Review Article

Printable Materials for the Realization of High Performance RF Components: Challenges and Opportunities

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Received 7 September 2017; Accepted 28 November 2017; Published 28 January 2018

Academic Editor: Félix A. Miranda

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Printing methods such as additive manufacturing (AM) and direct writing (DW) for radio frequency (RF) components including antennas, filters, transmission lines, and interconnects have recently garnered much attention due to the ease of use, efficiency, and low-cost benefits of the AM/DW tools readily available. The quality and performance of these printed components often do not align with their simulated counterparts due to losses associated with the base materials, surface roughness, and print resolution. These drawbacks preclude the community from realizing printed low loss RF components comparable to those fabricated with traditional subtractive manufacturing techniques. This review discusses the challenges facing low loss RF components, which has mostly been material limited by the robustness of the metal and the availability of AM-compatible dielectrics. We summarize the effective printing methods, review ink formulation, and the postprint processing steps necessary for targeted RF properties. We then detail the structure-property relationships critical to obtaining enhanced conductivities necessary for printed RF passive components. Finally, we give examples of demonstrations for various types of printed RF components and provide an outlook on future areas of research that will require multidisciplinary teams from chemists to RF system designers to fully realize the potential for printed RF components.

1. Introduction

Additive manufacturing (AM) and direct write (DW) printing have seen an explosion of tooling within the past decade, which has gone from large prototyping houses to consumer friendly benchtop models and engineering grade tool sets. This has enabled greater ease of access to produce interesting functional components [1, 2]. Here, we define AM as tools that fabricate in a layer-by-layer fashion, while DW is a selective deposition of materials with high resolution on any flat, conformal, or flexible surface. These printing methods are highly attractive because traditional fabrication required for radio frequency (RF) circuitry and electronics can be eliminated, while allowing for direct digital manufacturing of arbitrarily complex objects [3–6]. RF component design simulations reduced to fabrication can be an iterative process to refine, thus making printing methods ideal because they enable rapid prototyping and testing cycles. A large number of publications to date have demonstrated low-cost, low

performance-printed RF passive components fabricated by AM and/or DW processes that may impact the consumer market [7–10]. However, a considerable amount of research is still required to unlock the technological potential for printing, especially on high performance components including lumped elements (inductors and capacitors), antennas, transmission lines, and interconnects, which are based on all dielectric or metal-dielectric building blocks, especially for conformal and flexible surfaces. Reliable and high performing printed RF passives are within reach; however, printed counterparts for active RF electronic circuits including inorganic transistors are still very much in their infancy [11]. Active components such as transistors are still very much limited by the available material performance and printing resolution [12]. Passive components can now be partially or fully fabricated with a number of different AM techniques (FDM, SLA, DLP, inkjet, and aerosol jet) and manufacturable at scale with roll-to-roll, Gravure, and screen printing. With the recent advent of multimaterial

FIGURE 1: Methodology to obtain desired high performing RF components. Beginning with the initial RF component design, tailor the ink and resin chemistry around the required performance. Next, determine printing method(s) that would ideally have in-line metrology for surface profiles. The postprint processing is the key and needs to be compatible with materials chosen and end properties desired. Testing or characterization validates the initial design. Adapted with permission from [9, 14–20].

DW tooling, both metals and dielectrics may be printed concomitantly while previously these processes were decoupled to AM dielectric and then subsequently metallized with a separate technique. Advancements in printing technologies and processes will enable an entirely new class of fully 3D printed components on conformal surfaces that are not constrained to 2- or 2.5-D.

For many researchers, the overarching goal is to create printed, highly functional components with DC and RF properties near their bulk or non-AM counterparts while adding a degree of functionality that cannot be obtained with their planar counterparts. Achieving these bulk-like material properties will enable a wide application space, but at present, unfortunately there are several limits on which precursor materials are available to print and how well these functionally printed materials perform. Reliability is also a concern as these printed parts could potentially see extreme environments such as aerospace [13]. To this end, it becomes increasingly critical to understand the systemic effects of and controlling both the nano- and microstructures and topology of printed materials while expanding the “toolbox” of materials to print. Additionally, as conformal printing is near realization, flexible antennas and electronics require nanomaterials with high mobilities and on/off ratios such as carbon nanotubes (CNTs) and 2D materials. While the problem statement is simply defined, the execution is complex and rigorous. If successful, a new arena in high performing antenna materials and processes with disruptively fast turnaround times will be unlocked impacting the aerospace, medical, and communications industries.

