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Subwavelength Focusing and Resolution with Hyperbolic Transmission Line Metamaterial

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***Abstract*—We show the potential of using two dimensional hyperbolic metamaterials (HMs) made of microstrip transmission line (TL) grids loaded by lumped components for achieving subwavelength focusing and resolution at microwave frequencies. The designed planar HM exhibits a very flat wavevector-dispersion diagram over a wide frequency range, signature of the so-called canalization regime. The canalization regime allows us to transfer the field profile of a single point source at the interface through the HM, with full width half maximum of $\lambda_g/69$, where λ_g is the guided wavelength in the isotropic TL grid at 200 MHz. We also report the ability to resolve two point sources with subwavelength distance of $\lambda_g/15$.**

I. Introduction

Hyperbolic metamaterials (HMs) recently attracted attention for their ability to support a very wide spatial spectrum of propagating waves, much wider than the propagating spectrum in free space [1]. Recent applications of HMs include negative refraction and subwavelength focusing. The latter requires the transfer of both propagating and evanescent spectra emanated by a source to the focusing location. Transfer of wide spatial spectra can be achieved by using metal-dielectric multilayers [2], wire media [3], [4], and HMs [1], [5], [6]. Note that in such media the transfer does not make use of amplification of evanescent spectral components as in slabs with negative refractive index [7]. In this paper, we employ HMs for subwavelength applications. In [8], [9], "resonance cones" were observed both theoretically and experimentally in planar HMs comprising *LC*-loaded transmission line (TL) grids that allow subwavelength focusing [8]. Moreover, a periodic metal-dielectric layered HM exhibiting extremely flat dispersion diagram over a wide spatial spectrum has been reported for imaging with subwavelength resolution at optical frequencies [6], with $\lambda/20$ resolution using glass and metal layers. Here, we utilize a planar TL HM with very flat wavevector iso-frequency dispersion diagram. The very flat dispersion diagram has been associated to the so-called *canalization* regime [2], [3], [6] for which a wide spectrum is allowed to propagate with almost the same phase constant inside the HM medium. In this paper, the realization of very flat HM dispersion is obtained by employing two-dimensional (2D) loaded TL grids. We employ them for the purpose of demonstrating subwavelength focusing of the field emitted by a source located at the interface between an isotropic medium and a HM. We also show spatial resolution of two sources with subwavelength inter-distance.

II. Transmission Line Hyperbolic Metamaterial

We report in Fig. 1 the schematic of the 2D microstrip TL grid on a grounded substrate here proposed. The structure comprises two regions, namely the upper isotropic region [referred to as background medium, and depicted in light green in Fig. 1(a)], and the lower HM region [depicted in light blue in Fig. 1(a-b)]. The latter is made of microstrip lines periodically loaded by series lumped capacitors [unit cell is shown in Fig. 1(b)].

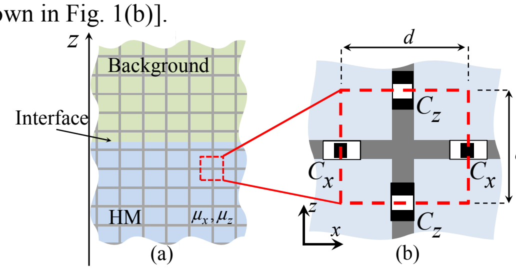

Figure 1. (a) Illustration of the 2D TL grid comprising background (isotropic) and HM regions. (b) HM unit cell including the lumped components.

The wavevector dispersion inside the TL-based HM can be evaluated by employing two methods, namely Bloch theory [10] and homogenization theory [9]. The latter is here explained in order to give a physical insight to the propagation of waves in HM. When the metamaterial period d is much smaller than the guided wavelength in the HM ($k_{x,z}d \ll 1$, with $k_{x,z}$ the transverse and longitudinal wavenumbers, respectively) and the wavelength in the microstrip TL ($\beta d \ll 1$, with β the wavenumber), the dispersion relation is of the form

$$\mu_x^{-1}k_z^2 + \mu_z^{-1}k_x^2 = \omega^2\varepsilon \qquad (1)$$

where

$$\mu_x = L_{\text{dis}} - \left(\omega^2 C_z d\right)^{-1}, \quad \mu_z = L_{\text{dis}} - \left(\omega^2 C_x d\right)^{-1} \qquad (2)$$

