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3D Printed Bonds for mmwave Interconnects: A Low-Complexity, Low-Loss Solution

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Abstract—This work addresses the limitations of traditional bondwires in millimeter-wave (mmWave) chip-to-PCB interconnections, particularly at high frequencies such as those in the E-band. The inherent inductance of bondwires significantly impairs impedance matching and contributes to elevated insertion loss as frequency increases. For instance, a single bondwire with a length of 480 μm exhibits poor performance, with a return loss (S11) of -2 dB and an insertion loss (S21) of -4.6 dB at 73 GHz. While using multiple bondwires can offer marginal improvement, the performance remains suboptimal for high-frequency applications. To overcome these limitations, we propose the use of XTPL's Ultra-Precise Dispensing (UPD) technology for forming 3D-printed interconnects. These printed microstructures demonstrate significantly improved RF performance. At 73 GHz, a dual printed bond achieves an insertion loss better than 1 dB and a return loss better than 10 dB, highlighting its potential as a superior alternative to traditional wire bonding in mmWave system integration.

Keywords—3D printing, impedance matching, insertion loss, printed bonds, wire bonding

I. INTRODUCTION

As the conventional RF spectrum becomes increasingly saturated and the demand for high-speed data continues to rise, the millimeter-wave (mmWave) frequency range is gaining prominence as a promising solution for next-generation communication and sensing systems [1]. Frequencies ranging from sub-6 GHz up to 100 GHz are actively being explored due to their capacity to support both ultra-fast data transmission and high-resolution radar functionalities [2]. Emerging system designs often aim to operate across wide frequency spans or offer switchable configurations to maximize spectrum utilization. These architectures, however, place stringent requirements on the interconnects—demanding low reflection and minimal insertion loss across broad bandwidths [3].

At millimeter-wave frequencies, conventional die-to-PCB interconnection techniques like bondwires remain popular because of their cost-effectiveness and ease of implementation [4]. Despite their affordability, bondwires present significant performance limitations in high-frequency applications. Due to the inductance and parasitics introduced by bondwires, they tend to introduce higher insertion loss, phase irregularities, and impedance mismatches, which can adversely impact

system efficiency and compromise beamforming accuracy [5]–[7]. Ensuring high system performance, especially in transitions between MMICs and antennas, demands meticulous design and optimization of these interconnections. Flip-chip methods, although more compact, face limitations in alignment precision and thermal dissipation—particularly problematic for high-power devices where the chip's backside must maintain efficient heat transfer [8].

3D printing technologies offer a compelling alternative, enabling the fabrication of complex, integrated interconnect structures with high precision and minimal manual intervention [9]. These techniques allow for the creation of customized and low-loss transitions between components, which are critical for maintaining signal integrity at mmWave frequencies. Additionally, 3D-printed interconnects can support multilayer and conformal geometries, facilitating tighter integration between MMICs and antennas in advanced packaging architectures. Advancements in 3D printing technologies are pushing the boundaries of high-frequency electronics fabrication, particularly with the emergence of Aerosol Jet 3D printers [10]–[12]. These printers support a wide range of materials, including dielectric inks (such as polyimide and Teflon) and conductive inks (such as silver and copper), enabling versatile multi-material printing.

In this study, we investigate the feasibility of 3D printed bonds using dispensing technology for interconnection in mmWave applications and also proposes compensation circuits for improving the matching. This paper is organized as follows: Section II discusses the simulation of the bond wire and the parametric analysis of the bond wire. Section III presents the design of the matching compensation structure at 73GHz. Sections IV discusses the measurements of bond wire with and without compensation structure. Finally, Section V presents the conclusions.

II. BONDWIRE PERFORMANCES IN E-BAND

To analyze bondwire performance and the losses, initially a single bondwire is simulated in CST. In this study, a gold bond wire with a diameter of 25 μm is considered as the baseline interconnect. The bonding pads are designed with dimensions of 100 μm in length and 450 μm in width, optimized for a 50 Ω characteristic impedance on a low loss

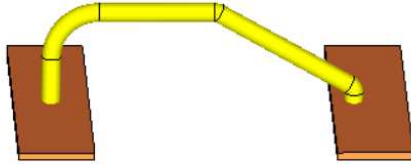


Fig. 1. Single bondwire configuration

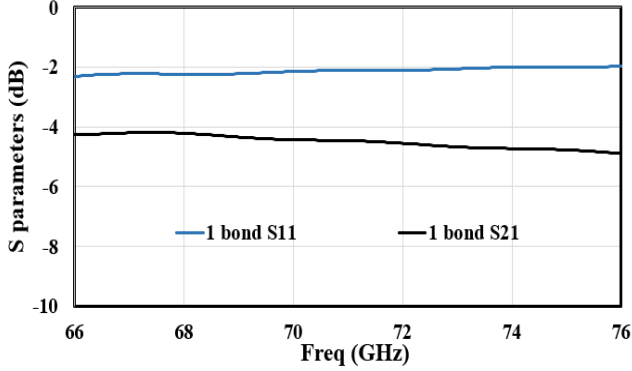


Fig. 2. Simulated S parameter results of the single bond-wire.

