A Reconfigurable Microfluidic Transmitarray Unit Cell

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***Abstract* — This paper presents a novel microfluidics based approach to develop a reconfigurable circularly polarized transmitarray unit cell. The unit cell comprises double layer nested split ring slots formed as microfluidic channels that can be filled by fluids. Split regions in the slots are realized by injecting liquid metal into the channels. Beam steering is obtained by implementing rotational phase shifting via manipulating the liquid metal in the slots. X-band unit cell prototypes are fabricated on glass substrate carrying a patterned metal film, and the slot channels are formed by Polydimethylsiloxane (PDMS) using soft lithography techniques.**

Index Terms—transmitarray, lens array, microfluidics, reconfigurable, beam steering, split ring, circularly polarized, liquid metal

I. INTRODUCTION

The need for high gain antennas is increasing especially for long range communication systems. Compared to other options such as parabolic reflector, dielectric lens, and phased array, transmitarray is a promising alternative that provides a planar, lightweight, low volume solution with a less complex and low loss beamforming network. The general mechanism of a transmitarray is to radiate the incident wave coming from a feed antenna with proper phase shifting applied on the planar array elements for achieving a planar phase front on the transmitting side. This adjustment in the transmitted phase of each element can be realized by changing the lengths of the delay lines (transmission line, stub, stripline) or radiators in the unit cells, by using phase shifters, or by rotating the elements in the array [1-6]. Also, beam of the antenna can be electronically steered by adjusting the progressive phase difference between array elements dynamically, by using MEMS components, pin diodes and varactors.

In this work, rotational phase shift approach is adopted to control the phase of transmitted wave of each element. This method can be applied to reflectarrays or transmitarrays illuminated by circularly polarized electromagnetic waves. Transmitarrays consisting of stacked microstrip patches and nested split ring slots employing rotational phase shift method have been presented in [4, 7]. In a dual frequency beam switching reflectarray given in [8], rotational orientation of the split rings has been implemented by integrating series RF MEMS switches. This application, as well as other reconfigurable reflectarray/transmitarray structures employing switches or varactors, requires bias lines which affect the performance of the antenna. Such parasitic radiation effects and complexity of fabrication of elements with several bias lines can be minimized by using a microfluidic approach. The use of microfluidics in antennas has started to attract attention very recently, and a few studies on microfluidic beam-steerable, flexible and stretchable antennas have been reported [9-11].

In this paper, we propose a patent pending concept of using microfluidics with a liquid metal, to develop a circularly polarized beam steering transmitarray unit cell based on element rotation principle.

II. DESIGN OF THE TRANSMITARRAY UNIT CELL

Figure 1 presents an illustration of the element rotation method. Under the incidence of a circularly polarized wave, the rotation of the transmitarray unit cell around surface normal as shown in Figure 1 results in a shift of transmitting wave phase equal to twice the angle of rotation (φ). In the design of such a unit cell, the element is excited by two orthogonal linearly polarized waves and the following conditions should be satisfied by the transmitted components: (i) there should be 180° of phase difference between the orthogonal components (i.e., x- and y- polarized components for the wave propagation in z-direction, T_x and T_y) of the transmitted wave at the frequency in which two waves have the same magnitude, (ii) the magnitude of the orthogonal transmission coefficients at that frequency should be maximized [4]. The details of the derivation can be found in [4].

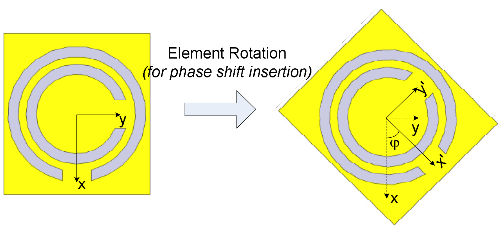

Figure 1. Element rotation method for phase shift insertion in transmitarray unit cells.

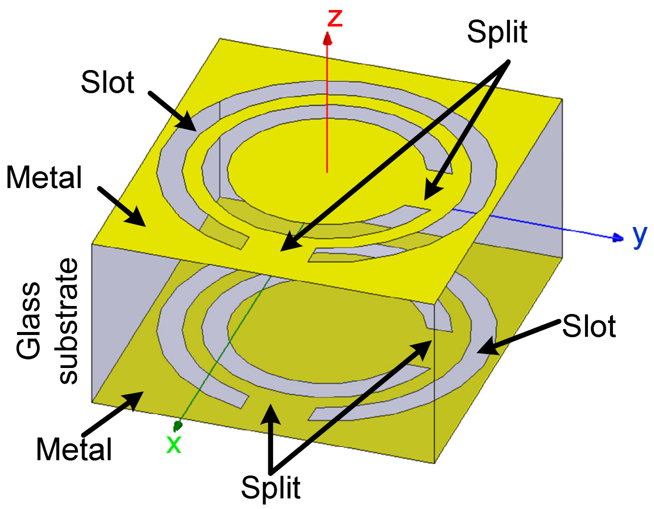

Figure 2. Dual layer nested split ring slot structure.

