Exploration of surface waves on pseudo-plasmonic metamaterials

H. J. Rance, A. P. Hibbins and J. Roy Sambles

Electromagnetic Materials Group, University of Exeter
Department of Physics and Astronomy, Stocker Road, Exeter, EX4 4QL, UK.
Tel: + 44 (0) 1392 264187; email: h.j.rance@exeter.ac.uk

Abstract

Some recent results from fundamental microwave studies of surface waves on pseudo-plasmonic metamaterial structures are presented. An exploration of both isotropic and anisotropic surfaces is undertaken and the potential to excite these modes via a novel ‘zig-zag’ geometry is revealed.

1. Introduction

Pendry *et al* [1] have stimulated much interest in the extension of surface plasmon (SP)-like concepts into the long-wavelength regime. Even in the perfectly conducting limit it was predicted [1,2], and later experimentally confirmed [3], that surfaces can support bound SP-like modes at microwave frequencies by texturing the surface on a sub-wavelength scale. An effective penetration depth is achieved by perforating the substrate with indentations (holes, dimples, grooves etc.), such that for frequencies below the cut-off of the indentations the fields decay exponentially into the holes, thus modifying the field matching condition at the surface. Crucially, it is exactly this characteristic that must be met for a surface mode to be supported. The dispersion of the mode asymptotically approaches a cut-off limit, which represents the effective surface plasma frequency. For a hole of infinite depth of side length, a, this is given by

$$\nu_{\text{cutoff}} = \frac{c}{2a\sqrt{\varepsilon_h \mu_h}} ,$$

where c is the velocity of light in a vacuum and ε_h and μ_h are respectively the permittivity and permeability of the material filling the holes. Since this frequency is defined by the structure rather than the composition of the surface, surface waves can therefore be created with chosen dispersion, and are often termed as “designer” or “spoof” SP-like modes.

One way to couple incident radiation to the surface mode, which has in-plane momentum above that possible for a grazing incident photon, is by the addition of a diffraction grating. The periodic corrugation provides the necessary in-plane wave-vector enhancement. However unlike conventional SPs, its placing with respect to the structure of the unit cell of the meta-surface is important. This is the focus of our first study.

Our second study involves breaking the symmetry of the unit cell along the direction of propagation to allow for diffractive coupling to the surface mode on a planar surface with no additional corrugation required. This is achieved by “zig-zagging” rhombus shaped tubes which introduces the necessary long pitch in this direction.

Finally, we utilise phase measurements to directly record the dispersion of a family of surface modes from an array of rectangular cross-section tubes. This provides an excellent opportunity to study surface waves on an anisotropic surface.

2. Grating excitation of microwave surface modes supported by metamaterials

In the grating-coupling of incident radiation to surface modes, their dispersion is perturbed by the grating that provides the necessary momentum enhancement. We show that this is particularly important in the excitation of “spoof” surface plasmons on meta-surfaces (Fig. 1 (a)) whose periodicity is often comparable to that of the coupling-in grating.

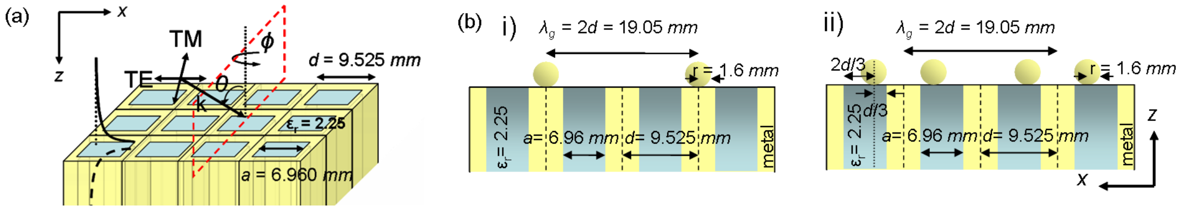

Fig. 1: (a) Plasmonic meta-surface. (b) Two arrangements of the coupling-in grating on the meta-surface.

Two samples have been explored, Fig. 1 (b) using TM polarised incident radiation. The coupling-in grating is formed from metal rods and has two alternative arrangements that maintain equivalent boundary conditions at the opening of every hole, and a 2*d* periodicity. An additional mode is observed when the grating is placed over the dielectric regions, (sample (ii)). The predicted results from finite element method (FEM) modelling [4] are shown in Fig. 2 (a), note that rod position is significant.

