On-Chip Miniaturized Cavity V-Band Coplanar Folded Slot Array with High Efficiency and Reduced Mutual Coupling

Seung Yoon Lee, David L. West, Sree Adinarayana Dasari and Nima Ghalichechian

Abstract— We present a V-band 1×8 on-chip miniaturized cavity coplanar folded slot antenna (CSFA) array with high efficiency and reduced mutual coupling. Substrate-integrated air cavities (SICs) are used to enhance efficiency and gain, diminish element-to-element coupling, and counter parasitic parallel-plate modes to improve CSFA efficiency. We developed CPW corporate feeds using SiO2 bridges and rounded bends to demonstrate beamsteering. The E and H-planes of the radiation pattern were measured with a custom robotic setup. The measured CSFA single element −10 dB bandwidth is 55.4–60.3 GHz (8.5%) with an efficiency of 93%. The measured broadside array’s bandwidth spans 52–60.2 GHz (14.6%), with a total efficiency of 67% and 11.0 dB gain. This study marks the first demonstration of beamsteering using on-chip antennas with SICs, steering up to 45°, and corresponding gains of 8.1, 8.9, and 9.2 dB.

Index Terms— on-chip antenna, high efficiency, phased-array antennas, millimeter-wave (mmWave) antennas, V-band.

I. INTRODUCTION

The cumulative monthly mobile network traffic for various generations including mobile 2G/3G/4G/5G and fixed wireless access (FWA) 3G/4G/5G is projected to reach 210 exabytes (10^18 B) by the end of 2024, escalating to 563 exabytes by 2029 [1]. Despite the potential of the 60 GHz unlicensed band for advanced high-speed communication systems, certain theoretical challenges exist. Notably, the 60 GHz band faces significant signal losses, with free space path loss exceeding 26 dB compared to the 2.4 GHz band. To increase the transmit and receive power of communication systems at 60 GHz, there is a need to develop V-band antenna arrays with beamforming capabilities that can be monolithically integrated into silicon chips, ensuring high radiation efficiency.

Leveraging silicon as an antenna substrate enables the monolithic integration of on-chip antennas (OCAs) with mmWave circuits without the need for heterogeneous integration. Unlike antennas based on other substrates, such as PCB [2] or glass [3], silicon-based OCAs do not require lossy interconnections like flip chips or wire bonds to integrate large arrays with silicon-based beamforming integrated circuits (ICs). Plus, silicon substrates with diverse characteristics can be accessed through collaborations with foundries, including CMOS [4], [5] and SiGe HBT BiCMOS [6], [7]. The high permittivity and low resistivity of silicon cause surface waves and thermal losses; as a result, OCAs on silicon often exhibit <10% radiation efficiency [8].

Fig. 1 illustrates ongoing efforts to address the low efficiency of OCAs in the V-band. An efficiency of 79% was achieved by bonding a dielectric resonator atop the antenna, reducing back radiation and enhancing efficiency [9]. Ion implantation was used to achieve a 59% efficient silicon-based dipole antenna [10]. Radiation efficiencies of 27.5% have been demonstrated using off-chip electromagnetic band gap structures [11]. Fig. 1 reveals a lack of V-band high-efficiency OCA arrays compared to single-element counterparts. Our group’s

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II. ANTENNA DESIGN CONSIDERATIONS

This research presents an innovative method that combines a backside conductor with a miniaturized SIC beneath a CFSA to enhance its radiation performance. Typically, a backside conductor placed under the coplanar slot antenna is expected to increase the gain by creating a unidirectional radiation pattern. However, traditional slot antennas with backside conductor experience up to a 50% efficiency loss due to the excitation field in the slot contributing to the parallel-plate TEM mode [18]. This issue has been addressed by employing metasurface [18], [19] or TEM mode phase cancellation [19]. Unlike prior work, the SIC introduced in this study is utilized in the slot antenna to effectively diminish both surface waves and TEM modes due to the Si-air-Si boundary in antenna substrates [20]. Furthermore, the antenna's miniaturized robust cavity, which is 3 to 20 times smaller than those of other planar antennas, achieves high efficiency. Integrating a backside conductor with a miniaturized cavity structure under a CFSA suppresses the TEM mode, fostering unidirectional radiation.

