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Phase shifter intelligent reflective surface design for 2.4 GHz

2.4 GHz için faz kaydırıcı akıllı yansıtıcı yüzey tasarımı

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Abstract

In this study, an intelligent reflective surface (IRS) design consisting of a 3x4 patch surface that intentionally changes the phase angles of incoming signals for the 2.4 GHz operating frequency is presented. In the design of this IRS, FR-4 is chosen as the dielectric material, and copper is used to create both the reflecting elements and the ground plane. Phase shifting characteristic is achieved by using varactor diodes on the designed two-dimensional surface. In order to test the behaviour of the IRS, a horn antenna is also designed to be used as a source with the ANSYS HFSS (v21) program. The obtained results are presented in terms of return loss and gain values of the IRS. The results of the simulations reveal that the phase angles of the incoming signals can be adjusted as expected by changing the capacity values of the varactor diodes modelled by their equivalent circuits on the IRS.

Keywords: Intelligent reflective surface (IRS), varactor diode, phase shifter, HFSS.

Öz

Bu çalışmada 2.4 GHz çalışma frekansı için 3x4 yama yüzeyinden oluşan gelen sinyallerin faz açılarını değiştiren akıllı yansıtıcı yüzey (IRS) tasarımı sunulmuştur. IRS tasarımda dielektrik malzeme olarak FR-4, yansıtıcı yüzeylerde ve toprak düzlemde bakır malzeme seçilmiştir. IRS tasarımında varaktör diyot kullanılarak tasarıma faz kaydırıcı özellik kazandırılmıştır. IRS tasarımını ve tasarımın faz kaydırıcı özelliğini test etmek için gerekli kaynak boynuz anten ve varaktör diyotlar ANSYS'in HFSS (v21) programı ile tasarlanmış ve simüle edilmiştir. Simülasyon sonucunda IRS'e gelen sinyallerin IRS üzerinde bulunan varaktör diyot eşdeğer devrelerinin kapasite değerleri değiştirilerek faz açılarının değiştirilebildiği ortaya konulmuş ve tasarıma ait geri dönüş kayıpları ve kazanç değeri verilmiştir.

Anahtar kelimeler: IRS, Varaktör diyot, Faz kaydırma, HFSS.

1 Introduction

In recent years, it has become difficult to achieve spectrum efficiency in wireless communications with the use of ultra-dense networks (UDN). In addition, it is known that network energy consumption and hardware costs are important problems that need to be taken into account in practical applications of massive multiple-input multiple-output (M-MIMO) systems and millimeter wave (mmWave) communications [1]. These systems require costly radio frequency (RF) chains and complex signal-processing techniques for efficient communication. On the other hand, adding too many active components, such as small cell base stations and relays, to wireless networks causes a more serious interference problem. Therefore, it is necessary to research to find both spectral and energy-efficient techniques with low hardware costs and to realize sustainable fifth generation (5G) wireless networks and beyond [2]. In order to achieve these challenging goals, intelligent reflective surface (IRS) technology is proposed as a promising, environmentally friendly, and cost-effective solution [3].

Passive reflective surfaces, which are the basis of the IRSs, have so far been used in various applications such as radar systems, remote sensing, and satellite relaying, but have rarely been used in wireless mobile communications. This is mainly because traditional reflective surfaces only have fixed phase shifters that cannot address dynamic wireless channels caused by the users' mobility. However, recent advances in micro-electro-mechanical systems (MEMS) and meta-materials have made it possible to reconfigure reflective surfaces by controlling phase shifters in real time dynamically, thus enabling their use in wireless mobile communications [4].

IRS, as a two-dimensional structure with a large number of passive reflector elements, is envisioned as one of the revolutionary technologies to provide both energy-efficient and intelligent wireless communications [5]. In fact, they basically consist of: *i)* a substrate made of dielectric material, *ii)* conductive ground and reflective microstrip patch layers, *iii)* semiconductor elements such as PIN or varactor diodes to process incoming signals, and *iv)* a microcontroller that controls these semiconductor elements [6]. The use of RISs in different scenarios has been discussed in the literature, such as data transfer between objects in IoT networks, positioning purposes, transferring signals to blind spots where signals cannot reach, sending jamming signals to unauthorized listeners other than the receiver in systems where secure communication is prioritized, etc. [7-12].

