Design of 1-Bit Digital Subwavelength Metasurface Element for Sub-6 GHz Applications

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***Abstract*—This paper proposes a novel 1-bit, electronically reconfigurable, subwavelength metasurface unit cell for sub-6 GHz applications. 180º phase shift is achieved by integrating a single PIN diode in the structure. The unit cell incorporates three layers: The top layer is used for wave reflection, the bottom layer is used for PIN diode placement and DC biasing, and the middle layer acts as a ground plane. The resonance of the unit cell is kept around 3.3 GHz. The magnitude of the reflection coefficient is above 90%. Besides, a phase difference of 180˚±20˚ is achieved over 200 MHz bandwidth. With these characteristics, the proposed unit cell can find its applications in programmable metasurface functions such as beam steering, beam focusing and beam scattering.**

Keywords— Metasurface; Reconfigurable; PIN diode

I. Introduction

Over the last decade, intensive research has been conducted in the field of Metamaterials. Metamaterials, a subsequent of artificial materials, exhibit unique electromagnetic (EM) characteristics that are not found in conventional materials [1]. This includes cloaking [2], superlenses [3], perfect absorbers [4] and many more. However, owing to their low cost and ease of fabrication, metasurfaces have risen as an alternative candidate to metamaterials.

Metasurfaces can manipulate EM wave propagation. Hence, their functionalities include focusing, steering, scattering and absorption of the EM waves [5]. A new class of metasurface has recently emerged known as the software-controlled metasurface or intelligent reflective surface (IRS) [6]. The ability to control the EM manipulation via a programmable device is gaining significant interest. The paradigm shift from analogue control of the metasurface elements using varactors, BST capacitors and Liquid crystal technology to digital control using Relay, MEMS and PIN diode has brought forth the amalgamation of EM domain with the digital domain.

In this regard, the concept of digital and programmable metamaterials was presented in [7, 8]. These coded metasurfaces assign each meta-unit cell with a binary digit. The phase of a metasurface is quantized and replaced with a coding sequence, e.g., a simplest coding sequence is 1-bit. The phase distribution on the surface is rounded to nearest 0˚ and 180˚ and is digitally represented with two states, i.e., 0 and 1. Hence, it is pertinent to design wideband, lossless, 1-bit metasurface elements to achieve the desired functionalities by these intelligent reflective surfaces.

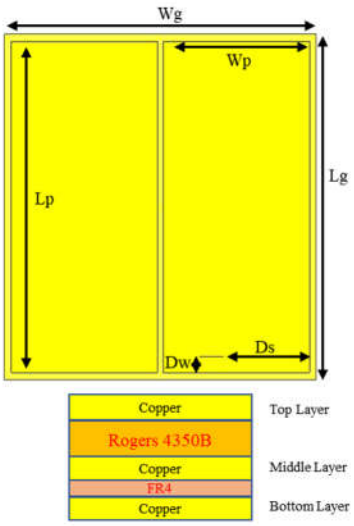

Fig. 1. Layout of the proposed unit cell. (Wg=22 mm, Wp=10 mm, Lg=22 mm, Lp=21 mm, Dw=1 mm, Ds= 5.7 mm

In the present literature, various N-bit reconfigurable element designs have been proposed. While the varactors provide continuous tuning abilities and full phase resolution, the disadvantage is that they provide reflection loss up to 2.7 dB in the ON state which significantly reduces the reflection efficiency [9]. With the ease of implementation and low cost various 1-bit PIN diode reflective elements have been proposed in [10-15]. The element design generally follows the conventional approach of keeping the element size near resonance and inter-element spacing is kept around half-wavelength. However, the focus is mostly on making the element bandwidth wider but aperture efficiency cannot be attained using this approach. It was shown in [16] that keeping the element size and interelement spacing lower than half-wavelength, a substantial improvement in the gain bandwidth of the reflective surface is attained and the aperture efficiency reaches to about 65%. The authors in [17, 18] have tried to achieve a wider bandwidth by optimizing the element size around 0.37λ. A relation with the aperture efficiency can be established with reduced element spacing. The maximum aperture efficiency achieved in [12] and [18] is around 17.9% and 25% with the same aperture size but with more elements in the latter work in the same aperture area.

Hence decreasing the element spacing may lead to improve aperture efficiency but element bandwidth is difficult to achieve due to high mutual coupling.

In this paper we propose a novel 1-bit programmable metasurface element with dimensions and interelement spacing of 0.25λ by meeting the bandwidth requirement of the element. The meta-element is realized using a square patch split into half from the centre. A PIN diode and the DC biasing circuit is realized on the opposite side of the reflecting surface making the structure very simple and less prone to EM scattering usually caused by components embedded within the reflective elements. The scope of this work is only limited to bandwidth achievement of the metasurface element.

