Reconfigurable intelligent surface (RIS) in mmWave: System design, analysis, and implementation

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밀리미터대역에서의 재구성 가능한 지능형 표면 (RIS): 시스템 설계, 분석 및 구현

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Abstract

This paper introduces the Reconfigurable Intelligent Surface optimized for the 26.5 GHz to 29.5 GHz frequency band. We show the design and simulation of a unit cell using PIN diodes to control reflection phases effectively and fabricated RIS test board. We test the implemented RIS test board to verify and improve its performance.

Ⅰ. Introduction

In recent years, Reconfigurable Intelligent Surfaces (RIS) have garnered significant attention as a promising technology for 5G-Advanced and 6G networks. RIS is a novel hardware technology that artificially reconfigures the electromagnetic environment to expand service coverage and enhance spectrum and energy efficiency in wireless networks. By appropriately adjusting the phase of the reflecting elements in Reconfigurable Intelligent Surfaces (RIS), the reflected signals can be combined with the direct-path signals, thereby enhancing the strength of the received signals or mitigating signal interference. This is particularly beneficial in high-frequency bands such as millimeter-wave used in 5G/6G communication systems, where obstacles may block direct-path signals.

In this paper, we propose a design of a 1-bit RIS unit cell operating in the 26.5GHz to 29.5GHz band using a PIN diode as a passive element to control the reflection phase. The rest of this paper is organized as follows: Section II provides the specific design structure and characteristics of the RIS unit cell and presents ADS (Advanced Design System) simulation results for designing the equivalent circuit to determine the RLC values. Also, we demonstrate various properties of the RIS unit cell using the CST Studio Suite program with a floquet port and Horn Antenna setup. SectionⅢ concludes this paper along with future work.

Ⅱ. Method

A. Unit cell design

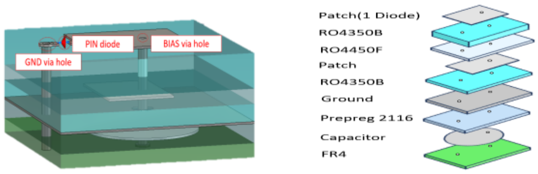

Fig 1. Unit cell design and layer stack-up

In this chapter, we explain the design of the RIS unit cell and 6-layer PCB stack up specifically. Unit cell comprises a six-layer structure with two antenna patches mounted on each RO4350B substrate. Prior RIS structures generally have a narrow bandwidth; therefore, this paper proposes a design that enhances the bandwidth by resonating two antenna patches. The unit cell is designed on Rogers RO4350B substrate, selected for its relative permittivity of 3.66 and thickness specifications of 0.51mm and 0.25mm for layer 1 and layer 3, respectively, as shown in Fig 1. To bond two RO4350B substrates, RO4450F bondply material is stacked in layer 2. For voltage application from the Bias line, a Bias via hole is drilled as shown in Fig 1, and the design allows the current to flow from the PIN diode to the GND via hole, enabling control via a control board. Also, a capacitor placed on the FR4-epoxy substrate is incorporated into the unit cell located on the fifth layer. To prevent the incident wave from being radiated beyond the backside of the RIS unit cell instead of being reflected, a capacitor is mounted on the FR4 substrate. This approach enhanced the performance of the unit cell.

