A 320 GHz Octagonal Shorted Annular Ring On-Chip Antenna Array

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ABSTRACT
In this paper, an octagonal shorted annular ring (OSAR) antenna array is presented based on 130-nm SiGe BiCMOS technology without any post-processes. The OSAR antenna consists of annular ring patch, an array of shorted pins and ground which is formed a cavity to enhance the gain and reduce surface waves. The \( 1 \times 2 \) OSAR antenna array is designed and fabricated with the die area of \( 550 \times 1100 \mu \text{m}^2 \). The measured \(-10\)-dB impedance bandwidth is more than 17 GHz (303-320 GHz). The proposed on-chip antenna array is achieved a measurement perk gain of 4.1 dBi at 320 GHz and the simulated radiation efficiency of 38%.

INDEX TERMS
An octagonal shorted annular ring, on-chip antenna array, terahertz (THz), 130-nm SiGe BiCMOS technology.

I. INTRODUCTION
Terahertz (THz) frequency has appealed in various applications ranging from high data rate shorting-rang communication, security imaging, etc. [1]–[4]. Recently, Silicon Germanium (SiGe) technology has been reported to achieve the operating frequency over 300 GHz [5]. The good performance of on-chip antenna is one of the fundamental components, including high gain and wide bandwidth. However, the silicon substrate has a relatively high dielectric constant and large thickness, which causes most of the energy to be trapped in the Si substrate. As a result, the on-chip antennas suffer from higher losses, higher backside power radiation and higher order surface waves. The gain and radiation efficiency of on-chip antenna are normally limited to 0 dBi and 10%, respectively [6].

Based on the above inherent flaws, several on-chip antennas including cavity antenna with low dielectric constant [7], slot antenna used substrate integrated waveguide (SIW) technology [8], [9], antenna loaded artificial magnetic conductor (AMC) structure [10] and dielectric resonator antennas (DRAs) [6], [12]–[15] have been reported to overcome losses of surface waves and increase the gain. In [7], the Si-cavity is design to remove the semiconductor underneath of antenna by micro-machined process, which achieves the low effective dielectric constant. However, the secondary fabrication process and additional support substrate is required. The designed on-chip Yagi antenna shows a peak gain of 4.7 dBi and radiation efficiency of 82%. In [8], a circular polarized SIW slot antenna is designed with a gain of \(-0.5\) dBi and a radiation efficiency of 48% at 410 GHz. The AMC structure can replace perfect electric conductor (PEC) plane for low-profile and high gain antenna. In [10], the double layer dipole on-chip antenna loading AMC is designed for wide bandwidth and low backward radiation. However, gain of the antenna is up to 0 dBi at 235 GHz. In [14], DRAs with a high-order mode can enhance the gain and the radiation efficiency to 7.9 dBi and 48% at 340 GHz. However, these works either show limited gain improvement, complex fabrication process and a large volume.

The shorted annular ring (SAR) antenna can significantly reduce the excitation of surface waves [16], [17], resulting in...
less back radiation and high gain. These characteristics make the SAR antenna ideal for applications where the supporting substrate or ground plane of the antenna is small, in which case diffraction of surface and lateral waves from the edges of the structure may be quite significant for conventional microstrip antennas. In [17], the SAR on-chip antenna is designed to achieve much lower levels of radiation along the horizon and toward the backside.

In this paper, a $1 \times 2$ OSAR on-chip antenna array is presented. The demonstrated antenna is fabricated using 130-nm SiGe BiCMOS process without any post-processes. An octagonal shorted annular ring structure is introduced to reduce surface waves and increase the gain. The die area of the proposed on-chip antenna array is $550 \times 1100 \mu m^2$. The $-10$-dB impedance bandwidth of more than 17 GHz (303-320 GHz) and maximum gain of 4.1 dBi at 320 GHz is observed through on-chip measurement. Good agreements between the simulated and measured results are obtained.

II. OSAR ANTENNA ELEMENT DESIGN

A. ANTENNA CONFIGURATION

In this design, a standard 130-nm SiGe BiCMOS process with 7 metal layers placed in SiO$_2$ substrate ($\varepsilon_r = 4.19$ and $\tan \delta = 0.01$) is shown in Fig. 1. The thickness of top metal (M1) is $4 \mu m$ and others (M2-M7) are $0.45 \mu m$, $0.55 \mu m$, $0.32 \mu m$, $0.32 \mu m$, $0.32 \mu m$, and $0.29 \mu m$, respectively. The silicon substrate has the thickness of $300 \mu m$ with the dielectric constant of 11.9. The widths of the shorting pins from M1 to M5 and M5 to M7 are $1.24 \mu m$ and $0.4 \mu m$, respectively.

