Microfluidically Tunable Paper-Based Inkjet-Printed Metamaterial Absorber

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***Abstract*—This paper describes a tunable metamaterial (MM) absorber that incorporates novel microfluidic channels and is realized using inkjet printing on a photo-paper substrate. The fabricated sample demonstrated frequency-switching capability owing to distilled water flowing in the microfluidic channels. In addition, the resonant frequency was changed from 4.42 to 3.97 GHz when the empty channels were filled with de-ionized water. An analysis of the results suggests that microfluidic technology is a simpler and more effective way to achieve tuning functionality. The proposed structure is the first microfluidic absorber based on a photo-paper substrate.**

***Keywords*—Metamaterials, Inkjet printing, Resonant frequency.**

I. INTRODUCTION

Metamaterials (MMs) are defined as materials possessing extraordinary properties, such as negative permittivity or negative permeability [1], which are not found in natural materials. Such materials have been widely applied in microwave and millimeter technologies [2].

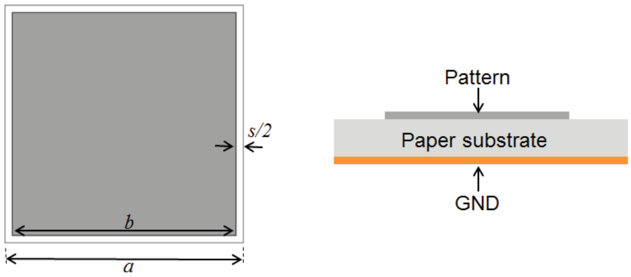
The MM absorber is an important application that can be realized by electronic-magnetic resonators. Recently, the wide reach of MMs has flown to tunable directions [3], where re-configurability on base of frequency is highlighted.

In this research, we exploited the interaction of resonant structures with microfluidic channels to achieve tuning functionality. Therefore, the resonant frequency varied with different fluids inside the capillary channels.

Moreover, instead of using traditional printed circuit boards (PCBs) as substrates, we carried out inkjet printing on paper substrates [4]. As a result, the conductive patterns could be conveniently printed on paper with silver-nanoparticle inks. Unlike a typical etching process, inkjet printing is an additive fabrication process in which no waste is generated, and it also makes the fabrication process simpler and more environmentally friendly.

II. ABSORBER DESIGN

The MM absorber design is based on an electromagnetic (EM) resonator. If the proper values of the effective relative permittivity and effective relative permeability are obtained, the MM will possess perfect relative impedance that completely matches the free space [5]. As shown in Fig. 1(a), we chose a simple square patch as the unit cell of the EM resonator. There was a grounded metal film on the back side of the structure, as shown in Fig. 1(b).



(a) (b)

Fig. 1. Unit cell of the MM absorber: (a) top view; (b) side view;

The resonance is originated by a dipolar coupling between two adjacent unit cells [6]. Therefore, the dipole resonance of the proposed absorber is determined by the side length of the square patch (*b*) and the gap between two adjacent unit cells (*s*). As a result, the resonance frequency f_r is approximately calculated by

$$f_r \cong \frac{c}{2(2b+s)\sqrt{\varepsilon_{avg}}} \tag{1}$$

where *c* is the velocity of light, and ε_{avg} is the average dielectric constant around the gap between two unit cells [7].

From Eq. (1) we know that the resonance frequency of the MM is dependent on both the geometrical dimensions of the conductive pattern and the average dielectric constant. Since the geometrical dimensions are much less likely to change after fabrication, we can have full use of the change in dielectric constant to achieve tuning ability. Compared to the air, liquid such as water has a higher dielectric constant. When a liquid is loaded on the surface of the unit cell, the dielectric constant will change significantly. As a result, the resonance frequency will vary with the properties of the fluid on the surface. The proposed tuning mechanism is material dependent, while varactor diodes or MEMS are voltage dependent. Therefore, the microfluidic technology does not require a complex bias network design or DC power consumption.

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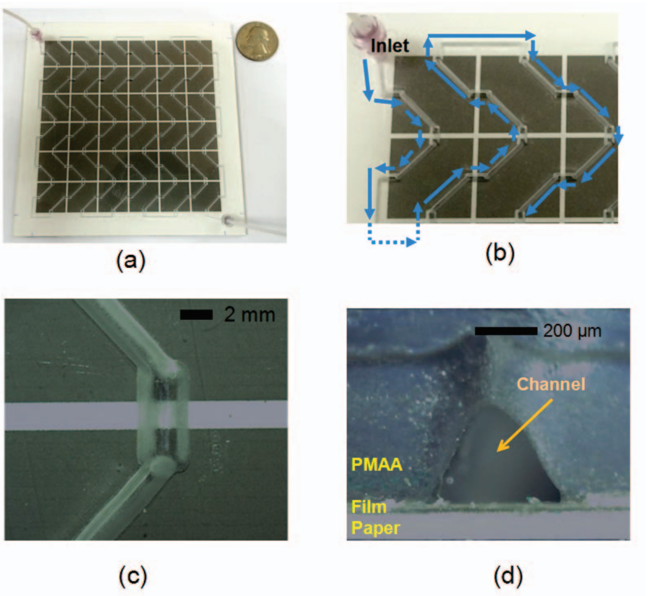

