# 100-GHz Quasi-Yagi Antenna in Silicon Technology

M. Sun and Y. P. Zhang

***Abstract*—This letter presents a 100-GHz integrated Quasi-Yagi antenna on silicon substrates of low resistivity 10 $\Omega \cdot$ cm. The fabrication was realized with the back-end-of-line process. The characterization was conducted on wafer with Cascade Microtech coplanar probes and an HP8510XF network analyzer. Reflection measurements show a return loss of 8.2 dB at 100 GHz and a −6-dB impedance bandwidth of 89–104 GHz. Gain measurements show a gain of 5.7 dBi at 100 GHz. The simulated radiation patterns are also presented. It is anticipated that the results presented here are useful and inspiring for engineers interested in 100-GHz complementary metal–oxide–semiconductor radio front-end designs.**

***Index Terms*—Complementary metal–oxide–semiconductor (CMOS) radio, integrated antenna, Quasi-Yagi antenna.**

## I. Introduction

The HIGH-FREQUENCY capabilities of complementary metal–oxide–semiconductor (CMOS) technology improve dramatically with time [1]. Taking the speed of voltage-controlled oscillators (VCOs) as an example, the first 51-GHz 0.12-$\mu$m CMOS VCO was reported in 2002 [2], the first 104-GHz 90-nm CMOS VCO was reported in 2004 [3], and the first 114-GHz 0.13-$\mu$m CMOS VCO was reported in 2005 [4]. This improvement makes CMOS increasingly become a viable technology to satisfy speed-intensive applications such as gigabits per second point-to-point links, wireless local area network with extraordinary capacity, and vehicular radar. RF CMOS transceivers are approaching 60-GHz band as the radio architecture and key RF building blocks for 60 GHz have been invented [1], [5]. This trend is also likely to continue toward the 77-GHz band for automotive radar applications. Motivated by this trend, the on-chip antennas in silicon that are suitable for these CMOS radios in gigahertzes have also become possible as the millimeter wavelength permits the integration of multiple antennas on one chip [6].

It is known that the Quasi-Yagi antenna has significantly higher gain and a better-controlled front-to-back ratio when it employs at least three elements. For frequencies up to millimeter-wave range, the integrated microstrip-fed Quasi-Yagi antennas have been built on conventional dielectric substrate for 24-GHz application [7]. They have also been demonstrated in silicon of low resistivity for 60-GHz radios [8]. In this letter, we present for the first time a 100-GHz on-chip Quasi-Yagi antenna on silicon substrates of low resistivity 10 $\Omega \cdot$ cm. We adopt the post-back-end-of-line (BEOL) process developed at the Institute of Microelectronics, Singapore for RF CMOS passives to fabricate our antenna. The design and fabrication are presented in Section II. The measured performance is analyzed in Section III. Finally, the conclusions are summarized in Section IV.

## II. Design and Fabrication of Quasi-Yagi Antenna

Fig. 1(a) shows the top view photograph of the on-chip Quasi-Yagi antenna. It consists of one driver, two directors, and a truncated ground plane that acts as reflector. The antenna is fed by a uniplanar broadband microstrip-to-coplanar strip transition. As shown from the cross section illustration of Fig. 1(b), the antenna is formed by two 2-$\mu$m aluminum layers separated by a 2-$\mu$m $SiO_2$ layer. The driver, two directors, and its feeding structure are etched on the top aluminum layer, while the truncated ground plane used as the reflector is etched on the bottom aluminum layer. The ground pads are connected to the truncated ground plane by vias to eliminate the capacitance effect between the two aluminum layers. It should be mentioned that the ground-signal-ground probes require the testing pads being squares of 80 $\mu$m by 80 $\mu$m with a pitch of 100 $\mu$m. The whole antenna structure is separated from the silicon substrate by a 20-$\mu$m thick $SiO_2$ layer. The analysis and design procedure are based on the full-wave electromagnetic solver of Zeland IE3D. Four parameters are considered in design, as shown in Fig. 1(a). It is found that the return loss is sensitive to the variation of parameters $L2$ and $L4$. They affect both impedance bandwidth and resonant frequency. The final dimensions are $L1 = 146$ $\mu$m, $L2 = 270$ $\mu$m, $L3 = 382$ $\mu$m, and $L4 = 426$ $\mu$m. For brevity, we only show the simulated $|S_{11}|$ result for the final dimensions in Fig. 2. As shown, the result shows a return loss of 28 dB at 100 GHz and a −10-dB impedance bandwidth of 93–106 GHz.

