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A Ka-Band Phased Array RF Front-End Module Based on 3D Heterogeneous Integration

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Abstract: In response to the demand for low-cost 3D heterogeneous integrated RF front-end and phase-controlled arrays, an integration Ka-band phased array RF front-end module based on 3D-integrated packaging is proposed in this paper. It can realize the miniaturization of the RF front-end system, greatly reduce the volume and weight of the radar system, and effectively control the total cost. The proposed module consists of final power amplification, drive amplification, low noise reception, phase shift, and attenuation control. The electronic scan range of this module is greater than 15° within the 32-38 GHz frequency passband.

Keywords. Ka-band, Phased Array, 3D heterogeneous integrated, RF front-end

1. Introduction

Millimeter wave phased array radars have the advantages of high angular resolution, high angular measurement accuracy, and strong target recognition ability. To realize remote detection, the number of integrated antenna units in the RF front end can reach millions [1-4]. The element spacing of phased array radar has a direct impact on the resolution of the radar, which should be less than half the wavelength. Therefore, the size of the RF front-end module and antenna feeding structure will seriously impact the overall performance of the radar system. The traditional packaging and integration method has low integration, high weight, and high cost, which seriously restricts the application of millimeter wave phased array radar. At present, the system-level 3D heterogeneous integrated active subarray is the most potential realization form of a thin, multi-functional, integrated, and highly integrated radar array [5-10].

In this paper, an integration Ka-band phased array RF front-end module is proposed to realize the miniaturization of radar RF front-end. The RF front-end module with 64 channels is based on the 3D silicon heterogeneous integrated design, including amplitude and phase control and transceiver amplifier chip, and the amplitude and phase of each channel can be adjusted independently. The 3D heterogeneous integration architecture designed in this paper can improve electromagnetic compatibility performance. In the operating frequency band of 32-38 GHz, the electronic scan range is ≥15°.

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2. Module Construction

Considering the low cost, high integration, and miniaturization design of the RF front-end TR module, a silicon-based through silicon via (TSV) transfer board is proposed for 3D heterogeneous integration. The functions of low noise amplifier, amplitude and phase control, and power amplification are integrated into a single module with ball grid array (BGA) packaging. Considering the simplicity, a quarter module of the schematic diagram is shown in Figure 1. The millimeter-wave RF front-end system is a transceiver module, among which the receive links realize the function of low noise amplification at the high-frequency band, the transmitting links realize the function of carrier frequency amplification, and the power control circuits have the function of working channel selection, power supply voltage regulation, filtering, and power modulation.

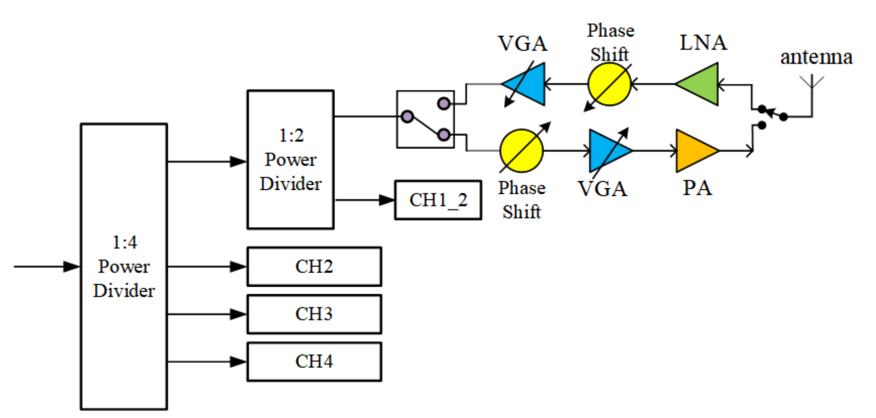


Figure 1. Schematic diagram of the quarter module

The structure of the RF module is shown in Figure 2, which is implemented based on silicon packaging technology. The module consists of an RF front-end layer and microstrip array antenna layer, which are vertically interconnected through BGA to achieve telecommunications interconnection. The redistribution layer on the chip and through silicon via interpolator is bonded with gold wire for signal transmission to the ball grid array on the back and finally transmitted to the array antenna. The layout of the RF front-end feeding network is shown in Figure 3. The three major functional layers of microwave, digital, and power are integrated into the network. The microwave layer contains three functional circuits of the leading signal power division synthesis network, aperture transformation network, and microstrip array antenna. The low-frequency layer contains several functional circuits of the power distribution network and beam steering distribution network. The TR components, power-supply chips, beam steering chip welding pads, and interfaces are integrated into the PCB layer. The common ports of the TR component are connected through the feeding network to form the total output port. The input and output ports of the power divider are converted into microstrip lines through vertical transition and connected to the external signal.

