Additive Manufacturing: A Key Enabling Technology for Next-Generation Microwave and Millimeter-Wave Systems

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I. WHAT IS ADDITIVE MANUFACTURING?

The terms additive manufacturing, 3-D printing, and digital manufacturing are commonly used to identify a class of technologies through which objects are built by selectively adding material, usually layer by layer, instead of machining raw material blocks as in subtractive processes like laser cutting, milling, or electroerosion. Initially adopted for rapid prototyping, to test the design before the final product development, additive manufacturing (AM) technologies have rapidly evolved toward the complete (one-pass) manufacturing of end-use components. Some examples are as follows:

- the transition of dental industry to digital dentistry thanks to the capability of AM technologies to efficiently deliver customized products;
- the redesign of aircraft components, such as fuel nozzles and brackets, in order to avoid brazing of several mechanical parts, thus improving lightness and robustness;
- the integration of electronic circuits on injection-molded thermoplastic objects through laser direct structuring (LDS). Thanks to the design freedom provided by this technology, electronic circuits can be efficiently embedded in any object, such as a smartphone [2].

As shown by these examples, AM technologies might lead to a digital revolution in many industrial sectors ranging from medical to aerospace [1], including microwave and millimeter-wave systems that are the focus of this article. The success of these technologies is determined by the true benefit behind them, that is, the free-form fabrication arising from the fact that

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no machining tools are used during a 3-D printing process. AM technologies could therefore allow the designers to develop products that are, in principle, independent of how they are manufactured, so focusing only on the intended application and functionality. As a matter of fact, high-quality and reliable parts can be obtained only by following design rules and considering limitations that are specific of each AM process. As a consequence, 3-D printing opens new perspectives (Section II), but at same time poses new challenges to the community of radio-frequency (RF) engineers (Section III). Maximum size of microwave components that can be built by 3-D printing depends significantly both on the technology and on the building direction. For instance, selective laser melting systems have building platforms in the order of tens of centimeters along each axis, and material jetting technologies usually print layers of a few millimeters thickness.

II. NEW PERSPECTIVES FOR THE RF ENGINEERS

In April 2016, a Google search produced over 350 000 results when entering the term “additive manufacturing of antennas.” Indeed, recently also RF engineers have started to leverage AM technologies to develop the next generation of microwave and millimeter-wave devices aimed at several applications operating from a few to hundreds of gigahertz, among which are millimeter-wave wireless communication systems for gigabit wireless local area networks, wearable sensors, automotive collision avoidance, high-resolution imaging systems, and satellite communications. In such areas, AM offers several advantages, including near-net shape manufacturing [i.e., the initial production of the component is very close to the final (net) shape, with almost no need for finishing], reduced tooling and fixtures, and almost no process waste. More importantly, AM technologies provide superior design and geometrical flexibility, since they can release RF engineers from several mechanical constraints that actually burden the electromagnetic performance of microwave and millimeter-wave devices. An example is the design of waveguide slot array antennas with optimized RF performances by adopting nonstandard waveguides without incurring into additional production costs [3]. In this perspective, compared to conventional machining techniques, AM can be applied to produce custom microwave devices at reduced lead time and costs.

The realization of multifunction parts, which is the implementation of several functionalities (electrical, thermal, or structural) in a single object, is another enabling advantage of AM processes. A meaningful example of multifunctionality implementation is the embedding of antennas and RF circuits directly onto the walls of small satellites for space-to-ground communications. In this way, RF performance is improved while reducing size, mass, and costs of CubeSats [4].

In satellite communications (SatCom), AM processes provide promising manufacturing solutions also for compact antenna-feed chains operating from Ku (15 GHz) to Q/V band (50 GHz) to be used in high-throughput satellites (HTS). In order to achieve an aggregated system capacity of terabits, the next-generation SatCom networks will be based on multispot architectures implementing space-diversity schemes. Because of the high number of necessary antenna-feed systems that have to be embarked on satellites, mass and envelope constraints are critical aspects in the development of the HTS payloads. Moreover, power handling in multicarrier regime can be limited by passive intermodulation (PIM) products generated at mechanical interfaces, and machining of small features inside complex compact devices is unavoidable. AM printing technologies can potentially overcome all such critical issues, because they provide a high degree of manufacturing flexibility enabling also the integration of RF components in the satellite supporting structures.

