Flexible Liquid-Metal-Tuned Higher-Order Bandpass Frequency Selective Surfaces

Kevin Xu
Department of Electrical Engineering
University at Buffalo, The State University of New York
Buffalo, NY, USA
kxu22@buffalo.edu

Jun H. Choi
Department of Electrical Engineering
University at Buffalo, The State University of New York
Buffalo, NY, USA
junhchoi@buffalo.edu

***Abstract*—This paper presents a new implementation of liquid-metal-tuned higher-order bandpass frequency selective surfaces (FSSs). The proposed multi-layer periodic structures are based upon a topology consisting of resonant FSS layers separated by thickness-controlling aperture coupling interlayers. These liquid metal layers are used in combination with an elastomeric substrate to realize a mechanically flexible and fluidically tunable device. Capacitive tuning slugs are integrated into the resonant FSS layers to enable real-time tuning of the bandpass filter's operating frequency range. To demonstrate the proposed higher-order liquid-metal-tuned spatial filters, both second-order and third-order bandpass FSSs, operating in the Ku-band, are designed and validated using full-wave electromagnetic simulation.**

***Index Terms*—Liquid metal, tunable filters, frequency selective surfaces, Galinstan, flexible metasurface, periodic structure.**

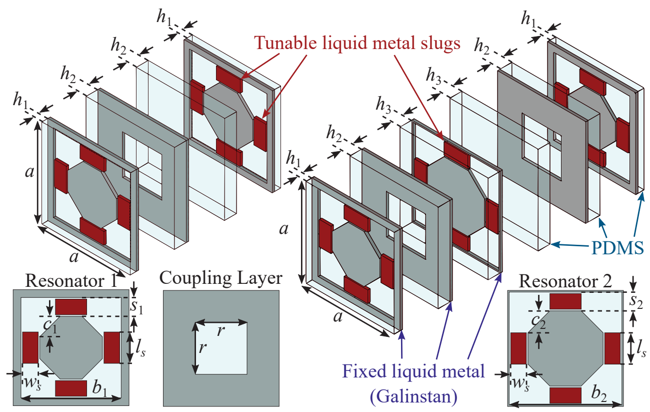

Fig. 1. Topology of second-order (left) and third-order (right) tunable bandpass frequency selective surfaces made of liquid metal embedded in PDMS.

I. Introduction

Frequency selective surfaces (FSSs), designed to transmit, reflect, or absorb electromagnetic (EM) waves of specific frequency bands, are indispensable microwave devices. Although many advancements have been made over the years, most only consider operation for fixed EM wave characteristics. On the other hand, real-time tunability is a very attractive feature for FSSs in dynamic EM environments, and can greatly benefit applications such as satellite communications [1], radio astronomy [2], absorbers [3], and wireless communications [4]. For applications requiring a broader bandwidth, sharper transition band, or higher out-of-band rejection, multi-pole designs are ideal.

Recently, liquid metal has gained a great deal of interest for use in tunable frequency selective surfaces due to their unique advantages, such as being able to change the physical geometry of the structure. Additionally, pneumatically tuned liquid metal devices provide stable operation in harsh electromagnetic environments since no electronic tuning elements are involved. However, much research is yet to be done regarding a design method for higher-order tunable liquid metal FSSs of arbitrary thicknesses.

In recent years, a generalized synthesis technique for the design of thickness customizable high-order ($N \geq 2$) bandpass FSSs has been developed [5], enabling simultaneous control of both the layer thicknesses and the EM response when designing multilayer (multi-pole) spatial filters. The thickness customizable design is realized by utilizing resonant bandpass FSS layers separated by thickness-controlling intercoupling layers. Such freedom in design is especially useful for integrating tuning components [6], [7], accommodating standard substrate thicknesses, or meeting custom structural specifications.

This work explores the applicability of the aforementioned synthesis technique to multilayer bandpass FSSs that incorporate liquid metal tuning elements. The aperture-coupled resonator filter topology is used to design tunable second-order and third-order bandpass FSSs, as illustrated in Fig. 1. The liquid metal layers are paired with polydimethylsiloxane (PDMS), an elastomer, to create a microfluidic device that is mechanically flexible in nature. Liquid metal slugs that can change position inside the resonator unit cell allow for continuous, real-time tuning.

