Characterization of Tunable Metamaterial Elements Using MEMS Switches

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***Abstract*—An experimental demonstration and analysis of a dual-state switchable magnetic metamaterial element in which the resonance excitation of the particle is controlled using an RF microelectromechanical (MEMS) switch is presented. By controlling the resonant properties of the individual ring, unit cells composed of such elements can be used to realize an effective dual-state switchable medium. Transmission and loss characteristics of the switchable element for two different switch topologies are compared. Experimental data shows that the MEMS switch allows for a switchable resonant particle with reasonably low losses.**

***Index Terms*—Metamaterials, microelectromechanical (MEMS).**

I. Introduction

Since Veselago's theoretical study of negative index media [1] and Pendry's study of wire structures [2] and split-ring resonators (SRRs) [3], many researchers have utilized this knowledge to create materials that were not previously possible. The majority of past research in metamaterials has examined passive linear devices with fixed bulk medium parameters that cannot be altered for a given cell geometry. Because this electromagnetic behavior usually relies on the self-resonant properties of the metamaterial constituents, the electromagnetic properties of a metamaterial medium are unalterable. Control of the effective electromagnetic parameters of a metamaterial is possible by examining the potential use of direct external tuning or engineering a built-in nonlinear response to the artificial medium. Studies have been carried out [4]–[8] that examine the ability to control the response of these materials using tunable devices such as varactor diodes to shift the resonant frequency of the rings. The implementation of switchable SRRs is discussed in [9], and transmission line-based tunable metamaterials are analyzed in [10].

We report here experimental measurements of a magnetic metamaterial particle externally controlled through a high-frequency microelectromechanical (MEMS) switch. Such switches can have large open-switch isolation and small closed-switch resistance which make them suitable for metamaterial applications. It will be shown later that the open state capacitance of MEMS switches limits the useable frequencies with which they can be used. In this letter, two switch topologies are explored that can be used to realize a dual-state switchable ring which can form the building block of a bulk effective medium. The MEMS particle is capable of switching between two electromagnetic states, and a medium composed of such elements can allow for switching between two distinct values of impedance and refractive index. This ability to switch between electromagnetic states can find use in many microwave applications, with antenna beam steering of particular interest. An effective medium composed of an array of these MEMS rings can switch between resonant and nonresonant states, allowing for an impedance-tunable medium that can switch between two distinct states. This effect would also allow one to steer a beam of radiation in a specific direction dependent on the material's effective refractive index, which can be tuned by carefully controlling the response the MEMS-loaded rings. Characterization of the MEMS switch parasitics will allow for the design of a bulk material with precise effective electromagnetic parameters.

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II. Analysis

Capacitively loaded metallic split rings are well known to produce a strong magnetic dipole moment from an incident magnetic field [3], and they form the basis for most magnetic metamaterials described in the literature. A simple way in which such a particle could be controlled from a switch is by altering the ring capacitance. However, it will be shown that the detailed electrical properties of the switch strongly dictate the tunable characteristics of the loop. The ring by itself is a resonant particle with resonant frequency $\omega_0 = (LC)^{-1/2}$, where C is due to the gap capacitance and L is due to the self inductance of the metal trace. A *Teravicta* RF MEMS switch is added to this ring to control the effective capacitance. This is used in the single-pole single-throw configuration design, operates from dc to 7 GHz, and requires a 68 V_{dc} actuation signal. The MEMS switch can be placed either in series or parallel with the ring gap, and we will now investigate the advantages and disadvantages of each configuration.

A. Series and Parallel Switch Configurations

Fig. 1 shows the schematic of the MEMS switch placed in series with the resonant loop. The closed switch is resonant at $\omega_0 = (LC)^{-1/2}$, while the open switch state shifts the resonant frequency of the ring to $\omega_0' = (LC')^{-1/2}$, where $C' = (CC_s)(C + C_s)^{-1}$ is the effective capacitance of the two series elements and C_s is the open-state MEMS switch capacitance. In both states, all circuit elements are in series, where the closed switch loop has a quality factor $Q = (\omega_0 C(R_s + R))^{-1}$ and $Q' = (C + C_s)(\omega_0 C_s C(R_s + R))^{-1}$ for the open switch loop. R_s is the series resistance of the MEMS switch, and R is the resistance of the metallic ring trace. The simple dependence of Q and ω_0 on the unknown switch parameters R_s and C_s in the