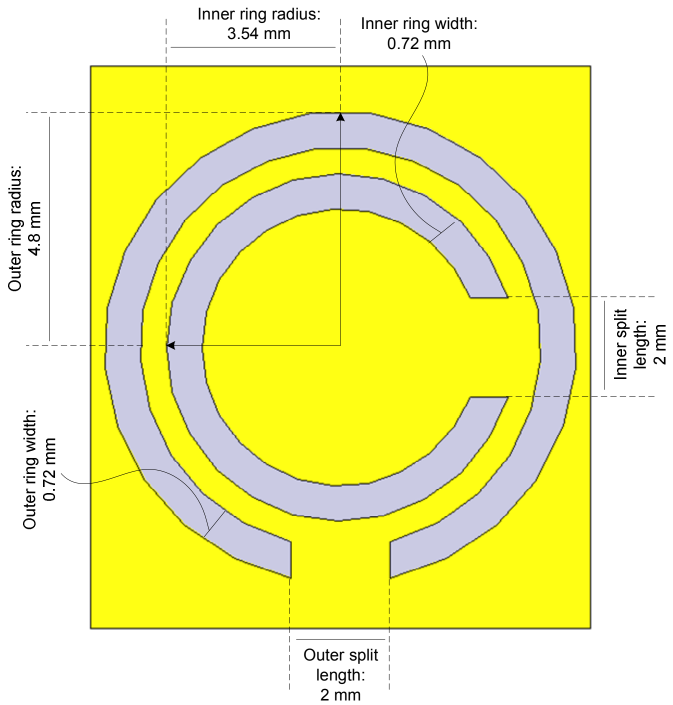

Figure 3. Top view of the nested split ring slot structure with the design parameters.

A split ring structure is a very appropriate structure to apply element rotation method due to its circular symmetry. Instead of rotating the element around its axis by means of a mechanical approach, the element rotation method of a split ring can also be implemented by changing the location of the split region along the ring slot. In this study, the split region is formed by injecting a liquid metal which is confined in a microfluidic channel composed of a dielectric material, Polydimethylsiloxane (PDMS), in the form of the slot rings. The location of the liquid metal in the channels can be adjusted using micropumps that are connected to these channels. The

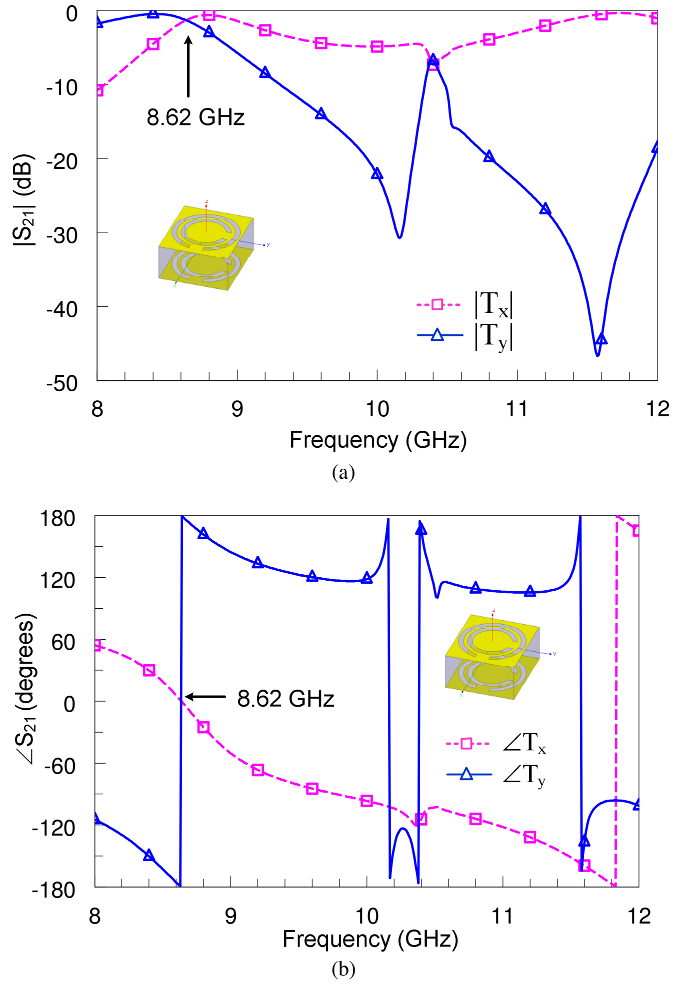

Figure 4. Simulated transmission coefficients for x- and y-polarized incident waves (a) magnitude (b) phase.

