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A D-Band Packaged Antenna on Organic Substrate with High Fault Tolerance for Mass Production

Bing Zhang, *Member, IEEE*, Camilla Kärnfelt, *Student Member, IEEE*, Heiko Gulan, *Student Member, IEEE*, Thomas Zwick, *Senior Member, IEEE*, Herbert Zirath, *Fellow, IEEE*

***Abstract*— A grid array antenna working around 145 GHz is proposed in this paper. The antenna is built on Liquid Crystal Polymer (LCP) and designed for the D-band Antenna-in-Package (AiP) application. The intrinsic softness of the LCP material is a limiting factor of the antenna's aperture size. A 0.5 mm thick copper core is used to compensate. By doing this, the rigidness of the antenna is effectively improved, compared with an antenna without the copper core. Wet etching is used to realize the patterns on the top and bottom conductor. Compared with a Low Temperature Co-Fired Ceramic (LTCC) counterpart, we obtain a considerable cost reduction with acceptable performance. The proposed antenna has an impedance bandwidth of 136 – 157 GHz, a maximum gain of 14.5 dBi at 146 GHz and vertical beams in the broadside direction between 141 – 149 GHz. The fabrication procedures of the antennas are introduced and a parametric study is carried out which shows the antenna's robustness against fabrication tolerances like the not well controlled etching rate and the substrate surface roughness. This makes the antenna a promising solution for mass production.**

***Index Terms* — grid array antenna, liquid crystal polymer, antenna-in-package, surface roughness, D-band.**

I. Introduction

THE requirement for mass production of mmWave antennas is a balance between cost and performance. On the one hand, dimensions of the antennas are in the range of tenth of millimeters, which requires sophisticated processes with tight tolerance for stable antenna performance. On the other hand, the considerable cost of such a sophisticated process hinders mass production. Generally, mmWave antennas can be categorized as on-chip or in-package antennas. Because of the process limit, the implementation cost of on-chip antennas is usually higher than that of in-package antennas. Moreover gain and efficiency of on-chip antennas are normally lower compared to in-package versions. Examples of realized on-chip antennas include a D-band on-chip end-fire Yagi-Uda antenna with 4.7 dBi peak gain and 76 % radiation efficiency based on a 130-nm SiGe BiCMOS process [1]; an on-chip dual dipole antenna with 7 dBi gain and 60 % efficiency implemented on a SiGe BiCMOS process [2]; and a slot antenna of -2 dBi gain and 18 % efficiency by a CMOS process [3]. Besides the limited antenna gain and radiation efficiency, the considerable clean room processing cost is another barrier for mass production. Moreover, an extra package is needed to when integrating the antenna with ICs. To implement mmWave in-package antennas, Low Temperature Co-fired Ceramic (LTCC) and Liquid Crystal Polymer (LCP) are popular choices [4-6]. To give some examples, a laminated waveguide horn antenna [7], a leaky-wave antenna [8] and a slot array antenna [9] have been reported on LTCC. However, in addition to the relatively high cost of the LTCC material and process, the shrinkage of the substrate in the planar scale of around 5 % makes it difficult for mass production.

Compared with LTCC, LCP features low material cost, large processing area and is compatible with a low-cost process like wet etching. The drawbacks of LCP are the low laminating temperature and its intrinsic softness. Though the softness is preferable for conformal devices, it causes detuned mmWave antenna performance when bended. For example a packaged D-band LCP rod antenna of 10.3 dBi has been reported in [10]. Because of the softness of the LCP material, the length of the LCP rod could not be maximized for increased gain. Besides, the softness increases with the temperature, especially when LCP is used for packaging, which gives rise to mechanical tension between the package and the mother board. As a result, the thermal stability of an LCP device should also be considered, when applied for antennas and packages.

This paper introduces a grid array antenna [11-13], of low cost and comparable performance to an LTCC version published in[14], on LCP substrate for D-band Antenna-in-Package (AiP) applications. The cost of the antenna is much reduced by the LCP substrate and the wet etching process. The conformal profile of the antenna and package are preferable for consumer electronics. The intrinsic softness of the LCP is compensated by a 0.5 mm thick copper core. The rigidness of the package is also enhanced. Low-cost fabrication procedures are also introduced. A parametric study shows the

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antenna's robustness against fabrication tolerance of over/under etching and surface roughness. Compared with the LTCC counterpart [14], the proposed antenna achieves a considerable cost reduction with acceptable antenna performance. This makes it a capable candidate for mass production. The paper is organized as follows. Section II describes the geometry and fabrication procedures of the antenna. Section III compares the simulated and measured performance of the antenna. Section IV conducts the tolerance analysis versus etching rate and conductor surface roughness, which proves the antenna's potential for mass production. Section V concludes the paper.

