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Novel 3D-/Inkjet-Printed Flexible On-Package Antennas, Packaging Structures, and Modules for Broadband 5G Applications

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***Abstract*—Additively manufacturing techniques including 3D and inkjet printing is used to fabricate antenna and packaging structure at mm-wave range for 5G applications. The 3D printed flexible material, FLGR02, is applied to the flexible mm-wave packaging application. The fabrication process and material characterizations including solutions to surface treatment for ink adhesion, smooth of surface roughness, and CTE mismatch between the flexible material and the silver ink are proposed. Then the proposed process is used to fabricated a broadband 5G on-package antenna. The measured S_{11} of the proposed on-package antenna is smaller than -10 dB from 22.4 GHz to 30.1 GHz. Besides, the measured realized gain is larger than 5 dB from 22 GHz to 30.5 GHz. The differences of realized gain within the operational bandwidth is smaller than 3 dB. The fractional bandwidth is 29.3 %. The proposed antenna is broadband enough to cover the whole 5G band from 24.5 GHz to 29.5 GHz. The size of the antenna is $5\,\mathrm{mm}\times 9\,\mathrm{mm}$ which is $0.44\lambda_0 \times 0.79\lambda_0$. The radiation patterns within the operational band is also measured. Finally, a proof-of-concept demonstration of SoP design is fabricated.**

***Keywords*-5G; mm-wave; packaging; 3D printing; inkjet printing; flexible; broadband;**

I. INTRODUCTION

The next-generation 5G wireless communication standard has been proposed to alleviate the constant desire for dramatically faster data transmission [1]. One of the reasons that 5G wireless communications can provide higher data rate is the use of significantly larger bandwidths at millimeter-wave (mm-wave) frequencies which results in highly interest and numerous researches within this frequency band [2]–[4]. In order to further reduce sizes of the 5G wireless communication system, system-on-package (SoP) topologies which integrated the integrated circuits (ICs) with peripheral components such as filters, couplers, and antennas has been proposed and attracted lots of attentions. One of the major challenges to realize 5G SoP designs is to reduce the large parasitics in packaged module configurations at mm-wave frequencies. Thus, the design of cost-/performance-efficient packaging solutions for 5G modules while minimizing parasitics has become one of the major research areas. In the meantime, deploying circuits at different locations is required for the age of Internet of Things (IoT) necessitating the design and implementation of flexible packages which have better resistant to the shocks and vibrations and can be fitted into different locations easily.

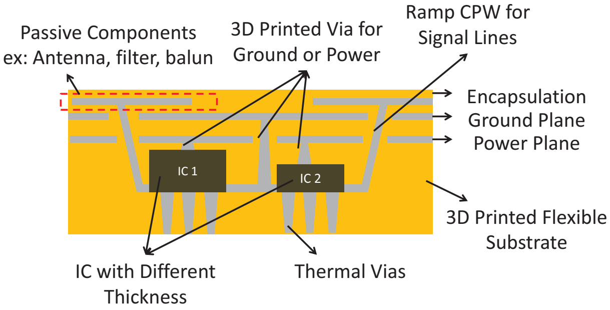

Figure 1. 3D and inkjet printed mm-wave SoP design.

Additive manufacturing techniques such as inkjet and 3D printing have been proven to be an effective solution to fabricate circuits with lower cost, less waste of materials, and higher on-demand customization. In [5], inkjet printing has been used to fabricate interconnects between IC die and packaging up to mm-wave range, featuring much smaller parasitics than using wire bonding. In [6], inkjet-printed transmission lines on 3D printed dielectric ramps have been used to serve as a substitution to conventional vias. Nevertheless, most previously reported efforts have demonstrated only characterization results of individual additively manufactured interconnects. Moreover, the interconnections in previous works are not flexible.

