Controllable Magnetic Metamaterial Using Digitally Addressable Split-Ring Resonators

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***Abstract*—An ideal metamaterial is composed of identical elements in a uniformly structured array so that the material response is a single magnetic or electric resonance. Variations in the metamaterial particle characteristics or array assembly result in undesirable broadening of the effective material response. When lumped circuit elements are used in metamaterial particles, this effect can be significant due to element variability. To mitigate this effect, we designed, fabricated, and characterized a magnetic metamaterial in which the response of each particle can be individually tuned. Such a material can be reconfigured into a variety of states for use in different applications.**

***Index Terms*—Tunable metamaterials.**

I. Introduction

THE field of metamaterials has seen significant progress in recent years, and ever since the pioneering work of Pendry [1] and Smith [2], researchers have sought utility for their exotic electromagnetic response. In designing a metamaterial for a specific application, it is desirable to be able to predict its response by analyzing an individual unit cell. One can predict the behavior of a metamaterial medium composed of an array of cells by assuming the cells are identical and in identical environments. However, for a realistically fabricated array of resonant magnetic or electric elements, variations of the intercell spacing or variations in the unit cell structure changes the coupling between resonators, which tends to broaden, weaken, or split the resonant response of the medium [3]. Even element parameter tolerances as low as $\pm 5\%$ can lead to strongly damped responses, reducing the performance of the metamaterial [3]. Adding tunable or switchable elements to a metamaterial structure can create a frequency-agile metamaterial. Approaches for realizing such a material include embedding varactor diodes [4], [5], semiconductors [6], ferroelectric-based tunable capacitors [7], and microelectromechanical switches [8] in split-ring resonators (SRRs). However, the detrimental effects of interelement variability are typically increased when fixed or variable lumped-circuit elements are embedded in the metamaterial structure because of the imperfect tolerance of these elements.

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II. Design Approach

We present an approach to reduce these sources of variation and increase the flexibility of a tunable metamaterial through an architecture that enables control over individual metamaterial elements with a small number of control lines independent of the number of elements in the overall metamaterial. Each SRR is loaded with a microwave varactor diode to tune its self-resonant frequency. We demonstrate this approach for a magnetic metamaterial composed of SRRs, although it can also be applied to electric metamaterials. We integrate a *Maxim* one-wire digital potentiometer configured as a variable voltage divider within each SRR to realize a computer "addressable" tunable SRR network. The individually addressable digital potentiometers enable the adjustment of the varactor diode bias loading each SRR. The fabrication and lumped element variations can be essentially eliminated, since each SRR in the medium can be adjusted to resonate at the same frequency. Moreover, the easy reconfigurability provided by this approach enables the creation of metamaterials with unusual transmission and reflection properties, some of which we demonstrate.

We begin by describing a tunable magnetic medium with the Lorentz model, given by [1]

$$\mu_r = 1 + \frac{F\omega^2}{\omega_0^2 - \omega^2 + j\frac{\omega\omega_0}{Q}} \tag{1}$$

where $\mu_r = \mu_r' + j\mu_r''$. $F = \mu_0 A_{\text{loop}}^2 / L_{\text{eq}} v_{\text{cell}}$ and $Q = \sqrt{L_{\text{eq}}/C_{\text{eq}}}/R_{\text{eq}}$ are the oscillator strength and quality factor of the resonance [9], and $\omega_0 = (L_{\text{eq}}C_{\text{eq}})^{-1/2}$ is the resonant frequency of the medium. The parameters L_{eq} and C_{eq} are the equivalent inductance and capacitance of each oscillator, R_{eq} is the equivalent resistance of each oscillator, A_{loop} is the area of each SRR, and v_{cell} is the volume of each unit cell in the medium [9]. To make the medium tunable, we insert *Skyworks SMV*1405-079 hyperabrupt junction tuning varactor diodes into each SRR gap to change C_{eq} and thus tune the self-resonant frequency of the SRRs. A dc voltage is required to bias the diode C_d, and an isolation capacitor (C_s) placed in series with the diode prevents the source from shorting. C_s must be carefully chosen since it is important in determining the tunable range (range of resonant frequencies excited by the ring) of the particle. Our design target is a material with a center resonant frequency of roughly 900 MHz, and *Ansoft HFSS* was used to iteratively find the SRR dimensions on FR4 substrate for this target frequency. The diode and isolation capacitances are much larger than the gap capacitance, so most of the electric field energy will be confined within C_d and C_s. Particle losses will be dominated

