Electromagnetically Functionalized Colloidal Dispersions and Microfluidic Reconfiguration Mechanisms for Phase-Reconfigurable Reflectarray Elements

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Abstract

This work presents an application of a unique antenna reconfiguration mechanism that exploits the bi-directional, pressure-driven flow of electromagnetically functionalized colloidal dispersions (EFCDs) through a coaxial stub microfluidic impedance transformer (COSMIX). The COSMIX used in this work has one coaxial RF port that connects to the antenna and two fluid ports (inlet and outlet); the coaxial structure is electrically capped at the end and terminated by an open circuit (recessed inner conductor). The COSMIX provides a wide range of reactive tuning by adjusting the volume fraction of colloidal material in the EFCD. As an integrated mechanism in a microstrip patch reflectarray element, this translates to more than a full cycle of phase shift with nominal losses. Simulated and measured results of a COSMIX using an EFCD composed of 400 nm colloidal barium strontium titanate dispersed in low-loss silicon oil, and its integrated performance with reconfigurable-phase reflectarray element, are presented for a 3 GHz design of microstrip patch reflectarray element.

1. Introduction

Antenna reconfiguration provides an attractive degree of freedom in the design of elements for reflectarray applications (e.g., [1-3]). The primary goal of these elements is to provide a large, variable phase shift at the antenna with minimal losses, which can be applied collectively in large planar arrays to emulate different reflecting contours (reconfiguration and beam-shaping). As one of the key elements in the performance of the reflectarray, the antenna's reconfiguration mechanism must provide a high degree of reactive tuning with minimal losses, and translate this behavior to the re-radiated phase of the antenna. This work presents a novel reconfiguration mechanism [4-5] which addresses these constraints through an amalgamation of concepts in a multi-port coaxial embodiment; enabling reconfiguration through the circulation and volume fraction of electrically dense colloidal materials (high dielectric nanoparticles of radius ~ 1 nm to 1000 nm) dispersed in a low permittivity liquid. These pressure-driven material systems remove the need for metallic biasing networks that can populate the aperture and limit the performance, and result in a one-port reconfiguration mechanism with a compact footprint and high degree of tunability. This strategic simplifies the design space for the antenna by removing structures which can create reactive loading and/or spurious radiation.

This work begins by discussing the materials used in simulation and measurement, their operational role in the geometry of the coaxial reconfiguration mechanism, and the integration of this mechanism with a microstrip reflectarray element. Simulated and measured results are then provided for the reconfiguration mechanism; including simulated results demonstrating the agility of re-radiated phase from a microstrip patch antenna enabled by the coaxial reconfiguration mechanism. A brief summary, acknowledgements, and list of references conclude the work.

2. Materials, Reconfiguration Mechanism, and Antenna Integration

2.1 Electromagnetically Functionalized Colloidal Dispersions (EFCDs)

The electromagnetically functionalized colloidal dispersion (EFCD) – the term given to the dynamic material system in this work – facilitates reconfiguration through changing the volume fraction ϑ of 60:40 colloidal barium strontium titanate ($Ba_{0.6}Sr_{0.4}TiO_3$) (diameter ~ 400 nm [6], ε_r ~ 1500, and σ ~ 0.01) dispersed in low loss silicon oil (ε_r = 2.4 and σ ~ 10^{-6}). The high electrical density of the unbiased colloidal BSTO and low permittivity of the silicon oil results in a mixture which has a minimal permittivity at $\vartheta = 0.0$ (with no

colloidal material) and a maximum at ϑ_{Max} (dependent on particle size, surface chemistry, etc.). This work limits the discussion on approximating the effective permittivity of the homogeneously mixed EFCD to the generic power mixing rule $s_{eff} = (1-\vartheta)s_1 + \vartheta s_2$, where s_1 and s_2 represent the material properties (ε_r <u>or</u> σ) of the silicon oil and BSTO, respectively. This provides an efficient means for examining the general trends of the EFCD in analytical models and simulations; effective medium theory (EMT) and other dielectric mixing rules (Claussius-Mossotti, Maxwell-Garnet, etc.) provide a more complete physical description of the EFCD but have been left for future discussions. In addition, the use of surfactants to create an electrical double layer on the colloids (particle coatings to reduce settling, coagulation, and other viscoelastic effects – e.g., lowering the viscosity of the EFCD) has also omitted (for brevity).