In this paper, a flexible 3D printed material, FLGR02, is first used on the design of 5G and mm-wave packaging structure. The characterization of this material such as the proper deal with light exposure time, surface treatment, ink adhesion, and thermal expansion are included. A broadband on-package antenna design operated at mm-wave range is proposed and fabricated using inkjet printed silver trace and 3D printed flexible substrate with this material. The proposed broadband on-package antenna antenna are integrated with the 3D printed ramp structure, coplanar waveguide (CPW) lines, and a sample IC to demonstrate the possibility

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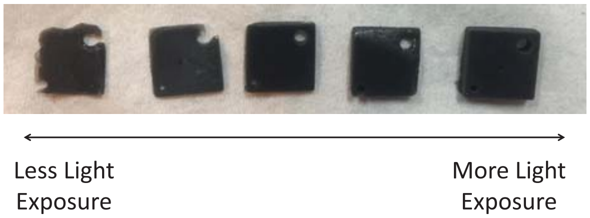


Figure 2. The effects of exposure time on the 3D printed substrates.

Figure 3. Demonstration of large-scale fabrication.

Figure 4. Flexibility of the 3D printed substrate.

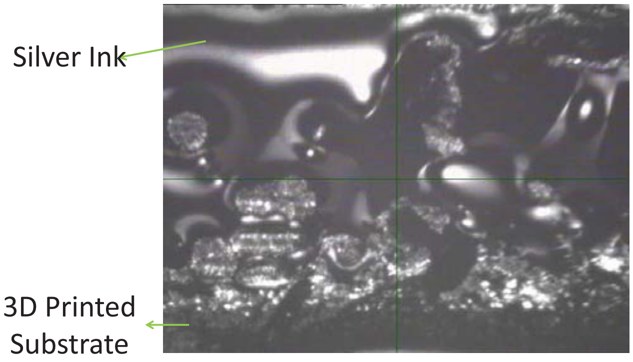


Figure 5. Ink adhesion while no surface treatment is applied.

of SoP design using additively manufactured procedures.

II. Potentials of Additively Manufactured 5G SoP Design

The concept of 3D and inkjet printed 5G SoP design is shown in Figure 1. The substrates can be fabricated layer by layer using 3D printing techniques. The conventional thermal vias and vias for ground and power plane can be fabricated by 3D printed via holes and filled with silver ink. However, via connections are not suitable for mm-wave range operation due to their high parasitics. On the other hand, 3D printed ramp structure and inkjet printed silver CPW traces on the ramp to form inter-layer connections are suitable since they are transmission lines and will induce less parasitics compared with convectional vias [6]. One of the benefits of using 3D printing technology is that ICs with different thickness can be integrated together easily. The passive components such as antennas, filters, and baluns can also be integrated into the package. Finally, the 3D printed encapsulation can be used to protect the whole SoP design.

III. Fabrication Process

A. 3D Printing

The substrate is fabricated using a digital light processing (DLP) stereolithography (SLA) 3D printer with flexible resin FLGR02 from FormLabs. Since, the material is cured around $405\,\mathrm{nm}$, white light projector is used to project the images of designs and cure the material layer by layer. The thickness resolution is set to be $50\,\mu\mathrm{m}$. The light exposure time each layer has significant effects on the design. As shown in Figure 2, not enough light exposure will result in the serious defects on the samples. For example, the hole is not complete and the thickness is not enough for the first couple of samples. On the other hand, too much light exposure will close the holes and deviate the design parameters. The light exposure time each layer is set to $13\,\mathrm{s}$ after testing with different setups. Another thing needs to be considered while using this material is that the adhesion for this material is weaker. Thus, the build plate has to be rough enough for the material to adhere to the build plate.