II. Design of Liquid-Metal-Tuned Multilayer FSSs

The proposed liquid-metal-tuned second-order and third-order bandpass FSSs are based on the coupled resonator filter topology used in the generalized synthesis method [5]. For an Nth-order response, there are N bandpass resonator layers

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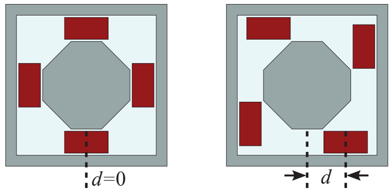
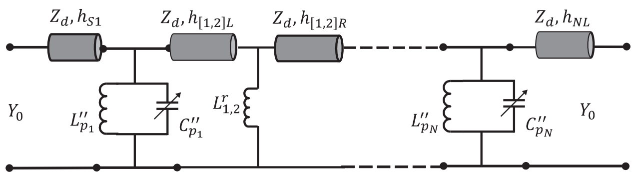
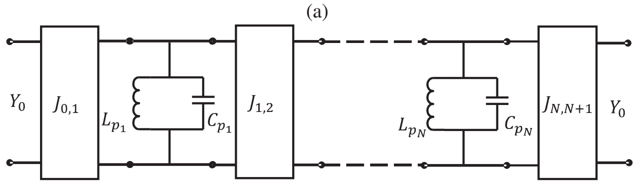


Fig. 2. Movement of liquid metal tuning slugs.



(a)



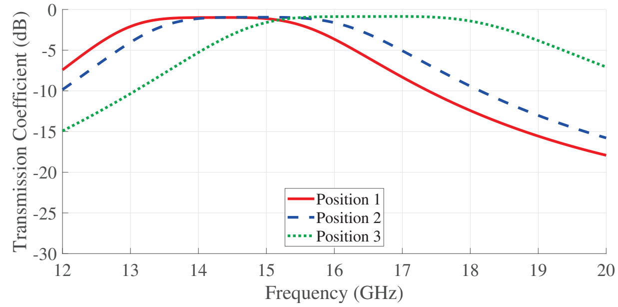
(b)

Fig. 3. (a) ECM of Nth-order spatial bandpass filter consisting of shunt parallel resonators with tunable capacitance and shunt inductors separated by short transmission lines. (b) Generalized ECM of Nth-order bandpass filter using admittance inverters (refer to [5] for detail on electrical parameters).

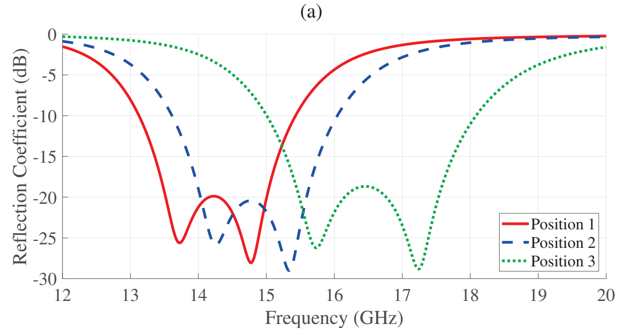
separated by $(N-1)$ aperture layers (intercoupling layers). To add the tunability feature to our new structure, the square loop slot bandpass resonator unit cells are modified to accommodate moveable liquid metal slugs, and the corners of the inner patch are chamfered, as shown in Fig. 1. The chamfered corners help to achieve a variable capacitance as the slugs are rotated around the unit cell, as shown in Fig. 2. The equivalent circuit model for this Nth-order structure is illustrated in Fig. 3a.

To design for a desired filter response (number of poles, center frequency, fractional bandwidth, etc.), one can begin from the generalized equivalent circuit model (ECM) of a bandpass filter using admittance inverters, as shown in Fig. 3b. Filter design and circuit transformation procedures detailed in [5] are used to construct the ECM shown in Fig. 3a. Each electrical parameter can then be mapped to the physical dimensions of the spatial filter. The circuit values (inductances and capacitances) can also be tuned at this stage to meet fabrication or design limitations while still maintaining the desired filter response.

The metallic layers are modeled with Galinstan, a eutectic alloy of gallium, indium, and tin, with conductivity $\sigma = 3.46 \times 10^6\,\mathrm{S/m}$. These liquid metal layers are embedded in PDMS with relative permittivity $\varepsilon_r = 2.3$ and loss tangent $\tan\delta = 0.015$. The physical dimensions of the two-pole and three-pole bandpass FSS designs are summarized in Table I. Full-wave EM simulation of both designs is carried out in ANSYS HFSS for several tuning positions to verify the tunability.



(a)



(b)

Fig. 4. Simulated (a) transmission coefficient and (b) reflection coefficient of the second-order tunable bandpass FSS.

