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Tunable Split-Ring Resonator Photonic Crystals for Left-Handed Electromagnetic Meta-Materials

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Abstract

Tunability of split ring resonator (SRR) arrays and back plane strip elements (plasmon meshs), known to achieve left handed metamaterial was investigated using varactor diodes connected between the split rings. Numerical simulations and measurements were carried out when these elements were placed in a slotted microwave waveguide. The slotted waveguide medium was preferred to simplify the connectivity of the bias voltage power supply to change the junction capacitance of varactor diodes. The resonance frequency of the split ring resonator and back plane strip configuration was determined using single element loaded waveguide measurements. The effect of the arrays of such elements, assembled into 2-d and 3-d photonic crystals, were measured and additional resonances were observed below the expected resonance frequency of the split ring resonator configuration due to internal interaction of the structure with the surrounding waveguide. Reverse bias voltage was applied to varactor diodes and tunability in terms of shift of the resonance frequency of SRR, broadening of the stop band region and further increase in the transmission loss due to loading with varactor diodes were observed. Preliminary numerical simulations are in agreement with the measurements. Further optimization for higher tunability is in progress for achieving tunable left handed metamaterials.

Introduction.

Meta-materials are viewed as a new class of artificial multi-component structures with superior physical (particularly electromagnetic) properties, not achievable in separate components. Creation of such functional structures meets two types of challenges: design of the optimal geometry and choice of proper constituent materials combination (able to provide new physics) and development of an appropriate processing method for fabrication.

Over 30 years ago a Russian scientist Victor Veselago [1], has predicted very unusual electromagnetic (EM) properties for a hypothetical material having both negative dielectric permittivity $\varepsilon(\omega)$ and negative magnetic permeability $\mu(\omega)$. If such material is created, it should have *negative refractive index n*, the *sign of Doppler effect* should be opposite to that of usual matter, and the *Cherenkov radiation cone* should direct *backward rather than forward.* The direction of the Poynting vector of power flow ***S*** and EM wave propagation vector ***k*** should have opposite signs and the *photon pressure would revert to photon tension.* Veselago [1] has also predicted that the shaped lenses made of left handed (LH) matter would be reversed due to negative refractive index, which has been recently proven for microwave frequency by Smith . What is even more interesting, the rectangular slab of LH matter should act as a new type lens called a super-lens.

A paper has been published recently that experimentally describes such a material called a left handed "meta-material" [3]. This first left handed meta-material represents the two-dimensional centimeter-scale periodic structure formed of an array of metallic rods, accountable for the negative $\varepsilon(\omega)$, alternated with an array of split ring resonators (SRRs), presumably accountable for the negative $\mu(\omega)$. The experimental work was based on the theoretical prediction by Pendry *et al.* [3] that the array of SRR (split ring resonators) should provide magnetism not by magnetic moments like in natural magnetics, but due to the loop currents flowing in the conductive rings strongly resonating with each other. While a split-in-ring topology allows better resonant coupling between rings and decreases the resonance frequency, largest down-shift in resonance frequency occurs due to capacitance between two coaxial rings [2]. Surprisingly, San-Diego University team's direct experimental reproduction of the suggested SRR geometry had simply led to the EM waves propagation with a pass band opening in the region of ω where $\varepsilon(\omega)$ and $\mu(\omega)$ exhibited negative values. Although this band is found in quite narrow frequency range located around 4 GHz, it appears to be consistent with the prediction of a left-handed material. Still the paper has prompted for many doubts both on the validity of negative $\mu(\omega)$ and the actual 1D character of the medium used in experiment. Unfortunately it is physically impossible to verify most interesting manifestations of left-handed matter properties like super-lens effect or negative refraction index $n < 0$ using the very construction described in the paper. High-frequency resonance characteristics of individual SSR greatly depend on the internal capacitance and inductance that are administered by the inter-rings distance and the ring's split size. Thus, by changing only these two geometrical parameters one may effectively control the value of μ. However, once desired value is obtained, it can not be altered until a new structure is fabricated having a new set of geometrical parameters. Thus, a meta-material built upon fixed geometrical parameters lacks the tunability option.

The core idea of our present work is to incorporate tunability as an additional functionality in the left-handed metamaterials. As an example previously demonstrated left handed structure formed of posts and SRRs could be altered to include tunability of its refractive index by converting internal capacitance and inductance from fixed to variable parameters, and thus create tunable meta-materials for microwave and high-frequency applications. We proposed to introduce tunable capacitive and inductive regions utilizing ferroelectric and/or ferrite materials for field coupling for tuning in 1-D, 2-D and 3-D L-H photonic crystal structures. The proposed structures are expected in mm to cm physical dimensions covering millimeter wave to microwave bands yielding further miniaturization using higher dielectric constant materials as well as further effort will be extended to optimize the tunability range and to achieve a wider band operation.

Results.

