Controllable Magnetic Metamaterial Using Digitally Addressable Split-Ring Resonators

Thomas H. Hand[1] ***and Steven A. Cummer***[2]

[1]Duke University, Durham, NC 27708. Ph: 919-613-9131. Email: thh5@duke.edu

[2]Duke University Durham, NC 27708. Ph: 919-613-9131. Email: cummer@ee.duke.edu

Abstract

Measurements of a unit cell addressable tunable magnetic metamaterial using a one-wire digital potentiometer network is presented. A medium consisting of SRRs loaded with varactor diodes tunes in frequency, but the wide tolerance of the diodes makes the resulting transmission response through the medium consist of resonances split apart in frequency. The diode variance also increases effective magnetic losses in the medium, and our experiment demonstrates how these losses can be significantly reduced with tighter control of the individual unit cell responses. By loading each SRR with a digital potentiometer configured as a voltage divider, we can control the bias across each diode and adjust each SRR to resonate at the same frequency. Comparison between the medium in the addressable and non-addressable states shows that the tight tolerance among unit cells is critical in strengthening the magnetic resonance and reducing losses.

1. Introduction

The field of metamaterials has seen significant progress in recent years, and ever since the pioneering visions of Veselago [1], researchers have sought utility for their exotic electromagnetic response. Pendry's study of wire structures [2] and split ring resonators (SRRs) [3] revealed that media composed of the combination of such structures possesses an effective negative index of refraction n. Smith, et. al. [4] supported Pendry's claims with experimental measurements describing the fundamental physics of such media. The focus of this paper is to examine tunable resonant magnetic metamaterials by controlling the SRR self resonant frequency with varactor diodes [5]. The voltage-tunable capacitance of the varactor diode offers a convenient way of controlling the SRR resonant frequency, but creating a tunable medium with many diode-loaded SRRs is challenging. The problem with applying a uniform bias to a medium of these SRRs is that the tolerance of the diodes prevents the medium from realizing a single tunable resonant frequency. The resonant frequencies of the SRRS tend to split apart as the medium is biased, and this reduces the oscillator strength and broadens the transmission response, which in effect increases the magnetic loss tangent. Our goal is to show that individually addressing each SRR helps to compensate for the diode variance and reduce the magnetic loss tangent of the medium. This addressing is accomplished through a network of digital potentiometers used in a voltage divider configuration to allow for individual control of each diode bias, and hence each SRR resonant frequency.

2. Tunable Particle Design

Realizing a tunable magnetic metamaterial with SRR-loaded varactor diodes is extremely difficult due to the tolerances of the individual diodes, and variances in SRR parameters as small as ±5 % lead to extremely damped responses [6]. A goal of creating a tunable magnetic metamaterial is to be able to theoretically model its permeability by analyzing the circuit parameters of a single SRR. Valid for a medium composed of identical resonators, the Lorentz model for the magnetic permeability (using $e^{+j\omega t}$ convention) is given by [3]

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

where $\mu_r = \mu_r' + j\mu_r''$ and the parameters F and Q are the oscillator strength and quality factor of the resonance, respectively [7]. What makes this model difficult to apply in practice is that it assumes each SRR is identical. In a medium composed of SRRs etched on a dielectric substrate, the tolerance between SRRs is tight and variances can usually be neglected. When trying to realize a tunable response by loading SRRs with external components, tolerances on their values has the undesirable effect of splitting apart the individual SRR resonances. Thus, the response cannot be predicted by equation (1), and we would need sophisticated mixing formulae that consider the SRR variances [6]. The first step in realizing a tunable magnetic medium is to design a single unit cell. *Skyworks SMV1405-079* hyperabrupt junction tuning varactor diodes were used as tunable capacitors, and the capacitance tunes down as the reverse bias is increased. Since the diode requires a DC bias voltage for tuning, an isolation capacitor must be placed in series with the diode to prevent the source from shorting. The value of this isolation capacitor C_s must be carefully chosen since it is important in determining the tunable range (range of resonant frequencies we can excite with the ring) of the particle, and hence, the medium. We define the tunable range of the diode loaded SRR as

$$\delta = \frac{1}{2\pi\sqrt{L_{eq}}}\left(\frac{1}{\sqrt{C_{eq}(V_0)}} - \frac{1}{\sqrt{C_{eq}(0)}}\right) \tag{2}$$

where L_{eq} and C_{eq} are the equivalent inductance and capacitance of the SRR, respectively. *Ansoft HFSS* was used to iteratively find the SRR dimensions on FR4 substrate for a target frequency of about 900 MHz (left picture in Fig. 1). It is desirable to create a SRR with a large oscillator strength F, and this requires that we minimize the self-inductance of the ring while maximizing its area [7]. The fabricated ring is shown in Fig. 1, and it has an equivalent inductance $L_{eq} \sim 35$ nH. When loaded with the varactor diode (C_d) and surface mount capacitor (C_s) of 1 pF, $\delta \sim 265$ MHz (895 MHz – 1.16 GHz).

