Achieving Fully Autonomous System-on-Package Designs: An Embedded-on-Package 5G Energy Harvester within 3D Printed Multilayer Flexible Packaging Structures

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***Abstract*— A novel multilayer flexible packaging fabrication process using only additively manufacturing techniques including inkjet and 3 dimensional (3D) printing is proposed. The 3D printed ramp structures and inkjet printed transmission lines on top of that are suitable for mm-wave inter-layer connections because lower parasitics are induced to the system. Moreover, a system-on-package (SoP) design for backscattering radio-frequency identification (RFID) is proposed. It has to be stressed, that an RF energy harvester operated at 26 GHz which is embedded inside the packaging using additively manufacturing techniques is proposed for the first time. The output voltage of the harvested energy at a distance of 20 cm away from the source is 0.9 V with transmitted equivalent isotropically radiated power (EIRP) equal to 59 dBm. The harvested energy is large enough to power the TS3001 timer for backscattering and can support all energy requirements of the entire SoP design so that the SoP design is fully autonomous and no external board or components are required. The system size can be shrunk to package level and thus paving the way for a multitude of novel miniaturized autonomous modules for wearable, IoT, and 5G applications.**

***Keywords*— 5G/mm-wave, RF energy harvester, inkjet printed, 3D printed, multilayer, packaging.**

I. Introduction

At the end stage of Moore's law, the idea of SoP which integrates multiple integrated circuits (ICs) with peripheral passive components such as antenna arrays, filters, and couplers using 3D stacking has been proposed to open a new era. Recently, SoP topology has attracted enormous attention because of the new fifth generation (5G) communication protocol. Since mm-wave frequencies are adopted for 5G communication to reach faster data transmission rates, the size of RF components can be reduced significantly and compatible with the size of packages [1]. However, conventional SoP designs are not fully autonomous because there are no energy sources within the package. Without an internal energy source, conventional SoP designs have to be connected to external boards or power supply elements to drive ICs inside the package and sustain the functionality.

In order to achieve a fully autonomous SoP design and shrink the functional system size from the board level to the package level, an energy source has to be embedded inside the package. While considering appropriate package-integrated energy sources, the conventional batteries are ruled out first because the lifetime is limited and it is impossible to replace them inside the package [2]. The ambient energy which can be accessed all day without the limitation of lifetime makes them suitable solutions to be used within the package. Among all ambient sources, RF energy is especially suitable for SoP design because the solar cells are typically too large to be integrated into the package while heat and vibrations are typically suppressed by the package [3], [4], [5]. Furthermore, for most of the SoP designs, the antenna is already integrated on the package and can be reused by RF energy harvesting. Furthermore, low power density for the RF energy [6] is no longer a problem since the EIRP allowed for the 5G communication is 75 dBm [7] which is much larger than other spectrums.

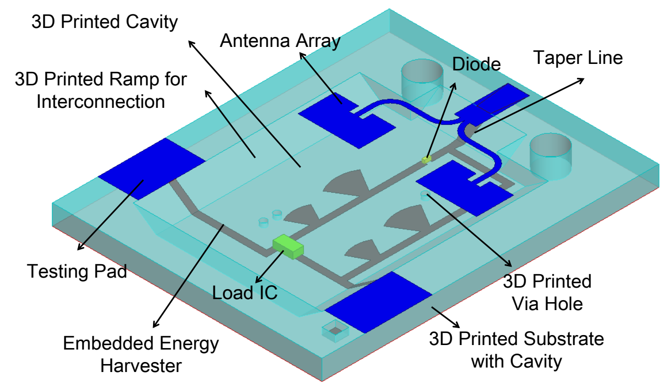

Fig. 1. The embedded-on-package energy harvester within 3D printed multilayer packaging structure.

There are also new challenges while operating at mm-wave frequencies. For example, the large parasitics for conventional package structures such as via would affect the system performance significantly. 3D printing techniques can be a good solution to solve the problem as well as achieving more compact integration [8], [9]. The material flexibility including flexible, durable, and high-temperature materials can offer more choices based on different applications. Furthermore, the structural flexibility can offer more 3D complex designs.