One of the key advantages for this techniques is the large-scale manufacture. Since the images of multiple samples can be projected and cured simultaneously, the fabrication time is similar for one sample and multiple samples. For example, as demonstrated in Figure 3, two samples are fabricated simultaneously with the same lead time as one sample. This is a significant advantages for large scale fabrication. Furthermore, a piece of glass is attached to the build plate and the samples are fabricated on the glass. Thus, the whole glass can be taken off and move to the inkjet printer while maintaining the relative positions of all samples so that metal trace for both samples can be fabricated using inkjet printer simultaneously, too. As shown in Figure 4, the resulting samples with thickness equals to $1.7\,\mathrm{mm}$ is folded on a $14.3\,\mathrm{mm}$ diameter torque wrench to demonstrate the flexibility of the samples.

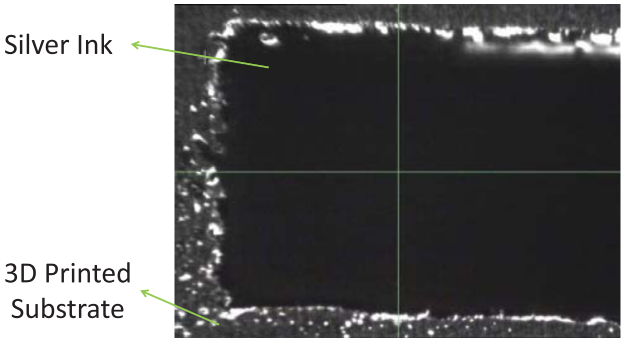


Figure 6. Ink adhesion while exposure to UV ozone before inkjet printing.

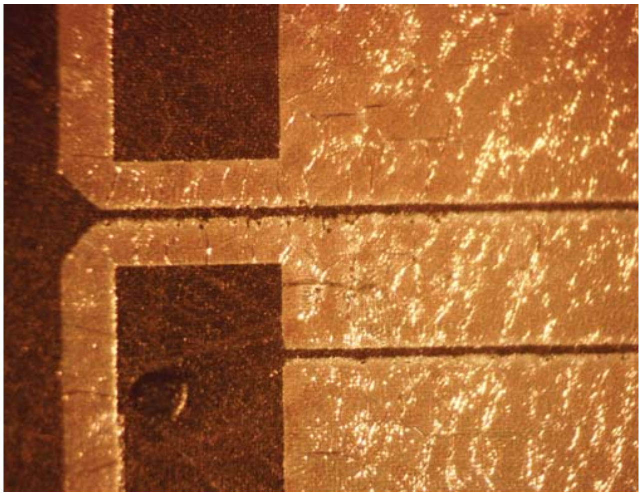


Figure 7. Inkjet printing results without SU8 coating.

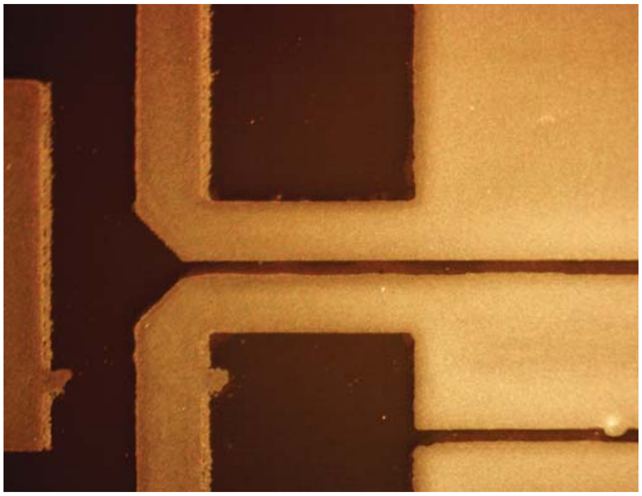


Figure 8. Inkjet printing results with SU8 coating.

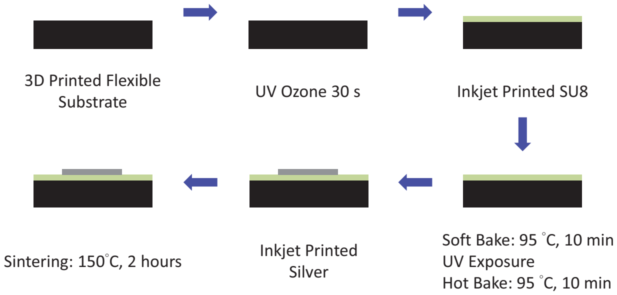


Figure 9. Steps for inkjet printing with surface treatment.

