



Kazim, J. u. R., Ur-Rehman, M., Al-Hasan, M., Mabrouk, I. B., Imran, M. A. and Abbasi, Q. H. (2020) Design of 1-Bit Digital Subwavelength Metasurface Element for Sub-6 GHz Applications. In: 5th International Conference on the UK-China Emerging Technologies (UCET 2020), Glasgow, UK, 20-21 Aug 2020, ISBN 9781728194882 (doi: [10.1109/UCET51115.2020.9205382](https://doi.org/10.1109/UCET51115.2020.9205382)).

This is the author's final accepted version.

There may be differences between this version and the published version. You are advised to consult the publisher's version if you wish to cite from it.

<http://eprints.gla.ac.uk/221488/>

Deposited on: 27 July 2020

Enlighten – Research publications by members of the University of Glasgow
<http://eprints.gla.ac.uk>

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

Jalil ur Rehman Kazim
James Watt School of Engineering
University of Glasgow
Glasgow, UK
j.kazim.1@research.gla.ac.uk

Masood Ur-Rehman
James Watt School of Engineering
University of Glasgow
Glasgow, UK
Masood.UrRehman@glasgow.ac.uk

Muath Al-Hasan
College of Engineering
Al Ain University)
Abu Dhabi, UAE
Muath.alhasan@aau.ac.ae

Ismail Ben Mabrouk
College of Engineering
Al Ain University)
Abu Dhabi, UAE
Ismail.mabrouk@aau.ac.ae

Muhammad Ali Imran
James Watt School of Engineering
University of Glasgow
Glasgow, UK
Muhammad.Imran@Glasgow.ac.uk

Qammer H Abbasi
James Watt School of Engineering
University of Glasgow
Glasgow, UK
Qammer.Abbasi@Glasgow.ac.uk

Abstract—This paper proposes a novel 1-bit, electronically reconfigurable, subwavelength metasurface unit cell for sub-6 GHz applications. 180° 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 $180^\circ \pm 20^\circ$ 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.

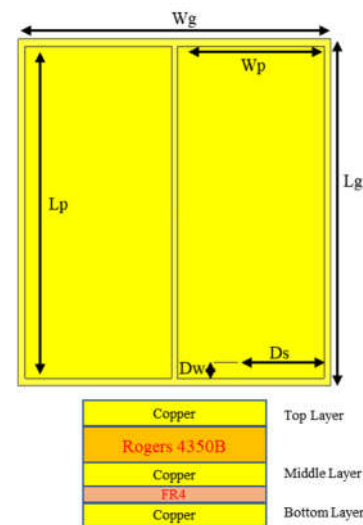


Fig. 1. Layout of the proposed unit cell. ($W_g=22$ mm, $W_p=10$ mm, $L_g=22$ mm, $L_p=21$ mm, $D_w=1$ mm, $D_s= 5.7$ mm)

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 ($\epsilon_r = 3.48$ and $\tan\delta = 0.0037$ at 10 GHz).

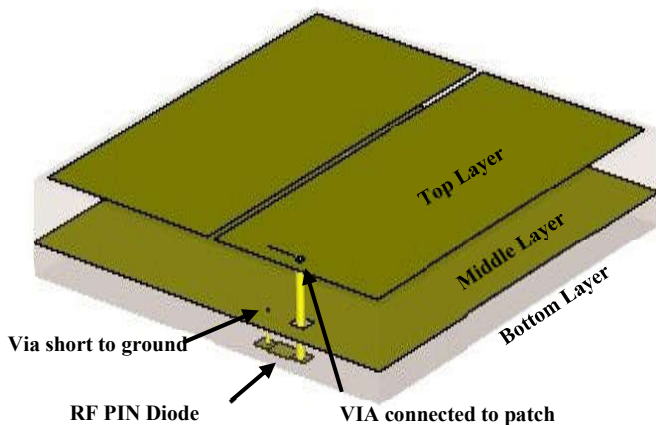


Fig. 2. Top and bottom view of the proposed unit cell with diode and via shorting position.

The thickness of the copper layer is kept at $17\ \mu\text{m}$. A $0.8\ \text{mm}$ thick FR-4 dielectric slab ($\epsilon_r = 4.4$) 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 $2.4\ \text{mm}$. The patch on the top layer is split into half with a spacing of $0.2\ \text{mm}$. 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 plane. The inter-element spacing which is the dimension of the

ground plane kept around $22\ \text{mm}$. This is approximately a quarter wavelength at the centre frequency of $3.3\ \text{GHz}$.

