W-Band Cavity-backed Folded-slot Antenna Using GaAs Integrated Passive Device Technology

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***Abstract*—A W-band cavity-backed folded-slot antenna based on GaAs integrated passive device technology is proposed in this paper for the first time. A via-cavity is formed to produce TE_{120} mode resonance and suppress surface waves, and an offset folded slot is designed to match the high impedance of the cavity. The simulated and measured S_{11} and the simulated radiation patterns are presented, which demonstrate that the antenna can operate from 97.8 GHz to 98.6 GHz with a maximum gain of 2.5 dBi while consuming a small area of only 0.84mm ×1.325mm. The proposed antenna is suitable for system-on-chip millimeter-wave applications where front-end modules and the antenna are built on the same chip for minimal signal transfer loss.**

***Keywords*— Antenna on-chip, integrated passive device, millimeter-wave antenna**

I. INTRODUCTION

Sub-millimeter wave imaging requires a high-power RF signal output for long-distance detection of objects. Due to the nature of high path loss at the sub-millimeter wave, good power handling is a critical feature of the system. With that being said, the RF front-end antenna also needs to fulfill the power requirements. In addition to the power capacity, the imaging system at such a high frequency is facing a challenge in terms of integration and packaging. System-on-chip (SoC) provides a high level of integration, and consequently, the interconnection loss and system size are greatly reduced. Antenna-on-chip enables not only chip-level integration but also down to micrometer-precision fabrication. Recent reports show that different types of antennas are studied with different chip technologies. In [1], a 4×4 patch antenna array is designed using gallium arsenide (GaAs) based integrated passive device (IPD) technology at the automotive radar frequency band. In [2], a Yagi-Uda antenna on glass IPD is proposed for the front-ends of 60 GHz radios. In [3], tightly coupled antenna arrays are designed on silicon IPD for very wideband operation from Ku to W band.

In this paper, we report a cavity-backed folded slot antenna using GaAs IPD. The antenna adopts the structure of a folded slot with a rectangular cavity formed by a series of vias. Thanks to the techniques of offset slot and quarter-wavelength ground coplanar waveguide (GCPW) transmission line (TL), the input impedance is reduced from an inherently high impedance of the folded slot structure to 50 Ω. The antenna is measured in regard to return loss, and the simulated radiation patterns are given. Measured results show that the antenna return loss is greater than 10 dB from 97.8 GHz to 98.6 GHz, and the simulated radiation pattern is broad sight. This antenna is designed for integration with passive and active circuits on a single GaAs chip with the uniform ground.

II. ANTENNA DESIGN

A. GaAs IPD Technology Introduction

The GaAs IPD technology adopted is a flexible integrated passive device platform fabricated on a 100 μm semi-insulating GaAs wafer. This technology targets high-voltage application that requires cost-effective high-Q matching networks. Three metal layers exist and can be stacked to provide up to 7 μm total Au thickness for low-loss Transmission Lines (TL) and high-Q matching elements. Low k dielectric crossovers and high resistance are used for moisture ingression at high voltage levels for better integration with high voltage active devices provided by, for example, gallium nitride technologies. Capacitors, inductors, resistors, and through-wafer via (TWV) are all provided for completed passive device designs. Backside metal is provided for uniform ground and is mandatory in this process.

B. Antenna Structure

The substrate relative permittivity is 12.9 for GaAs, and the thickness is 100 μm. As the substrate does not fulfill equation 1, it can be considered a moderately thick substrate for microstrip antennas [4].

