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Micromachined On-Chip Dielectric Resonator Antenna Operating at 60 GHz

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***Abstract*— This paper presents a novel cylindrical Dielectric Resonator Antenna (DRA) suitable for millimeter-wave on-chip systems. The antenna was fabricated from a single high resistivity silicon wafer via micromachining technology. The new antenna was characterized using HFSS and experimentally with good agreement been found between the simulations and experiment. The proposed DRA has good radiation characteristics, where its gain and radiation efficiency are 7 dBi and 79.35%, respectively. These properties are reasonably constant over the working frequency bandwidth of the antenna. The return loss bandwidth was 2.23 GHz, which corresponds to 3.78% around 60 GHz. The antenna was primarily a broadside radiator with –15 dB cross polarization level.**

***Index Terms*—On-chip antennas, dielectric resonator antennas, micromachining technology, mm-wave applications.**

I. INTRODUCTION

THE ever increasing demand for high performance communication systems has motivated the shift of wireless systems towards the millimeter-wave (mm-wave) range. At these relatively high frequencies, microstrip antennas suffer from high conductor and substrate losses resulting in the deterioration of the antenna radiation efficiency. The replacement of the lossy planar metallic antennas with high permittivity Dielectric Resonator Antennas (DRAs) is considered a good solution to this problem. The idea of using Dielectric Resonators (DRs) as radiating antennas was first introduced in 1983 [1]. Since that time, DRAs received great attention due to their appealing characteristics like small footprint, light weight, absence of surface wave and metallic losses. In addition, DRAs can have various geometrical topologies. DRAs can be excited using a variety of feeding structures like co-axial lines [2], microstrip lines [3], coplanar waveguides [4], aperture excitation [5], and even conformal strip excitation [6]. However, the fabrication of DRAs in the millimeter-wave range is challenging [7], owing to the relatively small features required. The thickness of the substrate carrying the feeding microwave circuit must be electrically thin in order to avoid surface wave modes excitation. Besides, any misalignment between the DRA and the feeding structure results in significant impedance mismatch [7].

Research carried out in the area of DRAs can be classified into two categories. The first category is concerned with improving the antenna electrical characteristics. The substrates carrying the driving circuit are made from non-semiconductor materials (neither silicon nor GaAs). Therefore, antennas in this category are not suitable for on-chip integration. In [8], the substrate used has relative permittivity, ε_r, of 10.2, whereas in [9-14], the substrates used were teflon with ε_r= 2.2. In [8], stacked DRAs were designed to achieve good radiation characteristics where a gain of 6 dBi and bandwidth of 24% were realized. Another technique for improving the gain was introduced in [9]. The gain of the DRA was enhanced by using a superstrate located at a certain distance from the DRA. A gain higher than 11 dBi and a bandwidth of 18.4% were obtained. Further enhancement for the gain has been made in [10], where the superstrate was stacked with multiple metallic strips. The gain of that antenna was higher than 15.4 dBi over its working bandwidth. Excitation of higher order modes of the DRA is also considered a method for improving the gain [11-14]. The higher order modes of the $TE_{11\delta}$ mode (TE_{115}, and TE_{119}) were excited in [11]; whereas the modes $HE_{15\delta}$ and $HE_{12\delta}$ were excited in [12], and [13-14], respectively.

The second category of DRAs uses either silicon [15-18] or GaAs [7] substrate that can carry the driving electronics. In [15, 16], a DRA was fed by a coplanar waveguide (CPW) to excite the $HE_{11\delta}$ mode. The proposed antenna in that work has a gain of 3.2 dBi. However, it suffered from low radiation efficiency (51%). In [17], the DRA was fed by a *H*-slot which excited the $TE_{11\delta}$ mode. This antenna has an improved radiation efficiency of 59% while its measured gain was 0.5