Rogers RO4003C substrate of thickness of 200 μm , ensuring proper impedance matching. The separation between the two pads is maintained at 320 μm , and the bond wire is positioned with a 40 μm offset from the edge of each pad. Taking these offsets into account, the total length of the bond wire is approximately 480 μm . A ground metal layer is also present on the other side of the substrate.

As the demand for high-data-rate wireless communication continues to grow, systems operating in the mmWave spectrum—particularly in the E-band are becoming increasingly important. Therefore, we have conducted our analysis in the 66-76 GHz frequency range. Fig. 1 shows our reference single bond wire. Fig. 2 shows the simulated S parameter performance of the bondwire. In the 70 GHz range, the insertion loss S21 falls below -4 dB and the reflection coefficient S11 is around -2 dB. These results indicate the possibility for significant signal degradation. Therefore, it is essential to account for the parasitic effects introduced by the bond wire and implement appropriate compensation techniques to achieve proper impedance matching and improved transmission performance.

Multiple bond wires have been shown to provide improved electrical performance in high-frequency interconnects. In our previous work, we demonstrated the benefits of employing multiple bond wires between an antenna array and an MMIC in the E-band [13]. Building on that, we have simulated a double bond wire configuration, as illustrated in Fig. 3. A spacing of 25 μm is maintained between the two bond wires. The simulated S-parameter performance for the double bond wire configuration is shown in Fig. 4. At 72 GHz, the insertion loss S21 improves to -2.5 dB, and the reflection coefficient S11 shifts to -3.8 dB—demonstrating slightly better performance compared to the single bond wire case. However, the improvement is still insufficient to ensure high-quality operation in the E-band. This highlights the need for advanced compensation techniques, or alternative interconnection approaches to enhance performance. If used, compensation circuits often increase the overall complexity

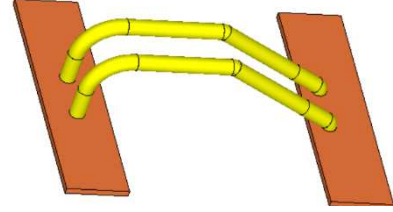


Fig. 3. Double bondwire configuration

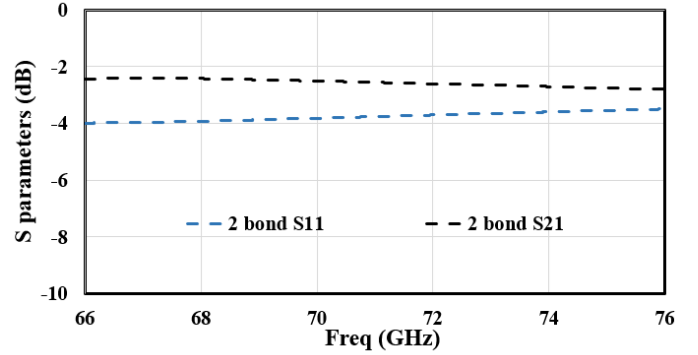


Fig. 4. Simulated S parameter results of the double bond-wire.

and footprint, which is undesirable. Additionally, implementing such compensation circuits on MMICs or RF chips complicates integration with PCBs, making it an impractical solution for compact mmWave modules.

III. PROPOSED 3D PRINTED INTERCONNECTIONS

To address the limitations of conventional bond wire interconnections—particularly their excessive parasitic inductance, poor impedance matching, and mechanical complexity—this work proposes the use of 3D-printed interconnects fabricated using XTPL's Ultra-Precise Deposition (UPD) printing technology [14] hosted at The University of Glasgow. This technique enables the creation of fine, free-standing conductive structures with precise

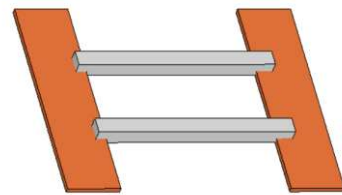


Fig. 5. 3D printed double bond configuration

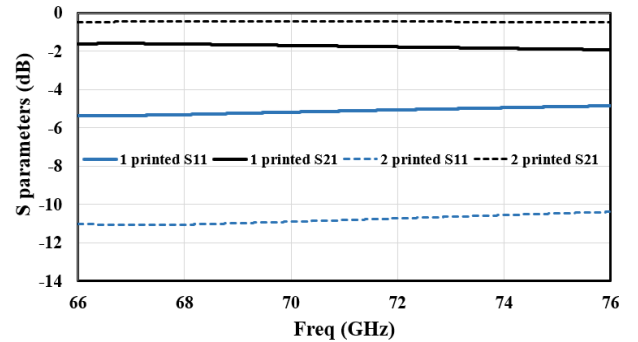


Fig. 6. Simulated S parameter results of the single and double printed bonds.

dimensional control and micron-scale accuracy. A key advantage of this approach is the ability to fabricate interconnects that are significantly shorter in length and positioned closer to the substrate compared to traditional wire bonds, also with good repeatability and manufacturing predictability. These characteristics are crucial for reducing parasitic effects and achieving lower insertion losses, which are especially critical in mmWave and E-band applications.

