# On-Package mm-Wave FSS Integration with 3D-Printed Encapsulation

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***Abstract*—This work outlines the design, simulation, and fabrication of a millimeter-wave (mm-wave) frequency selective surface (FSS) integrated directly onto a 3D-printed die encapsulation. The cross-shaped slot FSS is designed to function as a bandpass filter centered at 77 GHz for on-package tunability. Stereolithography (SLA) 3D printing is used to fabricate encapsulations for silicon dies attached to a metallic QFN leadframe. Surface profilometry is used to assess the roughness of the SLA-printed surfaces, yielding roughness 25× lower than standard fused deposition modeling (FDM) 3D printing techniques. Finally, inkjet printing is used in a post-process fashion to fabricate the package-integrated FSS directly onto a 3D-printed die encapsulation as a proof-of-concept demonstration.**

## I. Introduction

The emergence of millimeter-wave (mm-wave) technology in modern consumer electronics is allowing for the efficient development of the next generation of highly-functional wireless devices. These devices, operating in frequency between 30–300 GHz, take advantage of high-bandwidth channels for such applications as 5G mobile networks and automotive radar sensing. The presence of several challenges with mm-wave technologies, such as high wireless path and interconnect loss, has highlighted a focus on the development of highly-integrated wireless systems. System-on-package (SoP) solutions involve the integration of multiple components, such as wireless transceivers, antennas, and other system peripherals all into a single package in order to reduce both interconnect losses and physical dimensions.

Additive manufacturing technologies, such as 3D and inkjet printing, offer SoP solutions for wireless packages through the vertically-integrated fabrication of multimaterial 3D structures and 2D topologies. Inkjet printing has been demonstrated as an efficient technology for the realization of wireless SoP interconnects and antennas in the mm-wave regime [1]. The integration of 3D printing technology with post-process inkjet printing further allows for the development of more advanced and application-specific SoP solutions, such as periodic frequency selective surface (FSS) metamaterial structures used to selectively filter radiation into and out from a wireless system.

This work presents the design, simulation, and fabrication of a mm-wave FSS bandpass structure integrated directly onto a 3D-printed die encapsulation using stereolithography (SLA) technology. Surface profilometry is used to measure the surface roughness of the 3D-printed SLA structures to ensure post-process printability. Finally, a proof-of-concept demonstration of the design is presented using the outlined printing processes, highlighting the application-specific reconfigurability of the fabrication technology.

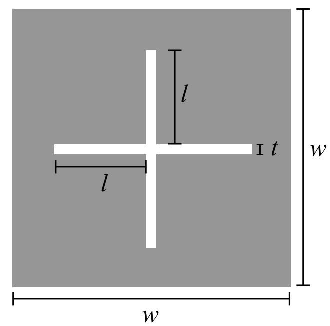



Fig. 1. (a) Unit cell for periodic cross-shaped slot FSS designed for 77 GHz with dimensions: $w$ = 1.9 mm, $l$ = 1.4 mm, and $t$ = 0.1 mm.

## II. FSS Design and Simulation

A cross-shaped slot FSS is designed to behave as a bandpass filter centered at 77 GHz. This design is the inverse of a common cross-shaped FSS which behaves as a bandstop filter [2]. Whereas a bandstop filter is useful for certain applications, a bandpass design is desired to highlight the post-process filtering and tunability of FSS-integrated wireless packages depending on their required application. Because the FSS will be present directly on top of the encapsulation of a wireless IC, the inclusion of the 3D-printed material is necessary for accurate modeling simulation. The 3D-printed material, discussed in the following section, has been characterized at 77 GHz through an E-band waveguide fill method and demonstrates the following electrical characteristics at 77 GHz: $\epsilon_r$ = 2.6 and tan $\delta$ = 0.017. The 2D topology and dimensions of the FSS unit cell atop a 1 mm thick 3D-printed dielectric are presented in Fig. 1.

Simulations of the FSS unit cell are performed in HFSS using master-slave boundary conditions and Floquet port excitation. Insertion and return loss characteristics across the frequency range of 60–90 GHz are shown in Fig. 2. The simulated S-parameters demonstrate a pass-band insertion loss of -1.22 dB at the target 77 GHz with minimal return loss.

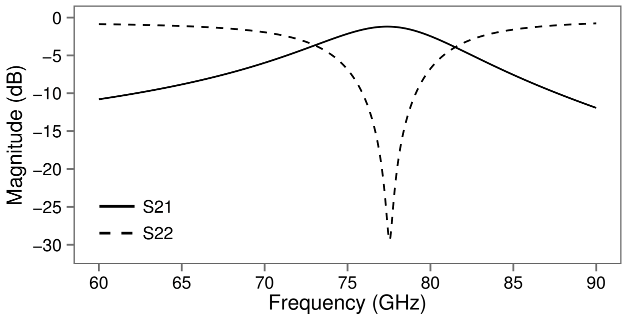



Fig. 2. S-parameter simulations of cross-shaped slot FSS unit cell.

