Design and Fabrication of Substrate-Independent Integrated Antennas utilizing Surface Micromachining Technology

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Abstract— **This paper presents several novel 3-D antennas topologies that feature the capability of substrate-independent integration for future mm-wave systems. The high-aspect-ratio surface micromachining technology has been utilized to implement these 3-D structures. A 100 GHz vertical Yagi-Uda antenna is fabricated and tested for end-fire radiation applications. In addition, an air-filled elevated microstrip antenna resonating at 25 GHz is built and characterized for broadside radiation. A completely substrate-independent multi-depth-well integration scheme for large-scale antenna arrays is also proposed. Simulation and measurement data are provided to demonstrate the effectiveness and feasibility of the proposed scheme.**

Index Terms— **surface micromachining, millimeter wave antenna, monolithic integration, 3D integration, substrate-independent performance.**

I. INTRODUCTION

Next generation microwave and mm-wave communication systems (i.e. ubiquitous access nodes) require the integration of an ever increasing number of functions into a compact module. The trend is to integrate RF, analog, digital and optical parts on single substrate or into one package [1]. However, this monolithic integration is a very challenging task due to different substrate property requirements. For example, antenna integration usually needs a low-ϵ low-loss substrate; Analog and digital circuitry, however, uses a doped high–ϵ silicon substrate; Optical modules are usually implemented on III-V compound substrates. Various methods [2][3] have been investigated for this problem. In this paper, a substrate-independent method for antenna integration is proposed for the first time. The antenna is either air-extruded or air-lifted on the top of the wafer and isolated from the substrate by metallizing the top of the substrate. Both broadside and end-fire radiation configurations are investigated for different applications as benchmarks for this approach. For the end-fire radiation, a W-band vertical Yagi-Uda have been developed and tested. For the broadside radiation, two Ka-band elevated patch antennas have been optimized and characterized. The simulation and measurement data demonstrate that the proposed integration scheme totally eliminates the substrate effects. The process is low-temperature and compatible with commercial CMOS technology, allowing easy integration with other modules into one single substrate/package.

II. INTEGRATION SCHEME FOR A W-BAND YAGI-UDA ENDFIRE ARRAY

The Yagi-Uda antenna array has been extensively used after it was proposed in 1926. In millimeter-wave systems the Yagi antennas are often fabricated in the printed circuit form benefiting from ease of manufacturing [4]. However, the direct placement of those antennas on a dielectric substrate is always accompanied by surface wave effects due to the substrate, resulting in electrical performance degradation. In our effort, we developed a substrate-independent Yagi-Uda antenna for W-band applications. The architecture and the prototype we built are shown in Fig. 1 and 2 respectively. In W-band, the feature size is at sub-millimeter scale. For instance, a quarter-wavelength wire monopole resonating at 94 GHz has a height of $800\mu m$ and a radius of several tens of microns. The fabrication difficulty associated with such 3-D structures has heretofore prevented them from being efficiently implemented in a traditional mechanical fashion. Advanced surface-micromachined 3-D MEMS technologies [5] have been introduced to meet this challenge.

Numerical EM simulations have been performed to optimize the design by Ansoft HFSS 9.1. The optimized heights of the reflector, the source (driving) monopole, and the directors have been found to be $800\mu m$, $720\mu m$, and $560\mu m$, respectively. The pitch between the adjacent monopoles p is fixed to be $480\mu m$ for all elements. The diameter of the monopoles is $80\mu m$. The whole structure is fed by coplanar waveguide using a wideband CPW-to-vertical-probe transition [6].