Both single and double 3D-printed bond structures were analyzed. Fig. 5 shows the simulated model of a 3D printed double bond configuration. As shown in Fig. 6, the single printed bond achieved a return loss (S11) of -5 dB and an insertion loss (S21) of -1.8 dB at 72 GHz, showing a notable improvement over the conventional single bond wire configuration. Further enhancement was observed with the double printed bond, which yielded an S11 of -11 dB and an S21 of -0.46 dB —indicating significantly improved impedance matching and extremely low transmission loss. This result clearly demonstrates that the 3D-printed double bond significantly outperforms the conventional gold double bond wire configuration. The insertion loss of less than 1 dB, combined with a return loss better than -10 dB, effectively eliminates the need for additional impedance matching or compensation circuits. This not only simplifies the overall interconnect design but also helps reduce the footprint and complexity of mmWave modules, making the approach highly attractive for compact and high-frequency system integration.

IV. MEASUREMENT RESULTS

Encouraged by the simulation results, a prototype of the double printed bond was fabricated by the University of Glasgow's XTPL UPD system [14] as illustrated in Fig. 7. The wire bonds were made of silver. S-parameter measurements were performed at the UKRI Millimetre Wave Measurement Laboratory at the University of Sheffield (TUoS) [15]. The measurements covered frequencies up to 76 GHz, utilizing a Keysight PNA N5245B network analyzer in combination with



Fig. 7. Fabricated 3D printed double bond

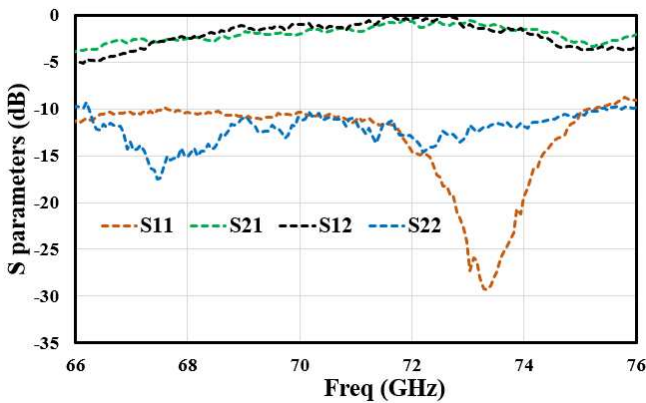


Fig. 8. Measured S parameters of 3D printed double bond.

WR15+ VDI frequency extenders and 100 μ m pitch GSG RF probes from Picoprobe. A two-port Thru-Reflect-Line (TRL) calibration was carried out directly on the same substrate as the device under test, for de-embedding the influence of the probe station and interconnect fixture from the measured data. This ensured accurate characterization of the standalone interconnect performance. The 3D printed double bond interconnection demonstrated excellent mechanical stability and dimensional consistency. Subsequent S-parameter measurements, shown in Fig. 8, validate the simulation outcomes. The measured return loss (S11) better than -10 dB across the entire 66–76 GHz frequency band, indicating good impedance matching. The insertion loss (S21) remains below 2 dB between 69 and 74 GHz, confirming that the structure supports efficient signal transmission within the E-band range.

These results highlight the strong potential of 3D-printed interconnects as a compact, low-loss, and low-complexity alternative to traditional bond wires in mmWave systems. The additive nature of the process offers significant benefits for integration with planar PCB structures, especially in scenarios where precise control over interconnect geometry is required and traditional compensation circuits are impractical due to space constraints. This approach opens new avenues for high-frequency packaging in applications such as 5G/6G front-ends, phased arrays, and compact radar modules, where electrical performance and form factor are critical design parameters.

V. CONCLUSIONS

Traditional bondwires exhibit significant performance limitations at mmWave frequencies due to high inductance and poor impedance matching, making them unsuitable for chip-to-PCB interconnections in the E-band. This work demonstrates that 3D-printed interconnects, fabricated using XTPL's Ultra-Precise Dispensing technology, offer a superior alternative with significantly improved RF performance. Simulations and measurements confirm that the double printed bond achieves lower insertion loss and better return loss across the 66–76 GHz range. These 3D-printed structures are compact, easy to fabricate, and eliminate the need for complex matching circuits, making them highly suitable for next-generation high-frequency electronic systems.

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