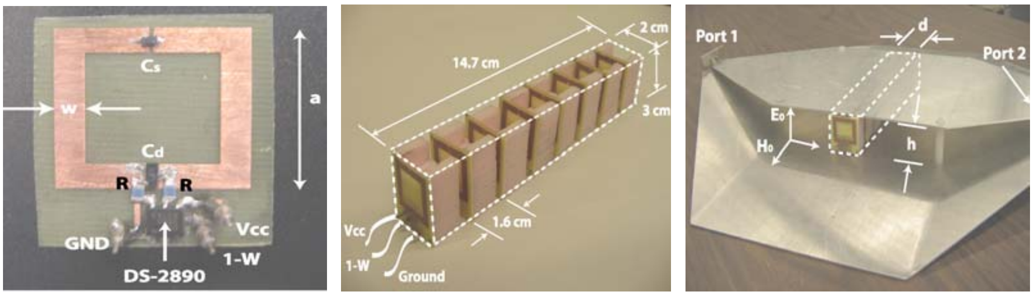

Figure 1: **Left**: View of an individual unit cell of the addressable slab, where w = 3 mm and a = 20 mm. The resistor R (127 kΩ) is used to isolate the SRR from the bias lines. The varactor diode C_d tunes continuously between 0.63 pF and 2.67 pF, and the surface mount capacitor (C_s= 1pF) is used to isolate V_{cc} from ground. **Center**: Photograph showing the fabricated addressable metamaterial medium used for measurement with the three control wires for individual SRR biasing. **Right**: Photograph of the addressable slab inserted in the microstrip waveguide (width 14.7 cm) for effective permeability retrieval, where d = 2 cm and h = 3 cm. Eight unit cells were spaced approximately 1.6 cm apart in the transverse direction to fill the entire transverse plane of the waveguide.

3. The Addressable SRR Medium

The left picture in Fig. 1 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 resistances values between 0-100kΩ (resistance between R_L and R_H pins shown in Fig. 2). Multiple *DS2890* chips can be linked together and operated independently through a common 1-wire bus. Grounding R_L and applying an external bias V_0 between R_L and R_H allows us to bias each diode between 0-V_0 volts by adjusting *WPR* over 256 positions between R_L (0Ω) and R_H (100 kΩ). The fabricated eight-cell addressable medium is shown in the center photograph of Fig. 1, where V_0 is applied between V_{cc} and ground. To avoid damaging the *DS-2890* chips, the maximum bias applied to R_H and R_L is V_0 = 10V. This decreases the diode tunability, which decreases δ to just over 100 MHz. The one wire line (*1-W*) is used to network all the addressable SRRs on a common bus, and this line is connected to a PC where software is used to locate and control the position of each *Maxim DS-2890* digital potentiometer. The right photograph of Fig. 1 shows the addressable slab placed in a microstrip waveguide, where the TEM fields are used to retrieve the effective magnetic permeability of the slab [8]. The microstrip waveguide is tapered towards the ports to provide a 50 Ω impedance match everywhere.

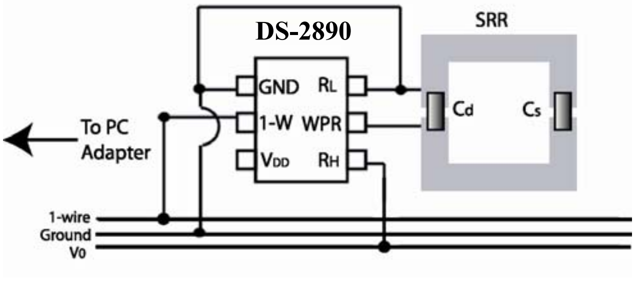

Figure 2: Integrating the DS-2890 digital potentiometer to the SRR. This design "addresses" each SRR and externally controls the bias across each varactor diode. It also allows the connection of many SRRs to the same one-wire network for convenient external control of each SRR resonance. The voltage across C_d is varied by adjusting the position of the *WPR* pin on the DS-2890.

