Microfluidically Switched Frequency-Reconfigurable Slot Antennas

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***Abstract*—This letter proposes a concept for frequency-reconfigurable slot antennas enabled by pressure-driven capacitive microfluidic switches. The switches are operated by pneumatically displacing a plug of eutectic gallium indium alloy (EGaIn) within an air-filled microchannel that traverses the slot orthogonally. Frequency reconfigurability is achieved by altering the displacement of conductive fluid within the channel, which reactively loads the slot. A transmission-line model is developed to capture the physical behavior of the fluid channel, and measurements are provided that show good agreement with the behavior of the model.**

***Index Terms*—Frequency-reconfigurable, microfluidic switch, slot antenna.**

I. Introduction

THE RAPIDLY dwindling availability of radio frequency bandwidth in the US demands that attention be paid to developing spectrum conserving solutions such as cognitive radio. The increasing demand for data is taxing the current static bandwidth allocation model. From smartphones and tablets to radar and military communications, bandwidth is becoming increasingly necessary, but is already scarce. Implementing cognitive radio by allowing radios to find and utilize locally unused frequencies promises to help relieve the problem.

While these systems can be implemented by using wideband or frequency-independent antennas with reconfigurable filters, the large footprint required for such a system will be restrictive for many applications. In order to address this shortcoming, reconfigurable antennas have been the focus of much research in recent years [1]. In addition to frequency reconfiguration, antennas have been developed to use pattern, e.g., [2], and polarization reconfigurability, e.g., [3], to reject interfering signals and improve reception, enhancing the promise of cognitive radio as a solution to the spectrum problem. Military radar and communications systems can also take advantage of the frequency agility and interference rejection provided by cognitive radio with reconfigurable antennas to make systems hard to detect and jam. While slot antennas have potential in a number of applications due to their easy incorporation into any electrically large metallic structure, their current applications are primarily radar systems.

Implementing reconfigurability in these systems with the current state-of-the-art reconfiguration mechanisms proves problematic due to issues such as nonlinearities in diodes and self-actuation in microelectromechanical systems (MEMS). Diode nonlinearities cause gain compression and degrade antenna performance and generate harmonics and intermodulation distortion, further cluttering the RF spectrum. Antennas with nonlinear elements also do not behave reciprocally because of the different power levels for receiving and transmitting antennas [2]. Self-actuation and stiction in MEMS switches caused by high strength fields limit the usefulness of these devices to low-power applications. Switches based on conductive fluid with purely mechanical actuation present a promising solution due to their linear behavior that is unaffected by strong fields.

A recent advance in structural composite manufacturing has provided a pathway for embedding microvascular networks and enabling conductive fluid to be used as a switch for a main radiating element made of solid conductor. In contrast to [4] and [5], which demonstrate frequency-reconfigurable dipoles with each radiator itself consisting of fluidic conductor in a flexible substrate, this method is designed for applications requiring the rigidity of a structural composite with operation similar to [6]. The microchannels are fabricated by weaving sacrificial polymer fibers into the composite textile reinforcement prior to epoxy resin infiltration so that after matrix solidification and subsequent heat treatment under vacuum, the sacrificial material sublimates, leaving behind an inverse replica vasculature [7]. The composite and solid radiator ensure that the operation is not sensitive to mechanical positioning issues, and a pumping mechanism, such as the one in [8], can deliver small amounts of liquid into and out of the channel quickly. This pump takes the place of the bias mechanisms in the electrical switches and varactors. The extra space required for the pump does not negate the advantage the reconfigurable antenna has over frequency-independent antennas that must include individual elements for a large variety of wavelengths.

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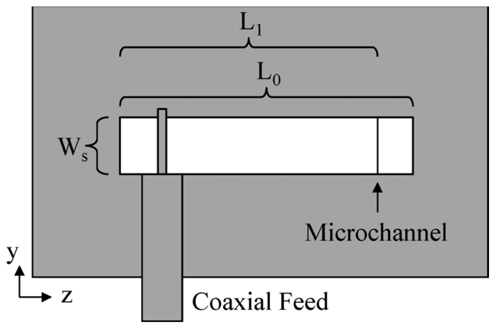

Fig. 1. Slot antenna with microchannel switch.

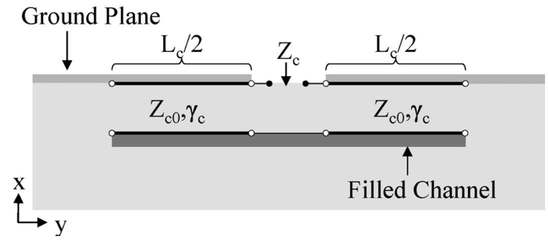

Fig. 2. Microchannel transmission-line model overlaid on the microchannel geometry.

