Microfluidic Mechanisms for Reconfigurable Dielectric Resonator Antennas

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Abstract

This work examines both the variable volume fraction of materials in electromagnetically functionalized colloidal dispersions (ECFDs) and their local displacement to create an impedance and radiation reconfigurable dielectric resonator antenna (DRA). Fluidic reconfiguration represents a compatible reconfiguration technique with several DRA geometries and excitation methods, and this approach creates a very large design space for elements capable of continuous frequency tuning across a wide bandwidth. The designs presented maintain single-mode operation, radiation pattern stability, and polarization stability over a large percent reconfiguration bandwidth. Simulated results of the VSWR, input impedance, and radiation patterns will be provided for two designs.

1. Introduction

Antenna reconfiguration has traditionally depended on electrical devices, most notably PIN diodes, RF MEMS, and photoconducting switches, to facilitate desired behavior and achieve a positive trade-off between performance and added design complexity [1-3]. Many reconfiguration technologies are useful for metallic antennas, but these reconfiguration mechanisms are not as easily applied to dielectric resonator antennas (DRAs). Electromagnetically functionalized colloidal dispersions (EFCDs) offer a novel solution for DRA reconfiguration. EFCDs are nanoparticles with judiciously chosen electromagnetic characteristics dispersed in a fluid media, which allows the creation of dynamic material systems with a wide range of electromagnetic properties. Using the transport and mixing behavior of EFCDs (e.g. capillary forces, wetting, etc.), a system of coupled-physical mechanisms can be integrated into reconfigurable antennas [4-6]. Fluidic reconfiguration allows a wide degree of freedom in reconfiguration design and creates a variety of material-based reconfigurable devices. The pressure-driven flow of these fluidic systems can also reduce the electrical complexity by removing wired bias and control structures from the radiating aperture. Previous research has investigated liquid RF devices [7-11], but fluidic antenna reconfiguration remains relatively unexplored. In addition, the electromagnetic properties of EFCDs add another dimension to research in liquid RF devices.

The effects of varying DRA height and constitutive parameters on DRA resonant frequency and bandwidth, from an analytical perspective, are examined first in this work. Next, a brief description of the design process shows how fluidic reconfiguration applies to two cylindrical DRAs utilizing different excitation mechanisms – one microstrip fed and one slot fed. An investigation of the frequency reconfiguration behavior of the two designs follows, with a brief conclusion highlighting the broad applicability of fluidic reconfiguration and areas for further research

2. Theoretical Model of DRA Reconfiguration

The theoretical treatment of radiation from DRAs applies to fluidic as well as solid structures. An effective analytical method for DRAs assumes that the walls are perfect magnetic conductors. Using Huygen's principle, the resonant frequency for a DRA of given size, geometry, and constitutive parameters can be determined. This approach gives accurate results for the resonant frequency of high permittivity DRAs ($\varepsilon_r \geq 20$). Eq. 1 (from [12]) provides the resonant frequency for a cylindrical DRA over a ground plane, which is a function of the resonator radius a and height d, constitutive parameters ε and μ, indices m, n, and p of TE (X_{np}) and TM (X'_{np}) resonant modes. Reconfiguration of the DRA in this work uses the EFCD to alter d and ε.

$$f_{npm} = \frac{1}{2\pi a\sqrt{\mu\varepsilon}}\sqrt{\left[\begin{matrix}(X_{np})^2 \\ (X'_{np})^2\end{matrix}\right] + \left[\frac{\pi a}{2d}(2m+1)\right]^2}\ , n = 1,2,3\ ; p = 1,2,3\ ; m = 0,1,2 \quad (1)$$