Since the 130-nm SiGe BiCMOS process cannot process the arc, the geometry of octagonal annular ring (OAR) patch is designed on M1, which is approximate to the circular annular ring (CAR) patch. The configuration of the octagonal microstrip antenna and the OSAR antenna based on the same process is shown in Fig. 2. The OSAR antenna consists of octagonal patch, feeding probe, an array of rectangle metal pins and ground. An array of rectangle metal pins connects between the octagonal patch (M1) and the ground plane (M8), which form the short-circuited boundary. The short-circuited boundary is established at an inner radius. The inner and outer radius ($l_5$ and $l_6$) are chosen to adjust the designed OSAR antenna resonant frequency.

According to the cavity model, a octagonal microstrip antenna can be modeled as a ring of magnetic current. A TM$_0$ surface wave field is given by [18]:

$$
\Psi = -2\pi a B(z) H_1^{(2)}(k_{TM_0}r) \cos \phi J_1'(k_{TM_0}a)
$$

$k_{TM_0}$ is the propagation wavenumber for the TM$_0$ surface wave. $B(z)$ is the amplitude factor depends on the source and $J_1'$ is the first kind Bessel functions their derivatives.

Equation (1) is a fundamental design equation, which states that a ring of magnetic current will not excite the TM$_0$ surface
wave. The outer radius \( r = l_6 \) is chosen to satisfy
\[
\frac{x_{11}'}{k_{TM_0}} = \frac{1.8412}{k_0} = \frac{1.8412}{2\pi f_0 \sqrt{\varepsilon_0 \mu_0}} \tag{2}
\]

If \( \varepsilon_r = 1 \), \( k_0 = k_{TM_0} \) is obtained.

The shorting pin is equivalent to inductance, which offset capacitor of dielectric substrate. The inductance of shorting pin can be calculated as [19]
\[
L = \left( \frac{\mu_0}{\pi} \right) \cosh^{-1} \left( 2d_1/a \right) \tag{3}
\]

Since at the operating frequency of the patch, \( C = 1/\omega_0^2 L \), the dielectric permittivity \( \varepsilon_r \) can be derived as follows:
\[
\varepsilon_r = \frac{C h}{\varepsilon_0 d_1^2} = 2.19 \tag{4}
\]

For formula (2) and (4), \( l_6 = 186 \mu m \).

The inner radius \( r = l_5 \) for \( TM_0 \) mode resonance satisfies the transcendental equation
\[
\frac{J_1 (k_{TM_0} l_5)}{Y_1 (k_{TM_0} l_5)} = \frac{J_1' (\frac{x_{11}'}{k_{TM_0}})}{Y_1' (\frac{x_{11}'}{k_{TM_0}})} \tag{5}
\]

\( J_1 \) and \( Y_1 \) are Bessel functions of the first and second kinds, \( k_1 \) the substrate wave number. \( Y_1' \) is the second kind Bessel functions derivatives.

| Parameters | Values | Parameters | Values |
|------------|--------|------------|--------|
| Octagonal microstrip antenna | \( l_1 \) | 80 | \( w_1 \) | 110 |
| | \( l_2 \) | 20 | \( w_2 \) | 20 |
| | \( l_3 \) | 90 | \( w_3 \) | 50 |
| | \( d \) | 15 | \( w_4 \) | 100 |
| OSAR antenna | \( l_4 \) | 550 | \( l_7 \) | 104 |
| | \( l_5 \) | 45 | \( l_8 \) | 121 |
| | \( h_1 \) | 12.83 | \( h_2 \) | 5.07 |

After optimization in HFSS, \( l_5 = 45 \mu m \) and \( l_6 = 156 \mu m \) are achieved. Table 1 presents the geometrical parameters of the antenna after all optimized design.

Fig. 3 presents the electric field distributions of octagonal microstrip antenna and OSAR antenna at 320 GHz. Results also show that the fields decay much faster along the substrate, due to the absence of the surface wave field. The electric field energy strength of OSAR antenna on the substrate (Si) is lower than that of microstrip antenna. The introduction of octagonal shorted annular ring can obviously suppress surface wave propagation and enhance gain.
B. PARAMETER STUDY

The various parameters of OSAR antenna are studied by HFSS. The inner radius ($l_5$) and outer radius ($l_6$) are key parameters in controlling the resonant frequency and impedance match. Fig. 4(a) illustrates that when $l_5$ increases from 43 $\mu$m to 49 $\mu$m, the resonant frequency increases from 314 GHz to 327 GHz. Figs. 4(b) show that when $l_6$ increases from 154 $\mu$m to 160 $\mu$m, the resonant frequency increases from 318 GHz to 327 GHz. Adjusting $l_5$ and $l_6$ is considered to be a good method of achieving the desired impedance bandwidth.