B. Inkjet Printing

Once the substrate is fabricated with 3D printer, it is switch to inkjet printer to print the metal trace with silver ink. As shown in Figure 5, the ink adhesion is terrible without surface treatment. Thus, the surface treatment is necessary before printing other inks on the flexible substrate. After testing different types of surface treatments, 30 seconds of ultraviolet (UV) ozone is adopted before printing the silver trace and the significant improvement can be observed in Figure 6. As the result of the surface treatment, the ink spreads uniformly compared with the results without surface treatment and the conductivity can be improvement significantly.

The other problem has to be solved is the thermal expansion (CTE) differences between the substrate and the silver ink. Since, the silver ink has to be sintered at 150 °C, the substrate will expand while sintering and cracks would appear due to the imbalance of CTE between the substrate and the silver ink as shown in Figure 7. The way to alleviate the situation is to print a thin layer of SU8 between the substrate and the silver to act as a buffer to smooth the difference of CTE. As shown in Figure 8, a thin layer of SU8 is printed on the substrate before printing the silver trace. Compared with the Figure 7, significant improvement can be observed. There are no cracks after sintering 150 °C. Another advantages of printed a layer of SU8 is to smooth the surface roughness of the 3D printed flexible substrate. As demonstrated in Figure 7, the edge of silver trace is sharper and straighter with less ink spread. Therefore, higher conductivity and more precise circuits can be achieved.

C. Summary of Printing Procedures

The procedure of fabricating precise samples with 3D and inkjet printing is summarized in Figure 9. The flexible material is first used to 3D printed the substrate. Then, the samples is exposure to UV ozone for 30 seconds to improve the ink adhesion. Then, a thin layer of SU8 is printed on the substrate to smooth the surface and buffer the CTE difference. The SU8 is soft baked at 95 °C for 10 minutes, exposure to UV for 2 minutes, and hot baked at 95 °C for another 10 minutes. The silver traces are then printed on the SU8 and sintering at 150 °C for 2 hours.

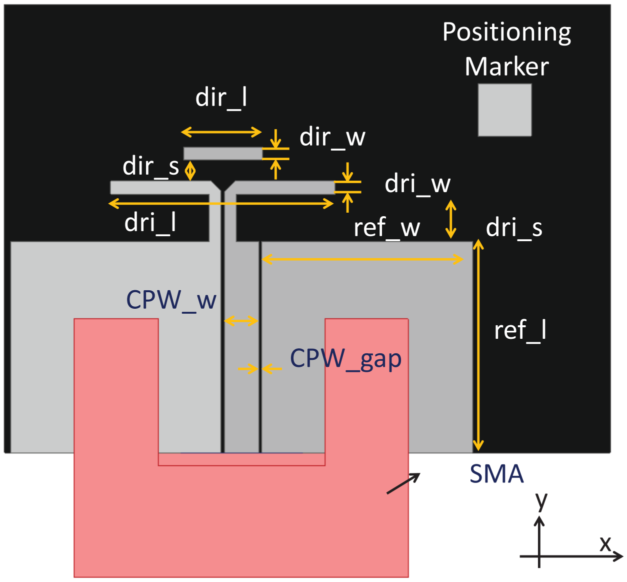


Figure 10. The proposed broadband on-package antenna.

