Effect of Wood's Anomalies on the THz Transmission Spectra of Free-Standing Metallic Hole Arrays

Carlo K.A. Hill, Andreas K. Klein, Claudio Balocco, David Wood, and Andrew J. Gallant
Durham University, Durham, DH1 3LE, UK

***Abstract*—A free-standing periodic array of subwavelength rectangular apertures has been designed to exhibit peak transmission which is dominated by localized aperture resonance in the THz region. By varying the incident angle, Wood's anomalies can be introduced; the observed effect upon the localized aperture resonance is reported and compared to FDTD simulations in the absence of plasmonic surface modes. Peak frequency transmission shifts of up to 150 GHz (~15%) while maintaining normalized peak transmission >85% have been observed by VNA CW frequency domain measurements.**

I. INTRODUCTION

EXTRAORDINARY optical transmission (EOT) through a subwavelength aperture array was first reported at THz frequencies in 2003 [1]. The underlying physics of this phenomenon is still not fully realized. However, it is widely accepted that surface plasmon polaritons, which exist at the interface between the metal and air, play a role in the effect. This work reports the extraordinary THz transmission properties of a shape-optimized subwavelength aperture array [2], the transmission properties of which have been shown to be dominated by localized aperture resonance. By altering the incident angle of the aperture array in a collimated beam, plasmonic modes, which are related to the periodic spacing, can be introduced. It is the interaction between these two resonant modes that is under study in this work.

Free-standing metallic aperture arrays provide greater transmission strength than those mounted upon a substrate; this is primarily due to the removal of substrate reflections and losses. Identical resonant conditions on the front and back metal-dielectric interfaces also create more pronounced plasmonic features due to stronger coupling.

Narrow band continuous wave Vector Network Analyzer (VNA) measurements provide high resolution frequency domain transmission data, ideal for observing changing spectral shape and sharp plasmonic resonances.

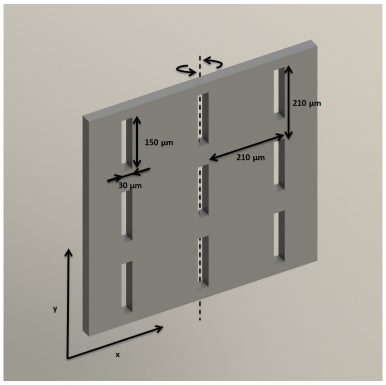

Fig.1. Array geometry and measurement alignment.

II. RESULTS

The shape optimized metallic aperture array is placed in a 25 mm collimated beam created by a pair of parabolic mirrors. The aperture array area exceeds the beam diameter. This allows for the entirety of the collimated beam to be incident upon the aperture array, even when the array is rotated.

With the long side of the aperture array aligned to the y-axis, perpendicular to the VNA E-field, the normal incidence transmission spectrum is observed. By rotating the array about the y-axis, a Wood's anomaly is observed as a sharp minimum of varying frequency dependent upon incident angle, as shown in Fig 1.

It can be seen from Fig 2 that increasing incident angle causes the minimum to move to lower frequencies, sharpening the transmission peak and moving the peak transmission frequency by up to 15%. The 40 degree incidence angle transmission spectra peak lies entirely outside of the normal incidence transmission peak.

Extensive FDTD simulations of a free standing perfect electrical conductor (PEC) with subwavelength apertures have shown a close match to experimental data for various aperture array geometries at normal incidence to the electric field. An FDTD analysis of a PEC cannot support resonant surface modes. Therefore, the transmission spectra can be attributed to localized aperture resonances. The good match between FDTD simulations and experimental data in terms of spectral shape, peak transmission strength and position breaks down when an angle of incidence is introduced, as shown in Fig 3. The differences between the measured and simulated spectra can be attributed to the increasing influence of surface plasmon mode as the incident angle moves away from normal. The surface plasmon mode is controlled by the periodic spacing in the x-direction, as displayed in Fig 1, creating a minimum closely related to that observed by Wood [3] and explained by Rayleigh [4].

