A Fully Additive Approach for the Fabrication of Split-Ring Resonator Metasurfaces

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Abstract— **Metasurfaces, as a two-dimensional (2D) form of metamaterial, offer the possibility of designing miniaturized antennas for radio frequency (RF) energy harvesting systems with high efficiency, but fabrication of these antennas is still a major challenge. Printed circuit board (PCB) lithography, utilizing subtractive etch-and-print techniques to create metal interconnects on PCBs, was the first technique used to create metasurfaces antennas and remains the dominant technique to this day. The development of large-area fabrication techniques that are flexible, precise, uniform, cost-effective, and environmentally friendly is urgently needed for creating next-generation metasurfaces antenna. The present study reports a new fully additive manufacturing method for the fabrication of copper split-ring resonator (SRR) arrays on a PCB as a planar compact metasurfaces antenna. This new method was developed by combining sequential build up (SBU), laser direct writing (LDW), and covalent bonded metallization (CBM) methods and called (SBU-CBM). In this method, standard FR-4 covered with a layer of polyurethane was used as a basic PCB. The polymer surface was coated with a grafting molecule, followed by LDW to pattern the SRR array on the PCB. Finally, in electroless plating, only the laser-scanned area was selectively plated, and copper covalent bond metallization was selectively plated on the SRR pattern. Copper SRR arrays with different sizes were successfully fabricated on PCB using the SBU-CBM method. Copper strip lines within the SRR repeating building block were miniaturized up to 5 µm. To the best of our knowledge, this is the smallest size of a PCB antenna that has been reported to date.**

Keywords- metamaterial; RF-energy harvesting; metasurface antenna; copper split-ring resonator; additive manufacturing; laser direct writing; electroless copper plating

I. INTRODUCTION

According to a new report by Lux Research [1], a leading provider of technology-enabled research and advisory services, metamaterial applications are poised to reach $10.7 billion by 2030 in radar and lidar for autonomous vehicles, telecommunication antennas, 5G networks, coatings, vibration damping, wireless charging, noise prevention and more.

Metamaterials are materials engineered to possess properties that are not present in naturally occurring materials. Metamaterial components are assembled from multiple layers of materials, including metals and plastics. The materials are arranged in repeating patterns at scales that are smaller than the wavelengths of the phenomena they influence. The properties of metamaterials are not derived from the properties of the base materials but from their newly designed structures. The combination of their precise shape, geometry, size, orientation, and arrangement enables them to manipulate electromagnetic waves, blocking, absorbing, enhancing, or bending waves to achieve benefits beyond what is possible with conventional materials. With an appropriate design, metamaterials can affect electromagnetic and sound waves in ways that are not possible with conventional materials [2]. These performance advantages are particularly valuable in communication antennas and sensors, such as radar and lidar. As 5G infrastructure and devices are set to be implemented soon, along with the rising popularity of connected and autonomous vehicles, metamaterials are becoming viable just in time for rapid growth in these new markets. Metamaterial devices, in the vast majority of cases, are not significantly more expensive to produce than conventional devices. The compact size, greater energy efficiency, and precision directionality of metamaterial devices bodes well for their use. In other words, once metamaterials reach the market, conventional offerings are unlikely to remain competitive [3]. Metamaterials are already being deployed for telecommunication antennas, electromagnetic sensors such as radar and lidar, vibration damping, energy harvesting, and wireless charging.