II. Geometry of the LCP Packaged Antenna

The proposed packaged antenna consists of two Rogers 3850 LCP (ε_r = 2.9, tanδ = 0.0025) substrates and three metallic layers as shown in Fig. 1. Dimensions of the antenna are (x, y, z) = (10, 10, 0.77) mm. The top and bottom metal layers are 18 µm copper with 5 µm Auto-catalytic Silver Immersion Gold (ASIG). The top and bottom substrates are 100 µm thick. They are bonded by 12 µm Dupont Pyralux LF Sheet Adhesive (ε_r = 4, tanδ = 0.05) to the 0.5 mm thick copper core. The copper core compensates the intrinsic softness of the LCP substrate. The softness might be preferable for conformal applications but is not desirable for a highly integrated package and a mmWave antenna that require substrate flatness and rigidness. For example, a tiny bendy structure can give rise to the deformation of the antenna's geometry, which in turn leads to detuned antenna's performance. Besides, the mechanical tension on the surface, which is brought about by the bendy substrate, would also challenge the adhesion of the package to the mother board. By adopting the 0.5 mm thick copper core, we introduce extra rigidness to compensate the intrinsic softness of the LCP substrate. Another problem is the heat generated by the dissipated power when the antenna is integrated with an active circuit, and then flipped to the mother board. For example, as the temperature increases with the functioning time, the softness of the LCP substrate increases given that it is a thermoplastic material with its lamination temperature at 285°C. This gives rise to a tension on the junction between the packaged antenna and the mother board. The 0.5 mm highly thermal conductive copper core facilitates the dissipation of heat. By adopting the copper core, we minimize the tension between the packaged antenna and the mother board, which is generated by components of different Coefficient of Thermal Expansion (CTE). A clearance via hole of 325 µm is drilled through the copper core and plugged by THP-100 DX1 (ε_r = 3.6, tanδ = 0.013). The 325 µm diameter of the clearance via is extremely large considering the ball map layout of the D-band RFIC, it is a compromise between the fabrication limitation and impedance matching of the antenna. The characteristic impedance of the coaxial structure formed by (1), (2) and (9) in Fig. 1 is 46.3 Ω. Since the 325 µm diameter clearance via will not be in direct contact with the D-band RFIC, the influence is negligible. A feeding via hole of 75 µm radius goes through the clearance via. By disposing the radiating array and the feeding network apart on each side of the copper core, mutual coupling between the antenna and the chip is minimized.

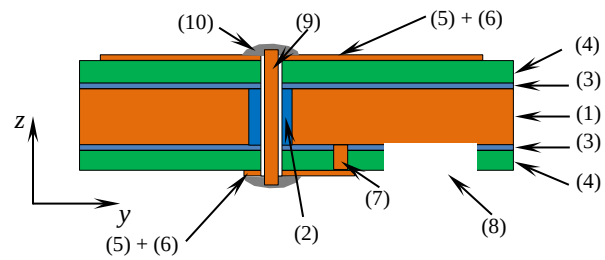


Fig. 1. Stack-up of the proposed D-band LCP packaged antenna: (1) copper core, (2) THP-100 DX1, (3) adhesive, (4) LCP, (5)+(6) copper + ASIG, (7) grounding via, and (8) chip pocket, (9) feeding via and (10) solder.

