On the Nature of Transmission in Resonant Metamaterial Transmission Lines

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Abstract

A detailed analysis of the transmission that occurs in various scenarios of a host medium with a capacitive gap and complementary split-ring resonator (CSRR) combination is presented. This is a typical situation where it is expected that left-handed propagation will occur in a certain band of frequencies. We now show that Epsilon-Near-Zero (ENZ) transmission may be obtained by tailoring the host structure geometry.

1. Introduction

Recently, a new subclass of metamaterials, Epsilon-Near-Zero (ENZ), was introduced for waveguide structures [1]. Subsequently, we have demonstrated the first implementation of ENZ structures in microstrip [2]. In this paper, our research on ENZ structures is extended. In the resonant approach to metamaterials [3], it is well established that the combination of a Complementary Split-ring Resonator (CSRR) and a gap in the transmission line host creates a left-handed transmission line over a narrow band of frequencies. In this work, we present a detailed analysis of the transmission that occurs in various scenarios of the CSRR and gap combination. We show how to obtain ENZ transmission, rather than the expected LH transmission, by tailoring of the parameters of the host structure.

2. Configurations under Analysis

The host structure is a half-wavelength resonator (HWLR), loaded with a single-ring CSRR etched in the ground plane, Fig. 1(a). CSRR is designed using 0.3 mm gaps, with the overall dimensions equal to a x b. Typically, the gaps of the resonator provide negative permeability and the CSRR is responsible for negative permittivity just above the CSRR resonance, resulting jointly in a left-handed transmission. The frequency at which μ is negative is determined by the gap series capacitance. Increasing this capacitance, e.g. using an interdigital capacitor instead of a simple microstrip gap, Fig. 1(b), will decrease the frequency of the zero crossover point for μ. In both host configurations, two CSRRs were considered: one with a=8.8 mm and b=10.3 mm, and the other with a=3.9 mm and b=4.2 mm. The smaller CSRR exhibits a resonance above the resonant frequency of HWLR, while the larger one resonates below the HWLR. This is clearly visible in the responses of all configurations, Fig. 1(c): they are all dual-band, where one transmission peak corresponds to HWLR resonance, while another transmission peak and a corresponding transmission zero are results of presence of the CSRR. In this work, we analyse in detail the nature of these new transmission peaks and zeros.

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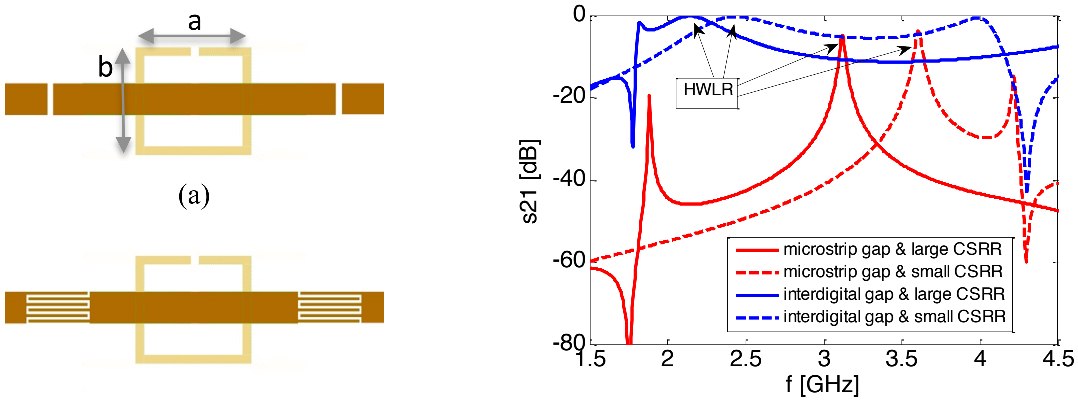
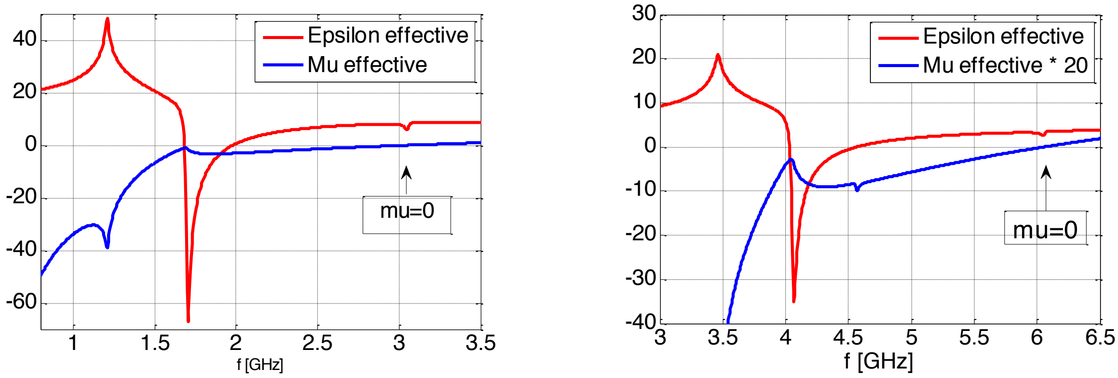


Fig. 1: Layout of the CSRR-loaded half-wavelength host structure with (a) microstrip gap and (b) interdigital capacitor. (Dark colour represents copper, light colour is the CSRR etched in metallization on the bottom layer.) (c) Responses of all four configurations analysed in this work.