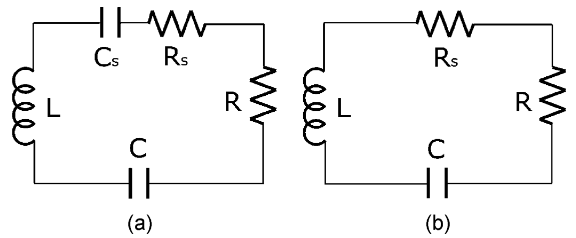

Fig. 1. Equivalent circuit of the loop with the MEMS switch used in a series configuration. The open switch (a) introduces a capacitance C_s, whereas the switch resistance R_s is present in both the open and closed (b) states.

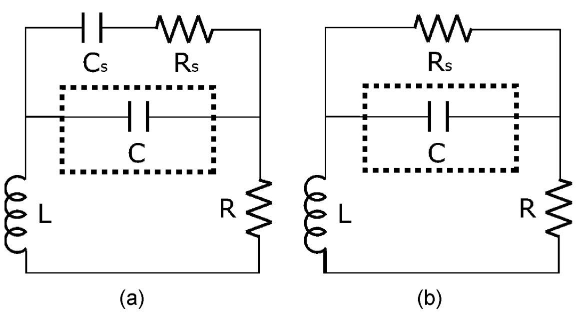

Fig. 2. Equivalent circuit of the loop with the MEMS switch used in a parallel configuration. The MEMS switch allows for switching between on and off resonant states. The open switch state (a) introduces a capacitance C_s into the resonant loop, and is absent on the closed state (b). The dashed box around C is meant to illustrate that its presence is optional, depending on the operating frequency. For small f, C is large and dominates the resonant response, but it becomes comparable to C_s as f increases.

series configuration will be exploited in measurements to determine their values. The switch in the series configuration essentially shifts the metamaterial particle between two resonant frequencies. As long as these frequencies are sufficiently spaced, a bulk medium composed of these elements could be switched between two distinct electromagnetic states.

The switch can also be placed in parallel with the gap capacitance C so that closing the switch shorts the loop and effectively eliminates the resonance. The schematic for this parallel configuration is shown in Fig. 2. It is easily seen that a significant resonance is only present in the open state at $\omega_0 = (LC_{\text{eff}})^{-1/2}$, where $C_{\text{eff}} = C + C_s$, and we are justified in neglecting R_s since $(\omega C_s)^{-1} \gg R_s$ within our frequency range of interest. The parallel configuration switches between resonant and nonresonant states, and thus an array of such switchable elements can form a metamaterial medium capable of tuning between dielectric and negative permeability states.

B. Frequency Limits of Both Configurations

The elements that compose metamaterials require precise control of their resonant properties, and in a tunable medium where MEMS switches are implemented, the open switch capacitance C_s is not precisely controlled from switch to switch. This consequently places an upper limit on the frequencies where each switch configuration may effectively operate.

In the series configuration, C is determined by the operating frequency and the particle size. The frequency limit can be quantitatively determined by examining how C and L change with frequency. A useful approximation for the inductance of a square ring in terms of the free space wavelength λ_0 and trace width d (see Fig. 3) is given by [11]

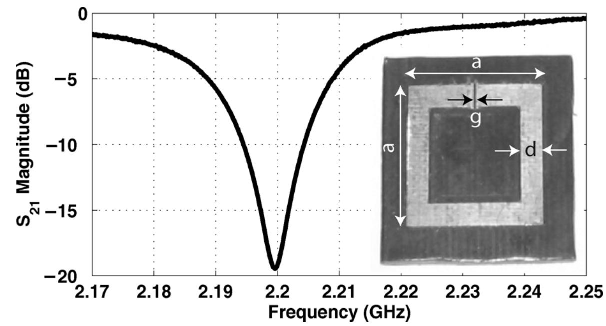

Fig. 3. The resonant copper ring on Rogers Duroid substrate ($\epsilon_r = 2.2$, $\tan\delta = 0.0009$) in the absence of the MEMS switch, with S_{21} measurements made in the WR-340 waveguide ($a = 16$ mm, $d = 2.5$ mm, and $g = 0.3$ mm). It was designed to be resonant at 2.2 GHz, and experimental transmission measurements placed very close to this frequency, where measured $Q \approx 600$.