The post-BEOL process has been illustrated in [8]. It is adopted to combat the large loss due to the low-resistivity silicon substrate as the frequency increases to millimeter-wave range. For this purpose, it is more compatible with the existing CMOS technologies than other commonly used techniques such as micromachining process or substrate thinning [9], [10] and proton implantation [11]. The 100-GHz Quasi-Yagi antenna was fabricated with the modified post-BEOL process with the cross section shown in Fig. 1(b), where the 20-$\mu$m thick $SiO_2$ layer is deposited via commonly used plasma-enhanced chemical-vapor-deposition process. It is obvious that the antennas can be built on CMOS IC chips using the post-BEOL process if they are proved to be successfully fabricated with the simplified post-BEOL process here.

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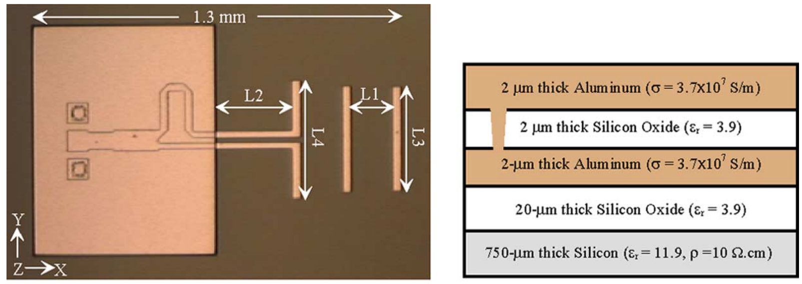


(a) (b)

Fig. 1. Quasi-Yagi antenna: (a) Top view photograph and (b) cross-sectional view illustration.

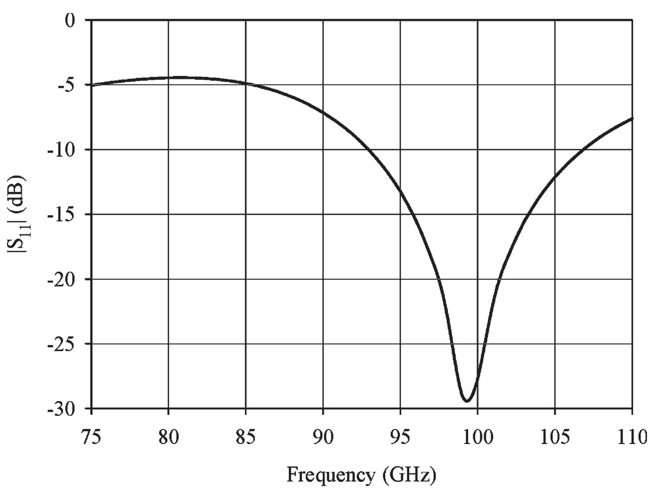


Fig. 2. Simulated $|S_{11}|$ as a function of frequency.

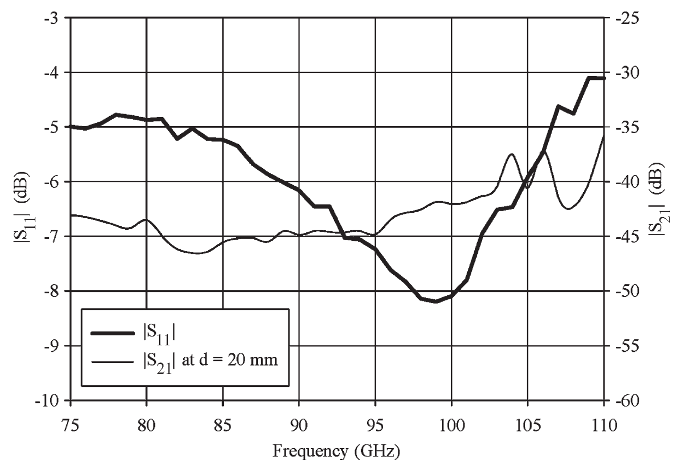


Fig. 3. Measured $|S_{11}|$ and $|S_{21}|$ as a function of frequency.