most commonly known liquid metal is mercury. However, due to its high toxicity, researchers are developing other materials with good conductivity and wide range of temperature of being liquid. In general, alloys of gallium, indium, and tin are preferred for this purpose. In this study, an alloy of 68.5% Ga, 21.5% In, and 10% Sn, a product of GalliumSource, LLC [12] is used.

To realize the element rotation method with microfluidics, the double layer nested split ring slot similar to the design in [7], as shown in Figure 2, is chosen as a transmitarray element. Double layer transmitarray designs have effect in reducing the insertion loss with respect to a single layer structure [14]. Also, in order to have a phase difference between T_x and T_y, the resonance frequencies of the structure for each orthogonal excitation (x- and y-) must be different. The difference in the resonance frequencies for each orthogonal excitations stems from the difference in the split lengths and the inequality of the radii of the inner and outer ring slots. The unit cell is simulated with Ansoft HFSS using periodic boundary conditions to implement the infinite array approach. The unit cell is excited by two orthogonal and linearly polarized (x- and y-polarized) waves in normal direction. The layers are separated by a glass

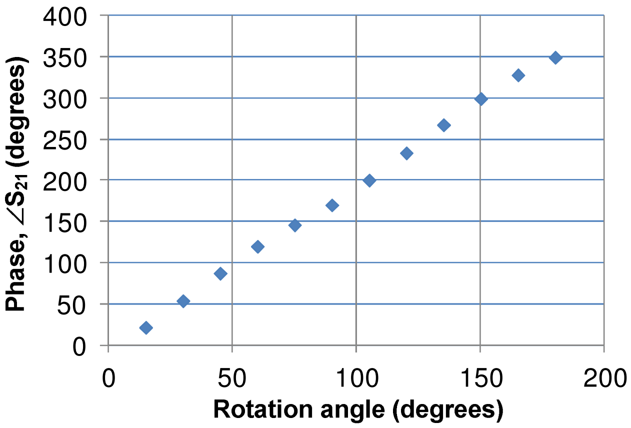

Figure 5. Phase design curve of the simulated transmitarray unit cell.

substrate (ε_r=4.6, tan δ=0.005). Adjusting the ring radius, substrate thickness, distance between the nested rings, ring width and split length, 180° of phase difference between the x- and y- polarized transmitted waves is achieved for the unit cell dimensions of 11.43 mm × 10.16 mm and substrate thickness of 5.3 mm. As the characterization of the unit cell is carried out using the measurement with WR-90 waveguide (22.86 mm × 10.16 mm), the unit cell is designed as having dimensions half of that of the waveguide in one direction (11.43 mm) and same as that of the waveguide in the other direction (10.16 mm). The physical dimensions and the values of these parameters are given in Figure 3. The transmission magnitudes of x- and y- polarized waves are maximized at that intersection frequency. Figure 4 presents the magnitude and phase of transmitted fields obtained by simulations. It is seen that mentioned conditions for proper operation are satisfied at 8.62 GHz. Figure 5 shows the phase design curve, (i.e. the phase of the transmitted wave versus angle of rotation of split on the slot ring structure) obtained by the simulations for normally incident wave. It is observed that the phase of the transmitted wave changes linearly with the rotation angle. Furthermore, the full 360 degrees phase range is obtained.

III. Fabrication of The Unit Cell

The microfluidic channels are formed using soft lithography techniques as depicted in Figure 6. The channel material is Polydimethylsiloxane (PDMS) which is shaped by a mold (silicon) wafer. The mold wafer is patterned using a DRIE (deep reactive ion etching) process where a photoresist layer is used as the mask (Figure 6.a and Figure 6.b). PDMS is coated on the mold wafer and cured at room temperature (Figure 6.c). After peeling off the PDMS layer from the mold wafer PDMS pieces are bonded on a glass wafer with the patterned antenna metal on it (Figure 6.d, e, f, and g). The liquid metal droplet is injected into the channel in order to form the split region (Figure 6.h). The position of the liquid metal in the slot can be adjusted using micropumps that are connected to the channels. In order to use the waveguide simulator [13] for the characterization, the prototype includes two unit cells that can strictly fit into the WR-90 waveguide. It should be noted that since PDMS adheres to the glass surfaces