Tunability of split ring resonators has been investigated in the waveguide environment. Rectangular waveguides have been thoroughly analyzed and provide advantages over the open region structures due to well defined wave interactions such as propagating modes.The waveguide used in this study was WR-187 waveguide with physical dimensions (1.872 X 0.872 inches) and a cut-off frequency of 3.152 GHz. For the accurate verifications of the resonace frequency measurements were also carried out in a WR-284 waveguide of dimensions (2.840 X 1.340 inches) and a cut-off frequency of 2.078 GHz. The dominant TE_{10} mode was excited during these simulations and measurements.

The split ring resonator dimensions aresimilar to one used in [3]. The substrate material used was GETEK with thickness of 10 mils and relative dielectric constant $\varepsilon_r = 4.2$. The tuning element consists of an array of three split ring resonators coupled to a strip on its back plane. In left-hand configuration, the back plane strip of the three element array is grounded. Each such cell in an array has the inter cell spacing of 17.5 mm.

The split ring resonator and the back plane strip is initially placed into a WR-187 waveguide. The purpose in the choice of this type of the waveguide is to keep the resonace frequency away from the cut-off frequency. Measured result in Figure 2 show that the split ring resonance occurs around f = 3.45 GHz far away from the cut-off frequency of 2,078 GHz.

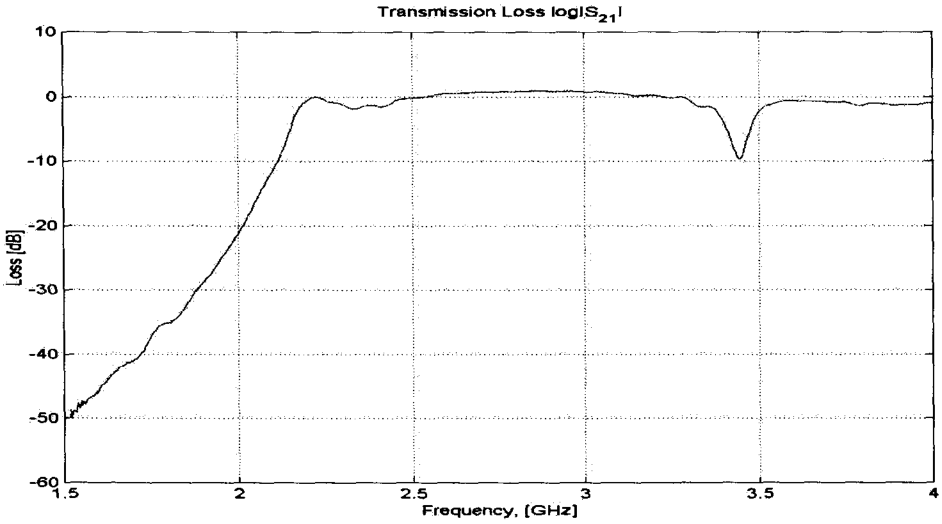

Figure 2. Transmission loss of the split ring resonator and a back plane strip in a rectangular waveguide (WR-284).

As the number of cells consisting of a split ring resonator and a back plane strip are doubled the resulting interaction results in a more complicated resonance behavior as shown in Figure 3.

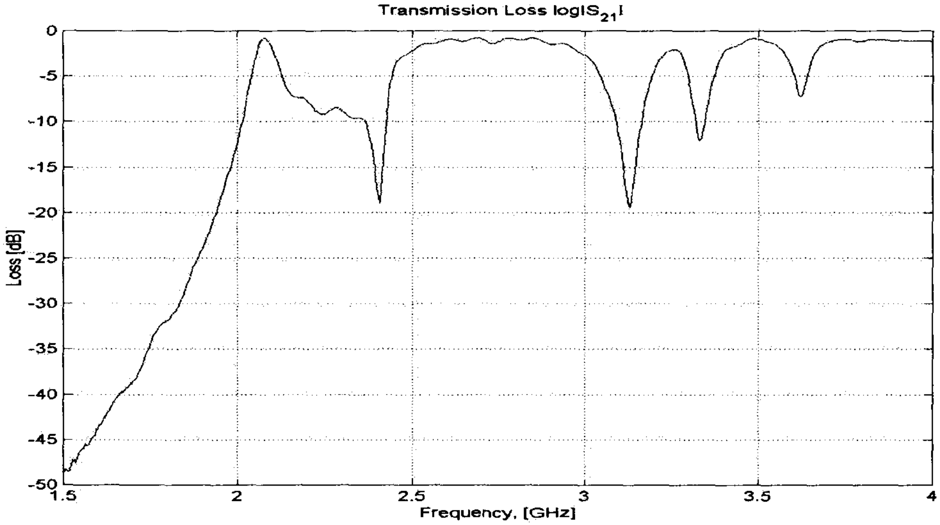

Figure 3. Transmission loss of the two elements each consisting a split ring resonator and a back plane strip placed in a rectangular waveguide (WR-284).

