Beam Forming Using a Zero-Phase-Shift Metamaterial

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Introduction

The science of metamaterials has presented the microwave community with a means to tailor permittivity and permeability including negative values [1]. The attraction of metamaterials stems from the possibility of realising a perfect lens from a planar slab of material exhibiting negative permittivity and permeability, called a left-handed material, is placed in a medium with positive permittivity and permeability, called a right-handed material [2]. A common microwave problem is to form a beam from a divergent source. A slab of left-handed material with graded refractive index can be used to form a beam [3][4]. A homogenous left-handed material can form a beam if one surface is parabolically shaped [5]. Metamaterials based upon the transmission line approach offer wide bandwidth compared to those constructed from resonators [6].

When left-handed and right-handed unit cells are alternatively cascaded, a relatively frequency insensitive zero phase shift can be achieved by a finite length guiding structure [7][8]. This phenomenon is termed infinite wavelength [7]. Infinite wavelength phenomena can be extended to two-dimensions using square-shaped left-handed and right-handed tiles arranged in a checker-board tessellation [9]. An important property of this tessellation is that once excited, plane waves emanate from straight edges of the tessellation and this can be used to transform cylindrical waves to plane wave [10]. However, a straight edge of the tessellation is sub-optimally matched to cylindrical waves leading to significant reflection and a slab of the tessellation is unable to focus a beam down to a point.

In this work we consider curved boundaries to the checker-board tessellation to improve matching to a cylindrical wave, and their application in a sectoral feed.

Zero-Phase-Shift Metamaterial

Fig. 1 shows a schematic of one part of the checker-board tessellation and lumped element equivalent circuits of the both types of square unit cells or tiles. Both tiles are 4-port circuits with the right-handed tiles (R) and the left-handed tiles (L) characterized respectively by a negative or positive insertion phase between any pair of ports. Both tiles can be realized using planar circuit technology [5][6].

If the left-handed tile parameters are C_L = 8.036 pF and L_L = 80.36 nH, and the right-handed tile parameters C_R = 0.318 pF and L_R = 3.18 nH, then at 1 GHz, the insertion phase between any pairs of ports is 11.3° and -11.3° for the left-handed and right-handed tiles respectively [10]. Using conventional transmission lines, the right-handed tiles are 0.031λ by 0.031λ, and are therefore electrically small. The left-handed tiles can be constructed to have the same physical size and therefore both tiles are much less than a wavelength. At 1 GHz, waves propagate across the checker-board tessellation with zero phase shift – thereby exhibiting infinite wavelength [8] in two-dimensions [9]. We call this structure the zero-phase-shift metamaterial or ZPS metamaterial.

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Matlab code was written to analyze large metamaterial structures comprising thousands of tiles, and includes a graphical-user-interface for editing each tile, or regions of tiles, of a large array. An absorbing boundary was placed on the perimeter of the analysis domain. Upon execution, the spatial response at a specified frequency is presented: (i) cosine of node voltage phase to reveal wavefronts, and (ii) magnitude of node voltage in dB to show levels of transmission and reflection.

In this work we considered domains 200 by 79 tiles or 6.27λ by 2.47λ. The homogenous right-handed medium in which the ZPS structures are immersed are constituted from the same right-handed tiles used in the ZPS. The extent of the domain as well as the very small size of the constituent tiles is consistent with material concepts [1]. Across the ZPS structure, the magnitude and phase of the node voltages does not vary [9] so are not shown and rather a filled polygon is used to indicate the position and shape of the ZPS structure.

Cylindrical Lens

When a slab of the ZPS metamaterial in a right-handed medium is excited, plane waves emanate from its edges [10]. When the right-handed medium has the same Bloch impedance as the ZPS metamaterial slab, a normal incident plane wave will pass through the slab unattenuated [10]. Whereas for either a cylindrical wave or an oblique plane wave incident on the rectangular slab, both reflection and transmission of normal plane waves [10]. In both cases, transmission is significantly reduced compared to a normal incident plane wave.

The proposal here is to shape an edge of the ZPS metamaterial region to match the shape of the wavefront. That is, for a cylindrical wave, the edge should be concave circular whose radius is equal to the distance, *r*, between the edge and the location of the focal point, *f*, as shown in Fig. 2(b). The ZPS lens was implemented with the above mentioned left-handed and right-handed tiles. The radius of curvature was 50 tiles or 1.57λ at 1 GHz.

Fig. 2 shows the spatial response at 1 GHz when a point source is placed at the focal point. It is apparent from Fig. 2(a) that the incident cylindrical wavefronts are parallel to the concave edge of the lens. From Fig. 2(b), the reflection coefficient is estimated to be -11 dB. So although there is some reflection at the concave edge of the lens, compared to a rectangular ZPS slab, the reflection is reduced by around 6 dB and transmission increased by around 2 dB. Simulations of a normal incident plane wave on the straight edge of the ZPS lens showed that it focuses the beam to the focal point on the concave side.

Sectoral Lens Feed

The proceeding section has demonstrated the beam forming properties of the concave ZPS lens. We now consider a sectoral shaped feed from a narrow transmission line to the concave edge of the lens. The width of the narrow end of the feed is 7 tiles or 0.22λ and the narrow end the taper begins at the lens focal point. Fig. 3 shows this feeding arrangement. The side boundaries of the transmission line and tapered section are open-circuit to mimic transmission line behavior. The left most end of the narrow transmission line is match terminated. Otherwise an absorbing boundary is placed along the rectangular perimeter of the analysis domain.