A. Coplanar Folded Slot Antenna Structure

Coplanar dipoles and slots are both attractive CPW-fed antenna architectures, but the requirement for a balanced feed line puts the dipole at a disadvantage. Consequently, various coplanar slot antenna structures have been explored in the literature, such as shared-aperture cavity [21], tunable matching network [22], and phase-change materials [23]. We provide a detailed examination of the CFSA's antenna structure. Fig. 2 shows a proposed CFSA design featuring a SIC and backed conductor. The CFSA conductor layer is composed of a layer of Ti/Cu. Silicon serves as the dielectric medium for the SIC and backed conductor. The CFSA conductor layer is fabricated beneath the CFSA using DRIE process, shown in Fig. 2(b). The remaining 10 μm thick silicon layer after the DRIE process serves as the structural foundation for both the slot antenna and the coplanar ground.

The fundamental resonance frequency ($f_r$) of a CFSA is theoretically related to the slot antenna's circumference $C = 2(W + L + G_L + G_B)$ and its relative permittivity ($\varepsilon_r$) as described in

$$f_r = \frac{c}{C} \sqrt{\frac{1 + \varepsilon_r}{2\varepsilon_r}}, \quad (1)$$

where $c$ represents the speed of light in a vacuum. Eq. (1) is used to derive analytical preliminary dimensions for the folded slot's length ($L$) and width ($W$), as well as the gap ($G_L, G_B$) between the coplanar ground and the folded slot antenna. The design dictates that $L$ is 11.6% of $W$, aiming to lower the cross-polarization level (x-pol). The $G_L$

| TABLE I
<table>
<thead>
<tr>
<th>SINGLE ELEMENT DESIGN PARAMETERS</th>
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<tr>
<td>Dimension (μm)</td>
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<tr>
<td>$W_{ew}$</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>2500</td>
</tr>
<tr>
<td>2036</td>
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</tr>
</tbody>
</table>

B. Miniaturized Cavity Design

The CFSA can be designed with dimensions of $W \times L = \lambda_o/2 \times \lambda_o/20$, diverging from the conventional patch antenna design approach with dimensions near $\lambda_o/2$, due to the resonance being determined by the slot circumference and a minimized length to maintain linear polarization. This design strategy significantly reduces the cavity's footprint beneath the slot, thereby enhancing mechanical stability. The cavity of the proposed CFSA measures approximately 0.03λ_o^2, marking a 3 to 20-fold decrease in size compared to the group of similar antennas [14], [24] depicted in Fig. 3(a). Its radiation efficiency is observed to be about 1.6 times greater than that of others with comparable cavity dimensions [25-27]. Hence, the proposed CFSA configuration, equipped with a backside reflector and minimized $P_{back}$, achieves comparable radiation efficiency with a small cavity.

III. LINEAR 1×8 ARRAY DESIGN

A. Mutual Coupling Reduction

The analysis of mutual coupling in slot antenna arrays is conducted by evaluating the scattering parameters $S_{nn}$ for $n \neq m$. The construction of the CFSA array shows high mutual coupling,
attributed to the narrow gap between adjacent slot edges, measured at 0.35 mm (0.07λ). In conventional antennas, mutual coupling, particularly from substrate modes, influences the reflection coefficient. At the resonant frequency of 60 GHz, significant mutual coupling between port 3 and 4 of up to −13.4 dB is observed in Fig. 3(b) when the source magnitude and phase at other ports are identical. To counteract coupling induced by substrate modes, additional SICs were placed between the array elements shown in Fig. 3(b), thereby diminishing the mutual coupling magnitude. SICs located outside of the CFSA element in the x-direction diminish the coupling compared to when the cavity is filled with silicon, thereby reducing mutual coupling within the array elements. This modification reduced the reflection coefficient to −19.3 dB at 60 GHz. The cavity's impact on isolation reduction becomes less significant above the center frequency due to its interaction with the reflection coefficient. The mutual coupling characteristics between port 1 and 2 are also reported, as shown in Fig. 3(b).

B. CPW-based Corporate Feed Design

We chose an array size of 1×8 CPW-based corporate feed, which is sufficiently large enough to demonstrate beamforming and scanning. Generally, designing such a CPW-based corporate feed can be accomplished using a multi-layer approach with a via process. This involves densely integrating vias connecting the top and bottom ground planes of CPWs, resulting in a grounded CPW configuration that mitigates parasitic parallel plate modes. However, for antenna designs employing silicon as a dielectric medium, like the proposed CSFA, this method mandates the use of a through-silicon via (TSV) process.

