Surface and volume mode coupling experiments for high power mm-wave sources

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***Abstract*—Periodic surface lattice (PSL) structures have been fabricated and measured. When the required conditions are met, volume and surface waves can couple to form a cavity eigenmode at a frequency determined by the PSL's parameters. The formation of such eigenmodes is relevant to the realization of high-power mm-wave and THz coherent sources.**

Keywords—periodic surface lattice; PSL; surface mode; volume mode; mode coupling; mm-wave sources.

I. INTRODUCTION

Research involving the exploitation of electromagnetic (EM) fields inside and on the surface of periodic lattices is relevant to the realization of high-power, coherent radiation sources operating in the GHz-THz frequency regimes. Such sources are suited to various applications including imaging and security, communications, the quality control of pharmaceutical products and monitoring atmospheric dust clouds and space debris. In order to avoid multi-mode excitation, which is detrimental to the efficient operation of the device, the cavity dimensions of EM sources tend to be comparable to the intended operating wavelength of the source. This decrease in cavity size with wavelength restricts the power output capability of mm-wave and THz sources. Overcoming this challenge, by introducing novel methods of mode selection in oversized cavities, allows high power output capabilities to be maintained at mm-wave and THz frequencies [1-9]. The technique proposed in this work involves the use of periodic surface lattices (PSLs) which, under certain conditions, are shown to facilitate coupling of volume and surface fields, resulting in the formation of a single cavity eigenmode. These structures may be described as high-impedance surfaces or effective metamaterials due to their small corrugation depth in relation to their operating frequency. PSLs of planar geometry, used to demonstrate the fundamental "proof of principle" coupling of volume and surface fields, are considered in this work. Such PSLs can be fabricated into cylindrical structures which can be combined with a suitable electron beam via conformal mapping.

Planar PSLs with different periodicities (1.50mm, 1.62mm, 1.74mm and 1.94mm) designed to operate at the 140-220 GHz frequency band, were obtained using laser and chemical etching techniques. The simplest structures, consisting of 0.3mm thick, copper PSLs without substrates, designed to study the surface field exclusively, were fabricated using laser etching. These PSLs share some similarities to inductive mesh structures used as high band-pass filters [10]. Planar PSLs mounted on dielectric substrates, with a transverse size of 40 periods and corrugation depth of 35μm, were fabricated by etching copper coated FR-4 sheets. To further vary the structures' properties, FR-4 substrates of three different thicknesses (0.4mm, 0.8mm, 1.4mm) and permittivity (5.69, 4.71, 4.45) were used. The permittivity of each sample was established by measuring the phase of a 140-220 GHz signal launched through the sample. For some structures, the copper backing of the coated dielectric sheets was left intact, whilst in the others, the copper was entirely dissolved. It has been shown that the copper backing improves the synchronisation of the lattice by confining the volume field within the dielectric and facilitating the coupling of volume and surface fields.

The PSLs are scalable and can be tailored to operate over different frequency bands. A shorter wavelength, 0.63mm PSL designed to operate within the 325-500 GHz band is photographed in fig.1.

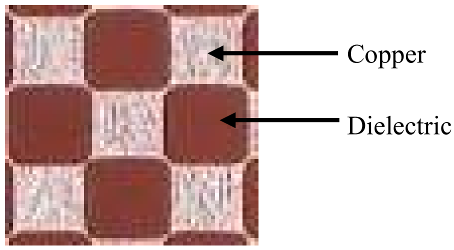

Fig. 1. Magnified image showing a section of the 0.63mm PSL structure designed to operate at 325-500 GHz. The PSL was fabricated using chemical etching techniques and photographed using a Hirox microscope.

II. RESULTS

Experimental measurements were carried out using an Anritsu Vector Network Analyzer (VNA) complemented by a pair of high-frequency heads as shown in fig.2. The PSLs were measured over various incident angles θ_i, whilst keeping the angles of the launching and receiving horns equal, θ_i=θ_r. For the set of mesh PSL structures without substrates, a sharp surface field resonance was measured at a frequency determined by the PSL's periodicity.

The surface field resonances were found to exhibit a clear angular dependence, shifting down in frequency with increasing angle.

With the inclusion of a dielectric substrate but no copper backing, multiple resonances were observed. Fig.3 shows the reflected power for a 1.62mm PSL etched onto a 0.4mm FR-4 substrate and measured over an angular range of θ_i= 40°- 65°. Resonance **3** corresponds to the PSL's surface field, while **1** is an internally reflected volume mode. Resonance **2** is suggestive of weak eigenmode formation due to the poorly synchronised PSL.

Fig. 2. Photograph showing measurements of the 1.50mm mesh PSL made at various incident angles. A pair of G-band horns were connected to 140-220 GHz heads of a Vector Network Analyzer (VNA) used to evaluate the scattering parameters.

