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A Flexible Liquid-Metal-Tuned Absorber

Kevin Xu, Zhi Li, and Jun H. Choi
University at Buffalo, SUNY, Buffalo, NY 14260, USA (kxu22@buffalo.edu, zli76@buffalo.edu, junhchoi@buffalo.edu)

***Abstract*—A flexible, low-profile, and polarization-insensitive absorber with a tunable absorption band is presented in this paper. The proposed metasurface absorber consists of a resonant liquid metal frequency selective surface (FSS) layer embedded in a thin (0.044λ) slab of polydimethylsiloxane (PDMS). By pneumatically controlling the position of liquid metal dipoles inside PDMS channels, continuous tuning of the absorption frequency is achieved over a 1.6 GHz (16 %) bandwidth in the X-band.**

***Index Terms*—Absorber, flexible metasurface, Galinstan, liquid metal, metamaterial, periodic structure, tunable.**

I. Introduction

Tunable absorber designs have been realized using components such as PIN diodes [1], varactors [2], MEMS switches [3], plasma shells [4], graphene [5], and liquid crystal [6]. Unlike other tuning mechanisms, liquid metal provides a chance to reconfigure the geometry of the conductor, which allows for an exceptionally diverse range of responses. In addition, when the liquid metal is injected into microfluidic channels made out of a polydimethylsiloxane (PDMS) substrate, the entire device becomes flexible, which is ideal for applications that require conformal or deployable designs.

Tunable frequency selective surface (FSS) [7], [8] and reflecting surface [9] designs using continuous movement of liquid metal have been previously explored. However, liquid metal absorber designs in the literature lack such continuous tunability. Current reconfigurable absorber designs [10], [11] inject or completely remove liquid metal to switch between a discrete set of absorption states. Another consideration for tunable absorber designs is fabrication complexity. For the ease of large-scale fabrication/implementation, it is beneficial to have a design without using lumped components or additional substrates that require separate processing.

In this paper we present a novel metamaterial-type absorber [12] design, with its metallic resonator pattern realized by liquid metal encapsulated in thin PDMS. The overall structure of the proposed design, including its tuning mechanism, is shown in Fig. 1. Although only an array of 4 × 4 elements is illustrated, the structure can be scaled to any desired size. By moving the coupling dipoles (shown in red) along the indicated directions, the frequency response of the absorber can be continuously tuned. In addition, this method of deployment makes it possible to minimize the number of inlets and outlets. In the ideal case, only one inlet and one outlet are required for control of the entire absorber. The feasibility of moving a train of liquid metal slugs has been studied in [13].

II. Liquid-Metal-Tuned Absorber Design

The topology of the proposed tunable absorber is shown in Fig. 1. The $0.2\,\mathrm{mm}$ thick liquid metal is embedded in PDMS of height $h_2 = 0.95\,\mathrm{mm}$, and covered on top by a slab with thickness $h_1 = 0.5\,\mathrm{mm}$. The resonant liquid metal FSS layer consists of bent dipoles (shown in black, to indicate fixed position) arranged in the shape of a slotted square. Coupling dipoles (shown in red) located between neighboring squares are movable along the PDMS channels. As the positions of the coupling dipoles vary, the operating frequency of the absorber shifts due to the changing capacitive loading.

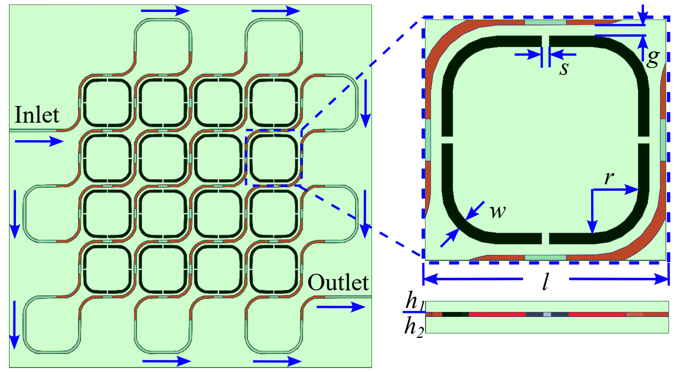


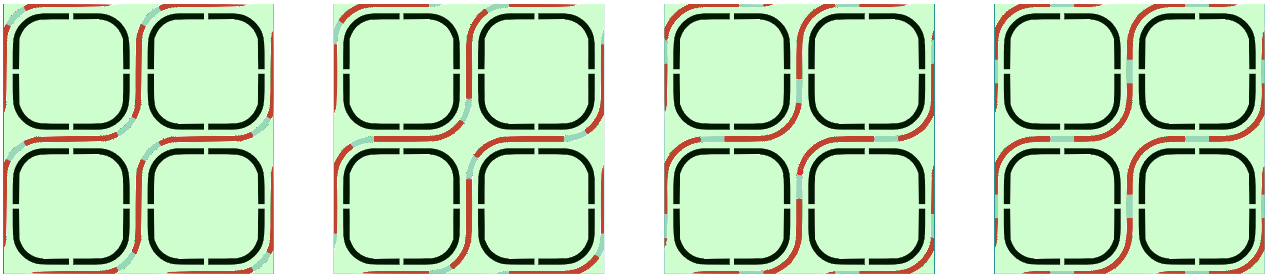
Fig. 1. Conceptual illustration of the liquid metal tuning and proposed absorber design ($h_1 = 0.5\,\mathrm{mm}$, $h_2 = 0.95\,\mathrm{mm}$, $l = 11\,\mathrm{mm}$, $w = 0.5\,\mathrm{mm}$, $r = 2\,\mathrm{mm}$, $s = 0.354\,\mathrm{mm}$, $g = 0.5\,\mathrm{mm}$).