Compact planar antennas are one of the most exciting applications of metasurfaces [4]. New advanced technologies, such as IoT, 5G, wearable electronics, and soft robotics, require batteries for functioning. However, battery lifetime is limited, and hence, the use of energy harvesting tends to decrease or completely remove the dependence on batteries. A promising energy harvesting technique is electromagnetic energy harvesting, particularly RF-energy harvesting systems, which have shown an ability to continuously supply power [5]. A typical RF-harvesting system consists of a rectifying antenna, which is able to harvest high-frequency energy from free space and convert it to DC power. As a key component of an RF-energy harvesting system, the antenna captures and converts incident energy into AC power, transferring it to the rectifier input for AC-to-DC conversion. While many types of antennas have been developed for RF-energy harvesting, the low RF power densities limit their usage over a wide range of applications. Furthermore, although in recent decades most electronic devices have seen significant shrinkage in size, shrinking antennas remains a challenge. Research has shown a direct correlation between an antenna's size and its bandwidth and efficiency. As a whole, smaller antennas tend to have a smaller bandwidth and a lower efficiency, which is why the miniaturization of antennas has been slower than the miniaturization of other electronic devices.

With the advent of metamaterials, the feasibility of designing miniaturized antennas with high efficiency for RF-energy harvesting systems is becoming realistic. The metasurface antenna is a category of compact planar antennas that harvests RF-energies from metasurface embedded in the antenna structure. In a metasurface antenna, an array of electrically small resonators is printed on a grounded dielectric substrate. In effect, each resonator effectively couples to the incident electromagnetic (EM) wave at resonance, thus capturing the EM energy from the ambient environment. The use of metasurface in antenna design results in size reduction, gain, and bandwidth improvement. Different metasurface structures are being developed today for antenna applications [6, 7, 8]. The periodic array of split-ring resonator (SRR) patterns on printed circuit boards (PCBs) is among the most effective metasurface antennas for RF-energy harvesting [9].

Although metamaterials have made it possible to miniaturize antennas while offering high efficiency, the precise fabrication of metasurface antennas is still a major challenge. Metasurface antennas can be constructed using the same processes used to create metal interconnects on PCBs. The most mature and common technology for creating metal interconnects on PCBs is lithography. The first metasurface antennas were actually fabricated through PCB lithography, and it remains the dominant technique even today [2]. This method involves first depositing a bulk layer of copper on a PCB and later patterning it using subtractive etch-and-print techniques to produce metamaterials on PCB. There are a number of limitations in this technique, such as using toxic chemicals and etchants and discarding a large number of metallic parts after etching. Despite, there have been some variations in lithography techniques over the years for metamaterial fabrication, still patterning methods rely on etching steps. Therefore, at present, fabrication techniques are one of the most important segments in metamaterial devices, especially metasurface antennas that require more research. To date, different fabrication methods, particularly a few types of lithography, 3D printing, and computer numerical control milling, have been used for metamaterial fabrication. A few types of lithography are offered for the fabrication of metamaterials, such as direct-write lithography (particle beam lithography, probe scanning lithography, laser lithography), pattern transfer lithography, and hybrid patterning lithography [10]. Although all these fabrication techniques have all played important roles in the fabrication of metamaterials and their unconventional applications, they each have certain limitations that leave room for further innovation and improvement. Metamaterial technologies of the future require large-area fabrication techniques that are flexible, precise, uniform, cost-effective, and environmentally friendly. Etch-free additive lithography is a new fabrication method that can meet these requirements [11, 12].

Additive manufacturing uses data computer-aided-design (CAD) software or 3D object scanners to direct hardware to deposit material layer upon layer in precise geometric shapes. As its name implies, additive manufacturing adds material to create an object. In contrast, when an object is created by traditional means, it is often necessary to remove material through milling, machining, carving, shaping, or other means. Developing a fully additive manufacturing methodology employing software-driven design for metamaterial fabrication at a large scale leads to rapid technology adoption at the speed of software, which is much faster than the pace of traditional new material innovations. For the first time, a new fully additive methodology is here proposed for patterning copper SRR arrays on PCB as a metasurface antenna for an efficient RF-energy harvesting system. The method is called sequential build up-covalent bonded metallization (SBU-CBM).

