On Using Magneto-static Responsive Particles as Switching Elements to Reconfigure Microwave Filters

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***Abstract*—This paper presents the use of novel Magneto-static Responsive Structures (MRSs) as switching elements in microwave filters to achieve frequency reconfigurability. A single MRS consisted of a small piece of substrate with a cavity drilled out of it. The cavity was then filled with microscopic magnetic particles and capped on both ends with copper tape. In the presence of a static magnetic field, the magnetic particles formed columns along the field lines and connected the two top and bottom conducting planes to form a short. In the absence of the magnetic field the columns collapsed, disconnecting the conducting plates resulting in an open switch. The theoretical design, optimization and performance of a single MRS as well as a reconfigurable filter using MRSs was simulated using the 3D full wave electromagnetic (EM) models in HFSS®. The laboratory prototypes with MRSs were then manufactured and attached to the reconfigurable band-pass filter prototype for validation. Measured results of the prototype filter showed good agreement with the simulations. Specifically, a 2.7 GHz center frequency with a 60 MHz bandwidth in the MRS `OFF' state and a 1.98 GHz center frequency with a 50 MHz bandwidth in the MRS `ON' state was observed. The simulated and measured insertion losses of the reconfigurable band-pass filter were 2.9 dB and 2.98 dB in the `OFF' and `ON' states, respectively. It was successfully shown that the proposed MRS can be used as an alternative switching technology in reconfigurable microwave filters in a frequency band from the 100 KHz - 3.0 GHz, with an additional benefit of not requiring directly connected biasing circuitry.**

I. INTRODUCTION

The adaptability of reconfigurable filters is highly desirable in current wireless communication systems due to the presence of multiple technologies on a single microwave platform. PIN diodes or RF micro electro-mechanical systems (MEMS) have been used in the past to achieve discrete reconfigurability in microwave filters. For example, microstrip filters were reconfigured using PIN diodes and are presented in [1]-[2], and reconfigurable filters using RF MEMS have been discussed in [3]-[5]. Other technologies such as varactor diodes, transistors, monolithic microwave integrated circuit (MMIC), ferromagnetic magnetic materials, yttrium-iron-garnet (YIG) films, and other ferromagnetic mechanisms have also been used in filter topologies to achieve switchable and tunable responses [5]-[10]. An overview of the existing technologies to achieve discrete reconfigurability or continuous tuning has been presented in [11]. All of the aforementioned technologies have their advantages and disadvantages: ranging from the good integration capabilities to high losses and the requirement of a directly connected biasing network [11].

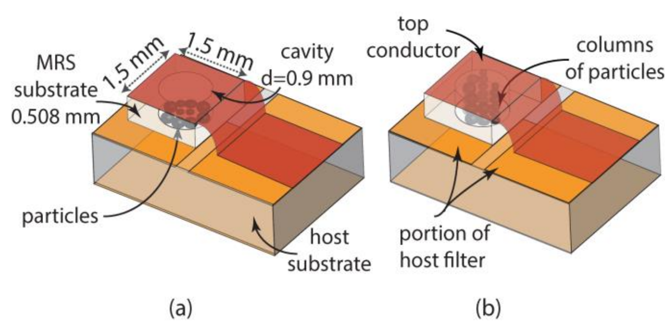

Fig. 1. Simulation model of a single Magneto-static Responsive Structure (MRS) in the (a) `OFF' state and (b) `ON' state.

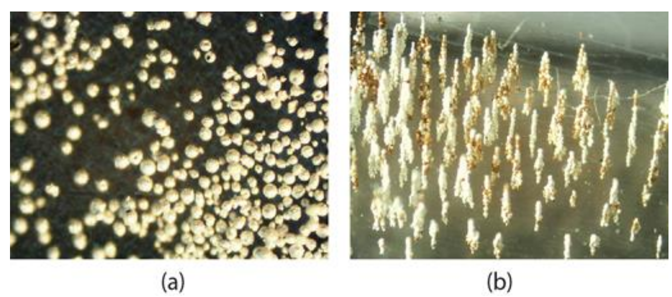

Fig. 2. Silver coated magnetic particles: (a) a microscopic view of the particles in the absence of the magnetic field and (b) the behavior of the magnetic particles in the presence of the magnetic field.

