Postprint: 39th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz) Tucson, Arizona, USA, 14-19 September 2014

Planar Periodic Surface Lattices for Use in Millimeter-Wave Sources

A. J. MacLachlan[1], A. R. Phipps[1], C. W. Robertson[1], A. D. R. Phelps[1], I. V. Konoplev[2] and A. W. Cross[1]
[1]Department of Physics, SUPA, University of Strathclyde, Glasgow, G4 0NG, Scotland, UK
[2]JAI, Department of Physics, University of Oxford, Oxford, OX1 3RH, England, UK

***Abstract*—Structures based on a periodic surface lattice (PSL) of planar geometry have been studied. It is shown that volume and surface fields can couple to form a cavity eigenmode, demonstrating the potential for novel mm-wave sources when combined in appropriate configurations with an electron beam.**

I. INTRODUCTION

Exploitation and control of EM fields inside and on the surface of periodic lattices is fundamental to the realization of compact, high-power coherent sources, in the GHz-THz range [1,2]. Periodic surface lattices (PSLs) [3] can be made by introducing shallow periodic perturbations to a metal surface and have been shown to facilitate coupling between volume and surface fields, resulting in formation of a cavity eigenmode. In previous work, a dispersion relation describing coupling of volume and surface fields inside a 2D PSL of cylindrical topology was derived [4]. It was shown that, under certain conditions, the structure can support a Cherenkov instability [3-5], demonstrating its potential for use in high power, coherent sources.

In this work, a planar structure with a shallow chessboard corrugation is considered (fig.1). Since the corrugation height is much smaller than the operating wavelength, the lattice may be described as a high-impedance surface, or effective metadielectric. The structure resembles a Fabry-Perot cavity, with the lattice acting as one of the mirrors, and is mounted on a dielectric waveguide, with a thin copper foil backing (second mirror). The volume mode trapped inside the dielectric acts as a global oscillator and ensures synchronization of individual lattice elements, while the surface currents excited along the boundaries of each cell allow a "cross-talk" between neighboring lattice cells.

II. RESULTS

PSLs have been constructed through a process of chemical etching, using printed circuit board (PCB) with a 35μm copper coating and FR-4 dielectric (fig.1). A set of PSLs with period d_z =1.50mm, 1.62mm, 1.74mm and 1.94mm have been etched onto PCB samples of various thicknesses (0.4mm, 0.8mm and 1.6mm) both with and without the copper backing, to investigate the fundamental EM properties of the PSLs.

Due to variations in the dielectric permittivity ε_r quoted for FR-4, and since the dielectric influences the properties of the volume mode, direct measurements of ε_r have been made for each sample using a change in phase method and by establishing the number of wavelengths within the material for each case. Values of $\varepsilon_r = 4.45; 4.71; 5.69$ were determined for the 1.6mm, 0.8mm and 0.4mm substrates respectively showing a significant fluctuation between samples.

The experimental set-up is illustrated in fig.2. Maximum power response is obtained by setting the angle of the receiving horn equal to the incident angle. Interesting experimental observations have been made. The 0.4mm PSLs with copper foil reflect the incident signal while the PSLs without the foil exhibit clear resonances that shift along the frequency band depending on the lattice period d_z. For the 0.4mm PSLs, the dielectric is too thin to support a volume mode within the 140-220 GHz band. However, the fundamental TEM mode may still exist and the observed resonances are indicative of an uncoupled surface mode with a possible TEM contribution.

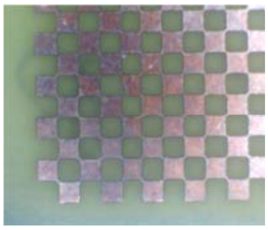

Fig.1. Photograph of copper planar PSL with a lattice period of 1.74mm, obtained through a process of chemical etching using FR-4 dielectric.

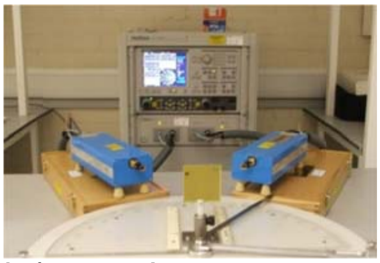

Fig.2. Photograph of experimental set-up. Scattering parameters of the PSL are measured at various incident angles using a pair of G-band horns attached to 140-220 GHz heads and connected to a Vector Network Analyzer (VNA).

Increasing the dielectric thickness to 0.8mm, in the presence of copper foil, results in much sharper resonances (~-40dB). Although there is a slight frequency shift with period, the position of these resonances is limited within a narrow frequency range (~145-165 GHz) for all lattice periods. Here, the volume field inside the dielectric is coupling with the surface field at the periodic surface as desired, resulting in eigenmode formation (fig.3). This phenomenon can be clearly seen when the copper foil is present, increasing the quality of the cavity structure and better synchronizing the modes. Such a high-Q cavity can form the interaction region of a novel coherent source excited by a suitable electron beam [6,7].