Metasurfaces with any planar geometry can be fabricated onto a wide range of substrates by SBU-CBM method [13, 14, 15]. SBU-CBM method holds great potential for the miniaturization of metamaterial devices with the shrinking of metamaterials to the micro/nanoscale [16]. SBU-CBM, as a cost-effective and environmentally friendly method, can provide a route for producing arbitrarily shaped metamaterials, which are known to have intriguing and potentially useful properties but are difficult to fabricate by other means. SBU, LDW, and CBM are industrially proven for large-scale production. Thus, the proposed SUB-CBM production method has the potential to be economically feasible for large-scale industrial production of metamaterial devices.

This study demonstrates, for the first time, fully additive fabrication of copper SRR arrays on PCBs as metasurface antennas using the SUB-CBM method. The possibility of miniaturizing metasurface antennas is studied by shrinking the unit cell of SRR arrays.

II. MATERIALS AND METHODS

A. *CAD Mask Design*

In their fundamental resonance, SRRs can be considered to behave like an LC oscillatory circuit containing a magnetic coil of inductance L and a capacitor of capacitance C. The LC resonance of the SRR is given as $\omega_m=1/\sqrt{LC}$ which is inversely proportional to the dimension of the SRR. Thus, it appears that the size of the SRR is the only factor that determines its response. By tuning the size of the SRR array, the response of the SRR array can be adjusted to a

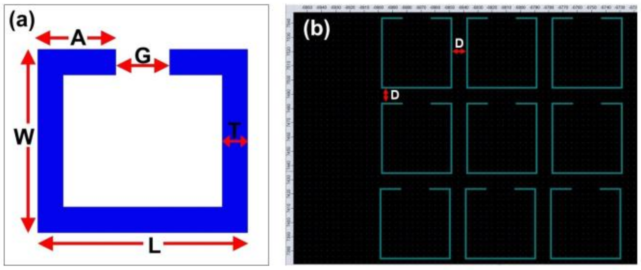

Figure 1. (a) Schematic diagram of a single SRR with its parameters and (b) mask designed with CAD software for LDW patterning.

large part of the electromagnetic spectrum, ranging from radio and microwave frequencies to infrared and optical frequencies [2].

In an SRR array, the dimension of the repeating building block determines the final size of the SRR array. A single-cell SRR, *i.e.*, a repeating building block of an SRR array, has a pair of enclosed loops with splits in them at opposite ends. The loops are made of nonmagnetic metals such as copper and have a small gap between them. The loops can be concentric or square and gapped as needed. A square-shaped SRR is arguably the most common building block used in forming SRR arrays. In this study, the focus is on the fabrication of a square-shaped SRR; the general geometry of a single SRR is presented in Fig. 1a.

To fabricate SRR arrays with different sizes, in the first step, different single SRRs with different dimensions were designed by changing the geometrical parameters. Afterward, an SRR array mask was created by using the commercially available CLEWIN software provided with the laser writing machine; the CAD mask (.CIF file) is presented in Fig. 1b.

B. *Materials*

UV-curable polyurethane (UV TP-1), grafting molecule (HP14), and electroless copper plating solutions (PEC-660 series) were purchased from J-KEM International, Stockholm, Sweden. FR-4 was purchased from Digi-key Electronics ltd. All chemicals in this study were used as received without further purification.