For instance, it was stated in [13] that highly efficient spectrum sharing can be achieved with the IRS to solve the problem of heavy data traffic on wireless networks in indoor

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environments such as conference halls and shopping malls. It was also shown that reducing the density in the RF spectrum is possible by shifting the phases of the incoming signals without making any hardware or software changes in the transmitters and/or receivers.

In another study [14], it was aimed to create a wireless network powered by a self-sustainable IRS with energy harvesting ability, similar to RF-powered backscatter-assisted relay communication. In this network, the IRS initially operates in energy harvesting mode to charge the capacitors within a specific time interval. Once the capacitors are charged, it works in reflection mode by adjusting phase shifts to assist in signal transfer from the access point to the receiver. In this way, a self-sufficient and environmentally friendly IRS that does not consume energy was presented.

Considering the above-mentioned points, an IRS is designed for this work and is intended to be used in environments where data traffic is dense in the target frequency band. The aim is to create a strong line-of-sight (LOS) path between the transmitter and the receiver by simply shifting the phase angles of the signals coming from the transmitter, thus steering the signals without any hardware modifications. Noting that the mid-band spectrum between 1 GHz and 6 GHz is considered perfect for 5G communications since it can carry a lot of data while traveling significant distances, the contributions of this study can be summarized as follows:

i) A design environment is created using the ANSYS HFSS (v21) program and a phase shifter IRS is designed for the operating frequency of 2.4 GHz. In this environment, a horn antenna operating in the same frequency band as the transmitting antenna is also designed.

ii) The phase angles of the signals coming from the horn antenna are consciously manipulated by using varactor diodes, which are assumed to be controlled by a microcontroller on the IRS.

iii) The reflection phase angles of the IRS are calculated at 2.4 GHz according to the capacity values of the varactor diodes in the 0-5 Volt range, The obtained results show that the reflection phases of the designed IRS can be arranged between -177.68° to 42.45°.

iv) The return loss and the gain of the IRS are also provided to provide more insights about the proposed design.

The details of the design and the obtained simulation results are presented in the following sections.

2 Materials and methods

This section is divided into three subsections. In the first one, the design parameters of the IRS are presented. In the second section, the features and design parameters of the source horn antenna that feeds the IRS are given. In the last section, the simulation environment is defined.

2.1 Phase shifter IRS design

In the IRS design to operate at 2.4 GHz, copper was chosen for the reflecting patches and ground plane, while FR4 material with a dielectric constant of Ɛr= 4.4 and thickness of h_a= 1.6 mm was chosen for the dielectric substrate. The proposed IRS design is given in Figure 1, in which the orange regions show copper microstrip patches and the green regions represent FR4 substrate. As shown in this figure, the RIS consists of a total of 12 reflective patches arranged in a 3x4 pattern. The sizes of the substrate used in the design is given with Wa = 250 mm width and La = 187.5 mm length. The copper ground plane on the back side of the reflecting surface is also the same size as the substrate material.

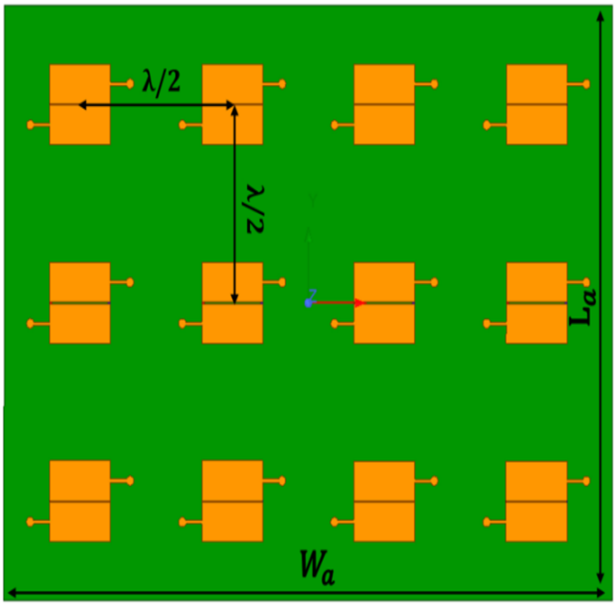

Figure 1. The proposed IRS design

The reflective patch design realized in the HFSS program is shown in detail in Figure 2. Here, the varactor diodes located between two rectangular patches and connecting them, are represented by red and blue colors. The width and length of the patch are denoted by W_y and L_y, respectively. Additionally, the length of the space between the two patches is represented by *d*, while the width and length of the connection points to be used to feed the varactor diodes are shown by W_1 and L_1, respectively. The diameter of the circular region in Figure 2 is indicated as *R*. All these design parameters of the proposed IRS are given in Table 1.

