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A Review of C-Band Silicon CPW Antenna for Realization of Miniaturization and Integrated SAR System Front-End

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ABSTRACT This article assesses the latest advancements in high-performance miniaturized silicon antennas designed for integration purposes. The primary objective is to fulfill the demands of advanced systems utilized in contemporary radar applications. Over the past years, diverse designs, reconfigurable approaches, and techniques for silicon antennas have been suggested and examined to accomplish this objective. The paper elaborates on the achievements of small silicon antennas, highlighting higher gains, favorable return loss, and expanded bandwidth. Additionally, the article underscores that the dependable integration of the antenna and RF module on the same silicon substrate is attainable.

KEYWORDS *Silicon Antenna, CPW Fed Slotted Antenna, Synthetic Aperture Radar (SAR) Miniaturization, C-band Antenna.*

I. INTRODUCTION

Synthetic Aperture Radar (SAR) is an active microwave radar known for its all-weather capabilities and exceptional resolution, making it a valuable tool for tactical and remote-sensing applications [1,2]. However, challenges such as bulkiness, high energy requirements, and elevated costs have historically limited the widespread use of SAR systems for long-term monitoring and frequent revisiting. A recent development involves the integration of SAR systems onto Unmanned Aerial Vehicles (UAV), addressing these challenges and providing enhanced operational flexibility and cost-effectiveness.

The concept of utilizing small platforms for SAR has been under research since the 1960s, but recent technological advances in computer architecture and microelectronic devices have enabled its practical implementation. UAV-based SAR systems offer clear advantages, including reduced costs, real-time data capabilities, and swift responsiveness [3-5].

Advancements in SAR instruments, such as multilayer ceramic carriers, highly integrated GaAs microwave monolithic integrated circuits (MMICs), and silicon control circuits in chip form, contribute to smaller size and weight. The development of a miniature front-end SAR system featuring an active phased array antenna [6] represents a cutting-edge technique in this field.

The phased array technique enhances the antenna aperture by incorporating thousands of discrete radiating elements, resulting in higher gain. Each radiator is individually controlled by a Transmit/Receive (TR) module, providing the antenna with maximum flexibility in beam formation.

Examining the front-end configuration of the SAR system, the antenna emerges as a crucial component, where design and material selection significantly influence overall size and performance. While SAR system antennas are traditionally large to achieve high resolution, ongoing efforts focus on miniaturization through advanced materials and design techniques.

As silicon technology matures, it emerges as a cost-effective option for manufacturing small antennas. This makes silicon an appealing choice for researchers and designers exploring various aspects of silicon antennas, encompassing design, fabrication techniques, and applications. The high dielectric constant and seamless integration potential with RF systems make silicon substrate an ideal material for small antenna fabrication, contributing to a substantial reduction in the overall size of SAR systems. Moreover, silicon's superior thermal conductivity and resilience at higher frequencies enhance its durability, establishing it as a reliable option in antenna fabrication.

II. EXISTING SMALL SAR SYSTEM

Utilizing small platforms for Synthetic Aperture Radar (SAR) systems presents numerous practical applications and holds the potential for substantial cost reductions in SAR surveillance and imaging of specific ground areas. An illustrative example is the development of the MicroASAR in 2004, derived from the BYU microSAR design but significantly enhanced for robustness and flexibility. Deployed aboard the NASA SIERRA Unmanned Aerial System (UAS) with notable features such as a large payload capacity (25 kg), medium size (6m wingspan), efficient mission planning software, and an in-flight programmable autopilot, the SIERRA is well-suited for extended-duration missions.

ARTEMIS, Inc. has played a pivotal role in SAR program development and manufacturing for over a decade, collaborating on experimental initiatives like UAVSAR, GLISTEN, NuSAR, and MicroASAR with renowned institutions such as Jet Propulsion Laboratory, Naval Research Laboratory (NRL), and Space Dynamics Laboratory (SDL).

Two noteworthy examples of high-performance, small, and cost-effective SAR systems designed for operation on small Unmanned Aerial Systems (UAS) are the SlimSAR and NuSAR [8,9]. The SlimSAR, operating at L-band frequency, weighs less than 3 kg, consumes 150 W (including a built-in motion measurement system), and can be converted to X-band frequency with a lightweight block frequency converter. Meanwhile, the NuSAR operates at either L-Band or X-Band, offering a 30 cm resolution and achieving size reduction through advancements in motion compensation techniques, enhancing processing efficiency and accuracy [10].