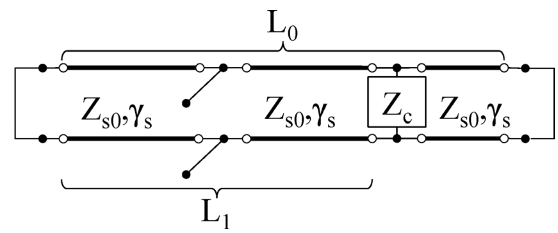

Fig. 3. Slot transmission-line model.

A design for a microfluidically switched slot antenna with reconfigurable operating frequency is presented in Section II along with the model used in the design process. The model is then verified with experimental results in Section III.

II. Microfluidically Switched Slot Antenna Design

A simple slot antenna is shown in Fig. 1. Resonances occur when the field distribution along the length of the slot is a tapered cosine of multiples of a half-wavelength. The resonant frequency, f_0, is therefore determined by the length of the slot, L_0, and the permittivity of the surrounding media. The antenna in this letter has a substrate on one side of the slot and air on the other, so the effective permittivity of the slot is approximately given by the average of the two. The resonant frequency can be shifted to f_1 by shortening the length of the slot to L_1, which is done by filling the microchannel with fluidic conductor. The reconfigured slot antenna should have a current distribution along L_1 at f_1 that is the same as the current distribution along L_0 at f_0 before reconfiguration, resulting in radiation patterns that are unaffected by the frequency reconfiguration.

The radiation from this slot can be modeled by using the equivalence principle. Across a slot of sufficiently narrow width, the electric field is constant, and the field generated outside of the slot is equivalent to having a magnetic surface current given by $\mathbf{M}_s = -2\hat{n} \times \mathbf{E}$. The tapered cosine field distribution yields a cosine magnetic current distribution, and the narrow slot appears as a half-wave magnetic dipole.

In order to adjust the resonant frequency of the antenna, the input impedance of the switch, Z_c, needs to be changed from an open circuit to a short, physically shortening the total length of the current path around the slot. This effect can be achieved with either a short circuit or an RF short at the operating frequency. Construction of a microchannel with a short circuit to the ground plane is difficult with the techniques developed in [7], as each direction change in the microchannel requires an anchor point for the sacrificial fiber during construction. The present work is limited to using an RF short across the radiating slot.

The microchannel is arranged as a straight line embedded in the substrate, just below the ground plane, as in Fig. 2. At its ends, the channel bends straight down and out the back of the substrate for easy access to fill the channel. These 3-mm-long portions appear as very poorly radiating monopoles, effectively just adding a small capacitance to the end of the channel that can be ignored. As the filled microchannel is going to have finite length, it will act like the transmission line in Fig. 2 (shown overlaid above the physical geometry of the channel). The switch is a series combination of two open-circuited stubs. The series combination requires both stubs to appear as short circuits at their inputs to obtain $Z_c = 0$. The length of the channel therefore needs to be $L_c = \lambda/2$, giving individual stub lengths of $\lambda/4$ when centered underneath the slot. The characteristic impedance, Z_{c0}, of the channel transmission line is calculated using the two-wire transmission line in [9] and adjusting L and C for a wire over a ground plane using image theory so that

$$Z_{c0} = \sqrt{\frac{L}{C}} = \frac{\eta}{2\pi} \cosh^{-1}\left(\frac{2h}{D}\right)$$

where $\eta = 377/\sqrt{\epsilon_r}$ is the impedance of the substrate material, h is the distance from the microchannel to the ground plane, and D is the channel diameter.

The slot antenna was modeled using the lossy transmission line pictured in Fig. 3. The model uses Cohn's method from [10] to calculate the slotline impedance Z_{s0} and lossless propagation constant β_s, where $\gamma_s = \alpha_s + j\beta_s$ and Z_c is an open circuit. The method places electric walls across a slotline at $\lambda/2$ spacing and then either electric or magnetic walls parallel to the slot. Mode matching is used in the resulting rectangular waveguide to find the impedance and propagation constant. As the walls parallel to the slot are moved farther from the slot, the desired values converge to those of the physical slotline.

The attenuation constant is found by calculating the power radiated by a slot with sinusoidal voltage distribution with a given magnitude at the feed, P_r as well as the power lost in the transmission-line model with the same voltage at the feed, P_i, using the values of β_s and Z_{s0} from Cohn's method. By finding α_s such that $P_i(\alpha_s) = P_r(\alpha_s)$ the power lost is equal to the power radiated [11].

Additional losses were introduced to both the slot and the channel models that are consistent with the dielectric loss tangent for the FR-4 substrate used to house the channels.