Table 1. IRS design parameters

Reflective Surface Design Parameters	Symbol	Dimensions (mm)
Patch width	w_y	25
Patch length	L_y	25.5
Substrate width	w_a	250
Substrate length	L_a	187.5
Substrate thickness	h_a	1.6
The gap between the patches	d	0.5
Supply line length of varactor diode	L_1	6.14
Supply line width of varactor diode	w_1	1
Distance between the patches	λ_1	62.5
The diameter of the circular port	R	4

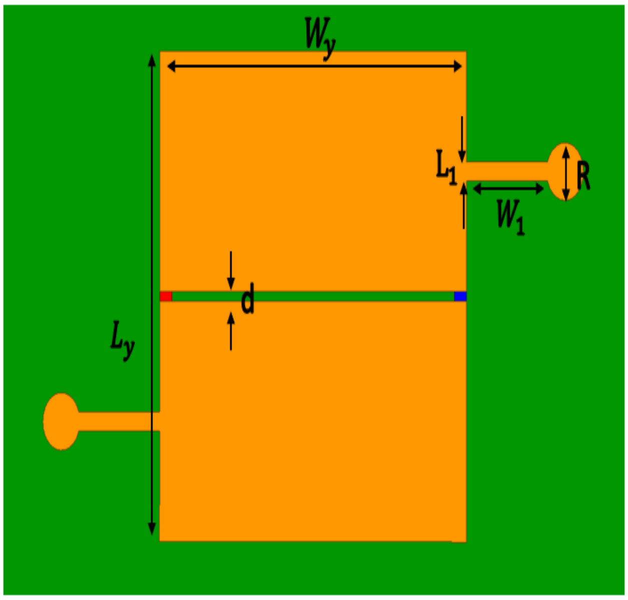

Figure 2. Detailed view of reflective surfaces

The distance between patches in reflecting arrays is directly related to the wavelength, represented by λ, depending on the operating frequency. Here, λ is given by

$$\lambda = \frac{c}{f} \tag{1}$$

in which c and f indicate the speed of light in vacuum, and the operating frequency, respectively. Using Equation (1) by considering the target operating frequency of 2.4 GHz, the distance between consecutive patches in the proposed design is set to λ/2 = 62.5 mm, as usual in the literature [15]. It is worth noting that a minimum distance of λ/2 between the elements ensures that the signals received from the antenna elements are almost independent of each other in rich scattering environments. Besides, keeping the distance around λ/2 helps to minimize unwanted sidelobes, and aliasing, thus improving the overall directivity.

To change the phase angle of the incoming signals, a total of 24 varactor diodes were used, assuming there were 2 in each reflector. Skyworks SMV1249-079LF model varactor diode with SC-79 case is modeled in HFSS by using its equivalent circuit given in data sheets. In order to control the capacity values of these varactor diodes, each diode pair is fed with a pulse-width modulation (PWM) signal produced in the range of 0-5 Volts. By changing the amplitude of the PWM signal, the capacity values of the varactor diodes are adjusted, and the phase angles of the incoming signals are manipulated. The capacitance values corresponding to the voltage values varying between 0-5 Volts with 0.5 Volt precision are given in Table 2 and visualized in Figure 3 based on the datasheet of the varactor diode model used in the proposed design [16].

2.2 *Source antenna design*

In this section, a horn antenna operating at 2.4 GHz frequency designed in HFSS program is presented as the source antenna to enable a simulation environment to examine the reflective feature of the proposed IRS.

The designed horn antenna mainly consists of two structures: a pyramidal horn part and a radiation box as shown in Figure 4. As can be seen here, the width, length, and height of the horn part are denoted by W_{h1}, W_{h2} and L_{h1}, respectively. Additionally, the width, length and height of the radiation box are indicated by W_{I1}, W_{I2} and L_{I1}, respectively. The red part at the bottom of the radiation box represents the wave port. The details on the parameters of the horn antenna design are given in Table 3.