Figure 1 depicts an approach to understand the initial component designs and simulated performance design trades (such as S-parameters) and then work towards achieving this by tailoring material properties. This could include nanoinks with nanoparticle size tuned to have compatible sintering

temperatures with the substrate. If near-bulk metal conductivity is required, the choice of solvents, ligand chemistry, and surfactants to prevent agglomeration needs to be chosen accordingly. Dielectric properties such as ϵ and $\tan\delta$ affect loss. If the design requires, utilize one or more printing methods with in line metrology to understand surface profiles and roughness, then perform postprocess sintering, curing, and characterization of the final component. Until techniques, materials, and design parameters are well enough established, this top down approach, while not as efficient, is an effective process to obtain high performance.

In this review, we will discuss the main challenges to the realization of high performance-printed RF antennas and components, the materials currently used for printing in highly functional RF components, including ink and polymer formulation, and overview of AM methods for printing with high precision. Also, we will offer perspective on the opportunities available to make major impacts to high-quality RF components that will offer similar performance to their simulated counterparts. In order to understand the contribution of losses and mitigate them, we will analyze structure-property relationships that will enable a path to optimal print and postprocessing properties. Since the opportunities outlined for improvement are universal to all printed parts, the authors note that there are likely other applications that will take advantage of these techniques outside of the RF community. Finally, we will review key demonstrations of conformally printed antennas and their performance factors and provide outlook on promising new paths in the arena of printed RF components.

2. Challenges Ahead

Currently, printing functional antennas, RF passives, and actives do not compete with more traditional manufacturing

approaches. AM and DW methods do enable innovative designs that cannot be obtained with traditional manufacturing, but several parameter spaces still need to be addressed in order for the components to match simulated performance. One of the main challenges for RF passives and an area ripe for material chemists is the development of new materials compatible with existing print processes that are tailored for their electromagnetic properties. Specific parameters include the electric permittivity (ϵ), metal conductivity (σ), and loss tangent ($\tan\delta$), each as a function of frequency. As miniaturization of circuitry and antennas becomes a driver, the permeability (μ) becomes the relevant variable to consider. These new materials could be printable inks and resin systems that are designed to be on the extreme ends of the spectrum for ϵ and μ , while making σ as high and $\tan\delta$ as low as possible. Dielectric polymers that intrinsically have $\tan\delta$ less than 0.06 and either very low (<2.5) or very high (>10) ϵ are very challenging to print as they are either short-chain or ceramic-filled polymers, respectively. The rheology of these materials is incompatible with current AM tooling. Conversely, for conductors, near-bulk metal σ has not been readily achieved. For RF, bulk σ is extremely important because of skin-depth effects, which unlike DC components cannot be compensated for by simply printing thicker with lower σ metals. With tailored silver (Ag) chemistries, researchers have been able to obtain near-bulk σ of Ag with DW methods [21, 22]. Since Ag is relatively inexpensive and the chemistry is very well understood, Ag-based inks have become ubiquitous in DW processes. Those well versed in print-compatible materials know that both Ag and copper (Cu) tend to degrade in σ over time as they are reactive even under modest ambient conditions being susceptible to sulfurization and oxidation, respectively. More robust inks such as gold have been developed; however, they are costly. The commercially available ones typically have short shelf lives and require handling under inert atmospheres. Since the palette of print-compatible materials has not been well developed for RF, this often leads researchers to develop their own inks and resins.

Due to coefficient of thermal expansion (CTE) and surface energy mismatches, printing metals onto printed dielectric substrates is challenging. In order to achieve high σ , a sintering step is necessary, which typically requires temperatures above that of the dielectric glass transition temperature (T_g) of the dielectric substrate. Surface-sensitive sintering techniques based on photonics have recently become popular in order to circumvent this challenge [23]. Since this type of sintering evolves under nonequilibrium conditions across multiple scales there are not well known, process-structure-property relationships must be developed. Additionally, the adhesion of DW materials on AM surfaces postsintering is also not well understood and warrants further research [24]. As buried metal on dielectric applications, such as through lines and 3D vias in multilayer/multimaterial printing, becomes more relevant, then nonthermal curing methods will also need to be further developed such as electrical sintering to obtain near-bulk σ [25].