Fig. 2. Fabricated microfluidic MM absorber. (a) Top view of overall structure in 6 × 6 array configuration with inlet and outlet tubes. (b) Fluid flow in the channel of the unit cell (blue arrows). (c) Magnified view of the water-filled microfluidic channels over the gap between two square patches. (d) Cross section of the PMAA layer with a microfluidic channel.

III. FABRICATION

The fabrication of the microfluidic MM absorber included three steps. In the first step, the microfluidic channels were etched on polymethyl methacrylate (PMMA) by laser etching. To facilitate the fluid injection, we connected dispersive channels altogether in the gaps. Adjacent gap capacitors were connected through narrow channels, which were carved using the same laser machine. These capillary channels not only allowed fluid to share the same microfluidic path, but also prevented the formation of air bubbles and uneven filling. In the second step, the square patches were inkjet-printed on photo paper using silver-nanoparticle ink. And, we introduced a Dimatix DMP-2831 materials printer to ensure the printing quality. After the conductive pattern was printed on the photo paper, the piece of paper was placed in a Thermo Scientific Oven for 1 h at 120°C to improve the conductivity of the pattern. Finally, a laminating film was added in the third step to complete the bonding process. It was used not only as a bonding layer, but also as an impervious diaphragm to prevent liquid leakage. Fig. 2(a) shows a picture of a sample of the final product, with two tubes inserted in the inlet and outlet on the PMMA for injection. The direction of the liquid flow is shown by the blue arrows in Fig. 2(b). A microfluidic channel and its cross section are magnified in Fig. 2(c) and (d), respectively.

IV. SIMULATED AND MEASURED RESULTS

The absorption of electromagnetic waves is described by the equation $A(\omega) = 1 - T(\omega) - R(\omega)$, where $T(\omega)$ is the transmission coefficient and $R(\omega)$ is the reflection coefficient. For our sample microfluidic MM absorber, there was a metal ground on the back side where the transmission tended to remain at zero. Therefore, we need to measure the reflectivity, if we want to know absorption ratio of the proposed absorber.

The experimental results in Fig. 3 show the tuning of the resonant frequency over a range of 3.97–4.42 GHz. The peak values in absorption are clearly between 3.97 and 4.42 GHz for the cases with and without water in the fluidic channels. Moreover, regardless of whether the channels were empty or filled with de-ionized (DI) water, the absorber showed high absorption (over 90%) for both horizontal and vertical polarizations.

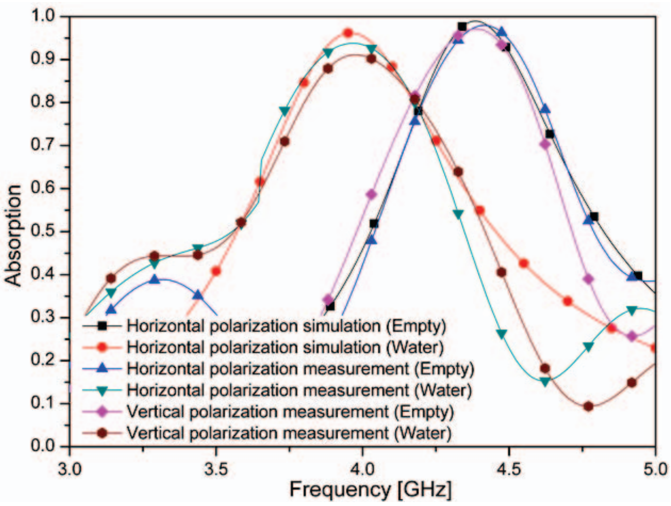

Fig. 3. Simulated and measured absorptivity with empty and distilled water-filled microfluidic channels for horizontal and vertical polarization incidence.

V. CONCLUSION

We demonstrated the performance of a microfluidically tunable metamaterial absorber fabricated from a 6 × 6 matrix array of conductive patches on a photo-paper substrate. Tuning over a frequency range of 0.45 GHz was achieved by filling the fluidic channels with de-ionized water. The fabrication process generated no waste which followed the concept of environmental protection. In addition, since the proposed MM absorber's resonant frequency can be changed by different injected fluids, this technique may have other potential prospects as a wireless sensor for a large area.

ACKNOWLEDGMENT

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