Fig. 2 shows the design view of the antenna. In the top view Fig. 2 (a), the radiating grid array is composed of 41 uniform interconnected grids. The working principle of a grid array antenna is explained e. g. in [11-13] and shall not be explained in detail here. The short side of the grid s is 0.72 mm, which is half the guided wavelength. The long side l is 1.44 mm. The width of both the short and long sides is $ws = wl$ = 0.06 mm. As shown in Fig. 2 (e), the short sides of each grid carry in-phase current, pointing to the same direction that contributes to the co-polarization. The current on the long sides are out-of-phase, pointing to the opposite direction, which contributes to the cross-polarization. A circular catch pad of 100 µm radius is designed near the radiating array's geometrical center for feeding. Fig. 2 (b) shows the bottom view. A pocket of (x, y, z) = (4, 3, 0.112) mm is designed to house the chip. A testing pad with a 100 µm radius circular catch pad for the 75 µm radius feeding via hole is designed for GSG (Ground-Signal-Ground) probe testing or wire bonding to the chip. Usually the wire bonding transition at the D-band will cause significant parasitic and insertion loss. The parasitic inductance can be compensated by extra capacitance, like the increased pad size. The insertion loss lies in the range of 1 ~ 3 dB in the D-band, which is not negligible [14]. However, the contribution of the bond wire insertion loss of a packaged antenna to the system is much less than that of an on-chip antenna, whose radiation efficiency is usually - 6 ~ - 10 dB. As a result, the packaged antenna is more preferable in terms of noise contribution. The test pad is DC-grounded by two grounding vias with 75 µm radius to form the GCPW structure. The clearance between the test pad and the cavity is 50 µm. The square pad arrays on the four corners of the bottom side are designed for flip chip testing. Fig. 2 (c) gives the dimensions of the feeding pad. The inductance of the feeding via is compensated by the catching pad and the section $l2$ in Fig. 2 (c). The CWP feed in section $l4$ has a 50 Ω impedance. The antenna is matched to the 50 Ω feed impedance via transmission lines through $l1$, $l2$, $l3$ and $l4$ by a high-low-high-low matching network. When the input signal goes from the testing pad through the feeding coaxial via to the radiating array, the structural discontinuities will cause reflection and radiation, like shown in Fig. 2 (d). This will give rise to Electro Magnetic Compatibility (EMC) complexities when the antenna is used in a highly integrated system, which should be taken care of seriously.

