Silicon-based on-chip four-channel phased-array radar transmitter with ferroelectric thin film at 100 GHz

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Abstract: A silicon-based phased-array transmitter working at 100 GHz is proposed in this study. Planar array ferroelectric film phase shifters (FPSs) are realised with patch antennas, DC bias lines, microstrip lines and power dividers on a monolithic silicon substrate. The system enables full process compatibility and avoids loss caused by multichip interconnection. The isolation layer uses benzocyclobutene polymer film with low permittivity and low loss tangent, providing large thickness physical isolation. The FPS has a compact length of 0.45 mm, and simulation results show that its phase shift degree at 100 GHz is 125.7° with 3.95 dB insertion loss and 11.4 dB reflection loss. The patch antenna shows that the maximum simulated radiation gain of the single antenna is 4 dBi and the four-element antenna array is 9.7 dBi at 100 GHz. The beam can be steered to ±10°. The proposed system lays an important foundation for the realisation of silicon-based system-on-chip radar RF front-end system.

1 Introduction

Phased-array radar has been widely used in modern military and civil fields such as battlefield recognition, airport security, anti-terrorism detection and space attack/defense. If phased array radars’ frequency band moves towards W-band (75–110 GHz), they will be beneficial to detect through barriers, high-resolution imaging [1] and equipment miniaturisation [2].

The design of radar compatible with the standard CMOS technology allows the production of fully integrated radar transceivers with mature and cheap fabrication. When the frequency band of phased array radar is raised to W-band, the reduction of device size makes it possible for the whole system implemented on a silicon chip.

Phase shifters (PSs) with scanning capability are one of the important building blocks. There are various types of phase shifters such as CMOS-, MMIC-, MEMS-, liquid crystal-, and ferroelectric-based designs. Among them, barium–strontium-titanate (BST) film PSs have been widely investigated in monolithic phase shifter modules [3]. BST is a ferroelectric material with DC voltage-related permittivity [4]. BST film in paraelectric phase exhibits high permittivity and low losses among high frequencies [5]. Generally, PSs based on BST films have the advantages such as large power capacity, small size, simple structure, easy fabrication, convenient tuning, low insertion loss and large phase shift degree. In this paper, BST ferroelectric thin film is used as the tunable material to constitute a FPS.

A 100 GHz phased-array transmitter front end can be seen in Fig. 1 with ferroelectric film phase shifters (FPSs), DC bias lines, patch antennas, microstrip lines and power dividers. It consists of three layers of metal. Commercial BCB (benzocyclobutene) polymer thin film is used as the isolation layer with low permittivity, low loss tangent (εr = 2.85, tan δ = 0.005@100 GHz) and good chemical and thermal stability, which is also used in microelectronic packaging and interconnection applications [6].

To characterise on-wafer microwave integrated circuits, probe stations are required [7]. Most of these test systems are equipped with probes compatible with CPW transmission lines to ensure a good reliability of the electrical contact. The input part of the feed network adopts the CPW structure, which is convenient to connect probes.

2 Ferroelectric film phase shifter

Ferroelectric film phase shifter (FPS) adopting right-handed transmission line structure is suitable for silicon-based planar technology and working at W-band. The right-handed transmission line-based phase shifter takes parallel capacitance and series inductance as the basic unit. Fig. 2 shows the layout of the distributed FPS, consisting of 11 periodical cells. The CPW transmission line is periodically loaded with tunable BST capacitors by using inter-digital electrodes drawn from the signal line and ground lines. The width of the inter-digital electrode is 3 μm, and the length is 70 μm. The FPS adopts 500 μm thick high-resistivity silicon (hrSi) substrate with the relative permittivity of 11.7 and the dielectric loss tangent of 0.24, and a 0.37 μm thick golden conductor with the bulk conductivity of 4.1 × 107 S/m. The 0.5 μm bottom BST thin film is fabricated on a hrSi substrate with relative permittivity of 250 at 100 GHz and dielectric loss tangent of 17.5%. The tunability of BST thin film is 40%, which means that the permittivity of BST film varies from 250 to 150 with DC
bias [8]. The total length of FPS is only 0.45 mm, which is really compact.

