Active Metamaterials with Gain Compensation

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Metamaterials are artificial composite materials that can provide unique and useful properties that do not normally exist in natural materials and may lead to many new and exciting capabilities for electromagnetic applications. However, many of the practical applications are limited by two fundamental issues that have not yet been solved, namely, loss and narrow bandwidth inherently associated with a typical passive metamaterial.

Introducing active gain or negative impedance in a metamaterial can theoretically overcome the intrinsic loss and narrow bandwidth issues of passive metamaterials [1]. This approach has been sought after for both optical and microwave regimes [2]. Besides overcoming the intrinsic loss and bandwidth limitations, active metamaterial may provide unconventional material properties such as negative conductivity in addition to the well-known negative permittivity and permeability, thus leading to more degree of freedom in application designs.

In this talk, active metamaterial incorporating gain medium / device will be briefly reviewed first. Experimentally demonstrated 1-D composite right- / left-handed transmission lines with simultaneous negative phase constant and negative attenuation constant [3, 4] will be discussed. Measurement results on the linear and nonlinear properties of the 1-D transmission line will be presented. Balanced and un-balanced designs as well as a zero-th order antenna consist of a single unit-cell [5] will be described. In addition, volumetric negative index structure based on wire and split-ring resonator arrays with net gain will be presented. This active metamaterial with embedded microwave tunnel diodes at the unit cell level exhibits a band-limited Lorentzian dispersion with an over-compensated loss (gain) and a negative refractive index is demonstrated [6]. It shows examples of sub-wavelength wire and SRR cells with embedded resonant tunneling diode with negative differential resistance (NDR). This kind of active metamaterial design is very interesting because of its versatility. For example, by incorporating the NDR diode in the wire (permittivity) / SRR (permeability) part of the unit cell, activeness associated with the permittivity / permeability can be selected independently, as shown in Fig. 1. Therefore, various model systems can be realized to investigate the rich physics related to active metamaterial.

Another promising aspect of active metamaterial is the possibility of realizing desired broadband effective medium properties without tradeoff of high loss. We will also review non-Foster circuit based active metamaterial with broadband behavior. We will discuss some remaining obstacles to realize a lossless and wideband metamaterial. For example, stability is a major challenging issue and should be rigorously considered in designing useful active metamaterial. Stability analysis methodology using return difference (or Normalized Determinant Factor) method based on Bode's feedback theory is developed. Circuit models are firstly built and a parametric study is conducted to find out the stable region and parasitic effects of active non-Foster element. Case study of an electrically small dipole antenna matched with negative impedance circuits is conducted [6].

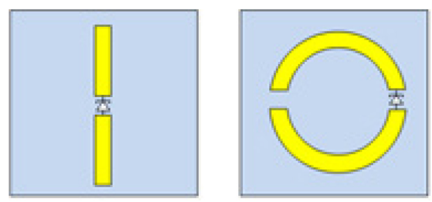

Figure 1. A schematic example of a NDR diode-loaded active metamaterial unit cell to compensate loss or provide gain while maintaining its negative permittivity (left) or negative permeability (right).

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