Large-Scale Fluidic Tuning of Subwavelength Periodic Structures

Tonmoy Bhattacharjee, *Student Member, IEEE*, Hongrui Jiang, *Senior Member, IEEE*, and Nader Behdad, *Senior Member, IEEE*

***Abstract*—In this letter, we present a technique to fluidically tune the responses of periodic structures with multiple unit cells and finite dimensions. The periodic structures are composed of subwavelength constituting unit cells. This technique is applied to a two-dimensional high-impedance surface with multiple unit cells, and the response of the structure is continuously tuned. The technique is based on embedding metal and glass balls inside several parallel channels within a dielectric substrate supporting the structure. In each channel, a periodic arrangement of metal and glass balls is assembled and is allowed to move freely within the channel. By moving this periodic train of balls over small distances with respect to the fixed periodic structure, the response of the structure is continuously tuned. Three-dimensional (3-D) printing technology is used to implement the dielectric substrate with embedded fluidic channels. An architecture for the fluid distribution network is proposed that ensures the movement of balls in all channels is synchronized. A prototype with 16 parallel channels accommodating several unit cells in each channel is fabricated, and synchronized movement of the balls is verified experimentally when the balls in channels are embedded in mineral oil and pressure driven. Using this substrate and an array of subwavelength capacitive patches fabricated on a thin dielectric substrate, a fluidically tunable high-impedance surface is designed and experimentally characterized.**

***Index Terms*—3-D printing, fluidics, large-scale, metamaterials, periodic structures.**

I. Introduction

PERIODIC structures have numerous applications in the RF and microwave area including the design of metamaterials [1], frequency selective surfaces [2]–[4], reactive impedance surfaces [5], and antenna arrays [6]. In recent years, with the emergence of the field of metamaterials, subwavelength periodic structures have received a significant amount of attention. As the use of multifunctional and sophisticated systems both in the commercial and in the military arenas is becoming prevalent, the demand for reconfigurable periodic structures possessing agile frequency responses is on the rise. In the past, different techniques have been explored for designing tunable periodic structures. By far, the most widely used technique for making tunable periodic structures is to integrate electronically tunable elements such as solid-state or microelectromechanical systems (MEMS) varactors with the unit cells of the periodic structure [7]. This technique, however, is rather challenging to implement in a physically large periodic structure with subwavelength constituting elements. In such a structure, in a relatively small physical area, hundreds or even thousands of unit cells may be packed, which makes the task of integrating active devices with them impractical. Other techniques have also been examined for making periodic structures tunable. Among these, using liquid substrates [8], liquid crystals [9], and magnetic MEMS devices [10] can be mentioned.

Recently, our group proposed a new fluidic tuning technique for designing tunable periodic structures with subwavelength periodicities [11], [12]. This technique does not rely on using any electronic devices and eliminates the need for using biasing networks or individually integrating active elements with each unit cell of the periodic structure. The technique is based on embedding capillary tubes filled with liquid metal droplets within a periodic structure composed of subwavelength capacitive and/or inductive impedance surfaces. By moving the liquid metal droplets within the unit cell of the structure, the capacitance values of the capacitive surface impedances can be changed in a continuous fashion very much like what is done using an electronic varactor [12]. Using such liquid varactors, tunable miniaturized-element frequency selective surfaces were designed and experimentally demonstrated at the unit-cell level. It was demonstrated that the frequency responses of such tunable FSSs can be continuously tuned over a very wide bandwidth. It has been also shown that this class of tunable FSSs is expected to be capable of handling significantly higher transient power levels as it does not use electronic devices that are inherently nonlinear [12].

The aforementioned studies examining liquid-tunable FSSs focused on characterizing the tuning capabilities of such structures at the unit cell level [11], [12]. However, in a large tunable periodic structure, multiple unit cells exist, and they have to be controlled simultaneously. Therefore, suitable implementation techniques need to be developed for expanding this tuning technique from the unit-cell level to a large-panel level. Specifically, we experimentally found out that using the liquid metal Galinstan in a liquid Teflon solution, a unit cell of a periodic structure can be tuned relatively easily. However, assembling trains of liquid Galinstan droplets and driving them synchronously to emulate multiple unit cells proved to be extremely challenging in the laboratory. Galinstan oxidizes rapidly in air and wets almost any surface [13]. Moreover, when trains of liquid metal droplets were assembled in a capillary tube, maintaining the spacing between two consecutive liquid metal droplets proved to be impractical when the entire system was pressure-driven.

