Sub-Wavelength Focusing and Dispersion Characteristics of Negative Refractive Index Transmission Line Media

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Materials exhibiting simultaneously negative values of permittivity and permeability have received widespread attention in recent years. John Pendry's (J.B. Pendry, Phys. Rev. Lett., **85**, 18, 3966-3969, 2000) prediction that a perfect lens could be made of such materials has revived interest in media exhibiting a negative refractive index (NRI), which were initially investigated by V.G. Veselago in the 1960's. The first implementation of a NRI composite material employed metallic wires to achieve negative permittivity and split-ring resonators to achieve negative permeability (R.A. Shelby, D.R. Smith, S. Schultz, Science, **292**, 77-79, 2001). Recently, a periodic L,C loaded two-dimensional transmission line (TL) network was shown to exhibit electromagnetic properties associated with NRI media. This network consisted of transmission line sections loaded with shunt inductors and series capacitors. It has been referred to as a dual TL structure due to its high pass configuration, as opposed to the low pass representation of a conventional TL. Previous work experimentally demonstrated backward-wave radiation leakage (A. Grbic and G.V. Eleftheriades, J. Appl. Phys. **92**, 10, 5930-5935, 2002) and focusing at microwave frequencies using such dual TL structures (G.V. Eleftheriades, A.K. Iyer, and P.C. Kremer, IEEE Trans. Microwave Theory Tech., **50**, 12, 2702-2712, 2002).

In this work, we present a periodic (Bloch) analysis of the dual TL structure to explain its various passbands and stopbands. From the analysis, useful design equations are derived and expressions for the effective material parameters are found at frequencies of homogeneous and isotropic NRI operation. The issues of impedance matching, proper termination and excitation of finite size structures are also addressed. Moreover, the two-dimensional dispersion characteristics of dual TL media are examined. Based on this analysis, the criteria for sub-wavelength focusing using dual TL slabs are established and sub-wavelength focusing results using a lens consisting of a dual TL structure are shown.