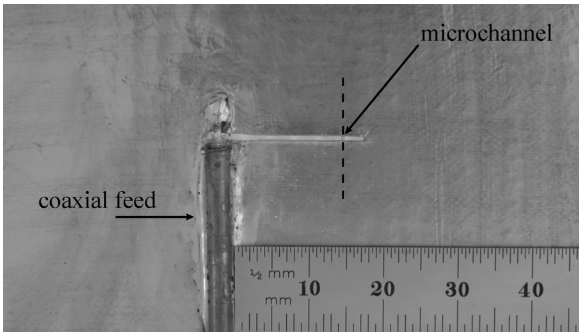

Fig. 4. Fabricated slot antenna.

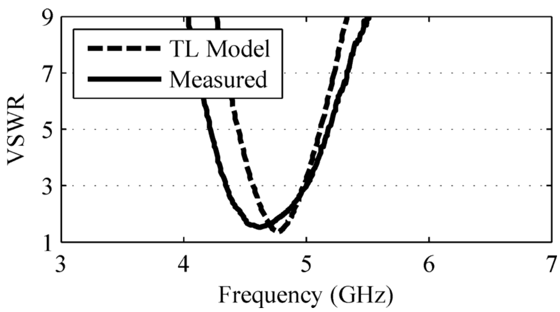

Fig. 5. Standing wave ratio with microchannel empty.

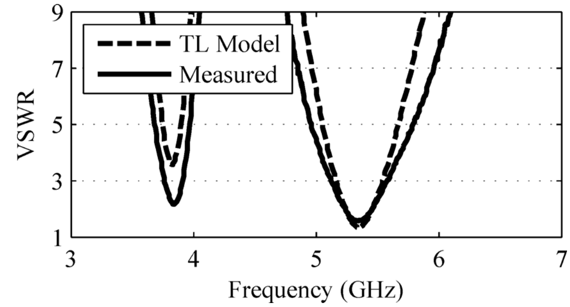

Fig. 6. Standing wave ratio with $\lambda/2$ microchannel filled.

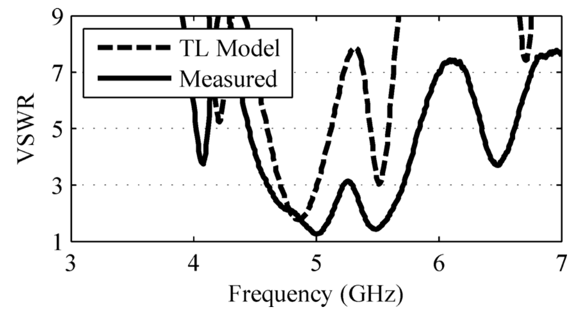

Fig. 7. Standing wave ratio with 4λ microchannel filled.

III. Results

The antenna shown in Fig. 4 was constructed on a $140 \times 140\text{-mm}^2$ 3-D woven (S-glass) composite substrate overlaid with a copper-tape ground plane. The centered slot had a length of 21.5 mm and width of 1 mm with a coax feed 1.5 mm from the end. The outer conductor of the coaxial cable was soldered to the ground plane to create a Dyson balun. The microchannel had a 500-μm diameter with a horizontal length of 17 mm and was embedded 500 μm below the ground-plane surface. The designed length was 15 mm, but fabrication was performed by hand, yielding a 2-mm difference. It intersected the slot 3.5 mm from the opposite end as the feed. Eutectic gallium-indium (EGaIn, 76% Ga 24% In by weight) was employed as the fluidic conductor, which is liquid at room temperature ($> 15.7\,^\circ$C) and exhibits relatively high electrical conductivity at 3.4×10^6 S/m [12]. The substrate had a relative permittivity of 3.4, yielding a slot with resonant frequency at 4.6 GHz.

The standing wave ratio for the transmission-line model and measured antenna with the channel unfilled is shown in Fig. 5. The slot model without the channel included is accurate in both match frequency and quality, especially for use in a first design pass.

By noting that the slot length is inversely proportional to the operating frequency, the operating frequency with the microchannel filled should be given by

$$f_1 = f_0 \frac{L_0}{L_1} = 4.6 \text{ GHz} \, \frac{21.5 \text{ mm}}{18 \text{ mm}} = 5.49 \text{ GHz}.$$

Fig. 6 shows that the actual operating frequency was 5.34 GHz, which is due to the 17-mm-long rather than 15-mm-long channel, adding electrical length and lowering the operating frequency. Incorporating the channel model into the slot model successfully predicted the effect of the switch at the design frequency. The channel also creates a transmission-line mode at 3.84 GHz, as is predicted in the model. This mode is generated by the highly frequency-dependent behavior of the transmission-line switch. This mode can be suppressed by using a microchannel that is physically connected to the ground plane to create a true short circuit rather than an RF short. The presence of this mode demonstrates a need to develop the fabrication technology to build a microchannel that allows the conductive fluid to contact the ground plane.