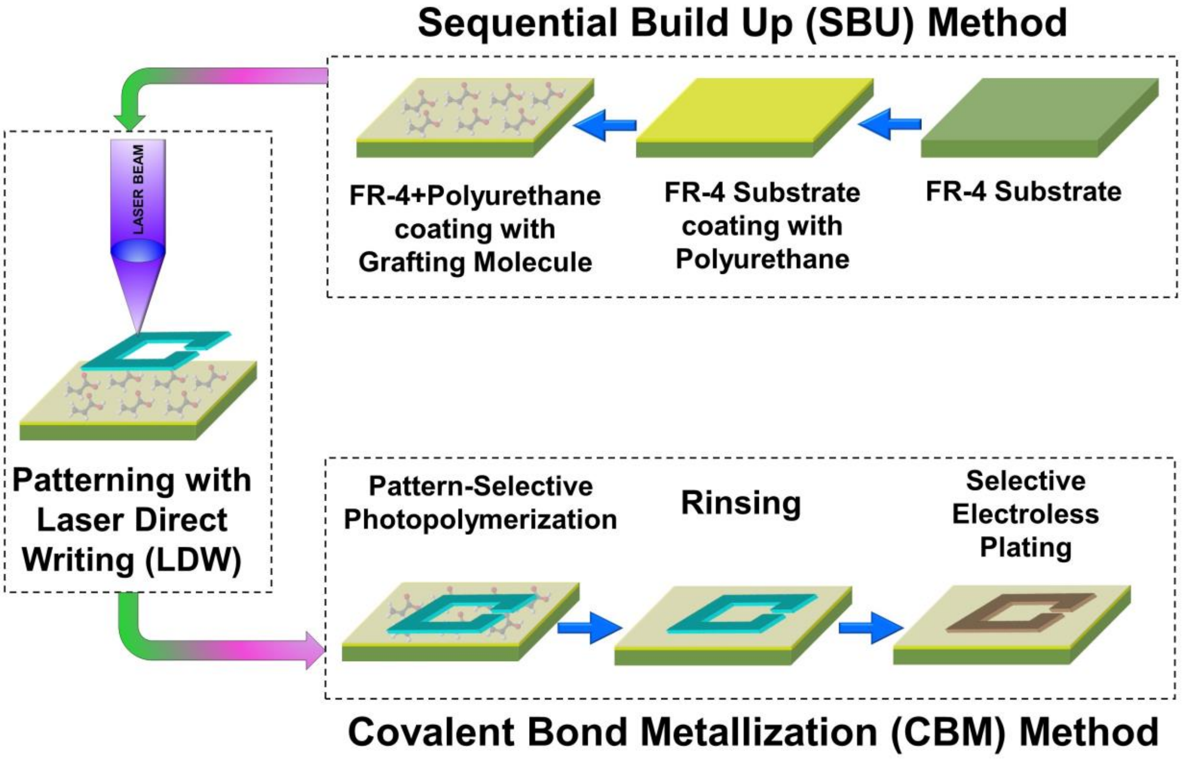

Figure 2. Schematic of the fabrication steps of copper SRR on PCB by the SBU-CBM method.

C. *Fabrication and Characterization*

In this study, FR-4, the most commonly used material in PCB construction, was used as the base PCB. In the first step, FR-4 was cleaned by ultrasonication in detergent, deionized water, acetone, and ethanol with deionized (DI) water rinsing in between each step. Then, polyurethane (PU) was spin-coated on FR-4, and the substrate was denoted FR-4/PU. Next, for polyurethane curing, FR-4/PU was exposed to UV light for three minutes. Afterward, the grafting molecules was spin-coated on FR-4/PU, and the substrate was denoted FR-4/PU/HP14. Immediately after HP14 coating, the SRR array was patterned on FR-4/PU/HP14 by an LDW machine, and the substrate was denoted FR-4/PU/HP14/SRR. For patterning, a gallium-nitride (GaN) laser source (LW405B laser machine by MICROTECH, Italy) with a wavelength of 375 nm was used. After patterning, the FR-4/PU/HP14/SRR was rinsed carefully with acetone to remove unbonded graft molecules, and then optical microscope analysis was performed to confirm the formation of the SRR pattern. Finally, the electroless copper plating solutions were prepared according to the supplier's instructions, and the FR-4/PU/HP14/SRR array was dipped in electroless copper plating baths for selective copper CBM. After electroless copper plating, the FR-4/PU/HP14/SRR was rinsed carefully with DI water, and then optical microscope analysis was performed to confirm the selective copper CBM of the SRR pattern. A schematic of the fabrication steps of copper SRR on PCB by SBU-CBM is shown in Fig. 2.