TABLE I
PHYSICAL DIMENSIONS OF THE PROPOSED BROADBAND ON-PACKAGE ANTENNA

Parameter	Dimension (mm)	Parameter	Dimension (mm)
dir_l	3	dir_w	0.6
dir_s	0.8	dri_w	0.6
dri_l	8.57	dri_s	1.8
ref_w	8	ref_l	8
CPW_w	1.3	CPW_gap	0.17

IV. BROADBAND ON-PACKAGE ANTENNA

After all the printing procedures are well-characterized, they are applied to fabricated test samples of the proposed broadband on-package Yagi antenna. To reduce the size of the 5G wireless communication system, the antenna has to be broadband enough to cover the whole 5G bandwidth so that only one antenna is required. The proposed 5G broadband on-package antenna is shown in Figure 10. Since the antenna is operated at mm-wave frequencies, the size of SMA would induce significant effects and has to be taken into consideration. Thus, the SMA structure is included while performing the full-wave simulation and design. An positioning marker is included in both the substrate and metal trace to align the 3D printed substrate and inkjet printing silver. The physical dimensions of the proposed broadband on-package antenna is shown in Table I. The minimal gap for CPW lines is $170\,\mu\text{m}$ which is much larger then the minimal resolution ($20\,\mu\text{m}$) of the inkjet printer. The dielectric constant is 3 and the loss tangent is 0.06. The thickness of the substrate is $1.7\,\text{mm}$. The total size excluding the positioning marker is $11.8\,\text{mm}\times17.8\,\text{mm}$. It can be further reduced to $5\,\text{mm}\times9\,\text{mm}$ which is $0.44\lambda_0 \times 0.79\lambda_0$ after excluding the structure for SMA connector.

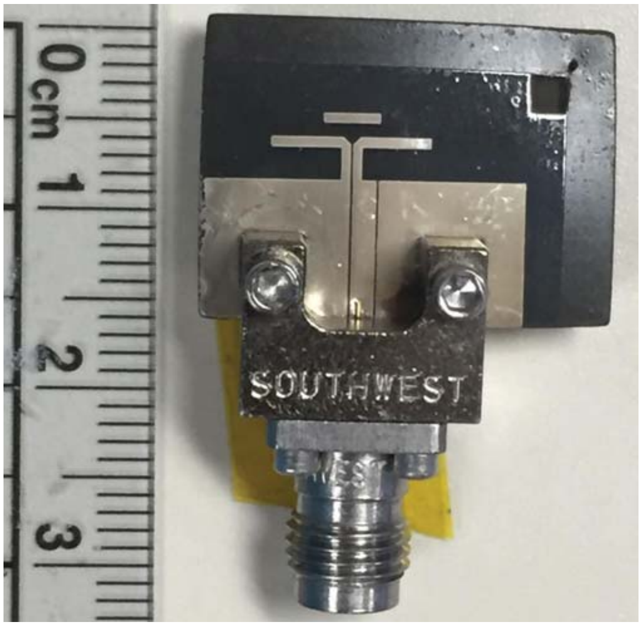


Figure 11. Inkjet and 3D printed broadband on-package antenna.