$$\frac{h}{\lambda} < \frac{0.3}{2\pi\sqrt{\varepsilon_r}} \quad (1)$$

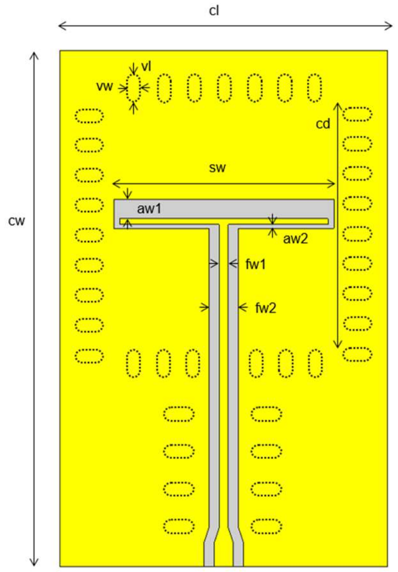
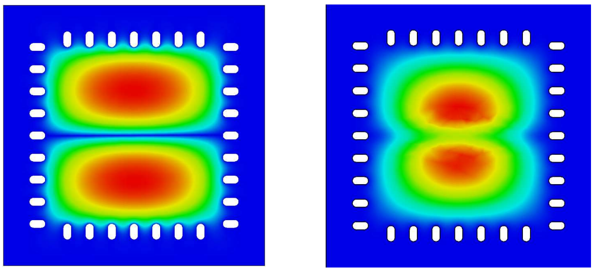


Fig. 1. Top view and dimensions of the proposed antenna



(a) (b)

Fig. 2. Cavity TE_{120} mode (a) without folded slot, (b) with folded slot

To reduce surface wave diffraction at the edge, a cavity is formed to facilitate strong resonances and broadside radiation. However, the trade-off would be limited bandwidth. A square cavity is chosen, and elliptical TWVs are placed as the side wall of the cavity with dimensions shown in Table I. The minimum via spacing of 55 μm is chosen because such distance satisfies the design rule in [5] where leakage loss is negligible. By performing characteristic mode analysis using CST studio suite, a cavity with a side length of 710 μm for resonating at TE_{120} mode without the slot. A folded slot is open then at the surface for radiation. The periphery of the slot is not that critical in determining the mode but does cause the frequency to vary to a small extent. The E field within the cavity shows that after slotting the surface, the center point of the TE_{120} mode is forced to move towards the folded slot, resulting in a larger mode size, and thus a lower resonating frequency. By offsetting the feeding strip position, the input impedance of the antenna can be tuned down from a very high value. Fig. 3 shows the effect of the parameter aw1 on antenna impedance. As the feeding strip is shifted towards the lower slot edge, the antenna impedance is reduced. Due to the limitation of design rules, the antenna impedance can not be tuned to 50 Ω by simply reducing aw1. Therefore, a three-quarter wavelength GCPW TL at 100 GHz with a character impedance of 78 Ω is added to transform impedance as well as feed the radiating slot. Vias are added along the GCPW to suppress substrate mode.

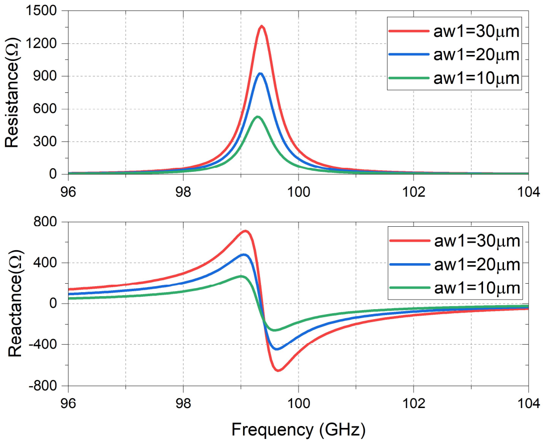


Fig. 3. Antenna input impedance (resistance and reactance) versus frequency for different slot width aw1.