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 $200\ \text{MHz}$ is achieved over a phase difference of $180^\circ \pm 20^\circ$ around the centre frequency of $3.3\ \text{GHz}$. 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.

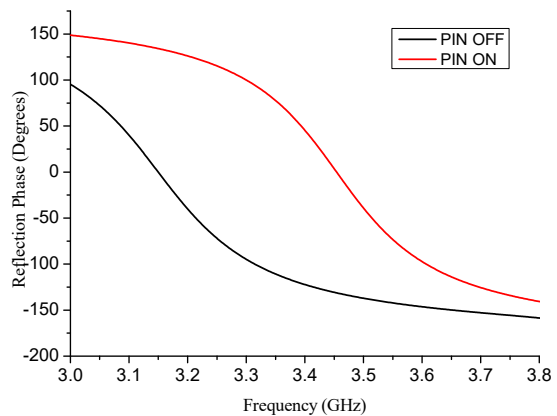


Fig. 3. Simulated phase of the unit cell with PIN diode OFF and ON

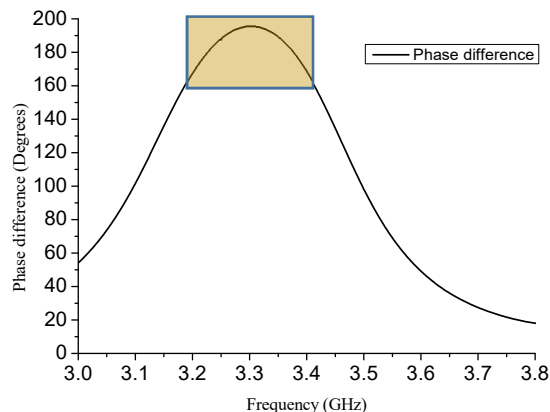


Fig. 4. Simulated 180° phase difference among adjacent unit cells with ON and OFF state.

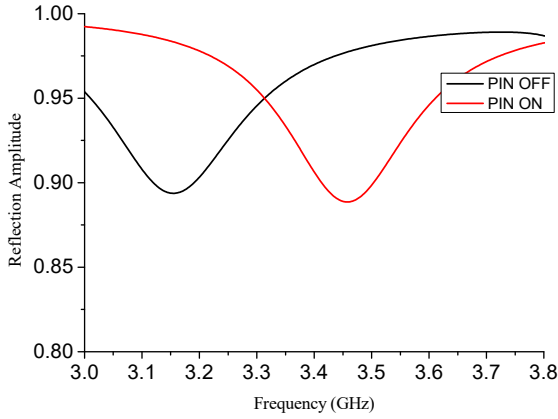


Fig. 5. Simulated reflection amplitude of the unit cell in OFF and ON state.

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.

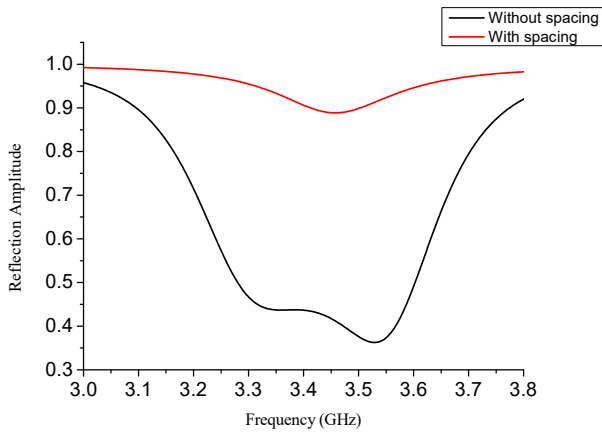


Fig. 6. Effect on reflection amplitude in ON state with spacing and without spacing between the patch.

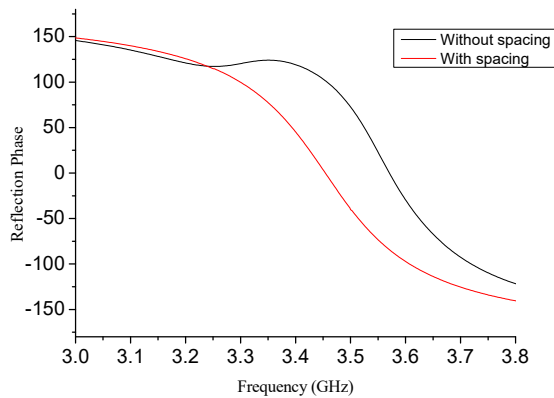


Fig. 7. Effect on reflection phase in ON state with spacing and without spacing between the patch

