ENHANCED ANTENNA PERFORMANCE AT 3.5 GHZ WITH A COMPACT AND INTELLIGENT REFLECTING SURFACE

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ABSTRACT: Intelligent Reflecting Surface (IRS) is an upbound 5G technology capable of intelligently controlling and altering an electromagnetic (EM) wave. IRS is a planar 2D metamaterial or metasurface made up of many passive element reflecting elements connected to a smart controller, which is capable of introducing an independent phase shift and/or amplitude attenuation (collectively termed as "reflection coefficient") to the incident signal at each reflecting element. Hence, in this research, an IRS was designed to operate at 3.5 GHz structured by a compact unit cell size of 21.4 mm x 21.4 mm with Circular Patch and Ring. The metasurface consists of FR-4 substrate with a dielectric constant of 4.3 and copper backplane as the ground plane. Generally, the IRS uses a PIN diode or varactor to achieve the configurability by the ON and OFF state. However in this research, the concept is proven by connecting and disconnecting metal strips to indicate the ON and OFF state. The reflection magnitude and phase are the main parameters that were analyzed in this research. In OFF and ON states, the magnitude of the reflection coefficient is -0.32 dB and -0.38 dB respectively with dynamic reflection range of 325°. A prototype for the OFF state has been fabricated and demonstrated as a reflecting surface for a horn antenna. The measured outcome, employing the reflecting surface positioned approximately 10 cm away from the horn antenna, indicates a decrease in return loss of approximately 72.2%. The results show that the proposed reflecting surface can be used as a good reflector in IRS at 3.5 GHz.

ABSTRAK: Permukaan Pemantul Pintar (IRS) merupakan teknologi terbaru 5G yang mampu mengawal dan mengubah gelombang elektromagnetik (EM) secara pintar. IRS adalah 'bahan meta' 2D satah atau permukaan meta 2D satah yang terdiri daripada sejumlah besar elemen pemantau pasif yang bersambung dengan pengawal pintar. Ia mampu mengadakan pergeseran fasa bebas dan/atau penurunan amplitud (secara kolektif iaitu sebagai pekali refleksi) kepada isyarat insiden pada setiap unsur reflektif. Oleh itu, kajian ini adalah berkenaan IRS yang beroperasi pada 3.5 GHz dengan struktur sel kompak bersaiz 21.4 mm x 21.4 mm seunit dengan tampalan kuprum berbentuk cincin dan bulatan. Permukaan meta ini terdiri daripada substrat FR-4 dengan pemalar dielektrik 4.3 dan satah kuprum di bahagian belakang. Secara umum, IRS menggunakan diod PIN atau varaktor bagi mencapai keboleh konfigurasi mengikut keadaan BERSAMBUNG dan TIDAK. Walau bagaimanapun, konsep ini dibuktikan dengan menyambung dan memutuskan jalur logam bagi menunjukkan keadaan BERSAMBUNG dan TIDAK. Magnitud pantulan dan fasa pekali merupakan parameter utama yang dikaji dalam kajian ini. Dalam keadaan TIDAK dan BERSAMBUNG, magnitud pekali pantulan ialah -0.32 dB dan -0.38 dB masing-masing dengan julat pantulan dinamik 325°. Prototaip pada keadaan TIDAK telah dibentuk dan menunjukkan sebagai permukaan pantulan bagi antena jenis tanduk. Dapatan hasil menunjukkan permukaan reflektif yang diukur pada jarak 10 cm dari antena tanduk mengalami penurunan kehilangan refleksi sebanyak 72.2%. Ini menunjukkan permukaan reflektif yang dicadangkan dapat digunakan sebagai reflektor IRS yang baik pada frekuensi 3.5 GHz.

***KEYWORDS:** reconfigurable intelligent surface, 5G, metasurface, Circular Patch and Ring (CPR), unit cell, measurement*

1. INTRODUCTION

In recent years, there has been an increasing trend of research and development for enhancement and improvement in wireless communication systems. This surge is propelled by the increasing number of communication devices and technologies that demand more robust wireless connections. Conventional wireless technologies are inadequate to meet the requirements of upcoming technologies, necessitating exceptionally high data rates, reduced interference, minimized signal attenuation, energy efficiency, and pervasive connectivity. These advanced technologies encompass Internet of Things, Virtual Reality (VR), Augmented Reality (AR), Artificial Intelligence (AI), smart cities, and Autonomous Vehicles (AVs). Consequently, an Intelligent Reflecting Surface (IRS) or so called Reconfigurable Intelligent Surface (RIS) [1] has emerged as a promising new technology anticipated to revolutionize wireless communication especially for the upcoming sixth generation.

Generally, IRS is a smart technology made of 2-dimensional (2D) metamaterials or metasurfaces having the ability to control the propagation of signals in the wireless communication channel. Hence, it potentially could improve spectral efficiency (SE) and energy efficiency (EE) to assist the sixth-generation (6G) and subsequent generations in providing the necessary data rate to assist current and forthcoming technologies [2].

A 2D metamaterial or metasurface consists of negative permeability and permittivity, categorizing it within quadrant 3 of materials, also known as Negative Index Material (NIM) [3]. Within the metasurface concept, the surface can be adjusted to alter the phase of individual reflecting elements, termed unit cells, thereby enabling signal beamforming and directing the signal toward a specific direction. Moreover, the technology behind 2D metamaterials is engineered to function across different frequencies, making it highly efficient for various technologies that operate within a range of frequencies [2].

A metasurface consists of many small reflecting elements called meta-atoms, meta-cells, or unit cells [4]. The unit cells consist of three layers where the middle layer is the dielectric substrate such as Roger RO4350B, FR4, and others while the upper layer consists of a copper patch and bottom part as copper ground are commonly used as the material. Electromagnetic (EM) properties of the unit cells are influenced by structural features of the metasurface such as geometry (split-ring, circular or hexagon), size, orientation, and arrangement [5].

The objective of controlling the electromagnetic wave through IRS can be achieved by modifying the reflection coefficient of individual unit cells. This can be accomplished using various methods, such as mechanical adjustments (rotation and translation), incorporating functional materials (like liquid crystal and graphene), and employing electronic devices (such as PIN diodes and Varactor diodes) [6].

Recent research conducted by [1] involved the design and prototype of an RIS working at 3.5 GHz, comprising 2430 unit cells equipped with varactor diodes for tuning purposes.