III. Simulation Results

The simulated transmission and reflection coefficients for the two-pole and three-pole liquid-metal-tuned FSSs are shown in Fig. 4 and Fig. 5, respectively. To demonstrate the tunability, three cases of liquid metal slug displacement values d are investigated for each design. For the second-order design, the slugs on both layers are shifted by $0\,\mathrm{mm}$, $1\,\mathrm{mm}$, and $2\,\mathrm{mm}$ for Position 1, Position 2, and Position 3, respectively. The respective slug displacements for Position 1, Position 2, and Position 3 for the third-order design are $0\,\mathrm{mm}$, $0.8\,\mathrm{mm}$, and $1.6\,\mathrm{mm}$ for the outer slugs and $0\,\mathrm{mm}$, $1\,\mathrm{mm}$, and $2.35\,\mathrm{mm}$ for the inner slugs.

It can be observed that desirable transfer response is maintained throughout the tuning range. Tuning of the center frequencies are observed to be from $14.2\,\mathrm{GHz}$ to $16.5\,\mathrm{GHz}$, and $14.4\,\mathrm{GHz}$ to $16.1\,\mathrm{GHz}$ for the two- and three-pole designs, respectively. The respective $3\,\mathrm{dB}$ fractional bandwidths for Positions 1, 2, and 3 for the two-pole design are $21.4\,\%$, $22.0\,\%$, and $25.3\,\%$ and $17.2\,\%$, $17.2\,\%$, and $19.5\,\%$ for the three-pole design. A sharper transition in the three-pole design is clearly shown. The nonlinearity displayed in tuning can be attributed to the nonlinear interaction between the liquid metal slugs and the inner patch: as the slugs move away from their initial positions, the gap size does not increase immediately at the tail end of the slug.

TABLE I
DESIGN CONFIGURATIONS FOR THE TWO-POLE AND THREE-POLE FSSS

# of poles	h_1	h_2	h_3	a	b_1	b_2	c_1	c_2	s_1	s_2	l_s	w_s
2	0.5 mm	1 mm	–	7.4 mm	6.5 mm	–	1.3 mm	–	1.2 mm	–	2 mm	1 mm
3	0.5 mm	1 mm	1 mm	7.4 mm	6.4 mm	7.2 mm	1.3 mm	1.4 mm	1.2 mm	1.2 mm	2 mm	1 mm

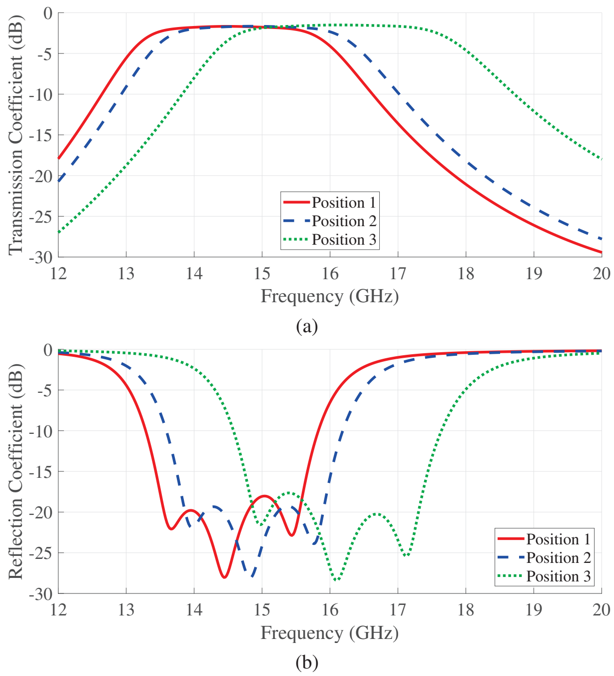


Fig. 5. Simulated (a) transmission coefficient and (b) reflection coefficient of the third-order tunable bandpass FSS.

IV. CONCLUSION

This paper introduces a new implementation of a general design method to create flexible liquid-metal-tuned multilayer bandpass frequency selective surfaces. Full-wave EM analysis of both two-pole and three-pole bandpass FSS designs operating in the Ku-band have been carried out in ANSYS HFSS for three different positions of the liquid metal slugs to verify the performance. The continuous real-time tuning of liquid metal is an attractive feature for applications that demand a stable high-frequency response when operated under a dynamic EM environment. Additionally, the unique flexibility feature brings the potential to produce deployable, transportable, and conformable metasurfaces.

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