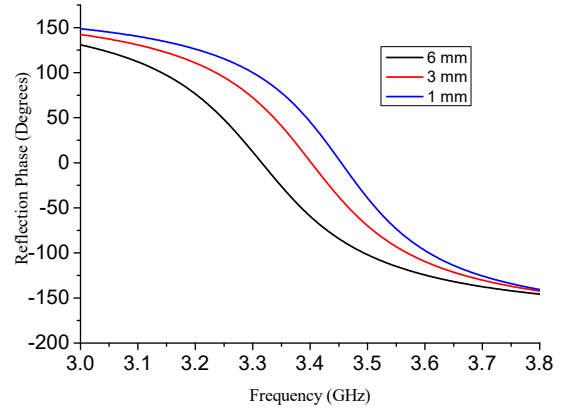


Fig. 8. Effect on reflection phase with variation in ‘Dw’ in the ON state.

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 $180^\circ \pm 20$. 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.

Acknowledgement

The research work in this paper has been funded by ADEK Award for Research Excellence, grant AARE19-245.

REFERENCES

- [1] D. Sievenpiper, Z. Lijun, R. F. J. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 11, pp. 2059-2074, 1999.
- [2] D. Schurig *et al.*, "Metamaterial electromagnetic cloak at microwave frequencies," *Science*, vol. 314, no. 5801, pp. 977-980, 2006.
- [3] J. B. Pendry, "Negative refraction makes a perfect lens," *Physical review letters*, vol. 85, no. 18, pp. 3966, 2000.
- [4] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect metamaterial absorber," *Physical review letters*, vol. 100, no. 20, pp. 207402, 2008.
- [5] H. Yang *et al.*, "A programmable metasurface with dynamic polarization, scattering and focusing control," *Scientific reports*, vol. 6, pp. 35692, 2016.
- [6] C. Liaskos, S. Nie, A. Tsiolaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "A new wireless communication paradigm through software-controlled metasurfaces," *IEEE Communications Magazine*, vol. 56, no. 9, pp. 162-169, 2018.
- [7] T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, and Q. Cheng, "Coding metamaterials, digital metamaterials and

- programmable metamaterials," *Light: Science & Applications*, vol. 3, no. 10, pp. e218-e218, 2014.
- [8] C. Della Giovampaola and N. Engheta, "Digital metamaterials," *Nature materials*, vol. 13, no. 12, pp. 1115-1121, 2014.
- [9] W. Xue, J. Han, C. Qiao, and L. Li, "Design of 1-Bit Digital Coding Reconfigurable Reflectarray Using Aperture-Coupled Elements Controlled by PIN Diodes," 2018.
- [10] H. Kamoda, T. Iwasaki, J. Tsumochi, T. Kuki, and O. Hashimoto, "60-GHz electronically reconfigurable large reflectarray using single-bit phase shifters," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 7, pp. 2524-2531, 2011.
- [11] E. Carrasco, M. Barba, and J. A. Encinar, "X-band reflectarray antenna with switching-beam using PIN diodes and gathered elements," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 12, pp. 5700-5708, 2012.
- [12] H. Yang *et al.*, "A 1-Bit 10×10 Reconfigurable Reflectarray Antenna: Design, Optimization, and Experiment," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 6, pp. 2246-2254, 2016.
- [13] H. Yang *et al.*, "A 1600-element dual-frequency electronically reconfigurable reflectarray at X/Ku-band," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 6, pp. 3024-3032, 2017.
- [14] J. Han, L. Li, G. Liu, Z. Wu, and Y. Shi, "A Wideband 1 bit 12×12 Reconfigurable Beam-Scanning Reflectarray: Design, Fabrication, and Measurement," *IEEE Antennas and Wireless Propagation Letters*, Article vol. 18, no. 6, pp. 1268-1272, 2019.
- [15] D. Wang *et al.*, "Design of a 1 Bit Broadband Space-Time-Coding Digital Metasurface Element," *IEEE Antennas and Wireless Propagation Letters*, Article vol. 19, no. 4, pp. 611-615, 2020.
- [16] D. Pozar, "Wideband reflectarrays using artificial impedance surfaces," *Electronics letters*, vol. 43, no. 3, pp. 148-149, 2007.
- [17] D. Wang, Y. Tan, L. Z. Yin, T. J. Huang, and P. K. Liu, "A subwavelength 1-bit broadband reconfigurable reflectarray element based on slotting technology," 2019.
- [18] H. Zhang, X. Chen, Z. Wang, Y. Ge, and J. Pu, "A 1-Bit Electronically Reconfigurable Reflectarray Antenna in X Band," *IEEE Access*, Article vol. 7, pp. 66567-66575, 2019.