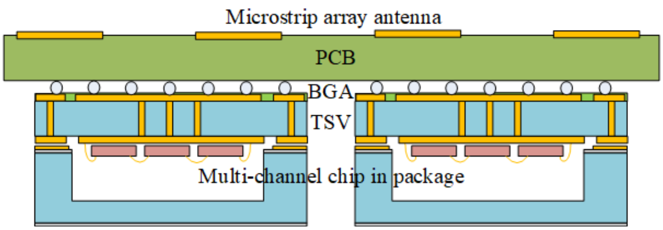


Figure 2. Structure of the RF module

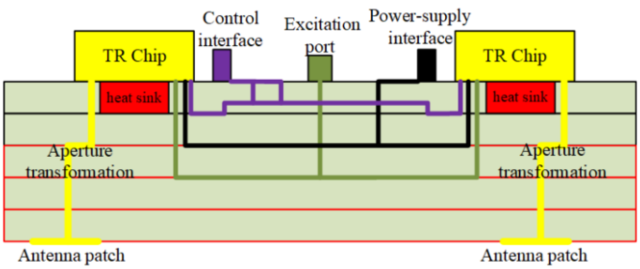


Figure 3. The layout of the RF front-end feeding network

3. Module Design

3.1. Antenna array design

In this device, a bow-tie antenna is proposed to design the antenna unit. The performance of broadband and wide scan angle can be achieved through the design of distributed antenna units and electromagnetic band gap (EBG). The dielectric substrate is RO6002, with a thickness of 0.762 mm. The antenna unit size is 5.4×5.4 mm^2. Figure 4 shows the simulated results of the Voltage Standing Wave Ratio (VSWR). The VSWR of the antenna unit within a two-dimensional ± 15 scanning range is less than 1.5.

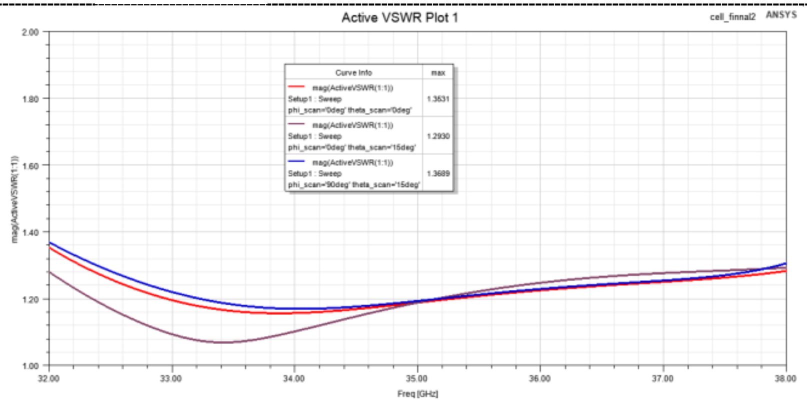
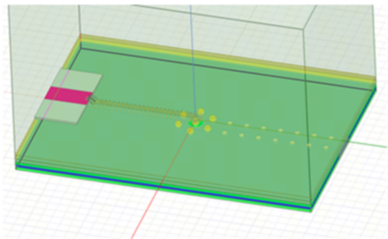


Figure 4. Simulated results of VSWR

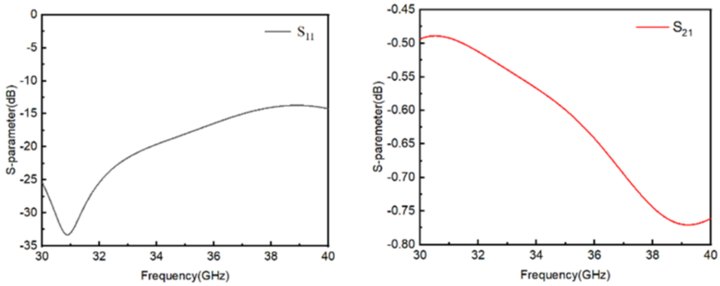
The 8×8 array antenna can be formed by expanding the designed antenna unit. Due to the difference between the output port of TR components and the feeding port of the array antenna, it is necessary to design an aperture transformation network. Phase compensation is performed in the phase shifter unit of the beam steering chip to compensate for the difference in the feeding phase.

3.2. Interconnection circuit

Based on the module structure design and the RF integration technology of the TSV adapter board, two vertical transition structures are designed to realize the communication between units. The silicon chip to PCB microstrip vertical transition structure and GaAs chip to PCB microstrip vertical transition structure are shown in Figure 5 (a) and Figure 6 (a). The height of the gold wire is 0.2 mm, and the horizontal length is 0.3 mm. The simulated S-parameters are depicted in Figure 5 (b) and Figure 6 (b), within the 32-38 GHz frequency passband. The return losses (S11) are less than -14 dB and -15 dB, and the insertion losses (S21) are greater than -0.74 dB and -0.64 dB, respectively.