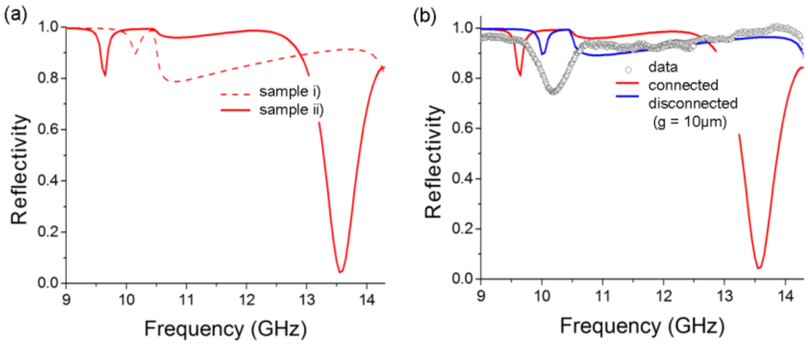

Fig. 2: (a) Predicted reflectivity response at $\theta = 30°$, $\phi = 0°$ from samples (i) and (ii). (b) Experimental data (circles) and FEM modelling, from the connected (solid red line) and disconnected (solid blue line) structure, at $\theta = 30°$, $\phi = 0°$, from sample (ii).

Further a gap (g) between the meta-surface and coupling-in grating of the order of λ/1000 is sufficient to significantly perturb the expected response, resulting in a complete absence of one of the modes (Fig. 2 (b)). These pseudo-plasmonic surfaces should be contrasted to a ‘true’ plasmonic surface, i.e. a metal in the optical regime, for which a translation of the coupling-in grating is irrelevant.

3. ‘Zig-zag’ hole array

The inherent geometry of the ‘zig-zag’ hole array (Fig. 3 (a)) provides the necessary momentum enhancement to couple incident radiation to the surface mode supported by the structure. Hence a SP-like mode can be excited using plane-wave incident radiation on a flat surface with no additional coupling-in grating required. The modelled reflectivity as a function of frequency is shown in Fig. 3 (b), together with the predicted electric field distribution at $\theta = 30°$. Note that the predictions of the electric field on resonance are strongly reminiscent of a SP-like mode [5]. A previously unreported and intriguing result is that the surface mode on the ‘zig-zag’ structure is excited by TE-polarised radiation when the short pitch grating vector lies in the plane of incidence.

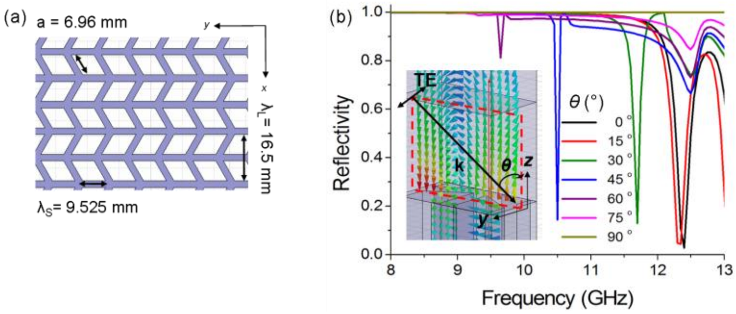

Fig. 3: (a) Schematic representation of ‘zig-zag’ sample. (b) Predicted reflectivity data. Inset: Predicted electric field distribution at $\theta = 30°$.

4. Rectangular hole array

In our final study we chose to directly record the dispersion of surface modes by employing a blade-coupling technique. In order to explore the character of more than just the fundamental surface wave, we exploit the anisotropic geometry of a rectangular unit cell (Fig. 4 (a)) to separate the frequency of the onset of diffraction from the cut-off frequency defined by the geometry of the waveguide.

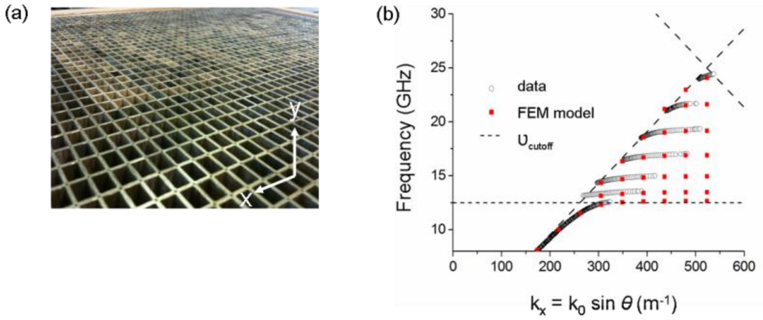

Fig. 4: (a) Rectangular hole array. (b) Experimentally measured dispersion (circles) together with the predictions from FEM modelling (squares).

Hence we can experimentally measure not only the dispersion of the lowest order surface mode, which is asymptotic to ν_{cutoff}, but also the higher order modes associated with the quantization of the field along the length of the guide (Fig. 4 (b)). The dispersion of this ‘family’ of surface modes shows excellent agreement with the predictions from numerical modelling.

References

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