3. Design Process

Fig. 1 shows the two designs examined in this work that exploit the use of EFCDs as a DRA reconfiguration mechanism – an aperture coupled, slot-fed DRA operating at S-band (right side of Fig. 1) and a proximity coupled, microstrip-fed DRA operating at C-band (left side of Fig. 1). Both DRAs share the initial design process based on Eq. 1 using $\varepsilon_r = 20$, TE mode indices $\{m, n, p\} = \{1, 0, 0\}$, and $\{a, h\} = \{6.35$ mm, 2.0 mm$\}$ and $\{15.875$ mm, 6.0 mm$\}$ for the proximity coupled and aperture coupled designs, respectively. A 1.6 mm thick polycarbonate ($\varepsilon_r = 2.9$) containment shell was added to hold the EFCDs in a cylindrical geometry. Once the initial design state was matched, each DRA was tuned according to its reconfiguration mechanism – altering the height h for the proximity coupled DRA by controlling the total EFCD volume in the polycarbonate shell and altering the permittivity for the aperture coupled DRA by adjusting the volume fraction of colloidal material in the EFCD. The treatment of EFCDs (their composition, synthesis, etc.) has been omitted.

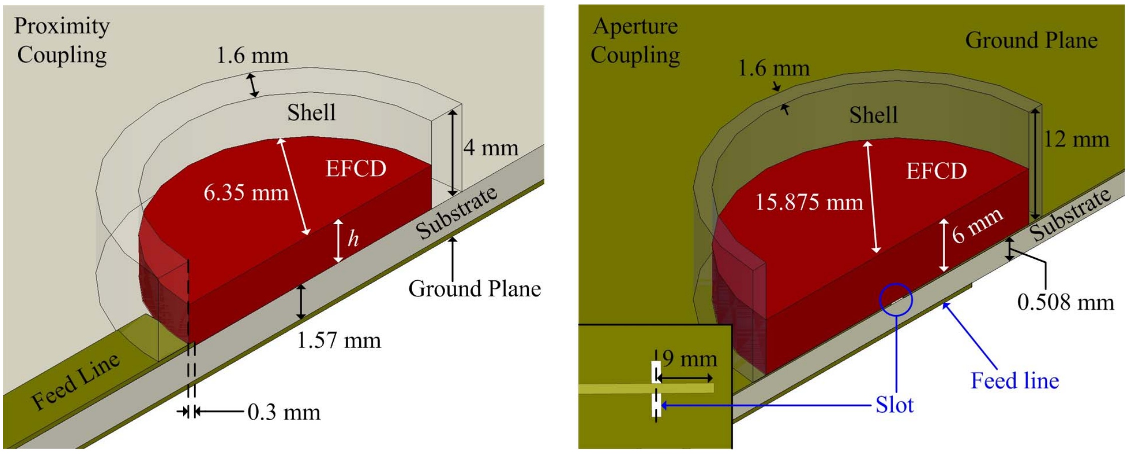

Fig. 1. Aperture coupled, slot-fed DRA operating at S-band (right) and proximity coupled, microstrip-fed DRA operating at C-band (left).

4. Results

The VSWR and impedance for the microstrip-fed DRA and the slot-fed DRA can be seen in Figs. 2 and 3, respectively. The microstrip-fed DRA achieves a 35% reconfiguration bandwidth for EFCD volume changes 2 mm $\leq h \leq$ 4 mm that result in Fig. 2, and the slot-fed DRA achieves a 40% reconfiguration bandwidth by adjusting the volume fraction of the EFCD to create $20 \leq \varepsilon_r \leq 50$. Fig. 4 shows the radiation patterns in the primary, elevation cut-planes for the upper and lower limits of each design (microstrip-fed and slot-fed on the left and right, respectively, and upper and lower bounds on the top and bottom, respectively). These have been included to demonstrate that both designs maintain single mode operation over the reconfiguration bandwidth and remain qualitatively similar.