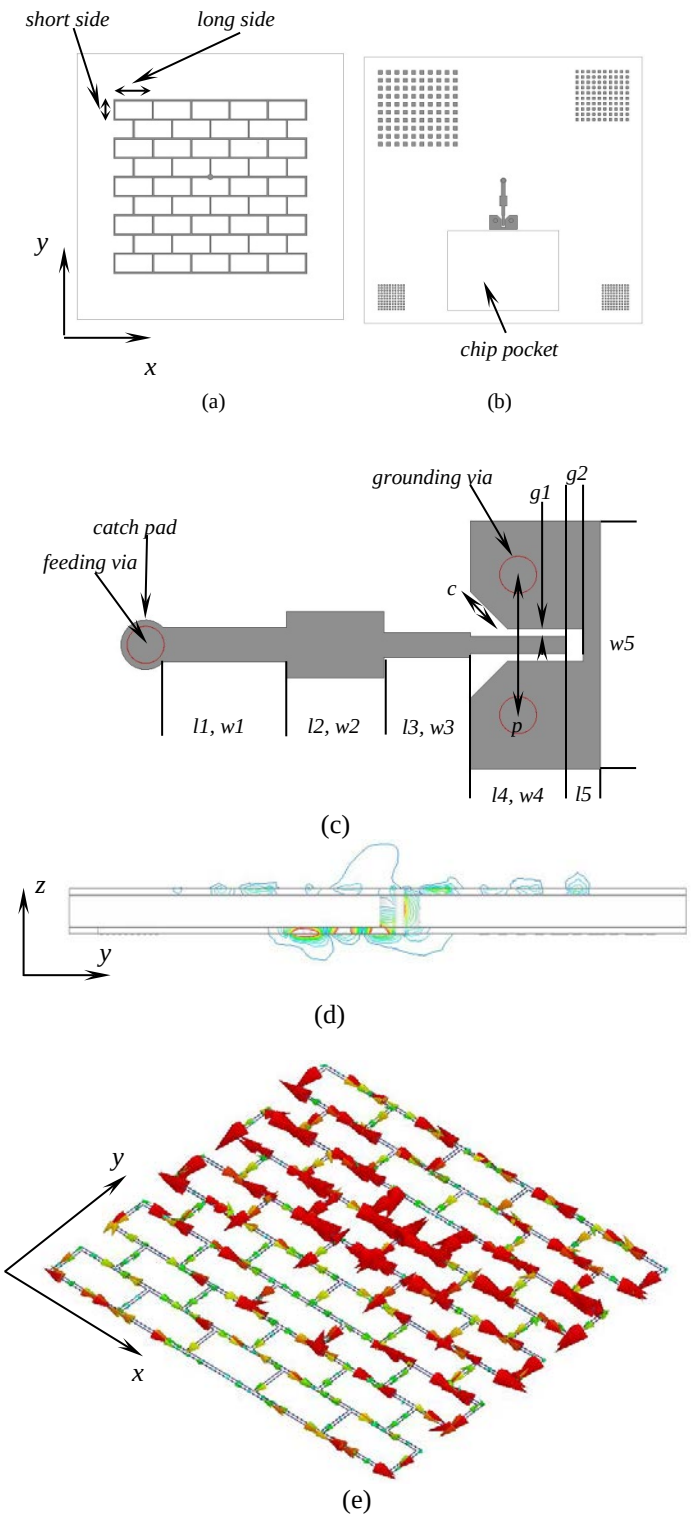


Fig. 2. Design view of the proposed D-band LCP packaged antenna: (a) top view, (b) bottom view and (c) zoomed view of the test pad: *c* = 212 µm, *g1* = 30 µm, *g2* = 100 µm, *l1* = 497 µm, *w1* = 139 µm, *l2* = 392 µm, *w2* = 268 µm, *l3* = 349 µm, *w3* = 100 µm, *l4* = 385 µm, *w4* = 70 µm, *l5* = 140 µm, *w5* = 465 µm and *p* = 565 µm, (d) cross section view of the E-field distribution at the coaxial transition through the copper core, and (e) current distribution on the grid.

Fig. 3 show photographs of the fabricated antenna. Fig. 3 (a) is the layout view of 336 antennas after one fabrication run on a 45.5 cm × 35.5 cm panel. The finished rate of the process is 95%. Fig. 3 (b) shows the radiating grid array on the top view. On the bottom view of in Fig. 3 (c), the test pad and the chip pocket are shown. From the side view in Fig. 3 (d), the stacked 0.5 mm thick copper core and the LCP substrates can be seen. The fabrication procedures start with the 0.5 mm thick copper core. A via clearance hole of 325 µm radius is firstly drilled, and then filled with THP-100 DX1. The 12 µm thick layers of DuPont Pyralux LF Sheet Adhesive are painted on both sides of the copper core, and heated to 190 ˚C to bond the Rogers 3850 substrates. Patterns of the top and bottom metal layers are realized by wet etching. Laser ablation is used to cut out the chip pocket, the gaps of the testing pad, the 75 µm radius feeding via hole and the 75 µm radius ground via hole. A 5 µm layer of Auto-catalytic Silver Immersion Gold (ASIG) is deposited on the 18 µm thick copper traces to enable wire bonding. The grounding vias are plated by ASIG as well. At last, a copper wire is soldered through the transition hole from the pad to feed the radiating array.

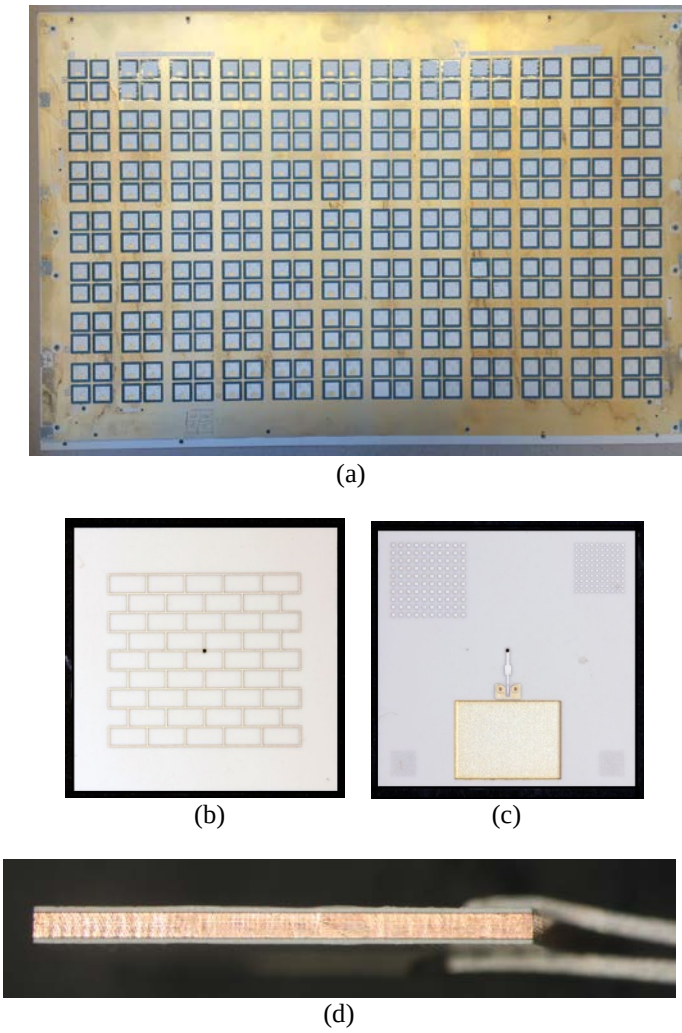
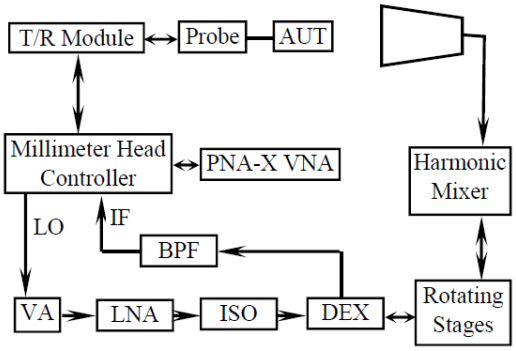


