A High Gain Lens-Coupled On-Chip Antenna Module for Miniature-Sized Millimeter-Wave Wireless Transceivers

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***Abstract*—This paper presents high gain and compact Transmit/Receive (TX/RX) integrated antennas in a standard BiCMOS 130nm technology for millimeter-scale millimeter-wave (mm-wave) applications, including high data rate radios and high resolution radars. The proposed TX/RX antenna module utilizes an integrated dipole antenna for the receiver and a slot antenna for the transmitter, placed orthogonally. The achieved gain and radiation efficiency are 5.7dBi and 41.3% for the slot antenna, respectively, and 6dBi and 39% for the dipole antenna. The link budget is improved by 16dB by optimization on the geometry as well as application of a high resistivity hemispheric silicon dielectric lens.**

Keywords*—5G, antenna efficiency, dielectric lens, dipole, energy efficiency, high-speed communication, isolation, low-power, mm-wave, radar, receiver, silicon integrated circuits, slot, transmitter, wireless communication.

I. Introduction

The demand for high data rate wideband wireless links is higher than ever, especially with the definition of 5G communication with high data-rates (>1Gb/s), autonomous vehicles, and smart homes. However, the scalability of these systems is limited due to their large form factors, which is dominated by antennas. Thus, miniature antennas can improve system integration and scalability and pave the way for massive numbers of connected devices. Utilizing on-chip antennas can reduce the system form factor to millimeter scale, but there are a few challenges. A major impediment is maintaining the radiation efficiency, comparable to off-chip antennas. At low frequencies, the miniature size significantly reduces radiation efficiency, as low as 1% [1], [2] for mm-scale system on chips [3], due to the use of electrically-small antennas. Nevertheless, smaller wavelength at mm-wave frequency bands is a key enabler of efficient on-chip antennas for mm-scale, mm-wave wireless systems. Among the mm-wave frequency bands, the unlicensed 60GHz band has increasingly gained attraction due to its wide bandwidth, providing 7GHz in the spectrum, making it a great fit for high resolution radars and high data rate point-to-point wireless communications, which could be utilized in smart cities, surveillance, security, smart homes, autonomous vehicles, and wireless high definition video streaming.

Despite the miniature size of mm-wave on-chip antennas and their superior performance compared with sub-10GHz on-chip antennas, they suffer from low radiation efficiency and gain, limiting a wireless links' range. In this work, we have mitigated this problem and maintained the mm-scale form factor simultaneously by optimal design of the antennas at 60GHz and utilizing a high resistivity dielectric lens to minimize substrate losses.

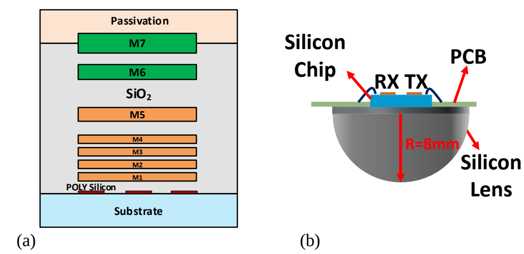

Fig. 1. (a) High resistivity silicon dielectric lens attached to chip backside, and (b) BiCMOS 130nm technology stack cross section.

II. High Efficiency Transceiver Antenna Design

According to state of the art, a typical on-chip antenna operating at 60GHz achieves only 10% efficiency and -4.4dBi gain [4], due to the low electric resistivity (~10Ω.cm) and high dielectric constant (ε_r=11.9) of the doped silicon substrate. In this work, we have designed a dipole and a slot antenna for a single chip transceiver. A dipole antenna has been used for the receiver because of its low input impedance at resonance frequency (~75 Ω) and differential feed, which is suitable for low-noise differential receivers with small input impedance. Similarly, slot antenna has been opted for the transmitter due to its compact size, compared to patch antennas, and single-ended feed, to be simply fed by a single-ended power amplifier stage. In Fig. 1 (a) the cross section view of the 130nm technology metal stack is shown. The slot antenna is designed using M1-M7 and occupies 1030µm×630µm, including the surrounding ground plane. The RF feed is composed of M7, while M1-M7 are utilized and connected using arrays of metal vias in the optimally-sized ground plane to maximize radiation efficiency. The dipole antenna occupies 1315µm×624µm and only uses the top metal layer (M7). Furthermore, in order to suppress the undesirable coupling between TX and RX, the dipole antenna is shielded with a ground plane using the top metal layer. Dipole antenna is horizontally polarized, while slot antenna is vertically polarized. Thus, the TX and RX antennas should be placed orthogonally in order to maintain their polarization matching. Moreover, in order to suppress the lossy substrate modes, we

Submitted On: September 1, 2020
Accepted On: September 5, 2020
https://doi.org/10.47037/2020.ACES.J.351159

have attached the silicon substrate to a high resistivity silicon dielectric lens, Fig. 1 (b). Finally, in order to maximize the gain of both antennas and the isolation between TX and RX antennas simultaneously, the position of TX and RX antennas on the chip has been optimized in HFSS. The overall 3D geometry, including the on-chip antennas and the silicon lens is shown in Fig. 2.

