

Reconfigurable Intelligent Surfaces with Integrated mmWave Chalcogenide Phase-Delay Elements

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Abstract—This paper presents a design approach for reconfigurable intelligent surfaces (RIS) by incorporating chalcogenide based reconfigurability within the phase-delay element monolithically, as an alternative to the commonly used variable size element or soldered components. This approach overcomes various challenges associated with typically used variable size elements, such as improved bandwidth, no static DC power consumption, reduced fabrication costs, and complex biasing requirements. A chalcogenide based phase shifter approach is discussed with measured response of single pole triple-throw back-to-back connected to form a loss compensated true-time-delay RFIC. The design is optimized to operate over 8 GHz band at 30 GHz center frequency. The phase response and group delay measurements demonstrate linear response over the band.

I. INTRODUCTION

Reconfigurable intelligent surfaces (RIS) or software-controlled metasurface, is an emerging technology that has the potential to greatly enhance the performance and capabilities of 5G-Advanced and 6G networks. An RIS consists of a large number of small elements (unit-cells) that can dynamically manipulate the propagation of electromagnetic waves. The popular approach of using size variation or capacitive electrical components in unit-cell design for RIS faces several challenges. The rapid variation in size near resonance frequencies makes it challenging to achieve accurate phase profiles, leading to significant errors in the desired reflection properties, especially at mmWave frequencies. This approach often encounters high losses due to the operation near resonance frequencies, reducing the overall efficiency.

The preference for phase-delay elements, driven by their linearity and associated benefits, has become evident in higher-frequency research endeavors [1]. Despite these advantages, phase-delay elements [2] face lower popularity compared to capacitive-controlled elements [3], primarily due to challenges associated with achieving reconfigurability.

In this paper, we propose a reconfigurable unit-cell based on the chalcogenide phase-delay elements. To address the difficulty to achieve reconfiguration in the unit-cell elements, while maintaining the linear characteristics of phase profile, a chalcogenide based phase-shifter [4] is monolithically integrated to the design providing broadband 8 GHz of linear operation at 30 GHz center frequency.

II. UNIT-CELL DESIGN

A. Phase-delay lines

To better understand the challenges posed by the unit-cell phase variation with variable size or capacitive methods and

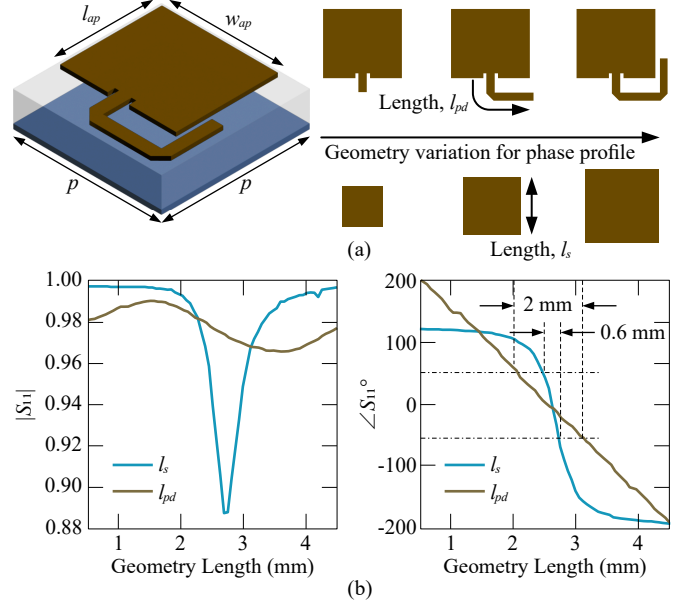


Fig. 1: A comparison of the geometry and the resulting reflection coefficient S_{11} between using the phase-delay lines and using the size variation for unit-cell design. (a) The isometric view of the unit-cell, with the aperture on top, the substrate and the ground plane on bottom. The variation on the controlled parameter is illustrated on the right side. The following parameters are designed for 30GHz: $l_{ap} = 2.93$ mm, $w_{ap} = 3.31$ mm, $p = 5.01$ mm, with Rogers 5880 laminate 20mil thickness. (b) The magnitude and the phase of the reflection coefficient with geometry variations.

the distinctive features offered by phase-delay elements, a comparative analysis between these approaches is presented in Fig. 1. The size-variation approach encounters two significant challenges near resonance, both of which are effectively addressed by the phase-delay approach. The main issue is the phase error triggered by a combined effect of fabrication tolerance and the rapid phase variation near resonance. As shown in Fig. 1(b), the phase undergoes a 100° change within a 0.6 mm range. With typical fabrication tolerances ranging from 0.07 to 0.20mm (3-8mil), this design becomes susceptible to phase errors at higher frequencies or when cost-effective lower precision is applied. Conversely, the phase-delay elements exhibit a flatter amplitude profile and a linear phase trend, mitigating these issues. Indeed, the phase-shift in this approach is proportional to twice the line length, given by [1]:

$$\phi = 2kl \quad (1)$$

where ϕ is the phase-shift, k is the propagation constant of the signal along the line, and l is the line length.