B. Experiment and results

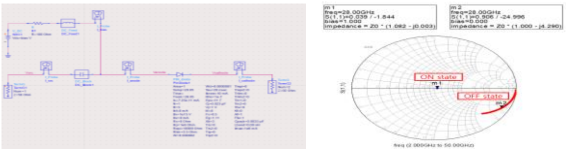

Fig 2. PIN diode Spice model

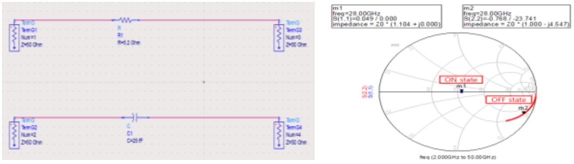

Fig 3. Equivalent circuit model of PIN diode

We use PIN diodes to control the reflection phase of the guided wave in RIS[1]. PIN diode can be modeled respectively as a series RLC circuit in the ON/OFF state. To validate the functionality of the PIN diode, we conducted S-parameter simulation and DC operating point Simulation. We selected the PIN diode with the part number MADP 000907-14020P from MACOM Company Ltd. We extracted the spice model data of the PIN diode from the datasheet. When diode is in the ON state, the resistor value presents on the Smith chart, resulting in a low reflection coefficient, which indicates minimal reflection and substantial signal transmission. When diode is in the OFF state, it appears as an open state on the Smith chart, showing high reflection coefficient, which indicates substantial reflection. As the frequency increases, the influence of the capacitor becomes more significant, so it is plotted as a curve on the Smith chart. So, we enhanced the accuracy for simulation by derived the lumped element values of the PIN diode (R = 5.2Ω in the ON state, C = 25 fF in the OFF state).

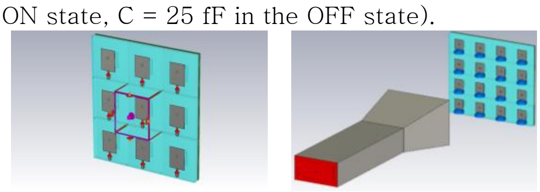
Fig 4. Simulation with floquet port and Horn Antenna

We conducted the CST simulation of the unit cell using two methods shown in Fig 4. We carried out floquet port simulation defining a boundary as a type of unit cell and designed a Standard Gain Horn Antenna that can operate in the 22 GHz to 33 GHz range, combined with a WR-34 waveguide.

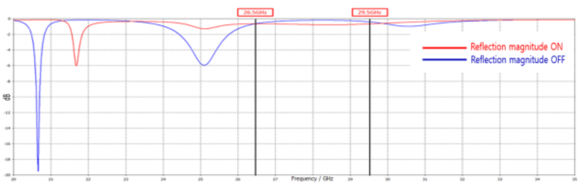

Fig 5. Reflection magnitude ON/OFF graph

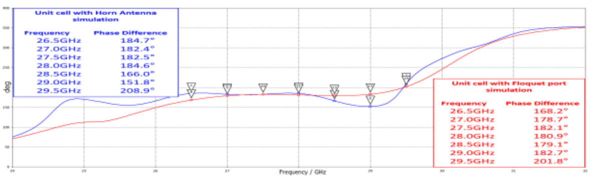

Fig 6. Phase difference radiated graph

When observing the reflection magnitude within the target frequency range, it occurs only a maximum of 1dB loss. When examining the phase difference radiated graph in two cases of simulation, it was observed that there was approximately a 180-degree phase difference between ON and OFF states within the 3 GHz frequency range between 26.5 GHz and 29.5 GHz. We derived the reflection coefficients directly by calculating the radiation impedance and the ON/OFF state impedance by S-parameter value when reflection is ON/OFF, respectively. We calculated the phase difference radiated graph by dividing the values when reflection is ON by those when reflection is OFF. To operate, the RIS is required to modify the phase of the reflected wave in comparison to the incident wave and not dissipate all the incident power. The maximum phase difference possible is 180 degrees, but any value close to it is enough[2].

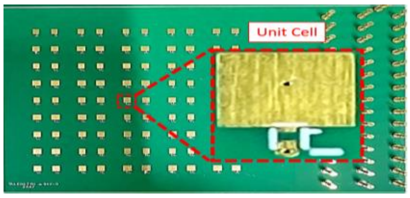

Fig 7. RIS test board

Therefore, we implemented a RIS test board verified through simulation and are currently deriving results through testing. We are also considering a method for RIS control.

Ⅲ. Conclusion

In this paper, we present a RIS optimized for mmWave frequency band. Through detailed design and simulations, including CST Studio Suite and ADS analyses, we validated our design. Currently, we are testing the implemented RIS test board to further verify and refine its performance. Future work will focus on expanding the RIS into larger arrays and designing and fabricating a RIS control board to independently control each unit cell.

ACKNOWLEDGMENT

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