Dense Microvasculature in Structural Composites for Reconfigurable Parallel Wire Screens

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***Abstract*—Widespread vascularization of a structural composite is used to enable reconfiguration of its electromagnetic parameters by injection and removal of liquid metal. Superposition of linear patterns enable frequency or polarization selective behavior similar to that of classical metallic wire grids. Simulations and measurements assess the accuracy of simplifying homogenization techniques over computationally intensive multiscale modeling. Repetition studies show that reconfigurations can be carried out consistently and reversibly over many empty / fill cycles.**

I. INTRODUCTION

The injection of liquid metal into patterned microchannels offers a unique modality in electromagnetic (EM) reconfiguration. Non-toxic eutectic gallium indium (EGaIn, $\sigma \approx 3 \cdot 10^6$ S/m) [1] is by far the most common liquid metal used in these applications. From local changes enabling the tuning of individual antenna elements (e.g., [2]) to periodic reconfigurable surfaces (e.g., [3]), nearly all implementations of microvascular-based reconfigurable electromagnetic systems are carried out within flexible materials that leverage the conformal advantages of liquid metal over traditional solid metallic structures. However, widespread vascularization of fiber-reinforced composites can enable the design of multifunctional materials that are able to reconfigure their effective bulk electromagnetic properties in desirable ways while also serving structural functions. Advances in using a thermally degradable polymer to form inverse replica vasculature in such composites [4] has enabled antenna reconfigurability via localized channels [5], [6], though many questions remain regarding the possibility of bulk material reconfiguration. Furthermore, the tradeoff for simultaneously optimizing electromagnetic and structural performance remains to be assessed.

This presentation covers recent experiments assessing the efficacy of dense microvasculature to emulate wire grid polarization selective surfaces within structural composites. Rather than the detailed assessment of a particular novel design, we study the performance of a canonical reflector topology implemented in the context of microfluidics.

II. MICROFLUIDIC SCREEN

Parallel or grid networks of wires are a standard method for emulating a conductive surface in applications where a solid conductive sheet may not be used. Here we study the ability of a dense network of microchannels to act as a reconfigurable version of this proxy conductive surface.

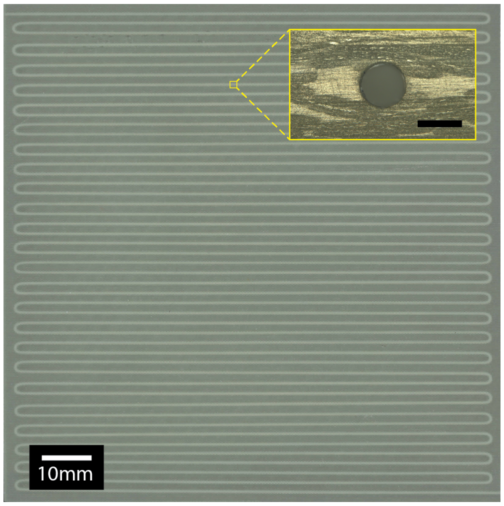

Fig. 1. Optical image of 3D printed serpentine pattern in glass-fiber composite with zoomed inset of microchannel cross-section post-vascularization (inset scale bar = 500 μm)

A parallel wire screen is approximated by a serpentine microchannel created within a thin, structural fiberglass panel as shown in Fig. 1. The vascularization (VaSC) process [4] is carried out through a combination of custom 3D printing of sacrificial polymer and conventional composite laminating.

When empty, the panel behaves as a dielectric slab. When filled with liquid metal, the microchannel acts as a single conductive path. Like a traditional parallel wire grid, normally incident plane waves co-polarized to the dominant channel direction interact with the conductive paths while cross-polarized waves do not. However, dielectric losses, the finite conductivity of liquid metal, and interactions due to the dielectric contrast of the host composite all detract from the panel behaving in these idealized ways.

