

Design of a Reconfigurable Intelligent Reflecting Surface (IRS) based Frequency Selective Surface at 3.5 GHz using PIN Diodes

P Kalaivani

Department of ECE

KIT-Kalaighnarkarunanidhi Institute of
Technology, Coimbatore, India
pkalai.ece@gmail.com

Dr.Sapna BA, M-IEEE

Department of ECE

PSG Institute of Technology and
Applied Research, Coimbatore, India
sapna79ece@gmail.com

Dr.K.Ramasamy

Department of ECE

KIT-Kalaighnarkarunanidhi Institute of
Technology, Coimbatore, India
ramasamy10366@gmail.com

Umesh Krishna A

Department of ECE

KIT-Kalaighnarkarunanidhi Institute of
Technology, Coimbatore, India
kit27.ece114@gmail.com

Sriramkumar D

Department of ECE

KIT-Kalaighnarkarunanidhi Institute of
Technology, Coimbatore, India
kit27.ece108@gmail.com

Sathish Kumar S

Department of ECE

KIT-Kalaighnarkarunanidhi Institute of
Technology, Coimbatore, India
kit27.ece312@gmail.com

Abstract -- In this paper, a design and simulation of a reconfigurable Intelligent Reflecting Surface (IRS) based Frequency Selective Surface (FSS) working at 3.5 GHz is introduced for 5G communication below 6 GHz. In the introduced design, a compact and interconnected H slot unit cell is adopted in which FR4 substrate is used as a substrate material and copper as the conducting material. For designing the reconfigurable IRS, two and four diodes are incorporated in the structure of the FSS. The IRS approach has been introduced to help achieve dynamic manipulation of the reflected electromagnetic waves by diode switching. The simulation has proved that there is a phase shifting amounting to about 13° using the four-diode IRS while there is a phase shifting amounting to only 6° using the two-diode IRS. Thus, the proposed structure is considered to be cost-effective, easy to operate, and very efficient in controlling adaptive electromagnetic waves in 5G wireless communications and IRS-based communication systems.

Keywords— Frequency Selective Surface, Pin Diode, Reconfigurable IRS, 3.5 Ghz, 5G, Phase Shift, H-Slot.

I-INTRODUCTION

Development in wireless communications systems, especially the development of fifth generation (5G) communications networks, requires development of electromagnetic structures with the ability to achieve signal control, perform well, and be flexible. In the various frequencies used by 5G networks for communication purposes, one that stands out is the 3.5 GHz sub-6 GHz frequency because of its balance of coverage and capacity.

Frequency Selective Surfaces (FSSs) consist of conductive periodic arrays placed over dielectric substrates, which act as electromagnetic spatial filters either passing or blocking specific frequency ranges. As a result of their filtering properties, Frequency Selective Surfaces (FSSs) have received significant attention in antennas, electromagnetic shielding, and wireless communication systems. Many researchers have studied various designs of FSSs in order to

enhance performance. In particular, Nguyen and Seo [1] presented a stop band FSS design using genetic algorithms to increase gain. Second order dual band FSSs with selective surface properties were proposed by Zhang et al. [2]. A wideband FSS to improve the gain of microstrip antennas was designed by Tiwari et al. [3], and the analysis and design of Frequency Selective Surfaces for Telecommunication applications were proposed by Afzal et al. [4]. A miniaturized quad stops band FSS based on convoluted and interdigital strips were designed by Dong et al. [5]. Moreover, a single layer bandstop FSS with wide angular stability was proposed by Gu et al. [6], and a monolayer FSS was designed by Chatterjee et al. [7] for wideband shielding and angular stability applications. Coutinho et al. [8] have proposed cascade FSS structures with Matryoshka type geometry to achieve better frequency response characteristics. Troudi et al. [9] proposed the integration of FSS structures with MIMO antennas for improving IoT and V2V communication characteristics. Costa et al. [10] have proposed the analysis and design of ultra-thin electromagnetic absorbers based on resistively loaded high impedance surfaces. Yang and Wang [11] have proposed a new class of FSS with enhanced bandwidth characteristics. Yao et al. [12] developed an FSS structure to improve antenna and wireless propagation characteristics. The tunable FSS with PIN diodes was proposed by Kiani et al. [13] with tunable frequencies enabled through the process of electronic switching. The theory behind the FSS analysis and design has been presented by Munk [14], and this work serves as an important theoretical base for the field. Liu et al. [15] studied stereometamaterials with unique electromagnetic properties.