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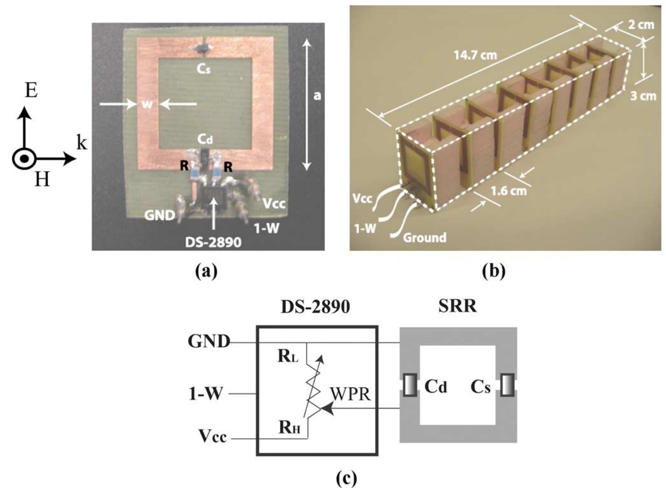

Fig. 1. (color online) (a) Addressable unit cell, where $w = 3$ mm and $a = 20$ mm. $R = 127$ kΩ isolates SRR from the bias lines. Varactor C_d tunes between 0.63 and 2.67 pF, and $C_s = 1$ pF is used to isolate V_{cc} from ground. The vector triplet shows that the SRR is excited when the incident magnetic field pierces the loop area. (b) Fabricated addressable metamaterial. (c) Schematic showing integration of the DS-2890 digital potentiometer into the tunable SRR.

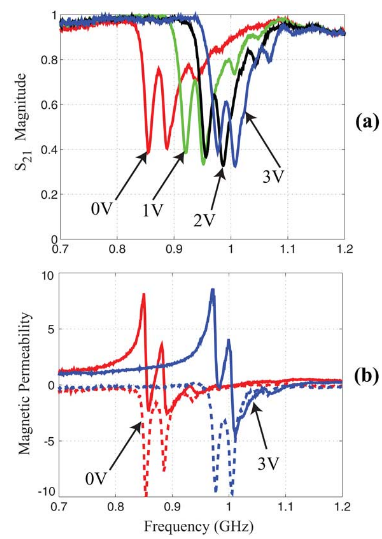

Fig. 2. (color online) (a) S_{21} through the 8-cell slab without control of SRR resonances for external biases $V_0 = 0$ V, $1V$, $2V$, and $3V$. (b) Retrieved magnetic permeability (μ_r' is solid, μ_r'' is dashed) for the uncontrolled medium ($V_0 = 0$ V, $3V$ applied across all diodes).

by the diode, isolation capacitor, and the copper ring trace. Designing a SRR that yields the largest oscillator strength F requires minimizing the self-inductance of the ring while maximizing its enclosed area [9]. A ring design to achieve this is shown in Fig. 1(a) with side length $a = 20$ mm and trace width $w = 3$ mm, which has an inductance $L_{\text{eq}} \approx 35$ nH. When loaded with the diode and a surface mount capacitor $C_s = 1$ pF, the particle tuned over a range of approximately 110 MHz (from 890 MHz to 1 GHz).