III. THREE-DIMENSIONAL PRINTING TECHNOLOGIES MOSTLY EXPLOITED IN THE MANUFACTURING OF MICROWAVE AND MILLIMETER-WAVE SYSTEMS

Today, several additive manufacturing systems have been established worldwide both at laboratory and commercial levels [1]. Although each AM system differs from the others in terms of technology, material, and postprocessing, still a categorization of the available processes is possible. According to the American Society for Testing and Materials (ASTM), the range of AM processes are classified into seven categories: material extrusion, material jetting, powder bed fusion, vat photopolymerization, binder jetting , direct energy deposition, and sheet laminations [5] (see Fig. 1). Each category includes several distinct processes, but all of them share the principle used for the selective modeling of the layers. Emerging systems can also combine different AM technologies and offer the capability of printing different materials during the same manufacturing process. Currently, the techniques most investigated for microwave and millimeter-wave applications are material extrusion, material jetting, powder-bed fusion, and photo-polymerization. Additionally, 3-D microprinting technologies have proved to be advantageous for manufacturing millimeter-wave components operating at very high frequencies (even above 100 GHz) [6], [7].

A. Material Extrusion

Material extrusion is a process by which material is heated and then dispensed through a nozzle layer by layer (Fig. 1). The diameter of the nozzle determines the shape and the size of the extruded filament and the minimum feature size that can be printed. Fused deposition modeling (FDM) is one of the most common material extrusion technologies

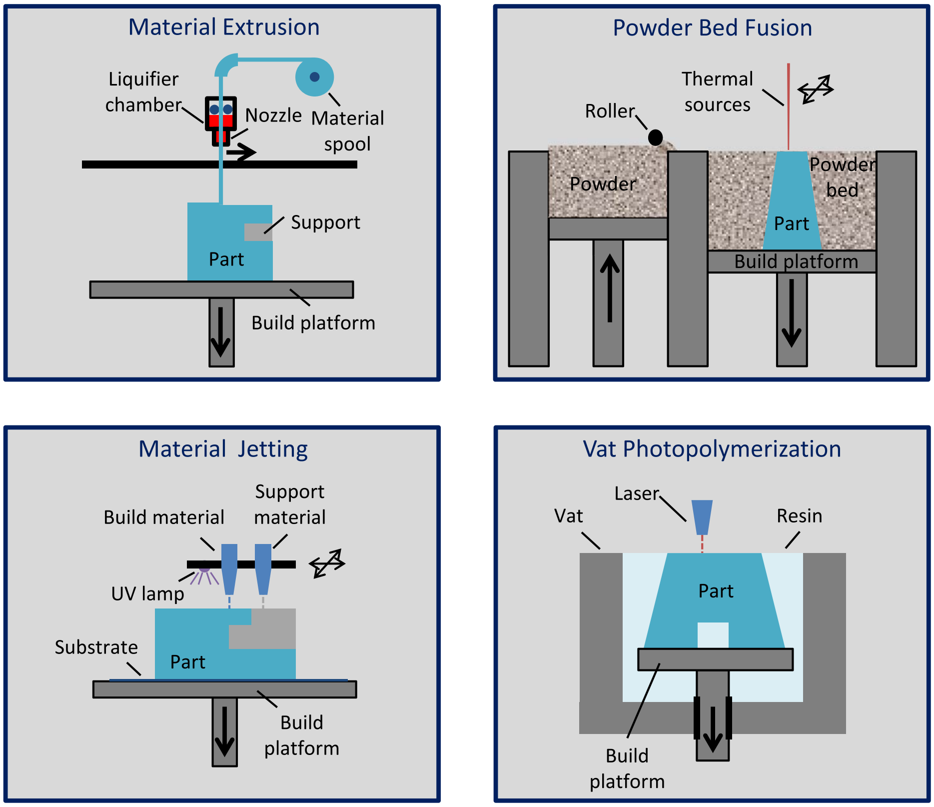

Fig. 1. ***Schematic diagrams of generic equipment for most common additive manufacturing technologies applied to build microwave and millimeter-wave devices.***