Fig. 3. Photographs of the D-band LCP packaged antenna: (a) layout view of 336 antennas in one fabrication run on a 45.5 cm

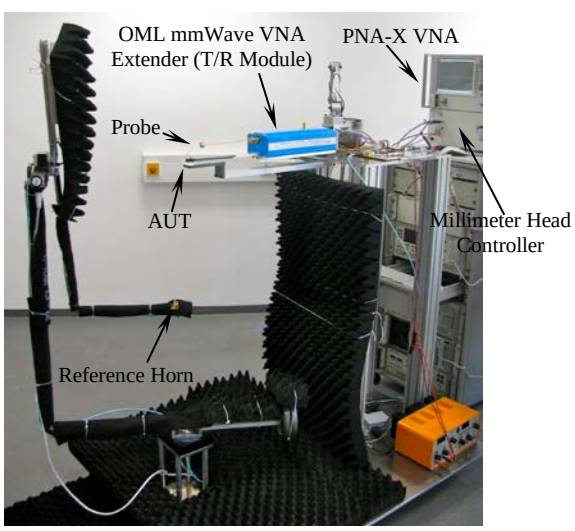
× 35.5 cm panel, (b) top view, (c) bottom view and (d) side view.

III. Simulated and Measured Antenna Performance

The full-wave Finite Element Method (FEM) simulator Ansoft HFSS is used to simulate the antenna. The fabricated antenna is measured in a far-field setup in Télécom Bretagne-Institute Mines-Télécom and Karlsruhe Institute of Technology [15]. A diagram of the measurement setup is shown in Fig. 4 (a). $|S_{11}|$ of the antenna is measured directly by accessing the GCWP pad of the antenna using a GSG probe, which is connected via a mmWave VNA extender to the PNA. Concerning the far-field measurement, rotating stages move a reference horn antenna around the AUT (Antenna under Test). The received signal is down-converted by a harmonic mixer, split by a diplexer, and then goes through a band-pass filter to the PNA. The LO signal goes from the millimeter head controller with a variable attenuator and an amplifier to ensure the correct LO level at the harmonic mixer. Fig. 4 (b) shows the photograph of the measurement setup.



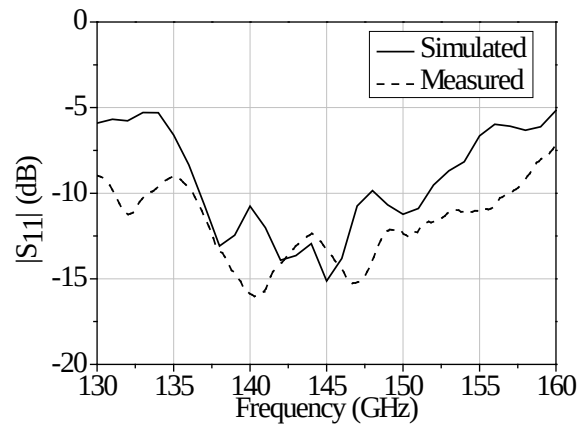
(a)