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dBi. In [7], a Dielectric Resonator Antenna above Patch (DRAP) was introduced. The substrate of the antenna was GaAs. This antenna has a good impedance bandwidth (29.2%), whereas it has a gain of 3.6 dBi. For all these designs, the DRA itself was constructed from a material different from the silicon or GaAs substrate material, which requires hybrid integration. In [18], a high resistivity (ρ_{si}= 300 Ω.cm) silicon was used as a material for both the substrate and the four DRAs arranged as 2×2 array. A number of BenzoCycloButhene (BCB) films were deposited on top of the slotted ground plane at the back-side of the substrate to realize the feeding microstrip network. The gain of this DRA array was about 11 dBi and its simulated radiation efficiency was 62%. Such antenna represents a complete on-chip solution in which the DRA is micromachined from the same wafer carrying the driving circuit.

In this paper, a novel cylindrical DRA suitable for on-chip applications is introduced. The proposed DRA is micromachined in silicon. A Coplanar Waveguide (CPW) structure is used to feed the proposed DRA, instead of the microstrip network used in [18]. Therefore, no BCB layers are required, which leads to a simpler and less expensive design. Unlike the CPW-fed DRAs presented in [8, 15-17], the CPW feeding line of the proposed design is placed at the underside of the substrate. This facilitates the construction of the DRA and its feeding network using a single wafer.

The paper is organized as follows: the structure of the new antenna together with its radiation mechanism is introduced in Section II. A parametric study that leads to the optimum antenna dimensions is presented in Section III. The fabrication technology used to realize the proposed antenna is outlined in Section IV. The optimum design is characterized both theoretically and experimentally in Section V. The important conclusions are stated in Section VI.

II. Antenna Structure and Radiation Mechanism

The structure of the proposed DRA is shown in Fig. 1. The cylindrical DRA, with radius R is defined in a high resistivity silicon wafer by etching the silicon around the cylinder as shown schematically in Fig. 1(b). The resistivity of the silicon wafer is 2,000Ω.cm, its dielectric loss tangent (tan δ) = 0.003 [19], and its relative permittivity ε_r= 11.9. The wafers used were 675 μm thick. The height of the DRA is 400 μm, whereas the remaining thickness for the substrate is 275 μm. Such relatively thin substrate prevents the excitation of all surface wave modes except for the fundamental TM_0 mode [20].The DRA is excited by a magnetic dipole with length L and width W. This dipole terminates the feeding CPW line, whose slot width and slots separation are 40 and 68 μm, respectively. The line's dimensions correspond to a characteristic impedance of 50 Ω.The feeding structure is located at the back side of the silicon wafer, as shown in Fig. 1. The lateral spacing between the center of the feeding line and that of the DRA is denoted by S.

The CPW feeding line is excited with its odd mode where the magnetic currents flow in the two slots of the CPW in opposite directions. This forces the magnetic currents to flow through the arms of the magnetic dipole in the same direction. The magnetic and electric field distributions of the DRA designed at 60 GHz is shown in Fig. 2, as calculated by HFSS using finite element method. The magnetic field distribution matches that of the $HE_{11\delta}$ mode of the DRA [21]. It is clear from Fig. 2 that the magnetic field along the DRA has the same direction as the magnetic current flowing through the feeding magnetic dipole, and the maximum magnetic field occurs at the interface between the DRA and the substrate. This ensures maximum coupling from the feeding dipole to the desired DRA mode. On the other hand, the electric field at the top of the DRA is along the x-axis, normal to the magnetic field. It is worth noting that the coupling magnetic dipole is not located at the center of the DRA in order to achieve best matching with the feeding CPW line.

