32nd URSI GASS, Montreal, 19-26 August 2017

Metamaterial Mediated EM Wave Amplification

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1. Extended Abstract

The use of Metamaterials for applications in Electromagnetics from MHz to optical frequencies has gained substantial interest in both research and industry across the world. Where a range of applications have been proposed and in some cases realised, such as antennas, phase-shifters, couplers, broadband/compact power-dividers and other devices such as beam steerers, modulators, band-pass filters and lenses.

Metamaterials are artificial sub-wavelength composite materials, that derive their properties not from there material composition but from their sub-wavelength geometry. The sub-wavelength scale is used so that collectively the structures act as a homogenised effective material, where the interaction between these materials and an EM wave can be described in terms of the, bulk, averaged response functions, permittivity (ε) and permeability (μ). These artificial materials offer the opportunity to specifically engineer the materials ability to, control, enhance and suppress EM wave propagation though these materials, either in a specific direction or altogether.

In this presentation we examine EM wave amplification mediated via novel artificial materials. We consider the difference in amplification between a simultaneous positive permittivity/permeability (DPM) and a simultaneous negative permittivity/permeability material (DNM), often referred to as a metamaterial. We start with Parametric Amplification between two waves, where energy is transferred between a pump wave (ω_1) to the signal frequency (ω_2). Where the interaction uses the frequency dependence of the permittivity/permeability such that ω_1 sees a DNM and ω_2 sees a DPM media, hence the Poynting vector and wave vector of ω_1 propagate in opposite directions. The amplification of ω_2 occurs through a three-wave coupling by converting the energy of the pump field ω_1 to the signal field ω_2.

We follow this discussion by considering the case where the pump signal is replaced by a charged particle beam. Using the charged particle beam to produce an EM field that replaces the pump field ω_1. In essence the metamaterial is engineered to act as a slow wave structure synchronising the EM wave phase velocity to the average beam velocity. The amplification process in these structures is explored using forms of Madeys theory and Pierce Theory to examine small and large signal gain respectively. Where we have modified Madeys theory and Pierce Theory to take into account the beam/wave interaction is mediated via a metamaterial.

We show that the introduction of a metamaterial gives rise to a novel dispersion curve that determines a unique amplification process via the frequency dependence of the metamaterial. Demonstrating that a metamaterial offers an additional factor to controlling the gain-frequency characteristics, compared to the conventional slow wave structures. In addition we show that as the charged particle beam potential is increased the frequency at which maximum energy exchange is achieved is shifted towards a lower frequency. We note that even for large differences in accelerating voltage the frequency shift is small, although this does offer a precise way to tune the frequency of operation of a metamaterial device. The disadvantages are that operation is bandwidth limited and highly dependent on the design of the artificial material used.