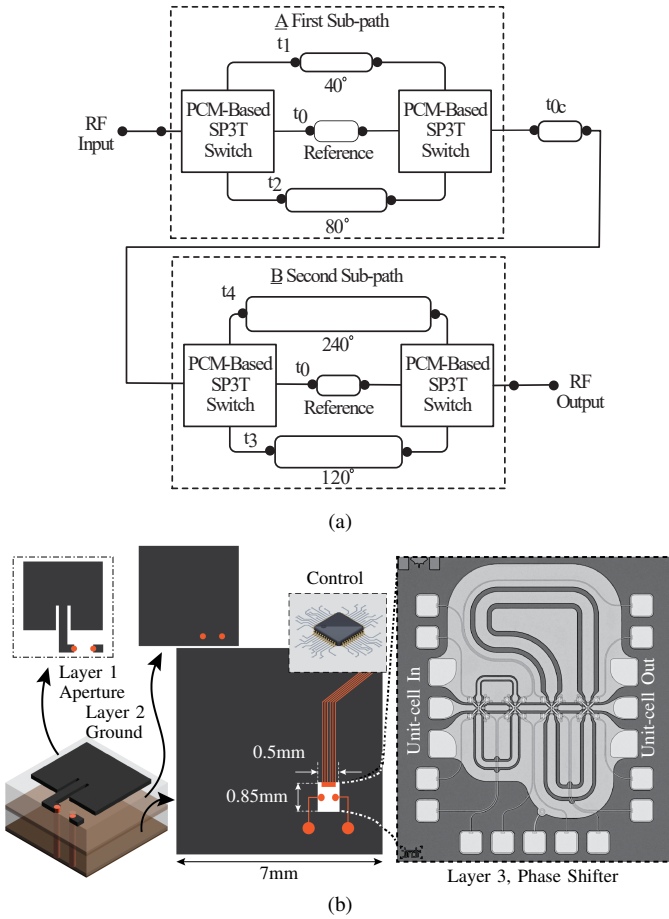


Fig. 2: The proposed reconfigurable unit-cell design with phase-delay element and a RF phase shifter: (a) The operating principle of the phase shifter, with a variable of stub length and switches. The combination provides a digitalized phase variation with a maximum range of 180° and a step of 20° . (b) The proposed 3 layer unit-cell design. The use of PCM based phase-shifter provides a compact design, with its size within $0.5 \text{ mm} \times 0.85 \text{ mm}$. The optical micrograph of the phase-shifter RFIC is shown on right.

B. Proposed design

In the existing literature, the phase-delay elements are commonly static with applications in higher frequency or cost reduction with lower fabrication precision [2]. A reconfigurable unit-cell based on chalcogenide phase-delay element is hence proposed as shown in Fig. 2. The reconfigurability is achieved using a chalcogenide based monolithic phase-shifter RFIC. The operating principle is shown in Fig. 2 (a). Multiple stubs with different lengths connected to the delay line are controlled by chalcogenide SP3T switches. The integration of SP3T switches offers a monolithic design, providing advantages in terms of compactness and a low profile compared to the use of off-the-shelf components. The chalcogenide phase shifter is confined within the dimensions of $0.85 \text{ mm} \times 0.5 \text{ mm}$, making it particularly advantageous for mmWave applications where unit-cell periodicity is reduced.

The measured response of the back-to-back connected chalcogenide SP3T switches in various states is shown in Fig. 3 with common input connected to the RFC port, highlighting exceptional low-loss performance at 30 GHz with

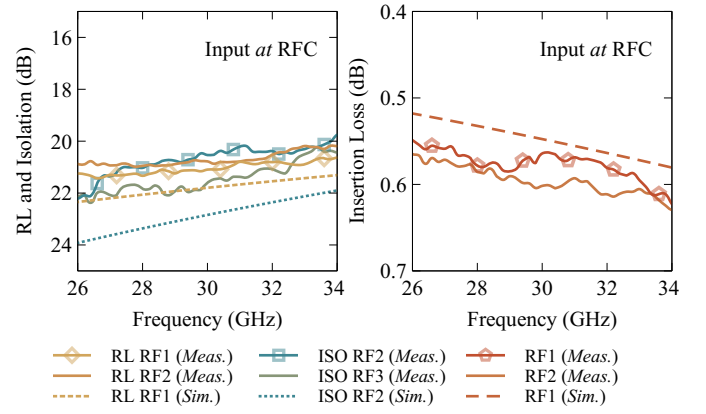


Fig. 3: Measured S -parameters of the integrated SP3T chalcogenide switches.

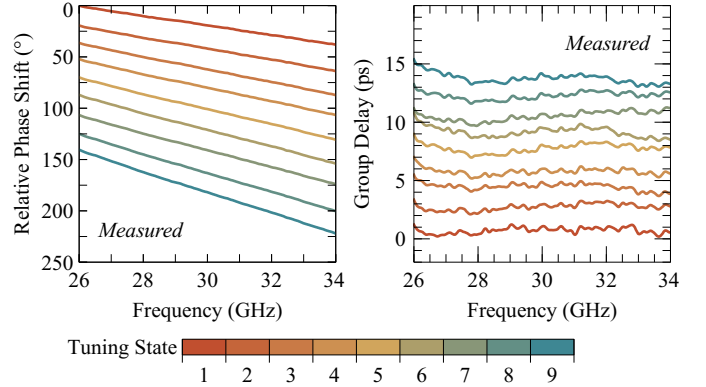


Fig. 4: Measured relative phase and group delay of the monolithic chalcogenide phase shifter.

8 GHz bandwidth. The measured relative phase response and the group delay of the phase-shifter RFIC is shown in Fig. 4 demonstrating linear quantized 3-bit broadband operation and precise delay variation in different tuning states.

III. CONCLUSION

A chalcogenide based fully integrated approach of designing RIS unit-cells is presented. The integration approach is detailed with measurement results and comparison to the typical phase-delay element approach. The presented monolithic integration offers various benefits in terms of energy efficiency, cost reduction, quantized tuning states and mmWave operation with ultra-low loss over the operation band.

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