The absence of TSV simplifies the fabrication process, yet introduces challenges in the CPW feed design. CPW-based corporate feeds exhibit varying electric field distributions due to differences in ground-to-signal spacing, particularly at T-junctions or 90° bends, leading to phase front disparities [28]. In 1×2 array configurations, equal surface current distribution can be achieved using a bridge that equalizes the potential at the T-junction with tapered impedance transformers. However, for larger arrays like 1×4, unequal electric field distribution at the 90° bends also manifests at the output stage, as illustrated in Fig. 4(c). The uneven division is exacerbated as array size increases. We propose that by combining bridges and rounded bends, phase front alteration can be effectively counteracted, enabling uniform signal amplitude. Fig. 4(a) and (b) present the optimized 1×4 array design, showing improved field distribution equality compared to the traditional 90° bend shown in Fig. 4(c). Fig. 4(e) displays the unequal electric field distribution of the output ports from a 1×4 CPW corporate feed without using the SiO2 bridges.

Fig. 5(a) shows an in-phase 1:8 corporate power divider with round bends and stepped SiO2 bridges. SiO2 bridges were implemented to connect the CPW ground planes, positioned atop the SiO2 dielectric layer with a set height of 1 μm. By incrementally adjusting the signal line width of the SiO2 bridge, the capacitance between the bridges and the CPW signal line was effectively minimized, thereby reducing insertion losses without altering the corporate divider width. Proposed stepped SiO2 bridges (Fig. 5(b)) and rounded bends (R = 500 μm) (Fig. 5(c)) were incorporated into the 1×8 array, with precise specific dimensions provided in Table II. The average insertion loss in the 1×8 corporate network is 0.23 dB/mm for a total of 2.4 dB shown in Fig. 4(d).

C. Beamforming Simulation

Fig. 5(a) illustrates the in-phase 1:8 feeding network, while Fig. 6(a)-(c) displays the network with predefined sequential phase delays for 15°, 30°, and 45° beam scanning. Fig. 6(d) shows that the simulated −10 dB impedance bandwidth for the broadside array spans 56 to 65 GHz, and for the 45° beam steering arrays, it extends from 55 to 67 GHz. Fig. 6(e) presents the co-polarization (co-pol) beamsteering patterns from 0° to 45°. The simulated realized gain for the OCA 1×8 linear array is 11.2 dBi, with 71% efficiency. The simulated gains for beam steering at 15°, 30°, and 45° are 9.9, 9.6, and 9.0 dB, respectively, with efficiencies of 63%, 66%, and 60% at the central frequency of 60 GHz.

IV. MICROFABRICATION PROCESS

The fabrication process flow is shown in Fig. 7. A float zone Si wafer with a resistivity of 10² Ω-cm is chosen as the substrate to reduce losses in the CPW 1×8 divider. NR9-1500PY negative...
photoresist is applied with a thickness of 3 μm to accommodate the 1 μm thick conductor layer. The initial conductor layer consists of a 20 nm Ti adhesion layer and a 1 μm thick Cu layer, deposited through evaporation. The CFSA single element and array patterns are created using a lift-off process. SiO2 is then deposited via plasma-enhanced chemical vapor deposition (PECVD). A 1.3 μm thick S1813 positive photoresist is patterned, followed by a reactive ion etch (RIE) to pattern the SiO2 layer to form the SiO2 bridge. The second metal layer of Ti/Cu is sputtered to the same thickness as the first layer. The SiO2 bridges are fabricated using a wet etch process, employing aluminum etchant type A for Cu and buffered oxide etch for Ti. For the SIC, a 6 μm thick SPR220 positive photoresist is patterned on the backside, and DRIE is performed with an Al2O3 carrier wafer to create the 290 μm SIC. The back conductor at the CFSA’s rear is fabricated by replicating steps 1–4 with a fused silica wafer. The Si wafer is placed on top of the fused silica, with the backside grounds aligned with the slot antennas. Fig. 8 illustrates optical micrographs and scanning electron micrographs (SEMs) of the fabricated 1×8 broadside array.