Table 2. Capacity value of the varactor diode according to the applied reverse voltage

Reverse voltage value (V)	Capacity value (pF)
0	37.35
0.5	25.88
1	18.18
1.5	12.08
2	7.27
2.5	4.44
3	3.40
3.5	2.96
4	2.72
4.5	2.51
5	2.38

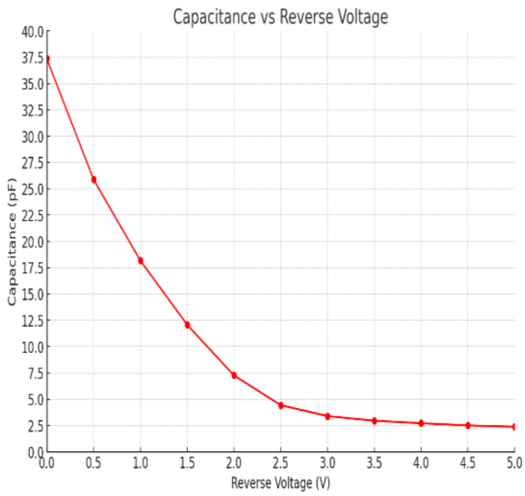

Figure 3. Capacitance vs Reverse Voltage

Table 3. Parameters of horn antenna

Horn antenna design parameters	Symbol	Dimensions (mm)
Horn width	w_{h1}	272
Horn length	w_{h2}	182
Horn height	L_{h1}	184.49
Radiation box width	W_{I1}	46
Radiation box length	W_{I2}	92
Radiation box height	L_{I1}	98

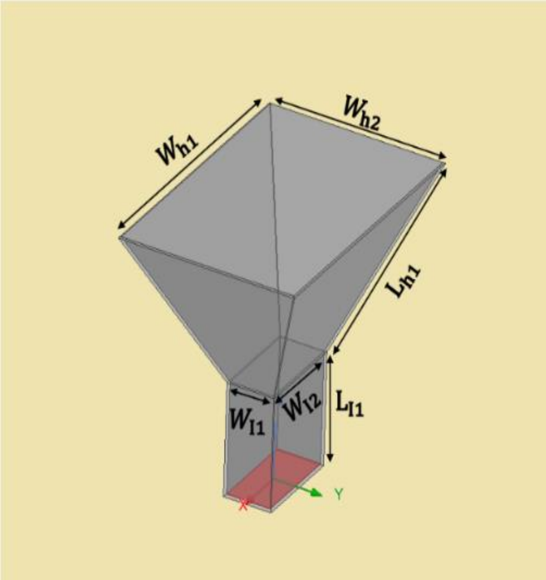

Figure 4. Horn antenna design

The return loss of the designed horn antenna is calculated, and a three-dimensional (3D) antenna gain graph is drawn through the simulations. The obtained results are provided in Figures 5 and 6. It can be seen in these figures that the return loss of the horn antenna is obtained as -36.2 dB and a gain of 14.2 dB is achieved at 2.4 GHz frequency. The standing wave ratio at 2.4 GHz frequency is also calculated via the simulations as 1.03. Hence, obviously, a producible high-gain directional source antenna is acquired as desired.

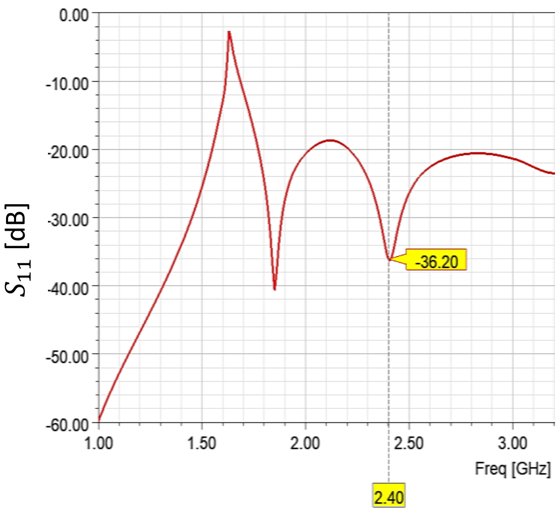

Figure 5. Return loss of the horn antenna

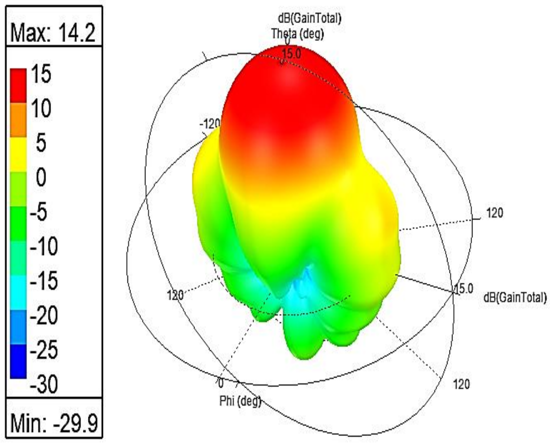

Figure 6. 3D gain graph of the designed horn antenna

2.3 Simulation design

In order to define the phase-shifting characteristics of the IRS, a simulation environment is generated in HFSS program consisting of the designed reflecting surface and the horn antenna as shown in Figure 7. As can be seen here, the horn antenna utilized as the source is assumed to be located 50 cm away from the reflecting surface with a 45° degree inclination.