4. Experimental Measurements

The slab was placed in the microstrip waveguide (right picture in Fig. 1), which was connected to an *HP-8720A* vector network analyzer for transmission and reflection magnitude and phase measurements. The left plot of Fig. 3 shows the measured transmission response (S_{21}) for various slab biases without addressing each individual SRR ($WPR = R_H = 100$ kΩ is set on all potentiometers so that the same voltage (V_0=10V) was dropped across each diode). The medium tunes, but the diode variance causes the resonant frequencies to split apart. The retrieved permeability for this uncontrolled medium (shown in the top plot of Fig. 4) reveals a magnetic response composed of split resonances, and this has the undesirable effect of reducing the oscillator strength and increasing the magnetic loss tangent. From the left plot of Fig. 4, $\tan\delta_m \sim 1$ for the lower resonance at 890 MHz and $\tan\delta_m \sim 0.55$ for the higher resonance around 1 GHz, where both loss tangents are given at the frequency where $\mu_r' = -1$ [9]. We compensate for the diode variance by applying V_0= 10V across all cells and adjust the *WPR* position on each unit cell to overlap all SRR resonances. To demonstrate the addressable concept, we show the slab tune to a single resonance at 900 MHz and 970 MHz and compare the retrieved permeability with equation (1). The right plot in Fig. 3 shows S_{21} for the addressable slab with *WPR* set on each potentiometer to get each SRR to resonate at around 900 MHz. The *WPR* pin on each SRR was then adjusted to excite a resonance at 970 MHz. The measured permeability of the addressable sample (right plot of Fig. 4) reveals a distinct resonance around these frequencies. The $\mu_r' = -1$ magnetic loss tangent is significantly reduced, where $\tan\delta_m \sim 0.57$ for the lower resonance at 900 MHz and $\tan\delta_m \sim 0.3$ for the 970 MHz resonance. These loss tangents are reduced by almost a factor of two compared to the uncontrolled sample, and makes it evident that tight control of SRR resonances yields stronger magnetic responses and lower losses. Since we can accurately estimate the SRR circuit parameters and because the unit cell geometry is known, we can find Q and F for the controlled medium and insert them into eqn. (1) for comparison with the theoretical Lorentzian.

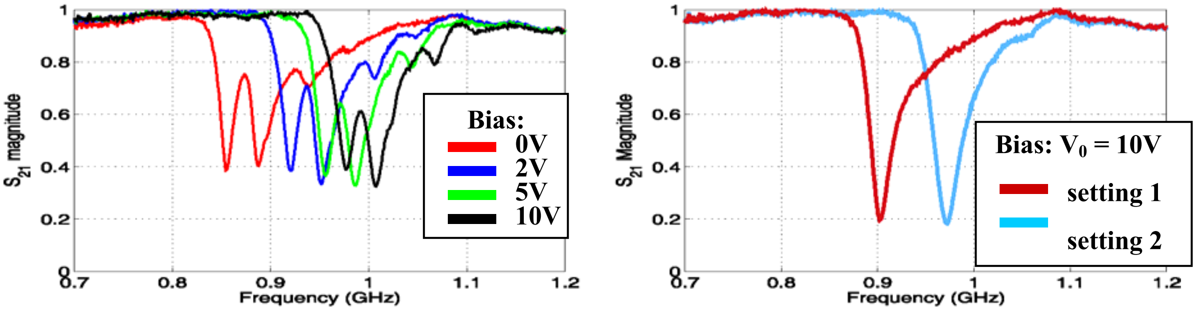

Figure 3: Left: S_{21} through the 8-cell slab without control of SRR resonances for external biases V_0 between 0V and 10V. The medium tunes over 100 MHz, but the diode variance splits and weakens the SRR resonances. **Right**: S_{21} through slab utilizing control with V_0 = 10V feeding each SRR. The effect of control improves the transmission response to a single unique resonant frequency that is narrower and stronger in magnitude. The transmission is shown for the addressable slab for *WPR* settings in two states.