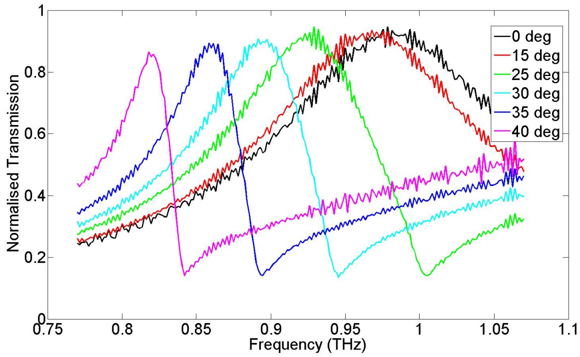

Fig.2. Measured transmission spectra for a free-standing metallic foil with rectangular apertures 30 x 150 µm in a periodic 210 µm square lattice.

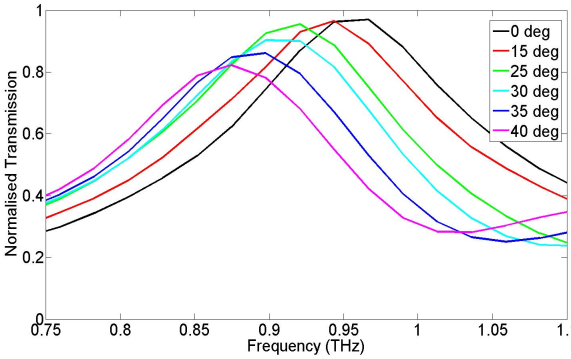

Fig.3. FDTD simulation spectra for a free-standing metallic foil with rectangular apertures 30 x 150 μm in a periodic 210 μm square lattice.

By randomly locating each slot aperture within its periodic lattice unit cell it is possible to largely remove the periodic nature of the aperture array while maintaining the same aperture size and density, as shown in Fig 4. The aperiodic aperture array displays localized slot resonance similar to that of a periodic aperture array, measured and simulated. However, this is with reduced peak transmission magnitude, due to a less well defined aperture spacing, as seen in Fig 5. As an angle of incidence is introduced, no well-defined minimum is observed in the aperiodic array, due to there being no fixed periodic spacing between apertures.

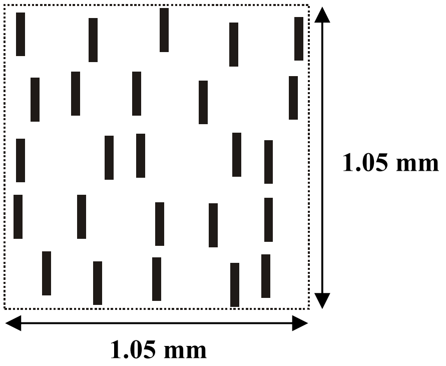

Fig.4. Aperiodic 5 x 5 rectangular apertures 30 x 150 μm within a 210 μm square unit cell.

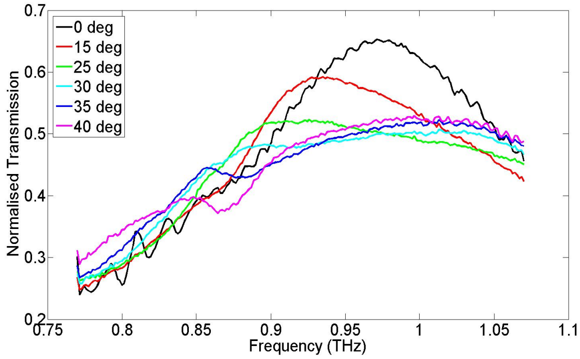

Fig.5. Measured transmission spectra for a free-standing metallic foil with rectangular apertures 30 x 150 μm in a periodic 210 μm random location lattice.

III. SUMMARY

Altering the incident angle of a periodic free standing metallic hole array has been observed to introduce a Wood's anomaly as a sharp minimum in the measured transmission spectrum. The minimum is not present in the PEC FDTD simulations which cannot support plasmonic surface modes. Mixing of the localized shape resonance and plasmonic surface modes has been shown to shift the resonant frequency peak by up to 150 GHz, entirely outside of FWHM measured at normal incidence. The location of the minimum is related to the periodic spacing normal to the long hole edge.

A Wood's anomaly is not observed in an aperiodic array with similar geometrical properties. Closely matched at normal incidence, in transmission peak shape and frequency, the aperiodic and periodic array deviate as an angle of incidence is introduced.

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