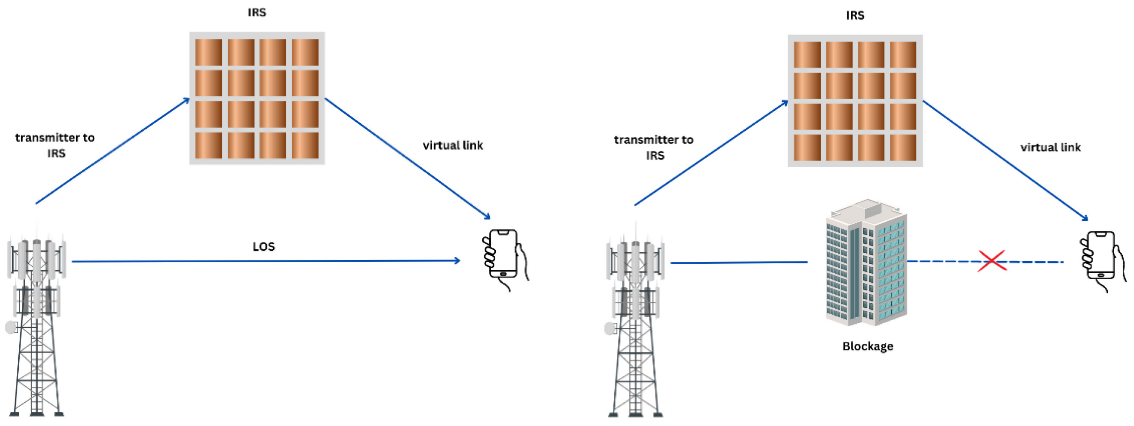
Additionally, [7] proposed achieving configurability in the IRS by integrating PIN diodes into the metasurface. Their design operates at 6 GHz, demonstrating a reflection loss of approximately 0.34 dB. Another IRS model detailed in [8] consisted of 160 meta-cells functioning at 5.8 GHz. This model was proposed and then fabricated to evaluate its performance in an anechoic chamber. By utilizing the PIN diode as an RF switch, the system indicates an almost 180⁰ phase difference across the operating band and incurs an approximate loss of 1.5 dB.

This paper introduces a metasurface employing a circular patch with ring unit cells designed to operate at 3.5 GHz. The selection of the 3.5 GHz frequency is due to medium band frequency for 5G. Furthermore, fabricating an IRS at 3.5 GHz is deemed practical, considering the availability of materials and measurement equipment tailored for 5G applications. This work is a continuity from [9], where the author illustrates the ON state by incorporating metal strips connected to the cells, whereas the strips are omitted for the OFF state of the IRS. This research explores the concept of modeling IRS without utilizing electronic tuning mechanisms for ease of configurations. Section 2 provides a review of existing works. Section 3 delves into the metasurface unit cell, array design, and measurement. Section 4 is dedicated to the analysis of results, while the conclusion is succinctly summarized at the article's end.

2. EXISTING RESEARCH ON IRS

2.1 Fundamental Theory of Intelligent Reflecting Surface

In a conventional wireless communication context, multi-path propagation arises, resulting in significant distortions to the receiving signals. This effect, known as fading, is a significant limitation in future wireless communication systems [5]. IRS is deemed to be a viable solution that can effectively boost the performance of wireless communication networks by smartly reconfiguring the channel environment with numerous passive reflecting features. Fig. 1(a) shows the function of IRS to improve the diversity of an LoS communication link by generating a replica copy [2].



(a) (b)

Fig. 1. Presence of (a) line-of-sight link and
(b) blocking element and absence of LoS link.

Fig. 1(b) depicts the scenario of the Non-Line-of-Sight (NLoS) communication link between the BS and EU. IRS serves as a virtual source to create NLoS communication link due to the blockage by some blocking elements including signboards, cars, and high rise buildings that can be found in most of the urban areas that have very high population density of people and infrastructure [2].

By controlling the channel environment, a specific metric objective, including the system workable rate or coverage, can be enhanced using the proper IRS phase shifts, amplitude, or both. This is fundamentally distinct from conventional wireless communication research, where optimization and design options are limited to a pair of transceivers [6].

2.2 Existing Research on Reflecting Element using Metamaterial

The metasurface consists of many small reflecting elements called meta-atoms, meta-cells, or unit cells. The term of unit cell will be used in this research. The unit cell consists of three layers where the middle layer is the dielectric substrate such as Roger RO4350B , FR4, and others while the upper layer is a patch and the bottom part, called ground, is commonly made of copper as the material.

The aim for the control of electromagnetic waves of IRS can be idealized by altering the reflection coefficient of each unit cell [10]. The authors in [11] proposed a design of unit cell with a PIN diode as the tuning element to alter the capacitance of each unit cell. The concept of this design is to control the electromagnetic response by changing the state of an element by biasing the voltage. The operating frequency of the proposed design is in the W-band at 100GHz.

The RIS work by [10] proposes a phase-shifting unit cell using PIN diodes to exhibit 8 discrete phase states at 5G mid-band. The substrate used in this design is F4B (lossy) with relative permittivity of 2.65. The authors utilized S-parameter data extracted from PIN diodes, revealing eight different phase states and an average reflection loss of 1 dB. Another work by [11] proposes an IRS in THz band (80-110 GHz) with configurable gain. The material used for the substrate is Taconic Company RF-43, having relative permittivity of $\varepsilon r = 4.3$, The results show that an average of 3.7 dB for amplitude and 300 degrees for phase have been achieved for reflected waves with a steering range of up to ∓ 84 for azimuth or elevation.

The existing IRS [1, 7, 8] show the complexity in fabricating the metasurface due to the very complicated structure and expensive external control board. Most of the research implements PIN diodes, varactors, and functional material (graphene & liquid crystal). Our proposed reflecting surface structure is a passive structure that is easy to fabricate, low cost, and requires no external complicated controller. The difference of our work in comparison with existing research is the representation of PIN Diodes using metal strips as an equivalent circuit in order to simplify the structure for the IRS.

2.3 Design and Working Principles of IRS

An Intelligent Reflecting Surface consists of three layers which can be briefly described as below:

- The first layer: Consists of many reconfigurable metallic patches and the main objective is to manipulate the electromagnetic wave of incident signals. The metallic patches are etched with a dielectric substrate.
- Middle layer: A layer of copper plate is used to avoid and reduce signal leaking when the reflection occurs.
- Third layer/ bottom layer: This layer is comprised of a control circuit board (such as FPGA [2]) that can manipulate the reflection phase and amplitude on a real-time basis.

In the design of IRS, there are some proposed ideas as the mechanism to tune the element in order to dynamically cater to the wireless channel [6]. The approaches can be described in Table 1. In addition, Table 2 summarizes the related works of the IRS, including the theory, design, and historical technologies.

Table 1. List of tuning mechanisms [6].

Mechanism	Description
Mechanical attenuation	Mechanical rotation, Mechanical translation
Functional material	Liquid crystal, Graphene
Electronic device	Positive-intrinsic-negative (PIN) diode, Varactor diode, Field-effect transistors, Micro-electromechanical systems (MEMS) switches

Table 2. List of IRS-related works.

References	Description
[2]	Discussion of the previous technology related to the concept of Intelligent Reflecting Surface. Further explanation of system and the architecture of IRS and IRS-aided wireless communication
[4]	Discussion of Reconfigurable Intelligent Surface (RIS) for the frequencies below 10 MHz. Theory of reflect array antenna and metasurface in IRS application.
[5]	Discussion of 6G wireless network associated with IRS technology. Implementation of IRS comparison between other up bound technologies including relay and backscatter communication.
[6]	Discussion on state-of-the-art of IRS and the fundamental of IRS technology.
[10]	Design of 2.75-bit reflecting unit cell of metasurface
[11]	Design of unit cell of metasurface with tunable element (PIN diode)
[12]	Discussion on RIS for 5G and beyond wireless communication. Analyze the principle of metamaterial and application. The integrating metasurface concept with other technologies.
[13]	Simulation and fabrication of an active metasurface based on PIN diodes that exhibit high absorption, reflection, and transmission in a single design.
[14]	Liquid-crystal based metasurface based real time configuration to achieve beamforming
[15]	Prototype of IRS using PIN diode as tuning element.
[16]	Theory of IRS and prototype of RIS.

