Extreme subwavelength electric GHz metamaterials

P. W. Kolb[1], T. S. Salter[1], J. A. McGee[1], H. D. Drew[2], W. J. Padilla[3]

[1]Laboratory for Physical Sciences
8050 Greenmead Dr., College Park, MD 20740
Fax: 301-935-6723; email: pkolb@lps.umd.edu, tsalter@lps.umd.edu, mcgee@lps.umd.edu
[2]Department of Physics, University of Maryland
College Park, MD 20742
Fax: 301-314-9465; email: hdrew@umd.edu
[3]Department of Physics, Boston College
Boston, MA 02467
Fax: 617-552-8478; email: willie.padilla@bc.edu

Abstract

We investigate GHz metamaterial resonator arrays that respond to only the electric field with the goal of reducing the resonator size in comparison to the excitation wavelength. By exploiting capactive coupling between the "electrodes" of adjacent resonators, we achieve a large effective capacitance and strong coupling to the applied electric field. By adding meander lines to connect the electrodes, we are able to lower the resonant frequency to obtain a ratio of wavelength to resonator size of about 30. In contrast to other low-frequency designs, our designs do not require vias and maintain strong coupling to the applied field.

1. Introduction

Of great interest in the field of metamaterials is achieving some effective permeability μ which may not be otherwise achievable with natural materials for applications such as large-bandwidth patch antennas [1], negative index lenses [2], RF lenses [3] and cloaks [4]. For some applications electric resonances may be preferred to magnetic ones [5], and an "electric-LC" (ELC) resonator design that respond only to the electric field was demonstrated by Schurig et al. who also proposed a low-frequency design [6]. Lowering the resonant frequency while keeping the size of the resonator cell the same increases the ratio of the operating wavelength to the cell size; this strengthens the validity of the effective parameter approximation of the metamaterial and mitigates complications such as spatial dispersion [7, 8]. In this paper, we evaluate the low-frequency design of Schurig et al. [6] and investigate designs that are more effective.

2. ELC designs

Our simulations of the original ELC design by Schurig et al., their proposed low-frequency, and four of our alternative designs are shown in fig. 1. In the first case, shown in fig. 1(a), the resulting transmission compares favourably with published results [6] with the ratio λ/a being about 7 at the minimum transmission where a = 3.33 mm, the resonator cell size. In general, the resonant frequency should follow $f \propto \frac{1}{\sqrt{LC}}$ where L and C are the inductance and capacitance of the resonator, respectively. Our simulation of the proposed low-frequency design does indeed show in fig. 1 (b) that the resonant frequency is lowered significantly with $\lambda/a \approx 31$, but the transmission only drops to about -2 db indicating a very weak coupling of the resonator to the applied electric field.

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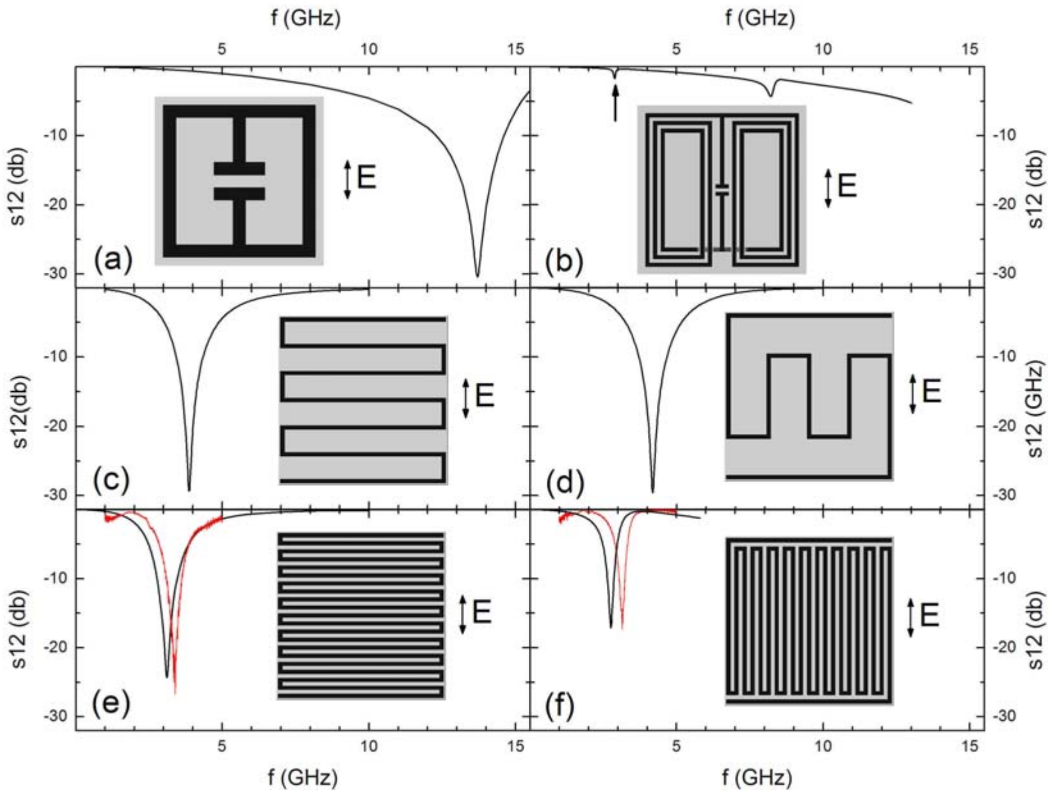