All varactor diodes on the IRS are modeled by using the equivalent circuit of the chosen diode model given in Figure 8 to reflect varactor diode characteristics to the simulation environment and provide the same capacity value for each. The adjusted capacitance values in response to the reverse voltage to be applied between 0-5 Volts with a sensitivity of 0.5 Volts during the simulations are given in Table 2.

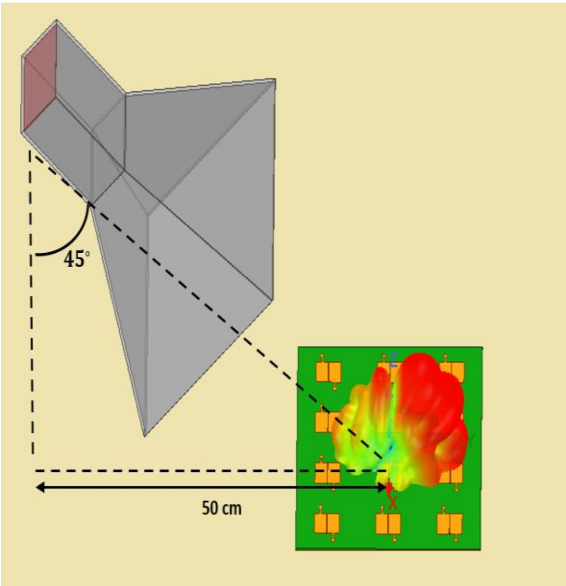

Figure 7. Simulation design

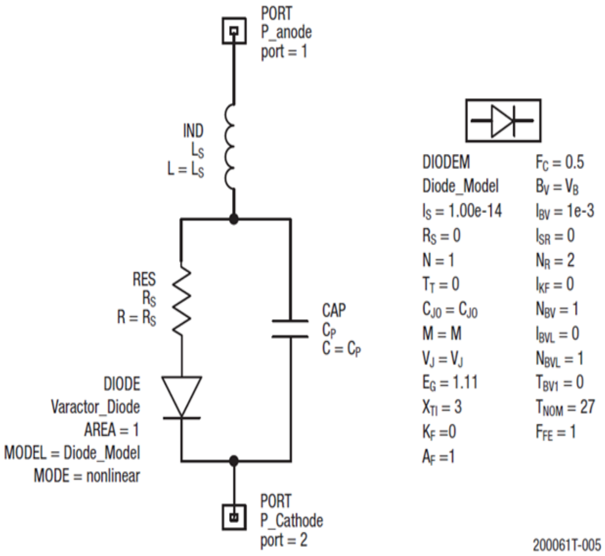

Figure 8. Equivalent circuit of the utilized varactor diode model

3 Results and discussions

In this section, various simulations are realized on the proposed IRS design, and the obtained results generated from the simulation environment given in Figure 7 are presented.

Firstly, the gain of the IRS is calculated for 2.4 GHz and a varactor diode capacitance value of 7.27 pF. The obtained 3D radiation pattern is introduced in Figure 9. Clearly, 11.6 dB gain at maximum is calculated for the IRS. Maximum gain values for other capacitance values of the varactor diode are also calculated to be an average of 11.6 dB.