II. Unit Cell design

The proposed unit cell is designed and optimized using CST Microwave Studio software. The simulation was performed by exciting the metasurface unit cell with a floquet port using 'Unit cell' boundary condition. Figure 1 shows the layout and dimensions of the proposed unit cell. The unit cell consists of three layers as depicted in Figure 1. The electromagnetic layer (top layer) is printed on the top of a conductor-backed Rogers 4350B substrate ($\varepsilon_r = 3.48$ and $\tan\delta = 0.0037$ at 10 GHz).

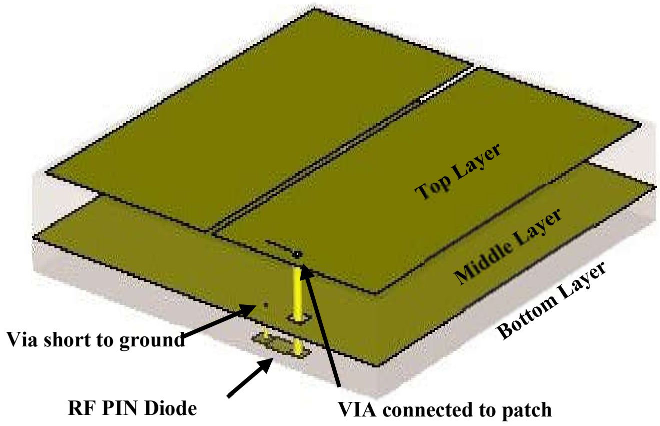

Fig. 2. Top and bottom view of the proposed unit cell with diode and via shorting position.

The thickness of the copper layer is kept at 17 µm. A 0.8 mm thick FR-4 dielectric slab ($\varepsilon_r = 4.4$) is placed underneath the ground plane of the top layer. The bottom layer is the control layer and consists of RF PIN diode and DC biasing circuit along with RF choke to isolate RF frequency from the DC source. Hence the overall thickness of the unit cell is around 2.4 mm. The patch on the top layer is split into half with a spacing of 0.2 mm. The phase difference is achieved by shorting one portion of the patch with the ground through RF PIN diode. Figure 2 shows a 3D view of the unit cell. An advantage of the proposed design is that the PIN diodes and the associated biasing circuits are placed on the bottom layer. This introduces ease of fabrication and eliminates EM scattering on the top layer due to interaction with the components and soldering material. When the RF PIN diode is on, the plated through via along with the blind via connects the top layer with the middle layer. In other words, some inductance is introduced in the unit cell. In the absence of via, there is the only capacitance between the patch and ground the plane. The inter-element spacing which is the dimension of the ground plane kept around 22 mm. This is approximately a quarter wavelength at the centre frequency of 3.3 GHz.

III. Result And Discussion

The reflection phase of the proposed unit-cell is shown in Figure 3. When the RF PIN diode is in the OFF state, the phase state is below 0˚, indicating capacitive patch. When the RF PIN diode is in the ON state, the reflection phase turns to positive and hence the patch becomes inductive. The shorting of the patch can be considered as impedance transformation from capacitive to inductive. Therefore, the patches act as an artificial impedance surface.

Figure 4 shows the phase difference of the proposed unit-cell. A bandwidth of 200 MHz is achieved over a phase difference of 180˚±20˚ around the centre frequency of 3.3 GHz. This corresponds to 6% bandwidth which previous works have achieved using metasurface element with dimensions beyond quarter wavelength. The magnitude of the reflection coefficient is well above 0.9 as shown in Figure 5. This indicates that 90% of the incident wave is reflected to the source.

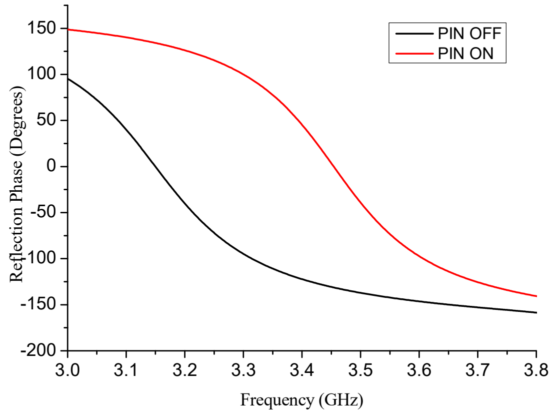

Fig. 3. Simulated phase of the unit cell with PIN diode OFF and ON

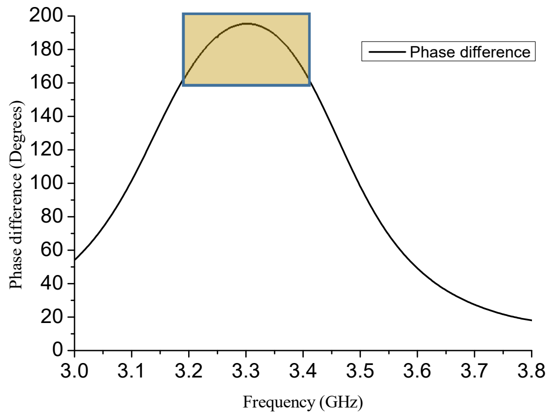

Fig. 4. Simulated 180˚ phase difference among adjacent unit cells with ON and OFF state.