The goal of the work presented in this paper is to demonstrate the use of the novel Magneto-static Responsive Structures (MRSs) shown in Fig. 1 to achieve reconfigurability in microwave filter topologies without a direct connection of biasing circuitry. A single MRS consists of a cylindrical cavity in a substrate with the silver coated magnetic particles [12]

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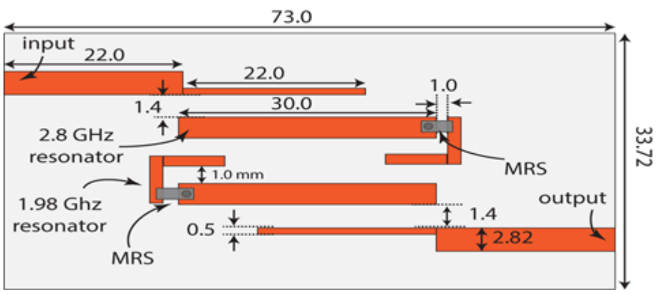

Fig. 3. Dimensions (in mm) of the reconfigurable band-pass filter.

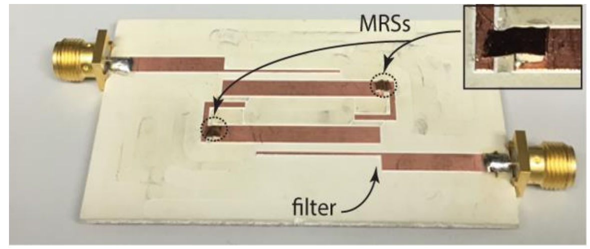

Fig. 4. A photograph of the manufactured Magneto-static Responsive Structures attached to the prototype reconfigurable band-pass filter.

shown in Fig. 2 placed within the cavity. The top and bottom surfaces of the cavity are covered with copper tape to create the enclosure. When a static magnetic field is applied to the MRS, the particles build columns along the field lines and connect the two copper tape planes. The behavior of the magnetic particles in the presence of the magnetic field is shown in Fig. 2. More specifically, Fig. 2(a) shows the behavior of particles in the absence of the magnetic field and Fig. 2(b) show the columns along the field lines. Because a static magnetic field is used to control the MRSs, they have an additional benefit of not requiring a direct connection with biasing circuitry. In the presence of a static magnetic field the magnetic particles stacked to connect the two conducting planes of the MRS in Fig. 1, which corresponds to the 'ON' state. On the other hand, the magnetic particles settled at the bottom of the cavity in the absence of the magnetic field, corresponding to the `OFF' state of the MRS. This phenomenon results in a behavior similar to an RF switching element.

A single MRS was first modeled using the full wave electromagnetic simulation software HFSS [13]. Next we apply the MRSs to the design of a compact microwave filter that can switch between two states. The switchable band-pass filter was fabricated and the MRSs were attached to the prototype for measurements and verification. It was shown from the measurement and simulation results that the proposed novel MRS can be used as an alternative to existing technologies below 3.0 GHz.

II. DESIGN PROCEDURE

A. A Magneto-static Responsive Structure (MRS) simulation model

The configuration of a MRS modeled in HFSS is shown in Fig. 1. A single MRS composed of a cavity having a diameter of 0.9 mm in a TMM4 substrate *(*$\epsilon_r = 4.5$*, tan* $\delta = 0.002$*, and thickness,* h*=0.508 mm)* and microparticles within the cavity. The particles were spherical silver coated magnetic particles with an average diameter of 40.0 um [12]. Conducting copper ½ oz. plates were used on the top and bottom of the proposed structure. The host substrate was modeled to represent the attachment of the proposed MRS to a filter topology. The size of the TMM4 substrate was 1.5 mm x 1.5 mm. Figs. 1 (a) and 1 (b) show the `OFF' and `ON' states of the MRS, respectively. To represent the `ON' state of the MRS, columns of spherical conductive particles were modeled to connect the top and bottom conductors. On the other hand, in the `OFF' state of the MRS, the spheres were modeled as a collection on the bottom conductor, as shown in Fig. 1 (a).