The design is modeled in ANSYS HFSS with Galinstan (conductivity $\sigma = 3.46 \times 10^6\,\mathrm{S/m}$) as the liquid metal and PDMS with relative permittivity $\varepsilon_\mathrm{r} = 2.4$ and loss tangent $\tan\delta = 0.02$. Based on the proposed control scheme, the same coupling dipole movement is repeated every two elements/squares along both horizontal and vertical directions, as shown in Fig. 1. Therefore, the unit-cell simulation should include a sub-array of 2 × 2 elements.

III. Simulation Results

Four cases of the continuously tunable absorber are shown in Fig. 2: State 1 (maximally loaded), State 2 (intermediate), State 3 (intermediate), and State 4 (minimally loaded). Due to the cyclical movement of the coupling dipoles with respect to the fixed dipoles, the geometry will be restricted between States 1 and 4. The simulated reflection coefficient of each state, at normal angle of incidence, is shown in Fig. 3. A tunable absorption center frequency ranging from $f_L = 9.12\,\mathrm{GHz}$ (State 1) to $f_H = 10.72\,\mathrm{GHz}$ (State 4) is exhibited, which corresponds to a $16\,\%$ tuning bandwidth. The total thickness of the absorber, $1.45\,\mathrm{mm}$, is equivalent to $0.044\lambda_0$, where λ_0 is the free space wavelength at f_L.

Simulated results of State 4 for oblique angles of incidence are shown in Fig. 4(a) and Fig. 4(b), for TE and TM polarizations, respectively.



(a) (b) (c) (d)

Fig. 2. Tuning of a 2 × 2 element sub-array (moveable liquid metal shown in red): (a) State 1, (b) State 2, (c) State 3, and (d) State 4.

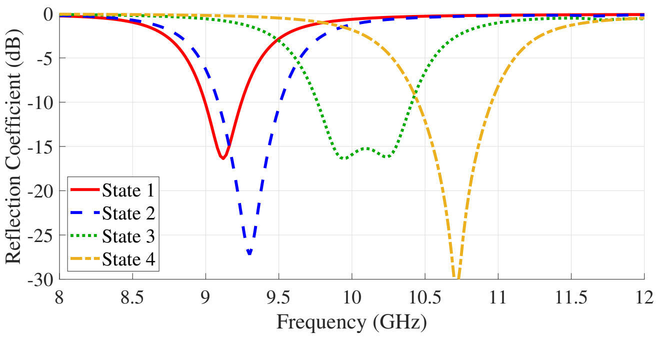


Fig. 3. Simulated reflection coefficient of the tunable absorber for various liquid metal positions.

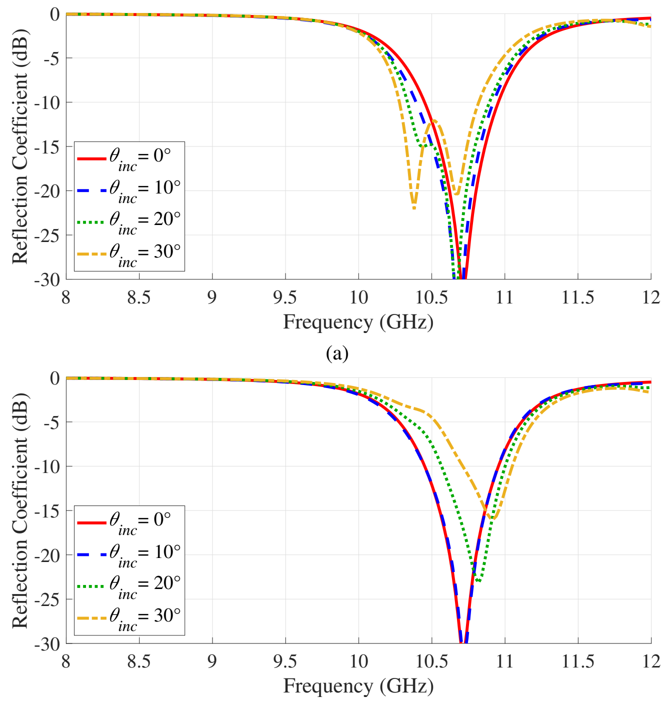


Fig. 4. Simulated reflection coefficient of the absorber (State 4) at various angles of incidence. (a) TE polarization. (b) TM polarization.

IV. Conclusion

The proposed absorber is the first to simultaneously provide continuous tunability, flexibility, and polarization insensitivity in a single design. The tuning mechanism allows easy manipulation of all unit-cells at once. Additionally, the design is not complex in terms of fabrication, using only PDMS and liquid metal. Unlike the existing liquid-metal-based reconfigurable absorbers, the liquid metal is utilized along the entire path of travel to obtain a continuously tunable absorption response.

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