Confinement of THz surface waves on sub-wavelength size metal waveguide

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Abstract

We investigate surface plasmon waves propagating on planar Goubau lines, so-called Goubau modes, using a guided-wave terahertz spectroscopy system based on a freely positionable electro-optic probe. We show the radial nature of the Goubau mode and its confinement around the Goubau line over few tenths of microns (λ/10).

1. Introduction

Significant progress on waveguides that capture and confine THz radiation generated in free-space have been reported in the past few years [1,2,3]. For instance, studies have shown that parallel-plate metal waveguides show low loss and low group velocity dispersion in the THz frequency range. In return, only few works have been focused on integrated waveguides in which the THz radiation is confined near a surface. Theses on-chip waveguides are very promising candidates for broadband THz near field sensing and imaging, spectroscopy of microfluidic systems and ultra-wide bandwidth circuits. Here, we report the experimental investigation of the THz surface waves propagating on planar Goubau lines (G-line) made of a single metal wire formed on a low-permittivity dielectric substrate.

2. Experiment

The G-line used in this work is formed by a 2-mm-long single rectangular-shaped conducting wire lying on a flat quartz substrate. The width of the cross-section signal conductor is 5 µm, made from Ti/Au 20/250 nm deposited on a 250 µm-thick quartz substrate. At each extremity, the G-line is linked to a tapered coplanar waveguide. The tapered coplanar waveguide role is the preshaping of the Goubau mode [4]. The guided-wave THz time domain spectroscopy system uses an erbium-doped fiber laser that delivers femtosecond pulses at 1.55 µm wavelength. The generation of single cycle THz pulses is achieved by the illumination of an ultrafast photoconductive switch made by a bonding lifted-off film of ion-irradiated $In_{0.53}Ga_{0.47}As$ material deposited onto the coplanar waveguide section (see Fig. 1). The detection of the THz pulses propagating along the G-line is achieved using a fiber-coupled ZnTe electro-optic probe [5].

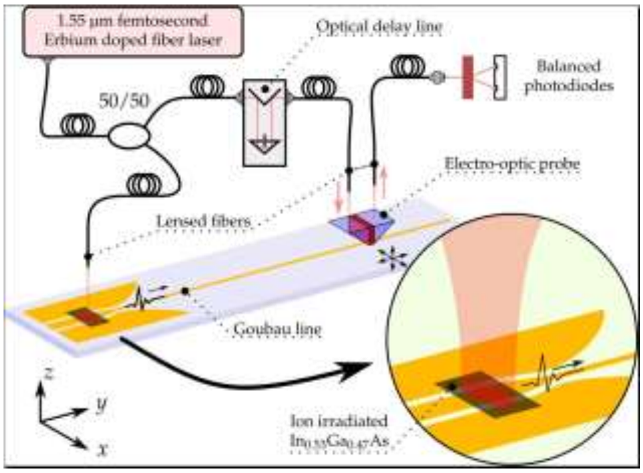

Figure 1: THz guided-wave time domain spectroscopy set-up.

The ZnTe crystal can be oriented to detect either the horizontally polarized component or the vertically polarized component of the THz electric field, with 15 µm spatial resolution limited by the spot size at $1/e^2$ of the optical pulses in the ZnTe crystal. The fiber-coupled electro-optic probe, attached to a supporting motorized three-axis translation stage, can be independently positioned from the other optical components. The whole system is fiber integrated.

3. Results

Figure 2a displays the transient electrical waveforms, generated by the ion-irradiated In0.53Ga0.47As photoconductive switch and measured by the electro-optic probe at the entrance of the G-line, and after 1 mm of propagation along the G-line. After 1 mm propagation distance, the pulse is distorted due to group velocity dispersion effects and its amplitude is decreased by a factor 1.75. This attenuation is essentially due to the energy dissipation in the substrate at high frequency and to the conductor skin-effect losses due to finite conductivity of the metal [6]. The dielectric losses are relatively small

(<0.02 mm-1) in quartz from 0-3 THz [7]. The total propagation losses could be significantly lowered by reducing the thickness of the substrate to less than the half the effective wavelength and at last by using a substrate with lower loss in the THz range such as Kapton or Topas. The amplitude of the spectra of these transient waveforms, obtained by fast Fourier transform are shown in Fig.2b. After 1 mm of propagation distance, the spectrum extends up to 0.9 THz with a dynamic of ~35 dB (Fig.2b).