In this paper, a package integrated energy harvester operated at 26 GHz within 3D printed multilayer flexible packaging structures is proposed for the first time. The whole system is fabricated with low cost and fast prototyping additive manufacturing techniques including inkjet printing and 3D

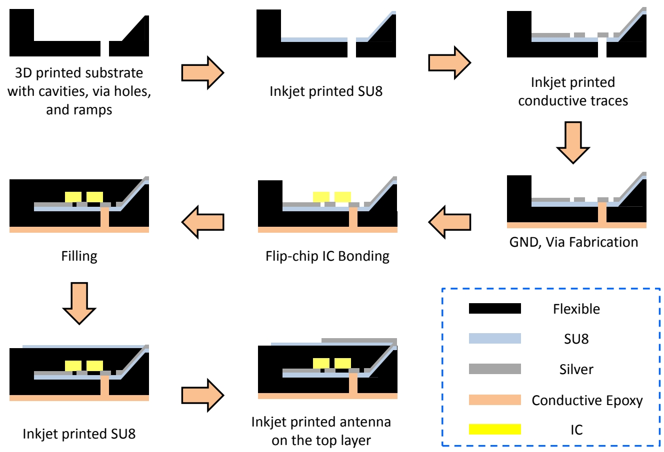

Fig. 2. Fabrication process for multilayer printing.

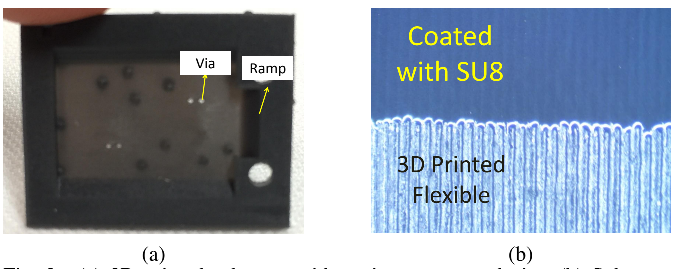

Fig. 3. (a) 3D printed substrate with cavity, ramps, and vias. (b) Substrate coated with SU8.

printing. The flexible substrate is adapted to resist better to shocks and vibrations. The system structure is demonstrated in Fig. 1. The energy harvester is embedded inside a cavity. The 3D printed ramp and the inkjet printed taper line on top of the ramp is used as inter-layer connections between the energy harvester and the antenna on the top layer to reduce parasitics. The antenna is printed right on the top of the energy harvester to reduce the overall size. The harvested energy is measured and the power level is large enough to drive a TS3001 low power timer which is used as the modulation control to build a fully autonomous backscattering RFID SoP design. The proposed package integrated energy harvester and the multilayer 3D printed process can be used to form a fully autonomous SoP design and bring the fully functional system size from the board level down to the package level.

II. Fabrication Process

The multilayer fabrication process of the system is demonstrated in Fig. 2. The first step is to 3D print the flexible base substrate with ramps, vias, and cavity and the result is shown in Fig. 3(a). The 3D printer used is formlabs SLA 3D printer. The flexible substrate used is FLGR02. The material is characterized using waveguides. The dielectric constant is 2.83 and the loss tangent is 0.03 at 26 GHz. The total thickness is $1500\,\mu\text{m}$ with cavity thickness equals to $1100\,\mu\text{m}$. Thus, the substrate thickness beneath the cavity is $400\,\mu\text{m}$. The z-direction resolution for this printer is $50\,\mu\text{m}$. In order to

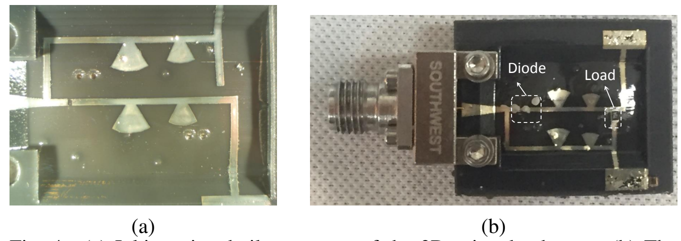

Fig. 4. (a) Inkjet printed silver on top of the 3D printed substrate. (b) The package integrated energy harvester.