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The authors are with the Department of Electrical and Computer Engineering, University of Wisconsin–Madison, Madison, WI 53706 USA (e-mail: tbhattacharj@wisc.edu; Hongrui@engr.wisc.edu; behdad@wisc.edu).

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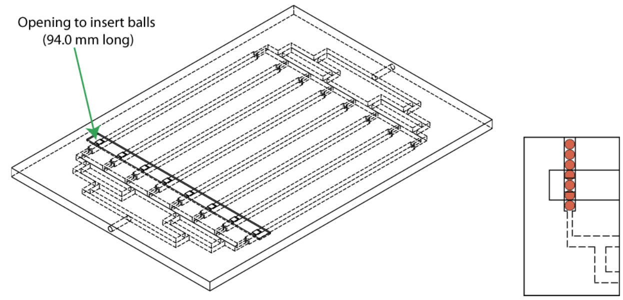

(a) (b)

Fig. 1. (a) Topology of a 3-D printed substrate with eight fluidic channels. (b) Zoomed in view with balls inside one channel (top view).

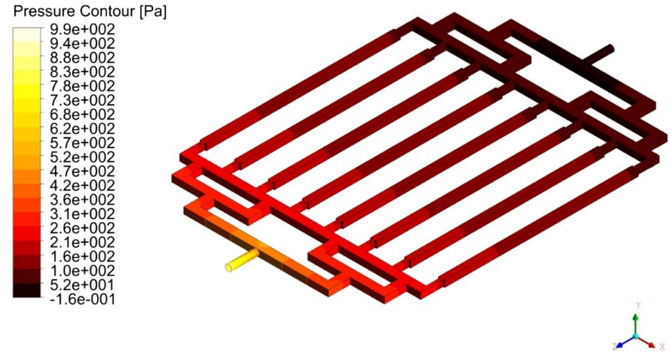

Fig. 2. Pressure distribution among the channels of the substrate shown in Fig. 1.

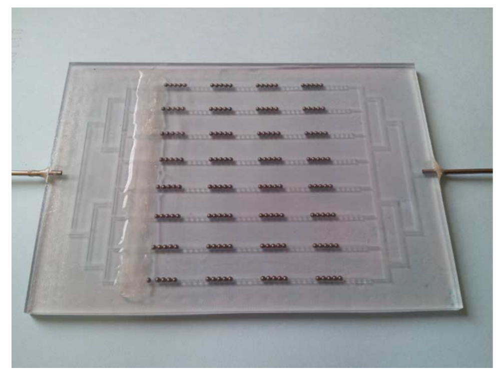

Fig. 3. Photograph of a fabricated prototype of the structure shown in Fig. 1 with periodic trains of metal and glass balls embedded in all channels.

Besides the use of Galinstan, an FSS consisting of periodic array of liquid mercury (Hg) droplets separated by gaps of mineral oil contained in an array of PTFE tubes was also presented [14]. However, mercury is an extremely toxic substance, and its use is not practical in real-life systems.

In this letter, we propose a new implementation technique for realizing fluidically tunable periodic structures that operates based on the same principles of operation as the Galinstan-tunable FSSs reported in [12]. Unlike the structures reported in [11] and [12], however, the demonstration of the fluidically tunable structure presented in this work is not done at the unit-cell level. Specifically, this structure has multiple unit cells in a two-dimensional periodic structure and achieves synchronous tuning of all the unit cells using the proposed fluidic tuning technique. Moreover, this new implementation technique does not use Galinstan or any liquid metals. Instead, a series of circular chrome steel and glass balls are used to replace the liquid metal slugs and the dielectrics separating them. These solid, nontoxic but movable metal balls can be easily handled and arranged to emulate a train of liquid metal droplets with fixed periodicity and spacing between each droplet. Additionally, with the new implementation technique, we also eliminate the use of any type of capillary tubes and replace them with a 3-D printed dielectric slab containing multiple embedded parallel channels capable of accommodating numerous unit cells.