III. RESULTS AND DISCUSSION

As shown in Fig. 1a, length (L), width (W), arm length (A), gap (G), and thickness of the strip line (T) are all geometrical parameters defining the final dimension of a single SRR. In addition to these parameters, for the SRR array, the distance between two single SRRs (D) is another critical parameter that determines the final dimension of the SRR array (Fig. 1b). In the current study using the SBU-CBM method, different SRR arrays on PCBs with different sizes were successfully fabricated by tuning these geometrical parameters.

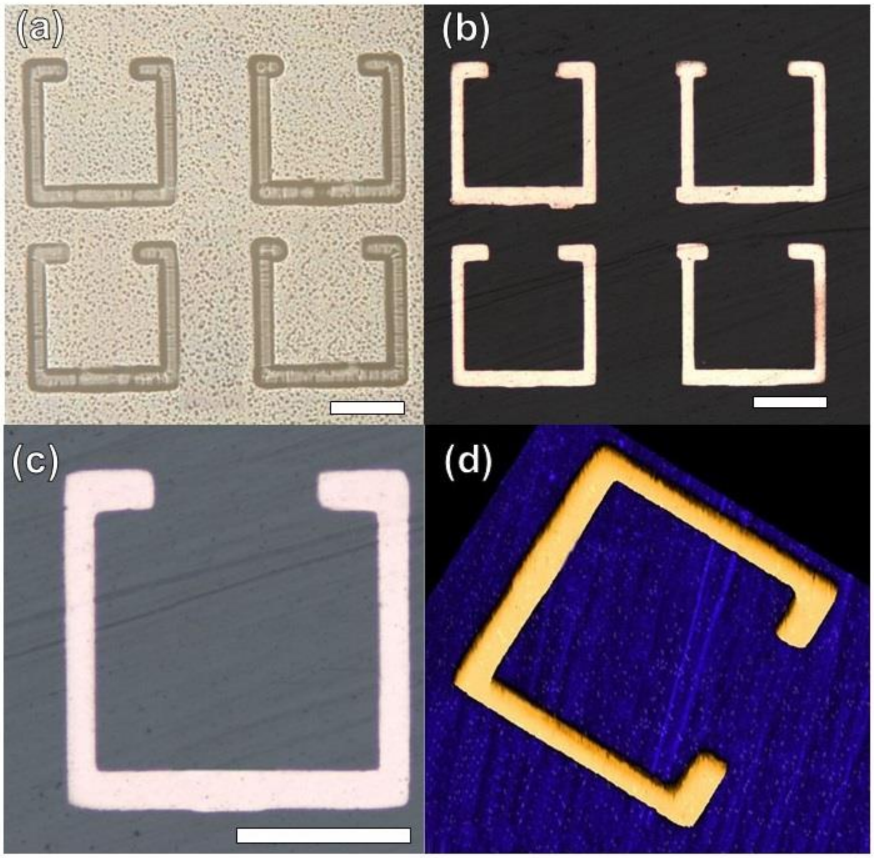

Figure 3. Optical microscopy images of the fabricated 2×2 SRR array on PCB with dimensions of L=200 µm, W=200 µm, A=50 µm, G=100 µm, T=20 µm, and D=120 µm: (a) after patterning with LDW and before copper CBM and (b-d) after copper CBM; the scale bar is 100 µm.

An SRR array on a PCB with dimensions of L=200 µm, W=200 µm, A=50 µm, G=100 µm, T=20 µm, and D=120 µm was fabricated successfully by the SBU-CBM method, and the results are shown in Fig. 3. To miniaturize the SRR array, the SBU-CBM method was used to fabricate a smaller SRR array on a PCB with dimensions of L=100 µm, W=100 µm, A=30 µm, G=40 µm, T=10 µm, and D=5 µm; optical microscopy images are shown in Fig. 4. In furtherance of the miniaturization trend, a smaller SRR array on PCB with dimensions of L=50 µm, W=50 µm, A=20 µm, G=10 µm, T=5 µm, and D=20 µm was fabricated by the SBU-CBM method; the results are shown in Fig. 5.

