Focusing THz radiation in μm-scale waveguides

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Abstract—**THz coplanar waveguides were fabricated on quartz wafers with integrated epitaxially transferred low temperature grown gallium arsenide photoconductive switches. THz radiation was excited on-chip and transmitted through a tapering of the coplanar waveguide structure where it was focused down to $\sim 1.66\mu m$. Theoretical modelling of the device confirms high E-field confinement and concentration.**

I. Introduction and Background

PLASMONIC devices are among the most promising for the control and focusing of THz radiation. The THz electric field couples to charge density oscillations in a metal allowing the effective transmission of THz radiation on metal waveguides on subwavelength length scales [4]. Possible applications include near-field imaging [1] and spectroscopy [5], while subwavelength control of THz radiation is a necessary step along the road to many potential integrated THz systems. In this paper, tapered coplanar waveguides (CPWs), are both modelled and fabricated. THz pulse propagation through a CPW with total width of $\sim 1.66\mu m$ is demonstrated experimentally.

II. Modelling

HFSS simulations were conducted for a tapered CPW. The starting width from ground plane to ground plane in the CPW was 50 μm, with the centre track having a width of 30 μm and gaps of 10 μm to the ground plane on each side, before being linearly tapered to a width of 1.66 μm over a distance of $500\mu m$. The centre track-to-gap ratio was maintained at 3:1 to avoid impedance discontinuities. Cross sections of the electric field were plotted at regular points along the tapered CPW, and the field intensity profiles extracted. The confinement area was defined as the area where the field is within an order of magnitude of the maximum value. Confinement area and the average field in this area are plotted against taper width in Fig. 1.

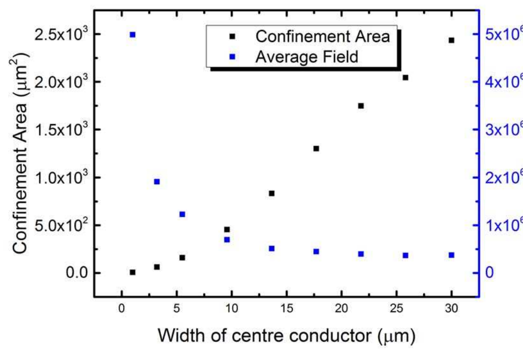

Fig. 1. The confinement area and the average field strength in that confinement area of each of the field distributions produced by HFSS is shown.

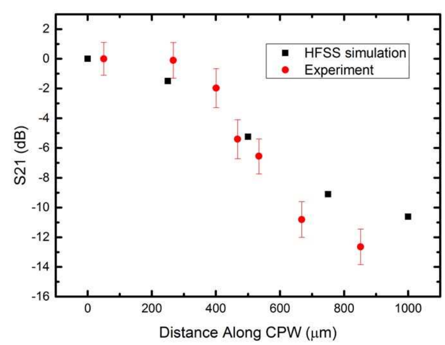

Fig. 2. The transmitted power as modelled in HFSS and as calculated from changes in the FFT of transmitted pulses.

III. Fabrication

300 nm of low temperature grown Gallium Arsenide (LT-GaAs) was grown on a Gallium Arsenide substrate at a temperature of 205°C with a 100 nm release layer of AlAs in-between. It was annealed at a temperature of 550°C in order to increase its dark resistivity [3]. Black wax was melted on to protect the LT-GaAs surface and the edges were cleaned using a non-selective fast sulphuric acid etch ensuring that the AlAs boundary layer was fully exposed. A slow HF acid etch was then performed for ∼24 hours at 3°C to separate the LT-GaAs and black wax from the GaAs substrate. The LT-GaAs was then transferred onto a quartz substrate, ensuring that there was a thin film of water between the LT-GaAs and the quartz. Next, the device was heated at 80°C for two hours to allow the water film to evaporate without boiling while also softening the black wax to allow for conformal adhesion. The black wax was then removed in trichloroethylene. Finally the device was baked at 250°C at a pressure of 30 mBar for 15 hours to ensure total dehydration and improve LT-GaAs adhesion to the substrate.

Electron beam lithography was used to define a narrow taper region with optical lithography used to define the rest of the waveguide and photoconductive switches. In both cases Ti/Au was evaporated, with thicknesses of (5/100)nm for the

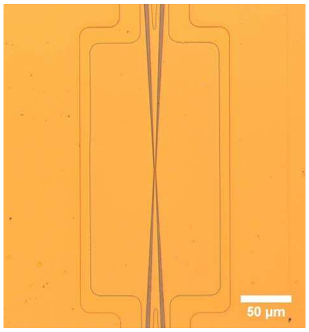

Fig. 3. A straight tapered CPW.

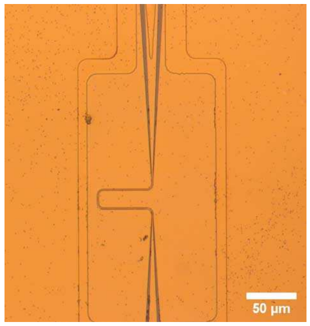

Fig. 4. Tapered CPW with curved delay section.

