Intelligent Reflecting Surface for 6G Wireless Communication

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ABSTRACT

In the context of future 6G wireless communication, addressing challenges related to non-line-of-sight communication is paramount. This paper presents the design and prototyping of Intelligent Reflecting Surfaces (IRS) as a solution to provide wireless connectivity in the absence of Line-of-Sight (LoS) propagation paths for effective wireless communication. We simulated phase-shifter unit cell structures of IRS utilizing CST Studio software suite. A prototype IRS consisting of a two-dimensional array of unit cells was designed and built. Our tests on the prototype revealed the effectiveness of the design exhibiting a remarkable 315o of dynamic range in phase shift performance at 2.4 GHz. The losses introduced by the IRS in reflecting an incident signal were brought down to an acceptable limit via an iterative design and simulation process. Measurements on phase shifting properties were performed using a low-cost Vector Network Analyzer (VNA). A comparative study was carried out on the simulation and experimental outcomes and good agreement was found confirming the effectiveness of the prototype IRS.

KEYWORDS: *Intelligent Reflecting Surface, 6G Wireless Network, meta-surface, reflect-array.*

1 INTRODUCTION

Wireless access is a crucial aspect in today's networked world for facilitating seamless data transfer, real-time video streaming, Internet of Things (IoT), and many other services. Despite the growing need for faster, more reliable, and pervasive wireless communication, satisfactory provisioning requires us to overcome issues pertaining to the nature of relevant wireless channels and network complexities. The distance between base stations or routers and user equipment, physical obstructions such as thick walls or floors, and the proliferation of a large number of devices on a single network contribute to signal deterioration and insufficient communication quality.

In the ongoing research, development, and standardization efforts to realize the wireless network of the future, namely, 6G networks, there is a tremendous interest in novel smart technologies to address the problems and opportunities in the dynamic landscape of wireless access. In this case, innovative solutions are required to meet the inherent issues of the fast-evolving ecosystem of wireless communication leading to 6G system and network (Akyildiz, Kak, & Nie, 2020) (Bariah, et al., 2020).

There, control of electromagnetic wave propagation by smart wall surfaces is considered a promising approach to enhance the access capability in 6G wireless communication (Subrt & Pechac, 2012). Intelligent Reflecting Surface (IRS) (Wu, Zhang, Zheng, You, & Zhang, 2021), aka Reconfigurable Intelligent Surface (RIS) (Chen, et al., 2021) (Liu, Liu, Mu, Hou, & Xu, 2021), is expected to be a viable technology to realize such smart walls. An IRS can be strategically affixed on a wall so as to receive the transmission from an outdoor or indoor antenna via a Line-of-Sight (LoS) path and to effectively redirect and focus the Electromagnetic (EM) energy therein at one or more receiver locations that are not in the LoS path with the transmit antenna (Figure 1). An intelligent controller connected to the IRS will assist the transmitter to periodically sense the directions of receivers and will optimize the properties of the reflecting surface to satisfactorily redirect the transmitted signal to intended users. This approach will be a paradigm shift in wireless communication, in which it enables us to modify the wireless propagation environment strategically to increase capacity and connectivity rather than using statistical models to describe the naturally existing wireless channel for optimizing capacity and connectivity as in the current design approaches (Dai, et al., 2020).

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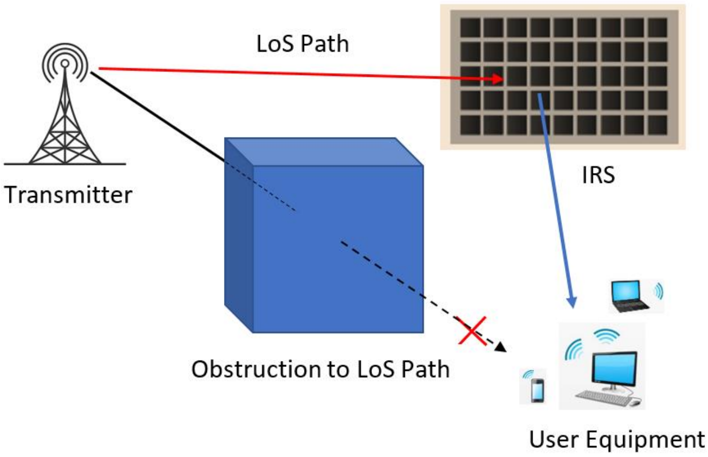


Figure 1. Effective communication using IRS in the absence of LoS path.

Our paper presents the results of an R&D project carried out to design, simulate, and implement a well performing, proof of concept IRS system. In the following sections of the paper, we delve into the adopted design methodologies, testing and data collection procedures, the discussion on the results from simulations and experiments, and the conclusion. In Section 2 to follow, the state-of-the-art in IRS is surveyed. In Section 3, the adopted simulation-based design procedure is explained. In Section 4, we elaborate on the fabrication of the IRS prototype and the test procedures used to assess the performance of the IRS. The test results are scrutinized and compared with simulations in Section 5. The paper concludes in Section 6.