3. METASURFACE UNIT CELL AND ARRAY

This section describes the simulation and fabrication process of metasurface unit cells and arrays. In addition, the measurement process has been performed using a 1-18 GHz wideband horn antenna (OBH-10180) in an anechoic chamber, MJIIT.

3.1. Unit Cell of Metasurface

Designing a metasurface requires the selection of suitable parameters based on the operating frequency. Fig. 2 shows the proposed unit cells which have been modeled into 2 different sizes. The unit cell boundaries along the X and Y axes delineate an infinite array of the metasurface. The Z-axis is designated as "Open," indicating that the metasurface is exposed and unbounded in the Z direction, both from the top and bottom. Waves are incident upon the metasurface from the Z direction.

Model 1 exhibits a unit cell of size 42 mm x 42 mm, while Model 2 showcases a reduced unit cell’s size of 21.4 mm x 21.44 mm. The size of the unit cells of Model 1 and Model 2 are calculated based on equations (1) and (2), respectively [17] and shown in Fig. 2(a). Notably, Model 2's dimensions are halved in comparison to the initial design, Model 1. The substrate used for the metasurface is FR4 with a thickness of 1.5 mm. The dimension of parameters for both models has been obtained through numerous simulations (trial and error) and summarized in Table 3 (as shown in Fig. 2(b)).

$$Length, L_1 = \frac{\lambda}{2} \tag{1}$$

$$Length, L_2 = \frac{\lambda}{4} \tag{2}$$

where L_1 and L_2 are the lengths of each side of the unit cell for models 1 and 2, respectively, and λ is the wavelength at the operating frequency.

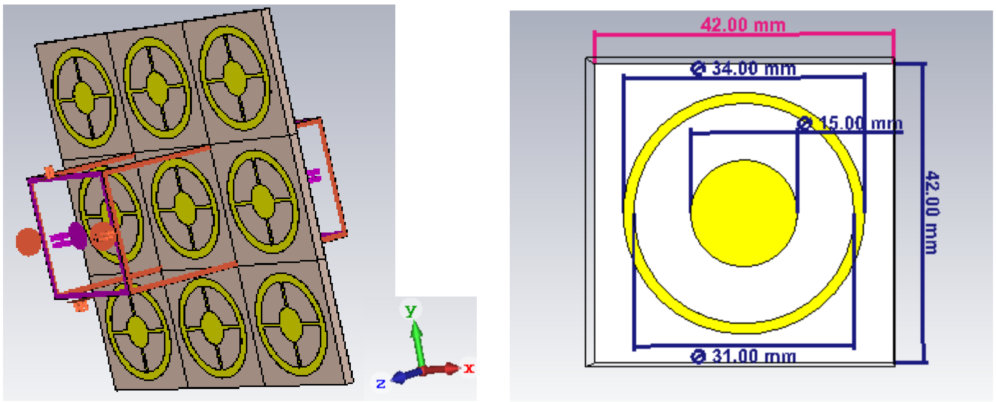


Fig. 2. The implementation of (a) Unit cells structure for Model 1 and 2, (b) Unit cell's dimension based on Table 3.

Table 3: Dimension of Unit Cell for Each Model.

Model	Dimension	Outer ring radius [mm]	Inner ring radius [mm]	Patch radius [mm]	Metal strip width [mm]
1	42mm × 42mm	17	15.5	7.5	2
2	21.4mm × 21.4mm	9	7.5	3	0.6

3.2 Array Design

The unit cell model indicates that the array size is infinite, which is impractical for fabrication. Therefore, an array size of 5 × 5 has been used in this analysis. The array, with an overall size of 107 mm × 107 mm, has been designed to accommodate both ON and OFF states. The selected size ensures that the unit cell is centrally positioned within the array. Additionally, the decision to use a 5 × 5 configuration is influenced by the observation that, as cell sizes increase, the array's performance closely aligns with that of a single unit cell. Fig. 3(a and b) depict the array in both the OFF and ON states.

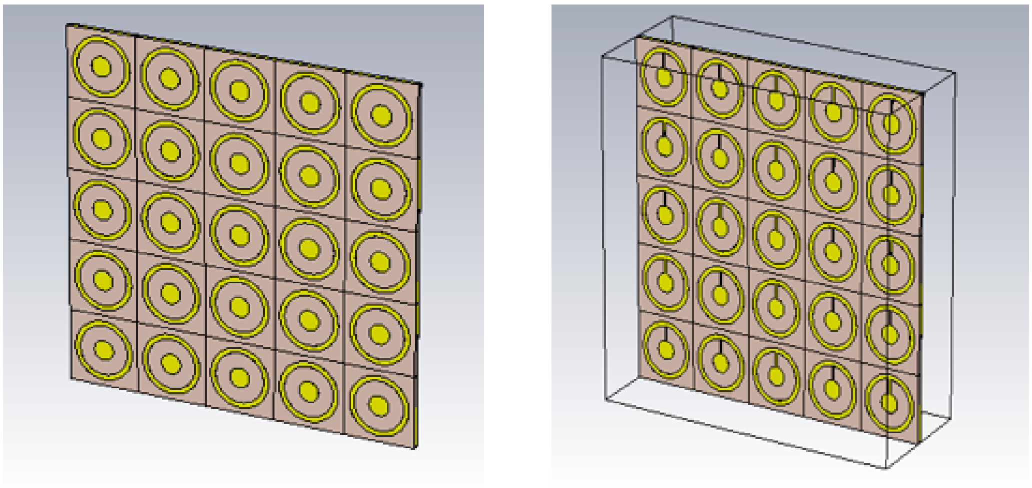


Fig. 3. 5 x 5 array for (a) OFF state (b) ON state '1000'

3.3 ON/OFF States of Metasurface

In order to demonstrate the tuning phase for the reflecting surface, the authors have placed 4 metal strips horizontally and vertically for tuning 'ON/OFF' or '1/0' states of the metal strips. The substitution of the PIN diode with a metal strip has been documented in numerous articles [18-20]. The metal strip is characterized as either an open or a short in the transmission line, as shown in Fig. 4. This configuration is more straightforward to simulate compared to the diode, resulting in faster and more accurate simulations. Additionally, the diode, being an active element, necessitates a complex bias circuit to regulate voltage and restrict current flow into the microwave circuits. The comparison between the simulated metal strip and the PIN diode, as noted in [18], reveals approximately a 6dB loss, which remains within the acceptable range.

