Liquid-Metal-Tuned Patch Element for Flexible and Reconfigurable Reflectarrays/Intelligent Surfaces

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***Abstract*—This paper presents a flexible and reconfigurable reflecting element based on liquid metal encapsulated in polydimethylsiloxane (PDMS). The proposed unit cell provides precise reflection phase tuning of over 360° by pneumatically extending or retracting liquid metal in channels spiraling outward from a square patch. The flexible materials are well suited to realize deployable or conformal reflecting surfaces for devices such as reflectarrays or reconfigurable intelligent surfaces (RISs). To demonstrate use of the reflecting element, a curved 12 element × 12 element array operating at 8.425 GHz is designed and verified using full-wave simulation.**

***Keywords*—Conformal antennas, flexible metasurface, Galinstan, liquid metal, reflectors, reconfigurable reflectarrays.**

I. Introduction

Reflectarrays are invaluable antennas that share advantages of both reflector antennas and phased arrays. They can be designed to focus a beam in a specified direction while at the same time provide convenience in terms of weight, shape, and manufacturability. Due to these advantages, deployable reflectarrays for space applications have become increasingly popular. Some examples include folded reflectarrays used in the recent Mars Cube One (MarCO) mission [1], large flexible membrane reflectarray [2], and inflatable reflectarray [3]. While flexibility is useful for conserving space pre-deployment, it is also an important trait for creating conformal reflectarrays [4].

One up-and-coming technology for flexible microwave devices is polydimethylsiloxane (PDMS) encapsulated liquid metal. In addition to its flexibility, the liquid metal may be geometrically reconfigured to tune the electromagnetic response. For example, the attractive liquid metal/elastomer combination has been explored for flexible frequency selective surfaces [5] that are tunable in real time. Since this unique technology does not rely on electronic tuning mechanisms, it is attractive for applications in harsh electromagnetic environments where a stable response is required.

II. Liquid-Metal-Tuned Patch Reflector Element

The proposed reflecting element shown in Fig. 1 is based on a spiral patch design [6] with phase response less sensitive

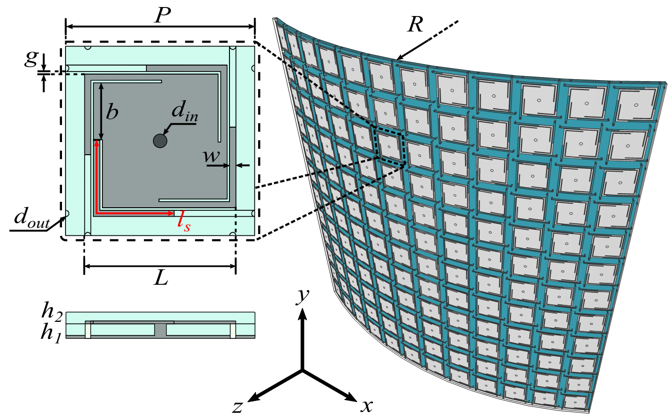

Fig. 1. Proposed liquid-metal-tuned spiral patch element and a 12×12 array (with bend radius R) consisting of these elements. Unit cell dimensions: $b = 4.5\,\mathrm{mm}$, $d_{in} = 0.5\,\mathrm{mm}$, $d_{out} = 1\,\mathrm{mm}$, $g = 0.2\,\mathrm{mm}$, $h_1 = 1\,\mathrm{mm}$, $h_2 = 1\,\mathrm{mm}$, $P = 15\,\mathrm{mm}$, $L = 12\,\mathrm{mm}$, $w = 0.5\,\mathrm{mm}$.

along the varied dimension compared to typical square patches. By altering the length of the spiral stubs, reflection phase of the element can be accurately tuned to the desired value. In our new design, spiral channels in PDMS serve as a guide for fine movement of liquid metal. The channels connect to vertical holes leading to the backside, where pressure may be applied to extend or retract liquid metal within the spiral stub volume. The spiral channels each connect to the patch, which has a via located in the center. This via allows liquid metal to flow in and out from the ground plane, which serves as a liquid metal reservoir.

Galinstan, with conductivity $\sigma = 3.46 \times 10^6\,\mathrm{S/m}$, is used as the liquid metal to construct the reflector elements in our simulation. The liquid metal is contained within the PDMS substrate modeled with relative permittivity $\varepsilon_\mathrm{r} = 2.3$ and loss tangent $\tan\delta = 0.02$.

The reflector element is simulated in HFSS with periodic boundary conditions. Both the length of stubs (l_s) and the incident angle are swept to generate sufficient data for the design of reflectarrays. As shown in Fig. 2, there is a large tuning range and close to linear response of reflection phase. The period P is less than half wavelength at 0.42 λ, in order to have adequate bandwidth and angular stability [7].