III. Fabrication and Measurements

The fabricated addressable medium (with eight unit cells) is shown in Fig. 1(b), where V_0 is applied between V_{cc} and ground. The one-wire line (1-W) is connected to a computer, where software is used to locate and control the state of each DS-2890 potentiometer. Fig. 1(c) shows the layout of the SRR loaded with the digital potentiometer circuit. *Maxim* DS-2890 digital potentiometers were used, which have a 256-position linear taper through resistance values between 0–100 kΩ [resistance between *WPR* and R_L pins is shown in Fig. 1(c)]. Multiple DS-2890 chips can be linked together and operated independently through a common one-wire bus. An external bias V_0 applied between R_H and R_L biases each diode independently between $0 - V_0$ volts by adjusting the resistance between *WPR* and R_L. Only three external signals (0, V_{cc}, and 1-W) are needed for each particle. Each fabricated particle [Fig. 1(a)] has three pins to enable connection to another particle so that any number of particles can be linked together. The addressable slab was placed in a microstrip waveguide, where transverse electromagnetic (TEM) fields were used to retrieve the effective permeability of the slab using standard retrieval techniques [10]. This waveguide approach has been used to retrieve the effective parameters of various metamaterials in the microwave regime [7], [11].

A. Measurements Without SRR Addressing

A *HP-8720A* vector network analyzer measured transmission and reflection, and Fig. 2(a) shows the measured transmission coefficient (S_{21}) of the assembled tunable slab tuned for a single bias voltage without exploiting individual SRR addressing. In other words, $WPR = R_H = 100\,\text{k}\Omega$ was set for all DS-2890 chips so that the same voltage V_0 was dropped across each diode. In Fig. 2(a), S_{21} is shown for $V_0 = 0$ V, $1V$, $2V$, and $3V$. It is clear from the plot that the medium tunes in frequency, but the variance in the diode capacitance results in multiple distinct resonant frequencies. The retrieved permeability for this uncontrolled medium [shown in Fig. 2(b)] also reveals a response consisting of split magnetic resonances, which has the undesirable effect of reducing the oscillator strength and increasing the magnetic loss tangent $\tan\delta_m = \mu_r''/\mu_r'$. From Fig. 2(b), $\tan\delta_m \approx 1$ for the lower resonance at 890 MHz, and $\tan\delta_m \approx 0.55$ for the resonance around 1 GHz, where both loss tangents are given at the $\mu_r' = -1$ frequency [12].

B. Measurements With SRR Addressing

We use addressability to compensate for SRR variations by applying $V_0 = 10$ V across all cells and adjusting *WPR* on each digital potentiometer to yield a desirable response. To demonstrate this concept, we tune the material to have a single transmission resonance at 900 MHz, and then one at 970 MHz, and compare the retrieved permeability with that of (1). The cell states were tuned manually by adjusting the wiper position for each SRR in the medium. Fig. 3(a) shows S_{21} for the addressable slab in these two states. The retrieved magnetic permeability of the addressable medium [Fig. 3(b)] shows that a single distinct resonance is present at both frequencies. With the added control that the digital potentiometers provide, the magnetic loss tangent is significantly reduced, where $\tan\delta_m \approx 0.57$ for the

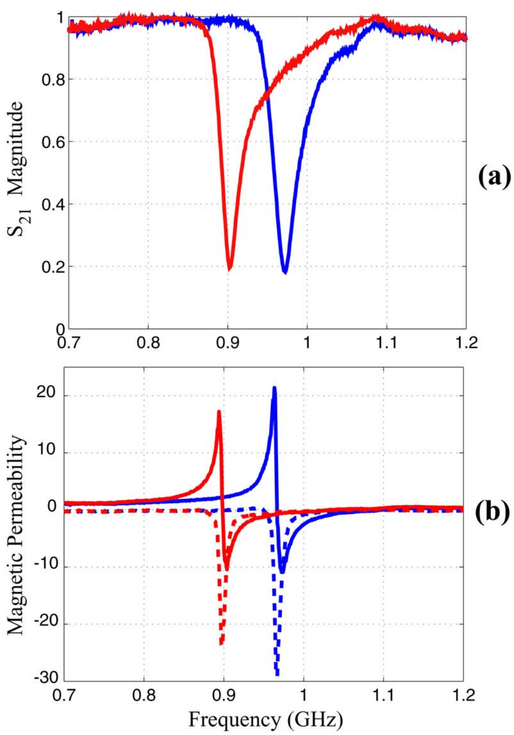

Fig. 3. (color online) (a) S_{21} through slab utilizing individual unit cell addressing with $V_0 = 10$ V feeding each SRR. (b) Retrieved magnetic permeability (μ_r' is solid, μ_r'' is dashed) of the controlled medium.

lower resonance at 900 MHz and $\tan\delta_m \approx 0.3$ for the resonance at 970 MHz at $\mu_r' = -1$.