IMSAR, a privately owned business, has been a key player in designing, building, and supporting security and intelligence products, particularly unmanned platforms featuring cutting-edge Synthetic Aperture Radar technology since 2009. A notable achievement is the deployment of a tiny synthetic aperture radar in a small UAV for tactical capabilities, measuring 15.7 x 19.1 x 11.4 cm and weighing less than 1 kilogram. The use of printed circuit board technology in the NanoSAR contributes to its affordability, differentiating it from standard synthetic aperture radars. IMSAR's commitment to innovation has significantly impacted the field of small SAR systems, expanding their potential applications. Tabulated in Table 1 is Systems and Images of MicroASAR, SlimSAR and NanoSAR.

III. STATE OF THE ART

The utilization of air cavities beneath silicon antennas, as observed in the rectangular microstrip patch silicon antenna [12], signifies an innovative strategy to address the challenges of dielectric constant and substrate losses. Although this approach widens the bandwidth, it comes at the expense of reduced antenna radiation efficiency. This trade-off underscores the intricate balance researchers navigate when striving for optimal antenna performance.

The meander dipole-type silicon antenna [13], with a bandwidth of 43%, showcases the versatility of silicon-based designs for radar and remote sensing applications. The success of this antenna highlights the potential for silicon antennas to cater to diverse technological needs. However, the absence of measured radiation pattern and gain data in the study points to a gap in comprehensive evaluation, urging future research to address these aspects for a more holistic understanding.

The integration of ultra-wideband (UWB) technology in healthcare, exemplified by the tiny loop UWB silicon antenna [15], demonstrates the adaptability of silicon antennas to specific application domains. The emphasis on reliable operation within the frequency range compatible with body tissues illustrates the strategic thinking in tailoring antenna characteristics for targeted applications, such as Body Area Networks (BAN) in healthcare.

The evolution of coplanar waveguide (CPW) antennas on silicon reveals a dynamic exploration of design possibilities. The inclusion of a ground slot in a CPW antenna [16] contributes to a measured gain of 2.5 dBi, although the limited bandwidth suggests room for improvement. Subsequent advancements, such as the CPW-fed slotted antenna on high resistivity silicon (HRS) [17], exhibit substantial progress with a 41% bandwidth and an 8.7 dBi simulated gain as shown in Figure 1.

The drive for miniaturization is evident in the continuous refinement of antenna designs. For instance, the miniaturization of a CPW-fed slotted antenna up to $\lambda/4$ with a 45% bandwidth and measured gain of 2.5 dBi [19] signifies a significant leap forward. This progress addresses concerns related to size reduction while maintaining or even enhancing antenna performance.

The widespread adoption of Coplanar Waveguide Antennas (CPW) in wireless communication and RF applications underscores their practical significance. The study of equilateral triangular microstrip slot antennas at 9 GHz [23] not only emphasizes the adaptability of CPW structures but also sheds light on the importance of strategic slot placement for achieving wide bandwidths and desirable radiation patterns.

The diverse shapes and techniques explored in CPW-fed microstrip slot antennas [20-22] reflect a nuanced approach to customization and tuning. This adaptability allows researchers to tailor antenna structures for balanced transmission lines and specific frequency bandwidths, ensuring optimal performance in varied applications as shown in Figure 2.

In conclusion, the evolution of silicon-based antennas showcases a journey of innovation, addressing challenges, and fine-tuning designs for enhanced performance across a spectrum of applications, from healthcare to wireless communication. The ongoing exploration of these antennas is marked by a continual quest for the ideal balance between size, bandwidth, and overall efficiency. Table 2 shows the SOTA table.