2.2 Coaxial Stub Microfluidic Impedance Trans(X)former (COSMIX)

A coaxial structure – referred to as the coaxial stub microfluidic impedance trans(X)former (COSMIX) – with one RF port and two fluid ports (inlet and outlet) acts as the reconfiguration mechanism in this work. The hollow structure has outer and inner coaxial diameters $2a$ and $2b$, respectively; is sealed at the end opposing the RF port with a conducting plate; and terminated with an open circuit through a gap distance d between the inner conductor and shorting plate. Fig. 1 shows a multi-phase EFCD to graphically illustrate the concept, the cross-section of the COSMIX including the lengths L_1, L_2, and L_3 (from the RF port to the inlet, from the inlet to the outlet, and from the outlet to the open-circuit termination, respectively), and the 3-port network model of the structure showing the coaxial RF port and the fluid inlet and outlet (modeled as circular waveguides of diameter d_f). The network model provides a very compact description of the structure which can be easily extended to N-port structures; a detailed analysis has been omitted in lieu of the discussion in the next section.

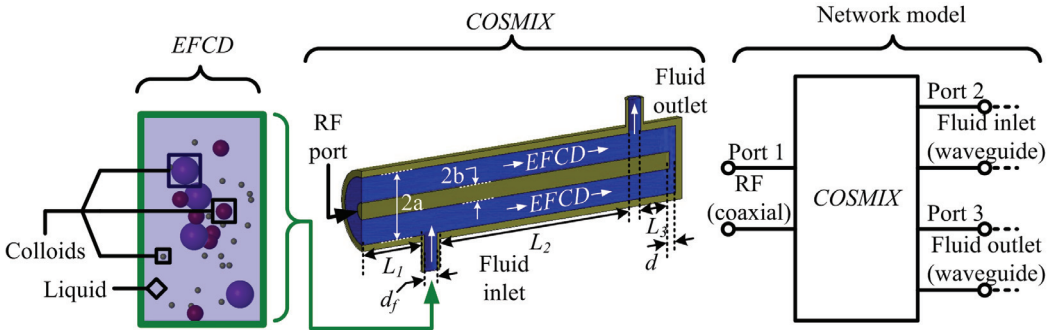

Fig. 1. (Left) Electromagnetically functionalized colloidal dispersion (EFCDs), (middle) coaxial stub microfluidic impedance transformer (COSMIX), and (right) the network model of the device.

2.3 Integration of the COSMIX with a Microstrip Reflectarray Element

Equivalent transmission line models of the microstrip reflectarray element and the COSMIX (shown in Fig. 2 with a cross-section of the CAD model) guide the integration of the two structures, provided the two following constraints are satisfied throughout the range of frequencies and effective wavelengths resulting from the EFCD: (1) the open circuit gap d remains electrically small and (2) the waveguide diameter of the fluid inlet and outlet remains much smaller than a half of an effective wavelength. Constraint (1) implies the shielded, open circuit termination can be modeled as a variable capacitive reactance jB_{OC} [7] and constraint (2) allows the fluid ports to be modeled as shunt reactances jB_{FI} and jB_{FO} [7] (impedances of the waveguide below cut-off). The COSMIX resides at the location where a matched, 50 Ω input impedance occurs. This location, at lengths L_A and L_B (along the resonant direction) from the radiation resistances R_{RAD} and edge capacitance of the radiating slots, represents a reference point for future work.

The right side of Fig. 2 provides a graphical illustration of the EFCD's role in the COSMIX, and demonstrates the conceptual impact of the EFCD (blue) on the open circuit capacitance ΔC_{OC} of the gap and the per-unit-length (PUL) transmission line parameters ΔL_{TL}, ΔR_{TL}, ΔG_{TL}, and ΔC_{TL} for a differential length dL coaxial line (for all L_1, L_2, and L_3 in Fig. 1. As a result of this, the characteristic impedance $Z_{Coax}(\vartheta)$ and propagation constant $\gamma_{Coax}(\vartheta)$ of the coaxial structure are functions of ϑ and represent two of the primary mechanisms responsible for the tuning (along with jB_{OC}, jB_{FI}, and jB_{FO} – also functions of ϑ). This model assumes a homogenized EFCD throughout the COSMIX (analogous to applying the power mixing rule a second time [4]), but the effects from a graded index of ϑ can be more accurately captured by relating the EFCD

properties to the PUL transmission line quantities and analyzing the sections all L_1, L_2, and L_3 with a tapered-impedance profile [8]. The COSMIX operates as a reflect-line (time-delay) phase shifter when the EFCD had matched dielectric and magnetic properties (and an impedance match); using a dielectric mixture creates reactive loading that translates its agility into the antenna by reconfiguring the re-radiated phase.