2 IRS - STATE OF THE ART

In this section, we present a concise survey of the existing body of research in IRS and the recent success towards demonstrating the applicability to wireless communication systems of the future. The development of IRS is based on the notion of artificial surfaces called meta-surfaces that can reflect EM waves impinging upon them in ways different from that of a plane metallic or non-metallic surface. The meta-surface of our interest consists of periodic structures of elements known as unit cells. A unit cell includes a metallic structure etched on one side or both sides of a dielectric substrate. Depending on the design of the unit cell, the meta-surface may show interesting properties such as negative permittivity and permeability (Glybovski, et al., 2016) (Smith, Padilla, Vier, Nemat-Nasser, & Schultz, 2000).

A unit cell of a meta-surface can be designed to introduce a specific phase shift to incident EM waves with frequencies around the resonance frequency of the unit cell. Thus, a desired phase shift can be introduced to the reflected EM wave. The amount of phase shift can be controlled by varying the size and shape of the metallic element. This technique is used in reflect-array (Nayeri, Yang, & Elsherbeni, 2018) (Kamoda, Iwasaki, Tsumochi, Kuki, & Hashimoto, 2011) which is a smart flat panel replacement for a parabolic reflector to generate a plane wave using the transmission from a feed antenna placed at the focal point. Unit cells of a meta-surface are electronically tuneable by suitably incorporating a PIN diode (Clemente, Dussopt, Sauleau, Potier, & Pouliguen, 2012) or a reverse-biased varactor diode (Hum, Okoniewski, & Davies, 2005) (Zouhdi, Ratni, & Burokur, 2022). A PIN diode simply works as a switch to connect and disconnect different sections of the metallic structure of the unit cell thereby enabling binary control of phase shift values (Kaina, Dupre, Lerosey, & Fink, 2014). A varactor diode on the other hand shows continuously varying capacitance as a function of the reverse bias voltage applied between the anode and the cathode thus enabling phase shift in a continuous range (Rotschild & Abramovich, 2021) (Hum, Okoniewski, & Davies, 2005). Figure shows typical unit cell structures with two sections interconnected with electronic components for reconfigurability. Each of these designs may show different phase shifting behaviours for a frequency range of operation. The choice of unit-cell pattern and size depend on the frequency of operation and the required phase shift ranges.

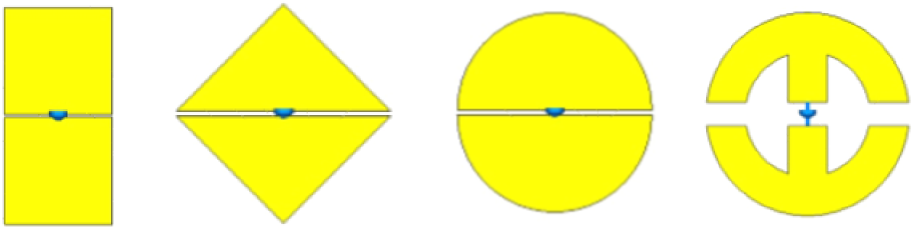


Figure 2. Unit-cell structures of two sections interconnected by a PIN diode or varactor diode.

The concept of IRS extends the idea of electronically tuneable reflect array to reflect and redirect a transmission from a distant transmit antenna to one or more receiver locations with no LoS paths to the transmitter. In achieving this goal, the phase shifts introduced by unit cells of the IRS are chosen such that the collective result is the formation of a radiation pattern with a strong transmission in the direction of the intended receiver(s) and little transmissions in other directions. Recent literature on IRS report theoretical and simulation studies as well as proof concept hardware/software realizations. Design and modelling of tuneable reflect arrays were presented in (Hum, Okoniewski, & Davies, 2007). The idea of realizing a programmable wireless environment using Large Intelligent Surface/Antennas (LISA) was discussed in (Liang, et al., 2019). The authors laid out the theoretical framework and illustrated the feasibility of using LISA for downlink transmission with single and multiple users. The applicability in wireless power transfer, cognitive radio networks, and physical layer security also has been discussed in that paper. A comprehensive analysis of the beamforming properties of an IRS using physical optics techniques was carried out (Özdogan, Björnson, & Larsson, 2020). A plausible explanation was presented as to how an IRS with a large number of unit cells, each capable of phase shifting the incoming signal, can form a beam with a certain beamwidth and an angle of departure.

There have been a couple of proofs of concept IRS prototypes reported by leading research groups in the recent academia. An IRS with 1100 controllable unit cells operating at 5.8GHz was reported in (Pei, et al., 2021). The prototype uses receiver-RIS links feedbacks for over the air reconfiguration. The prototype has been reported to achieve 26 dB power gain compared to a plane metallic surface and low power consumption in the order of 1W. Live video transmission via reflected path was demonstrated. Another large IRS prototype consisting of 2430-unit cells operating at a frequency of 3.5GHz was reported in (Araghi, et al., 2022). The prototype can self-reconfigure to anomalously reflect the incoming EM wave to a direction of interest.