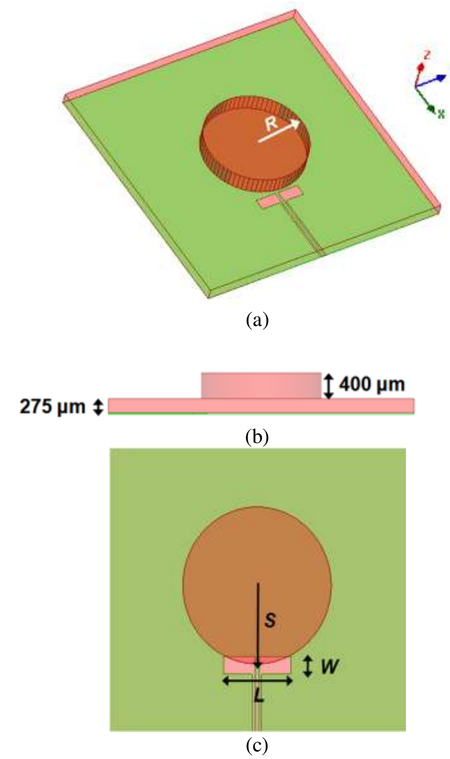
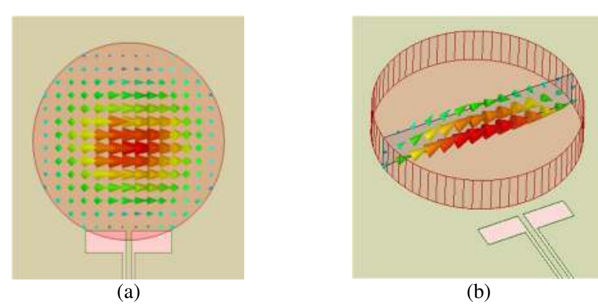


Fig. 1. Structure of the proposed DRA: (a) 3D view, (b) side view, and (c) projected top view.



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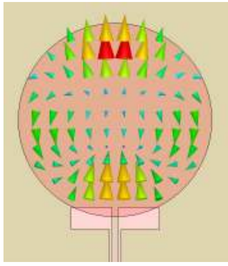

(c)

Fig. 2. Field distribution of the DRA at 60 GHz: (a) Magnetic field along the top face of the DRA, (b) Magnetic field along the central plane perpendicular to the substrate and parallel to the magnetic dipole, and (c) Electric field along the top face of the DRA.

III. PARAMETRIC STUDY AND OPTIMUM DESIGN

This section shows the effect of varying the geometrical design parameters of the DRA: *R*, *L*, *W*, and *S*, shown in Fig. 1, on its frequency response. The DRA dimensions determine the resonant frequency. Table I shows the sensitivity of the resonance frequency and return loss of the DRA to 10% perturbation (increase) of its design parameters around their optimum values. The optimum values are listed in Table II. It is worth mentioning that in this study, the height of the DRA was kept constant. Since, we are bounded by the wafer thickness (675 µm), increasing the height of the DRA implies decreasing the substrate thickness which affects the mechanical stability of the antenna. On the other hand, decreasing the height of the DRA adversely affects the antenna's radiation characteristics. The choice of H = 400 um is considered a compromise between both factors. From Table I, it can be observed that the most effective parameter to tune the resonance frequency is the radius of the DRA, *R*. This is expected as the DRA is the radiating element whose size must control most the value of the resonance frequency. Fig. 3 shows the HFSS simulated return loss of the DRA versus frequency for different values of the DRA radius, *R*. As *R* increases the value of the resonance frequency decreases, while good matching is maintained.

According to Table I, the length, *L*, and location, *S*, of the feeding dipole play the major role in achieving good matching between the DRA radiating mode and the feeding line. In other words, the input impedance of the DRA is mostly controlled via the two parameters *L* and *S*.

Fig. 4 shows the variation of the input impedance of the DRA simulated using HFSS at 60 GHz versus *L* and *S*. According to Fig. 4(a), as *S* increases, the input resistance slightly increases due to the decrease and the increase of the DRA modal current and voltage, respectively, which are proportional to the modal magnetic and electric field, respectively. The modal magnetic field is shown in Fig. 2. This behavior is similar to the effect of varying the location of the probe feeding a microstrip patch antenna. In a similar manner to a microstrip patch electromagnetically excited by an inductively coupled slot terminated by a short-circuit [22], the input resistance of the proposed antenna is strongly dependent on the length, *L*, of the feeding magnetic dipole. As *L* increases, the real part of the input impedance decreases significantly, as shown in Fig. 4(a).