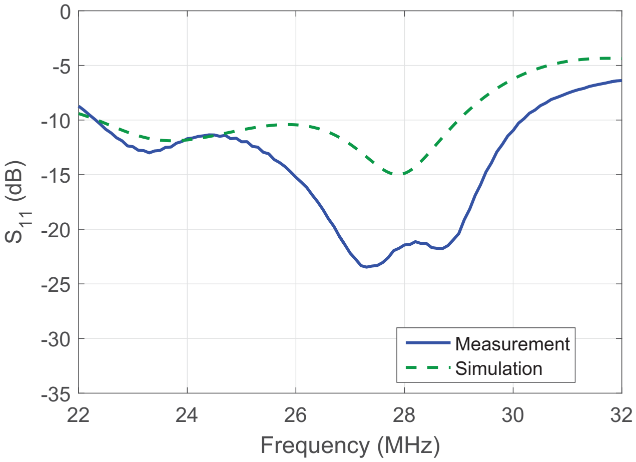
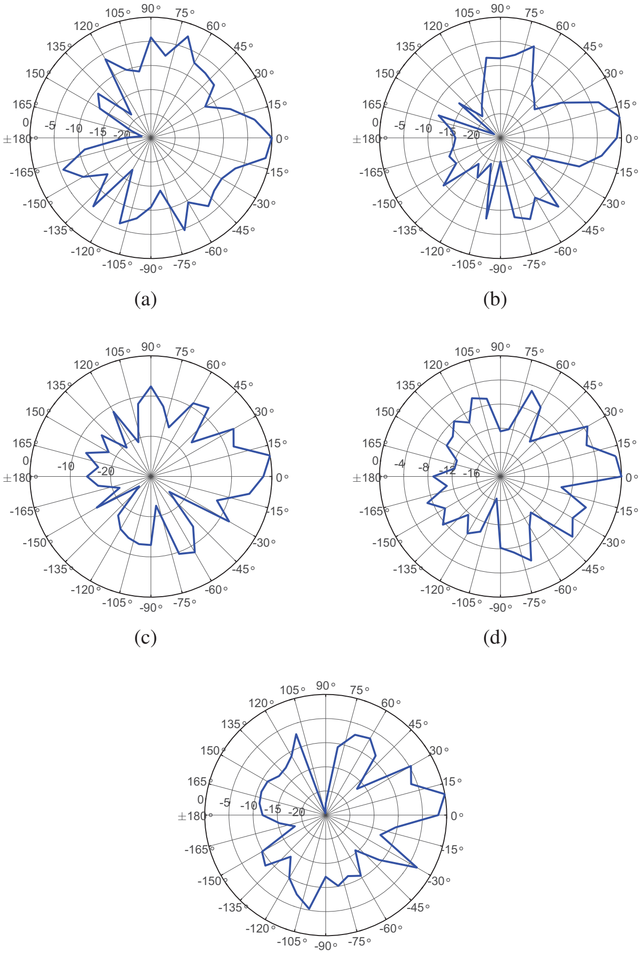


Figure 12. Measured and simulated S_{11}.

The fabricated sample is shown in Figure 11. A transparent layer of SU8 and silver traces can be observed in the figure. The S_{11} of the proposed broadband on-package antenna is measured and shown in Figure 12. The full-wave simulated results using Ansoft HFSS are also included for comparison and good agreement can be observed. The differences between the measured and simulated results are due to the higher conductive loss in fabrication and minor thickness inconsistency for the substrate. Despite the differences, the general trend and the location of zeros are the same for the simulated and measured results. The measured S_{11} is smaller than -10 dB from 22.4 GHz to



(a) (b) (c) (d) (e)

Figure 13. Measured radiation pattern of the proposed broadband on-package antenna at (a) 22 GHz (b) 24 GHz (c) 26 GHz (d) 28 GHz and (e) 30 GHz.

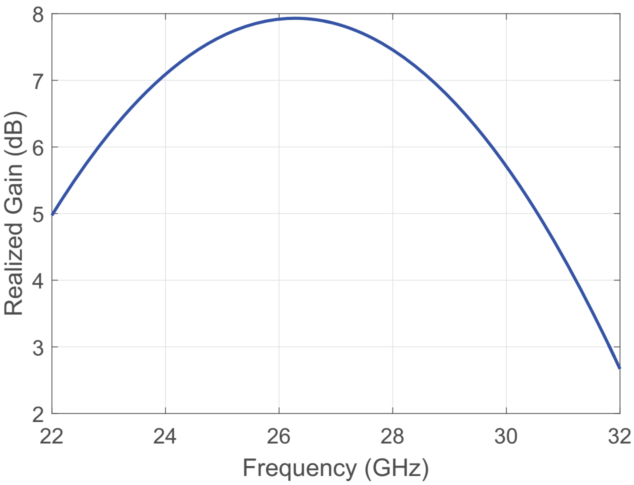


Figure 14. Measured gain of the proposed on-package antenna.