B. Reconfigurable band-Pass filter design

We demonstrate the efficacy of reconfiguring a bandpass filter able to switch between the two bands of 2.7 GHz and 1.98 GHz using the proposed MRSs, a reconfigurable based on the design topology and techniques discussed in [14]. The filter topology and associated dimensions are shown in Fig. 3. This structure was modeled in HFSS with the geometry of the proposed MRSs (shown in Fig. 1(a) and 1(b)). The microstrip reconfigurable filter was designed on a TMM4 substrate having a thickness of 1.524 mm *(*$\epsilon_r = 4.5$*,* and *tan* $\delta = 0.002$*).* The center frequency was controlled by adjusting the lengths of the high frequency resonator and the bandwidth was controlled by adjusting the capacitive coupling between the high frequency resonator and the folded resonator [14]. Two MRSs were used between the high frequency resonator and folded resonator to switch between the two frequency bands. The MRSs were attached to the fabricated filter topology, as shown in Fig. 4. In the laboratory prototype, the MRSs were activated using a permanent magnet on the bottom side of the reconfigurable band-pass filter. It should also be noted that this did not require a direct connection to a biasing circuit.

III. RESULTS AND DISCUSSIONS

Initially, the S-parameters of the individual MRSs were computed in HFSS in the `ON' and `OFF' states and are shown in Figs. 5 and 6, respectively. In the 'ON' state, a good match was shown from 100 KHz-3 GHz, as shown in Fig. 5. In the `OFF' state, more than 10 dB of isolation was observed from 100 KHz-3 GHz.

Next, the reconfigurable band-pass filter in Fig. 3 including the two MRSs was studied, and the simulation and measurement results were compared. These results are shown in Figs. 7 and 8 for both the 'OFF' and 'ON' states. The results show that the filter can be reconfigured between the 2.7 GHz and 1.98 GHz bands using the MRSs and a static magnetic field. Specifically, the values in Fig. 7 show that a good match is obtained with the simulated values in both switching bands. The $|S_{21}|$ results in Fig. 8 also show that the insertion loss of the reconfigurable filter at 2.7 GHz (i.e., 'OFF' state) is around 2.9 dB, while the insertion loss at 1.98 GHz (i.e., 'ON' state) is 2.98 dB. Furthermore, the bandwidths of the 'OFF' and 'ON' sates were 60 MHz and 50 MHz, respectively. Overall, good agreement was obtained between the simulation and measurement results.

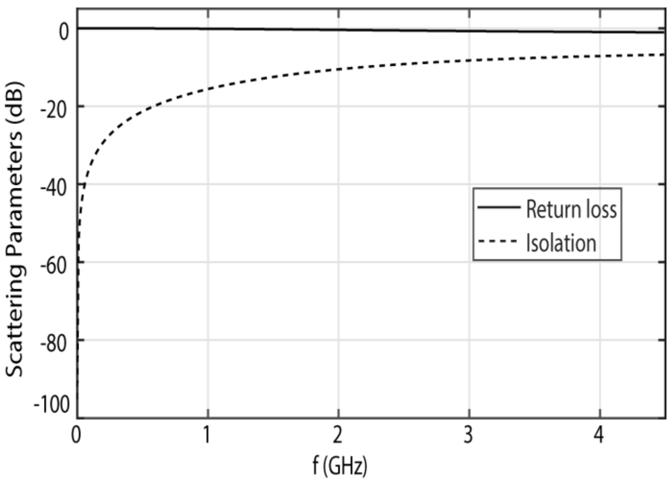

Fig. 5. Simulated S-parameters in the `ON' state.