Another antenna was constructed with channels running the entire length of the ground plane in order to confirm the transmission-line model's accuracy. The results appear in Fig. 7. The model accurately predicts the circuit behavior of the antenna away from the ideal situation of a $\lambda/2$ channel length, indicating that the transmission-line model can be used generally for a single filled microchannel.

The measured radiation patterns appear in Fig. 8 for both the empty channel and the filled channel at their respective operating frequencies. The E-plane pattern is the pattern in the xy-plane, or the omnidirectional pattern from the magnetic dipole, while the H-plane pattern is measured in the xz-plane, which resembles the familiar dipole pattern. At each of these operating frequencies, the measured pattern is approximately as expected. The lobed behavior is a result of the finite ground plane generating radiation from its edges and can be diminished by using a larger ground plane.

To estimate the switching time for this antenna, the pump rate for the pump in [8] is used. With a 500-μm channel diameter, the conductive fluid can be evacuated from the channel and moved away from the radiating slot in less than 100 ms. While this is certainly slower than diodes and MEMS devices, it is sufficiently fast to be of use to many applications.

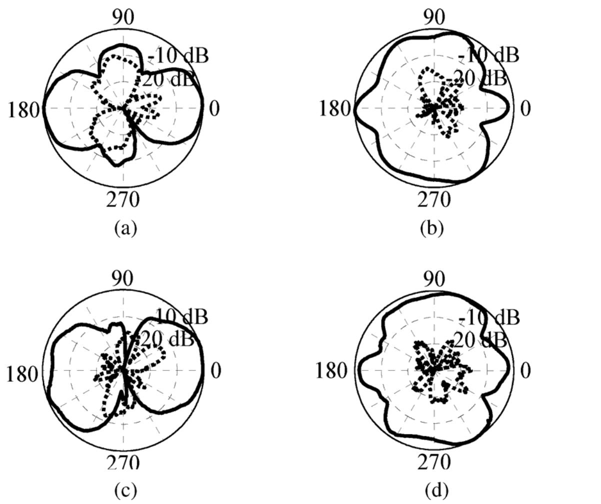

Fig. 8. Normalized radiation patterns with cross polarization in dotted lines: (a) H-plane pattern, empty channel. (b) E-plane pattern, empty channel. (c) H-plane pattern, $\lambda/2$ channel filled. (d) E-plane pattern, $\lambda/2$ channel filled.

A possible issue that arises with fluidic switching is the film of conductive/semiconductive gallium oxides which may be left behind on the microchannel surface [13]. After the measurements were taken with the channel filled, the channel was evacuated using pressurized air, followed by a rinse with ethyl alcohol. The measured results did not differ in any significant manner from the results of the originally empty channel, demonstrating the ability to deactivate the switch. In the future, this ability could likely be improved through the addition of a coating or other treatment (use of wetting liquids, etc.) that would reduce the amount of oxidized material and other residue on microchannel surface. Additional measures could also be taken within the channel to reduce the contact of oxidizing agents with the EGaIn material.

While multiple channels could certainly be used to allow for further reconfiguration, the coupling between filled channels would likely affect reconfiguration performance. However, coupling would be decreased if the fluid in the microchannels is physically shorted to the ground plane, further motivating future work to build such an antenna.

IV. Conclusion

Microfluidic channels filled with liquid conductor have been demonstrated as viable switches for reconfigurable antennas. While successfully shifting the operating frequency of the antenna by effectively shortening the length of the slot, the radiation patterns are not significantly distorted, allowing for operation to be unimpeded by unpredictable radiation behavior generally generated by switches. The switching method is also entirely linear, removing concerns about gain compression, intermodulation distortion, and lack of reciprocal behavior.

During the design process, a transmission-line model of the switch was developed that can be used to accurately describe the behavior of the antenna when the switch is activated while being easily incorporated into a model for the antenna itself. This transmission-line model provides an expedient method to design the antenna for a given application quickly and accurately, minimizing the need for time-consuming full-wave simulations.

In order to fully characterize the capabilities of microfluidic switches, power handling analysis needs to be performed to understand the range of operation of this antenna compared to current state-of-the-art switching and tuning mechanisms. The linear nature of the microfluidic switch anticipates that these reconfigurable antennas are likely to be able to handle higher power levels, but a full analysis is still required.

Future work also includes improving the fabrication process to be able to construct the microvascular channel so that the conductive fluid physically contacts the ground plane, suppressing the transmission-line modes generated in the current design. This switch will simplify the electrical design process further and remove the dependence of the resonant frequency on the precise length of the channel.

Microfluidic RF switches have the potential to bring reconfigurability to high-power applications that cannot currently take advantage of the advances that have been developed for low-power systems. Rather than depending on static devices and hoping for the best, radar and communications devices will be able to use frequency agility along with polarization and pattern reconfigurability to adjust to their environment, improving the robustness of the system in the presence of interference without the issues generated by nonlinear reconfiguration mechanisms.

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