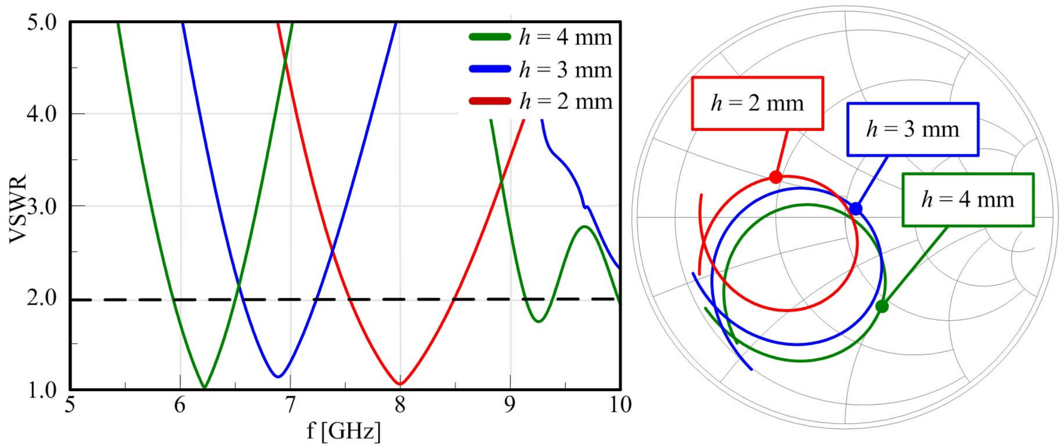

Fig. 2. VSWR (left) and impedance (right) of the S-band, slot-fed DRA with a fixed permittivity EFCD ($\varepsilon_r = 20$) and variable height 2 mm $\leq h \leq$ 4 mm. The impedance loops cover frequency ranges 6.6 GHz – 10 GHz, 5 GHz – 8.75 GHz, and 5 GHz – 8 GHz, for h = 2 mm, 3 mm, and 4 mm, respectively.

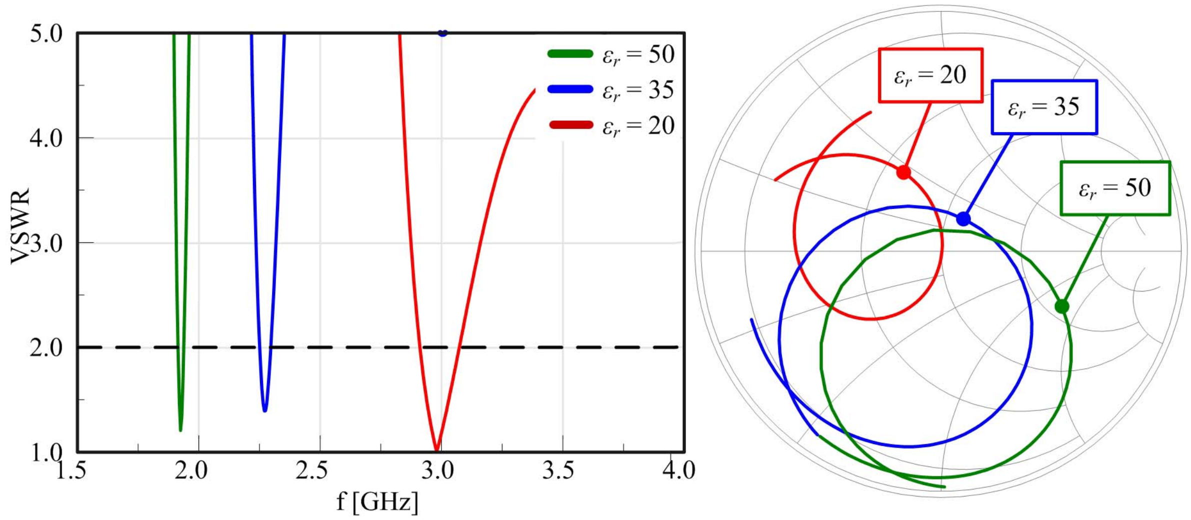

Fig. 3. VSWR (left) and impedance (right) of the C-band, proximity coupled, microstrip-fed DRA demonstrating reconfiguration by adjusting the EFCD permittivity $20 \leq \varepsilon_r \leq 50$ for a fixed height (h = 6.0mm). The impedance loops cover frequency ranges 2.8 GHz – 3.65 GHz, 2.15 GHz – 2.7 GHz, and 1.8 GHz – 2.3 GHz, for ε_r = 20, 35, and 50, respectively.

