Investigating Stacked-Ring Based Cells for Phase Shifting Surfaces

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***Abstract*—This paper investigates a stacked-ring based unit cell design for near-field phase-shifting metasurfaces developed for beam-steering applications. The unit cell has two dielectric layers sandwiched between three thin patterns of conductive material. Each of the three conductive patterns has a circular ring of varying sizes to produce the required spatial phase variation across the metasurface. To validate the performance of the unit cell, a metasurface was designed to tilt the beam of a 4x4 microstrip array. The numerical simulations predict that the array beam can be tilted by an angle of 28.8º without severe degradation, verifying the unit cell phase-shifting characteristics.**

Keywords—Unit Cell; Phase Shifting Surface; Beam Steering; Microstrip Array; Ring Structure.

I. INTRODUCTION

Beam steering of an antenna or array has been explored in the literature for decades. The two most common methods are electronic steering using phase shifters and mechanical steering through rotating antennas or arrays. Both methods have their pros and cons [1] [2]. A recently demonstrated near-field meta-steering method, although mechanical, has several advantages such as low profile, low power requirement, high performance, simplicity and polarisation flexibility when compared with traditional mechanical beam-steering antennas. In one of its implementations, a phase shifting surfaces (PSS) tilts the beam at an offset angle in elevation while azimuth steering is achieved by rotating the PSS [3] [4].

A PSS is made of fundamental cell elements. Each cell is designed to produce a phase shift in the near electric field while maintaining the same near-field amplitude. Typically, these cells are made of alternating dielectric and metal layers. In this paper, we are investigating a stacked ring structure for phase shifting and then incorporate it in a PSS for the beam steering of a 4x4 microstrip antenna array.

The paper is organized as follows. Section II provides the details of the stacked ring cell design which is then used in section III to produce a PSS. The designed PSS is then combined with a 4x4 microstrip array in section IV to investigate its effectiveness as a steering surface. We conclude the paper in section V.

II. UNIT CELL DESIGN

The configuration of the cell is shown in Figure 1 (a). It consists of two substrates and three printed metal patterns. The substrate chosen for this design is Rogers RT5880, which has a dielectric constant of 2.2 and a loss tangent of 0.0005. The thickness of the substrate is 0.762 mm. There are three printed layers consisting of rings. Rings on the top and bottom layers have the same radius (r_{r_out}) while the middle layer has a different radius (r_{r_in}). The width of the rings in top/bottom layer is w_1 while that for the middle layer is w_2. Parametric sweeps were carried out for r_{r_out}, r_{r_in}, w_1, and w_2 to select best values. The cell was simulated in CST Microwave Studio and its transmission characteristics were analysed. These simulations indicate that the cell can provide phase shifts from 0° to 300º while maintaining transmission magnitude larger than -3 dB with the exception of few discrete phase values around the range -133° to -24°.

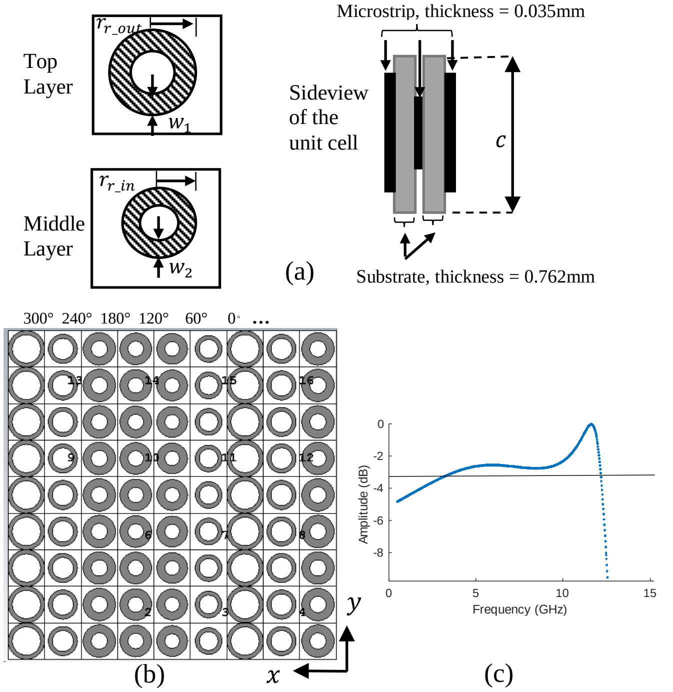

Figure 1. (a) Top-left: The top view of the top and middle metal patterns; Top-right: sideview of a generic cell, (b) a PSS constructed by cascading the designed cells, (c) Transmission magnitude versus frequency.

Additionally, some cells were investigated in a band around the centre operating frequency to estimate the bandwidth of one cell. The transmission magnitude of this cell is plotted against frequency in Figure 1 (c), which indicates that it has a large -3 dB bandwidth (8.3 GHz).