$$L \approx \frac{\lambda_0 \mu_0}{5\pi}\left(2.3\log_{10}\left(\frac{8\lambda_0}{5d}\right) - 2.85\right) \tag{1}$$

where the side length $a = \lambda_0/10$. Thus, the corresponding capacitance needed to realize a resonance at ω_0 is $C = 1/\omega_0^2 L$. To be useful in practice, ω_0 and ω_0' must be reasonably spaced in frequency. As the operating frequency is increased, C must decrease (for fixed L), and the fractional change in resonant frequency $\delta\omega_0 = |\omega_0 - \omega_0'|/\omega_0$ consequently decreases. For our ring geometry, $\delta\omega_0 > 0.1$ for $f < 3.8$ GHz (based on experimental measurements). This means that we can operate up to 3.8 GHz in order to be assured that $\delta\omega_0$ will be greater than 10 percent.

The advantage of the parallel switch configuration is that its closed state resonance is negligible. C_s should have a small influence on the open state ω_0 so that a collection of such elements would be resonant at the same frequency. Above the crossover frequency 2.2 GHz (where $C = C_s$). C_s strongly influences ω_0, and the operating frequency needs to be considerably lower in order for the particle to be useful in application. An upper frequency limit for a particle of size $\lambda_0/10$ in the parallel switch configuration is approximately 900 MHz. In order for this configuration to be useful at higher frequencies, either C_s needs to be reduced or tightly controlled from switch to switch. Both of these problems can be resolved with better fabrication techniques to achieve tighter tolerances on C_s. Another advantage of the parallel switch configuration is lower loss in the open state since R_s does not add serially with R.

III. Experimental Measurements

The goal of this study is to be able to fully characterize the electromagnetic properties of the MEMS-loaded resonant ring. Effective medium properties of an array of these elements are completely controlled by the parasitics R_s and C_s of the MEMS switch, and thus accurately determining their values completely characterizes the electromagnetic response of the particle. We first study the MEMS ring in the series configuration (schematic in Fig. 1), where S-Parameters are used to

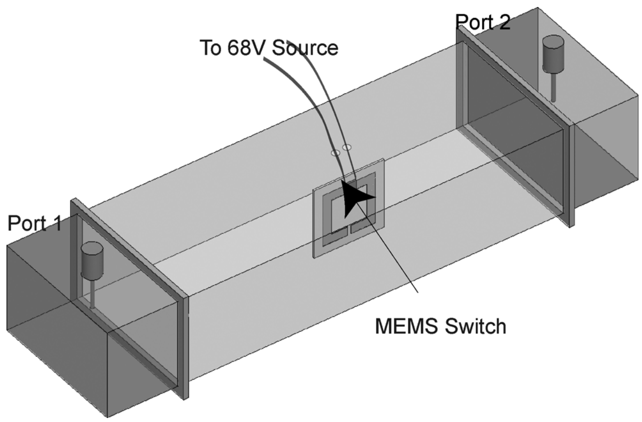

Fig. 4. Diagram of the dual-state switchable ring placed inside the WR-340 waveguide.

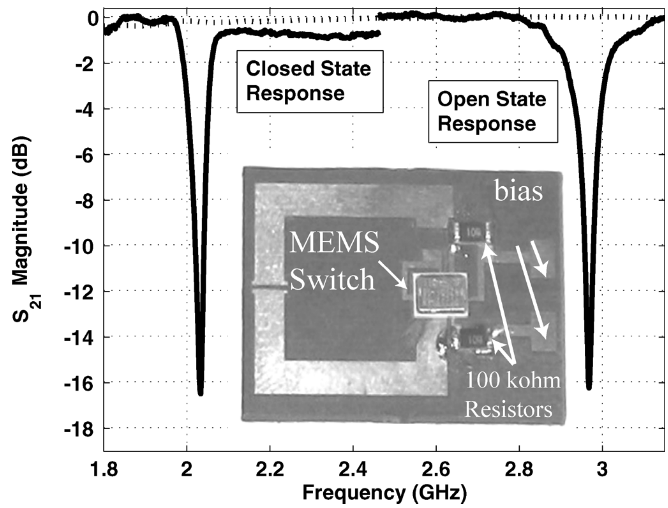

Fig. 5. Open and closed switch responses for the series resonant circuit, where $Q_{\rm closed} \approx 150$ and $Q_{\rm open} \approx 250$, and the dashed plot shows S_{21} for the unloaded waveguide. Also shown are the pads for the dc bias and 100 kΩ resistors used for isolation of the external dc voltage source.

