Microfluidic Reconfigurable Nested Split Ring-Regular Ring Transmitarray Unit Cell

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Abstract

A reconfigurable, circularly polarized transmitarray unit cell consisting of double layer nested split ring-regular ring formed as microfluidic channels inside Polydimethylsiloxane (PDMS) is designed and fabricated. The operation of the unit cell is based on the element rotation method. The liquid metal is injected into the channels and it forms the conductive part in the structures whereas the split region in the outer ring is air. The movement of the liquid metal together with the split around the outer ring realizes the rotation of the element around its surface normal. The rotation of the element provides a phase shift proportional to the rotation angle and the phase of the transmitted wave can be tuned by controlling this rotation using micropumps. The unit cell is designed to operate at 8.15 GHz and it can be easily scaled to other frequencies.

1. Introduction

Transmitarrays are high gain, planar, lightweight antennas collimating the incoming electromagnetic wave by tuning the phase of the transmitted wave at each element. This tuning of the phase 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]-[4]. Dynamical adjustment of the transmitted phase enables steering of the radiated beam. Microelectromechanical systems (MEMS) components and varactors are used to change the effective length of the delay lines or loading the resonators for reconfiguration [5][6].

The element rotation method provides 360° of linear phase shifting for the structures excited by circularly polarized electromagnetic waves. Rotating the elements around the normal to the plane of the array, the phase of the transmitted field can be changed by two times of the rotation angle. Transmitarrays employing this method and having stacked microstrip patches and nested split ring slots as elements have been presented in [4][7]. Also, in a dual frequency beam switching reflectarray, rotational orientation of the split rings has been implemented by integrating 6 series RF MEMS switches uniformly distributed on the ring [8]. Although this approach is successful in orienting the beam, continuous beam steering is not possible due to finite number of switches. Also, when switches or varactors are employed to reconfigure the reflectarray/transmitarray antennas, the performance of the antenna is affected by the parasitic radiation arising from the DC bias lines. Microfluidics enable continuous tuning of the transmitted phase for the element rotation together with the prevention in the deterioration in the RF performance due to the metallic bias lines or cabling. The use of microfluidics in antennas and microwaves has started to find applications, and recently, microfluidic beam-steerable, flexible and stretchable antennas and fluidically tunable frequency selective and phase shifting surfaces are developed [9]-[12]. In addition, concept of using microfluidics with a liquid metal, to develop a circularly polarized beam steering transmitarray unit cell based on the element rotation principle is presented in [13][14]. In these studies, design details and measurement results for nested split ring slot and nested ring-split ring unit cells are given and satisfactory agreement between the simulations and measurements is demonstrated. In this work, following the same methodology, nested split ring-regular ring structure is designed and fabricated. Between two layers of nested rings foam is used instead of a glass layer to reduce the losses.

2. Unit Cell Designs

The proposed unit cell is designed in the infinite array environment with a Floquet port excitation using Ansoft HFSS. The scattered fields are decomposed into modes at the Floquet ports in HFSS. When the unit cell size is smaller than a half wavelength, for a plane wave propagating along z- axis, only x- and y- polarized wave modes propagate [4]. Under these circumstances, the following conditions should be satisfied: (i) The orthogonal components of the transmitted wave (T_x and T_y) at the frequency in which two waves have the same magnitude should be out of phase, (ii) the magnitude of the orthogonal transmission coefficients at that frequency should be maximized [13].

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The structure of double layer nested split ring-regular ring transmitarray unit cell is shown in Figure 1. The outer ring has a split whereas the inner ring is implemented as a regular ring, i.e. without any split on it. The design is optimized to satisfy the aforementioned conditions by tuning the split length, the widths and the diameters of the rings, and the foam thickness in between substrates. The rings are implemented as a microfluidic channel inside a dielectric material, PDMS. The injected liquid metal in the channels forms the conductive part of the unit cell whereas the split is the air region in the outer channel. In this study, an alloy of 68.5% Ga, 21.5% In, and 10% Sn, a product of GalliumSource, LLC [15] is used as the liquid metal. The dimension of the unit cell is 11.43 mm × 10.16 mm, approximately 0.3λ at 8 GHz. This dimension is half of the aperture of a WR-90 waveguide so that two adjacent unit cells fits in the aperture to enable characterization of the fabricated unit cells using the waveguide simulator method [16].