While prospects of IRS as a key technology in the future generation of wireless systems are good, several challenges including power consumption and practical implementation hurdles remain to be addressed. Researchers have also outlined future research directions, suggesting advancements in materials and algorithms which may further optimize IRS performance (Kamoda, Iwasaki, Tsumochi, Kuki, & Hashimoto, 2011) (Pei, et al., 2021) (Araghi, et al., 2022) (Chen, et al., 2021) (Wu, Zhang, Zheng, You, & Zhang, 2021) (Abeywickrama, Zhang, Wu, & Yuen, 2020) (Zhang, et al., 2022) (Feng, Wang, Li, & Wen, 2020).

Our literature review underscored the burgeoning interest in the IRS and its role in augmenting the wireless communication environment for increased capacity and connectivity within the emerging 6G context. The insights achieved paved the way for our research project, in which we were able to design, simulate, and implement an IRS prototype capable of achieving a dynamic range of phase shifts exceeding the reported values in the recent literature for the chosen frequency band of operation.

3 IRS UNIT CELL DESIGN AND SIMULATION

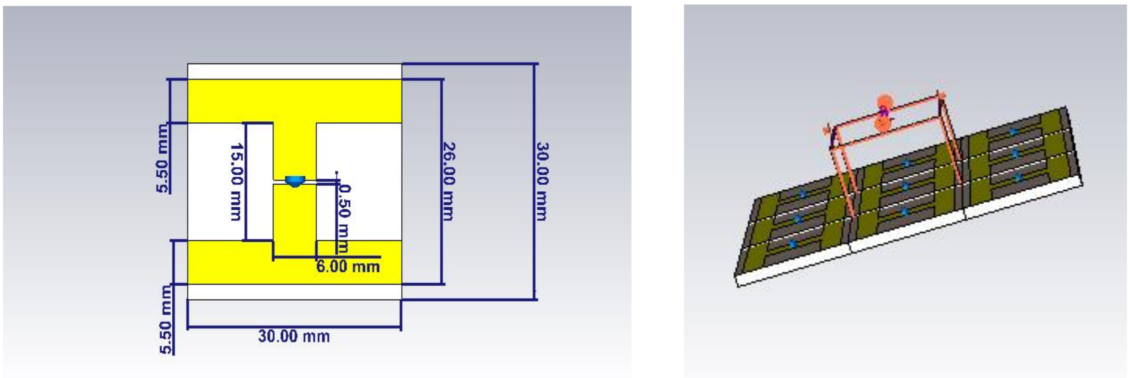
The IRS prototype presented in this paper was designed and built to operate in the ISM frequency band around 2.4GHz. This choice makes it convenient in terms of licensing requirements, and availability of necessary transceiver and antenna hardware for experimentation. Further, the unit cell structures at this frequency have sufficiently large dimensions to fabricate with precision using readily available low-cost equipment and technical expertise available at the university environment. Nevertheless, the design and fabrication process can be readily adopted for designing IRS at millimetre wave frequencies with suitable upgrade to the equipment.

For the design of periodic structures to serve as IRS, we started by designing the elementary unit cell. The main requirement here was an inductive-capacitive (LC) resonance behaviour that allows us to achieve a sufficiently large range of phase shift together with a high reflectivity (low absorption). While the phase shift at full resonance is 0o, the unit cell is required to show a total phase variation exceeding 300o at off-resonance conditions. The unit cell in this context consists of a two-part metallic pattern etched on a dielectric substrate. A reverse biased varactor diode connected between the two parts acts as a variable capacitor enabling a tuneable LC resonance circuit. To this end, several candidate unit cell structures ranging from pairs of rectangular patches to more complicated split-H structures were studied.

With an iterative design and simulation process using the CST Studio software suite, we concluded in favour of the split-H unit cell with parameters shown in Figure 3(a). A unit cell design similar to this was adopted in (Zouhdi, Ratni, & Burokur, 2022). Nevertheless, the dimensions in our design are optimized to provide the best results at 2.4GHz. The unit cell of choice extends over a square area of 30mm on each side and is composed of an FR-4 dielectric substrate with relative permittivity $\epsilon_r = 4.3$ and thickness $t = 3$ mm. The unit cell pattern etched on the top copper layer is composed of two sections with a 0.5mm gap in which a varactor diode is affixed. The bottom layer is composed of a continuous copper ground plane. The separation between the parallel strips of the top layer allows for a capacitive response when the electric field is oriented perpendicular to these strips. The dimensions of the strips bring in inductive effects. The combination of the capacitive and inductive effects therefore achieves the desired resonance properties. The continuous ground plane fully reflects the incident electromagnetic wave.