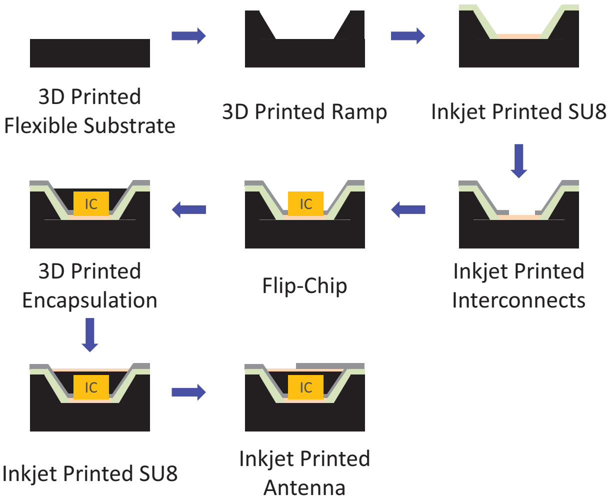


Figure 15. Process steps for 3D and inkjet printed SoP design.

30.1 GHz. The fractional bandwidth is 29.3 %. The antenna is broadband enough to cover the 5G bandwidth around 28 GHz.

The normalized radiation patterns of the proposed antenna are also measured and shown in Figure 13. Since the proposed antenna is a broadband antenna, the radiation patterns at 22 GHz, 24 GHz, 26 GH, 28 GHz, and 30 GHz are all included. The 0° is the end-fire direction and the patterns are rotate in the x-y plane as shown in Figure 10. As shown in Figure 13, the main beam direction is at the end-fire direction which is as expected. The realized gain of the proposed broadband on-package antenna is measured using three antennas measurement (receive, standard, and test antennas). The measured results are shown in Figure 14. The measured realized gains are larger than 5 dB from 22 GHz to 30.5 GHz. Moreover, the differences of realized gain within this operational band is smaller than 3 dB. The fabricated antenna can be served as a successful prove of applying this flexible 3D printed material and the process developed in this paper to mm-wave applications.

V. SoP Design

The antenna, ramp interlayer connections, and IC are integrated together to demonstrate a SoP design. The process steps are summarized in Figure 15. The fabrication starts with 3D printed flexible substrate and ramp. The layer thickness resolution is reduced to 10 μm to achieve smoother ramp structure. Then the SU8 is printed to further smooth the surface roughness and act as CTE buffer. The metal connections are then injet printed on the ramp and on the bottom of the cavity. The IC is attached to the bottom of the cavity using conductive epoxy. Then, the flexible material is used to seal the cavity. The SU8 is printed again for the

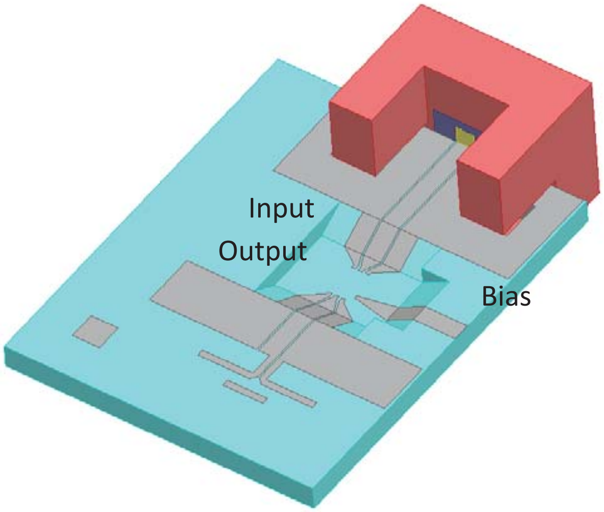


Figure 16. 3D and inkjet printed SoP design.

