Metamaterials as artificial electromagnetic boundaries in experimental geometries

A. P. Hibbins[1], T. H. Basey-Fisher[2], E. M. G. Brock[1], J. D. Edmunds[1], E. Hendry[1], J. R. Sambles[1], I. J. Youngs[3]

[1]Electromagnetic Materials Group, School of Physics, University of Exeter, EX4 4QL, UK.
Tel: +44 (0) 1392 722100; email: a.p.hibbins@exeter.ac.uk
[2]Nanoplamonics Group, Imperial College London SW7 2AZ, UK.
[3]Dstl, Salisbury SP4 0JQ, UK.

Abstract

We present a summary of work being undertaken at Exeter associated with the use of metamaterials as artificial boundary conditions. Using experimental microwave techniques, and numerical and analytical modelling, we explore geometries including those that facilitate sub-wavelength confinement of surface waves and propagation in waveguides beyond their conventional frequency range.

1. Introduction

The patterning of surfaces with small, closely spaced elements is well known to influence their interaction with electromagnetic radiation. For example, early radar engineers [1] considered the addition of a sub-wavelength corrugation to a metal: the geometrically induced surface reactance strongly binds surface modes at the interface. More recently the concepts of electromagnetically "hard" and "soft" surfaces [2] have been borrowed from acoustics to describe such surfaces. The former describes a surface with reflection coefficient $r = -1$ (i.e. the reflection form a perfect electrical conductor (PEC), e.g. a metal in the microwave/radar or terahertz regimes), and the latter, $r = +1$. Of course, the latter does not occur naturally, and metamaterial substrates that provide this "magnetic wall" boundary condition are referred to as Artificial Magnetic Conductors (AMC) [3].

In the work presented in this article, we undertake a number of studies that demonstrate how metamaterial surfaces ("meta-surfaces") can be utilised to introduce artificial boundary conditions in experimental geometries. We employ analytical and numerical modelling to provide understanding of the interesting phenomena observed.

2. Laterally Confined Surface Waves

Transverse-magnetic (TM) polarised surface waves are guided by the interface between a dielectric and a substrate if the permittivity of the substrate is dominated either by a negative real part, or a large positive imaginary part. The negative real permittivity leads to an inductive surface impedance, a condition which is met for metals in the visible regime. The modes supported are known as "surface plasmons" since they correspond to the hybridisation of a grazing photon with the resonance of the electrons at metal's surface. The latter condition, i.e., a large imaginary permittivity, is met for metals in the microwave regime, where the surface impedance of metals has small and equal resistive and inductive components. Hence these surface waves are only loosely bound and are essentially simple surface currents. However patterning of these highly conducting metals with an array of sub-wavelength inclusions or cavities can enhance the surface reactance [1] below their resonant frequency. In essence, the grazing photon hybridises with the structural resonance to produce a strongly bound surface wave [4].

In this study we discuss our experimental validation of a recent theoretical study, which suggests that a chain of closely spaced metallic cuboids ("dominos") in contact with a metallic surface (Fig. 1a) can support laterally confined modes ("domino plasmons") [5]. TM-polarised radiation, incident in a plane orthogonal to the dominoes' long axes, excites transverse electromagnetic (TEM) waveguide modes within each of the parallel-sided cavities that separate the domino elements. Quantization along the depth of the cavity produces a family of standing wave resonances. The boundary condition at the top of the dominos, at frequencies below the fundamental resonance, is therefore somewhat analogous to that of the surface of a Drude metal in the visible regime (e.g., Ag or Au), with fields exponentially decaying into each cavity. These meta-surfaces are thereby able to support bound TM surface waves that are cut off at this resonant frequency. Crucially, when the sides of the domino chain are left open, the boundary condition at the edges of the cavities resembles a magnetic wall. Therefore there is no component of the magnetic field tangential to these boundaries, and there is no means of quantization along the cavity width. Not only is the mode propagation insensitive to the chain's width, but this width, L, can even be made sub-wavelength with little effect (Fig. 1b).