The varactor diode adds a variable capacitance so as to electronically control the response of the unit cell. A DC reverse bias voltage is applied to the varactor diode via the two parallel copper strips. The SMV2202-040LF varactor diode was selected in our design due to its low losses and high tuning factor. This varactor diode is available for purchase at an affordable per unit price. In the simulation of the unit cell, the varactor diode is modelled as a series RLC network where $R = 0.7\,\Omega$ represents the ohmic losses, $L = 0.4\,nH$ is the inductance due to the effect of packaging and C is the capacity of the reverse biased junction variable in the range of 0.31 - 3.4 pF. Along with the varactor diode parameters, parts of metallic structure of the unit cell and the ground plane constitute an equivalent RLC circuit.

In the unit cell structure simulation using CST Studio software, the Floquet port method was used. (Figure 3 (b)). Its boundary conditions were based on the assumption of an infinite array of unit cells.



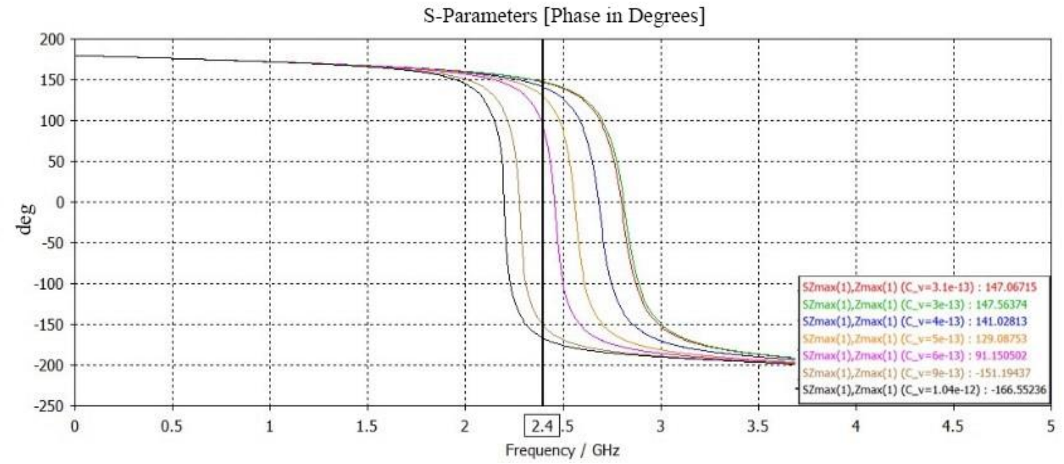
(a) Split-H unit-cell structure

(b) Periodic structure of unit-cells

Figure 3. Periodic structure design and simulation setup in CST Studio.

The simulation results given in Figure 4 are the reflection coefficients, or S parameters. Figure 4 (a) shows the phase versus frequency characteristics and Figure 4 (b) shows the attenuation versus frequency characteristics. As indicated in the legends, different curves are for different varactor diode capacitance values. The legends also indicate the phase shift and the attenuation by the IRS unit-cell at 2.4GHz obtained by slicing the curves.

(a)



(b)

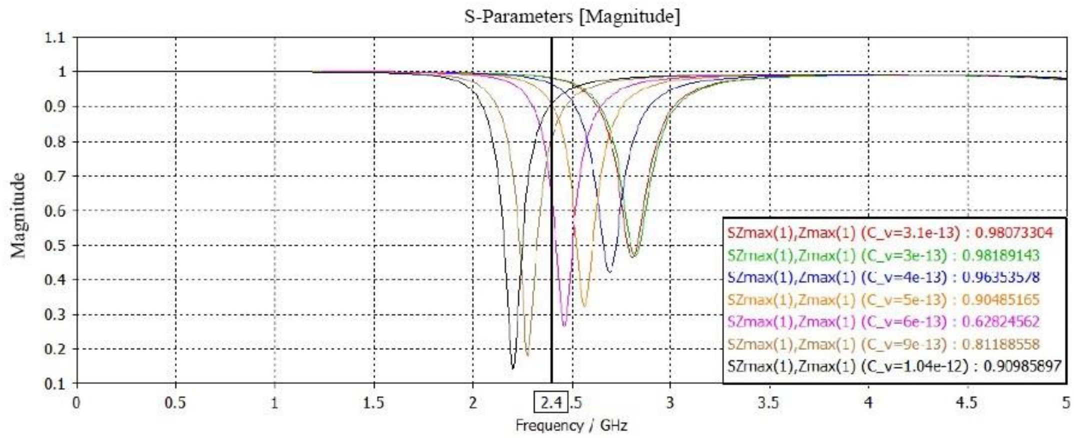


Figure 4 a & b: *S*-parameter (reflection coefficient) plots from CST Studio Simulation of IRS.

The results show that the range of available capacitance with the varactor diode of choice allows a variation of resonance frequency in the range from 2.1873 GHz to 2.8291 GHz, when the capacitance of reversed biased varactor diode varies from 1.04 pF to 0.31 pF (decreasing order). Further, it is observable from the simulation results (Figure 4 (a)) that at the frequency of 2.4GHz, the phase shift can be varied from -170o to +145o by varying the capacitance. A comparison of Figure 4 (a) and (b) reveals that the signal energy absorption peaks at resonance frequency for each capacitance value at which point the phase shift is 0o. At the operational frequency of 2.4 GHz, the resonance occurs for a capacitance value of 0.65 pF.