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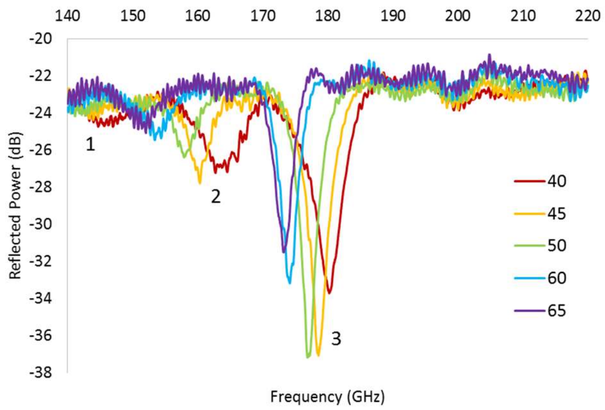

Fig. 3 Reflection measurement for a 1.62mm PSL mounted on a 0.4mm FR-4 substrate with no copper backing. Three resonances relating to volume and surface fields are observed.

Coherent eigenmode formation observed for a 1.62mm PSL mounted on a 0.8mm copper-backed substrate at a fixed incident angle of 45° is shown in fig.4.

The three overlaid traces which were recorded on three different occasions separated in time by several months demonstrate the reproducibility of the results. When the copper is positioned behind the PSL and substrate in an arrangement similar to a Fabry-Perot cavity (with the PSL and copper backing acting as mirrors) the individual lattice perturbations are synchronised by the volume field inside the dielectric. The single resonance is 'mode-locked' to a particular frequency and no longer shifts with incident angle. Such high-Q cavities, when mapped into cylindrical geometry can form the basis of a novel coherent source when excited by a suitable electron beam passing through the cylindrical cavity. The advantage of using such PSLs to form eigenmodes in overmoded structures is that they facilitate the disruption of the usual scaling of output power with frequency. Instead of using conventional scaling ratios of D/λ ~ 1, where D represents the diameter of the cylindrical structure and λ is the wavelength, using this method of eigenmode formation and selection, it is believed to be realistic to achieve coherent, relatively efficient radiation sources with D/λ ~ 7 and eventually D/λ ~ 10. The latter represents a hundredfold increase in the cross-sectional area of the interaction structure, with consequential increases in the maximum output power obtainable from short wavelength mm-wave and sub-THz sources. Because of the mode selectivity provided by the volume mode/surface mode coupling mechanism the device power output and efficiency are not expected to decrease, as is usually the case when insufficient mode selectivity is provided and an overmoded device operates in a multimode manner.

The results of this generic work suggest that sources working at several 100's of GHz can be designed to provide output powers and efficiencies comparable with conventional sources with D/λ ~ 1 operating at lower frequencies such as ~100 GHz.

It should be noted that although printed circuit boards (PCBs) involving dielectric materials have been used for these planar two dimensional "proof of principle" PSL experiments, in an electron beam driven cylindrical PSL the structure is intended to be all-metallic and fully compatible with high vacuum, high power electron beams [11,12] and intense electromagnetic fields. The coherent combination of electromagnetic fields within an over-sized/overmoded structure to produce higher powers is an alternative approach to coherently combining electromagnetic fields together externally from several phase-synchronised discrete sources [13].

The construction of all-metallic cylindrical PSL structures based on the same fundamental mode-coupling principles and suitable for being excited and driven by an electron beam is the subject of another related paper being presented in this Workshop [14].

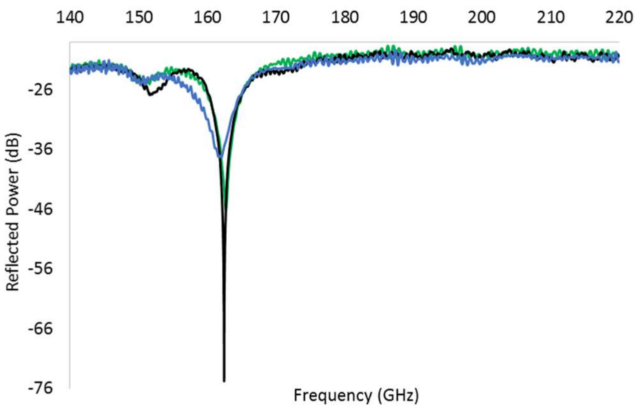

Fig. 4 Coherent eigenmode formation due to coupling of the surface and volume fields for a 1.62mm PSL etched onto a 0.8mm FR-4 substrate with a 35 μm copper foil backing measured at 45°. The 3 overlaid traces demonstrate the reproducibility of the measurements.

III. SUMMARY

The coupling of volume and surface modes and coherent eigenmode formation in planar PSL structures has been successfully demonstrated. The parameters of these structures were carefully chosen to facilitate coherent eigenmode formation and to obtain a single high Q resonance suitable for use in a high-power, high frequency source.

When the necessary conditions are met, PSL structures have the potential to provide effective interaction regions for novel, coherent sources of radiation. All the PSLs considered are scalable and are therefore applicable to a broad range of frequencies from the microwave and mm-wave range and stretching into the THz and far-infrared regions of the electromagnetic spectrum.

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