Table 1: Systems and Images of MicroASAR, SlimSAR and NanoSAR

YEAR	SYSTEM	DIAGRAM/PHOTO
2004 – 2008	• MicroASAR • C Band • Weight 25Kg • Flown on NASA SIERRA UAS • BYU	
2008 – 2011	• SlimSAR/NuSAR • L & X Band • Size 55x31x36 cm • Weight 3 Kg • flown on various sizes of ○ platforms (small to large) • ARTEMIS/ NRL/SDL	
2009 – 2021	• NanoSAR • Ku Band • Size15.7x19.1x11.4 cm • Weight 1 Kg • Flown on UAV/UAS • IMSAR	

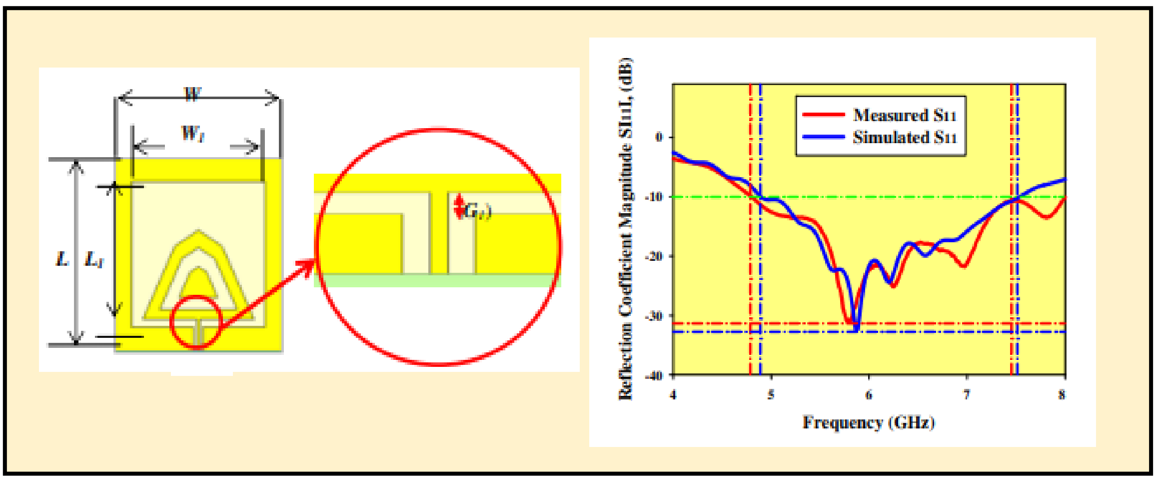


Figure 1: Silicon CPW Fed Slotted Antenna with Simulated and Measured $|S_{11}|$ Results [17].