## III. Results and Discussion

The Quasi-Yagi antennas with structures, as shown in Fig. 1, were fabricated in one wafer, including many identical ones placed face-to-face. The wafer, which is sitting flat directly on a probe station of metal chuck in a large testing room, was measured with the Cascade Microtech coplanar probes and the HP8510XF network analyzer. The absorbing materials were not used around the probes because it was found in measurements that the probe's effect on the antenna performance at 100 GHz is negligible. The $S$-parameters were measured up to 110 GHz without de-embedding. Fig. 3 shows the measured $|S_{11}|$ result of the Quasi-Yagi antenna. A return loss of 8.2 dB can be obviously observed at 100 GHz. Using a threshold of $-6$ dB, which is usually acceptable in practical applications, the measured impedance bandwidth is 89–104 GHz. The measured resonant frequency agrees with the simulated one. However, the matching is not good to achieve the lower return loss at the resonant frequency as simulated. Fabrication tolerance might be the cause of the discrepancy between the measurement results and the design goals. For example, the deviation of the thickness of 2 $\mu$m for the top silicon oxide layer will decrease the return-loss performance greatly, as shown in [8].

In the gain measurement, two identical Quasi-Yagi antennas were placed face-to-face in far field with a separation distance of $d = 20$ mm. One antenna functions as a transmit antenna and the other as a receive antenna. Fig. 3 shows the measured $|S_{21}|$ result. It is $-42.5$ dB at 100 GHz. From transmission measurements, the antenna gain can be estimated by [12]

$$G^2 = \frac{|S_{21}|^2}{\left(1-|S_{11}|^2\right)\left(1-|S_{22}|^2\right)\left(\frac{\lambda}{4\pi d}\right)^2 e^{-2\alpha d}} \tag{1}$$

where $\lambda$ is the wavelength and $\alpha$ is the attenuation constant, which is obtained from the simulation using electromagnetic solver of Ansoft HFSS and also confirmed by extracting the measured $|S_{21}|$ parameters of the Quasi-Yagi antenna pair at varied separation distance. As shown, the antenna gain $G$ is extracted by taking into account the propagation loss effects, including the conduction loss and de-embedding the mismatch loss using $|S_{11}|^2$ and $|S_{22}|^2$. This will make the calculated gain value more accurate than the one calculated using the technique presented in [8] without considering these effects. By measuring the two-port $S$-parameters of the antenna pair and calculating using (1), a gain of 5.7 dBi is obtained at 100 GHz. For wireless communication application, the gain increase can be also expected by employing an antenna array.

The simulated radiation patterns of the Quasi-Yagi antenna in H (YZ) and E (XZ) planes at 100 GHz are shown in Fig. 4. As shown, the E-plane cross-polarization radiation is obviously low at 100 GHz, while it is not for H plane.

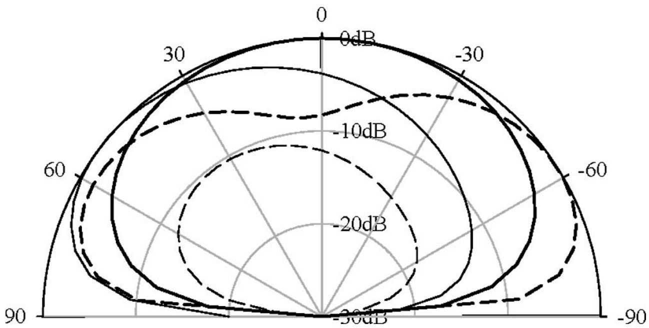


Fig. 4. Radiation patterns at 100 GHz with solid lines for copolarization components, short dash lines for cross-polarization components, normal lines for E plane, and thicker lines for H plane.

## IV. Conclusion

A 100-GHz on-chip Quasi-Yagi antenna was reported for the first time. The antenna was fabricated on silicon substrates of low resistivity 10 $\Omega \cdot$cm using the post-BEOL process. The antenna was tested on-wafer for return loss and gain. The measurement results show a return loss of 8.2 dB and a gain of 5.7 dBi at 100 GHz, as well as a $-6$-dB impedance bandwidth of 89–104 GHz. The simulated radiation patterns are also presented. It is anticipated that the results presented here are useful and inspiring for engineers interested in 100-GHz CMOS radio front-end designs.

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