As a result, 16 designs of metasurfaces have been investigated due to the implementation of metal strips. The combinations are 0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111, 1000, 1001, 1010, 1011, 1100, 1101, 1110 and 1111. The '0' indicates the metal strip has been removed while '1' indicates the metal strip is connected. The most significant bit defines the Metal Strip 4 (MS 4) while least significant bit represents Metal Strip 1 (MS 1). Illustration of the metal strips position at the unit cell is shown in Fig. 5. The 0000 configuration is fixed to be the OFF state for both models.

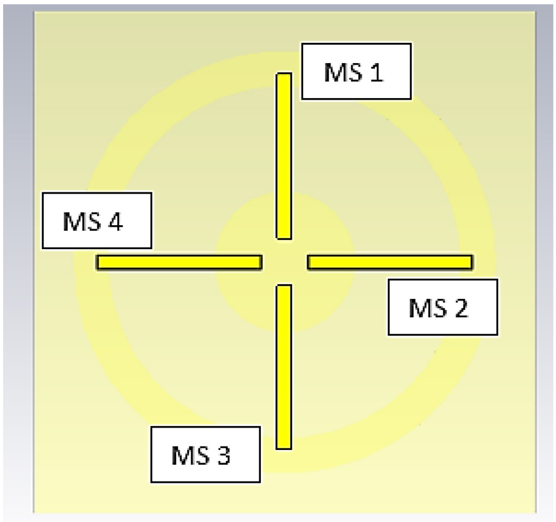
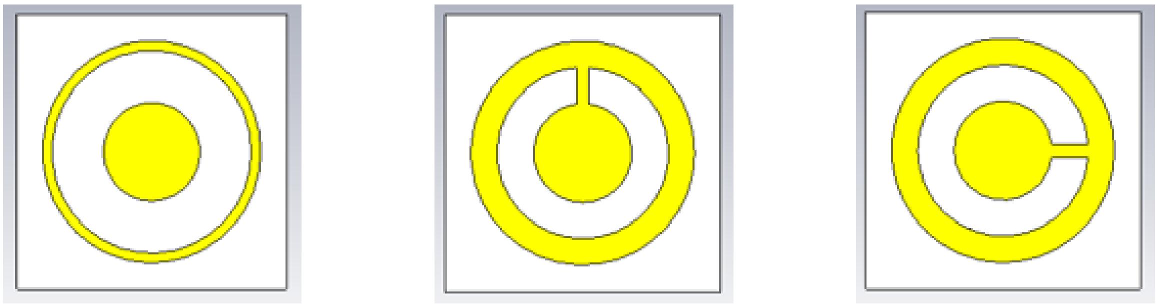


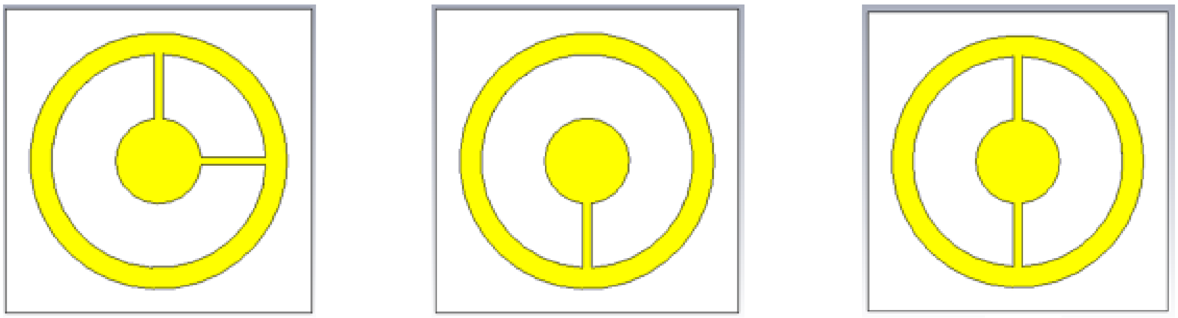
Fig. 4. Metal strip position for a unit cell on the metasurface.

Fig. 5 and 6 depict several designs of unit cell configurations for Model 1 and Model 2, respectively.



0000 0001 0010

Fig. 5. Configurations of Model 1



0011 0100 0101

Fig. 6. Configurations of Model 2

3.4 Fabrication and Measurement of Metasurface.

A prototype of the Intelligent Reflecting Surface (IRS) in the 'OFF' state has been fabricated using FR4 material. The choice of material and design was influenced by considerations of cost and material availability. Fig. 7(a) displays the fabricated structure, which consists of a 5 x 5 array of circular patches with ring arrays. This specific configuration was selected to balance fabrication simplicity and effective functionality. The prototype aims to demonstrate the fundamental characteristics and performance of the IRS in a controlled state before further enhancements.

Meanwhile, Fig. 7(b) illustrates the measurement setup designed to assess the IRS's matching condition and overall performance. The setup employs a wideband horn antenna (OBH-10180), capable of operating within the 1-18 GHz frequency range. The reflection coefficient, a critical parameter indicating the efficiency of the reflecting surface, was measured using a vector network analyzer. The measurements were conducted in two distinct conditions: first, with the IRS placed in the path of the horn antenna's emitted waves, and second, without the IRS, serving as a baseline for comparison.

The separation between the horn antenna and the IRS was precisely set at 10 cm to ensure consistent measurement conditions. This setup allows for accurate evaluation of how the IRS modifies the incident electromagnetic waves, reflecting them in a controlled manner. The data obtained from these measurements are crucial for validating the IRS's design and operational principles, paving the way for future optimizations and applications in various communication systems.

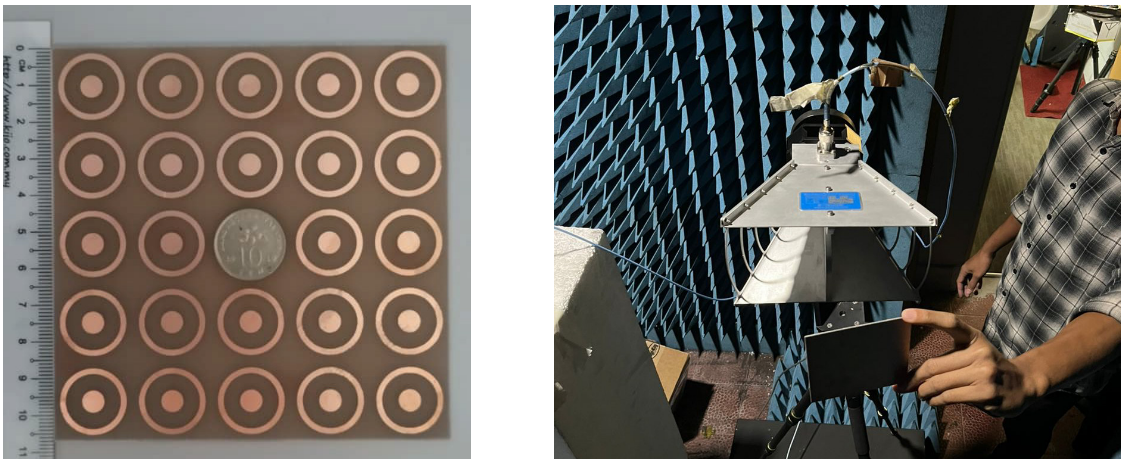


Fig. 7. Prototype (a) A fabricated of 5 x 5 array IRS in OFF state using FR4, (b) Measurement setup of IRS using a wideband horn antenna 1-18 GHz.