infer realizable effective medium properties from an assembly of these switchable elements (i.e., loss tangent). Full wave reflection and transmission measurements of a single switched particle are made in a WR-340 closed rectangular waveguide (TE_{10} mode cutoff frequency of 1.77 GHz). To operate safely in the single mode regime, transmission measurements inside the waveguide must be made between 2.2 and 3.3 GHz. Using Ansoft HFSS, a copper ring on Rogers Duroid substrate (1 mm thick) was iteratively designed to be resonant at 2.2 GHz. The method proposed in [12] details effective constitutive parameter retrievals using S-Parameters. A parametric sweep of g, a, and d (see Fig. 3) was used to find a ring geometry resonant at 2.2 GHz. Ansoft Q3D Extractor was used to find the lumped circuit parameters of the ring: $R \approx 0.3\ \Omega$ (copper alone), $L \approx 22$ nH and $C \approx 0.24$ pF. Given these ring parameters, the quality factor $Q = \sqrt{L/C}/R \approx 1000$, where radiative and substrate losses are neglected. Measurement of this particle in the closed waveguide will lead to a lower experimental Q due to loading effects. Fig. 4 shows an illustration of the fabricated MEMS loaded ring placed inside the waveguide for transmission measurements. The ring was placed in the middle of the two sidewalls (where the electric field of the TE_{10} mode is maximum). Wires biasing the MEMS switch were fed into the waveguide through small holes, where they were connected to an external dc voltage source.

The presence of the MEMS switch alters the behavior of the ring and must be accounted for in designs where a tight tolerance on Q and ω_0 is crucial. It is necessary to investigate the series and parallel switch configurations in order to accurately determine C_s and R_s, and also to see how each configuration affects ω_0 and Q.

A. Measurements of the Unloaded Ring

The trace thickness and gap spacing of the ring was chosen after Ansoft Q3D Extractor simulations were used in the design for a resonant frequency $f_0 = 2.2$ GHz. This corresponded to $a = 16$ mm, $g = 0.3$ mm, and $d = 2.5$ mm (see Fig. 3). The design was fabricated on a 1-mm-thick Rogers Duroid substrate, where S_{21} measurements in the WR-340 waveguide were used to show that $Q \approx 600$ with a resonant frequency $f_0 \approx 2.2$ GHz. It can be shown that for waves impinging on a magnetically resonant slab, $\sqrt{1/|S_{21}(f)|^2 - 1}$ has a Lorentzian lineshape from which Q can be accurately estimated.

B. Series Switch Measurements

To determine C_s and R_s, the response of an individualMEMS-loaded ring was tested in the serial configuration (shown in Fig. 5). C_s was determined by examining the shift in resonance caused by the placement of the switch in the loop, and the new resonant frequency is given by

$$\omega_o' = \frac{1}{\sqrt{LC'}} \tag{2}$$

where $C' = (C_s C)(C_s + C)^{-1}$. Since L does not change with the addition of this series switch (the switch has negligible effective series inductance), $C' = 1/\omega_o'^2 L \approx 0.139$ pF and$C_s = C'(1 - C'/C)^{-1} \approx 0.33$ pF. It is also important to note that the closed switch configuration eliminates C_s and pushes the resonance back down to 2.04 GHz (see Fig. 5). The switch parasitics play a role in the measured responses, and one may wonder why the series closed switch resonant frequency differs from the unloaded ring resonant frequency since their equivalent circuits are the same. Close examination of the circuit traces reveals that the MEMS-loaded ring circuit introduces parasitic parallel capacitance which lowers the closed-state resonant frequency. These parasitic effects are unavoidable and must be considered in practice.

The next step is to determine the switch resistance R_s. Our approach is to find the real part of the effective ring impedance $R_{\rm eff}$ and relate it to an effective ring resistance based on the loaded quality factor, Q_L. From Fig. 5, $Q_L \approx 150$ (utilizing the same method as for the unloaded ring) for the closed switch state. The effective ring resistance $R_{\rm eff}$ is related to Q by

$$Q = \frac{\omega_o L}{R_{\rm eff}} \tag{3}$$

where $R_{\rm eff} = R + R_s$ equivalent resistance of the ring with the series MEMS switch present. Since the self-inductance of the ring is known, $R_{\mathrm{eff}} = \omega_o L/Q \approx 1.9\ \Omega$ which implies $R_s \approx 1.6\ \Omega$. The actual MEMS switch resistance is slightly less than 1.6 Ω due to the loading effects of the waveguide and network analyzer.