An ideal IRS should have negligible signal absorption within the frequency range of operation and the phase shift values of interest. Normally, most of the unit-cells of an IRS would operate at off-resonance to achieve desired phase shift values substantially larger than 0o and the signal absorption is significantly lower than the maximum at such phase shifts. Therefore, it is possible to operate the IRS with sufficiently small enough absorption levels (large enough reflection coefficient).

4 IRS PROTOTYPE FABRICATION AND TESTING

The final design of unit cells for the IRS to be prototyped was decided based on the simulations as described in Section 3. Initially, a 12 unit-cell (4 x 3) array was fabricated and tested. Figure 5 shows the array with varactor diodes soldered and with the testing apparatus. All the varactor diodes of unit cells in a column in this design get equal reverse bias voltages and hence cause equal phase shifts. However, the varactor diodes in different columns of unit cells can be supplied with different reverse bias voltages to obtain different phase shift values. In effect, the IRS can beamform and beam-steer in the two-dimensional plane perpendicular to the IRS surface. The horn antennas used in the tests were designed and fabricated to operate at 2.4GHz (Dissanayake, Keerthirathna, Haleem, Kumara, & Hirshan, 2022). A VNA interfaced to a laptop computer monitored and recorded the reflection properties of the IRS.

The effect of variation in the varactor diode capacitance on the S parameter was readily observable from the tests with the small size array. Following the success of this qualitative test, a larger cell-array consisting of 54 unit-cells (6 x 9) was fabricated for quantitative assessment of phase shifting properties (Figure 6). This larger array facilitated sufficiently accurate measurements of unit cell properties. The array could be accommodated in an A4 size FR4 substrate. The transmit and receive horn antennas were placed at a distance of 1.5m away from the IRS and 1m away from each other. The orientations of antennas with respect to the IRS were adjusted to obtain equal incident and reflection angles so that the measured phase shift was that of IRS alone.

The VNA used in the test has two ports. A two-port device can be connected between these ports to measure the S parameters. The Device Under Test (DUI) in our case is the communication channel consisting of the transmit antenna, the IRS, the receiving antenna and the wireless propagation paths. With this setup, S_{21} is the ratio of the received signal (in amplitude and phase) to the transmitted signal. Hence the total path loss is given by the modulus $|S_{21}|$ and the total phase change occurred in the signal when traveling from the transmit antenna to the receive antenna via the IRS corresponds to the angle of S_{21}. The VNA carries out a frequency sweep in a specified range while measuring the S parameters. Hence the signal loss and the phase shift introduced by the IRS during reflection i.e., the S_{11} parameter of the IRS can be extracted from measured S_{21} of the total propagation path. Since the purpose here is to assess the phase shifting property of the unit cell structure, an equal reverse bias voltage was applied to all varactor diodes so as to achieve uniform phase shift across the entire surface.

VNA measurements were recorded at each setting of reverse bias voltage on varactor diodes (equal bias voltage for all diodes). Figure 7 shows a sample VNA measurement data display at 6V of reverse bias voltage applied to the varactor diodes. The phase and magnitude plots of S_{21} parameter represent the phase and magnitude of the IRS unit cell reflection coefficient.

(a) (b)

Figure 5 (a) IRS of 12 unit-cell array and (b) laboratory testing setup to assess phase shifting performance.

Figure 6. IRS of 54 unit-cell array and laboratory testing setup to assess phase shifting performance.

