Tunable plasmonic structures for terahertz frequencies

Thomas H. Isaac

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature:...........................

Acknowledgements

Since I started working on my Ph.D here in Exeter I have been maintaining a list at the back of my first lab-book of all the people who have assisted at some stage along the way. I think it is a testament to the helpfulness and enthusiasm of all the people, both in the Electromagnetic Materials group and in rest of the department, that my list has overflowed the gap at the end of the last page and is encroaching on to both a dispersion diagram and a time-domain trace of a terahertz pulse. However, I shall attempt to do my list some justice herein.

Firstly, I could not have completed any of my project without the highly proficient and capable supervision of Dr. Euan Hendry and Prof. Bill Barnes. Euan has an (almost dangerously) infectious enthusiasm for science, coupled with a great deal of creative flair; the fact that some of the more complicated work in this thesis started of as ‘a quick and easy experiment’ is a testament to both his adventurous style as an experimentalist and his dedicated pursuit of explanations and results. I am extremely grateful to him for his guidance over the last three years. Similarly, Bill has proved to be an invaluable and reliable source of instruction throughout - he has patiently taught me some fundamental physics, and has contributed a great deal to the work in this thesis through his pertinent questions as well as with ideas and understanding. I very much appreciate his support and assistance. I can state honestly that I could not have asked for better supervision than that which I have received from Euan and Bill in this project.

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Publications

The work in this thesis is, in part, based on the following publications:

Journal articles:

- **Chapter 3:** T. H. Isaac, J. Gómez Rivas, J. R. Sambles, W. L. Barnes and E. Hendry, *Surface plasmon mediated transmission of subwavelength slits at THz frequencies*, Physical Review B **77** 113411 (2008)
- **Chapter 4:** T. H. Isaac, W. L. Barnes and E. Hendry, *Determining the terahertz optical properties of subwavelength films using semiconductor surface plasmons*, Applied Physics Letters **93** 241115 (2008)
- **Chapter 5:** T. H. Isaac, W. L. Barnes and E. Hendry, *Surface mode lifetime and the terahertz transmission of subwavelength hole arrays*, Physical Review B **80** 115423 (2009)
- **Chapter 6:** T. H. Isaac, J. Gómez Rivas and E. Hendry, *Optical control over transmission of terahertz radiation through arrays of sub-wavelength holes of varying size*, Physical Review B *(in press)* (2009)

Conference papers:

- **Chapter 4:** T. H. Isaac, W. L. Barnes and E. Hendry, *Terahertz surface plasmons for subwavelength sensing and spectroscopy*, Proceedings of TERA 2008, Ukraine, p. 10 (2008)
- **Chapters 5, 6:** T. H. Isaac, J. Gómez Rivas, W. L. Barnes and E. Hendry, *On the link between surface mode propagation length and the transmission of sub-wavelength hole arrays*, SPP4 2009, Amsterdam, **O-07** p. 32 (2009)

Abstract

The terahertz frequency range is a relatively unstudied region of the electromagnetic spectrum. However with the emergence of numerous applications for terahertz light in diverse areas such as security scanning, biological imaging, gas spectroscopy and astrophysics there has been considerable recent growth in the volume of research activity in this area. The studies presented in this thesis aim to introduce the physics of surface plasmons to the terahertz frequency range, and on the way to use some of the unique capabilities of terahertz spectroscopy to try and find new information about fundamental surface-plasmon based electromagnetic structures.

Four distinct experiments are described in this work, all of them underpinned by the technique of terahertz time-domain spectroscopy (Chapter 2). This is a very powerful and adaptable spectroscopic method which allows us to measure the electric field of pulsed terahertz radiation as a function of time. This in turn allows us to directly extract both phase and amplitude of the terahertz light as a function of frequency, over a broad frequency range. Furthermore, this method of terahertz spectroscopy can be combined with photoexcitation pulses of visible/NIR light which can be used to make dynamic changes to the properties of materials in the terahertz beam.

The first experiment reported (Chapter 3) measures the propagation of coupled surface plasmons in a resonant slit cavity. We use terahertz time-domain spectroscopy to determine the characteristics of the cavity resonances in a semiconductor slit near the surface plasma frequency of the material, where we are able to measure very large red-shifts in the frequency of the cavity resonance. By considering the phase information which can be extracted directly from time-resolved terahertz measurements we are able to link the behaviour of the resonances to the propagation characteristics of the surface plasmon modes inside the slits.

The second experiment (Chapter 4) is a more direct measurement of surface plasmons, propagated over the surface of a semiconductor wafer. We show that the electric field of the surface plasmon is confined to a subwavelength region around the surface, and that the confined field is useful for spectroscopy of very thin layers above the surface. We are able to measure films with thickness less than $1/600^{th}$ of the wavelength of the terahertz light.

After these two experiments with confined semiconductor surface plasmons we move on to a pair of experiments looking at terahertz surface modes mediating the transmission of light through holes in metal films. In the initial experiment (Chapter 5) we use the time-domain data from terahertz spectroscopy to determine the role that surface mode lifetime plays in modifying the amplitude and width of Extraordinary Optical Transmission (EOT) resonances, which arise from the periodicity of a hole-array lattice. By changing the temperature of the lossy dielectric semiconductor substrate we are able to modify the surface mode lifetime, and link this to the resonant transmission characteristics.

In Chapter 6 we extend the hole array EOT experiment by making dynamic changes to the propagation of the surface mode which mediates the transmission. This is achieved by photo-exciting the semiconductor substrate inside the holes and forming a thin layer of material with high charge carrier density on the surface. Interaction of the surface mode with the photoexcited region quenches the resonant transmission. We show that by changing the hole size so that the surface-mode mediated transmission pathway predominates in the spectrum it is possible to use optical pulses to modulate the transmission of terahertz radiation with very high efficiency.

In the conclusions (Chapter 7) we link together some of the insights and inferences which can be drawn from the above results, as well as evaluating the efficacy of the experimental and simulation methodology.

Definitions

Abbreviations

- **SPP / SP:** Surface Plasmon Polariton / Surface Plasmon
- **THz-TDS:** Terahertz Time-Domain Spectroscopy
- **FEM:** Finite Element Model
- **EOT:** Extraordinary Optical Transmission
- **FP:** Fabry-Pérot

Symbols

Other symbols are used in the text, but the following are assumed throughout.

- t **:** Time
- ω **:** Angular frequency
- ν **:** Frequency
- λ **:** Wavelength
- k **:** Wave-vector
- k_{SP} **:** Surface plasmon wave-vector
- L_{SP} **:** Surface plasmon decay length
- E **:** Electric field
- H **:** Magnetic field
- c **:** Speed of light in vacuum

Wavelength ranges

At various points a range of wavelengths is referred to by a name; although these names are often loosely defined, in this thesis they fit in to the ranges below.

- **Radio (RF):** $\lambda > 0.1$m
- **Microwave, Gigahertz (GHz):** 0.1m $> \lambda > 1$mm
- **Terahertz (THz):** 1mm $> \lambda > 30\mu$m
- **Infrared (IR):** 10μm $> \lambda > 750$nm
- **Near-Infrared (NIR):** 1.5μm $> \lambda > 750$nm
- **Optical:** 3μm $> \lambda > 350$nm
- **Visible (Vis):** 700nm $> \lambda > 380$nm
- **Ultraviolet (UV):** $\lambda < 380$nm

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