Fig. 1. Simulated transmissions at normal incidence through a variety of ELC resonator arrays: (a) the original ELC resonator demonstrated by Schurig et al. [6], (b) their proposed low-frequency design, (c) a low-frequency design with meanders parallel to the resonator "electrodes," (d) a low-frequency design with mirror symmetry of resonator cells with perpendicular meanders, (e) a design with the maximum number of parallel meanders and (f) a design with the maximum number of perpendicular meanders (and mirror symmetry). The electric field is polarized vertically relative to the orientation of the inset schematics. Transmission measurements through corresponding fabricated arrays are shown in (e) and (f).

To improve upon this design, we move the "capacitor electrodes" as far as possible to the edge of the cell and add inductive meanders inside the cell. The former produces considerable capacitive coupling to the adjacent upper and lower cells which adds in parallel to the internal capacitance of the resonator and lowers the resonant frequency. Meanwhile the coupling to the applied field remains strong. We reduce the gap and wire width to no less than 0.003" because this is the smallest gap and width reasonably achievable by current etching techniques.

The inductive meanders can be added either parallel to or perpendicular to the electrodes as shown in figs. 1(c) and 1(d) respectively. In the latter case, the simulations predict optical activity which shows up as rotation of the incident (vertical) polarization A signature of bi-anisotropy, the optical activity can be effectively eliminated by replacing the exact periodicity of the resonators with mirror periodicity. The simulations show the resonant frequency drops as the number of meanders and overall inductance increases. Of course, the physical limitations ultimately dictate how many meanders can be added in this way, in our case at 19 for parallel meanders (not including the electrodes themselves) and at 21 for perpendicular meanders; the resulting simulated frequencies are 3.12 GHz ($\lambda/a \approx 29$) and 2.76 GHz ($\lambda/a \approx 34$) as shown in figs. 1(e) and 1(f) respectively. In both cases, the attenuation of the transmission is about -20 db at the resonant frequency.

Square arrays with approximately 12 inch sides corresponding to the geometries of figs. 1(e) and 1(f) were fabricated. To avoid possible complications due to potential variances in the permittivity that have been associated with FR4 [9], we decided to use Rodgers 5870 instead. Measurements of the transmission through the arrays were made relative to the transmission without the arrays using horn antennas and intervening RF absorbing foam (to reduce multiple reflections). The resulting measurements, plotted in red in figs. 1(e) and 1(f), show a slightly higher resonant frequency than the simulations but otherwise agree quite well. The slight discrepancy we ascribe to the difference in the permittivities of FR4 and Rodgers 5870, reported to be 4.4 and 2.33 respectively.

3. Conclusion

We have used simulations to test metamaterial resonator arrays with responses to only the electric field to understand how to reduce the resonator size in comparison to the excitation wavelength without greatly reducing the coupling strength to the applied electric field. We are able to mitigate the frequency-coupling competition by exploiting capactive coupling between the electrodes of adjacent resonators to simultaneously achieve a large effective capacitance and a large surface area for coupling to the applied electric field. By adding meander lines to connect the electrodes, we are able to further lower the resonant frequency to obtain a ratio of wavelength to resonator size of about 30 at 3 GHz and still achieve about -20 db drop in transmission at the resonant frequency. Designs using meander lines perpendicular to the electrodes require the addition of mirror symmetry in the arrays to defeat optical activity.

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