The distance between shorting pins ($d_1$) is a key parameter in controlling the inductance loaded on the dielectric substrate. Fig. 5 shows the effect of the resonance and gain with different $d_1$. It is can be seen that when $d_1$ changes from 2.48 $\mu$m, 4.96 $\mu$m, and 7.44 $\mu$m, the resonant frequency increases from 320 GHz to 322 GHz, while the gain decreases from 1.4 dBi to 0.7 dBi.

The simulated results of microstrip antenna and OSAR antenna are compared in Fig. 6. The simulated $-10$ dB impedance bandwidth of microstrip antenna, OSAR antenna are 10 GHz (318-328 GHz) and 13 GHz (317-330 GHz), respectively. The simulated gain are 0.7 dBi, 1.4 dBi and efficiency is 35.4 $\%$, 41 $\%$ at 320 GHz, respectively. The OSAR antenna element achieves 0.8 dB higher gain at 320 GHz, which are much higher than the traditional on-chip patch antenna.

III. A 320 GHz 1 $\times$ 2 OSAR ON-CHIP ANTENNA ARRAY DESIGN

Since the high gain performance is required to ensure long distance communication, 1 $\times$ 2 OSAR on-chip antenna array is designed to improve the gain, as shown in Fig. 7. The 1 $\times$ 2 OSAR antenna array consists of two OSAR antenna
FIGURE 6. Performance comparison of microstrip antenna and ORAR antenna (a) $S_{11}$ versus frequency (b) Gain at 320 GHz (c) Gain and efficiency versus frequency.

of OSAR antenna element is 100 Ω to design without $1/4\lambda_g$ impedance transformer. The feeding network is placed on the M2 layer, which connect by the feeding probe from M1 layer to M2. The G-S-G pad is design to 50 Ω for measurement.

The length ($w_6$) and the width ($w_7, w_8$) of the power divider are 480 $\mu$m, 20 $\mu$m and 30 $\mu$m, respectively. The simulated results are shown in Fig. 8. From the 302-330 GHz, the $S_{11}$ is below $-10$ dB. The output ratio matches the request of 1:1 and insertion loss of the power divider is less than 1.7 dB.
A 320 GHz 1 × 2 OSAR on-chip antenna array is fabricated with the die area of 550 × 1100 μm², as shown in Fig. 9. The designed on-chip antenna array is measured by Keysight PNA-X with the VDI extender from 220-320 GHz. A G-S-G probe with a pitch of 100 μm is touched on the GCPW (grounded coplanar waveguide) line of the proposed antenna for measurement. The simulation −10 dB impedance bandwidth is 12 GHz (311-323 GHz). The measurement −10 dB impedance bandwidth is more than 17 GHz (303-320 GHz), as shown in Fig. 11. The measurement resonant frequency is 1 GHz lower than the simulation results. Discrepancies between measurement and simulation of the proposed antenna could be arose from the probe.

IV. RESULTS AND DISCUSSION

The three-dimensional (3-D) schematic of the probe feeding the designed on-chip antenna is analyzed using the HFSS and shown in Fig. 10. The measured loss of waveguide-to-GSG probe is 4.87 dB from 220-320 GHz, which is fed the RF signal to the antenna under test (AUT). The gain of standard horn antenna is 12.1-16 dBi from 220 to 320 GHz. Since the rotation in the x-z plane is blocked by the scope lifting bar on the probe station, the measured x-z plane patterns are limited to 180° < θ < 50°. The measured peak gain is calculated based on [20]:

\[ G_{\text{AUT}} = P_{\text{AUT}} - P_{\text{horn}} + G_{\text{horn}} + \text{Loss}_{\text{p}} + L_{\text{cable}} \]  

where \( P_{\text{AUT}} \) and \( P_{\text{horn}} \) are the power at the spectrum analysis and the standard horn, \( G_{\text{horn}} \) is the gain of the standard horn antenna, \( \text{Loss}_{\text{p}} \) and \( L_{\text{cable}} \) are the insertion losses of the G-S-G probe and coaxial cable. The simulated and measured gain of the proposed on-chip antenna array are presented in Fig. 11(a)-(d). The simulation results after adding the probe is consistent with the measurement results. When the probe is added, the resonant frequency decreased 1 GHz and the bandwidth increased 4 GHz due to the coupled field generated by the probe. The simulated and measured peak gains are 5.4 dBi and 4.1 dBi at 320 GHz, respectively. However, the measured main beam direction is −5°. The radiation pattern has a lot of burrs. Seem form the Fig.12, the main beam offset, gain reduction and burrs are due to the electromagnetic wave reflection generated by the probe and coaxial cable. The simulated results with probe and measured results agree well.