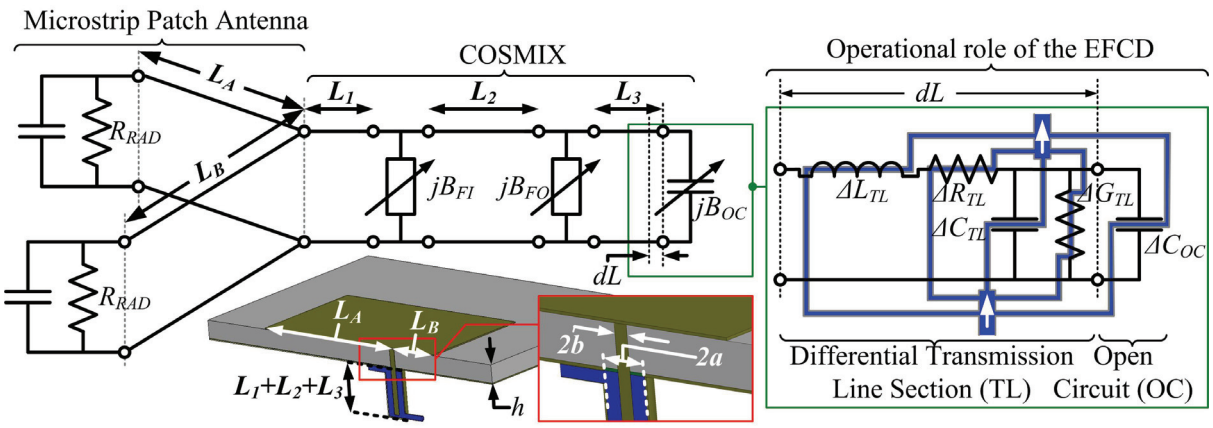

Fig. 2. (Top left) Transmission line and cross-section of the CAD model of the COSMIX attached to a microstrip patch antenna, and (right) the conceptual impact of flowing EFCDs (blue) through a differential length of the coaxial transmission line and the open circuit termination.

3. Results

The smith chart on the left side of Fig. 3 shows both simulated [9] and measured results for a COSMIX with dimensions a = 2.05 mm, b = 0.615 mm, d = 0.5 mm, d_f = 0.5 mm, and $\{L_1, L_2, L_3\}$ = {0.0 mm, 9.5 mm, and 0.0 mm} operating at 3.0 GHz. This includes a lossy material system (liquid with $\varepsilon_r = 2.4$, $\sigma \sim 10^{-6}$ S/m and colloidal material with $\varepsilon_r = 1000$ and both $\sigma = 0.001$ S/m and 0.1 S/m) similar to the measured BSTO in silicon oil, over the volume fraction range of $0.0 \le \vartheta \le 0.033$ – resulting in a nearly complete reactive impedance loop. The smith chart demonstrates the unique degree of reactive loading this structure can achieve under ideal operational conditions, subsequently providing a full range of reactive loading, which conceptually resembles a variable-length tuning stub with minimal losses (the range $0.0 \le \vartheta \le 0.033$ has been included to shows the general trends). The rapid decrease in $Z_{Coax}(\vartheta)$ for increasing ε_{eff} (of the EFCD) indicates the use of small ϑ to exploit this behavior. The measured shown in the smith chart underperforms the simulated data due to an overestimation of the power mixing rule used in simulations, but the general trends are in excellent agreement.