C. Estimating the Quality Factor and Oscillator Strength of the Addressable Medium

Since the SRR circuit parameters can be estimated, and because the unit cell geometry is known, we can find values for Q and F of the medium and insert them into (1) for comparison with the retrieved permeability. For our unit cell geometry and resonator density, the oscillator strength $F \approx 0.2$. The quality factor $Q \approx 140$ for the lower resonance ($f_0 \approx 900$ MHz). These values were inserted into (1) and overlaid with the retrieved magnetic permeability of the controlled medium (Fig. 4), which shows close agreement. The agreement between the retrieved permeability and (1) was also very close for the higher resonance ($f_0 \approx 970$ MHz), which is not shown. The measurements strongly suggest that tight control of the SRR resonances allows the medium to be closely modeled by the theoretical Lorentzian curve.

D. Addressable Metamaterial Configured as a Transmission Band-Stop Filter

The addressable SRR medium is very versatile and can be tuned to a variety of other useful states. Fig. 5 shows the measured transmission S_{21} through the slab when the digital potentiometer states are configured to excite three evenly spaced and equal magnitude resonances. This demonstrates the slab's effectiveness as a band-stop filter, where the ripples in the stop band can be suppressed by implementing more resonators. This response is likened to an analog filter, where the resonances are poles caused by the LC tank circuits of the SRRs.

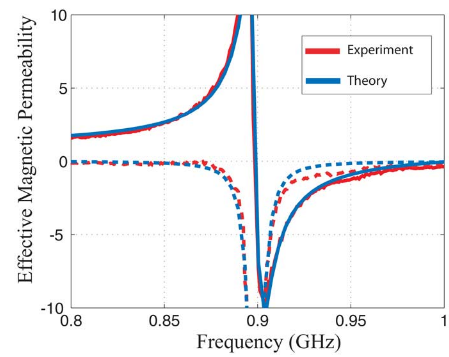

Fig. 4. (color online) Overlay of measured permeability (μ_r' is solid, μ_r'' is dashed) for controlled medium with theoretical Lorentzian with parameters $F = 0.2$, $Q = 140$, and $f_0 = 900$ MHz.

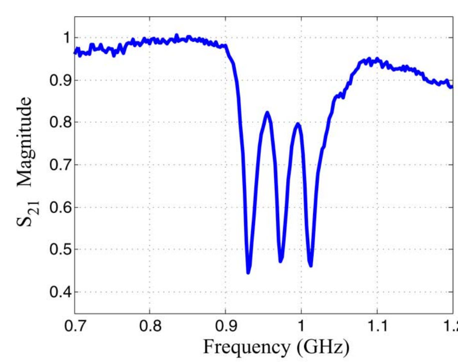

Fig. 5. (color online) Transmission response S_{21} for the addressable slab configured as a band-stop filter. To achieve this response, the DS-2890 chips loading each SRR were programmed to excite three resonances equal in strength and frequency spacing.

IV. Summary

To conclude, we have demonstrated a metamaterial architecture that can compensate for fabrication and lumped-element variations that can make it difficult to achieve a tightly controlled resonance. Our approach integrates addressable voltage control within each SRR to enable independent tuning of each metamaterial cell. Experimental measurements of this addressable medium confirm that individual particle tuning can yield optimal metamaterial performance. An advantage of the addressable metamaterial over conventional tuning approaches is that it is easily reconfigurable. The ability to control the state of each SRR enables the creation of metamaterials with unusual but practically useful transmission and reflection responses.

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