4. RESULTS ANALYSIS

This section discusses the simulation and measurement results, including future works for this study.

4.1. Comparison of Unit Cell and Array Analysis

Model 2, having smaller dimensions than Model 1, has been chosen for the analysis. In Fig. 8, a comparison of the magnitude of S11 between the unit cell and the 5 x 5 array of Model 2 is illustrated. The observed magnitudes of S11 at 3.5 GHz are -0.319 dB and -0.329 dB, respectively. The simulation results indicate a small difference of 1.05% between the unit cell model and the array.

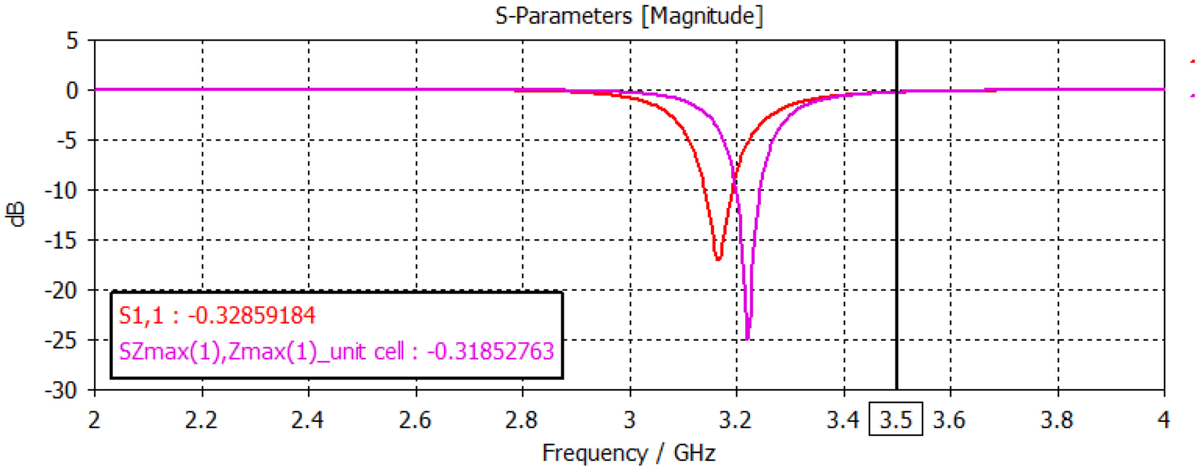


Fig. 8. S11 comparison between unit cell and 5x5 array of Model 2.

4.2. On/Off State of Metasurface

Fig. 9 and Fig. 10 display the graphs of the reflection magnitude of Model 1. The designs are compared to get the best reflection coefficient. It is desirable to achieve the magnitude of S11 as close to 0 to represent the full reflection of the signal from the IRS. The OFF state of Model 1 (0000) has the highest magnitude of reflection coefficient at 3.5 GHz with around -

0.32 dB, which means 96.4% impinged wave is reflected back toward the desired direction. The magnitude for the 0101 configuration was around -0.46 dB, with an efficiency of 94.78%, reflecting the incoming wave. Fig. 11 and Fig. 12 depict the graphs of the reflection magnitude of Model 2. It has been noted that this model's 0000 setup likewise results in a similar reflection coefficient, approximating -0.32 dB. Several designs, such as configurations 0001, 0010, 0100, 1000, 1010, and 1110, with magnitudes higher than -0.5 dB, provide about 90%.

The best designs are determined by comparing the response for each configuration based on the reflection magnitude and its phase at 3.5 GHz. The parameter's primary concentrate is having the maximum reflection magnitude and the greatest phase difference between the ON and OFF states. By tuning the ON/OFF states, the IRS is able to independently control the phase of the reflected signals.

The comparison between the two models is based on the reflection coefficient, where both model 1 and model 2 exhibit the same magnitude of -0.32 dB. However, the performance differences between the two models become evident when they are in the ON state. Model 1 demonstrates its optimal ON state configuration as 0101, with a reflection magnitude of -0.46 dB. On the other hand, model 2's best ON state is represented by the configuration 0001, featuring a reflection magnitude response of -0.38 dB. Furthermore, the 0001 configuration of model 2 outperforms model 1 in terms of phase difference. The phase difference between the ON and OFF states of model 1 and model 2 is approximately 4^{o} and 325^{o}, respectively. In summary, the configurations 0000 (OFF state) and 0001 (ON state) of model 2 exhibit superior performance in the IRS system, as indicated by the results analysis.

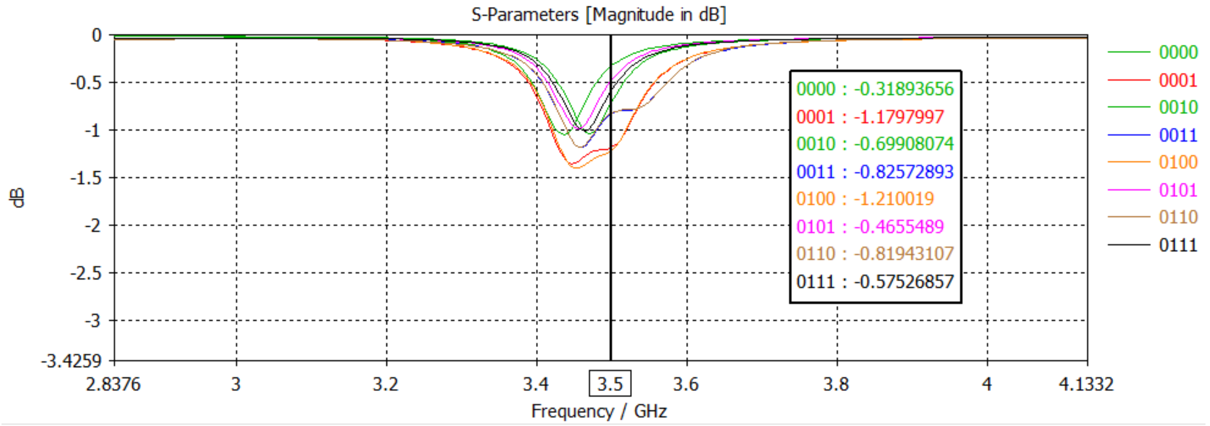


Fig. 9. Reflection magnitude response Model 1 (0000 to 0111)