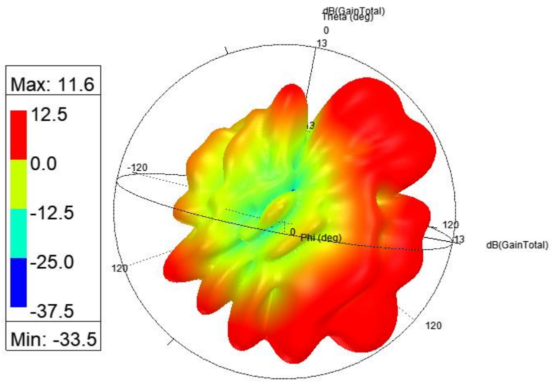

Figure 9. 3D gain graph of reflective surface

Next, the return loss of the IRS is calculated for varying capacitance values of the varactor diodes on the IRS design. The obtained return loss values for the frequency values between 1 to 3 GHz are given in Figure 10. Each of the eleven curves presented here specifies the values for predetermined capacity values given in Table 2, while the return losses corresponding to these values are shown in detail in Table 4. As seen from both Figure 10 and Table 4, the lowest return loss for 2.4 GHz is obtained as -55.90 dB with a capacity value of 2.38 pF when the varactor diode is fed with 5 Volts.

Lastly, the reflection phase angles of the IRS are calculated at 2.4 GHz according to the capacity values of the varactor diodes in the 0-5 Volt range, and the obtained results are included in Table 4. It is observed that the phase angles of the reflected signal change according to the capacity values of the varactor diode, and thus, the phase shifting characteristic is achieved for the IRS designed in this study. Figure 11 is also given to both visualize and extend this observation for the frequency values between 1.2 – 3 GHz

Table 4. Phase angles formed according to the capacity values of the varactor diode

Reverse voltage value (V)	Capacity values of varactor diodes (pF)	Return loss (dB)	Phase Angles (degree)
0	37.35	-38.40	-170.10
0.5	25.88	-39.21	-151.48
1	18.18	-39.39	-161.35
1.5	12.08	-30.45	-177.68
2	7.27	-45.72	42.45
2.5	4.44	-31.75	-99.41
3	3.40	-40.95	-63.36
3.5	2.96	-40.48	-68.80
4	2.72	-48.57	-71.03
4.5	2.51	-42.61	-71.33
5	2.38	-55.90	-146.63

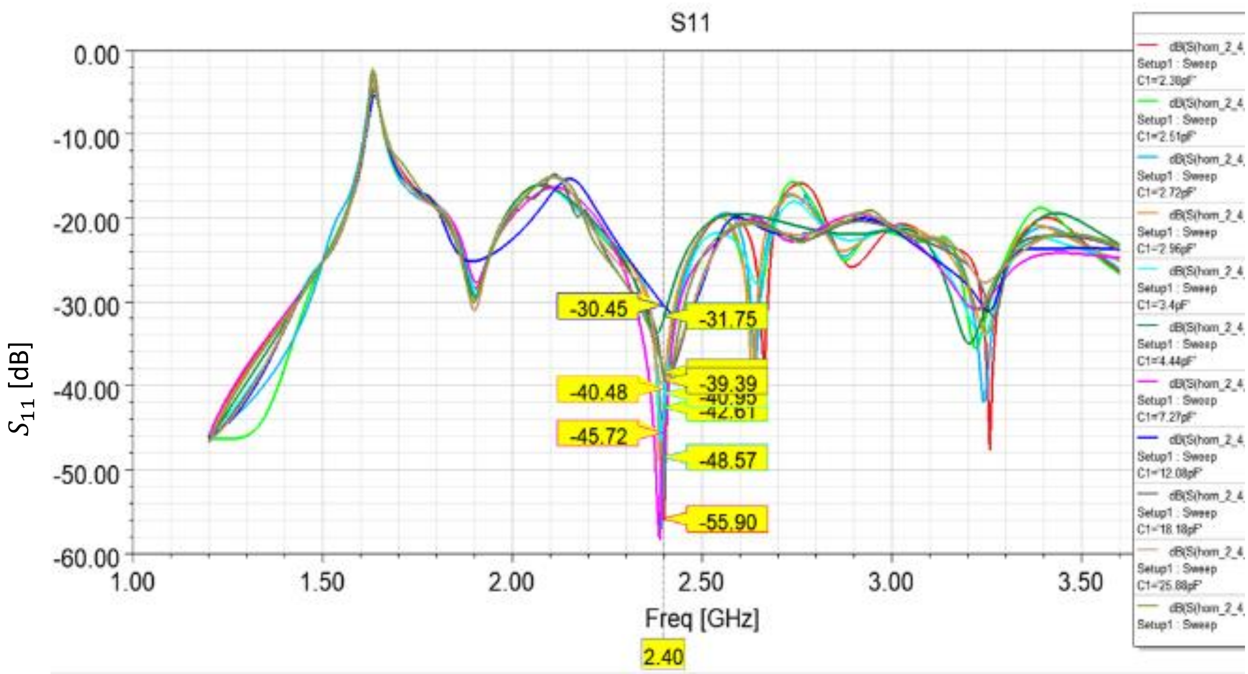

Figure 10. Return loss for different capacitance values.