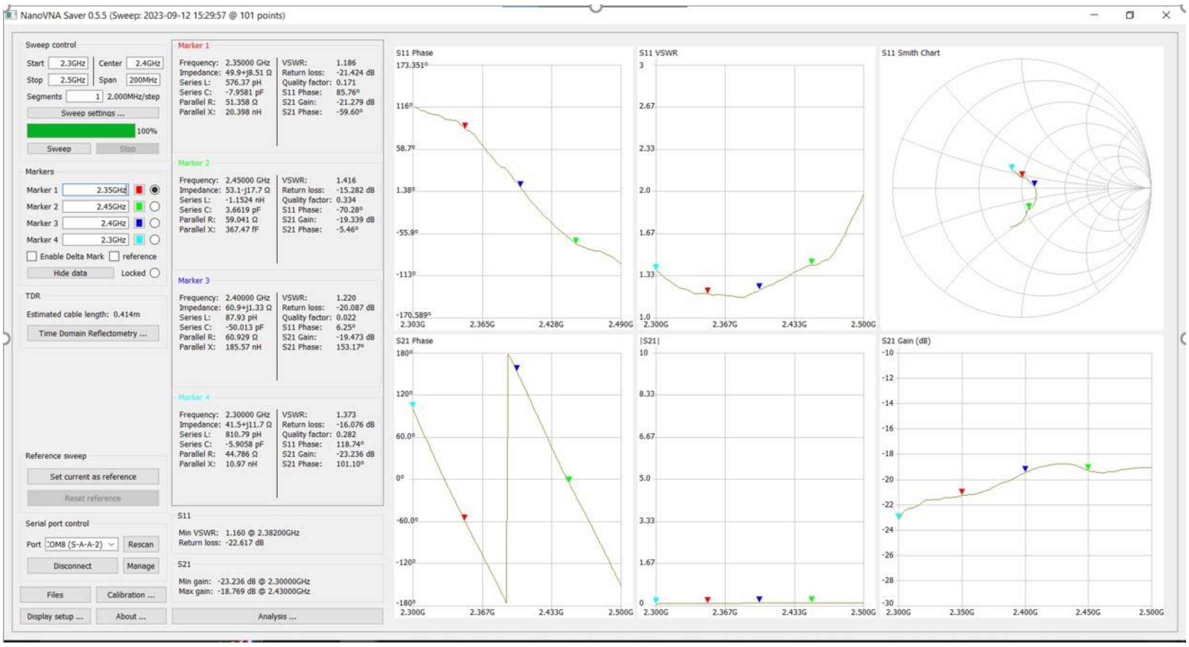
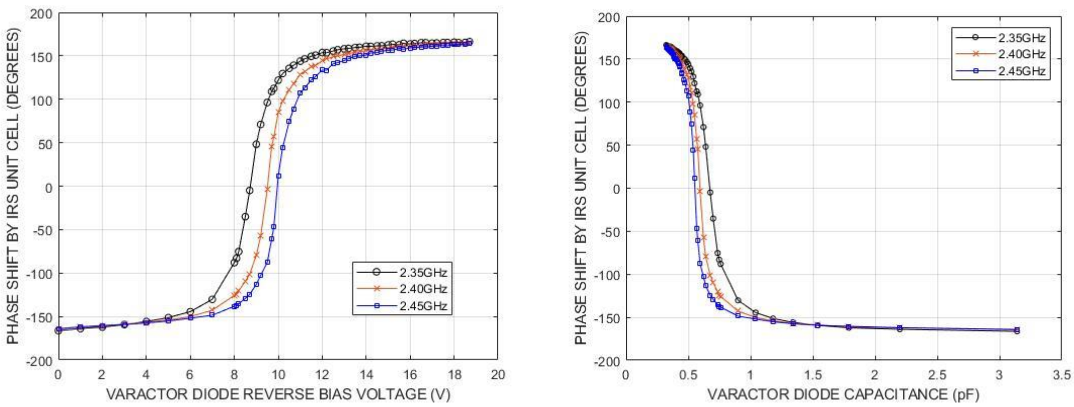


Figure 7. Sample screen shot of VNA measurement data.

5 TEST RESULTS

The phase shift occurred in the EM wave reflected by the IRS was measured using the VNA at different settings of varactor diode reverse bias voltage in the range of 0-20V. As per the data sheet, the varactor diode of choice has a variation of capacitance in the range of 3.14 to 0.31 pf, for the variation of reverse bias voltage in the range 0-20V. For each measurement, the voltages applied to all diodes of all unit cells were set to equal values. Thereby, all unit cells of the IRS shift the phase of EM wave impinging on the surface by equal values. The phase shift caused by the IRS on the EM wave therefore provides an estimate of the phase shift by a single unit cell.

Measured data were calibrated based on the fact that the phase shift at resonance is 0o and the phase shift versus voltage curves are symmetric around the resonance points. The raw data may indicate a non-zero phase shift at resonance in the received signal due to the phase changes occurring due to the propagation delay in the wireless channel. The calibration process is to remove such phase changes in the data. Figure (a) shows the measured and calibrated phase shift versus varactor diode reverse bias voltage characteristics of the IRS prototype. The figure shows the measurement results at 3.35, 3.40, and 3.45GHz.



(a) (b)

Figure 8. Measured phase shift characteristic of 54 unit-cell IRS with equal reverse bias voltages applied to all varactor diodes.

While the measured phase shift is a function of varactor diode reverse bias voltage as in Figure 8(a), the simulation results of Figure 4 provide phase shift versus capacitance curves. In order to make a comparison of measurements with simulation results, the voltage values need to be mapped to corresponding varactor diode capacitances. This was achieved using device data. The data sheet for the selected varactor diode, namely, Skyworks SMV2202-040LF, provides tabulations of varactor diode capacitance values at different reverse bias voltages. These tabulations were used in converting the voltage axis of Figure 8(a) to the capacitance axis as in Figure (b). The varactor diode capacitance has an inverse relationship to the diode reverse bias voltage hence the plots of Figure 8(b) appear as a distorted mirror image of Figure 8(a) around the vertical axis.