Samples without the copper foil backing and identical waveguide dimensions have electromagnetic responses that have some similarities due to the common volume field within the dielectric. Fig.4 compares 0.8mm thick samples with different lattice periods (1.74mm and 1.94mm). A shift in frequency of approximately 10 GHz is observed between the two sets of resonances, with those at the higher frequencies corresponding to the smaller lattice period. This frequency shift suggests that the surface field is influencing the behavior of the volume field. The weaker reflection off the back surface of the dielectric, compared with when the copper foil is present may be expected to produce a lower Q volume mode, insufficient to provide the strong synchronization necessary for coherent scattering and clear eigenmode formation as observed in fig.3.

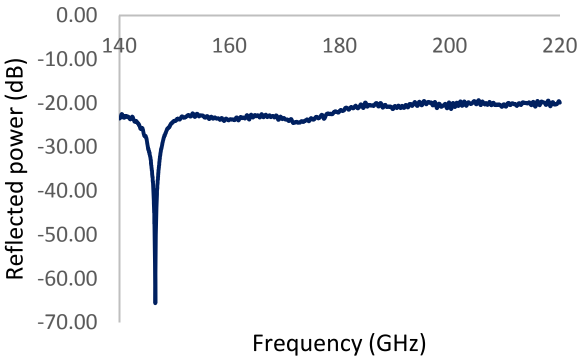

Fig.3 Coherent eigenmode formation due to coupling of surface and volume fields in a PSL with lattice period 1.94mm, dielectric thickness 0.8mm, and a 35 μm copper foil backing.

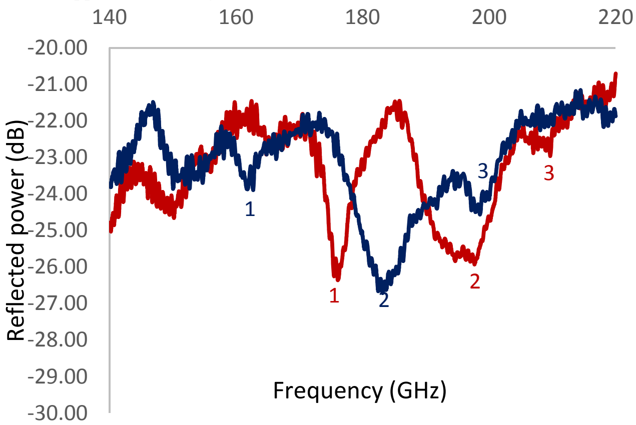

Fig.4 Reflected signal from PSL structures with 0.8mm dielectric substrate with no copper foil backing, irradiated at an incident angle of 30°. The red and blue plots correspond to lattice periods of 1.74mm and 1.94mm respectively. 3 resonances can be identified in each case.

For the set of 1.6mm samples the resonances are less well-defined and not as constrained, possibly due to absorptive losses within the dielectric and also the capability of the thicker dielectric waveguide to become over-moded. The plot provided in fig.5 demonstrates less coherent eigenmode formation for a 1.6mm thick sample with lattice period 1.94mm and copper backing. Around 150 GHz a resonance (~-10dB) is observed, similar to that shown in fig.3. In this case other effects are also present and the volume and surface modes are not tied down to one particular frequency.

For all the structures, the exact position of the resonances is dependent on the angle of irradiation. Fig. 5 shows the variation of frequency with angle. For the 150 GHz resonance the frequency shifts up with increasing angle. However, for the resonance observed around 210 GHz, the opposite is true.

Extending the work in this paper will involve studying PSLs at higher frequencies. New samples are being designed to operate within the 325-500 GHz band. Numerical modelling is being carried out to further understand the coupling of volume

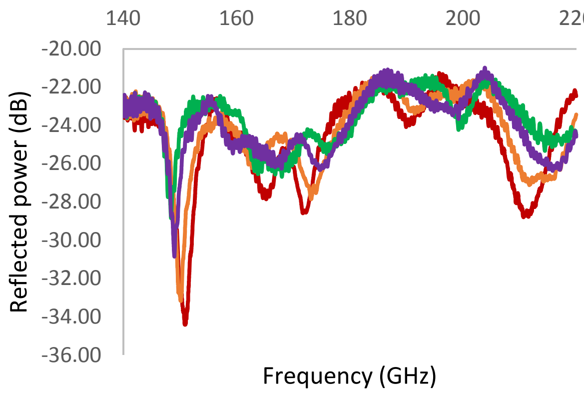

Fig.5 Reflected signal from 1.6mm structure with lattice period 1.94mm and copper foil for various angles of irradiation. The green, purple, orange and red plots correspond to incident angles of 40°, 35°, 30° and 25° respectively.

and surface modes at the lattice interface and the effect of varying dielectric and lattice parameters. Using CST Microwave Studio, a single unit cell is irradiated by plane waves over a range of angles and the scattering parameters are measured by a "Floquet" port. An alternative approach involves modelling a small section of the structure to provide a more realistic representation of the experiment by taking into account phenomena such as edge effects. All the PSLs considered are scalable and these concepts are applicable to a broad range of frequencies including THz and infrared.

III. SUMMARY

The coupling between volume and surface modes and coherent eigenmode formation in PSL structures has been successfully demonstrated. It has been shown that the parameters of these structures must be carefully chosen to facilitate the resonant coupling of modes. When the necessary conditions are met, these structures can provide an interaction region for novel, coherent sources of radiation.

ACKNOWLEDGEMENTS

Amy J. MacLachlan and A. R. Phipps thank the EPSRC for supporting their postgraduate studentships.

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