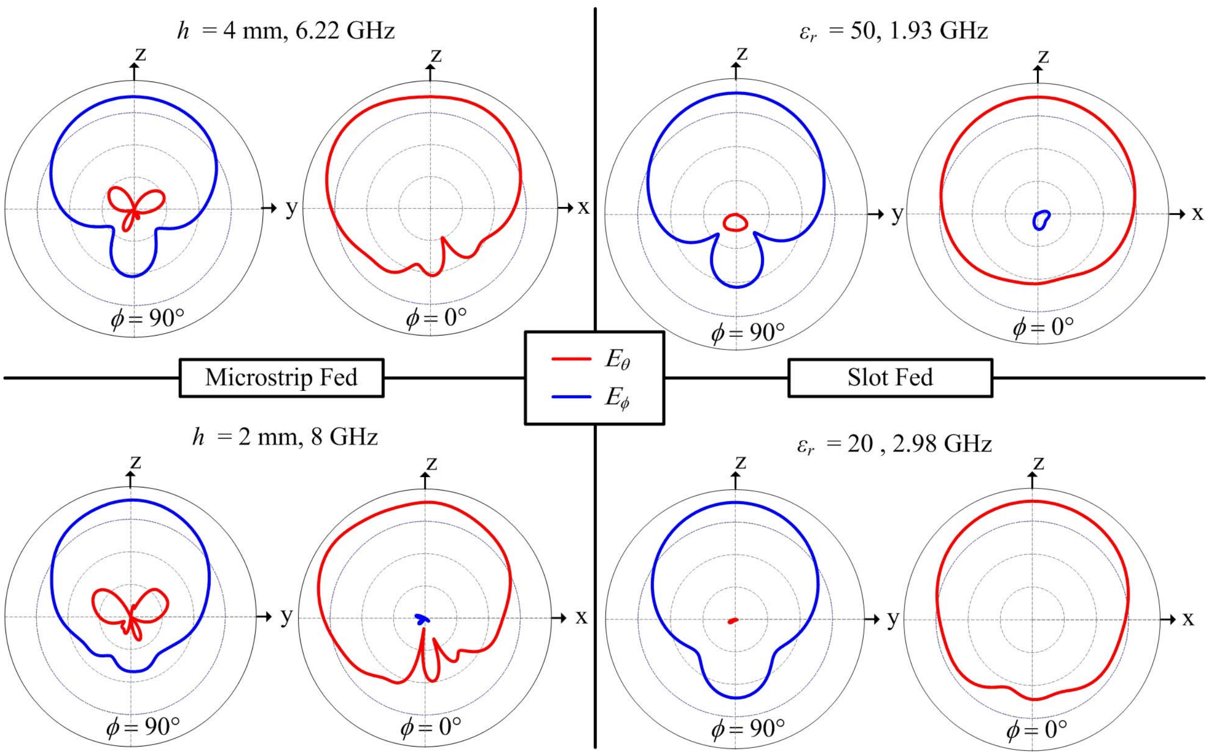

Fig. 4. Radiation patterns in the two primary elevation cut planes for the upper and lower limits of each design; microstrip-fed and slot-fed on the left and right, respectively, and lower and upper bounds on the top and bottom, respectively.

5. Conclusion

Two frequency reconfigurable cylindrical DRAs have demonstrated the potential applications of microfluidic reconfiguration mechanisms using EFCDs. A study of two different, EFCD-based reconfiguration mechanisms showed significant frequency tuning and validated the design approach. The design process focused on achieving matched VSWR and omni-directional radiation patterns for a single radiation state, then utilizing either height or permittivity variation to tune the resonant frequency and bandwidth. Results indicate that fluidic reconfiguration will only be limited by the requirement for single-mode operation. Areas for further research include microfluidic frequency reconfiguration of other DRA geometries and excitation methods, fluidic tuning of matching networks for enhanced bandwidth, and fluidic DRA design for multi-mode operation.

6. References

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