TABLE I. MAIN PARAMETERS OF THE ANTENNA (UNIT: MICRO METER)

cl	cw	aw1	aw2	vw	vl	fw1	fw2	sw	cd
840	1325	50	10	30	60	23	75	564	710

III. ANTENNA SIMULATION AND MEAUREMENT RESULTS

Antenna return loss was measured at Taiwan Semiconductor Research Institute (TSRI) using a 110-GHz vector network analyzer. The measurement setup is depicted in Fig. 4. The simulated and measured return loss of the antenna are shown in Fig. 5(a). The measured antenna operating frequency is from 97.8~98.6 GHz. About 1 GHz frequency deviation is observed due to a mismatch from probing the chip. At the time of publication, the radiation pattern and gain measurements are not available. Therefore, only simulated results are shown in Fig. 5(b). The antenna features a broad sight radiation pattern, and the peak gain is 2.5 dBi.

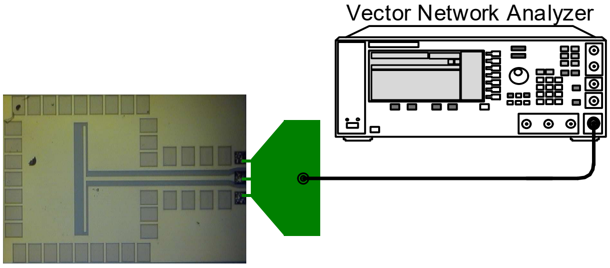
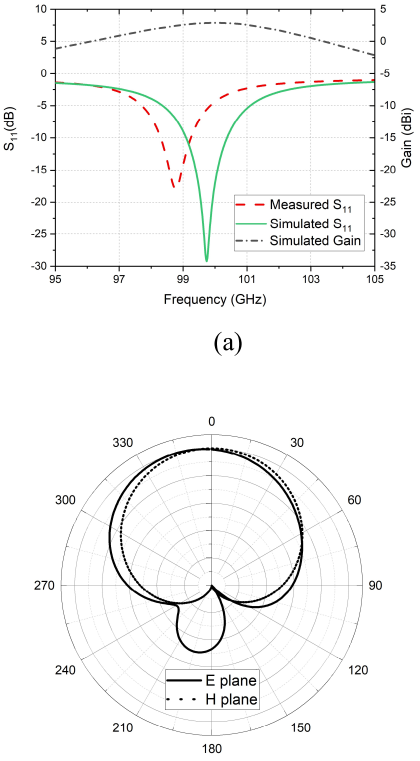


Fig. 4. Measurement setup.



(a)

(b)

Fig. 5. (a) Antenna S_{11} and gain (b) radiation pattern.

IV. DISCUSSIONS

A W-band cavity-backed folded-slot antenna was proposed in this paper. The optimized antenna was based on GaAs IPD substrate. Backside metal and CPW feedlines were used for easy integration with a passive and active circuit on a single chip. The cavity-resonator mode was designed based on the substrate technology for minimizing substrate mode and folded slot was designed to reduce the high impedance of the cavity slot. The proposed antenna with a small chip area is shown to be a good candidate for integration with millimeter-wave front-end modules and components for system-on-chip applications.

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REFERENCES

[1] T. Y. Lin, S. G. Lin, Y. C. Chang, etc. Compact 77 GHz 4×4 patch array design using backside metal grounded GaAs-based IPD technology. *2019 IEEE CPMT Symposium Japan (ICSJ)*, pp. 139-140.

[2] F. Huang, C. Lee, C. Kuo, etc. “MMW antenna in IPD process for 60-GHz WPAN applications”, *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 565-568, 2011.

[3] N. Khiabani, C. W. Chiang, N. C. Liu, etc. “An ultrawide Ku to W-Band array antenna package using flip-chipped silicon integrated passive device with multilayer PCB technology”, *IEEE Microwave Wireless Component Letters*, vol. 31, no. 7, pp. 861-864, 2021.

[4] R. Garg, Microstrip antenna design book, 2001, pp.46.

[5] D. Deslandes and K. Wu, "Accurate modeling, wave mechanisms, and design considerations of a substrate integrated waveguide," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 6, pp. 2516-2526, 2006