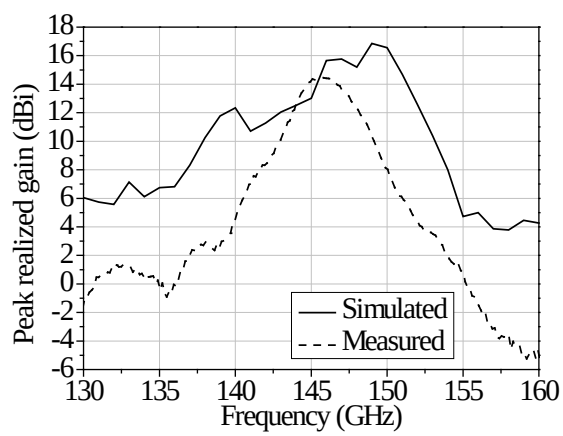
(b)

Fig. 4 Measurement setup of the D-band LCP packaged antenna: (a) block diagram and (b) photograph.

Fig. 5 (a) compares the simulated and measured $|S_{11}|$ of the antenna. In simulation, the -10 dB bandwidth is 137-152 GHz, while in measurement it is 136-157 GHz. Fig. 5 (b) shows the simulated and measured gain. The antenna has the maximum gain of 16.8 dBi at 149 GHz in simulation, while it is 14.5 dBi at 146 GHz in measurement. The calculated aperture efficiency is 61.8 %. It is comparable with the calculated 67.9 % aperture efficiency of the antenna in [14]. The comparison of the aperture efficiency proves that the proposed antenna features equal performance with low cost. The antenna has vertical beams in the broadside direction between 141 GHz and 149 GHz. Fig 5 (c) and (d) show the radiation patterns at 146 GHz. The antenna is measured to have a 15˚ 3-dB beamwidth and -27 dB cross-polarization in E-plane; while 18˚ 3-dB beamwidth and -40 dB cross-polarization in H-plane. The difference between the simulated and measured results may be caused by fabrication tolerance, which will be investigated in the following section.



(a)



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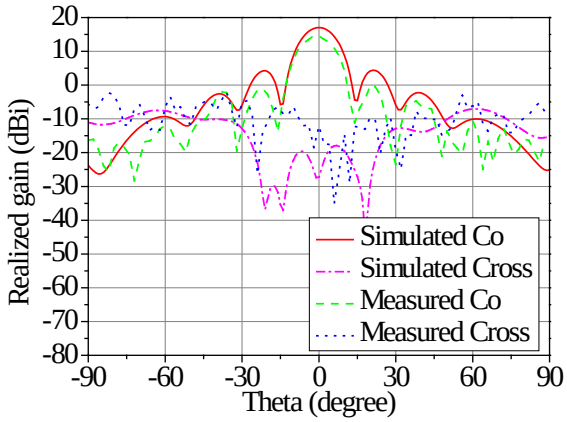

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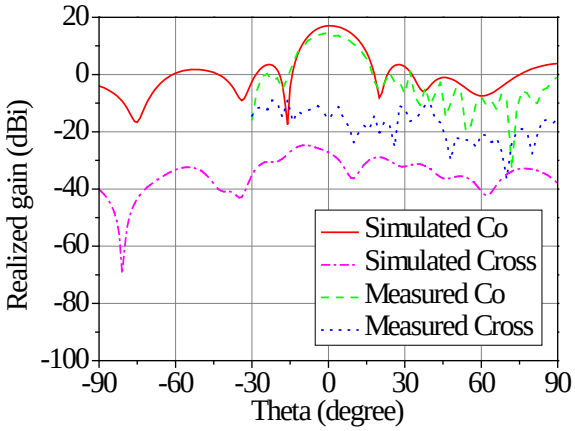


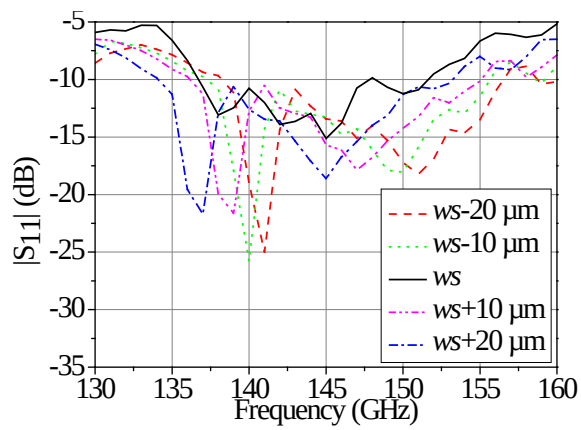
(d)

Fig. 5. Simulated and measured performance of the D-band LCP packaged antenna: (a) $|S_{11}|$, (b) peak realized gain, (c) E-plane radiation patterns at 146 GHz and (d) H-plane radiation patterns at 146 GHz.