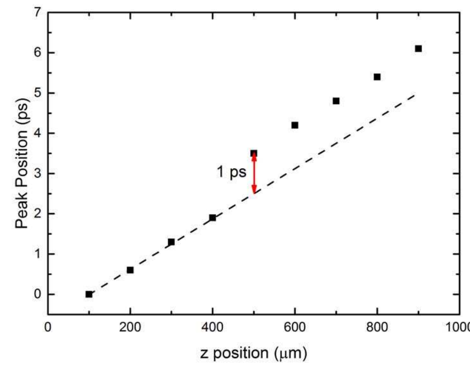

Fig. 5. The THz peak position plotted against the laser probe pulse z position on the CPW. The change in peak position at the centre is clearly visible.

EBL step, and (5/150)nm for the optical lithography step. An example device is shown in figure 3 where the transition from optical lithography to EBL can be seen at the top and bottom of the image. The dimensions of the waveguide were designed to be as close as possible to the theoretical model. However, the necessity of transitioning from an optical lithography layer to an EBL layer means that the overlap region will have two layers of Ti/Au, and also that any misalignment will result in deviations from the model design.

IV. Results

A sliding switch method was used to measure THz pulse generated current at different points along the tapered waveguide. The transmitted power S21 was calculated for 1 THz; it shares a similar functional form with the model as shown in Fig. 2. This was measured for two devices, with similar results seen for both, though for the second device, the measured results deviated from the model in the overlap region between the EBL and optical layers. This is presumed to be due to slight alignment errors in the fabrication process.

To confirm that the THz pulse was confined to the waveguide, and not transmitted through substrate modes or direct (in-air) coupling, a CPW was also made with a curved section that added at most 110 μm perpendicular to the track length (figure 4). Previously measured Au CPWs-on-quartz gave pulse velocities of $1.69 \times 10^8 ms^{-1}$, so this additional length of waveguide should delay the pulse by at least 500 fs.

The device was mounted on a stage that allowed measurable variation in the z direction, and this was used to vary the position of the probe laser pulse along the CPW. THz time domain scans were taken at 100 μm increments, and the position of the pulse peak noted. This can be seen in Fig. 5. There is a clear discontinuity in the peak location around the middle of the waveguide where the extra curved section lies. This demonstrates that the THz pulse was confined to the CPW, and did not simply couple across. HFSS models confirm this confinement through the curved region. The reciprocal of the slope of the data before and after the discontinuity gives a pulse velocity of $(1.54 \pm 0.02) \times 10^8 ms^{-1}$, which is slower than previously measured devices, possibly due to the effect of the sheet of high permittivity GaAs. In previous devices, the GaAs was etched away everywhere but the switches. This removes its influence on the transmitted pulse, but does not allow the use of the sliding switch method of measurement.

For constant pulse velocities in the extra loop , the largest discontinuity that could be expected was $724fs$, however the change in the time delay was found to be $1 \pm 0.1ps$. This is likely due to a slower pulse velocity in the tapered region compared to a untapered waveguide, caused either by focusing effects [6] or by increased interaction with the GaAs as the field is confined in this region.

V. Conclusion

Transmission of THz radiation through tapered CPWs was demonstrated experimentally and modelled in HFSS. Transmitted powers follow a similar functional form between the model and experiment. The high field confinement, associated with the ability to guide THz radiation via lithography defined waveguides opens the possibility of direct sensing or excitation of submicron electronic/spintronic devices.

VI. Acknowledgements

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References

[1] M. Awad, M. Nagel, and H. Kurz. Tapered Sommerfeld wire terahertz near-field imaging. *Citation: Applied Physics Letters Phys. Lett. J. Appl. Phys*, 94(98):51107–14910, 2009.

[2] D. K. Gramotnev, D. F. P. Pile, M. W. Vogel, and X. Zhang. Local electric field enhancement during nanofocusing of plasmons by a tapered gap. *Physical Review B*, 75(3):035431, jan 2007.

[3] I. S. Gregory, C. Baker, W. R. Tribe, M. J. Evans, H. E. Beere, E. H. Linfield, A. G. Davies, and M. Missous. High resistivity annealed low-temperature GaAs with 100 fs lifetimes. *Applied Physics Letters*, 83(20):4199, nov 2003.

[4] D. M. Mittleman. Frontiers in terahertz sources and plasmonics. *Nature Publishing Group*, 7, 2013.

[5] C. Russell, C. D. Wood, A. D. Burnett, L. Li, E. H. Linfield, A. G. Davies, and J. E. Cunningham. Spectroscopy of polycrystalline materials using thinned-substrate planar Goubau line at cryogenic temperatures. *Lab on a Chip*, 13(20):4065, 2013.

[6] J. Takahara, S. Yamagishi, H. Taki, A. Morimoto, and T. Kobayashi. Guiding of a one-dimensional optical beam with nanometer diameter. *Optics Letters*, 22(7):475, apr 1997.