Traditional FSS architectures exhibit good frequency-selective characteristics but cannot be configured. To address this challenge, a small-sized interconnected H-slot FSS cell designed for the implementation of IRS in 5G wireless

networks operating at 3.5 GHz is suggested. The design of the proposed cell uses FR4 substrate material and copper as the conducting element, where two-PIN diode and four-PIN diode schemes have been employed for reconfiguration.

II. Proposed Work

In this research work, a design and analysis of a reconfigurable Intelligent Reflecting Surface (IRS) Frequency Selective Surface (FSS) unit cell at 3.5 GHz for 5G communication applications is described. The designed unit cell employs a small size interconnected H-slot geometry on an FR4 substrate, which is illustrated in Fig. 1. The values of relative permittivity and thickness for the substrate are fixed as $\epsilon_r = 4.4$ and $d = 1.6$ mm respectively. To enhance the electrical conductivity, copper has been selected as the metallic material for the designed FSS unit cell structure. The design is aimed at achieving electromagnetic wave control, stable frequency selective behaviour, and controllable phase response at the specified resonance frequency of 3.5 GHz.

In order to study the characteristics of the proposed unit cell, electromagnetic simulations were performed by applying periodic boundary conditions along with Floquet port excitation. The S11 and S21 scattering parameters were measured to determine the resonance frequency and to study the filtering properties of the unit cell. Additionally, the behavior of the unit cell was also analyzed considering the phase characteristics of the simulation results. The idea of IRS was integrated into this design whereby the FSS unit cell would help to steer electromagnetic waves dynamically through switching operations. The placement of PIN diodes in the H-slot FSS occurs at crucial junction points, where surface current density is most prominent, for the reason of obtaining frequency reconfiguration. Various electromagnetic responses occur due to the variation in the states of the PIN diodes ON/OFF, leading to a change in the current flow and consequently an effective electrical length of the FSS unit cell. In the ON position, the PIN diode is equivalent to a short circuit, providing a constant current path through the FSS and hence giving rise to certain phase responses. In the OFF state, the diodes behave as open circuits, interrupting the current flow and altering the resonant behaviour of the unit cell.

The Performance evaluation of the suggested FSS is carried out based on analysis of the scattering parameters and the phases at varying states of switch ON/OFF. From this analysis, it is found that the suggested FSS design is able to provide controllable frequency reconfiguration. Hence, this design can be adopted for reconfigurable intelligent reflecting surfaces (IRS) and adaptive wireless communications in the 3.5 GHz 5G technology band.

Fig 1. Shows the proposed unit cell structure which works for the resonant frequency of 3.5GHz

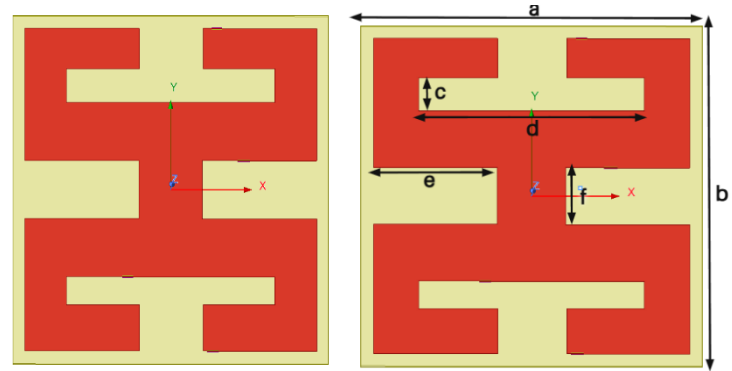


Fig. 1. Geometry of the proposed antenna with the key dimensional parameters: aa and bb denote the overall width and height, while cc, dd, ee, and ff represent the corresponding slot and structural dimensions.