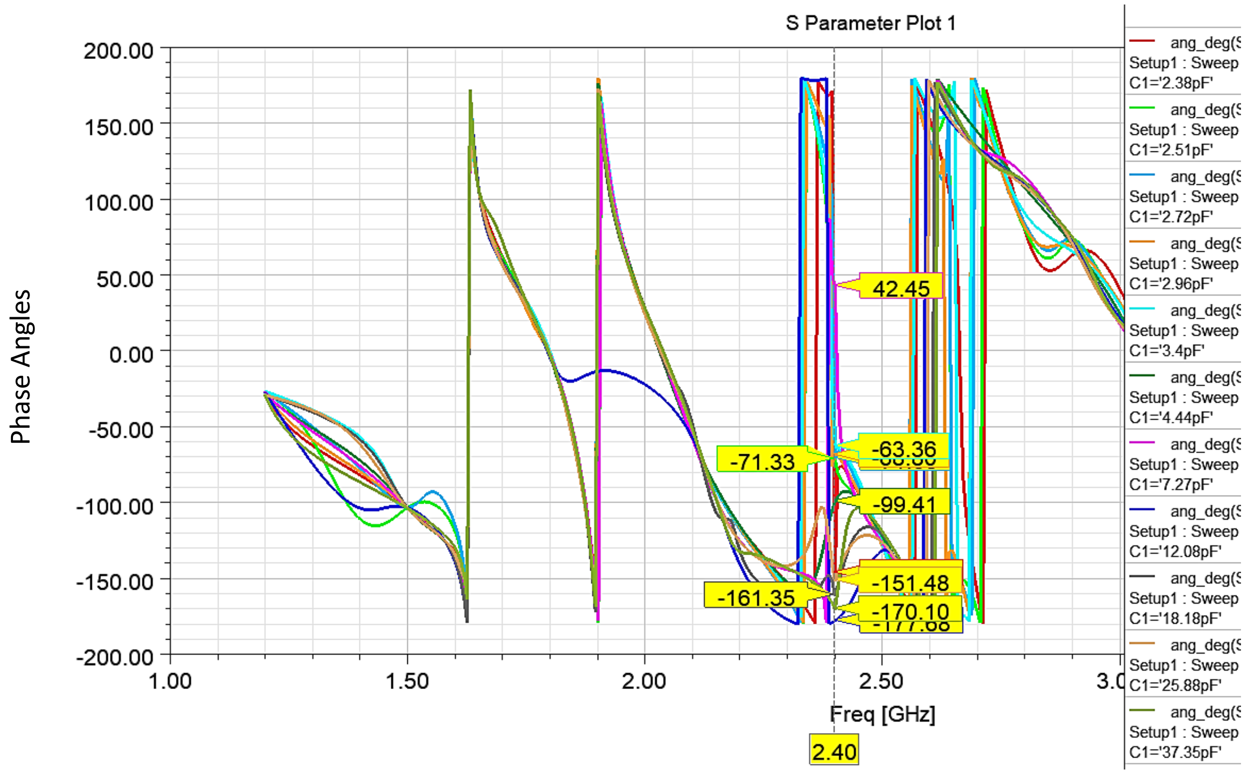

Figure 11. Phase angles according to the frequency values

4 Conclusions

In this study, an IRS design that operates in the mid-band of the 5G spectrum is designed for wireless communication networks with heavy data traffic. Specifically, it operates in the 2.4 GHz frequency band and can change the phase angles of the incoming signals according to the reverse voltage values to be applied between 0-5 Volts simulated by the capacity values of its varactor diodes. In practice, these voltage values can be provided as varying PWM signals. In other words, it has been demonstrated that by changing the capacity values of the varactor diodes on the IRS, the phase angles of the signals coming from the source antenna in the 2.4 GHz frequency band can be changed for a fixed operating frequency. In this way, it is expected that the provided design will be a solution to problems such as transferring the signal to blind spots and reducing data traffic. Considering that this is a preliminary study, it should be noted that the proposed IRS needs further improvements and specifications in the future.

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Conflict of interest

The authors declare that they have no conflict of interest.

Similarity rate (Turnitin) : %13

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