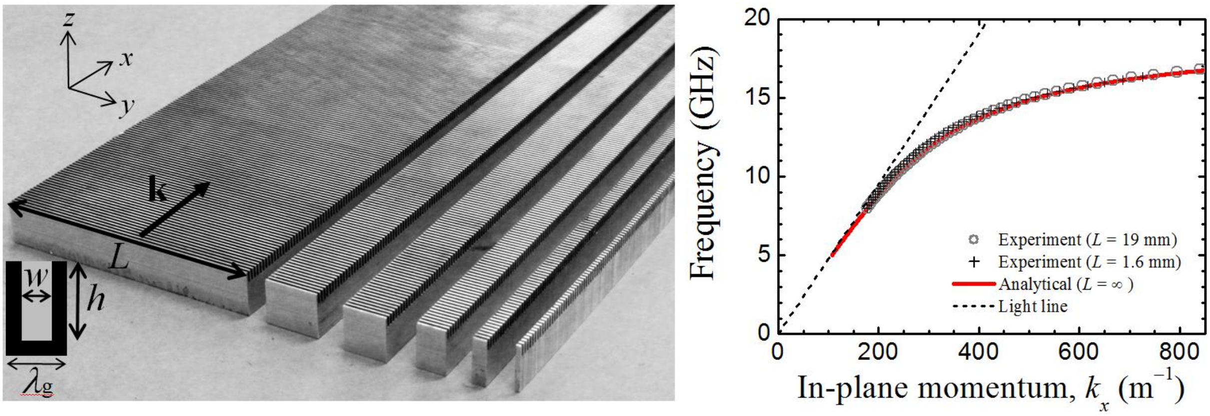

Fig. 1: (a) Experimental samples, L = 100 mm, 19 mm, 15 mm, 10 mm, 5 mm and 1.6 mm (left to right). The periodicity of the corrugation, λ_g = 1.6 mm = 2w, and the cavity depth, h = 3.75mm. (b) Vector network analyser phase measurements of the dispersion of the surface mode for two different lateral widths. Also shown is the prediction from a modal-matching analytical model [6] for $L = \infty$. Note that all experimental samples, apart from L = 100 mm and L = 19 mm have lateral widths smaller than the resonant wavelength of the surface wave.

3. Waveguides Beyond Cut-off

This study has been inspired by the work of Shin et al [7] who demonstrated that open-ended holes in plasmonic metals (e.g., Ag and Au in the visible regime) support propagating modes below the cut-off of PEC-walled structures. Hence, we demonstrate that there is potential for extending the operational bandwidth of conventional metallic microwave waveguides by introducing artificial boundary conditions. A meta-surface, comprised of an array of dielectric-filled sub-wavelength holes, replaces two opposite walls within a square cross-section waveguide (Fig. 2a). The holes in the walls are themselves designed to be beyond their own cut-off in the frequency region of interest, hence providing an inductive surface impedance at two of the waveguide walls. Experimental observations are compared to the predictions of numerical modelling, and we demonstrate that the conventional cut-off frequency of a waveguide may be decreased by around 15% (Fig. 2b).

4. Resonant Mirror Fabry-Perot Cavities

Arrays of metallic crosses are employed as the reflecting surfaces in a Fabry-Perot (FP) cavity (Fig. 3a inset). The resonant frequency of these cavities was found to be shifted from the typical condition $(f = cN/2d)$, with the direction of the shift dependent on whether the FP-cavity mode is above or below the fundamental resonant frequency of the crosses (f_+) [8]. The shift is due to the frequency dependent phase response of the arrays close to f_+, which results in a change of boundary condition of the reflecting planes. Below f_+, the reflecting plane is capacitive, and hence the FP cavity appears shorter than its physical length. Conversely, f_+, the impedance of the reflecting plane is inductive and the cavity is effectively made longer.