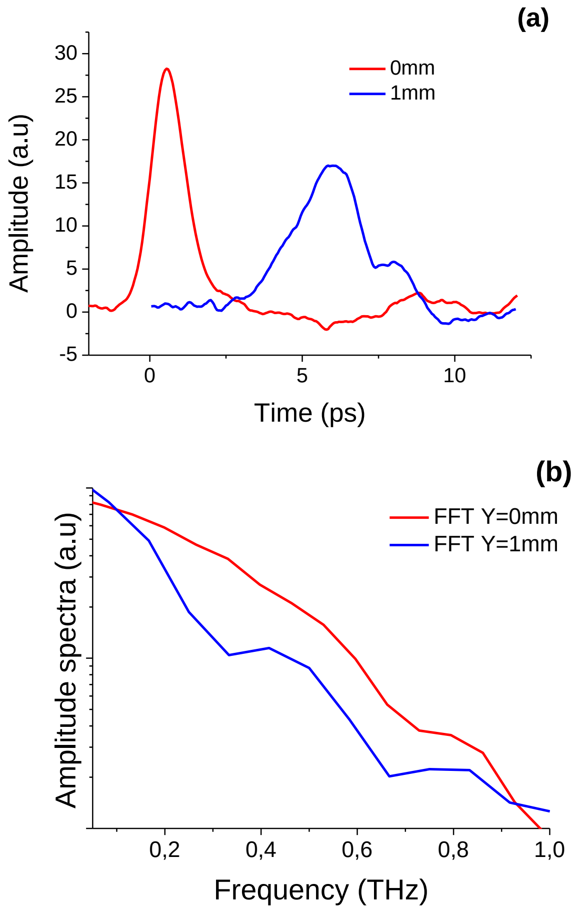

Figure 2: (a) THz waveforms measured at the entrance of the G-line (0 mm) and after a propagation distance of 1 mm. (b) Spectra in amplitude of the temporal waveforms.

The spatial profile of the mode is measured by scanning the electro-optic detector in a plane perpendicular to the G-line axis, with a time delay fixed at the peak of the THz pulse. Figure 3a and b show the spatial distribution of the projection of the electric field onto the horizontal and the vertical direction respectively, measured using electro-optic probes with distinct orientations of the ZnTe crystal. The polarity reversal of the horizontal component of the electric field as the electro-optic probe scans across the G-line clearly shows the radial nature of the Goubau mode. The amplitude of the vertical component of the electric field above the G-line (in the z direction) falls to 1/e of its maxima value at 64.5 µm, demonstrating the confinement of the Goubau mode around the wire. This value represents the broadband surface plasmon decay length weighted over the broad spectrum of the THz pulse used.

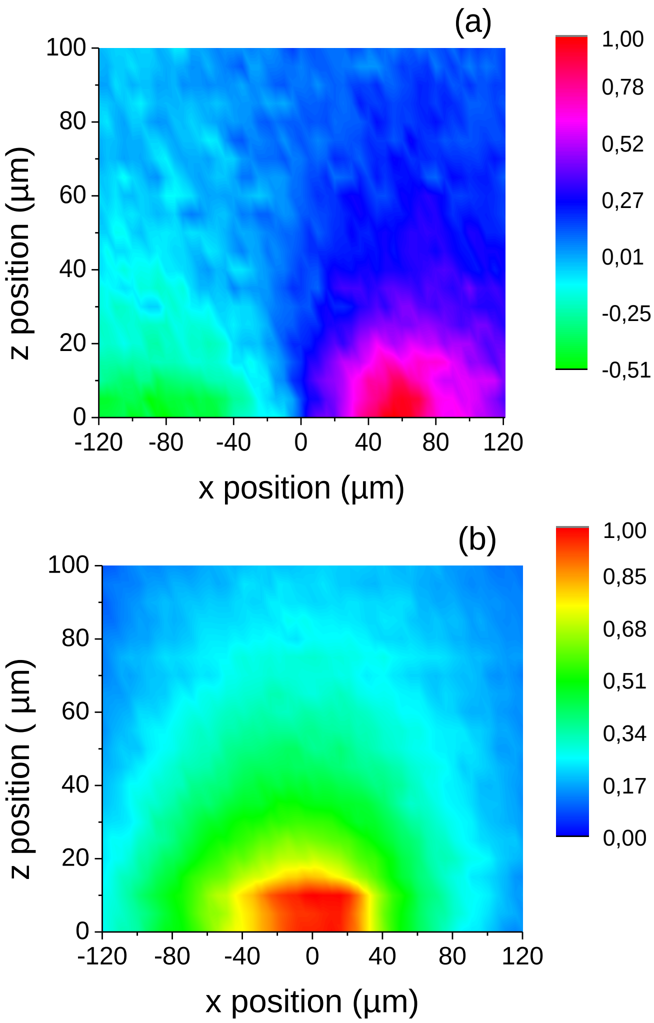

Figure 3: The spatial distribution of the projection of the electric field onto the horizontal direction (a) and onto the vertical direction (b). The spatial resolution of the measurements is limited by the spot size of the optical beam in the ZnTe crystal to ~15 µm.

4. Conclusion

In conclusion, we demonstrated that the THz electric field of the surface plasmon waves propagating on planar G-lines is confined around the wire over few tenths of microns (λ/10) making waveguides based on G-lines very promising for many applications such as high resolution imaging and spectroscopy.

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