3. Analysis of Structures

Effective parameters were extracted for a unit cell which consists of a microstrip gap over a CSRR, following [5] and [6]. The extraction was performed for all four cases and the results are shown in Fig 2 and Fig. 3, respectively. It can be seen that the capacitance of a conventional gap results in a negative μ from low frequencies to well over the resonance of the CSRR and the ENZ point, Fig. 2. As expected, the passbands that occur in both cases are of LH nature. The transmission zeros correspond to evanescent propagation i.e. to single-negative medium due to negative permeability and to increased values of imaginary parts of effective epsilon and mu. However, this is not necessarily the case when the capacitance of the gap is sufficiently increased, e.g. when the interdigital capacitor is used instead of a simple microstrip gap. The interdigital capacitor was designed in such a manner that it exhibits μ =0 at lower frequencies then previously. In the case of the larger CSRR, again the LH transmission is observed below the host resonance, Fig. 3(a). However, in the case of the smaller CSRR, μ is positive and ENZ transmission occurs above 4 GHz, Fig. 3(b). This is the special case out of four examples.

To validate the nature of the transmission for HWLR with interdigital capacitors, the phase of the z-component of the electric field has been extracted along a line halfway between the ground plane and microstrip layer, and calculated using FEKO. Fig. 4 shows this phase vs. position, at the central frequency of each passband. It can be seen that only in the case of the small CSRR, the phase shift across the length of CSRR is reduced to practically zero, which is consistent with ENZ media.



(a) (b)

Fig. 2: Extracted effective parameters for microstrip gap and CSRR with the resonant frequency (a) below host resonance, (b) above host resonance

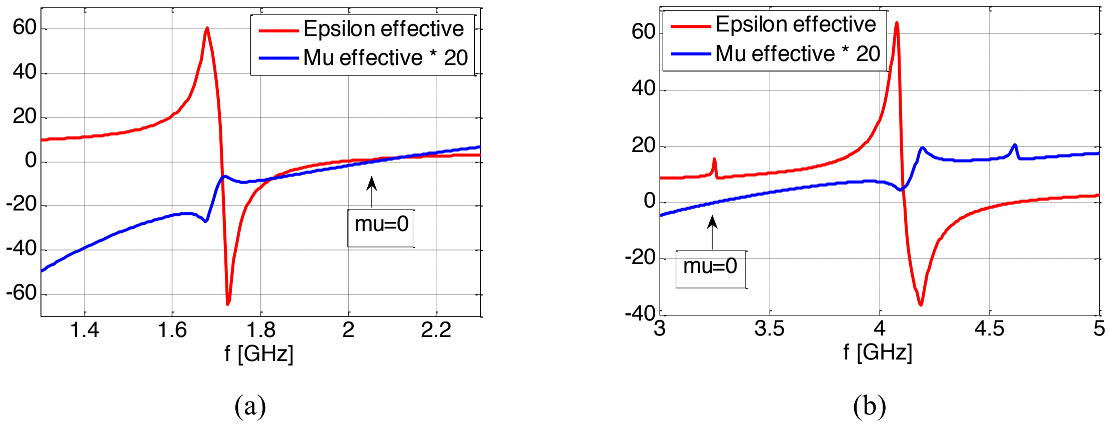


Fig. 3: Extracted effective parameters for interdigital gap and CSRR with the resonant frequency (a) below host resonance, (b) above host resonance

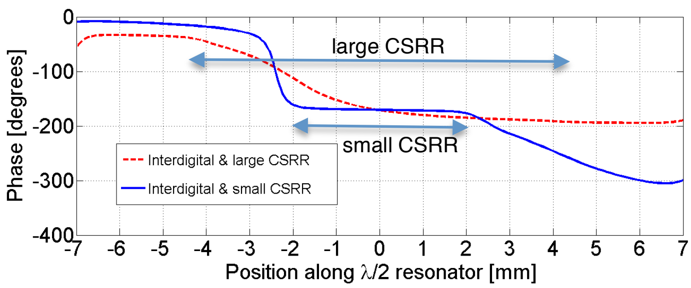


Fig. 4: Extracted phase versus position for the interdigital cases of Fig. 1(b) at the respective CSRR resonant frequencies shown in Fig. 1(c). The small CSRR extends from -2.1 to 2.1 mm and the large CSRR extends from -4.4 mm tot 4.4 mm. Over these regions the phase should be constant in the case where the propagation is ENZ.

4. Conclusion

We demonstrated that it is possible to manipulate the parameters of a host structure coupled to a CSRR particle, to obtain ENZ propagation, in cases where one would normally expect LH transmission. This will find application in the design of practical structures, e.g. filters and antenna feeding networks, based on this phenomenon.

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