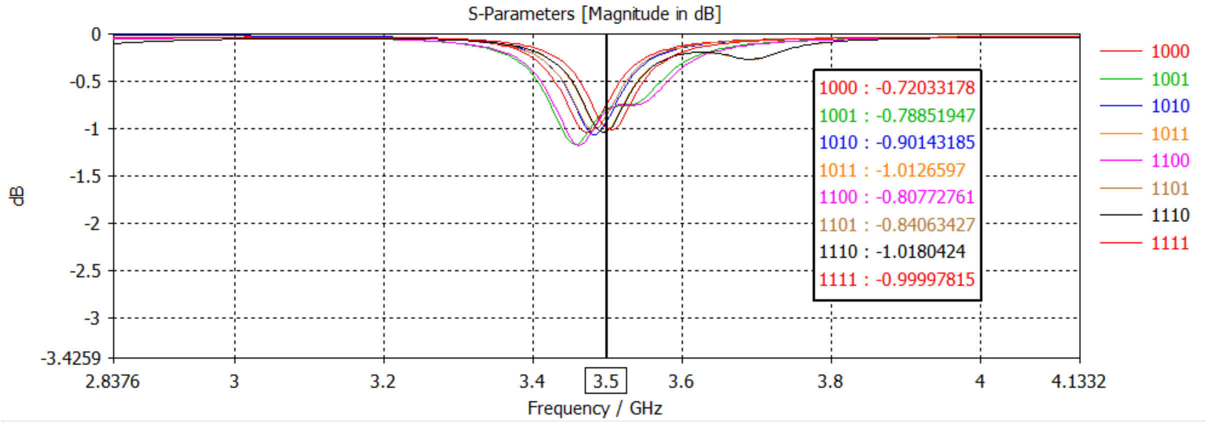


Fig. 10. Reflection magnitude response Model 1 (1000 to 1111)

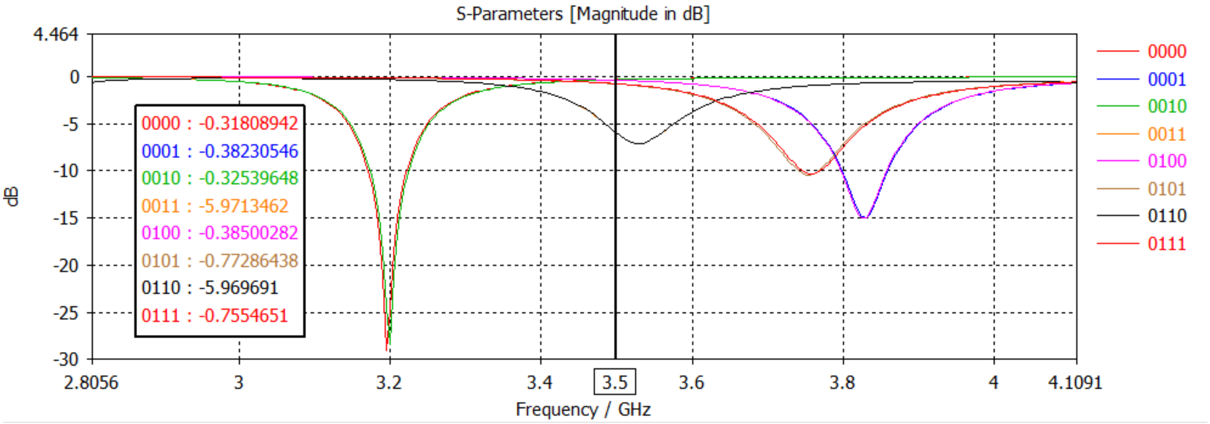


Fig. 11. Reflection magnitude response Model 2 (0000 to 0111)

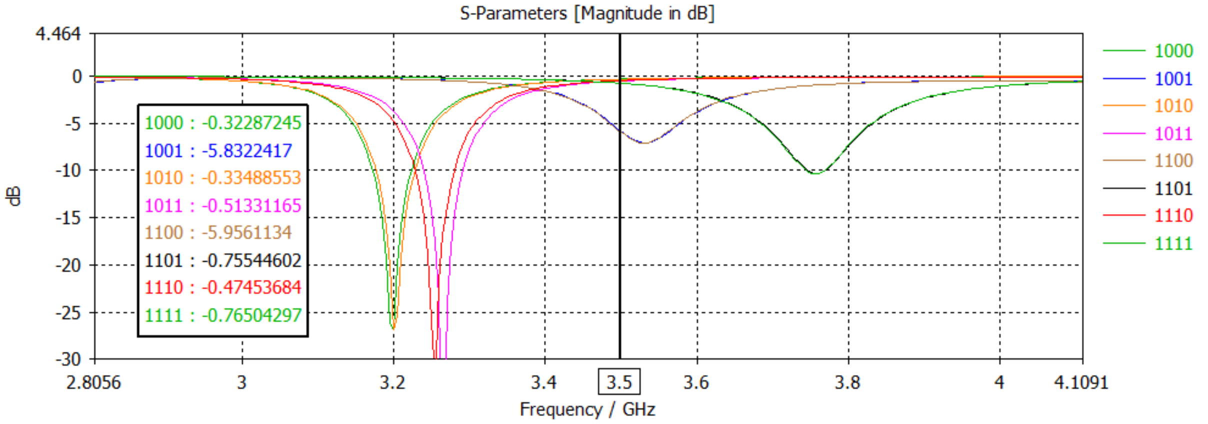


Fig. 12. Reflection magnitude response Model 2 (1000 to 1111)

Fig. 13-14 and 15-16 illustrate the phase response of Model 1 and Model 2, respectively. The phase of the configuration 0000, representing the 'OFF' state, is measured at -329.73°. To achieve a higher phase difference, comparisons were made between each configuration and the 0000 state. Configurations 0001, 0011, 0100, 0110, 1001, and 1100 exhibit a reflection range of 324°. A larger phase range correlates with improved performance of the IRS, as it allows for more precise control over the reflected signals. Table 4 provides a comprehensive summary of the performance comparison between Model 1 and Model 2, focusing on the reflection coefficient and phase response. On average, Model 1 demonstrates an S11 magnitude of -0.82 dB and a phase of 18.7°. In contrast, Model 2 shows an average S11 magnitude of -1.86 dB and a phase of -129.4°. This indicates that while Model 1 has a superior magnitude of S11, suggesting better impedance matching and lower reflection loss, Model 2 excels in achieving a larger phase difference in the reflected signal. Therefore, Model 2, with its significant phase difference, is better suited for applications requiring precise phase manipulation. In contrast, Model 1's performance in terms of reflection coefficient makes it ideal for scenarios prioritizing signal strength and stability.