Table 1. Dimensions of the designed unit cell

Parameter	Value
a	50 mm
b	54 mm
c	4 mm
d	36 mm
e	20 mm
f	10 mm

Table 1. contains the optimized parameters of the IRS unit cell intended to operate at 3.5 GHz, along with their geometric parameters.

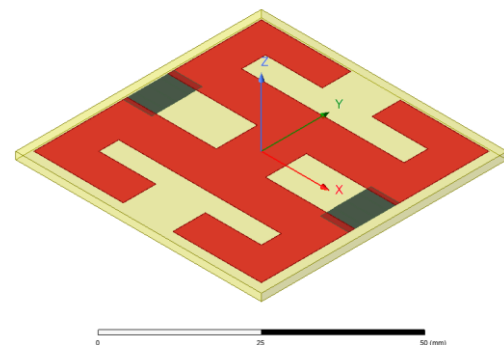


Fig 2. Integrated 2 Pin diode in a unit cell

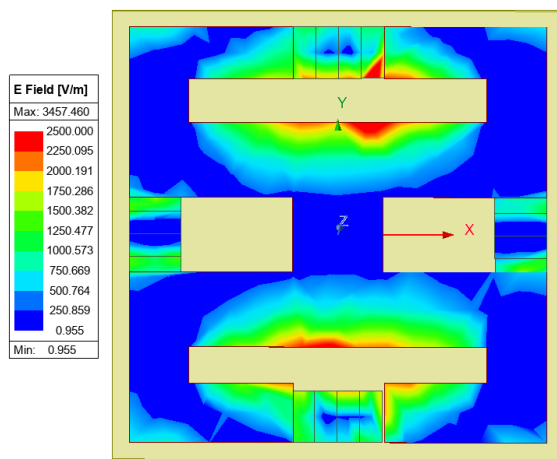


Fig 8. E Field of 4 Pin ON condition

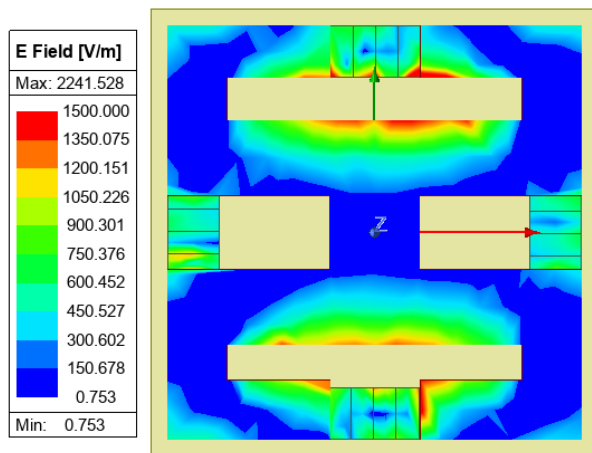


Fig 9. E Field of 4 Pin OFF condition

The distribution of electromagnetic fields with four PIN diodes in ON and OFF positions is illustrated by Figs. 8 and 9, respectively. It is clear from the figures that there is an observable difference in the distribution of electric fields during switching. It proves that the proposed design works in various situations depending upon the switching pattern.

Figures 8 & 9 show the distribution of the electric field in the unit cell of the proposed metamaterial in both the ON and OFF configurations of the two-PIN diodes and four-PIN diodes. It is clear from these figures that as the ON/OFF configuration of the PIN diodes changes, there occurs a change in the current distribution in the circuit, which results in change in electromagnetic field distribution.