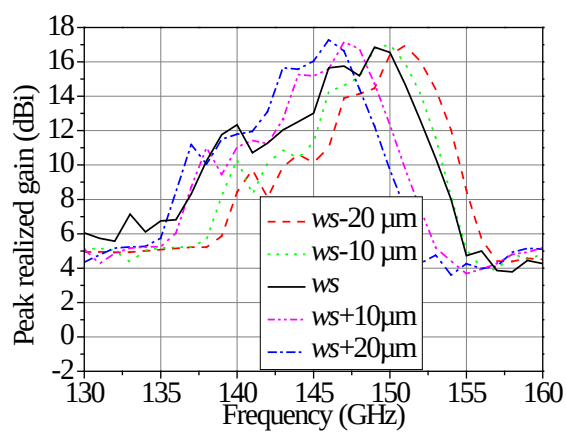
IV. Fabrication Tolerance Analysis for Mass Production

To satisfy the need for mass production, which requires a balance between cost and performance, wet etching is used to implement the top and bottom conductor patterns for low-cost consideration. However, the dimensional tolerance of wet etching is not always well-controlled. The microscopic inspection shows 10 – 15 µm etching tolerance of the conductors, and the cross-section of the conductor is trapezoid rather than rectangular.

To evaluate the antenna's vulnerability against the not-well-controlled etching rate, a parametric study is conducted in simulation. The antenna's input impedance and gain are simulated under the condition that the width of the radiating array varies as *ws*-20 µm, *ws*-10 µm, *ws*, *ws*+10 µm and *ws* + 20 µm, representing an over- or under-etching in fabrication. Fig. 6 (a) shows the input matching of the antenna. The input impedance Z_{in} of the antenna is determined by the characteristic impedance Z_0 of the conductor trace, while the Z_0 of the conductor trace is affected by its width. As a result, the dimensional variation of the conductor trace is reflected by the Z_{in} of the antenna. Frequency shifts of ± 5 GHz can be observed in Fig. 6 (a), while the antenna's impedance bandwidth still covers a range of 141-148.5 GHz when the not-well-controlled etching rate is taken into consideration. The antenna is composed of interconnected grids. The frequency shift is caused by the variation of the length of the grid. Widths of both the short and long sides (*ws* and *wl*) are affected by the etching rate. As a result, when the *ws* is changed by the etching rate, the length of the conjunctional long side *l* is also varied which in turn shifts the operational frequency. The antenna's impedance bandwidth proves its robustness against the etching rate. As it can be seen in Fig. 6 (b) the antenna's maximum gain is not much affected by the dimensional deviation, but shifts ± 5 GHz in frequency. This is because the dimensional variation of the grid will shift and vary the gain of each short side, which has the same mechanism as a half-wave dipole. The variation and frequency shift of each short side of the grid contribute to that of the whole antenna.



(a)



(b)

Fig. 6 Parametric study of the D-band LCP packaged antenna's performance against dimensional tolerances given by simulation: (a) $|S_{11}|$ and (b) peak realized gain.

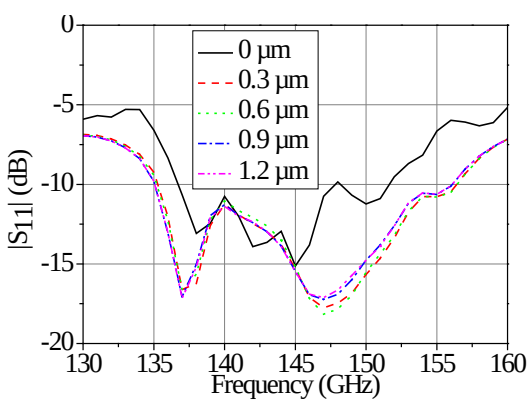
Another influential factor on a microstrip antenna's performance is the surface roughness. In practice, certain surface roughness is needed to ensure good adhesion between the substrate and the conductor, while the surface roughness is also partly responsible for the conductor loss. Especially when the frequency goes up to the mmWave and the surface