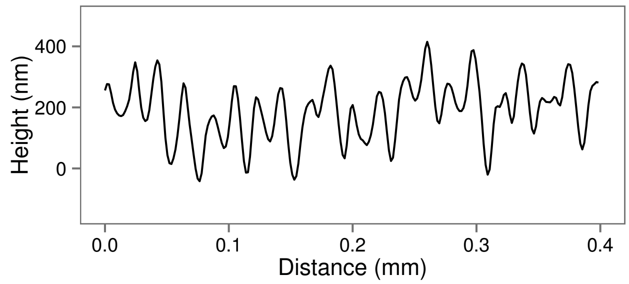
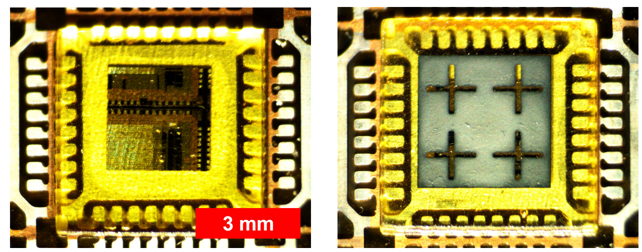



Fig. 3. Profilometer measurement of a 3D-printed SLA encapsulation surface.




(a) (b)

Fig. 4. Proof-of-concept 3D-printed SLA encapsulations for wireless IC packaging: (a) bare encapsulation and (b) inkjet-printed FSS-integrated encapsulation.

## III. Printed Encapsulation Fabrication

SLA 3D-printing is utilized to fabricate proof-of-concept encapsulations for wireless IC packages. Fundamentally, SLA technology uses the selective UV exposure of a photopolymer resin in a layer-by-layer fashion to realize a 3D structure, where the resolution of the structure is determined by the minimum increment of the build plate stepper motor (Z-axis) the resolution of the UV light source (X/Y-axis).

Encapsulation samples are printed using a custom LittleRP SLA 3D printer with a Viewsonic PJD7820HD DLP projector, providing an X/Y resolution of 38 μm as a result of the focal length and size of a pixel. The SLA photopolymer resin material for this demonstration is Vorex (orange color), an acrylate-based resin from MadeSolid designed to cure at UV wavelengths between 350–410 nm. 50 μm thick layers are printed with an exposure time of 7 seconds to cure each layer. After the printing is complete, the samples are submerged in two baths of isopropyl alcohol to remove any excess resin. Finally, the 3D-printed samples are given a post-print 1 J/cm$^2$ UV exposure to complete the fabrication process.

### A. *Surface Roughness of 3D-Printed SLA Structure*

The roughness of a 3D-printed SLA surface must first be investigated in order to ensure the efficient printability of post-process multilayer structures on top of a printed encapsulation. An Alpha-Step D-500 surface profilometer from KLA Tencor is used to measure the surface of an SLA encapsulation. The surface measurements, shown in Fig. 3, exhibit a $\sim$40 μm periodicity that is to be expected from the width of the DLP projector pixels used to pattern each layer of the 3D print. The distance from the valley to the peak of each period is less than 400 nm, a 25$\times$ reduction compared to the minimum surface roughness typically achieved with standard fused deposition modeling (FDM) 3D printing technologies [3]. This drastic reduction in surface roughness allows for the post-process printing of metallic and dielectric topologies without the need for intermediary passivization films.

### B. *Inkjet-Printed On-Package FSS Structures*

With the printability of the SLA encapsulation surface verified, inkjet printing is used to realize the previously detailed FSS structure directly onto the 3D-printed encapsulation using a Dimatix DMP-2831 inkjet printing system. EMD5730 silver nanoparticle-based ink from Sun Chemical is printed to pattern the cross-shaped slot FSS designed to function as a bandpass filter centered at 77 GHz. The proof-of-concept FSS topology is presented in Fig. 4(b) along with a bare 3D-printed SLA encapsulation in Fig. 4(a) for comparison.

## IV. Conclusion

This work outlines the integration of inkjet and 3D printing technologies for the purpose of developing more advanced wireless SoP packaging solutions. A mm-wave cross-shaped slot FSS is designed and simulated to function as a package-integrated bandpass filter. SLA 3D printing is used to fabricate die encapsulations, where surface measurements are performed yielding a 25$\times$ reduction in surface roughness from standard FDM technologies. Finally, the proposed FSS is fabricated directly onto a 3D-printed encapsulation using inkjet printing. The integration of these additive manufacturing technologies highlights the robust and easily-reconfigurable nature of printing for the fabrication of application-specific wireless mm-wave technology.

## References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[3] D. Ahn *et al.*, "Representation of surface roughness in fused deposition modeling," *Journal of Materials Processing Technology*, vol. 209, no. 15, pp. 5593–5600, 2009.