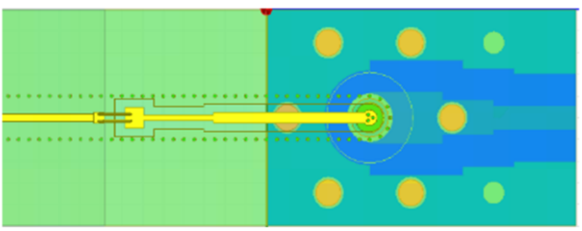


(a) Silicon chip to PCB microstrip structure

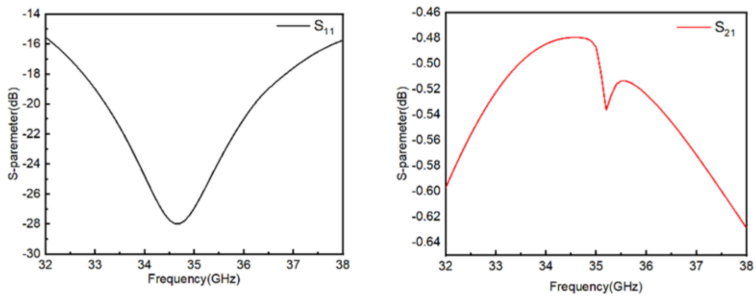


(b) Simulated results

Figure 5. Silicon chip to PCB microstrip vertical transition structure and simulated results



(a) GaAs chip to PCB microstrip structure



(b) Simulated results

Figure 6. GaAs chip to PCB microstrip vertical transition structure and simulated results

3.3. Silicon-based substrate fabrication

High-resistance silicon material is selected as the packaging material. Considering manufacturing process capabilities and signal transmission requirements, the thickness of silicon substrate is 200 μm and the diameter of through silicon via is 30 μm. The silicon-based substrate manufacturing process flow with TSV is shown in Figure 7: (1) TSV on the upper surface of below adapter board; (2) Top wiring; (3) Temporary bonding and backside thining; (4) Top wiring; (5) De-bonding; (6) Etch cavity on the upper adapter board and deposition passivation layer; (7) Top wiring; (8) Chip bonding and adapter board bonding; (9) BGA mounting.

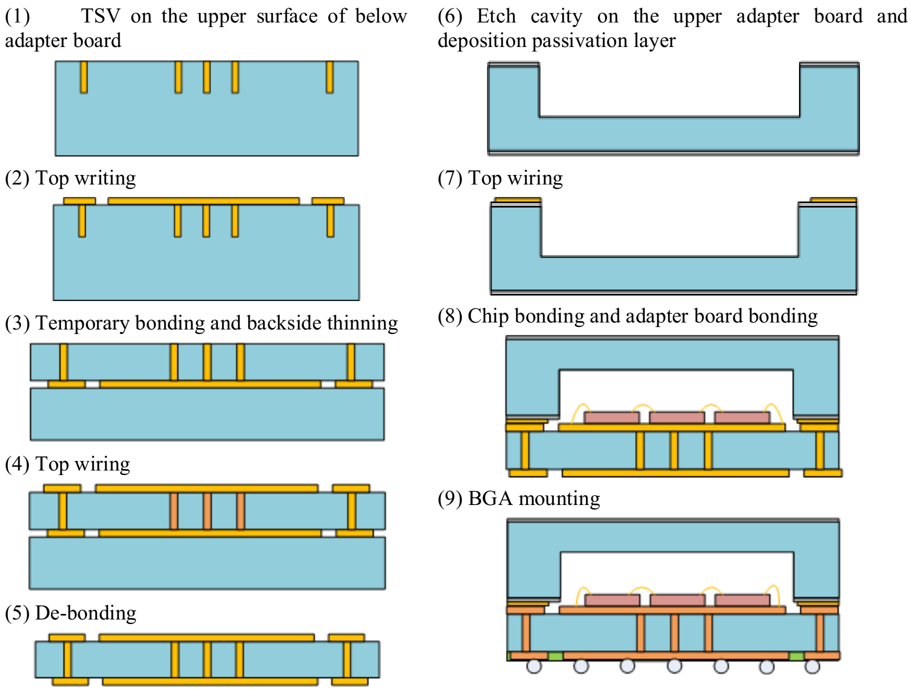


Figure 7. Silicon-based substrate manufacturing process flow

4. Conclusion

Due to the requirements of low cost, high integration, and miniaturization of RF micro-systems, a 3D encapsulated Ka-band RF micro-system based on TSV is proposed in this paper. The RF front-end architecture integrates the microstrip array antenna with silicon-based 3D packaging, significantly reducing the cost of the RF front end, improving system integration, and reducing interconnection loss. It can effectively achieve a dense array design of the RF front-end and promise broad application prospects in high-performance radar communication.

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