roughness is comparable with the skin depth, the influence of surface roughness on the conductor loss becomes obvious. A bare LCP substrate, whose copper cladding is chemically etched by the same process as antenna fabrication, is scanned by the AlphaStep500 profilometer under room temperature to deduce the conductor-substrate surface roughness. The root mean square (RMS) surface roughness is 0.3 µm, while the skin depth of 140 GHz electromagnetic waves on copper is 0.175 µm. To investigate the antenna's vulnerability against surface roughness, a parametric study is conducted. The antenna's impedance bandwidth and gain are simulated against the surface roughness of the substrate in the range of (0, 1.2) µm with a 0.3 µm step. In Fig. 7 (a), it is reasonable that the increased conductor loss by surface roughness does not deteriorate but improves the input matching of the antenna because of decreased Q factor of the antenna, which is a resonant component. For example in the ideal case of the smooth substrate, the impedance bandwidth of the antenna is 137.5 – 152 GHz. When the surface roughness increases, the impedance bandwidth extends to 135 – 155 GHz. Thus, the antenna's impedance bandwidth is robust against substrate surface roughness.

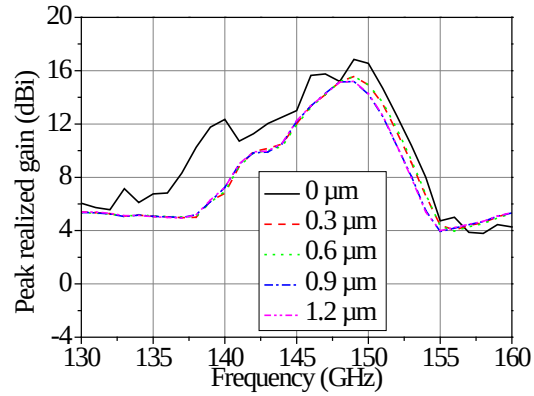
In Fig. 7 (b), the increased surface roughness gives rise to decreased antenna gain. According to the equation of surface roughness related to conductor loss [16]

$$c' = c\left\{1+\frac{2}{\pi}\tan^{-1}\left[1.4\left(\frac{RMS}{\delta}\right)^2\right]\right\} \quad (1)$$

where c' is the conductor loss of a rough microstrip line, c is the conductor loss of an ideal microstrip line, *RMS* is the root mean square of the surface roughness and δ is the skin depth. To give example when the surface roughness is 0.3 µm in Fig. 7 (b), the conductor loss increases by 2.67 dB, which is testified by the 2.3 dB decrement between the antenna's gain with 0 µm and 0.3 µm surface roughness. When the surface roughness increases to 0.6 µm and keeps increasing, the conductor loss stays stable at twice value of the ideal microstrip line. As a result, the difference between the gain of an ideal LCP antenna and that with surface roughness larger than 0.6 µm is stabilized at 3 dB, which is in accordance with eqn. (1). From the parametric study above, it can be seen that that antenna's performance is robust against fabrication tolerance of not-well-controlled etching rate and surface roughness, which is a highly appreciated advantage for low-cost mass production.



(a)



(b)

Fig. 7 Parametric study of D-band LCP packaged antenna's performance against substrate surface roughness from simulation: (a) $|S_{11}|$ and (b) peak realized gain.

V. Conclusion

This paper demonstrates a low-cost D-band LCP packaged antenna for mass production. The intrinsic softness of the LCP is compensated by a 0.5 mm copper core. Comparing with a LTCC counterpart, a considerable cost reduction is achieved by the proposed antenna due to the low-cost substrate and process. The fabrication procedures are introduced and explained. The simulated antenna performance agrees well with measurement. The antenna's performance remains stable against fabrication tolerance of the not-well-controlled etching rate and the surface roughness. This makes the antenna preferable for mass production.

VI. Acknowledgement

The author would like to acknowledge Mr. Raymond Jezequel from Télécom Bretagne-Institute Mines-Télécom for antenna measurement; Dr. Per-Åke Nilsson, Dr. Robin Dahlbäck and Dr. Zhaoyao Zhan from Chalmers University of Technology for surface roughness measurement and photograph taking; Dr. Yinggang Li, Dr. Mingquan Bao, Dr. Jonas Hansryd and Dr. Thomas Emanuelsson from Ericsson for the discussions; Professor Yue Ping Zhang from Nanyang Technological University for the comments.

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