are the entries of a permeability tensor in Cartesian coordinates and $\varepsilon = 2C_{\text{dis}}$. The TL branches along *x* and *z* are loaded by capacitors C_x and C_z, respectively, as illustrated in Fig. 1(b). Furthermore, L_{dis} [H/m] and C_{dis} [F/m] are the distributed (per-unit-length) inductance and capacitance of the isolated microstrip line, and $\beta = \omega\sqrt{L_{\text{dis}}C_{\text{dis}}}$ is the wavenumber in the microstrip TL. For multilayered three-dimensional HMs it has been shown that when close to the edge of the Brillouin zone, homogenization theory is in disagreement with Bloch theory [1]. Similarly, in this planar case due to periodicity in both *x* and *z* directions, we observe a slight disagreement between the two methods close to the Brillouin-zone edge. However, for the design reported in Sec. III, the two methods are found to be in perfect agreement (not shown for brevity).

III. Subwavelength Focusing and Resolution

Equation (2) is used to design a 2D TL HM. The design consists of a printed circuit board on a FR4 grounded substrate with relative permittivity $\varepsilon_{\text{FR4}} = 4.5$ and 0.76 mm thickness. We use a short circuit for C_z and $C_x = 0.005\,\text{pF}$ (realized by a gap on the microstrip branches along the *x* direction, designed with full-wave simulations in HFSS, a commercial finite-element solver from Ansys Inc.) that lead to $\mu_x > 0$ and $\mu_z < 0$, resulting into hyperbolic dispersion. Both background and HM TL grids are here made of 1.5mm-wide microstrip lines with 1cm×1cm unit cell dimensions. There are 12×23 cells in the background region and 11×23 cells in the HM region where the interface is normal to the *z* axis as depicted in Fig. 1(a). The size of the designed circuit board is 23cm×23cm ($0.4\lambda_g \times 0.4\lambda_g$), where $\lambda_g = 57.5$ cm is the guided wavelength in the background medium (unloaded TL grid) at 0.2 GHz. The circuit board model is schematically implemented using the microwave circuit simulator ADS (Agilent's Advanced Design System). The edges of the TL grid are terminated by resistances close to the proper Bloch impedances [10] of the waves emanating from the impressed source such that the reflection from the edges of the circuit board is minimized. We report two different simulation results: First, we exert *a single* shunt voltage source at the center of the interface between the background and the HM and show the focusing capability. Secondly, we exert *two voltage sources* with subwavelength separation distance ($\approx \lambda_g/15$) and show that we are able to resolve the two sources. In Fig. 2(a), we show the voltage sampled on microstrip lines along the interface between background and HM regions, where the source is exerted, and along the background (+*z*) and HM (−*z*) edges of the circuit board. It is observed that the voltage profile along the HM–background interface is transferred to the lower HM (−*z*) edge without any significant change, whereas on the upper background (+*z*) edge the source peak feature is lost. We observe that the source full width half maximum of $\lambda_g/69$ is preserved across the HM. We then show in Fig. 2(b) the resolution of the two sources located at the background-HM interface, for which we obtain similar conclusions as the case described in Fig. 2(a), i.e., the two sources are resolved at any constant-*z* line within the HM, whereas the same does not happen in the isotropic region (background upper edge). This result shows the importance of employing HMs exhibiting flat dispersion diagrams for subwavelength applications. The focusing results have been further verified experimentally (not shown here) using the fabricated sample of the circuit board described at the beginning of this section, and found in very good agreement with the results reported in Fig. 2(a).

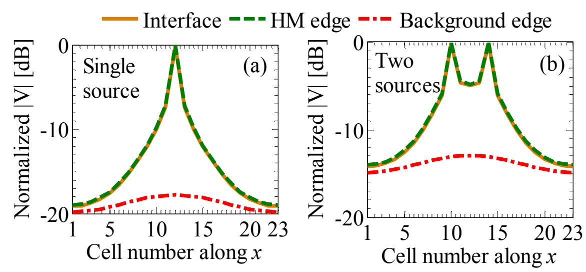

Figure 2. The voltage profile (normalized by the maximum voltage) along the background-HM interface, and along the lower HM (−*z*) edge and the upper background (+*z*) edge when (a) a single voltage source is placed at the interface center, and (b) two sources with subwavelength spacing ($\approx \lambda_g/15$) are placed at the interface, at 0.2 GHz.

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