Single element measurements of the ring can be extrapolated to provide the properties of an effective medium composed of an array of such tunable elements [13]. Achievable loss tangents of a metamaterial medium composed of these tunable elements can be estimated from Q-factor measurements. From [13], $\min|\tan\delta| \approx 4/FQ$, and the oscillator strength $F = \mu_0 A^2/Lv$, where L is the self-inductance of the ring, A is the area enclosed by the ring, and v is the unit cell volume [14]. Typical values for F range between 0.16 (cubic unit cells) and 0.5 (tightly packed lattice). Thus for the series switch configuration, $\min|\tan\delta| \approx 0.17$ for a cubic lattice and $\min|\tan\delta| \approx 0.05$ for a more tightly packed lattice of such elements. This provides an upper bound on the loss tangent since we are taking into account loaded Q values.

C. Parallel Switch Measurements

For comparison with the series switch configuration, a parallel switch ring was fabricated and S_{21} data was retrieved to determine ω_0 and Q. Using the parallel switch configuration at low frequencies where $C \gg C_s$ makes this circuit topology more useful, since C dominates the response and C_s can be neglected. However, since we are analyzing a $\lambda_0/10$ ring at high frequencies ($f > 2$ GHz since we are making measurements in a WR-340 waveguide), C is forced to become comparable with C_s (since L can only be reduced so much by widening the trace width). For meaningful measurements in the waveguide, C is omitted to reduce the effective capacitance which shifts f_0 above 2 GHz – safely in the passband of the waveguide. The resulting ring (inset of Fig. 6) is identical to the ring of Fig. 5, except now C is shorted and d is increased (to reduce L and increase f_0). The fabricated particle was inserted into the waveguide for S-parameter measurements. From Fig. 6, $f_0 \approx 2.26$ GHz with $Q \approx 300$. It is important to reemphasize that in order for this switch to be useful at high frequencies, C_s needs to be tightly controlled from switch to switch.

IV. Summary

We experimentally demonstrated the feasibility of a dual-state tunable metamaterial element utilizing a *Teravicta* RF MEMS switch. Experimental measurements show the results of a dual-state switchable resonant ring for the MEMS switch placed in series and parallel configurations. Because of the impact of the open switch capacitance on the particle resonant frequency, the series switch configuration is better suited for high frequency applications, while the parallel switch configuration is more appropriate for lower frequencies and provides slightly lower loss. The parallel switch configuration presents problems at high frequencies since the gap capacitance required to achieve an electrically small ($\lambda_0/10$) ring becomes comparable to the open switch capacitance and places an upper limit on the self-resonant frequency. Q-factor measurements show that the losses in the rings for both configurations are reasonably small for frequencies below 3 GHz, suggesting that this tunable element can be used to form a dual-state switchable bulk medium.

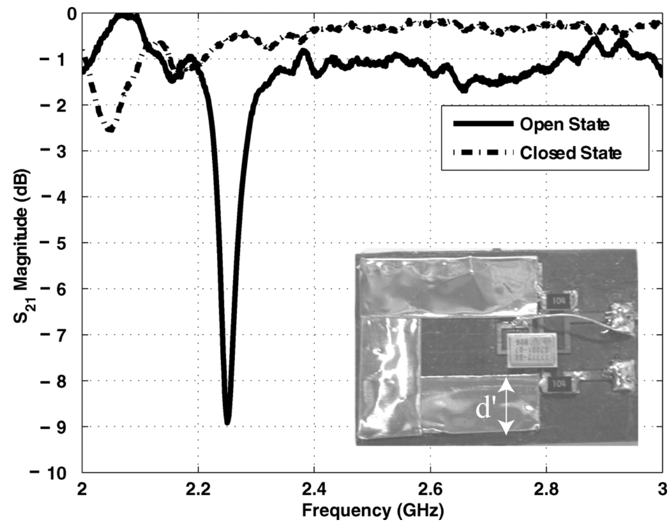

Fig. 6. Open and closed switch responses of the parallel circuit configuration. The resonant response of our ring from Fig. 5 with the gap capacitance C shorted is at the edge of the waveguide passband, and so we decreased L to raise f_o by increasing the trace thickness to $d' = 5.5$ mm.

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