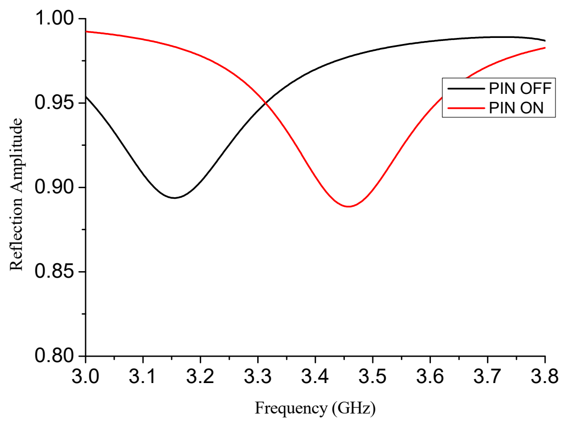

Fig. 5. Simulated reflection amplitude of the unit cell in OFF and ON state.

Parametric studies have been carried out to show the effect of the patch spacing. Results are shown in Figures 6 and 7. It can be seen that the spacing in the centre of the patch element significantly reduces the reflection loss with very little effect on the reflection phase of the metasurface element. The shorting position of the patch to the ground 'Dw'is illustrated in Figure 8. As the shorting position is kept closer to the edge, the inductive effect increases, which is beneficial to achieve a 180˚ phase difference in the ON and OFF state of the PIN diode.

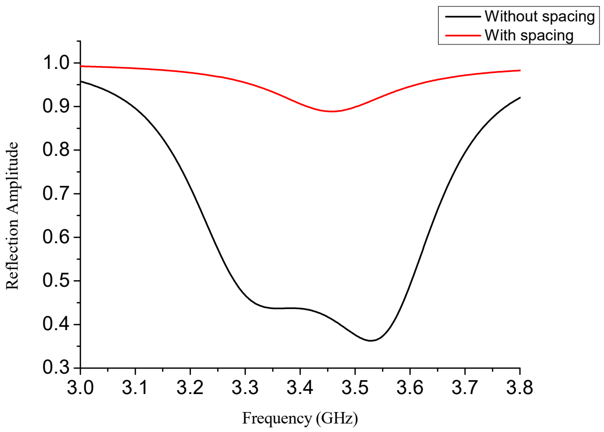

Fig. 6. Effect on reflection amplitude in ON state with spacing and without spacing between the patch.

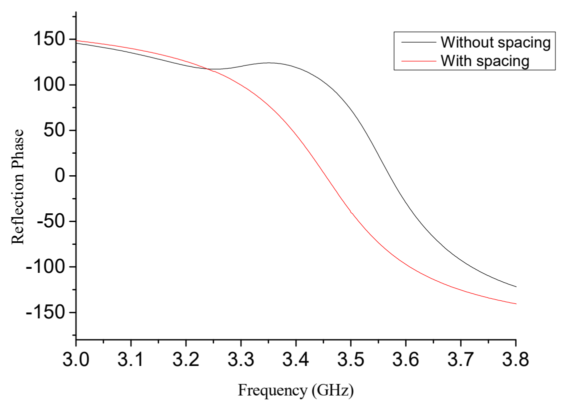

Fig. 7. Effect on reflection phase in ON state with spacing and without spacing between the patch

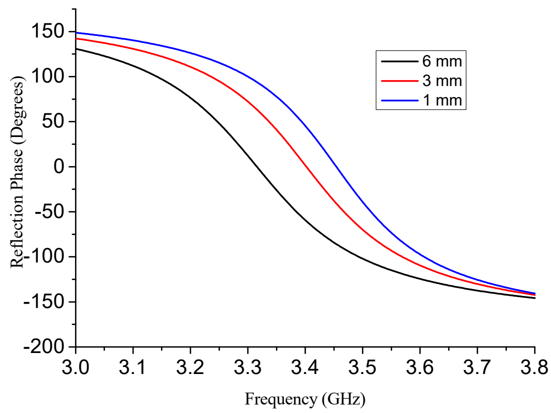

Fig. 8. Effect on reflection phase with variation in 'Dw' in the ON state.

IV. CONCLUSION

A novel and simple, 1-bit programmable metasurface element is designed for Sub-6 GHz applications. The proposed metasurface element operates around 3.3 GHz with a bandwidth of 200 MHz in the phase difference of 180˚$\pm$20. The 180˚ phase difference is achieved by shorting the patch at the edge. Without shorting the patch to the ground, it behaves as a capacitive patch. The reflection amplitude is above 0.9 which depicts low losses and hence, contributes to higher reflection efficiency. The proposed metasurface element is an ideal candidate for future programmable digital metasurface.

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