II. Design Procedure and Simulation

In our initial design, we primarily focused on designing a device that eliminates the use of tubes and liquid metal slugs and investigated how to move several periodic trains of metallic and glass balls in multiple channels synchronously. A slab consisting of 8 parallel channels was designed using a computer-aided design (CAD) tool, SolidWorks, as shown in Fig. 1(a). Channels of smaller cross sections are placed in between the longer channels and the networks of branch channels on both ends to prevent the balls from exiting their dedicated channels. The structure is simulated using ANSYS Fluent to verify synchronous movement of fluid inside the channels. Simulation result shows evenly distributed pressure among all the channels as shown in Fig. 2. The channel dimensions are $2.2 \times 2.2 \times 90.0$ mm^3. Eight $1.0 \times 2.2 \times 5.0$-mm^3 channels are placed between the 90.0-mm-long channels and the branch networks. A 94.0-mm-long opening is placed on one face of the slab so that metal and glass balls can be easily inserted into the channels and is sealed off with a 3-D printed thin strip and epoxy. The overall slab has dimensions of $108.0 \times 4.2 \times 153.6$ mm^3. Then, a prototype is printed using a Viper Si2 3-D printer. The printer uses Accura60—a type of photopolymer resin—as the printing material. After the prototype is fabricated, trains of metal and glass balls are created inside the channels in an alternate fashion as shown in Fig. 3. Each train of metal balls and glass balls consists of five metal balls and five glass balls, respectively, which are 2.0 mm in diameter. Then, two blunt needles are inserted through the inlet and outlet and sealed off with epoxy to prevent movement and leakage of liquid. Using an inlet, the channels are filled up with mineral oil using a 5-mL syringe. After all the channels are filled up, the outlet needle is assembled with a 5-mL mineral-oil-filled syringe. As one of the syringes is pushed, the trains of metal and glass balls are observed to move in a synchronous fashion. This process was found to be repeatable after multiple back-and-forth movements of the balls within the channels. Therefore, using the slab with parallel channels and branched pressure distribution network is an effective technique to achieve synchronous movement of periodic objects in multuple channels for large-scale fluidically tunable structures.

III. Design of a Fluidically Tunable Reactive Impedance Surface

The eight-channel prototype we built demonstrated that synchronous movement of metal and glass beads can be achieved for a periodic structure panel consisting of multiple unit cells. To study the use of this tuning concept in designing tunable periodic structures, the eight-channel design was scaled to a 16-channel one, which would then be integrated with a periodic arrangement of subwavelength capacitive patches to obtain a

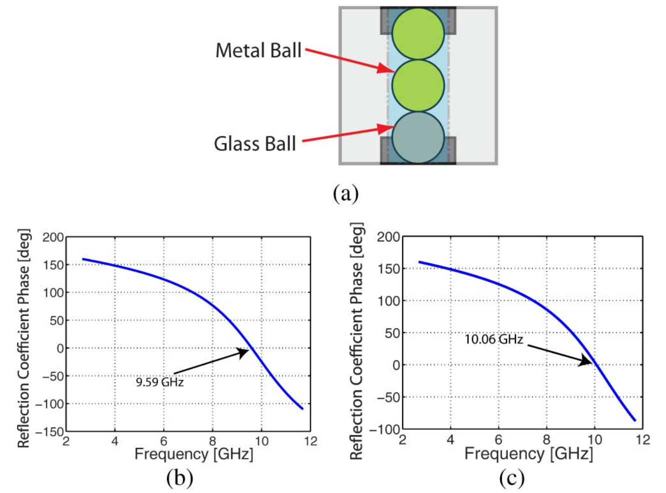

Fig. 4. (a) Unit cell of one embodiment of the proposed tunable reactive impedance surface (back view). This structure has unit cell dimensions of 6×6 mm^2 and uses three balls per unit cell to achieve tunability. (b) Simulated phase response when the metal ball is underneath the gap. (c) Simulated phase response when the glass ball is underneath the gap of capacitive patches.