TABLE I
SENSITIVITY OF THE RESONANCE FREQUENCY AND RETURN LOSS TO THE PERTURBATION OF THE DRA DESIGN PARAMETERS

Antenna Parameter	Resonance Frequency Sensitivity (GHz/10% Perturbation)	Return Loss Sensitivity (dB/10% Perturbation)
R	−3.29	6.95
L	−0.59	12.29
W	−0.18	3.49
S	0.56	14.49

TABLE II
OPTIMUM DIMENSIONS OF THE DRA

Antenna Parameter	OPTIMUM VALUE	Antenna Parameter	Optimum Value
L	1.068 mm	*W*	265 µm
R	1.18 mm	*S*	1.2 mm

Unlike the resistive part of the input impedance, which is affected mainly by *L*, its imaginary part is affected by both *L* and *S*, as shown in Fig. 4(b). As *L* increases, the antenna input impedance becomes more inductive due to the increased spacing between the short-circuit termination of the magnetic dipole and the feeding point. On the other hand, as *S* increases the DRA becomes more capacitive due to the increase in the modal voltage as one move away from the center of the DRA. It is worth mentioning that the region of maximum current, i.e. magnetic field, corresponds to minimum voltage, i.e. electric field, and vice versa. All geometrical parameters of the proposed structure are simultaneously optimized using HFSS so as to obtain maximum gain and minimum return loss at 60 GHz.

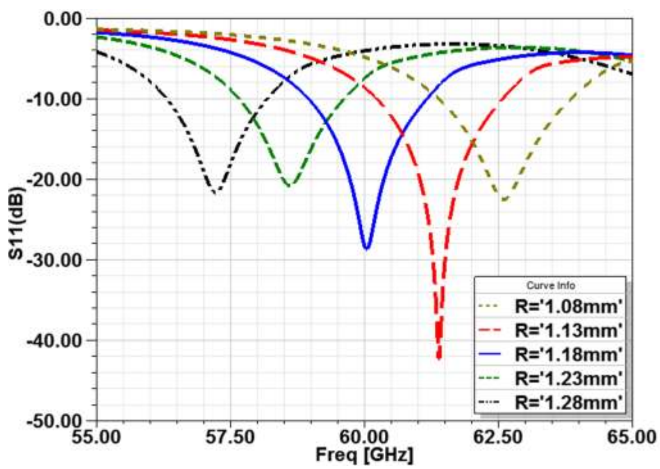

Fig. 3: Return loss of the DRA versus frequency for different values of the radius, *R*. The rest of parameters are kept constant at L = 1.068 mm, S = 1.2 mm, and W = 265 µm.

