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Multilayer Rotman Lens Fed Antenna Array for System Packaging

#Jaeheung Kim [1], Woosung Lee [2], and Young Joong Yoon [2]
[1] Yonsei Inst. of Convergence Technolgy, Yonsei University
162-1, Songdo-dong, Yeonsu-gu, Incheon, 406-840, South Korea, jaeheung@yonsei.ac.kr
[2] Dept. of Electrical and Electronic Engineering, Yonsei University
134 Shinchon-dong, Seodaemun-gu, Seoul, 120-749, South Korea
[2]pinkallure@yonsei.ac.kr, [2]yjyoon@yonsei.ac.kr

1. Introduction

The millimeter-wave applications attract more research due to the advance of microelectronics at higher frequencies. They have beneficial aspects such as compact size and wide bandwidth, which are favorable for both communications and radars. In many applications, a beamformer is required to generate beams that are manipulated. At the system level, electronic packaging technology is driving towards packing more components in limited space to facilitate the design of compact systems. The packaging technology is focused on MMIC package, system-in-package (SiP), and system-on-package (SoP) [1]. Of particular interest in this research is how to design the lens to pack into system package. In this paper, two types of multilayer lenses have been presented. One is a two layer Rotman lens antennas and the other is a three layer asymmetrical feeding Rotman lens.

2. Two Layer Rotman Lens Fed Antenna

So far, a Rotman lens has been typically designed on a single layer with antennas. A simple approach to reduce the size is to use a high dielectric substrate, but the degree of reduction is limited [2]. The multi-layer implementation of the lens-fed antenna array would be favorable in the era of SiP, which is an easy way to realize a beamforming module. The design of the constrained lines and the connections between the Rotman lens and radiating elements is a new contribution, and will be demonstrated. It will also be useful for applications in which a surface mount is required because the lens system has a low profile and occupies a relatively small area. The lens-fed antenna array was designed in the form of a two-layer structure as shown in Fig. 1. The lens body is placed on a bottom metal layer, and the antennas are placed on a top metal layer. Therefore, the lens body and the antenna array are separated by a common ground plane, and the slot-coupled transitions are used to feed the lens and antenna array through the common ground.

The concept of a two-layer structure is an elegant approach for size reduction. As shown in Fig. 1, the twofold design can considerably reduce the total size, which is desirable for SiP. Moreover, the proposed two-layer Rotman lens separates the antenna array from the lens body and the constrained lines by a ground plane. The separation is helpful to prevent spurious radiation which may affect the radiation pattern. In addition to the two-layer structure, this work proposed a new approach to shorten the delay lines with less bending. This method can minimize the length of the delay lines and eliminate the meandering part in the delay lines. This is a very effective way to reduce the size of the Rotman lens, since the delay lines generally occupy considerable area in the lens system [3]. The second advantage is the performance improvement due to short, less bent lines. In the case of a bent line, there are spurious radiation and unexpected phase shift along a rapidly bent section. The prototype of the lens consists of seven array ports, five beam ports, and six dummy ports. It was fabricated on an RO3003 substrate whose electric permittivity is 3.0, thickness is 0.508 mm, and loss tangent is 0.0013. Both the focal angle and the corresponding scanning angle are 30° and the spacing between antennas is 0.6 λ_0 at 24 GHz. The diameter of the lens medium is approximately 27 mm and the overall size of the lens including the lens body, ports, and transitions is 75 mm × 80 mm. The lens is fed by 50 Ω microstrip lines whose corresponding width is 1.28 mm.

The performance of the transition across layers is critical to the overall performance of a multilayer system. Typically, the transition can be implemented in forms of vias or slot couplings. Both can be implemented with insertion loss of less than 1 dB at millimeter-wave frequency [4], [5]. In this paper, the slot transition has been chosen to demonstrate the two-layer lens since it can be easily fabricated in an etching process. The measured insertion losses are less than 1.85 dB and the return losses are over 10 dB from 22 GHz to 26 GHz. In addition, the phase change through the transition is stable enough to maintain a true-time-delay line.