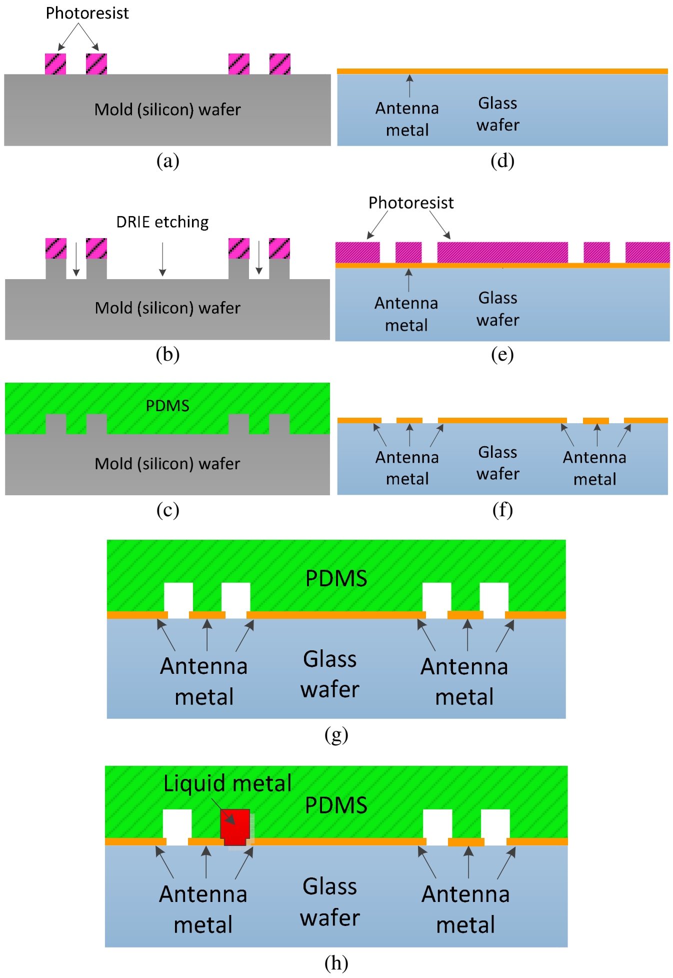

Figure 6. Fabrication process flow.

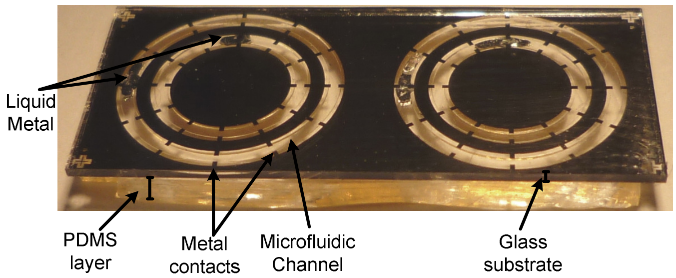

Figure 7. Fabricated transmitarray unit cell (single side is shown only).

better than metal, the antenna metal is modified to increase the contact area between the glass and PDMS and to decrease the possibility of leakage of the liquid metal. Metal inserts in radial direction are patterned on the antenna metal to provide the direct contact of the liquid metal and the antenna metal. Figure 7 shows one of the fabricated structures with metal contacts extended through the ring slot. Further details of the fabricated elements and measurement results will be presented in the conference.

IV. CONCLUSION

This paper presents a microfluidic based reconfigurable transmitarray unit cell employing element rotation method. The unit cell consists of a nested ring slot antenna and microfluidic channels aligned with the slot rings. A liquid metal droplet is injected into the channel in order to form the split region. The reconfigurability in the insertion phase is enabled by the movement of liquid metal inside the ring channels. Due to the circular symmetry of the unit cell, rotation of the element is achieved with the controlled movement of the liquid metal resulting in a shift of transmitting wave phase equal to twice the angle of rotation. The major advantage of this structure is the 0°-360° continuous phase shifting capability provided by the movement of the conductive fluid inside the ring channels, without using any additional phase shifting mechanism and without increasing the size of the unit cell. Moreover, the structure does not require any metallic bias lines, which are essential for MEMS and varactor-based unit cells but also causing parasitic effects. Instead, a non-conductive microfluidic feed network can be implemented without deteriorating the electromagnetic characteristic of the structure. The proposed microfluidic approach can also be used to implement reconfigurable reflectarrays. In order to characterize the unit cells using waveguide measurements, a prototype which includes two unit cells fitting into the WR-90 waveguide, is manufactured using microfabrication techniques.

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