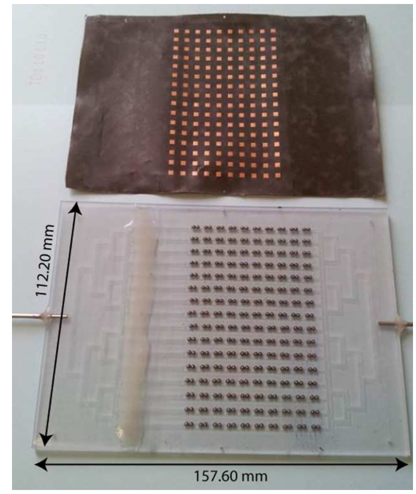

Fig. 5. *(top)* Photograph of the capacitive patch array fabricated on a 5-mil-thick Rogers 5880 laminate. *(bottom)* 3-D printed slab with 16 fluidic channels.

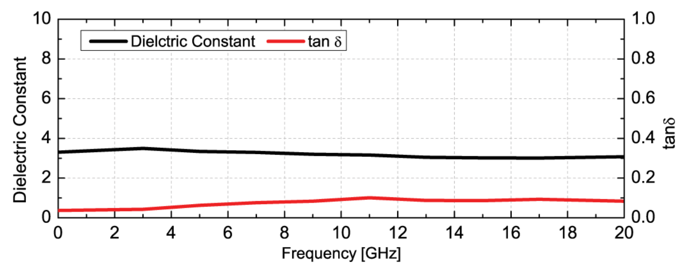

Fig. 6. Dielectric constant and loss tangent values of Accura 60 material.

tunable reactive impedance surface (RIS). The 3-D printed substrate is sandwiched between the array of patches and a ground plane. The capacitive patch array is fabricated on a 5-mil-thick Rogers 5880 laminate. Preliminary simulation of a unit cell of this structure was performed using CST Microwave Studio to evaluate its tuning capability. It was found out that a structure with a unit cell size of 6.0 mm with an overall substrate thickness of 3.22 mm can provide 0.47 GHz of tuning range. The 3-D printed substrate thickness was chosen by taking into account the minimum dimensions of the channels that the 3-D printer can accurately fabricate. The unit cell had two metal balls and one glass ball, all with a diameter of 2.0 mm [see Fig. 4(a)]. The metal balls are modeled as PEC, and the glass ball is modeled as a dielectric with $\epsilon_r = 6.9$. With regards to the conductivity of the metal balls, as discussed in [12], the specific conductivity is not very important as long as the conductivity is high enough to create significant fringing fields in the capacitive gap areas. For dielectric balls, it is desired to have low dielectric constant values.

The gap between the two adjacent capacitive patches was 3.6 mm, which was determined based on the design guidelines mentioned in [12]. The position of each ball was moved one at a time, and the phase of the reflection coefficient was recorded to evaluate the tuning range. The unit cell configuration of Fig. 4(a) gives the response shown in Fig. 4(b). As the balls move, the phase change occurs gradually and eventually provides the response shown in Fig. 4(c), when the glass ball is underneath the gap. Fig. 5 shows the photograph of the 3-D printed dielectric substrate with 16 embedded fluidic channels. The printing material used to build the structure was Accura 60. Each ball was inserted into the channels one at a time by hand. The channels in the printed structure had a tolerance of 10%, which was intentionally included in the design for easy cleanup of the residues of support structures built by the printer during the printing process as well as for the easy movement of the balls inside the channels.

Before covering one side of the printed slab with a ground plane and the other side with a periodic array of subwavelength capacitive patches, the outlets on two sides were sealed off with blunt needles. The insides of the channels were then filled with mineral oil using 10-mL syringes. As one of the syringes was pushed, synchronous movement of the trains of metal and glass balls was observed.