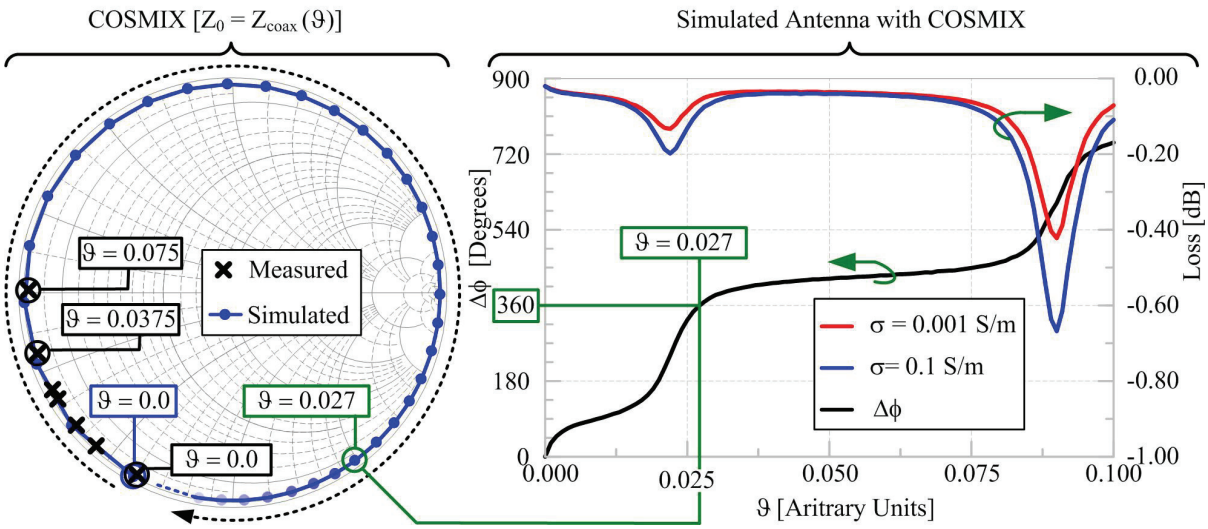

Fig. 3. (Left) Smith chart showing the COSMIX's simulated (blue) and measured (black) performance as a function of volume fraction from $0.0 \le \vartheta \le 0.033$ (simulated) and $0.0 \le \vartheta \le 0.075$ (measured), and (right) the simulated performance (phase shift and loss for $\varepsilon_r = 1000$, $\sigma = 0.1$ and 0.001 S/m) of the microstrip reflectarray element and COSMIX as a function of volume fraction from $0.0 \le \vartheta \le 0.1$.

The right of Fig. 3 shows the simulated performance of the reflectarray configuration (COSMIX attached to a reflectarray element), obtained by placing the integrated antenna into a waveguide configuration; centered, and surrounded by metallic walls 15.0 mm from the patch edges. The element has a width w = 50 mm, length L = 43.5 mm (L_A = 10.8 mm and L_B = 32.7 mm), and resides on a grounded Rochelle foam substrate (shown on the bottom left of Fig. 2) with a height h = 3.0 mm and permittivity $\varepsilon_r \sim 1$ [4]. The choice of substrate was made to isolate the effects of the COSMIX from other mechanisms that might contribute to the overall performance (surface waves, etc.). The moving average of $\partial\Delta\phi(\vartheta)/\partial\vartheta$ (the slope) shows a maximum over the range $0.0 \le \vartheta \le 0.033$ (related to the full impedance loop shown smith chart), with a full cycle of phase shift occurring over the range $0.0 \le \vartheta \le 0.027$. This indicates the COSMIX lengths L_1, L_2, and L_3 and choice of EFCD have a significant effect on performance. To determine the figure of merit $[°/dB]$ for the reflectarray element, the maximum loss of 0.20 dB (at the COSMIX resonance when $\vartheta = 0.021$, where $\partial\Delta\phi(\vartheta)/\partial\vartheta$ is maximum) has been used for a full cycle of simulated phase shift to provide a minimum figure of $1.8\times10^3\,[°/dB]$.

4. Conclusion

A unique antenna reconfiguration mechanism for reflectarray applications has been presented and its performance has been evaluated. The materials (EFCDs), models, and results were presented for a one-port coaxial embodiment (the COSMIX) with a microstrip patch reflectarray element, which achieved a very large phase shift with nominal losses. A discussion of equivalent network and transmission line models has been used to develop physical insight into its operation and the integration with a reflectarray element and several resulting performance attributes have been examined. The trends of simulated and measured results for colloidal barium strontium titanate dispersed in silicon oil have also been used to demonstrate the operation. While the results may seem optimistic (certainly overestimated by the power mixing rule), realizing a fraction of the simulated performance provides a very competitive degree of phase shift for nominal losses. The resulting agreement of general trends between measurements with simulations creates compelling and interesting result that indicates a significant degree of reconfigurable performance can be achieved by the COSMIX (and other N-port mechanisms enabled by EFCDs), which can be very useful in other RF/microwave/mm-wave applications.

5. Acknowledgements

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6. References

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