Here we design an experiment to assess the impact of these parameters by comparing the frequency dependent transmission between a wire monopole in the presence of the panel under varying orientations and fill states. With the panel located a fixed distance d from the monopole and neglecting minor

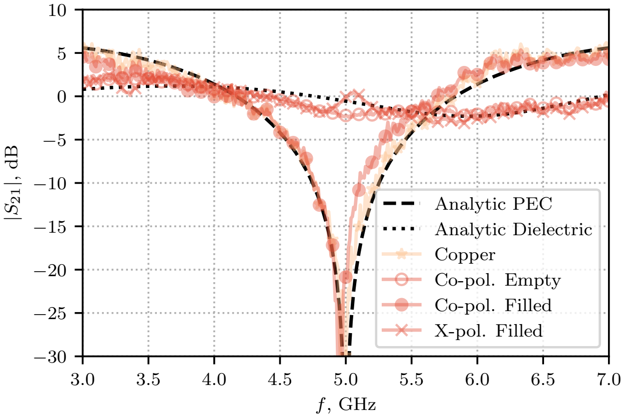

Fig. 2. Measured forward transmission from a vertical monopole antenna in the presence of a vascularized structural composite in varying states. Measured data using a copper panel as well as analytic models for ideal empty (dielectric) and filled (PEC) states are also shown. Data normalized to measurements taken with no panel present.

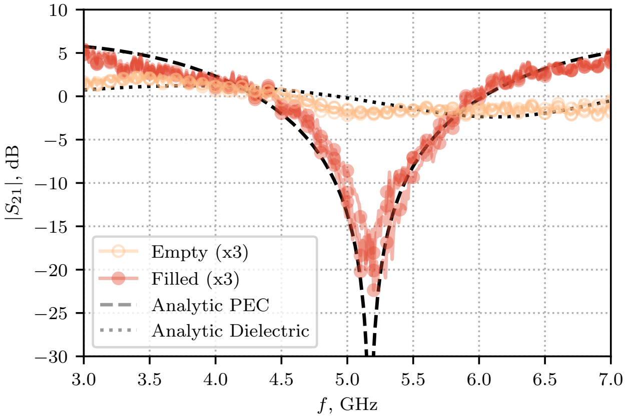

Fig. 3. Measurements taken over multiple filled (solid markers) and empty (hollow markers) cycles using a single vascularized panel in co-polarized orientation.

variations due to impedance effects, broadside transmission can be calculated in closed form under the assumption of ideal behavior as either an infinite perfect electric conductor or an infinite dielectric slab of finite thickness.

Results from a single experiment are shown in Fig. 2, where normalized transmission is plotted as a function of frequency; normalization is with respect to measurements taken without a panel present. The test setup consists of a transmitting monopole $15\ \mathrm{mm}$ tall with the vertically oriented composite panel ($100 \times 100 \times 2\ \mathrm{mm}$) at a distance $d = 30\ \mathrm{mm}$ behind, in reference to a co-polarized receiving horn. The undulating microchannel located in the center of the panel has roughly circular cross-section with a radius of $500\ \mu\mathrm{m}$ and spacing at $2\ \mathrm{mm}$ intervals. Though not matched over the entire bandwidth of interest, the transmitting monopole radiates sufficiently well at each frequency to obtain data above the measurement noise floor.

The empty structural panel behaves similarly to the analytic model of a homogeneous dielectric slab, with minor (± 2 dB) deviations from the control normalization. When filled with liquid metal and oriented parallel to the transmitting monopole (co-pol.), the structural panel behaves nearly identically to a solid copper panel of the same orientation and dimensions, with the expected null in transmission at $d = \lambda/2$ and $+6$ dB peaks at $d = \lambda/4$ and $d = 3\lambda/4$. The filled composite and copper panels follow the predicted analytic curve with excellent agreement. When the filled panel is rotated by $\pi/2$ (x-pol.) such that the dominant channel direction is orthogonal to the polarization of the monopole, the panel is more or less transparent as expected of a traditional parallel wire grid.

Repeatability and consistency of reconfiguration is evaluated by measuring the response of the system under multiple empty / fill cycles. In each pair of trials, a panel is filled with liquid metal and flushed with ethanol to empty. The measured data, including a measurement before the channel's first filling, in Fig. 3 show that reconfiguration is extremely consistent. The slight upward shift in the position of the null as compared to Fig. 2 is attributed to a $1\ \mathrm{mm}$ change in position of the panel between experiments.

III. CONCLUSIONS

Measurements of a parallel wire screen constructed by liquid metal infill of a vascularized, structural composite show that polarization selective reflectivity can be readily reconfigured in a manner consistent with installing and removing a traditional parallel wire grid. When reflective, the microvascular composite performs comparably to a solid copper panel of the same size. Multiple measurements show that this reconfiguration is repeatable. This proof of concept provides foundational understanding in the design of large scale, multifunctional structural materials with electromagnetic reconfigurability enabled by microfluidic networks.

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