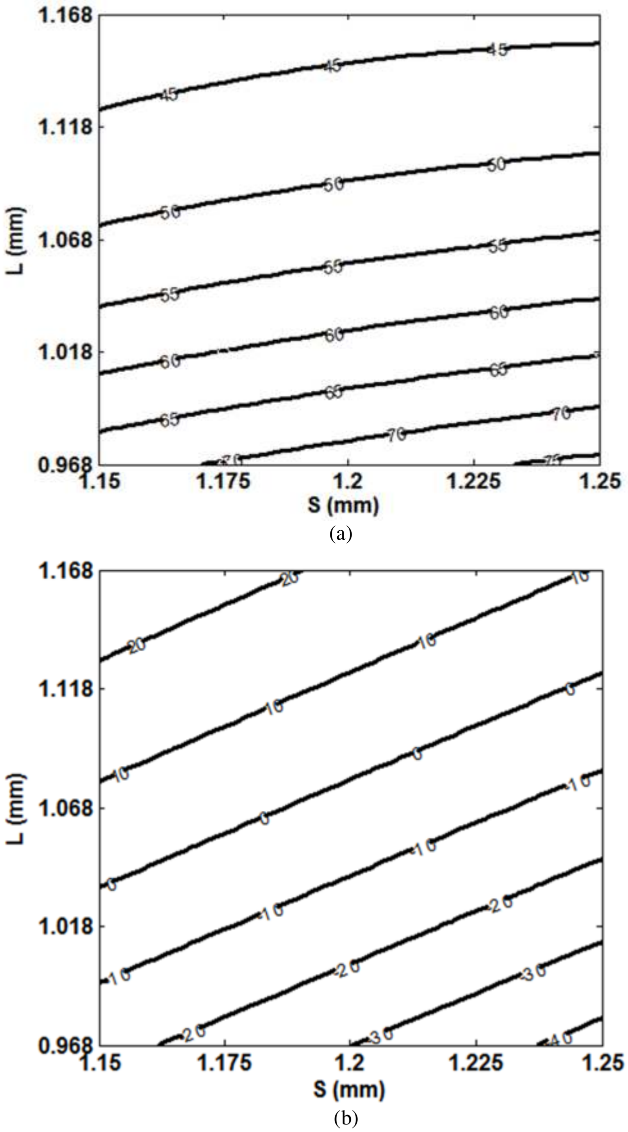

Fig. 4: Input impedance of the DRA at 60 GHz versus the feeding dipole length (*L*) and spacing (*S*): (a) real part, and (b) imaginary part. The other two parameters are kept constant at R = 1.18 mm, and W =265 µm.

IV. Fabrication

The structure of the proposed DRA is relatively simple and can be fabricated using micromachining technology in three steps. Six inch double sided polished high-resistivity silicon wafers ($\rho_{si} \geq$ 2,000 Ω.cm and thickness = 675 µm) were used for fabrication. One side of this wafer was etched through a depth of 400 µm using a Deep Reactive Ion Etching (DRIE) process in order to remove the silicon around the DRA [23-25] while maintaining vertical cylindrical sidewall. It is worth mentioning that a number of DRA prototypes were fabricated within the same wafer. Ideally, the silicon has to be removed totally in between adjacent DRAs. However, this process requires etching of huge amount of silicon. For fabrication simplicity, sufficient amount of silicon was etched away around the DRA, such that a minimum distance of 4 mm is kept clear in all directions. This leaves silicon walls surrounding the DRAs. The presence of these walls has a minor effect on the antenna's characteristics, as discussed later in section V. The unetched bottom side of the wafer acts as the substrate for the antenna's feeding network. The backside was coated with a copper film having a thickness ≥ 5 µm using an electroplating process. Then, the backside Cu was patterned using dry etching to define the feeding network. The schematic diagram in Fig. 5 gives an overview of the fabrication process.

The main advantage of the proposed process is that the DRA is fabricated using a two-mask process on a single wafer. This enhances the accuracy of the fabricated antenna since the misalignment between the DRA and the feeding network is minimized. In addition, this simple structure implies more mechanical stability and less fabrication costs compared to alternative mm-wave DRAs that require hybrid integration. It is clear from the SEM images displayed in Fig. 6 that the fabricated DRA prototype has sharp vertical walls.

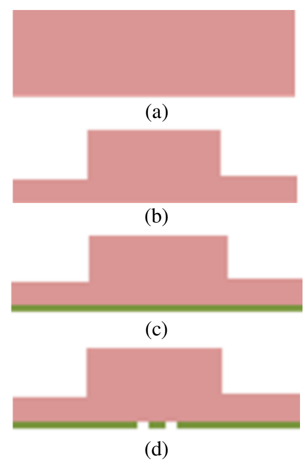

Fig. 5: Process flow for fabricating the proposed DRA: (a) start-up silicon wafer, (b) DRIE from top-side, (c) copper electroplating at back-side, (d) copper patterning.

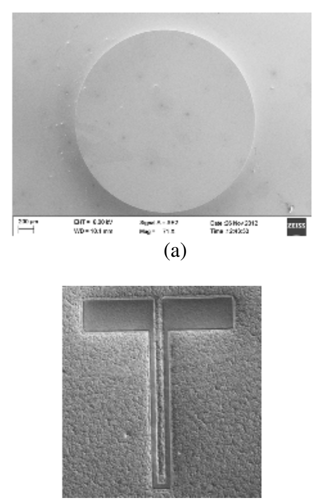

Fig. 6: SEM photos of the fabricated DRA: (a) top side showing the DRA, and (b) bottom side showing the feeding CPW line terminated by the magnetic dipole.