IV. Measurement Results

Measurements were performed for the RIS in a laboratory setting. The dielectric constant and loss tangent of a slab of Accura 60 were characterized using the methods described in [15], and the results are shown in Fig. 6. An X-band standard-gain horn antenna was used to measure the reflection from the structure. The horn was placed approximately 68 mm away from the structures in a way so that the E-field of the radiated wave is parallel to the channels. The trains of balls were moved by pushing one of the syringes attached to the slab through a blunt needle. After each small movement of the trains, the reflection coefficient measurement was performed using an Agilent N5225A PNA. Before placing the RIS on top of the 3-D printed slab, a brass sheet with the same thickness and dimensions as those of the RIS was placed on top of the slab, and the reflection coefficient was measured. The reflection coefficient phase from the brass sheet was later used to normalize the measured phase of the capacitively loaded periodic structure. Thus, the actual phase response of the structure was extracted. From these measurements, the maximum tuning range achieved was observed to be 0.31 GHz—as can be seen in Fig. 7(b). It should be noted that the frequency range of the reflection coefficient phase data is limited by the available bandwidth of the X-band horn. A rather significant deviation from the simulated response, shown

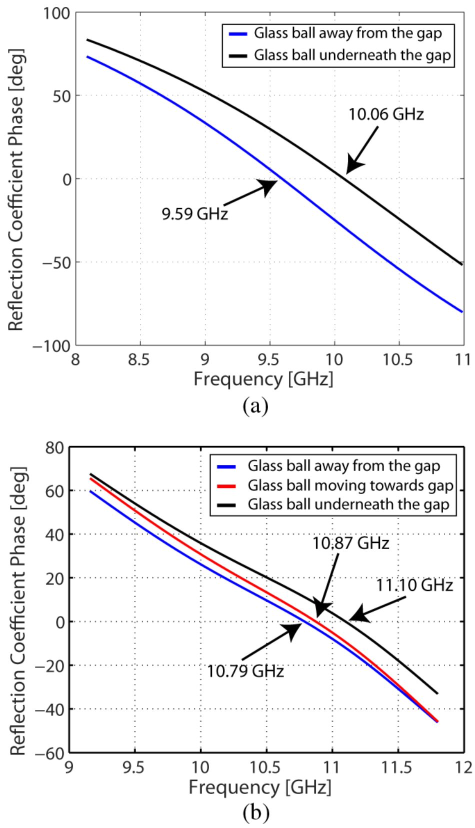

Fig. 7. Tuning range of the structure (a) Simulated and (b) Measured.

in Fig. 7(a), is also observed. This is primarily attributed to the limited accuracy of the measurement technique used to characterize the dielectric constant and loss tangent values of Accura 60 substrate (see [15]). Additionally, it was observed that the balls inside the channels were oriented in a slightly zigzag fashion due to space available from the tolerance incorporated into the channels during the design process. Finally, because of the small thickness of the laminate used to fabricate the capacitive patch array, isolated air gaps were observed to exist between the capacitive patch array and the 3-D printed substrate. Since these air gaps were isolated and did not exist uniformly over the entire surface area of the RIS, they were not modeled in the simulations. Therefore, the discrepancies between the measurement and simulation results can be attributed to the above-mentioned factors.

V. Conclusion

We presented a technique that is expected to enable the fluidic tuning of large-scale periodic structures with multiple unit cells. The proposed technique eliminates the use of liquid-metal-filled capillary tubes by using a 3-D printed dielectric slab with embedded channels and populated with metal and glass balls. A prototype with eight parallel channels was fabricated and synchronous movement of periodic trains of metallic and glass balls in different channels was observed experimentally. Then, an array of subwavelength capacitive patches was combined with a 16 channel prototype to obtain a tunable RIS, and a frequency tuning range of 10.79–11.10 GHz was experimentally demonstrated. The mechanical tuning speed of the structure is constrained by the 10-mL syringes, the inside surface roughness of the channels, and them being free of residues. A 6-mm unit cell of the structure with a 2-mm diameter channel results in 18.84 μL. Based on the availability of various commercial micropumps, the tuning speed can vary between several microseconds to few milliseconds. During this process, a 16-channel prototype consisting of 7.0-mm unit cells is built with smaller channel cross sections. It has been observed that synchronization of ball movement is difficult to obtain due to manufacturing limitations associated with 3-D printing. However, based on simulations performed, the structure is observed to be capable of giving 1.5 GHz of tuning range, and from measurement, a 0.81-GHz tuning range has been achieved. Additional simulation has shown that a structure consisting of 8.8-mm unit cells and 0.8-mm-diameter balls can provide 2.14 GHz of tuning range.

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