The use of extra two PIN diodes in the four PIN diodes setup results in more current pathways that pass through the resonator hence, the enhancement in the electromagnetic fields is achieved by increasing the electromagnetic field confinement. This is facilitated by the increase in current density.

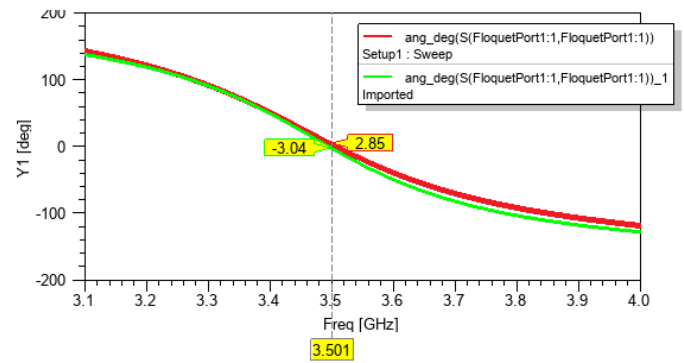


Fig.10 Phase shift of using 2 Pin diode

A phase response for the proposed Intelligent Reflecting Surface (IRS) element was analyzed for both ON and OFF states of the PIN diodes. Switching between these states changes the current distribution within the interconnected H-slot structure, resulting in a variation in phase response. In fig 10. the obtained results show that the phase difference for the 2 PIN diode configuration is approximately 5° , indicating basic reconfigurable behavior of the structure. This phase variation demonstrates the ability of the proposed IRS element to provide controllable electromagnetic response through electronic switching, making it suitable for applications such as beam steering, adaptive wireless communication, and 5G systems.

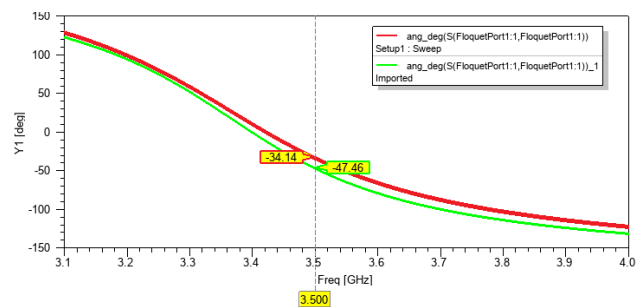


Fig.11 Phase shift of using 4 Pin diode

Fig 11. shows the phase response characteristic of the output of the unit cell based on the 4-PIN diode configuration. The changes in phase response characteristic occur due to changes in the current distribution and electrical length of the interconnected H slot when the PIN diodes toggle their states from ON to OFF state and vice versa. Simulation analysis reveals that the phase difference between the two states of operation is about 13° .

In case of the 2-PIN diodes structure, there is an approximate phase difference of 5° between the ON and OFF cases. On the other hand, the structure using the 4-PIN diodes offers an increased phase difference of about 13° . From this information, we observe that the use of more PIN diodes allows greater control of the electromagnetic response of the proposed IRS element.

IV. CONCLUSION

In this research work, a reconfigurable interconnected H-slot IRS unit cell with a frequency of operation of 3.5 GHz was proposed and modeled using both 2-PIN-diode and 4-PIN-

diode structures. Simulated results indicated the presence of resonant frequencies at the target frequency and confirmed that the structure is reconfigurable via PIN diode switches. Electromagnetic properties were investigated using electric field distribution and S-parameter analysis. Results indicated that the 4-PIN-diode configuration had better performance concerning electromagnetic control and reconfigurability than the 2-PIN-diode configuration. Phase shifts were measured to be about 5° and 13° for the 2-PIN-diode and 4-PIN-diode configurations, respectively. The results confirmed the efficiency of the IRS structure for adaptive wireless communications.

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