The FPS was simulated using the 3D finite element method simulation tool. We performed a W-band simulation with distributed metallic circuitries on a hrSi substrate including a BST layer. 150 and 250 are used to represent the permittivity of BST thin films with and without DC bias in simulation. When the electric field intensity is 20 V/μm, the permittivity of BST is reduced to ∼150, which results in the phase shift. Meanwhile, the insertion loss also changed. The electromagnetic simulation results are shown in Figs. 3 and 4. The phase shift degree at 100 GHz is 125.7°. A $|S_{21}|$ of 3.95 dB and a $|S_{11}|$ of 11.4 dB can be seen at 100 GHz.

### 3 Four-channel antenna array

To assess the beam-steering capability of antenna array with integrated FPSs, a four-channel microstrip antenna array was designed on a 20 μm BCB polymer film. The experimental results show that the BCB substrate dielectric constant is 2.85 for W-band and the dissipation factor is 0.005 at 100 GHz. The four-channel passive antenna array was designed to evaluate the overall performance including power dividers, antennas, and transmission lines, as shown in Fig. 5.

The input signal is split to feed four patch antennas using three power dividers. The power dividers split the power equally and all elements in the array are excited in-phase. All ports in the feed network are 50 Ω. The construction of 100 Ω Wilkinson power divider is very difficult at 100 GHz. Therefore, we use quarter-wave matched T-junction divider to constitute the feed network, as shown in the inset of Fig. 5. The impact of 90° bends is significant, so tapered transmission lines are used at 90° corners. Therefore, the optimisation of the overall circuit is performed by considering the bends and length of the quarter-wave transmission lines with fixed width for each power divider to achieve port matching. Power dividers and the feed network were optimised with simulator. Simulated S-parameters of the feed network for return loss $|S_{11}|$, insertion loss ($|S_{21}|$), and isolations ($|S_{32}|$ and $|S_{42}|$) are 22 dB, 6.23 dB, 18.5 and 15 dB at 100 GHz, respectively. Since this is a four-port output network, the ideal lossless value of $|S_{21}|$ is 6 dB.

The layout of the four-channel antenna array was simulated. The space between adjacent antennas is 1.8 mm. Fig. 6 shows the simulated results of $|S_{11}|$ among 90–110 GHz. Scattering parameter results state that both the proposed single and four-channel antennas resonate at 100 GHz. The return loss of single patch antenna is >35 dB with 1.6 GHz bandwidth. The simulated two-dimensional radiation patterns of the single- and four-channel patch antennas in XoZ-plane and YoZ-plane are presented in Fig. 7. The proposed design has a simulated gain of 4 dBi for single-patch antenna and 9.7 dB for four-channel antennas array, respectively.

### 4 Four-channel phased-array transmitter

Integrating FPS before each antenna input allowing beam steering along the direction, on which the antennas are aligned (XoZ-plane). Noteworthy, each FPS needs to connect a DC bias (red lines shown
in Fig. 1) so as to implement the phase shift function, so four DC lines are needed in total for beam-steering. The DC lines wired on the third metal layer can cause the crossover between DC and RF lines. The 5 μm BCB polymer film is used to insulate between the second metal layer and the third metal layer.

Transmitting beam steering simulations show the beam-forming functionality over a −10°–10° range at 100 GHz with FPSs (shown in Fig. 8a). Table 1 shows the input signal of each antenna when the maximum angle of antenna composed beam is scanned. The RF signal is transmitted to four branches with equal amplitude and phase. After the signal of each channel pass through FPS, the phase and amplitude changed simultaneously. The insertion loss of FPS decreases from 4 to 1.5 dB when the BST permittivity changes from 250 to 150. Therefore, we use 4–7 W to represent the changes of signal powers. Meanwhile, the signal phase changes from 0° to 120°. In order to analyse the influence of the difference of signal amplitudes on antenna beam-forming, simulations have been conducted with and without the diverse of the signal amplitude of each branch. Simulation results are indicated in Fig. 8b, which shows that the different signal amplitudes of various branches have little effect on the overall antenna composed beam. Therefore, the diversity of the signal powers caused by FPS in the phase shift process can be ignored.

5 Conclusion

This paper presents a fully integrated silicon-based four-channel phased-array transmitter for 100 GHz radar system. The chip occupies an area of 8.5 × 4.5 mm² with ferroelectric thin film phase shifters, DC bias lines, patch antennas, microstrip lines and power dividers. The phase shifters can modulate the signal phase continuously with ferroelectric thin film and DC bias and has an insertion loss of 3.95 dB at 100 GHz with 125.7° phase shift degree. The on-chip patch single antenna has a gain of 4 dBi with the return loss of 35 dB. The layout of the full chip is presented. The fabrication of the system is now under progress.

6 References

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