Based on the unit cell geometry and resonator density, $F \sim 0.2$ (using [7] and the parameters of the SRR from Fig. 1). The Q (determined using [7] and the SRR circuit parameters) of each SRR is approximately 140, but changes slightly with increasing diode bias. These values were inserted into eqn. (1) for f_0 = 900 MHz and f_0 = 970 MHz and overlaid on the retrieved magnetic permeability of the controlled medium (Fig. 5). Tight control of the SRR response allows the medium to be closely approximated by a Lorentzian curve, and the close agreement between the measured and theoretical magnetic permeability clearly demonstrates the ability of the addressable medium to compensate for the variances in the varactor diodes.

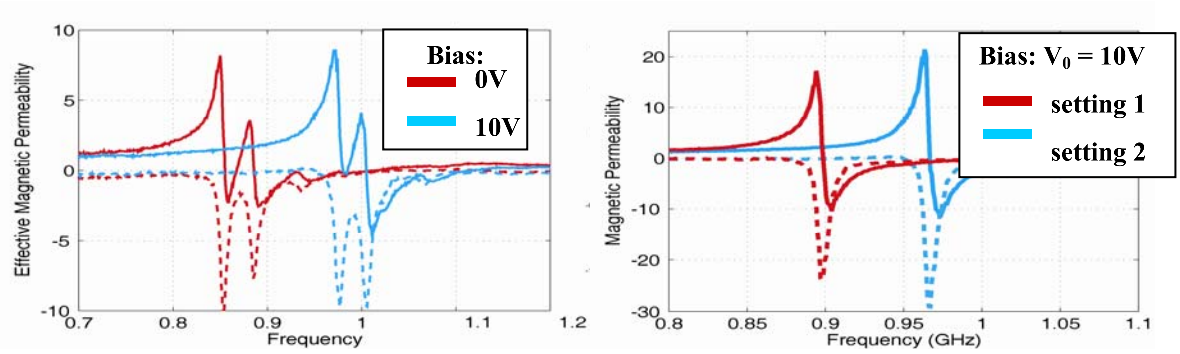

Figure 4: Left: Retrieved magnetic permeability for the uncontrolled medium (V_0=10V applied across all diodes). **Right:** Retrieved magnetic permeability for the controlled medium. By adjusting the wiper on each digital potentiometer to align the SRR resonances, the resulting magnetic permeability resembles a Lorenztian (eqn. 1), and the μ_r = -1 loss tangent is significantly reduced.

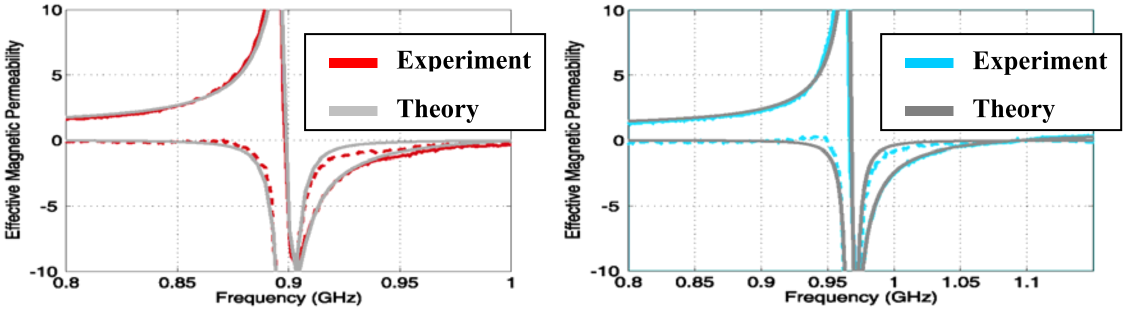

Figure 5: Left: Overlay of measured permeability (dashed) for controlled medium with Lorentzian with parameters F = 0.2 , Q = 140, f_0 = 900 MHz. **Right:** Measured permeability with Lorentzian for controlled medium with parameters F = 0.2, Q = 120, f_0 = 970 MHz.

5. Conclusion

Experimental results of a digitally addressable tunable magnetic metamaterial was presented. Loading SRRs with varactor diodes and biasing the medium uniformly does not yield a single tightly controlled resonance. By integrating digital potentiometers within each SRR unit cell in a voltage divider configuration, the variance of the varactor diodes is significantly reduced, as the bias on each diode can be set independently. The result is the ability for the medium to tune with one strong and distinct resonance, and this tight control reveals much improvement in the strength of the magnetic permeability as well as a reduction in the magnetic loss tangent.

6. References

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