According to the optical microscopy images in Fig. 1-3, all different SRR arrays with different sizes are manufactured with excellent structural quality. The results demonstrate the feasibility of fabricating SRR arrays of different sizes using SBU-CMB method for high-performance metasurface antenna applications.

Loss of selectivity during copper deposition is one of the main integration issues in PCB antenna fabrication, which can result in high leakage of copper between repeating unit cells [17]. The images in Fig. 1-3 demonstrate that copper metallization with a high degree of selectivity was carried out at the site of patterned SRR arrays by LDW. There is no copper leakage between the single SRR units in all fabricated arrays. This high degree of copper metallization selectivity is due to the systematic design of the SBU-CBM method.

In the search for innovative fabrication techniques, it is important to remember that a new fabrication technique could also be developed by combining some existing fabrication techniques. The SBU-CBM method was developed by combining SBU, LDW, and CBM methods. The SBU method is a manufacturing technique used to produce multilayer PCB in several lamination sequences. Due to the additive nature of the SBU process, this method has been adopted by all leading electronics manufacturers [18]. LDW is a maskless direct-write lithography that utilizes computer-controlled optics to project the desired micro/nanoperiodic patterns directly onto photoresist by holding the mask in software. LDW is also one of the adapted manufacturing techniques for micro/nanopatterning [19, 20]. Directly preparing complex high-resolution patterns is a unique advantage of the LDW technique. The CBM method itself is a combination of electroless plating and self-assembly. Electroless plating is a well-known additive method to coat nonconductive (dielectric) substrates, such as PCBs, polymers, glass, and ceramics, with a conductive, metallic layer [21]. Electroless plating is a controllable and stable process and has been adopted by most of the world's leading PCB manufacturers. CBM uses electroless plating to deposit a metal film on polymers by forming covalent bonds between the metal and polymer. When compared with typical electroless plating, CBM can significantly increase the robustness of the deposited metal due to the formation of covalent metal-organic networks between the deposited metal and organic substrate. In this method, to form a covalent bond, the surface of the polymer is first coated with a grafting molecule. UV irradiation is then applied to the polymer coated with the grafting molecule, and photopolymerization is induced between the polymer and grafting molecule. In the end, the photopolymerized substrate is electroless plated, and covalent bonds form between grafting molecules and the metal. In the SBU-CBM method, LDW is used to activate grafting molecules and trigger their photopolymerization. During the LDW process, the laser only scans specific areas defined by a mask to obtain the desired pattern on polymer-coated graft molecules, so photopolymerization occurs only where the pattern is defined. After the LDW process, the sample is rinsed to remove unbonded grafting molecules that are outside the pattern. Finally, in electroless plating, only the laser-scanned area can be selectively plated, and covalent bond metallization selectively occurs on the pattern.