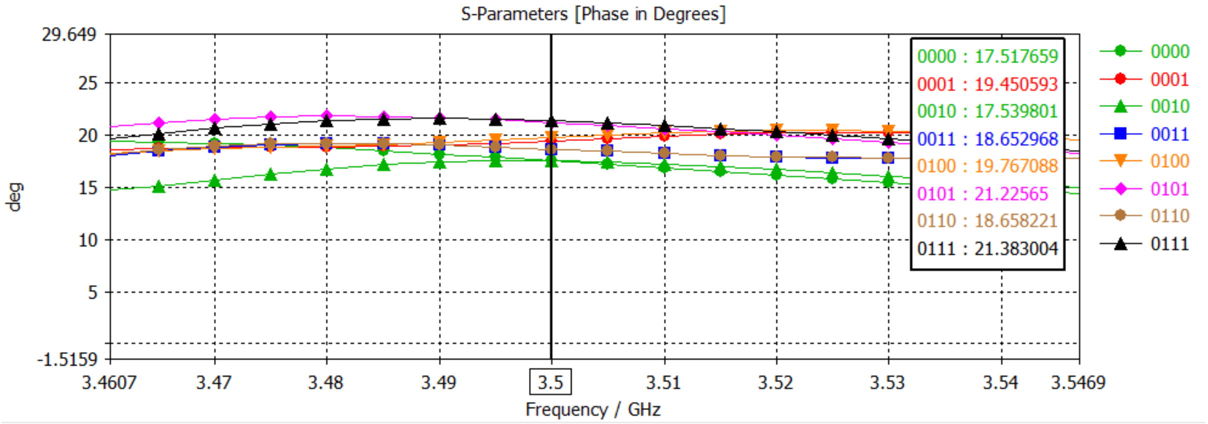


Fig. 13. Unwrap phase response Model 1 (0000 to 0111)

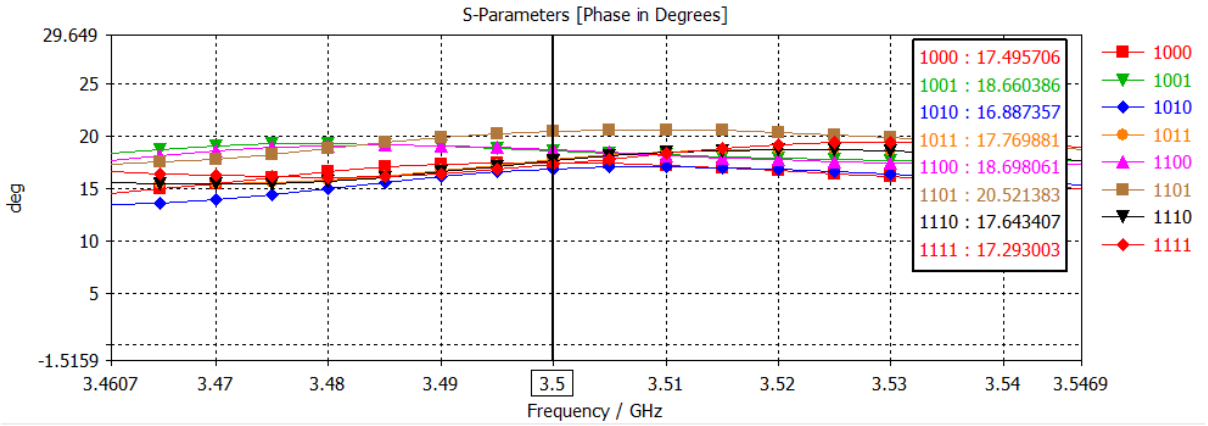


Fig. 24. Unwrap phase response Model 1 (1000 to 1111)

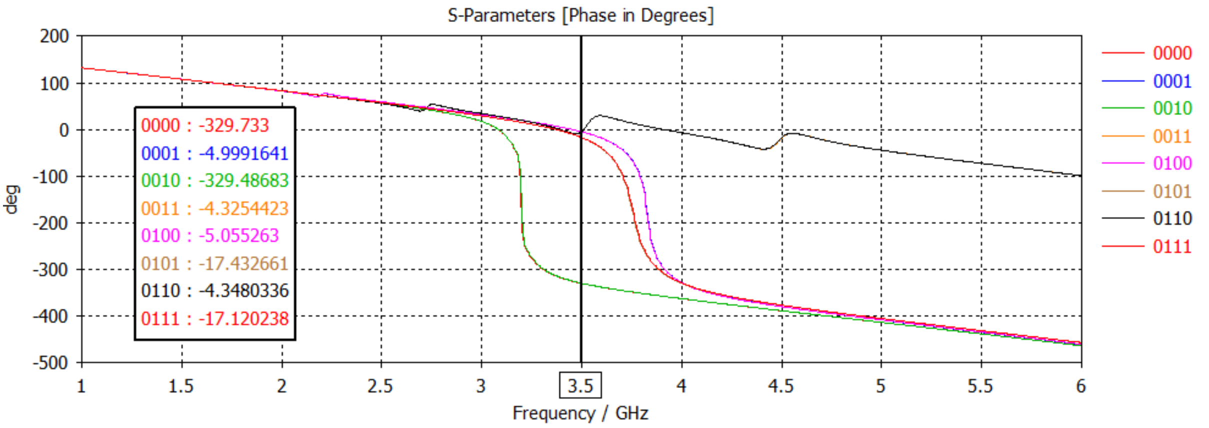


Fig. 35. Unwrap reflection phase response Model 2 (0000 to 0111)

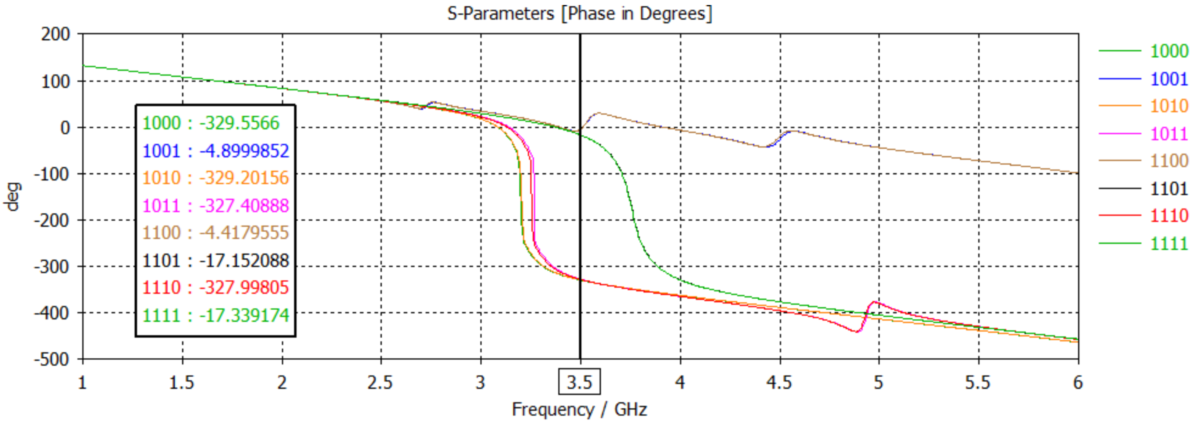


Fig. 46. Unwrap reflection phase response Model 2 (1000 to 0111)

Table 4. Comparison of Model 1 and Model 2 for the ON/OFF states.

