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Advanced 3D-Printing Technologies for Transformative Radio Frequency and Optical Devices

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Additive manufacturing technology has garnered significant attention in modern three-dimensional (3D) fabrication processes due to its rapid prototyping capabilities. It is particularly appealing because of its compatibility with a wide range of dielectric and metallic materials, enabling the creation of design prototypes for nearly any 3D structure. Recently, its ability to precisely manufacture functional devices with microscale features and high repeatability has made it even more attractive (Min, 2016; Otter and Lucyszyn, 2017; Zhang et al., 2017; Xin and Liang, 2017). This makes it highly suitable for fabricating functional mm-wave and THz components, such as dielectric lens antennas (Vorobyov et al., 2017; Yi et al., 2016; Furlan et al., 2016), waveguides (Li et al., 2017; Hong et al., 2018; Hong et al., 2018), sensors (Li et al., 2017), and filters/splitters (Kaur et al., 2015; Pandey et al., 2013; Hernandez-Serrano et al., 2017; Wu et al., 2008; Busch et al., 2014), facilitating the development of cost-effective and complex THz systems.

3D printing methods commonly employed in mm-wave and THz technologies can be categorized into five main types: (1) fused deposition modeling (FDM), (2) selective laser sintering (SLS), (3) stereolithographic apparatus (SLA), (4) digital-light-processing (DLP), and (5) polymer jetting (PJ). Among these, the FDM technique offers the lowest printing resolution and exhibits high surface roughness compared to other additive manufacturing processes. These limitations restrict its applicability to frequencies below 400 GHz (Hernandez-Serrano et al., 2017), as the relatively large structure sizes and high surface roughness contribute to excessive propagation losses at higher frequencies. Thermoplastic materials, typically available in filament forms, are used to produce 3D structures by selectively depositing melted filament material along predefined paths. The layer heights of FDM printing typically range from 50 to 500 µm, with a minimum achievable single-layer width of approximately 100 μm^2. These dimensions are primarily influenced by the nozzle size and the viscosity of the melted filament material. The best surface roughness attainable using FDM is around 35 µm (Alsoufi et al., 2017).

The SLS technique employs a high-intensity laser beam to sinter polymeric powder material layer-by-layer, offering superior printing resolutions between 20 and 80 µm, depending on the microparticle sizes of the powder material. Despite achieving low surface roughness of about 6 µm (Sachdeva et al., 2013), SLS suffers from material shrinkage of approximately 3-5%. Additionally, the limited availability of microparticle powders compatible with this process

(Schmid et al., 2015; Gross et al., 2014) constrains its use in mm-wave and THz applications.

SLA and DLP techniques utilize either a laser beam or ultraviolet (UV) light, respectively, to selectively cure resin-based photopolymers, forming 3D structures with resolutions determined by the spot size used for patterning. These methods deliver excellent surface roughness of less than 10 μm and are capable of achieving resolutions of 40–250 μm in structure width and 25 μm in structure height for SLA (Udroiu and Mihail, 2009). The DLP technique (ASIGA: PICO2 HD) achieves even finer resolutions of 27 μm in width and 1 μm in height, making it one of the most accurate techniques for mm-wave and THz applications. This range covers most THz frequencies between 100 GHz and 1.0 THz. However, despite the availability of numerous photopolymers, comprehensive data regarding the electromagnetic and optical properties of these materials is scarce and fragmented, often covering only limited frequency points or narrow frequency bands (Furlan et al., 2016; Li et al., 2017; Hong et al., 2018).

PJ technology provides exceptional printing accuracy and resolution by employing a process similar to inkjet printing. It uses printhead nozzles to deposit liquid photopolymers onto a build platform, where the materials are simultaneously photocured and patterned using UV light. This technique can achieve resolutions of approximately 14 μm in structure height and 23 μm in structure width. Additionally, PJ offers surface roughness values below 10 μm (Kechagias and Maropoulos, 2015; Kampker et al., 2017). Consequently, it is regarded as one of the most preferred methods for mm-wave and THz applications. However, similar to other techniques, PJ materials lack comprehensive electromagnetic and optical property data at THz frequencies, limiting their applicability in such systems.

Summary: Additive manufacturing has emerged as a transformative tool in radio frequency (RF) and optical applications, leveraging its precision and versatility to enable the design and fabrication of advanced components. In RF applications, 3D printing has been utilized to produce antennas, waveguides, filters, and resonators that support high-frequency operations, including mm-wave and THz ranges. These components benefit from the rapid prototyping and high structural accuracy provided by techniques such as SLA, DLP, and PJ, which ensure low losses and high performance. Furthermore, the ability to tailor geometries and material properties facilitates the design of custom RF devices that meet stringent performance criteria.

In optics, additive manufacturing allows for the creation of intricate lenses, photonic crystals, and optical waveguides. The high resolution and smooth surface finishes achieved through processes like SLA and PJ make them ideal for fabricating micro-optics and freeform optical elements. Additionally, advancements in photopolymer materials and post-processing techniques continue to improve optical performance, enabling integration into sensing, imaging, and communication systems.

The convergence of 3D printing with RF and optical technologies opens new avenues for designing multifunctional systems, including integrated RF-optical devices and hybrid platforms. This integration supports emerging applications in wireless communications, biomedical sensing, and terahertz imaging, where complex geometries and precision fabrication are critical. As additive manufacturing technologies advance, innovations such as multi-material printing, gradient-index designs, and metamaterial structures are becoming viable solutions. These enhancements not only enable better performance but also open possibilities for tunable and reconfigurable components. Emerging approaches like direct-write printing and nanoscale 3D fabrication are pushing the boundaries of miniaturization and performance optimization, enabling rapid development cycles for next-generation devices and systems.

Moreover, recent breakthroughs in bioprinting and hybrid printing technologies have expanded the capabilities of additive manufacturing. Hybrid approaches combining traditional techniques with additive manufacturing have led to the creation of complex, multifunctional structures for biomedical and photonic applications. In RF systems, innovations such as flexible and conformal antennas have been developed, allowing seamless integration into wearable devices and non-planar surfaces. Additionally, advanced photopolymer formulations are being tailored for optical and electromagnetic performance, ensuring compatibility with evolving communication standards and sensing technologies.

Future advancements are expected to include AI-driven design processes, automated optimization algorithms, and integration with simulation tools, further enhancing the precision and efficiency of 3D-printed structures. These developments will drive the adoption of additive manufacturing across industries, enabling smarter, more compact, and highly functional devices for next-generation wireless, optical, and sensing technologies.

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