V. Theoretical and Experimental Characteriation

In this section, the measured electrical characteristics of the fabricated DRA are presented and compared with the simulated results. For accurate comparison, the silicon walls surrounding the DRA were taken into consideration in the simulation. Fig. 7 shows the measured and simulated return loss of the optimized DRA versus frequency. The simulations of the optimized DRA were carried out using HFSS. The return loss curves show good agreement between simulations and measurements. The measured resonance frequency was 59 GHz very close to the value determined by HFSS, which is 59.5 GHz. Measurements showed better matching and slightly wider bandwidth than simulations. This is mainly due to extra losses that are not considered by the simulators. The measured –10 dB impedance bandwidth was 2.23 GHz, which corresponds to 3.78% at 59 GHz. Such bandwidth is considered sufficient for a number of mm-wave wireless systems. For WPAN applications where the bandwidth extends from 57 GHz to 64 GHz, a few more proposed DRAs with different dimensions are required to cover the entire passband.

The 3D radiation pattern of the proposed DRA is shown in Fig. 8, as simulated using HFSS at 59.5 GHz. As shown, the antenna is radiating mainly towards the boresight. The simulated gain, directivity, and radiation efficiency are 8.27 dBi, 8.11 dBi, and 92.04%, respectively. The –15 dB back-side radiation is attributed mainly to radiation from the magnetic dipole etched within the ground plane.

Fig. 9 shows the measured and simulated co- and cross-polar components of the far field at the corresponding resonance frequency along the *E*- and *H*-planes. The detailed measurement setup is presented in [26]. The *H*-plane is the plane parallel to the magnetic dipole, while the plane perpendicular to it is the *E*-plane. There is reasonable agreement between simulations and measurements. The reason for the observed discrepancy is the fact that during measurements, the DRA structure is mounted within a large ground plate which is part of the measurement equipment. This alters the radiation patterns, mainly above 60°. It is also observed that around –10°, there is a noticeable difference between simulations and measurements since there is no complete isolation between the probe positioner side and the radiating side. Thus, reflection from the positioner gives rise to this dip as it appears in one plane at one side only. Comparing the co- and cross- polarization components in the *E*- and *H*- planes, it is clear that the proposed DRA enjoys a high degree of polarization purity especially in the broadside direction. The simulated and measured cross-polar levels in the broadside direction are –42.25 dB and –15.00 dB, respectively. The relatively higher measured cross-polarization level is mainly due to unwanted reflections within the measurement setup. The measured 3-dB beamwidth of the proposed DRA is 45° and 114° in the *E*- and *H*- planes, respectively.

Fig. 10 shows the simulated and measured gain versus frequency. From the figure, it is clear that antenna has an average gain of around 6.5 dBi along its working bandwidth. A maximum gain of 7 dBi was measured at the resonance frequency (59 GHz). The radiation efficiency of the fabricated antenna can be calculated from the measured gain, and the estimated directivity of the antenna. In our calculations, we used the approximated formula of the directivity, *D*, which is given by [27]:

$$D = \frac{32400}{\theta_E \theta_H} \tag{1}$$

where θ_E and θ_H are the measured 3-dB beamwidths along the *E*- and *H*- planes, respectively. At 60 GHz, the calculated radiation efficiency is 79.35% compared to the simulated efficiency of 92.04%.It is clear that the approximated directivity is a source of error. The alternative is to measure the whole radiation pattern in all directions and calculate the directivity according to its definition. However, this is rather unpractical and would take a much longer measurement time. Looking at Fig. 9(b), it can be seen that the radiation pattern widens once more outside the 3-dB beamwidth which implies that the real directivity is less than the approximated one.