Model 1 Configuration	Magnitude [dB]	Phase [º]	Model 2 Configuration	Magnitude [dB]	Phase [º]
0000	-0.3189	17.517	0000	-0.3181	-329.733
0001	-1.1180	19.451	0001	-0.3823	-4.999
0010	-0.6990	17.540	0010	-0.3254	-329.487
0011	-0.8257	18.653	0011	-5.9713	-4.325
0100	-1.2100	19.767	0100	-0.3850	-5.055
0101	-0.4655	21.226	0101	-0.7729	-17.433
0110	-0.8194	18.658	0110	-5.9697	-4.348
0111	-0.5753	21.383	0111	-0.7555	-17.120
1000	-0.7203	17.496	1000	-0.3229	-329.557
1001	-0.7885	18.660	1001	-5.8322	-4.900
1010	-0.9014	16.887	1010	-0.3349	-329.201
1011	-1.0127	17.770	1011	-0.5133	-327.409
1100	-0.8077	18.698	1100	-5.9561	-4.418
1101	-0.8406	20.521	1101	-0.7554	-17.152
1110	-1.0180	17.643	1110	-0.4745	-327.998
1111	-1.0000	17.293	1111	-0.7650	-17.339

In Fig. 17, the graph illustrates the phase difference concerning the number of bits for both Model 1 and Model 2. Notably, it is evident that Model 1 exhibits a constant and lower phase difference when compared to Model 2. The comparison confirms that Model 2 surpasses Model 1, as it presents a more substantial phase variation, an average of -129.4°, in contrast to 18.7° for Model 1. Therefore, Model 2 has been selected for the fabrication process in the OFF state due to its more compact design compared to Model 1, favorable S11 magnitude, and a broad range of S11 phase variations.

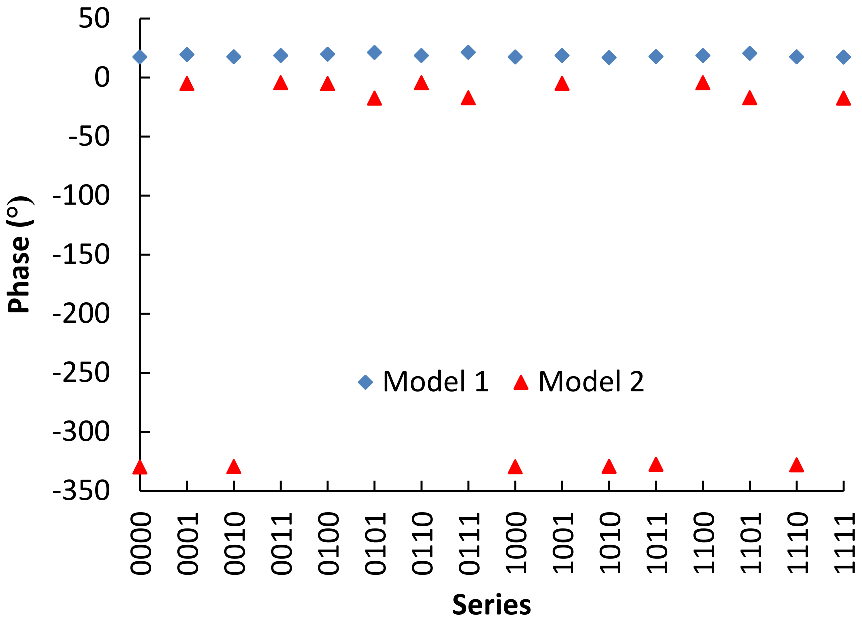


Fig. 17. Comparison of phase shift versus no. of bits between Model 1 and 2.

Table 5 compares the simulation results of Model 1 and Model 2 together with the previous work by [17] for the Off-state. The work by [17] does not provide a numerical study for the ON state. It is observed that for the OFF state (0000), Model 2 has better magnitude and phase variation of S11 at 3.5 GHz.

Table 5. The comparison of proposed work with [17].

Reference	**Dimension (mm)**	**Magnitude of S11(dB)**	**Phase of S11 (°)**	**On/Off State**
[17]	42 x 42	-1.6	-150	No
Model 1 (**this work**)	42 x 42	-0.3189	17.517	Yes
Model 2 (**this work**)	21 x 21	-0.3181	-329.733	Yes

4.3. Fabrication and Measurement

An IRS prototype for the OFF state has been fabricated and demonstrated as a reflecting surface for a horn antenna based on Fig. 7. Fig. 18 has shown that there is an increase to the S11 of the horn antenna at 3.475 GHz from -21.72 (6.73 mW) to -27.27 dB (1.87 mW). The improvement is calculated at around 72.2%. In addition, it illustrates that the resonance frequency of the horn antenna remains constant despite the presence of IRS. It proves that the proposed IRS is a good reflector that improves the matching condition of the horn antenna.

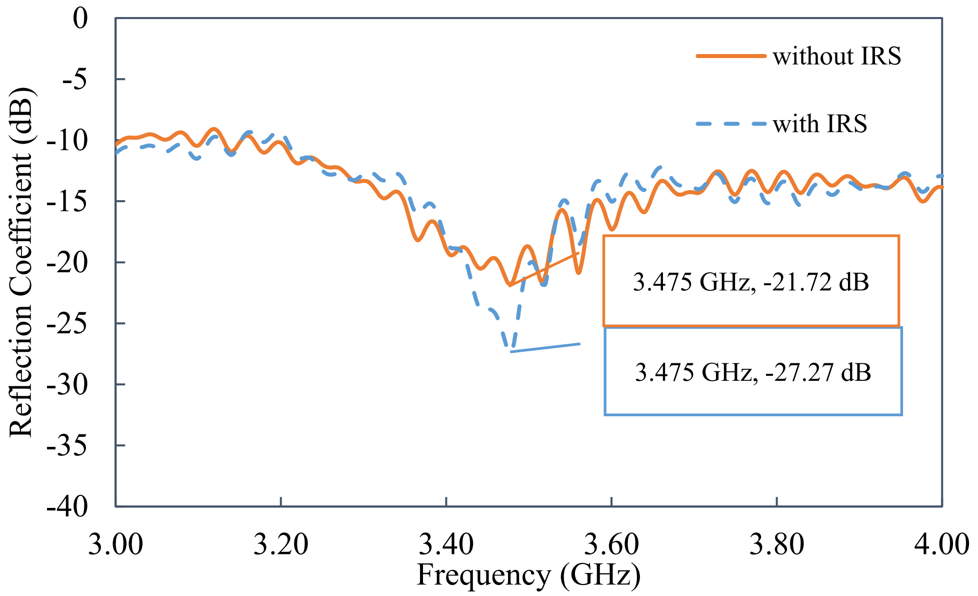


Fig. 18. The measured reflection coefficients of horn antenna with and without reflecting surface at OFF state.

5. CONCLUSION

In this research, an IRS was developed to operate at 3.5 GHz, considering both the magnitude and phase of the reflection coefficients. A circular patch with a ring metasurface was successfully designed by comparing two models with varying sizes. The unit cell dimensions for Model 1 and Model 2 were 42 mm x 42 mm and 21.4 mm x 21.4 mm, respectively. Each design featured 16 different ON/OFF configurations to manipulate the phase of reflected signals. Model 1 demonstrated superior performance with an average of -0.82 dB, compared to -1.86 dB for Model 2, across the 16 ON/OFF states. Regarding phase, Model 2 exhibited a larger variation, averaging -129.4°, in contrast to 18.7° for Model 1. However, for the OFF (0000) state, Model 2 has been selected due to smaller size, high S11 magnitude and larger phase variation for array fabrication. When the IRS was applied to a horn antenna, it resulted in a significant 72.2% improvement in the matching condition of the horn antenna. Future works include analysis of equivalent circuits for the proposed structure and extensive measurement study of reflection coefficients.

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