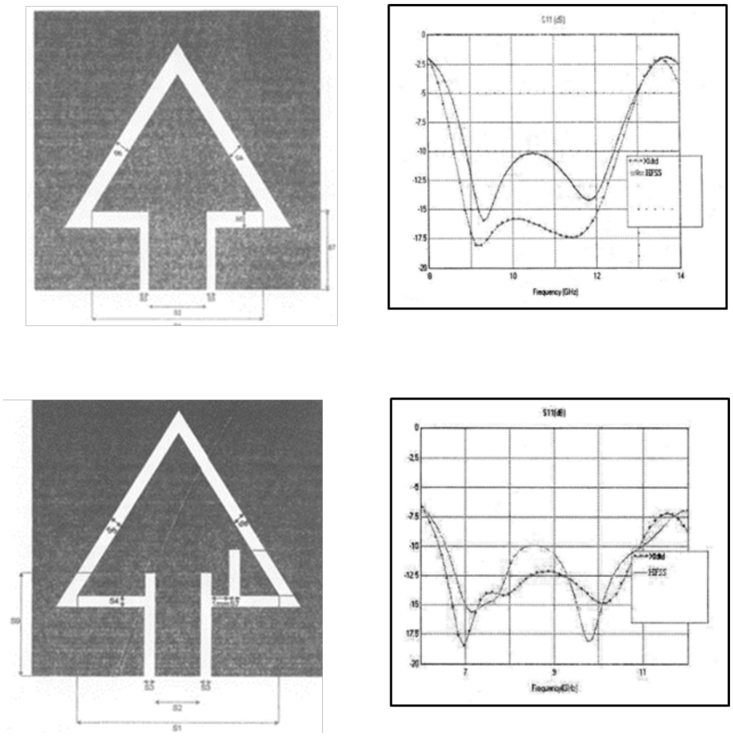
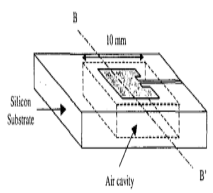
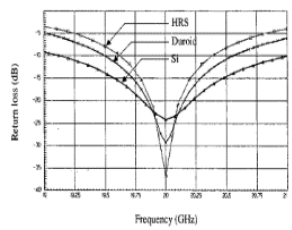
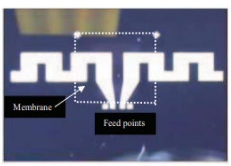
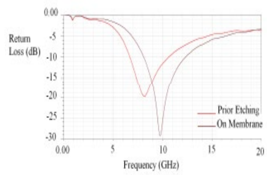
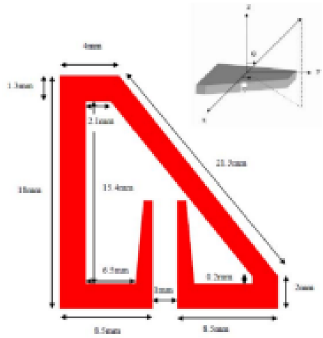
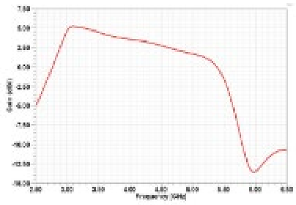
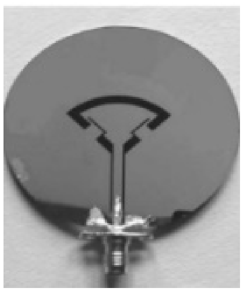
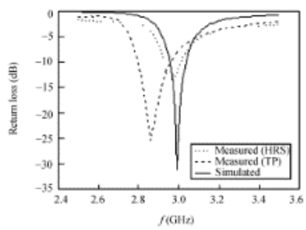
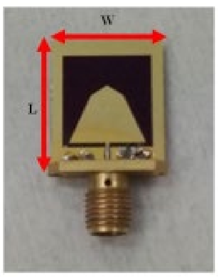
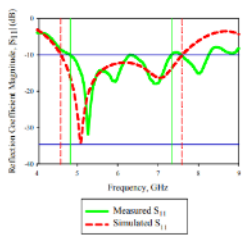
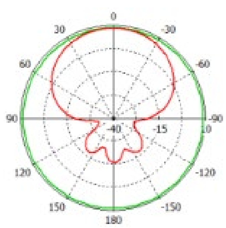
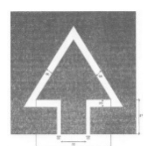
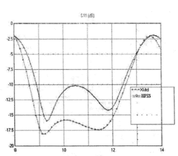
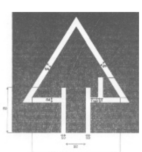
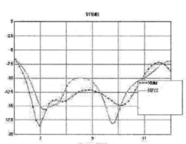


Figure 2: Shows CPW Antenna with a wide bandwidth between 40% to 50% [23].

Table 2: State of The Art (SOTA) Table

Paper Reference No	Methodology & Results	Advantages and Disadvantages
[12]	Rectangular Microstrip Patch Antenna  	Advantages: improvement in bandwidth Disadvantages: Complicated to low dielectric constant
[13]	Meander Dipole Antenna  	Advantages: Wide bandwidth Disadvantages: Complicated design

[15]	Small UWB Antenna  	Advantages: Small but high gain Disadvantages: Restricted to conductivity and permittivity of body tissues.
[16]	Coplanar Waveguide (CPW) Girth S Slot Antenna  	Advantages: Compact and compatible with antenna integration Disadvantages: Narrow bandwidth
[17]	Coplanar Waveguide (CPW) Slotted Antenna   	Advantages: Compact, wide bandwidth and high gain Compatible for full integration Disadvantages: omnidirectional radiation pattern
[23]	Wide-Band Equilateral Triangular Slot    	Advantages: Wide bandwidth Disadvantages: Not compatible for full integration

V. CONCLUSION

This article investigate into recent breakthroughs in silicon antenna technology, with a particular focus on the promising avenue of integrating antennas and other devices on a shared silicon substrate. Notably, techniques like Coplanar Waveguide (CPW) and the strategic incorporation of slots in patch antennas have emerged as key contributors to heightened antenna performance.

By employing these techniques, significant advancements have been achieved. The observed outcomes include a notable enhancement in antenna bandwidth, ranging impressively from 3.4% to an expansive 45%. Simultaneously, there has been a discernible reduction in the physical size of the antennas. These developments underscore the efficacy of innovative methodologies, such as CPW and strategic slot integration, in pushing the boundaries of silicon antenna capabilities.

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