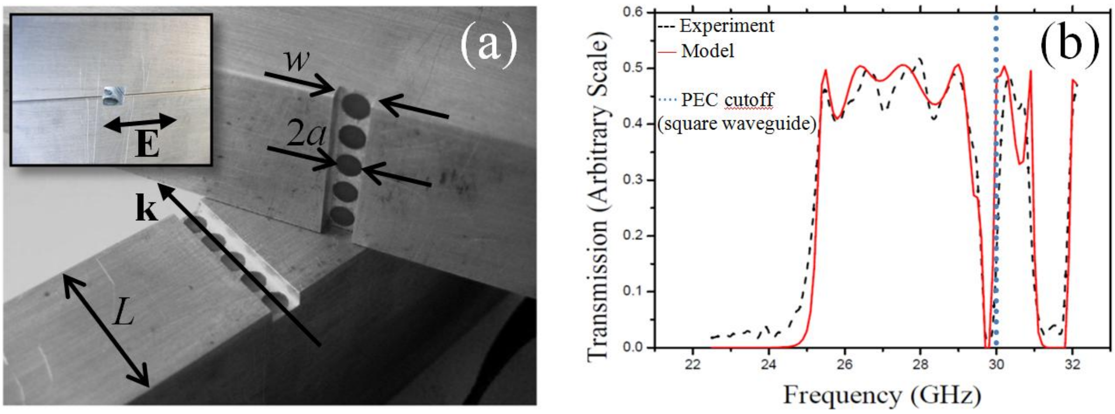

Fig 2: (a) Waveguide fabrication from aluminium blocks. L = 25.4 mm, w = 5.0 mm, a = 2.0 mm, cylindrical holes depth, d = 15 mm, refractive index of dielectric filling cylindrical holes, n = 1.5. (b) Experimental transmission of waveguide sample, and predictions from finite element method modelling [Ansoft HFSS]. The cut-off frequency of an untextured waveguide sample is also shown. The oscillations and stop-bands in the transmission are associated with the finite length of the waveguide, and the finite number of holes along its length.

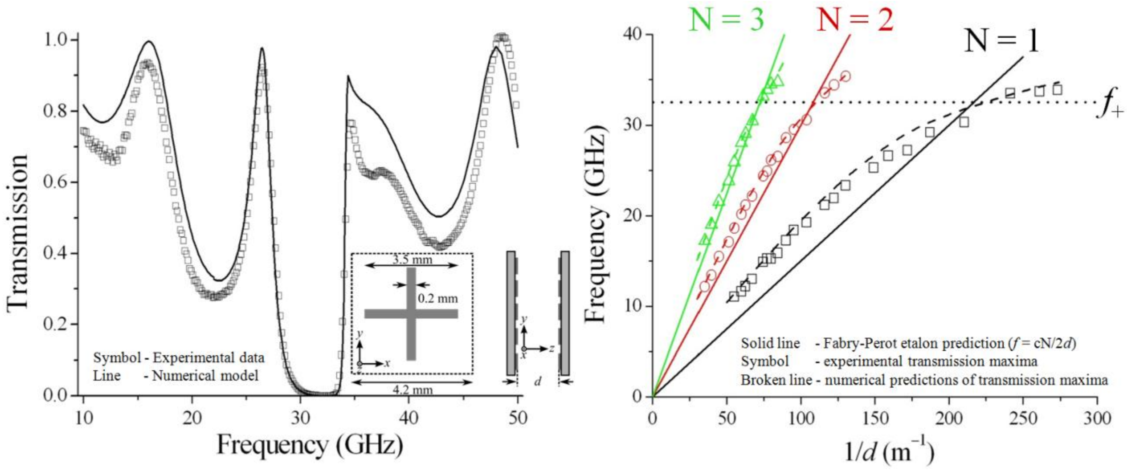

Fig 3: (a) Experimentally measured transmission through a FP-cavity bounded by parallel arrays of metallic crosses, separated by d = 11.9 mm (inset). (b) Transmission maxima plotted as a function of $1/d$. The first 3 modes are shown. Below the resonant frequency of the crosses (f_+), the effective length of the FP-cavity is increased beyond its physical length, while the opposite is true above f_+. The array of crosses behaves as an ideal conductor at f_+, and hence the resonance of the FP cavity coincides with the conventional cN/2d condition.

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