Compared with previously, reported on-chip antennas based on CMOS process as shown in Table 2, the proposed antenna has a broader bandwidth of about 17 GHz and a higher efficiency above 38%. Unlike the traditional slot antenna [3], [5], [8], [9], which has high loss and low gain, the gain of OSAR antenna array improved gain. Moreover, in comparison with the DRA [14] and array [15], the proposed antenna achieved similar efficiency without loading Dielectric resonator.

### TABLE 2. Comparison between proposed and reported on-chip antenna.

| Ref. | Type                  | Process    | Postprocess | Area(μm²)         | BW (GHz) | Gain (dB) | Efficiency (%) |
|------|-----------------------|------------|-------------|-------------------|----------|-----------|---------------|
| [3]  | Patch antenna         | 40-nm CMOS| No          | 194×23.15 (patch area) | 340*     | −5.5*     | 6.5*          |
| [8]  | circular polarized SIW antenna | 65-nm CMOS | No         | 990×990           | 32 (251-283)* | −0.5*     | 21.41*        |
| [9]  | SIW slot antenna      | 130-nm SiGe BiCMOS | No | 200×200 | 2% 410* | −0.5* | 49.8* |
| [12] | Dipole loaded AMC     | 130-nm SiGe BiCMOS | No | 250×410 | 81 (200-281) | 0* | 65* |
| This Work | OSAR antenna         | 130-nm SiGe BiCMOS | No | 500×500 | 13 (317-330) | 1.4* | 41* |

* simulated results
A wideband and high efficiency $1 \times 2$ OSAR on-chip antenna array has been presented and investigated at 320 GHz. The octagonal shorted annular ring has mainly contributed to improve gain and reduced surface wave based on 130-nm SiGe BiCMOS. The proposed antenna has a die area of $550 \times 1100 \mu m^2$. The measurement $-10$-dB impedance bandwidth is more than 17 GHz (303-320 GHz). The antenna reaches 4.1 dBi measured gain at 320 GHz. The impact of probe in bandwidth and gain was analysed and both the simulated and measured results agree well. It is demonstrated that the proposed antenna array can be a promising candidate for THz communication systems.

V. CONCLUSION

A wideband and high efficiency $1 \times 2$ OSAR on-chip antenna array has been presented and investigated at 320 GHz. The octagonal shorted annular ring has mainly contributed to improve gain and reduced surface wave based on 130-nm SiGe BiCMOS. The proposed antenna has a die area of $550 \times 1100 \mu m^2$. The measurement $-10$-dB impedance bandwidth is more than 17 GHz (303-320 GHz). The antenna reaches 4.1 dBi measured gain at 320 GHz. The impact of probe in bandwidth and gain was analysed and both the simulated and measured results agree well. It is demonstrated that the proposed antenna array can be a promising candidate for THz communication systems.

REFERENCES

[1] Z.-C. Hao, J. Wang, Q. Yuan, and W. Hong, “Development of a low-cost THz metallic lens antenna,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 1751–1754, 2017.
[2] M. S. Rabbani and H. Ghafouri-Shiraz, “Liquid crystalline polymer substrate-based THz microstrip antenna arrays for medical applications,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 1533–1536, 2017.
[3] C.-H. Li, C.-L. Ko, M.-C. Kuo, and D.-C. Chang, “A 340-GHz heterodyne receiver front end in 40-nm CMOS for THz biomedical imaging applications,” IEEE Trans. Terahertz Sci. Technol., vol. 6, no. 4, pp. 625–636, Jul. 2016.
[4] H. S. Bakshi, P. B. Byreddy, K. O. Kenneth, A. Blanchard, M. Lee, E. Tuncer, and W. Choi, “Low-cost packaging of 300 GHz integrated circuits with an on-chip patch antenna,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 11, pp. 2444–2448, Nov. 2019.
[5] Z. J. Hou, Y. Yang, X. Zhu, S. Liao, S. K. Man, and Q. Xue, “A 320 GHz on-chip slot antenna array using CBCPW feeding network in 0.13-\mu m SiGe technology,” in IEEE MTT-S Int. Microw. Symp. Dig., Jun. 2017, pp. 843–846.
[6] X.-D. Deng, Y. Li, W. Wu, and Y.-Z. Xiong, “340-GHz SiW cavity-backed magnetic rectangular slot loop antennas and arrays in silicon technology,” IEEE Trans. Antennas Propag., vol. 63, no. 12, pp. 5272–5279, Dec. 2015.