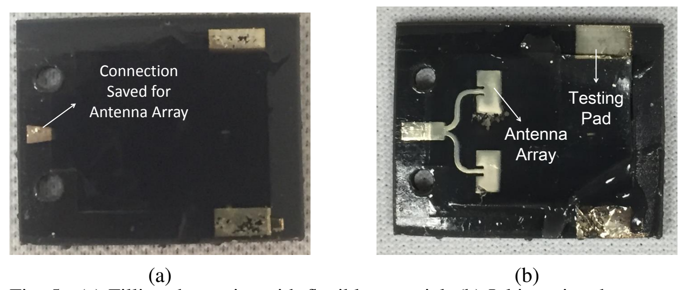

Fig. 5. (a) Filling the cavity with flexible material. (b) Inkjet printed antenna array on the top layer.

print the samples with more accurate thickness and higher z-directional resolution, the samples are printed with a 30° tilt angle. The thicknesses of three printed test samples are measured. The average total thickness is $1529\,\mu\text{m}$ which is very close to the design value, $1500\,\mu\text{m}$. The average thickness beneath the substrate is $392\,\mu\text{m}$ and again very close to the design value $400\,\mu\text{m}$.

The second step is to inkjet print a thin layer of SU8. The purpose of this layer is to smooth the surface roughness of the 3D printed substrate. As depicted in Fig. 3(b), there are stripes on the surface of the 3D printed substrate due to the 30° tilting angle which results in the increase of surface roughness. However, with the coating with a layer of SU8, the surface roughness can be improved significantly. Furthermore, the SU8 layer also serves as a buffer to balance the different thermal expansion between the substrate and the silver ink.

The silver traces are inkjet printed on the SU8 coated substrate and the result is shown in Fig. 4(a). The silver is first cured at 60 °C and then sintered at 150 °C. The printing results show clear gaps and sharp edges. Furthermore, the silver traces on the ramp demonstrate a good connectivity. The other side of the 3D printed substrate is coated with conductive epoxy to create a ground plane. In the meantime, the vias are filled with conductive epoxy, too. Then the sample is put on the hot plate at 120 °C for 15 minutes for the conductive epoxy. The ICs are flip-chip bonded on the inkjet printed silver traces with conductive epoxy as shown in Fig. 4(b). The cavity is then filled with the flexible material to create a new layer. As shown in Fig. 5(a), the filling is flat and the inter-layer connection is ready for the antenna array op the top layer. To print the antenna on the top layer, a thin layer of SU8 is applied first and then inkjet print the silver trace on top of

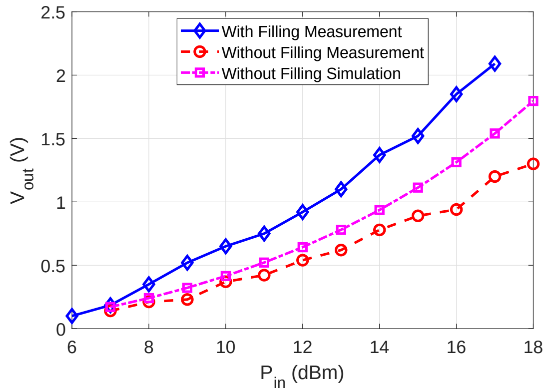

Fig. 6. Measured and simulated output voltage with respect to different input power at 26 GHz for the embedded energy harvester.

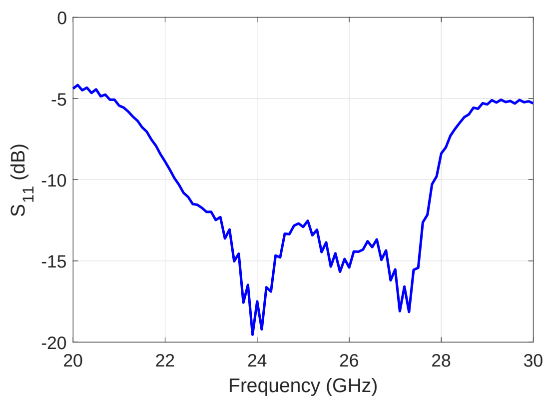

Fig. 7. Measured S11 for the embedded energy harvester after filling.

that as shown in Fig. 5(b).