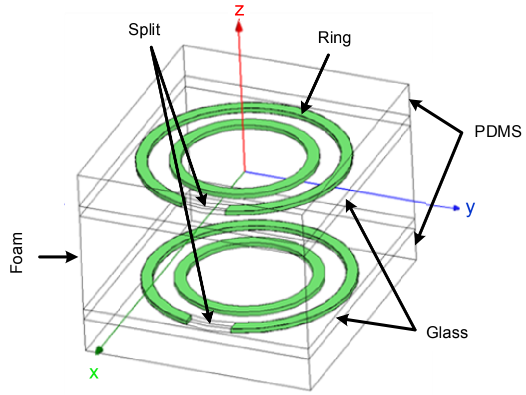

Figure 1. Geometry of the double layer nested split ring transmitarray unit cell.

The depth of the channels are 0.2 mm and the PDMS layers (ε_r = 2.77, tan δ = 0.0127) have thicknesses of 1.5 mm. The PDMS layers are bonded to 0.5 mm – thick glass layers (ε_r = 4.6, tan δ = 0.005). The substrate between the glass layers is foam (ε_r = 1.07). In order to have a phase difference between T_x and T_y to satisfy the condition in (i), the characteristic impedance of the structure for x- and y- polarized propagations should be made different to diverge the resonance frequencies of the structure for these propagations. The difference in the resonance frequency results in phase difference between T_x and T_y. The placement of the split on the outer ring provides the difference in the characteristic impedance. The radii of the rings, foam thickness, ring width and split length have effect on the amount of the phase difference between T_x and T_y and the insertion loss as they change the frequency difference between the resonances of each orthogonal propagation. The design is optimized such that the phase difference between T_x and T_y is 180° at 8.15 GHz. The split length on the outer ring is 2.75 mm and the foam thickness is 4.5 mm. The rings have 0.5 mm of width and the midpoint of the inner ring radius is 3.4 mm whereas it is 4.5 mm for the outer ring. Figure 2 shows the simulated transmission and phase characteristics of the optimized unit cell.

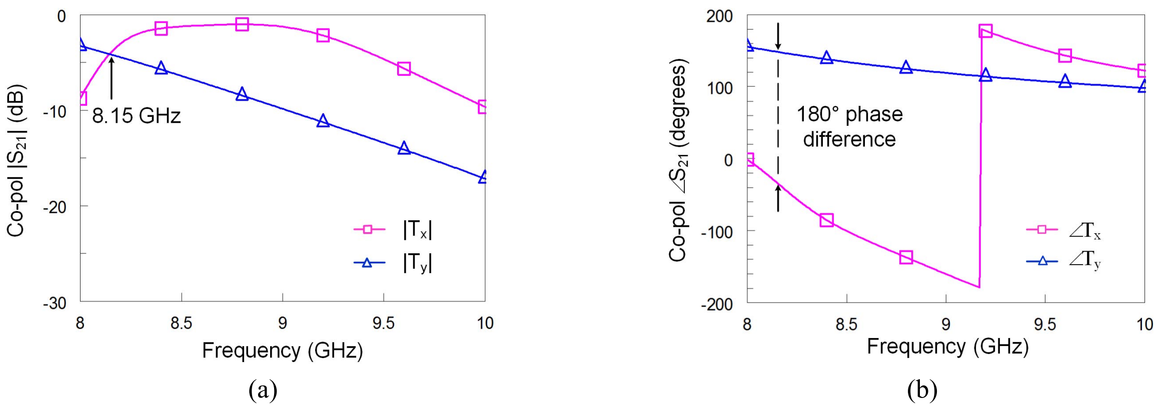

Figure 2. Simulated transmission coefficients for *x*- and *y*-polarized incident waves (a) magnitude of the co-pol transmission coefficients (b) phase of the co-pol transmission coefficients.