available and has already been applied to the manufacturing of high-gain dielectric lenses operating at millimeter-wave and terahertz bands. The capability of the FDM process in manufacturing parts with arbitrary shapes and complexity, such as lattices of cubes either connected by thin rods [8] or exhibiting internal holes [9], is exploited to both implement the phase correction needed to transform the spherical wavefront into a planar one and to integrate antireflection structures in order to reduce the reflection coefficient at the air-dielectric interface. Another important microwave application of the FDM technology is the development of planar and nonplanar conformal antennas. The dielectric layers and the metallic structures (e.g., patches, dipoles, baluns, via holes) of the antennas are printed via multimaterial AM systems that integrate FDM of thermoplastic polymers with microdispensing of conductive inks [10]. The effective dielectric constants of the different antenna dielectric layers can be easily implemented by varying the volume fraction of the printed polymers to air.

An almost unique feature of the AM process is the possibility of printing antennas either directly on 3-D surfaces or on flexible layers that are subsequently attached to the housing objects [11]. Key functional blocks for miniaturized and low-cost wireless systems, such as planar antennas with high-permittivity dielectrics, are modeled through a screen printing process, in which dielectric and conductive pastes are selectively deposited on the substrate across the screen openings [12].

B. Material Jetting

Material jetting processes are similar to inkjet printing, where drops of material are deposited through a print head and layers are cured or hardened using a UV lamp that follows the head (Fig. 1). Most material jetting machines use a multinozzle print head to increase speed and to deposit different materials. Inkjet printing technology has already been demonstrated to be a valuable solution to integrate multilayer planar antennas in microwave circuits operating up to 25 GHz [13]. The conductive elements, such as radiating elements and lines, are patterned through the subsequent deposition, drop by drop, of layers of nanoparticle inks, that are then subject to curing and sintering in order to achieve a reliable bonding with the substrate.

Similarly, low- and high-dielectric constant materials are realized through the printing of polymers exhibiting moderate loss. Current and future research in this technology includes printing of thick material films for the fabrication of multilayered structures, such as substrate-integrated waveguide (SIW) circuits with via holes [14], improvement of electrical conductivity exhibited by nanoparticle metallic inks, and minimization of manufacturing errors, such as nonuniform thickness distribution of the printed layers and formation of cracks caused by irregular ink shrinkage during sintering.

C. Powder Bed Fusion

Powder bed fusion includes several additive manufacturing processes, such as selective laser sintering (SLS), direct metal laser sintering (DMLS), and electron beam melting (EBM). These processes use a laser or an electron beam to fuse powder particles that are spread over a building platform. Components are, hence, built by overlapping several constant-thickness layers.

Laser-based technologies were originally developed for plastic prototypes and, then, extended to metal and ceramic powders. Currently, selective laser melting (SLM) is the AM technology mostly exploited to build all-metal microwave components, since it allows one to build complex-shape devices in a single metal block with good shape accuracy and mechanical properties and, possibly, without requiring surface coating to improve electrical conductivity. These features are particularly significant for high-power applications, where passive intermodulation products can arise in the contacting flanges, and in spaceborn applications, where severe mass and size constraints are set.

In an SLM system (Fig. 1), layers of metal powder are sequentially spread over the platform and fused by a high-power laser that scans the part cross sections.

To reduce deformation of parts caused by internal stresses arisen during the manufacturing process, parts undergo a stress-relieving process at high temperature. Subsequently, surfaces are smoothed through different treatments (polishing, shot peening, sand papering) and plated (depending on metal powders used). Appropriate design of the supporting structures and orientation of parts in the building chamber can significantly reduce the risk of dross formation and warping, thus increasing the manufacturing quality. In the microwave field, to date, SLM has been used to realize a variety of waveguide components operating up to Ka-band (30 GHz), such as filters (Fig. 2), orthomode transducers, and beamforming networks [15], [16].

Another powder-bed fusion process is selective heat sintering (SHS), where a thermal printing head heats layers of powdered thermoplastics. The main difference with SLS is that SHS employs a less intense thermal printing head instead of a laser, making it not only a cheaper but even a desktop solution. SHS has been already used for manufacturing in-the-ear antennas integrated in hearing devices for body-area networks [17].