A comparison of simulation results and laboratory test results on the phase shift properties of the fabricated RIS was accomplished by extracting data from the results of Figure 4(a) and Figure 8(b). There is an asymmetry in the phase shift versus capacitance curve around 0o phase shift in the simulation results of Figure 4(a). A fair comparison is required in shifting these curves downward to achieve symmetry. Accordingly, the test results are compared with CST Studio simulations in Figure 9 for the operating frequency of 2.4 GHz. Among the reasons for discrepancies between the simulation and test results are the non-ideal environment in which the tests were carried out, the edge effects of the moderate sized IRS, and deviations in permeability and thickness of substrate from the values used in simulations.

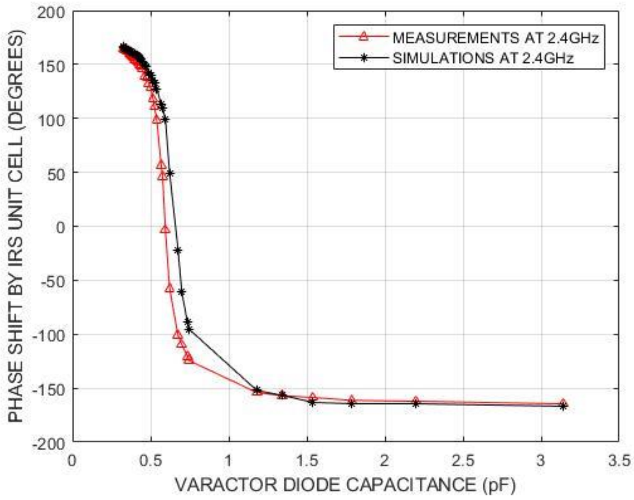


Figure 9. Comparison of experimental measurement of phase with CST Studio simulations.

6 CONCLUSION

Intelligent Reflecting Surfaces (IRS), aka Reconfigurable Intelligent Surfaces (RIS) have the potential to artificially augment the wireless propagation environment so as to increase the coverage and capacity in the future generation (6G) wireless communication systems. A prototype IRS was designed and fabricated in the laboratory. The design work included simulation of several unit-cell structures to decide on the structure showing the best observed phase shift range while limiting the signal absorption. Based on the simulations in this phase, the split-H structure was chosen. Further simulations were carried out to fine tune the dimensions of the unit-cell structure to maximize the phase shift range at the operational frequency of 2.4GHz. The final design showed an impressive dynamic phase shift range of 315o for the capacitance range specifications of the selected varactor diode incorporated to the unit-cell. This value is more than the ranges reported in the recent literature for the selected operational frequency.

The phase shift properties of the prototype IRS were tested and the results are in good agreement with those of simulations. The results of our work show that it is possible to design and fabricate well performing IRS with readily available materials and components and using moderate laboratory facilities and skills.

The project reported in this paper is to continue so as to realize a large IRS suitable for a demonstration of live transmission of audio and video between a transmitter and a receiver hidden from each other due to obstructions. The IRS in this context will redirect and refocus the EM waves to user locations that change with time. Design of appropriate adaptive signal processing algorithms and implementations are in progress.

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REFERENCES

Abeywickrama, S., Zhang, R., Wu, Q., & Yuen, C. (2020, Sep.). Intelligent Reflecting Surface: Practical Phase Shift Model and Beamforming Optimization. *IEEE Transactions on Communications, 68*(9), 5849–5863.

Akyildiz, I. F., Kak, A., & Nie, S. (2020). 6G and Beyond: The Future of Wireless Communications Systems. *IEEE Access*, *8*, 133995-134030.

Araghi, A., Khalily, M., Safaei, M., Bagheri, A., Singh, V., Wang, F., & Tafazolli, R. (2022). Reconfigurable intelligent surface (ris) in the sub-6 ghz band: Design, implementation, and real-world demonstration. *IEEE Access, 10*, 2646-2655.

Bariah, L., Mohjazi, L., Muhaidat, S., Sofotasios, P. S., Kurt, G. K., Yanikomeroglu, H., & Dobre, O. A. (2020). A Prospective Look: Key Enabling Technologies, Applications and Open Research Topics in 6G Networks. *IEEE Access, 8*, 174792-174820.

Chen, Y., Bo, A., Zhang, H., Niu, Y., Song, L., Han, Z., & Poor, H. V. (2021, May). Reconfigurable Intelligent Surface Assisted Device-to-Device Communications. *IEEE Transactions on Wireless Communications, 20*(5), 2792-2804. doi:10.1109/TWC.2020.3044302.

Clemente, A., Dussopt, L., Sauleau, R., Potier, P., & Pouliguen, P. (2012). 1-Bit reconfigurable unit cell based on PIN diodes for transmit-array applications in X - Band. *IEEE Transactions on Antennas and Propagation, 60*(5), 2260-2269.

Dai, L., Wang, B., Wang, M., Yang, X., Tan, J., Bi, S., . . . Hanzo, L. (2020). Reconfigurable intelligent surface-based wireless communications: Antenna design, prototyping, and experimental results. *IEEE access, 8*, 45913-45923.