In packaging, a microstrip patch antenna is the most favorable candidate because of its low profile and planar structure. To utilize more area of the common ground, a series-fed microstrip patch array has been employed instead of a single microstrip patch antenna. The width of the patch is 4.4 mm and the length is 3.4 mm, designed to resonate at 24 GHz. The series-fed patch array has four patches. The patches are connected in series by a narrow microstrip line because each patch has an input impedance of 360 Ω; hence the width and the length of the line are sensitive to impedance matching and phase distribution. The distance between patches is 3.0 mm and the patches are positioned periodically with a spacing of 6.4 mm (0.512 λ_0 at 24 GHz). The center frequency of the fabricated array met the designed frequency of 24 GHz, with bandwidth from 23 GHz to 25 GHz. Finally, the series-fed microstrip patch arrays were connected to each array port, resulting in a 7 by 4 antenna array.

The two layer lens-fed antenna array was realized in the form of a two-layer structure using two Rogers© RO3003 substrates. The radiation patterns of the fabricated lens antenna were measured in a near field measurement system. All the other ports except the port under test were terminated with 50 Ω loads. The measured beam patterns are compared to the calculated patterns in Fig. 3. In the calculation of beam patterns, the lens-fed antenna array generates five beams at -29.2°, 14.8°, 0°, 14.8°, and 29.2°, respectively. Each beam has a half-power beamwidth of 13.8°, 12.5°, 12.0°, 12.5°, and 13.8°, respectively. The measurements showed that the beam directions are -28.1°, -14.9°, 0°, 15.5°, and 28.6°, respectively and the beamwidths are 13.4°, 13.2°, 12.8°, 13.5°, and 13.0°.

3. Three Layer Asymmetrical Feeding Rotman Lens Fed Antenna

To realize a compact beamforming system, it is necessary to package antennas, a beamformer, and circuits. For multi-layer packaging, three layers should be secured to accommodate the three components in a single package. In general, integrating antennas, a beamformer, and circuits in a single package is challenging because of the complexity involved in the electrical and structural design. In the previous section, a two layer structure was presented. The two layer Rotman lens has two layers for antennas and a lens with a new design of the constrained lines between the Rotman lens and the antennas. However, another layer is required for circuits for a whole system. The design of a beamformer is a key factor to implement a compact package because a beamformer is placed between antennas and circuits. Ground plane and connections at each layer should be deliberately designed to integrate antennas, a lens, and circuits. A three-layer asymmetrical Rotman has been proposed to accommodate a whole beamforming system.

In this paper, a three-layer asymmetrical structure has been proposed to implement a compact lens antenna system. The lens antenna was designed in the form of a three-layer as shown in Fig. 3. The antennas are placed on a top layer and the lens is placed on a middle layer, and circuits are supposed to be placed on a bottom layer. Each layer is separated by a common ground plane and slot-coupled transitions are used to connect between layers through the common ground. Each slot is located at 1.4 mm (about $\lambda_g/6$ at 24 GHz) from the end of a microstrip line for coupling. To secure a common ground plane on both layers of antennas and circuits, the lens is designed to have half of the ground plane on the beam port side and the other half on the array port side.

The design of a three-layer asymmetrical Rotman lens is to realize a whole and compact system. Typically, the circuits occupy small area because most of circuits are integrated in MMIC. The prototype of the lens consists of seven array ports, five beam ports, and six dummy ports. It was designed on three Taconic TLC30 substrates whose electric permittivity is 3.0 and thickness is 0.508 mm. Both the focal angle and the corresponding scanning angle are 25° and the spacing between antennas is 0.6 λ_0 at 24 GHz. The radiation patterns from the simulation are shown in Fig. 4 at 24 GHz.

4. Conclusion

In this paper, compact designs of the Rotman lens-fed antenna array have been demonstrated. From a new design of the constrained lines and the connections, the size of the lens-fed antenna array can be dramatically reduced with short and straight delay lines. In addition, a new design of the asymmetrical feeding structure can secure an additional layer for circuits. The simulation and measurement show that the overall performance of the proposed lenses is in good agreement with the calculation. In conclusion, with the advancement in packaging technologies such as SiP and SoP, both of the designs would be a useful for millimeter-wave system package.