3. Fabrication of the Unit Cell

The fabrication process of a microfluidic transmitarray unit cell is summarized as follows: The microfluidic channels are formed by using soft lithography techniques as depicted in Figure 3. The channel material is 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 3.a). PDMS is poured on the mold wafer and cured at room temperature (Figure 3.b). After peeling off the PDMS layer from the mold wafer, PDMS pieces are bonded on glass pieces (Figure 3.c). PDMS-glass bonding process requires a surface activation process which is carried out by an oxygen plasma equipment for 20 s at 30 mT pressure. Prior to bonding process, glass samples are cleaned inacetone. The liquid metal is injected into the channel in order to form the ring (Figure 3.d) and split ring structure. Double layer is formed by stacking two single layer structures back to back (glass sides facing each other) with a 4.5 mm-thick foam in between them. The rotation of the liquid metal along the channels and fixing its position can be provided by using micropumps attached to the channels as implemented by the previous work in the literature [9].

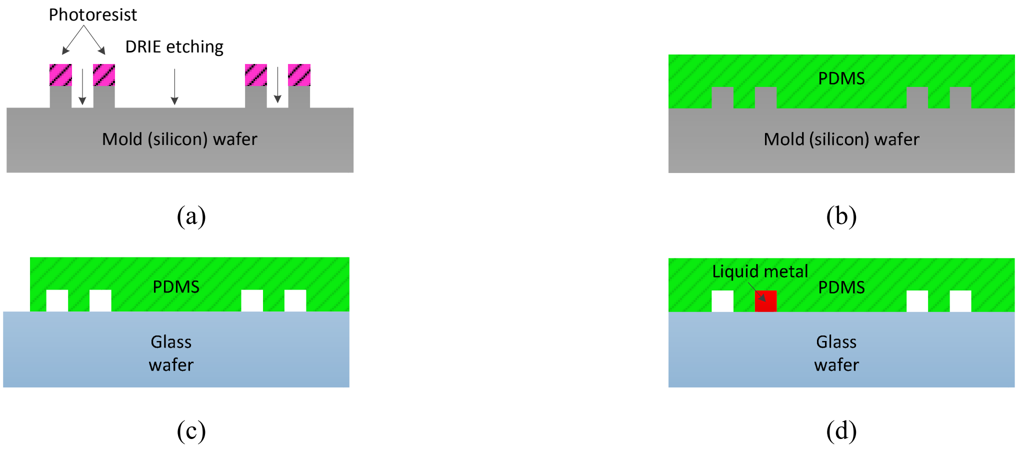

Figure 3. Fabrication process flow: (a) mold wafer preparation via DRIE process, (b) PDMS coating, curing, and peeling off, (c) PDMS-to-glass bonding process, and (d) Liquid metal injection.

Figure 4 shows single layer of the fabricated double layer nested split ring-shorted ring transmitarray unit cell. The measurements of the unit cells are performed by using the waveguide simulator method with WR-90 waveguide and the results will be presented at the conference.

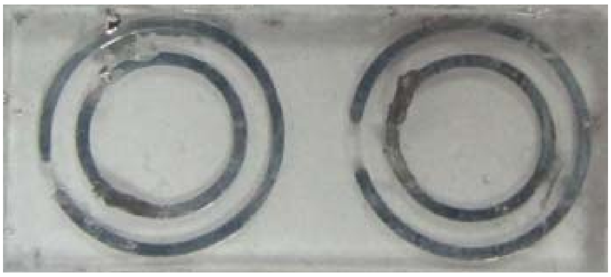

Figure 4. Top view of the fabricated nested split ring-regular ring transmitarray unit cell (single layer is shown only).

4. Conclusion

This paper presents microfluidic based reconfigurable double layer nested split ring-shorted ring transmitarray unit cell employing the element rotation method. The major advantage of this approach 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 design can be easily scaled to different frequency bands since the structure and the channels are manufactured using micromachining techniques that enable the high precision fabrication capability required particularly for high frequency applications.

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