Dissanayake, C. S., Keerthirathna, P. S., Haleem, M. A., Kumara, W. G., & Hirshan, R. (2022). Design and Prototyping of High Gain Horn Antennas for Imaging Radar. *International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET)* (pp. 200-205). Bandung, Indonesia: IEEE. doi:10.1109/ICRAMET56917.2022.9991209.

Feng, K., Wang, Q., Li, X., & Wen, C.-K. (2020, May). Deep Reinforcement Learning Based Intelligent Reflecting Surface Optimization for MISO Communication Systems. *IEEE Wireless Communications Letters, 9*(5), 745–749.

Glybovski, S., Tretyakov, S., Pavel, A., Belov, P., Kivshar, Y., & Simovski, C. (2016, May 24). Metasurfaces:FromMicrowavestoVisible. *Physics Reports*, 1-72.

Huang, C., Zhang, C., Yang, J., Sun, B., Zhao, B., & Luo, X. (2017). Reconfigurable metasurface for multifunctional control of electromagnetic waves. *Adv. Opt. Mater., 5*(22).

Hum, S. V., Okoniewski, M., & Davies, R. J. (2005). Realizing an electronically tunable reflectarray using varactor diode-tuned elements. *IEEE Microwave and Wireless Components Letters, 15*(6), 422-424.

Hum, S., Okoniewski, M., & Davies, R. (2007). Modeling and Design of Electronically Tunable. *IEEE Transactions on Antenna and Propagation*, 2200 - 2209.

Kaina, N., Dupre, M., Lerosey, G., & Fink, M. (2014). Shaping Complex Microwave Fields in Reverberating Media with Binary Tunable Metasurfaces . *Scientific Reports, 4*(6693), 1-8.

Kamoda, H., Iwasaki, T., Tsumochi, J., Kuki, T., & Hashimoto, O. (2011). 60-GHz electronically reconfigurable large reflectarray using single-bit phase shifters. *IEEE transactions on antennas and propagation, 59*(7), 2524-2531.

Li, W., Qiu, T., Wang, J., Zheng, L., Jing, Y., Jia, Y., . . . Qu, S. (2021, Jan.). Programmable Coding Metasurface Reflector for Reconfigurable Multibeam Antenna Application. *IEEE Transactions on Antennas and Propagation, 69*(1), 296-301. doi:10.1109/TAP.2020.3010801

Liang, Y., Long, R., Zhang, Q., Chen, J., Cheng, H. V., & Guo, H. (2019). Large Intelligent Surface/Antennas (LISA): Making Reflective Radios Smart. *Journal of Communications and Information Networks*, *4*(2), 40-50.

Liu, Y., Liu, X., Mu, X., Hou, T., & Xu, J. (2021). Reconfigurable Intelligent Surfaces:. *Communications Surveys & Tutorials*, 1546 - 1577.

Nayeri, P., Yang, F., & Elsherbeni, A. Z. (2018). *Reflectarray Antennas: Theory, Design, and Applications.* Wiley-IEEE Press.

Özdogan, Ö., Björnson, E., & Larsson, E. G. (2020). Intelligent Reflecting Surfaces:. *IEEE Wireless Communications Letters*, 581 - 585.

Pei, X., Yin, H., Tan, L., Cao, L., Li, Z., Wang, K., . . . Björnson, E. (2021). RIS-aided wireless communications: Prototyping, adaptive beamforming, and indoor/outdoor field trials. *IEEE Transactions on Communications* , *69*(12), 8627-8640.

Rotschild, D., & Abramovich, A. (2021). Realization and validation of continuous tunable metasurface for high resolution beam steering reflector at K-band frequency. *Int J RF Microw Comput Aided Eng., 31*(4).

Smith, D., Padilla, W., Vier, D., Nemat-Nasser, S., & Schultz, S. (2000, May 1). Composite Medium with Simultaneously Negative Permeability and Permittivity. *PHYSICAL REVIEW LETTERS, 84*(18), 4184-4187.

Subrt, L., & Pechac, P. (2012). Controlling propagation environments using Intelligent Walls. *6th European Conference on Antennas and Propagation (EUCAP)*, (pp. 1-5).

Wu, Q., Zhang, S., Zheng, B., You, C., & Zhang, R. (2021, May). Intelligent Reflecting Surface-Aided Wireless Communications: A Tutorial. *IEEE Transactions on Communications*, *69*(5), 3313–3351.

Zhang, Y., Shen, K., Ren, S., Li, X., Chen, X., & Luo, Z.-Q. (2022, Aug.). Configuring Intelligent Reflecting Surface With Performance Guarantees: Optimal Beamforming . *IEEE Journal of Selected Topics in Signal Processing, 16*(5), 967–979.

Zouhdi, Z., Ratni, B., & Burokur, S. N. (2022, july 1). Electronic Beam-Scanning Antenna Based on a Reconfigurable Phase-Modulated Metasurface. *Sensors, 22*(13), 1-16. doi:https://doi.org/10.3390/s22134990