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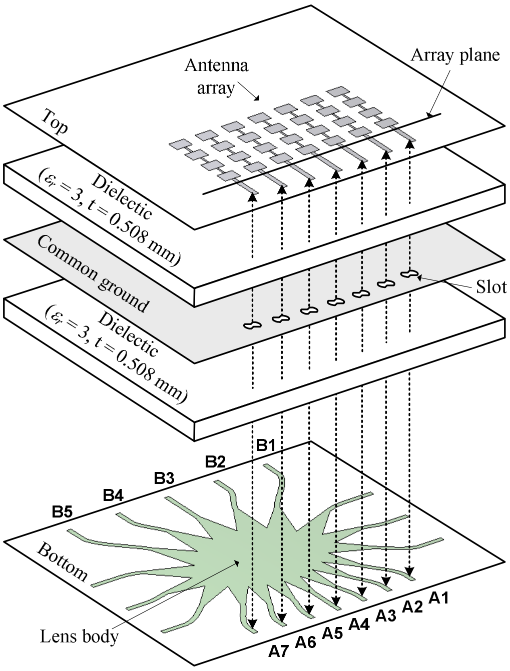

Fig. 1. The geometry of the two layer Rotman lens-fed antenna array

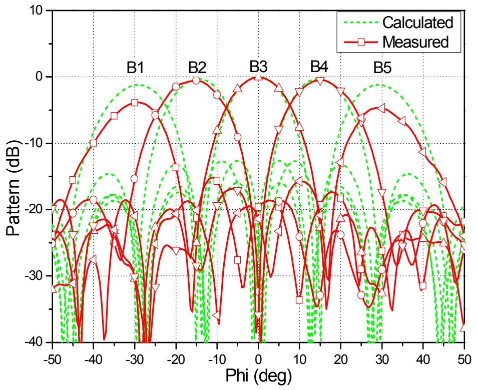

Fig. 2. The measured and the calculated beam patterns of the two layer lens antenna at 24 GHz.

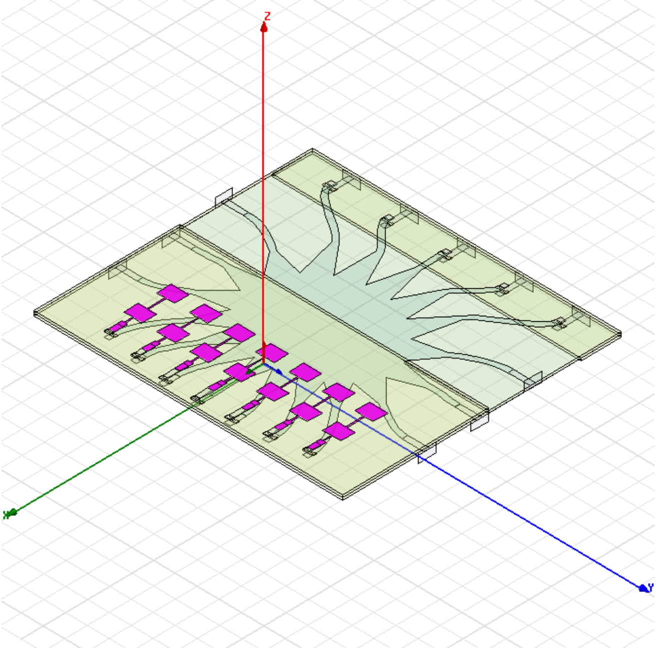

Fig. 3. The geometry of the three layer Rotman lens fed antenna array

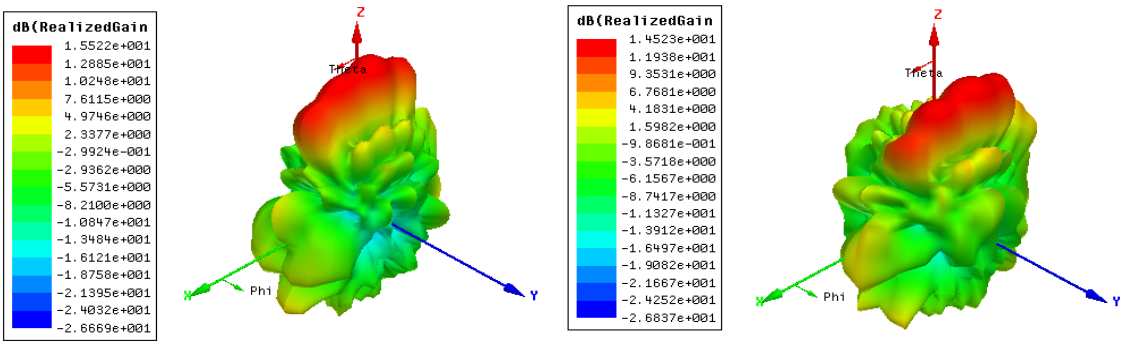

Fig. 4. The beam patterns at the center beam port (b3) and the outer beam port(b1)

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