The proposed fabrication process utilizes the concepts of high-aspect-ratio surface micromachining technology and metal coated epoxy core [7]. The fabricated prototype was characterized using an Agilent 8510XF network analyzer. A 5-element Yagi-Uda antenna shows a below-10 dB return loss from 96 to 108 GHz as shown in Fig. 3, leading to a 12% below-10 dB bandwidth. This broadband feature is superior to that of the conventional printed antennas that commonly have a narrowband nature (3%-5% typically) due

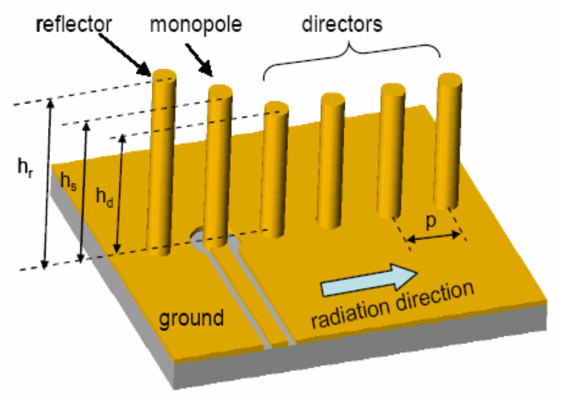

Fig. 1. Proposed vertical W-band Yagi-Uda arry

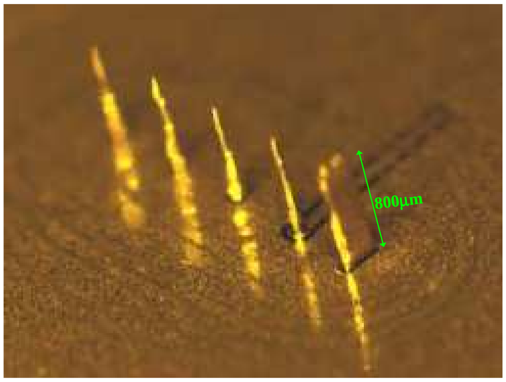

Fig. 2. Photo of fabricated Yagi-Uda array under a microscope

to the substrate effects. Radiation pattern measurements are currently in progress. Simulations demonstrate an endfire radiation characteristic with a maximum directivity of 8.2 dBi in the direction of the horizontal axis (See Fig. 4).

III. Integration Scheme For Ka-Band Broadside Patch Antennas

We have also developed integration schemes to fabricate elevated patch antennas, since microstrip patch antennas are widely used due to their low manufacturing cost, relatively good performance and mature optimization tools. Typically, low-ϵ substrates are preferred for microstrip antenna design. Nevertheless, the requirement of compactly integrating other RF components/passives in planar or 3D modules is typically achieved utilizing high-ϵ materials. This conflict can either lead to a hybrid integration solution or both antennas and other RF parts to be built on the same substrate with an intermediate ϵ and get a suboptimal component performance instead of best performance for each part. We propose two alternative schemes. The first one is an air-lifted patch, that is fed by a vertical metal probe and supported by polymer posts. The second one is to put both the feeding microstrip line and patch antenna into pre-etched wells, with different well depths for different function modules.