III. PHASE SHIFTING SURFACE

Using the cell design given in Section II, a linear phase progression PSS was designed to tilt the beam of an antenna array to an offset angle θ, following the procedure explained in [2]. According to the basic array theory [5] [6], for an array to steer its beam towards an elevation angle θ, the excitations of the individual elements of the array should have progressive phase difference of ϕ_e which is given by:

$$\phi_e = \frac{2\pi}{\lambda_0} d \sin\theta \qquad (1)$$

where λ_0 is the frequency of operation, and d is the inter-element spacing of the array.

In the case of PSS, a single column of the PSS produces this phase shift in the near field. Thus, the PSS should have a phase shift equal of ϕ_e between adjacent elements in one direction, as shown in Figure 1 (b). We designed the surface to tilt array's beam towards $\theta = -28.8°$ for which the required progressive phase between adjacent cells is $\phi_e = 60°$. Thus for PSS to steer the beam towards $\theta = -28.8°$ the columns of the PSS should produce the following phase shift in the near field: $0°, 60°, 120°, \ldots, 360°/0°, \ldots$. It is to be mentioned here that the absolute phase value is not important but the phase progression is critical for the surface design. Furthermore, the phase can be wrapped after completing cycle of 360°. Table 1 shows the phase values and corresponding physical dimensions of the cells used in PSS design.

Table 1. Values of the cell parameters selected for the PSS.

Required Phase (°)	Achievable Phase (°)	Trans. Amplitude (dB)	Parameter Values (mm)
-180	-179.1	-0.314609	r_{r_in}: 0.3, a_2: 3, r_{r_out}: 3.5, a_1: 1
-120	-121.63	-3.6745	r_{r_in}: 1, a_2: 1, r_{r_out}: 2.6, a_1: 3
-60	-62.54	-1.4797	r_{r_in}: 1.2, a_2: 3, r_{r_out}: 2, a_1: 2
0	0.35	-0.1542	r_{r_in}: 1.2, a_2: 3, r_{r_out}: 1.9, a_1: 2
60	60.15	-0.1619	r_{r_in}: 0.5, a_2: 3, r_{r_out}: 1.8, a_1: 2
120	120.20	-0.1003	r_{r_in}: 2.5, a_2: 1, r_{r_out}: 2.3, a_1: 1

IV. BEAM STEERING WITH PSS

To demonstrate beam steering, we simulated the designed PSS with a 4x4 microstrip patch array that has a fixed beam in normal direction. The far-field patterns of the original array along with the steered beams are shown in Figure 2, which confirms beam tilt to $\theta = -28.8°$ elevation angle due to the PSS. With rotation of the PSS relative to the patch array, the azimuth angle of the beam can be changed and the results for $\phi = 0°, 90°, 180°, 270°$ are shown in this figure at 11.5 GHz frequency. This azimuth steering was achieved by physically rotating the PSS with a step size of 90^{o} along its axis. Figure 2 shows that steering was achieved with acceptable accuracy. The error in the steering is only 1.2° and -0.5° when the PSS was placed along the x-axis and the orthogonal axis, respectively. Despite the small error, the accuracy of the presented cell and the PSS is acceptable for many applications. It provides a cost-effective alternative to the existing expensive steering mechanisms. By introducing a second identical PSS above this one, the beam can be directed to any elevation angle within a larger angular range [2].

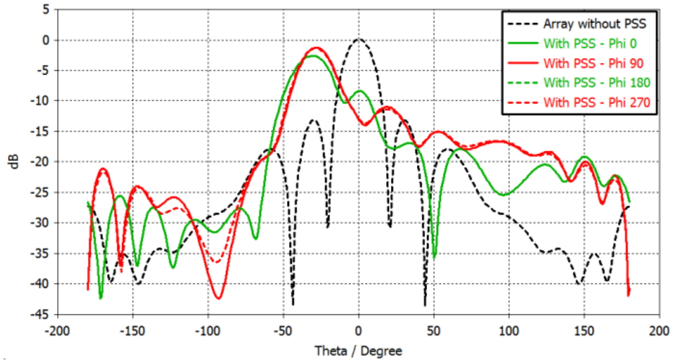

Figure 2. Computed radiation patterns of a 4x4 array, steered using the stacked-ring PSS.

V. CONCLUSION

A new cell design based on stacked rings is presented in this paper, which can be used for several applications. Using the designed cells, a phase shifting surface (PSS) was designed and simulated to investigate steering of the beam of a 4x4 patch array. Beam tilting of the array was successfully achieved with the PSS with minor error. The results presented prove the concept and shows good accuracy of beam steering. The accuracy may be further improved by making the near-field phase of the 4x4 array homogeneous using a phase correcting surface or other methods.

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