[7] H. Chu, Y.-X. Guo, T.-G. Lim, Y. M. Khoo, and X. Shi, “135-GHz micromachined on-chip antenna and antenna array,” IEEE Trans. Antennas Propag., vol. 60, no. 10, pp. 4582–4588, Oct. 2012.

[8] Y. Shang, H. Yu, H. Fu, and W. M. Lim, “A 239–281 GHZ CMOS receiver with on-chip circular-polarized substrate integrated waveguide antenna for sub-terahertz imaging,” IEEE Trans. THz Sci. Technol., vol. 4, no. 6, pp. 686–695, Nov. 2014.

[9] S. Hu, “A SiGe BiCMOS transmitter/receiver chipset with on-chip SIW antennas for terahertz applications,” IEEE J. Solid-State Circuits, vol. 47, no. 11, pp. 2654–2664, Nov. 2012.

[10] J. Xiao, X. P. Li, Z. H. Qi, H. Zhu, and W. W. Feng, “Cavity-backed on-chip patch antenna in 0.13 μm SiGe BiCMOS technology,” J. Inf. Millim. Waves, vol. 38, no. 3, pp. 310–314, 2019.

[11] H. Zhu, X. Li, W. Feng, J. Xiao, and J. Zhang, “235 GHz on-chip antenna with miniaturised AMC loading in 65 nm CMOS,” IET Microw. Antennas Propag., vol. 12, no. 5, pp. 727–733, Apr. 2018.

[12] M. Nafe, A. Syed, and A. Shamim, “Gain-enhanced on-chip folded dipole antenna utilizing artificial magnetic conductor at 94 GHz,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 2844–2847, 2017.

[13] Z. Ahmad, and J. Hesselbarth, “On-chip dual-polarized dielectric resonator antenna for millimeter-wave applications,” IEEE Antennas Wireless Propag. Lett., vol. 17, no. 10, pp. 1769–1772, Oct. 2018.

[14] X.-D. Deng, Y. Li, C. Liu, W. Wu, and Y.-Z. Xiong, “340 GHz on-chip 3-D antenna with 10 dBi gain and 80% radiation efficiency,” IEEE Trans. THz Sci. Technol., vol. 5, no. 4, pp. 619–627, Jul. 2015.

[15] C.-H. Li and T.-Y. Chiu, “Single flip-chip packaged dielectric resonator antenna for CMOS terahertz antenna array gain enhancement,” IEEE Access, vol. 7, pp. 7737–7746, 2019.

[16] L. Li, Y. Huang, L. Zhou, and F. Wang, “Triple-band antenna with shorted annular ring for high-precision GNSS applications,” IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 942–945, 2016.

[17] H. Zhu, X. Li, W. Feng, J. Xiao, and J. Zhang, “A compact 267 GHz shorted annular ring antenna with surface wave suppression in 130 nm SiGe BiCMOS,” IEEE Antennas Wireless Propag. Lett., vol. 17, no. 5, pp. 760–763, May 2018.

[18] D. R. Jackson, J. T. Williams, A. K. Bhattacharyya, R. L. Smith, S. I. Buchheit, and S. A. Long, “Microstrip patch designs that do not excite surface waves,” IEEE Trans. Antennas Propag., vol. 41, no. 8, pp. 1026–1037, Aug. 1993.

[19] H. Sanad, “Effect of the shorting posts on short circuit microstrip antennas,” in Proc. IEEE Antennas Propag. Soc. Int. Symp. URSI Nat. Radio Sci. Meeting, Jun. 1994, pp. 794–797.

[20] D. Hou, Y.-Z. Xiong, W.-L. Goh, S. Hu, W. Hong, and M. Madhiah, “130-GHz on-chip meander slot antennas with stacked dielectric resonators in standard CMOS technology,” IEEE Trans. Antennas Propag., vol. 60, no. 9, pp. 4102–4109, Sep. 2012.

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