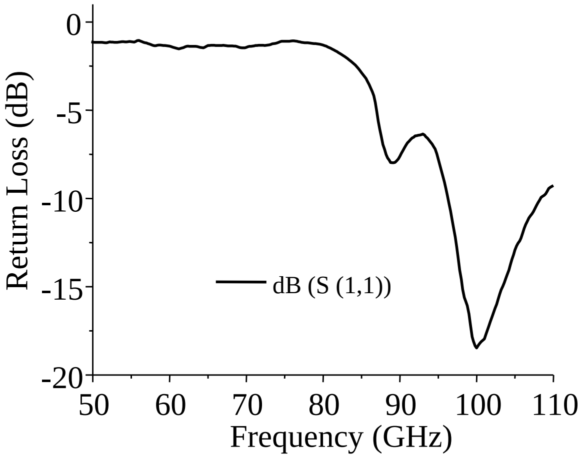

Fig. 3. Measured return loss of W-band Yagi Uda array

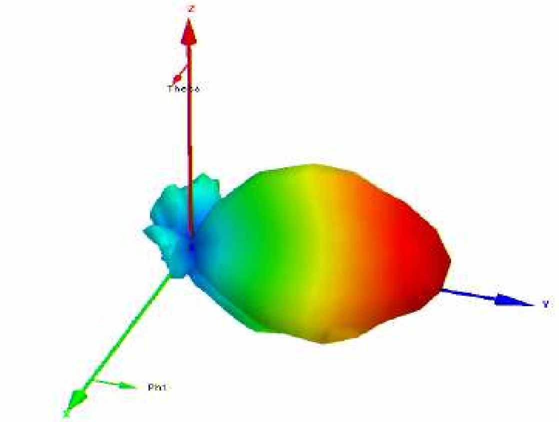

Fig. 4. Simulated radiation pattern of W-band Yagi Uda array

A. *Elevated Patch Antenna*

The patch antenna is air-lifted into air by means of surface micromachining technology. Both metal posts and polymer posts are used to provide mechanical support, as well as electrical feeding. The fabricated prototype is shown in Fig.5. The 7% below-10 dB bandwidth, centered at 25 GHz was observed with the aid of an Agilent 8510C network analyzer and is demonstrated in Fig. 6. The mirror image of the elevated patch antenna also appears under microscope due to the shining ground. The proposed structure is superior to the conventional patch in terms of bandwidth, efficiency and lower side lobe. While the traditional patch antenna directly printed on substrate usually gives a 3%-5% bandwidth and 70%-80% radiation efficiency, the proposed elevated patch will double the fractional bandwidth and gives a theoretical 97% radiation efficiency, which is achieved by eliminating the substrate loss.

B. *Multi-depth Wells For Integration of Patch Antenna with Feeding Lines*

For large scale mm-wave antenna arrays, the losses due to the feeding network is a very important issue. H.S. Lee [8] reported an elevated microstrip feedline at a height of several tens of microns. Nevertheless, it is hard to monolithically

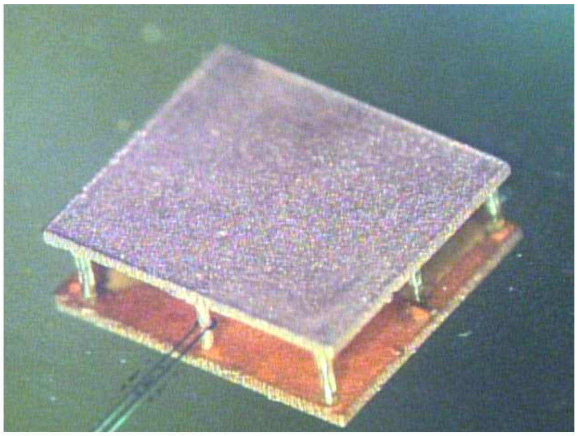

Fig. 5. Photo of fabricated elevated patch antenna, along with its mirror image on the ground

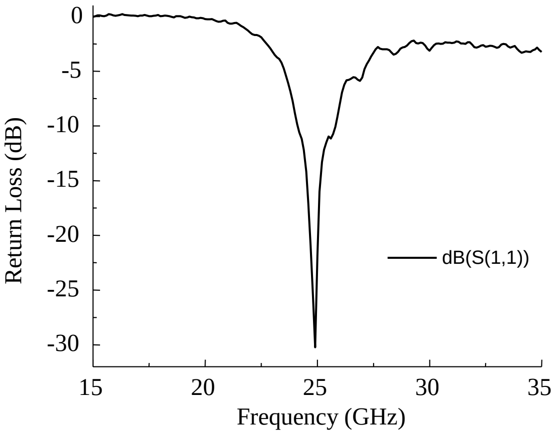

Fig. 6. Measured return loss of the elevated patch antenna

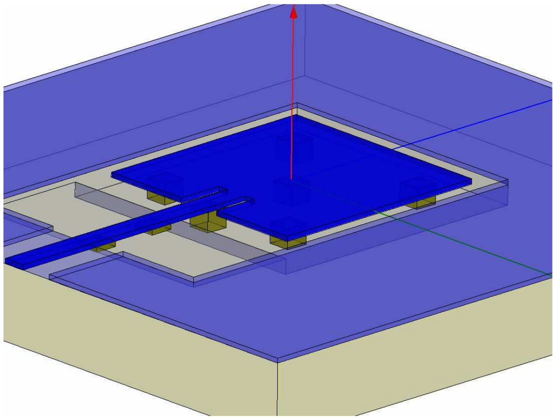

Fig. 7. Proposed multi-depth well integration scheme of the patch antenna and feeding lines