V. MEASUREMENT

The radiation pattern measurement involves adjusting the distance and angle between a standard gain horn antenna (SGH), attached to a 6-joint robotic arm, and the antenna under test (AUT) [29], [30]. The AUT is excited by a ground-signal-ground (GSG) probe (Formfactor ACP65-AW-GSG-150). To minimize scattering, absorbers are affixed to several components, including the probe station platens, wafer chuck, and robot. The realized gain is ascertained using the IEEE standard gain-comparison method, which entails comparing the AUT's unknown gain against a SGH’s known gain, as described in

\[ G_{AUT} = P_{AUT} - P_{SGH} + G_{SGH} + L_{probe}, \]

where all values are expressed in decibels. The terms \( P_{AUT} \) and \( P_{SGH} \) represent the power received by the vector network analyzer (VNA) (Keysight N5227B) with the AUT and SGH as the receiving antennas, respectively, while \( G_{SGH} \) denotes the SGH's known gain. \( L_{probe} \) accounts for the GSG probe insertion loss of 0.7 dB. The H-plane’s measurement span is from -60° to +60°, whereas the E-plane is measured from 0° to 44° for a single element and from 0° to 22° for arrays, with the E-plane’s limited scope designed to accommodate the robotic arm’s movement range and mitigate unwanted reflections from the GSG probe.

The measured −10 dB impedance bandwidth for a single element ranged from 55.4 to 60.3 GHz (8.5%), exhibiting a 2 GHz shift compared to the simulation result shown in Fig. 9(a). The simulation, which has been revised to account for the wafer’s actual thickness of 295 μm and the measured \( h_{SIC} \) value of 281.5 μm, exhibits a −10 dB impedance bandwidth from 56.5 to 60.6 GHz (7%). The total measured gain at 58.3 GHz is 6.1 dBi, with an efficiency of 93% calculated from a simulated directivity of 6.4 dBi. In Fig. 9(b) the CFSA array’s measured −10 dB impedance bandwidth varies with beam angle: at broadside, it ranges from 52 to 60.2 GHz (14.6%), and at 45°, from 53 to 59 GHz. The measured total efficiency reaches 67% with a total gain of 11.0 dBi at broadside calculated from a simulated directivity of 12.7 dBi. The OCA radiation pattern has ripples due to interference between the GSG probe, probe station, and AUT that can be constructive or destructive to the signal, particularly in the E-plane where greater ripples are observed, but the overall trend is similar in both simulation and measurement as shown in Fig. 10 and 11. The co-polar results of the 1×8 broadside array demonstrate a high correlation between the measured and simulated data in Fig. 11. The sidelobe levels were recorded between −13 and −15 dB. Elevated x-pol values...
are linked to scattering within the measurement setup. Scattering interference can be further mitigated by using a dielectric chuck or by implementing the GSG-probe feed from the bottom of the chuck.

Fig. 12 depicts the measured beamsteering capabilities of 1×8 CFSA arrays alongside simulated data. Beam steering at 15°, 30°, and 45° yields gains of 8.1, 8.9, and 9.2 dBi, respectively. The diminished gain for certain beam angles can be attributed to interference caused by non-uniform DRIE positioning, which will be further discussed in Section VI. The measured radiation pattern aligns with a cos\(^1.5(\theta)\) taper, suggesting that beam steering up to 53° with 3 dB scan loss is feasible using commercial beamforming ICs.

VI. DISCUSSION AND CONCLUSION

The diminished gain for certain beam angles can be attributed to variations in the DRIE process across the wafer. The utilized wafer had a thickness of 295 μm, with a DRIE etch rate averaging 0.93 μm per cycle. Variations in wafer thickness lead to diminished radiation performance since elements such as the impedance transformer of the T-junction and the radius of round bends are optimized for 300 μm-thick silicon and 290 μm of hSIC at 60 GHz. SIC depth at 17 locations, measured using an optical surface profiler, showed an average of 282.9 μm and a standard deviation of 2.4 μm. Differences in silicon etch depth throughout the wafer and positional discrepancies are inevitable, as detailed in [31]. In the case of the CFSA 15° array located centered-top, the average etching depth was found to be less than expected, at 278.7 μm. This under-etching leads to a decrease in efficiency. Cavity height measurements indicate that at 0°, the average of three readings is 281.7 μm, closely comparable to 282.4 μm at 45°. At 30°, the average of the three data points is 285.4 μm, which indicates over-etching compared to the broadside array's average depth. The hSIC's susceptibility to non-uniform DRIE positioning causes a shift in resonant frequency. This shift raises the average insertion loss at 60 GHz in the optimized integrated feed, reducing the realized gain.