D. VAT Photopolymerization

Vat photopolymerization is based on the solidification of a photosensitive liquid resin and has been the first available AM technology. The system consists of a vat full of liquid resin, a platform that can move up and down in the vat and a radiating source that activate polymerization (Fig. 1). Two different scanning approaches are available for selectively curing the liquid resin, namely:

- the surface of the layer is scanned with a laser (vector scan);
- a large beam irradiates the entire layer at one time (mask projection).

Stereolithography (SLA) is the most common process; it is applicable to both ceramic and polymer materials. Resolution can be better than 30 micrometers along with good surface finish (low roughness). Waveguide components produced by SLA on polymers can be successfully metal plated either by electroless

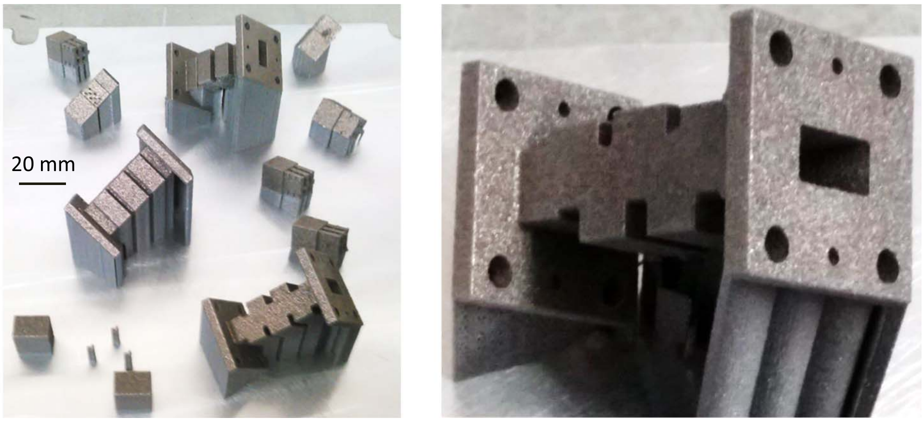

Fig. 2. ***Microwave filters as built on the platform of a selective laser melting machine using aluminum powder. (Courtesy of the Italian Institute of Technology.)***

copper/gold plating or by electroplating. In the latter case, the RF design has to be modified in order to accommodate holes or cuts necessary to achieve a uniform distribution of electric currents inside the components. Some aspects to be properly considered when adopting SLA on polymers are the long-term durability, the operating temperature range, and mechanical properties.

Photopolymerization-based AM processes have successfully been applied to a large variety of microwave components, including waveguide and dielectric filters, horn and lens antennas, and corrugated mirrors [18], [19].

IV. PROSPECTS AND CHALLENGES

Additive manufacturing technologies will lead to the successful development of a next generation of microwave and millimeter-wave systems exhibiting enhanced electromagnetic performance, while properly accommodating all the tight structural and mechanical constraints set by the specific application domains. To achieve this goal, two main challenges have to be overcome.

The first one deals with the technology itself, to the extent that fabrication parameters (e.g., tolerance, surface finishing, and material properties) are improved. In this respect, a very fast evolution of AM technologies is envisaged. Indeed, hybridization of several technologies, including conventional computer-numerical-control (CNC) machining, and multimaterial printing capability are expected to provide valuable solutions.

The second challenge refers to the high interdisciplinary skills demanded to the RF engineers. Indeed, the successful 3-D printing of a high-quality microwave component requires a deep knowledge of the specific process used in order to conform the RF design to the manufacturing constraints while exploiting the technology flexibility at the most. One example for all is the cleaning of the internal channels of a waveguide filter from the residual unbound material. Unless an AM-oriented design is developed, this production step could make most of the 3-D printing technologies inapplicable to the manufacturing of several filter architectures. In this perspective, universities, research institutions, and professional societies should promote educational activities focused on the design of microwave and millimeter-wave components oriented to 3-D printing. Master of science and doctoral students in electronics or telecommunication engineering could greatly benefit from attending short courses focused both on the description of AM technologies and on the implementation of RF components through these technologies. ■

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