As more elements are inserted into the waveguide, the energy is coupled into split ring resonators and more attenuation in the pass band is observed.
The comparison for the different number of split ring resonator elements are summarized in Figure 4.

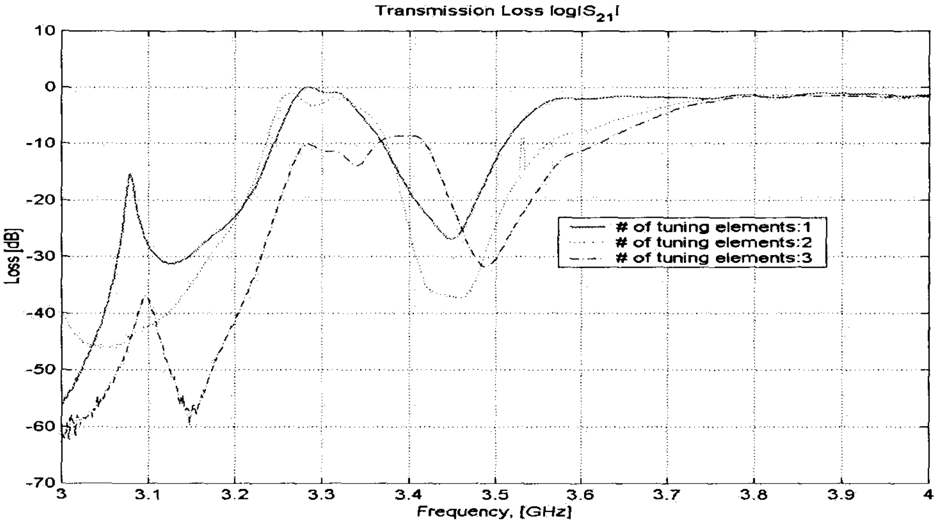

Figure 4. Transmission loss for different number of split ring resonator elements.

The tuning in split ring resonator geometry was achieved by connecting a varactor diode between two split rings. The diode used was M/A COM MA 46H200 with package type 1088. The tuning range varied with capacitance variation in the range of 0.2-1.2 pF. Three arrays of tuning elements consisted of split ring resonators, varactor diodes and a back plane strip.

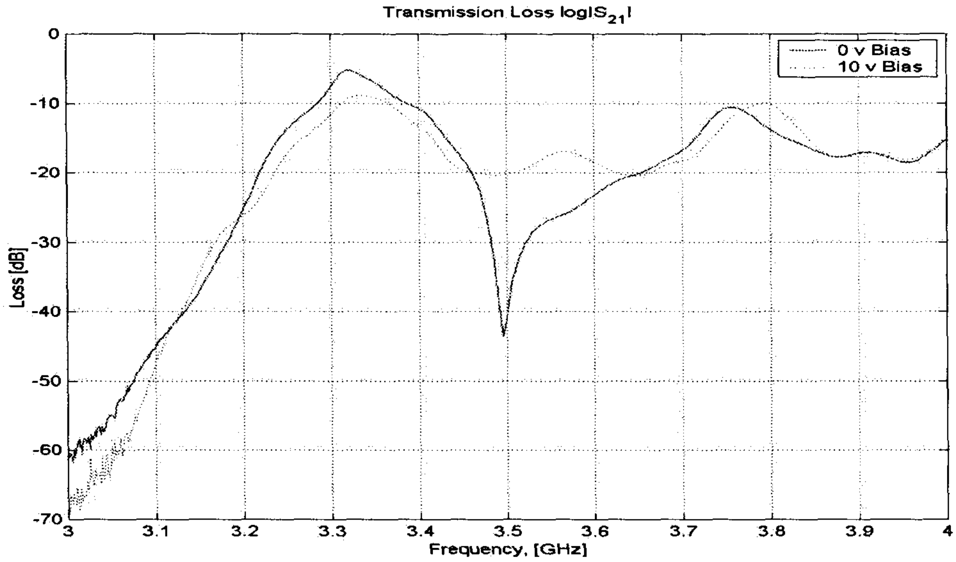

Figure 5. Transmission loss of tunable single array element placed in a rectangular waveguide (WR-187) with a cut-off frequency of 3.0 GHz. Each element consists of an array of three split-ring resonators and varactor diodes backed by strip on the back plane.

As seen in Figure 5, the bias voltage changes the resonance region of the array element as well as introduces little loss due to finite Q of the varactor diodes used. There were slight variation from sample array to another. The tuning is also achieved using three arrays placed parallel to each other near the slot region of the waveguide .

Tunability have been observed up to 5 GHz which is primarily limited by the varactor diode limitations. Additional resonances appeared due to interaction between the waveguide and the tuning array elements. There is pass band region which is a precursor to the left hand media observed between 3.6 and 3.8 GHz. However, only three arrays did not induce high losses as reported for the left handed media. As observed before shifting the bias to 10 V introduced only light loss.

References:

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