The overall size of the entire circuit is 25 mm x 20 mm. However, the size can be reduced to 12 mm x 15 mm if the testing features such as the SMA and testing pads are eliminated. The fabrication process can be extended to more layers of printing by repeating the filling 3D printed materials and inkjet printed silver traces. The use of different 3D printed materials can offer more material and structural flexibility. For example, the 3D printed ramp which can only be printed using 3D printing techniques and inkjet print silver trace on top of the ramps to serve as inter-layer connection induce less parasitics compared with conventional via connections. The effects are more significant when operating at mm-wave frequencies. Thus, this multi-layer printing process is suitable for mm-wave SoP design.

III. Embedded 5G Energy Harvester

The fabricated embedded 5G energy harvester is shown in Fig. 4(b). The energy harvester starts with a taper line from the top layer to the cavity. The tapered line is used to take into consideration the thickness change between the line and the ground. The MA4E2038 diode is used for rectification. Only one-diode topology is used because the effect of loss is more significant than the efficiency increase while adding more diodes at 26 GHz. After the rectification, both DC and harmonics are generated. Thus, the sector shape open stubs are used as the termination for the harmonics at 26 GHz and 52 GHz. Moreover, the DC reference plane is connected to the diode anode to avoid the via and high parasitics. A $750\,\mathrm{k\Omega}$ resistor is placed at the load position to mimic the timer TS3001 from Silicon Labs. Two testing pads are branching out and connect to the top plane through 3D printed ramps for testing after filling the cavity.

The cavity embedded energy harvester is connected to a signal generator through Southwest SMA connector. The output voltage probing is performed by two testing pads for different input power levels at 26 GHz and measurement results are shown in Fig. 6. The simulation results of the energy harvester before the filling of the cavity from Advanced Design System harmonic balance simulation is also included for comparison. The microstrip line model is used for simulating the results before filling. As shown in Fig. 6, the simulation and measured results are very close with each other. The measured output voltage after filling the cavity is higher than before filling. The reason is that the frequency shift due to filling is taken into consideration. Thus, the optimal operation point for the design before filling is not at 26 GHz but the optimal operational point after filling is at 26 GHz. The input scattering parameter of the energy harvester after filling the cavity is measured and shown in Fig. 7. The S11 at 26 GHz is around -15 dB indicating good matching is achieved.

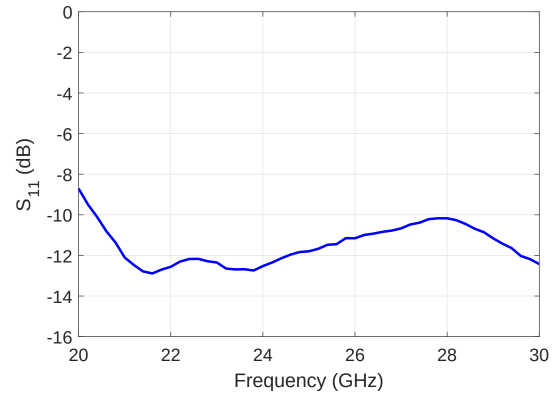

Fig. 8. Measured S11 for the antenna array.

IV. Antenna Array on the Top Layer

The antenna array printed on the filled cavity is composed of two patch antennas. The patch size is 4.52 mm x 2.75 mm. The distance between the two elements is $4.2\,\mathrm{mm}$. The final circuit is shown in Fig. 5(b). The parameters are measured with a VNA and the results are shown in Fig. 8. The S11 at 26 GHz is smaller than -10 dB. The broad bandwidth of this antenna is due to the thick substrate of the patch antenna. The radiation pattern is also measured and shown in Fig. 9. The zero degree is the direction of broadside radiation. The main beam is tilted to 30° toward the substrate. It is also because of the thick substrate and the long distance from the edge of the patch antenna to the edge of the substrate.