Table III presents a comparative analysis of OCA structures with SICs. Notably, most research focuses on single element designs, with no studies exploring beam steering capabilities. We successfully extended beam steering up to 45° using CFSA array with minimized cavity structures. We reported a 93% radiation efficiency and a 6.1 dBi gain for a single element, which is notable relative to other studies with comparable cavity areas. We note that there are few other studies on arrays with cavity structures, limited to 1×2 and 2×2 arrays, which are listed in the table for comparison [14], [32]. Leveraging the monolithic

### TABLE III

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Type</th>
<th>Process</th>
<th>Freq (GHz)</th>
<th>Gain (dBi)</th>
<th>Eff. (%)</th>
<th>Cavity Area (λ/2)</th>
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<tr>
<td>[25]</td>
<td>Inverted F (Single)</td>
<td>BCB + BM*</td>
<td>24</td>
<td>-0.7</td>
<td>56**</td>
<td>0.01</td>
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<tr>
<td>[24]</td>
<td>Patch (Single)</td>
<td>BCB + BM*</td>
<td>92</td>
<td>8.2</td>
<td>95</td>
<td>0.17***</td>
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<td>[6]</td>
<td>Dipole (Single)</td>
<td>SiGe + BM*</td>
<td>130</td>
<td>8.4</td>
<td>60**</td>
<td>0.5</td>
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<td>[27]</td>
<td>Monopole (Single)</td>
<td>BCB + BM*</td>
<td>130</td>
<td>6*</td>
<td>88**</td>
<td>0.11</td>
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<tr>
<td>[5]</td>
<td>Slot (Single)</td>
<td>CMOS</td>
<td>140</td>
<td>-2*</td>
<td>18**</td>
<td>0.16</td>
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<td>[7]</td>
<td>Yagi (Single)</td>
<td>SiGe + BM*</td>
<td>143</td>
<td>5.1</td>
<td>76</td>
<td>0.45</td>
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<tr>
<td>[14]</td>
<td>Patch (1×2)</td>
<td>BCB + BM*</td>
<td>135</td>
<td>8.66</td>
<td>83.5**</td>
<td>0.33***</td>
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<tr>
<td>[32]</td>
<td>Magnetic Loop (2×2)</td>
<td>SiGe</td>
<td>340</td>
<td>7.9</td>
<td>48</td>
<td>0.08*** (SIW)</td>
</tr>
<tr>
<td><strong>This work</strong></td>
<td>CFSA (Single)</td>
<td>BM*</td>
<td>60</td>
<td>6.1</td>
<td>93</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>This work</strong></td>
<td>CFSA (1×8†††)</td>
<td>BM*</td>
<td>60</td>
<td>11.0</td>
<td>71**/67†</td>
<td>0.05**</td>
</tr>
</tbody>
</table>

*BM: Bulk Micromachining **Simulation result ***Through Silicon Trench 'Broadside array †Area per # of array elements ††Area/0°/15°/30°/45°††*

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integration potential of the process, we aim to combine it with additional RF components and further validate real-time beamforming capabilities.

We introduce a high-efficiency V-band 1×8 CFSA array with reduced mutual coupling and up to 45° 1-D beam steering capabilities. Incorporating SICs and backside conductors in the CFSA enhances both efficiency and gain, while the inclusion of extra SICs diminishes element-to-element coupling within the array. The CFSA exhibits a -10 dB bandwidth of 55.4-60.3 GHz and 93% efficiency. Incorporating stepped SiO2 bridges and rounded bends suppresses CPW odd modes, achieving an 11.0 dB i 1×8 array gain and 67% efficiency with a corporate feed. This work, to our knowledge, marks the first demonstration of OCA beam steering with SIC technology, incorporating SICs and backside conductors in the CFSA enhances the efficiency with a corporate feed. This work, to our knowledge, marks the first demonstration of OCA beam steering with SIC technology, achieving beam steering angles of 15°, 30°, and 45° with gains of 8.1, 8.9, and 9.2 dB, respectively. The proposed OCA arrays offer the potential for monolithic integration with RF circuitry for V-band system-on-a-chip applications that demand high data throughput.

REFERENCES