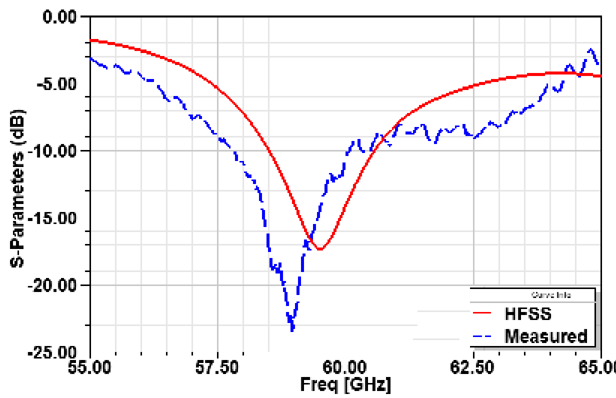

Fig. 7: Measured and simulated return loss versus frequency for the optimized DRA.

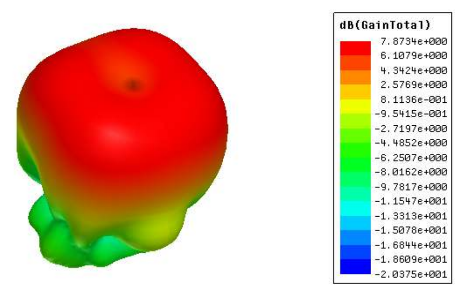

Fig. 8: 3D radiation pattern of the DRA at its resonance frequency as simulated with HFSS.

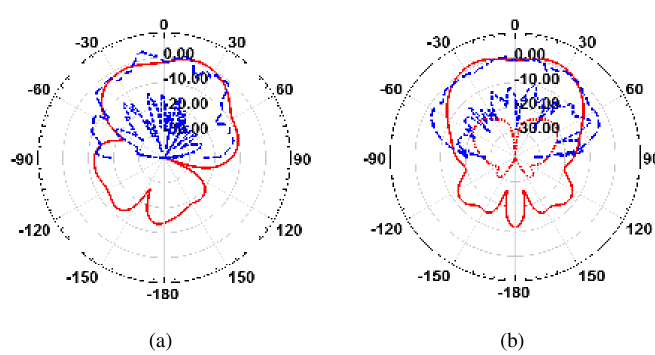

Fig. 9: Measured and simulated radiation pattern of the DRA at its resonance frequency (—HFSS,- - - Measured):(a) co- and cross-polar components in *E*-

plane, (b) co- and cross-polar component in *H*-plane.

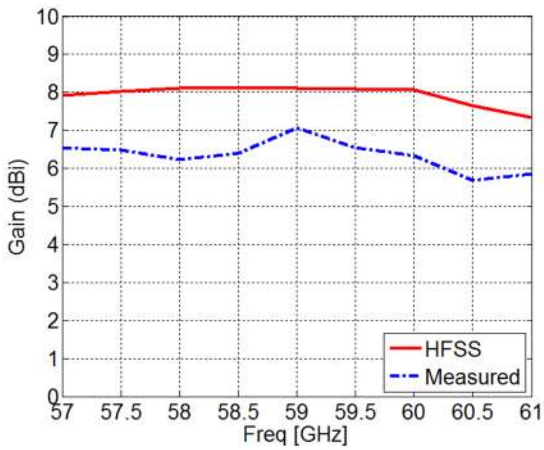

Fig. 10: Simulated and measured gain versus frequency for the proposed DRA.

VI. Conclusion

In this paper, a micromachined on-chip DRA with single silicon wafer is designed, fabricated, and measured for the first time. A complete parametric study for the proposed antenna has been presented. The new antenna has a number of appealing characteristics, such as: fabrication simplicity, high radiation efficiency, high gain, and low cross-polarization level. In addition, the proposed antenna is suitable for monolithic integration with the driving electronics. Such feature has a high value in the millimeter-wave range because the added parasitics due to hybrid integration may deteriorate the performance of such high-frequency systems.

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