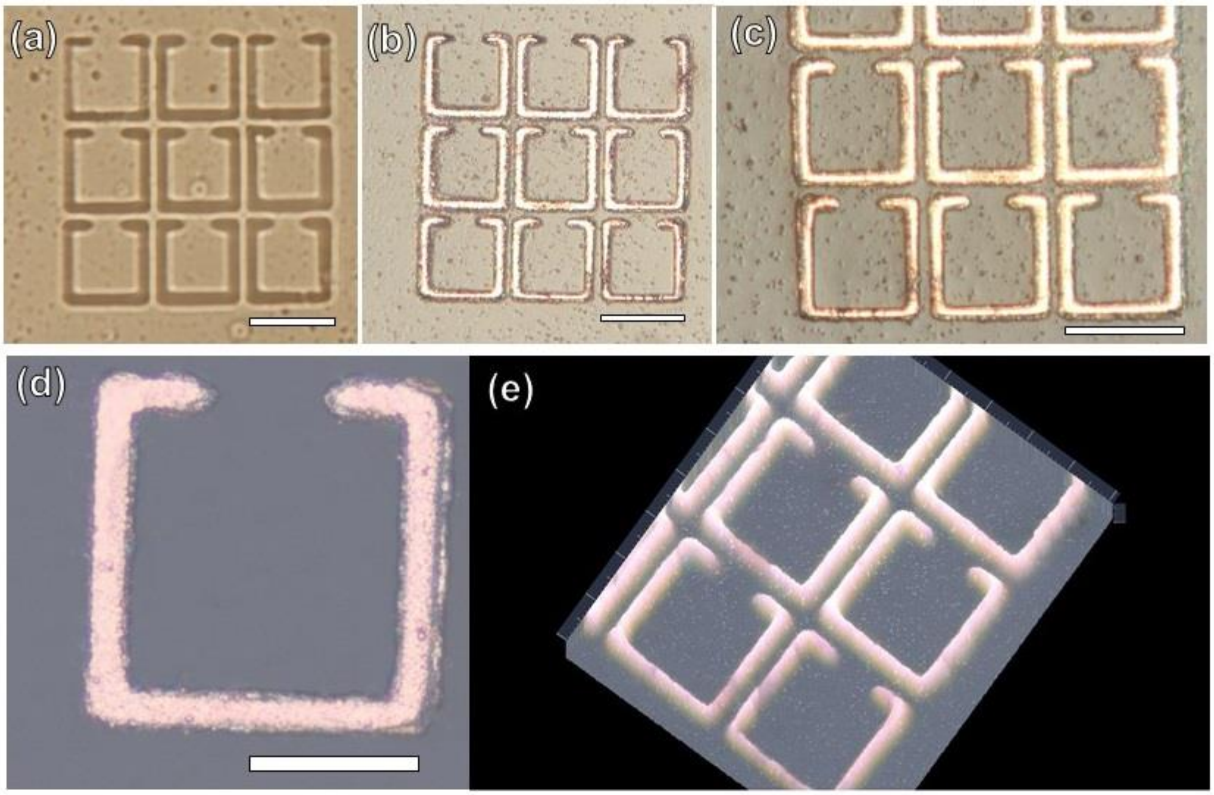

Figure 4. Optical microscopy images of the fabricated 3×3 SRR array on PCB with dimensions of L=100 µm, W=100 µm, A=30 µm, G=40 µm, T=10 µm, and D=5 µm: (a) after patterning with LDW and before copper CBM and (b-e) after copper CBM; the scale bar is 100 µm in (a-c) and 50 µm in (d).