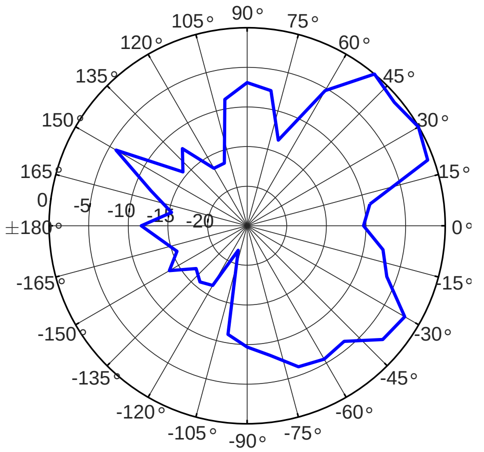

Fig. 9. Measured radiation pattern at 26 GHz for the antenna array.

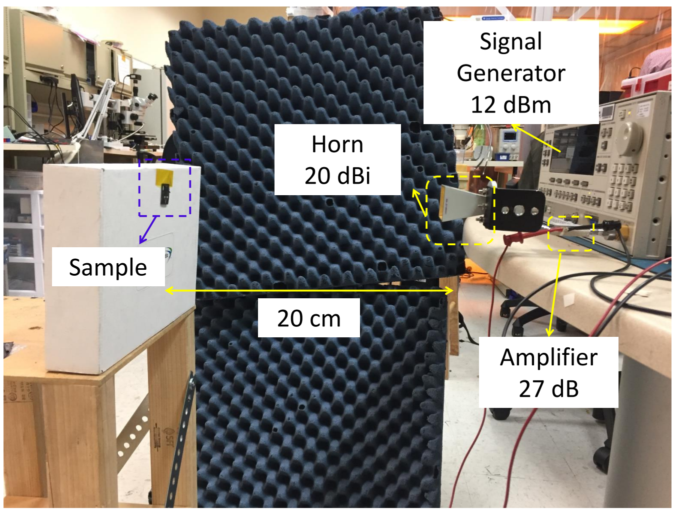

Fig. 10. Wireless performance evaluation for the system.

V. System Performance Evaluation

The entire system is measured wirelessly to evaluate the harvested energy. The measurement setup is shown in Fig. 10. The signal generator's output is 12 dBm. The amplifier is 27 dB and the gain of the horn antenna is 20 dBi. The distance between the sample and the horn antenna is $20\,\mathrm{cm}$. The output voltage at the load of the energy harvester is 0.9 V which is large enough to turn on and supply the TS3001 timer from Silicon Labs. Since the EIRP limit for 5G communication is around 75 dBm [7], the range can be extended to more than $1\,\mathrm{m}$ if 75 dBm EIRP is used.

The proposed embedded energy harvester can be used to form a fully autonomous backscattering SoP RFID module. The energy harvester is used to harvest energy to power a TS3001 timer. The timer would alter the oscillation frequency based on the resistance value for the sensor. The oscillated signal is used to control a CE3521M4 switch to create modulated signals and backscatter the information back to the reader. The detailed measurement results will be reported in the future extension.

VI. Conclusion

The first additive manufacturing multilayer process including inkjet and 3D printing is proposed for mm-wave packaging structures and modules. The process can be extended to even more layers by repeating the filling and printing process. The structural flexibility offered by 3D printed substrates can help reduce the parasitics which is important at mm-wave frequencies. Furthermore, the first package-integrated RF energy harvester is reported. The energy harvester is embedded inside a 3D printed cavity and the antenna is printed right on top of it to reduce the size. The harvested energy at 26 GHz is large enough to power up a TS3001 timer for backscattering. 0.9 V output power is measured at 20 cm range with 59 dBm EIRP, while more than $1\,\mathrm{m}$ range is expected while the full 75 dBm EIRP for 5G communication is used. The package-integrated energy harvester can support the energy requirements for the entire SoP design and thus enabling the drastic shrinkage of the size of the fully autonomous system from the board level to the package level.

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