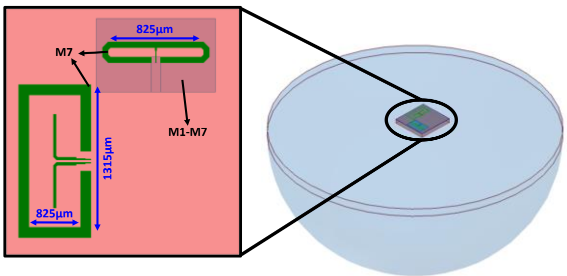

Fig. 2. HFSS geometry 3D model including the chip and silicon lens.

III. Results and Discussions

ANSYS Electronics Desktop is used for the design and optimization of the antennas. Using the aforementioned dimensions, resonant frequency of the slot antenna is found to be 60GHz with approximately 6.75GHz bandwidth (11.25%). The proposed geometry provides 150Ω input impedance (at the resonant frequency), which can be matched to a power amplifier stage. Similarly, dipole antenna's resonant frequency is obtained to be 60GHz with 17 GHz bandwidth (28.33%) and an input impedance of 70Ω. Fig. 3 summarizes the simulated S-parameters for the TX/RX antennas. As can be observed, the proposed antenna geometry provides a minimum of 21dB isolation between TX and RX across the band.

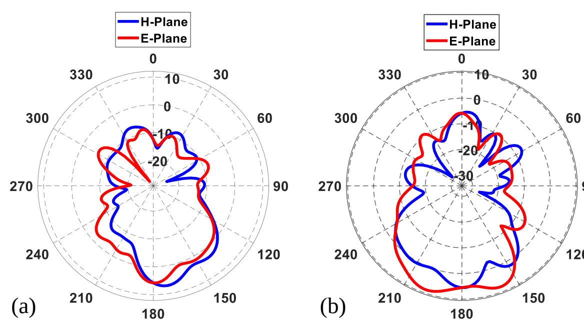

Fig. 3. Simulated radiation pattern: (a) dipole antenna and (b) slot antenna.

Fig. 4 depicts the simulated radiation pattern and the gain of TX/RX antennas. The slot antenna offers 6dBi gain, while the dipole antenna's gain is around 5.7dBi. The radiation gain in each antenna has been improved more than 10dB compared to prior work in [4].

Based on simulation results, the slot antenna and dipole antenna provide 41.3% and 39% radiation efficiency, respectively, which *is* improved more than twice compared to previous on-chip antennas [4]. Additionally, the achieved gain is improved more than 1dB compared to those reported in [5] and [6], using a dielectric resonator antenna and off-chip antenna with plastic lens, respectively.

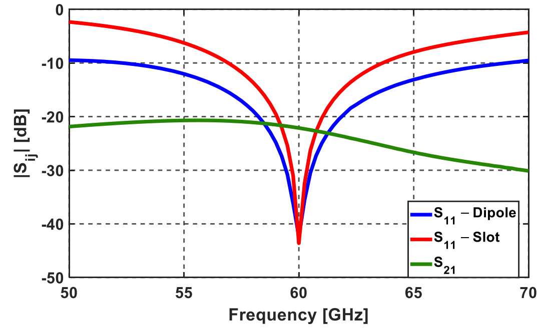

Fig. 4. Simulated S-Parameters of the antennas.

IV. Conclusion

A slot antenna and a dipole antenna, providing 11.7dB TX/RX gain, are designed in a standard 130nm SiGe process for fully integrated, mm-scale wireless systems. By design optimization and utilizing a high resistivity silicon lens, the gain is improved >8dB in each of the antennas, as shown in Table I, through suppressing the lossy modes in the low-resistivity doped silicon substrate. The designed antennas can be efficiently integrated with mm-wave wireless communication and sensing circuits and are suitable for low-power applications such as short-range IoT.

TABLE I. Summary and Comparison of the State-of-the-Art

	Frequency	*Type*	*Gain*	*Technology*
This Work	60GHz	Lens coupled on-chip dipole	6dBi	130nm BiCMOS
[4]	60GHz	On-chip AMC based	-4.4dBi	0.18µm CMOS
[5]	60GHz	Dielectric resonator antenna	5dBi	65nm CMOS SOI
[6]	60GHz	Off-chip antenna with plastic lens	4dBi	HDI organic sub

Acknowledgment

This work is supported by US Department of Energy, Office of Energy Efficiency and Renewable Energy, under award number DE-EE0008225.

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