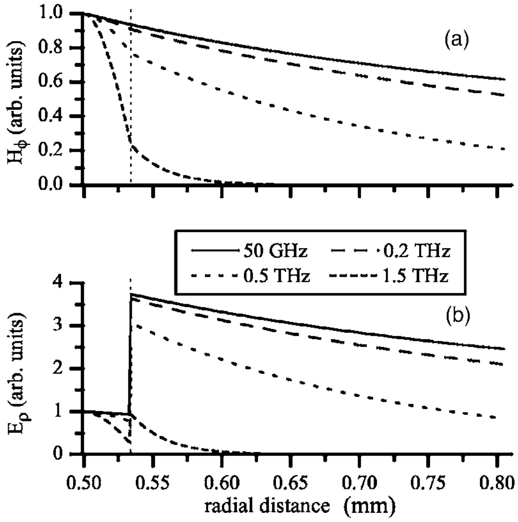

FIG. 3. Electric field amplitude in the radial direction (a) and magnetic field in the azimuthal direction (b), both as a function of the radial distance from the center of the wire ρ. The position of the coating-air interface is indicated by the vertical thin dotted line.

the dispersive wave propagation, and has been neglected here.

It is interesting to speculate on the sensitivity of the technique to detect the presence of extremely thin dielectric layers on wires. Surface plasmon polaritons on wires do not spread out, as do surface plasmon polaritons on flat surfaces,[15] thus enabling long interaction lengths. A calculation for a copper wire with a diameter of 1 mm and a 100 nm thick coating (refractive index 2.0) shows a measurable $\pi/20$ phase shift at 0.5 THz for a 59 cm long wire. We believe, therefore, that the detection of coatings with thicknesses in that range should be feasible.

In conclusion, we have presented time-domain measurements that show the effect of a thin coating on the propagation of terahertz surface plasmon polaritons along metal wires. After propagation over 4 cm of coated wire, we found that the terahertz surface wave becomes fully dispersed, resulting in a terahertz signal that lasts tens of picoseconds, which is not the case in the measurements of an uncoated wire. A comparison with a theoretical model based on Maxwell's equations shows that the pulse distortion originates from the dispersive nature of wave propagation along the coated wire. This is explained by a frequency-dependent increase in the effective refractive index of the coated wire. Our work shows that metal-wire waveguides could serve as sensitive probes of thin layers at terahertz frequencies.

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