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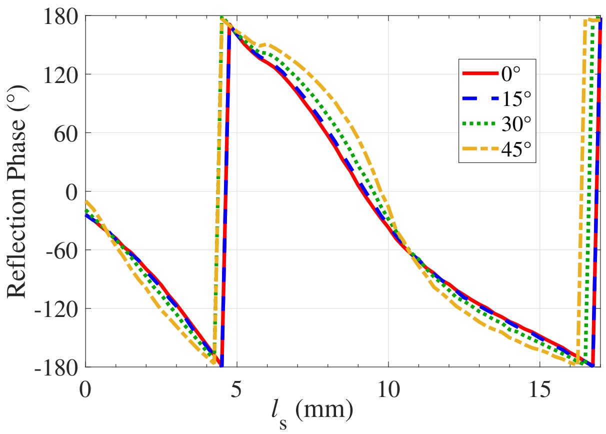

Fig. 2. Simulated reflection phase versus stub length l_s of the unit cell for various incident angles up to 45°.

III. Conformal Reflecting Surface Design

An example of a bent 12×12 array excited by a plane wave is simulated to demonstrate the effectiveness of the proposed element in flexible or conformal reflectarray and reflecting surface designs. The physical size of the array is $18\,\mathrm{cm} \times 18\,\mathrm{cm}$ (approximately $5\lambda \times 5\lambda$). The radius of curvature, R, is $36\,\mathrm{cm}$. The plane wave excitation is placed at $X_F = 0$, $Y_F = 0$, $Z_F = 36\,\mathrm{cm}$.

The phase required for each element (at position $\mathbf{r_i}$) to point the main beam in the direction $\hat{\mathbf{r}}_b$ is

$$\begin{aligned}\phi_i &= k_0(R_i - \mathbf{r}_i \cdot \hat{\mathbf{r}}_b)\\ &= k_0(R_i - (x_i \cos\varphi_b \sin\theta_b + y_i \sin\varphi_b \sin\theta_b + z_i \cos\theta_b)),\end{aligned} \tag{1}$$

where k_0 is the free-space wavenumber and R_i is distance from the center of the ith element (x_i, y_i, z_i) to the phase center of the feed (X_F, Y_F, Z_F). In contrast to planar arrays, the curved array elements contain non-zero z_i terms along with modified x_i and/or y_i coordinates depending on the bend direction and radius of curvature R.

The angle between the z-axis and the normal of each element is used to determine which phase versus l_s curve to use, such as in Fig. 2. This angle is rounded to the closest multiple of 5°, which is the increment of incident angles used in simulation for the unit cell. Then, the appropriate stub length is assigned from the curve based on the required phase. This quantized approach is sufficient provided that the phase response is relatively insensitive to the chosen angle increment.

The colormap in Fig. 3(a) shows the required phase for each element to point the beam at $\theta_b = 15°, \varphi_b = 90°$. From the radius of curvature, the previously defined angle is found for each element as in Fig. 3(b). Using both results, the length matrix of spiral stubs is completely determined. The simulated normalized reflection pattern from $-90°$ to $90°$ shown in Fig. 4 verifies the design method.

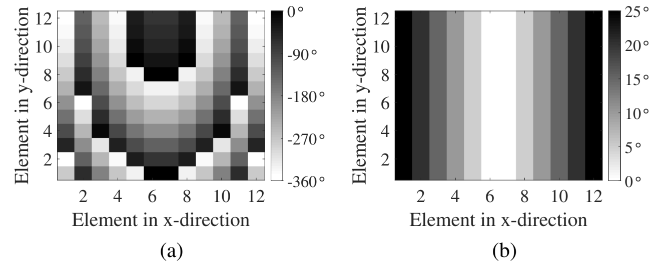

Fig. 3. (a) Required phase shift provided by each element. (b) Bend distribution.

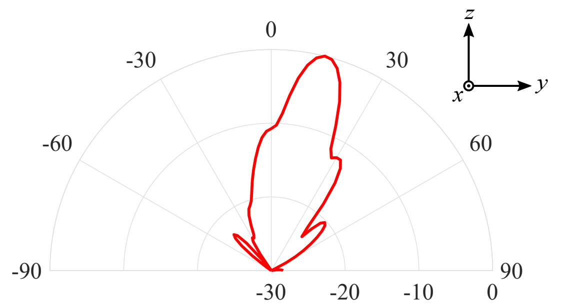

Fig. 4. Simulated normalized reflection pattern of the 12×12 curved array in the yz-plane (designed to point at $\theta_b = 15°, \varphi_b = 90°$).

IV. Conclusion

A flexible and reconfigurable liquid metal reflecting element with over 360° phase variation is presented. The device's adaptability to different configurations (such as bending, arbitrary feed positions, beam direction(s), etc.) on demand makes it ideal for applications such as flexible or deployable reflectarrays/reconfigurable intelligent surfaces that can be tuned in real time.

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