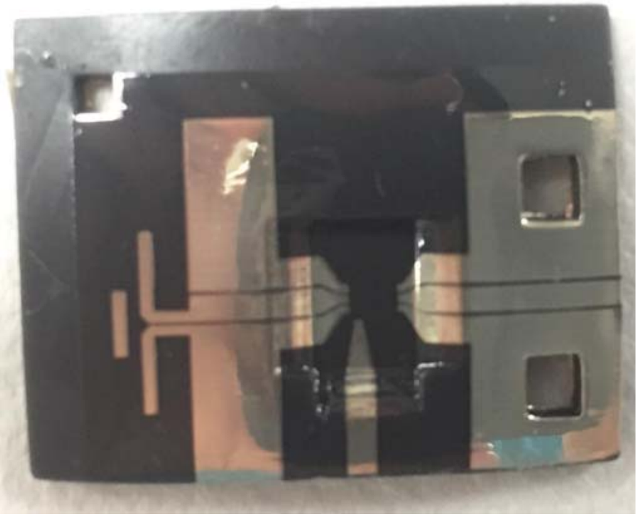


Figure 17. Test samples of 3D and inkjet printed SoP design.

same reason. The final step is to print passive components suce as antenna on the top of the seal.

The SoP structure is shown in Figure 16. There are three sets of ramp. One is for CPW lines for the IC input. Another is for CPW lines for the IC output. The final one is for the DC bias. The ramp height is $1.2\,\mathrm{mm}$ with the slope angle equals to $30°$. The SMA connectors and the positioning marker are also included in the figure. The fabricated sample is shown in Figure 17. Three layers of SU8 are printed on the substrate and can be observed on the figure. Since the thickness resolution is $10\,\mu\mathrm{m}$, the ramp would be staggered structure with height equals to $10\,\mu\mathrm{m}$. This would cause conductivity issue for the silver trace. However, the staggered structure can be smoothed out with three layer of printed SU8. The IC is attached on the silver trace using silver conductive epoxy as shown in Figure 18 (a). Furthermore, the structure after sealing with flexible material is shown in Figure 18 (b). The structure size can be reduced significantly by removing the SMA and placed the antenna on the top of the IC as shown in Figure 19.

(a) (b)

Figure 18. SoP design (a) with IC attached and (b) seal with flexible material

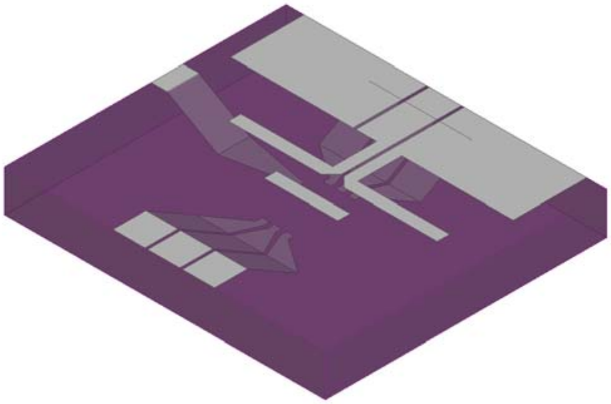


Figure 19. Miniaturized 3D and inkjet printed SoP design.

VI. CONCLUSION

For the first time, the 3D printed flexible material, FLGR02, is applied to the mm-wave packaging application. A fabrication process including solutions to surface treatment for ink adhesion, smooth of surface roughness, and CTE mismatch between the flexible material and the silver ink are proposed. The process is used to fabricated a broadband 5G on-package antenna. The S_{11} of the proposed on-package antenna is smaller than -10 dB from 22.4 GHz to 30.1 GHz while the realized gain is larger than 5 dB from 22 GHz to 30.5 GHz. The fractional bandwidth is 29.3 %. The proposed antenna is broadband enough to cover the whole 5G band around 28 GHz. The size of the antenna is $5\,\mathrm{mm}\times 9\,\mathrm{mm}$ which is $0.44\lambda_0 \times 0.79\lambda_0$. The radiation patterns within the operational band is also measured. Finally, a proof-of-concept demonstration of SoP design is fabricated.

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