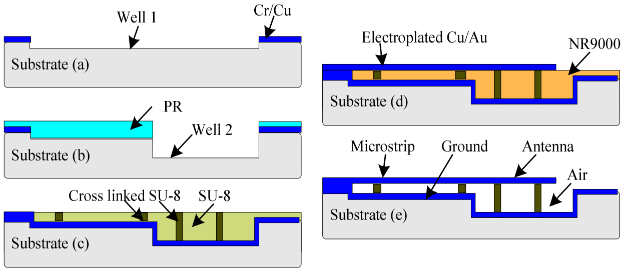

Fig. 8. Fabrication steps of the multi-depth well integration scheme

integrate this elevated microstrip with the elevated patch antenna described in the previous paragraph due to the different elevation height requirements for the microstrip line and the patch antenna. A patch antenna is required to be air-lifted by several hundred microns to maximize the radiation. However, a 50Ω microstrip line will be as wide as several millimeters when it is being elevated into air by the same height. This dimension is comparable with the size of the patch antenna in Ka-band, thus the parasitic radiation generating from the feeding microstrip can not be neglected.

In our work, multiple wells with stepped depths into the wafer are fabricated and utilized to elevate both feeding lines and antennas. To get optimal performances, microstrip feeding lines are put into the shallow wells to reduce the radiation, while the patch antennas use deeper wells to enhance the radiation. Only polymer posts are needed for this integration scheme since the feeding network and the antenna array are at the same height level. This can reduce the fabrication complexity a lot.

The proposed scheme is shown in Fig. 7 and its fabrication steps shown in Fig. 8. The full wave simulations predict a below 10 dB return loss from 26.5-28.5 GHz, which corresponds to a 7 % fractional bandwidth, centering at 27 GHz. It also demonstrates a nearly constant broadside radiation pattern over these frequencies, with a 10.4 dBi directivity at center frequency and low side/back lobes (all below -20 dB) as shown in Figs. 9-10.

IV. CONCLUSIONS

We have presented a novel substrate-independent antenna integration approach for millimeter-wave applications. The scheme can eliminate the undesired substrate effects for integrated antennas and can be used on most substrates to monolithically integrate RF, analog and digital functions. The surface micromachining technology is used to build the benchmarking prototypes, including a W-band vertical Yagi-Uda and two Ka band elevated patch antenna topologies. In addition, a multidepth-well scheme is proposed to demonstrate the potential benefits of the combination of elevation schemes

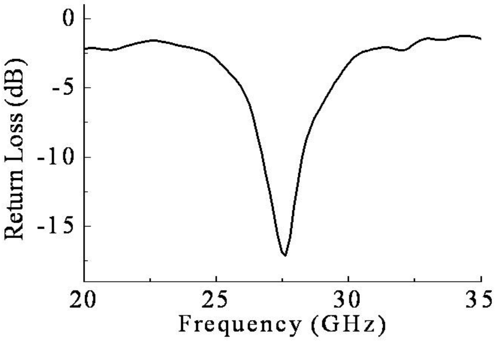

Fig. 9. Return loss of the patch antenna in a multi-depth well

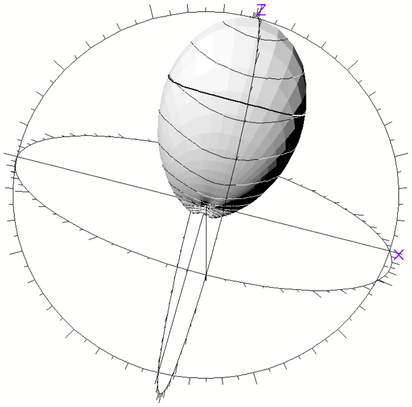

Fig. 10. Simulated radiation pattern of the patch antenna in a multi-depth well

for antennas and feeding transmission lines.

V. ACKNOWLEDGEMENT

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