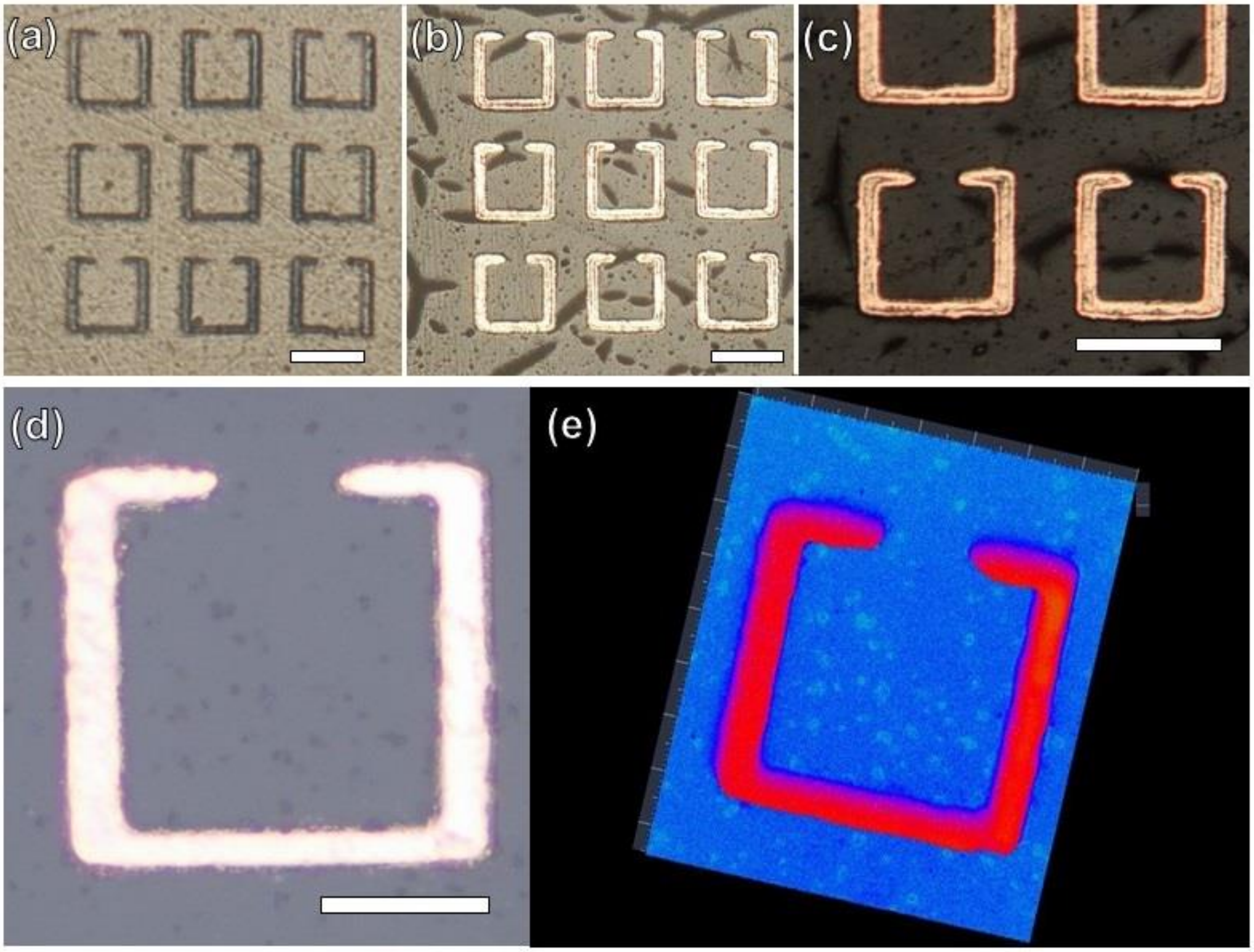

Figure 5. Optical microscopy images of the fabricated 3×3 SRR array on PCB with dimensions of L=50 µm, W=50 µm, A=20 µm, G=10 µm, T=5 µm, and D=20 µm: (a) after patterning with LDW and before copper CBM and (b-e) after copper CBM; the scale bar is 50 µm in (a-c) and 20 µm in (d).

IV. CONCLUSION

In summary, a novel fully additive manufacturing method was proposed and demonstrated for the fabrication of copper SRR arrays on PCB. The developed method called SBU-CBM was used to produce uniform copper SRR arrays of different sizes on PCB. Copper strip lines within the SRR repeating building block have been miniaturized up to 5 µm. To the best of our knowledge, this is the smallest size of a PCB antenna that has been reported to date. The SBU-CBM method was demonstrated to be unique in selective copper metallization without copper leakage between individual SRR unit cells. There are significant advantages to the approach, such as lesser processing steps without etching and being environmentally friendly. For large-scale production, this method allows for an economical working process because it uses less copper, and the entire process proceeds at room temperature. Additionally, this method is beneficial for the miniaturization of metasurface antennas.

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