Fig. 3 shows the spatial response when a point source is placed in the narrow transmission line feeding the tapered section. Cylindrical waves emanate from the junction of the transmission line and the tapered section and are formed into a beam by the ZPS lens. The match is not perfect and this is somewhat due to the geometric implementation restrictions resulting from finite sized square tiles. The transmission is higher than the corresponding case in the previous section which stems from the concave edge of the lens interfacing directly to a guided wave structure rather than an unbounded region. Simulations showed that a plane wave normal incident on the straight edge of the lens focused into the transmission line.

Conclusion

In this paper, we have demonstrated that a zero-phase-shift metamaterial lens structure with a concave edge and a straight edge can form a beam from a point source or focus a beam into a point. The zero-phase-shift metamaterial lens was constituted from equal-sized left-handed and right-handed square tiles and arranged in a checker-board tessellation. The left-handed tiles have an insertion phase between any two sides equal to but opposite to that of the right-handed tiles. The addition of a tapered transmission line to feed the concave edge of the lens improves the transmission and could serve as a useful component in a planar power divider.

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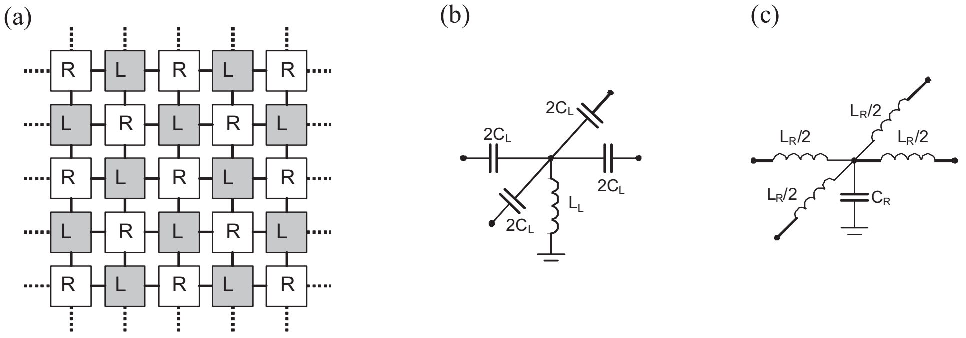

Figure 1. Defining schematics: (a) part of the checker-board tessellation, (b) equivalent circuit of the left-handed tiles (L), and (c) equivalent circuit of the right-handed tiles (R).

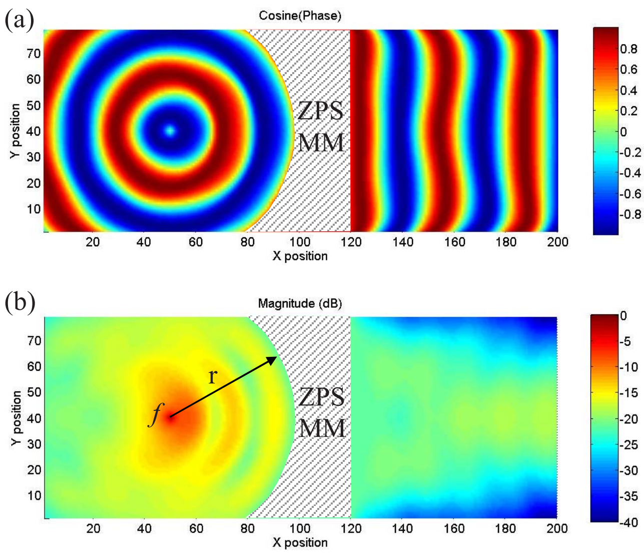

Figure 2. Node voltage spatial response at 1 GHz when a ZPS lens in a right-handed medium is excited by a point source located at the focal point: (a) cosine(phase), and (b) magnitude in dB. (In color.)

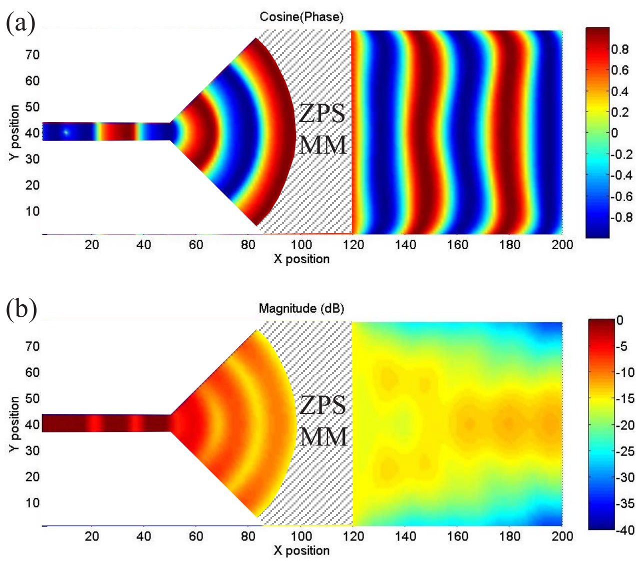

Figure 3. Node voltage spatial response at 1 GHz when a ZPS lens is fed by a tapered transmission line with source driving the transmission line: (a) cosine(phase), and (b) magnitude in dB. (In color.)