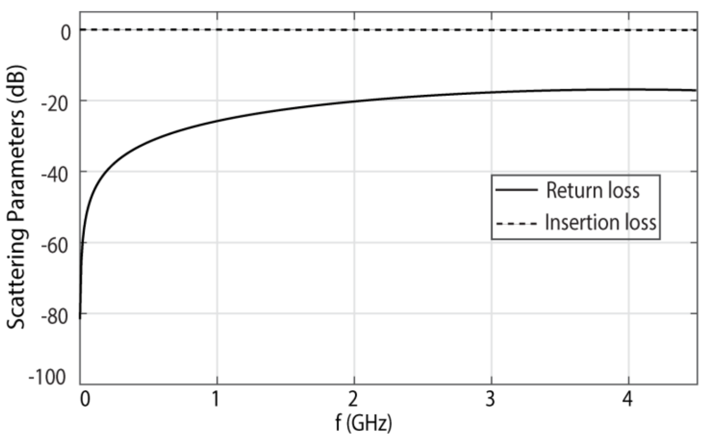

Fig. 6. Simulated S-parameters in the `OFF' state.

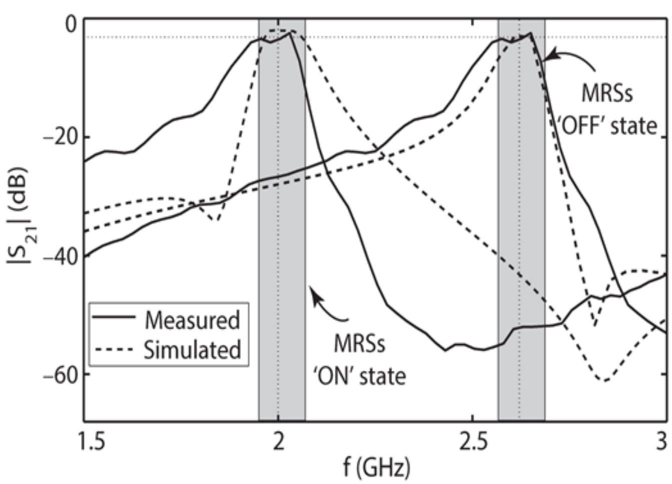

Fig. 7. Simulated and measured $|S_{21}|$ of the reconfigurable band-pass filter prototype in the `OFF' and `ON' states.

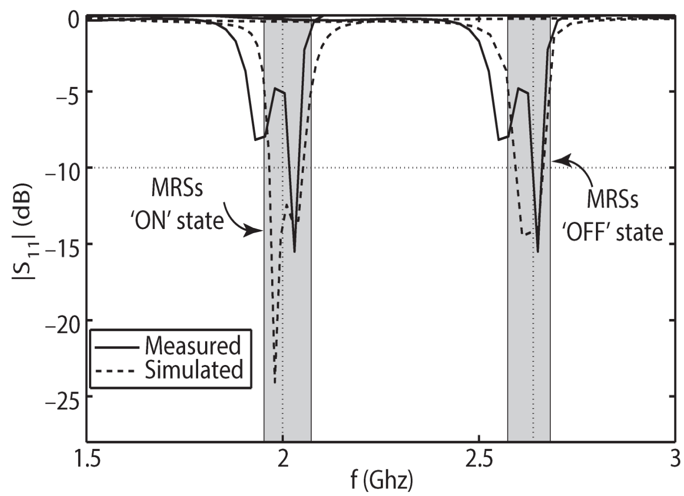

Fig. 8. Simulated and measured $|S_{11}|$ of the reconfigurable band-pass filter prototype in the `OFF' and `ON' states.

IV. CONCLUSIONS

A new Magneto-static Responsive Structure (MRS) was introduced in this paper and was demonstrated to control frequency reconfigurability of a microwave filter. The S-parameters of an individual MRS were studied. Next, the MRS was embedded into the design of a filter to achieve frequency reconfigurability. A prototype was then fabricated and measured. Overall, the measurements compared well with simulations and we demonstrated that a frequency reconfigurable filter could switch between the 1.98 GHZ bands using the proposed MRS structures without the requirement of a directly connected biasing circuit

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