Surface roughnesses of both the printed metal and dielectrics are currently much higher than is desired when

compared to bulk manufacturing processes. Lithography and wafer-based antenna components can reach low nanometer (nm) resolution in root-mean squared (RMS) surface roughness values, while machined parts and circuit boards can be in the hundreds of nm RMS resolution. Stereolithography (SLA) and fused deposition modeling (FDM) processes are in the few micrometers (μm) and tens of μm RMS surface roughness regimes, while inkjet and aerosol jet metal line profiles are quite variable. While this may not be an issue for low frequency (i.e., MHz) applications, the roughness can seriously degrade S-parameter loss at GHz frequencies. To mitigate the roughness limitations, a postprocess polishing step is currently necessary, which unequivocally reduces the utility of printing; however, if the desired structure is nonplanar, then polishing may even be precluded. New surface planarization techniques or software-based topology optimizations need to be developed to achieve RMS surface roughness comparable to at least machined surfaces on both printed metals and dielectrics. The development of roughness models also will play a dominant role in the optimization of antenna performance as both the dielectric and metal surface profiles are nonuniform [26].

As frequency increases, the size of the components drastically decreases, which limits the AM techniques that can be employed due to their resolution. While high-resolution techniques such as two-photon lithography and electrohydrodynamic printing are available with nm resolution, there becomes a trade space between resolution, total area, and throughput. These processes may be amenable to high-frequency antennas (EHF), but they do not scale well to low-frequency antennas that require much larger size features. Additionally, as antenna systems become more functional and complex, it will become necessary to traverse the different size regimes (nm to cm) seamlessly, which would require either incorporating more robotics to go in between printing tools with different resolution or further integration of multimaterial printing beyond what is currently available [27–29]. Ideally, in situ or in-line monitoring of critical process parameters that have been outlined above can be implemented into the print process steps similar to practices employed in the more mature semiconductor industry. To date, little research in this area has been demonstrated [30].

3. Methods and Materials for Printing RF Components

In this section, we will discuss the common methods for DW and AM techniques and review the materials that have been developed for printing RF components. For each method, there are specific requirements for the inks and resin systems to be compatible with the tool parameters. As new inks and resins are designed for the electromagnetic properties, these constraints will need to be well understood in order to optimize RF performance. Additionally, we focus on the methods for realization of high performance including scalability. While there are many emerging technologies for both DW and AM, we focus on those most well understood that will enable true micro- and macromanufacturing of complex RF assemblies. Laser sintering and electron beam

melt approaches will not be covered in this review; while they have recently gained interest in microwave horns, research to date has almost entirely focused on structural-mechanical properties.

3.1. Methods for Direct Write. Compared to traditional photolithography methods, DW approaches are faster, lower cost, and more environmentally friendly because they rely on additive rather than subtractive processes. AM of metallic lines encompasses a broad range of technologies, including Gravure printing and screen printing, but these techniques tend to be low quality and low-precision processes. The most common routes to printing high-precision metals to date are inkjet printing (IJP), aerosol jet printing (AJP), and direct ink writing (DIW). These methods use a computer-aided design (CAD) file input to dispense inks containing colloidal suspensions of metal nanoparticles (NPs) or other materials of interest (such as 2D materials and dielectrics) and may be used to print patterns of varying thicknesses by increasing the number of overprints. However, there are significant differences in print resolution, design flexibility, and process scalability arising from the respective mechanisms of deposition, so each method has advantages depending on the desired application. In this section, we will discuss the mechanism of printing, the effect on the morphology and properties, and finally, we will present a comparison of the three methods.

3.1.1. Inkjet Printing (IJP). IJP has been the most ubiquitous DW process used to date, which utilizes a low viscosity ink expelled through a nozzle in a dropwise fashion. A pattern is created by overlapping the droplets so that a continuous line is formed. The characteristics of the print may be altered by changing the overlap percentage or the print direction [31]. The spacing must be less than 65% overlap [32] in order to prevent bulging of the printed line, and the ultimate resolution is a function of the droplet diameter as well as the spreading upon contact with the substrate surface [19, 31, 33]. Currently, the smallest achievable feature sizes of 25–50 μm are comparable to or even better than processes such as screen printing and photolithography [33]. Still, AJP or electrohydrodynamic (EHD) printing may be necessary for further miniaturization.

A significant challenge is the lack of uniformity in printed lines. A “coffee-ring” height distribution has been well documented, in which the height of the line is depressed in the center as compared to the outside edges. The printed drop is thinner at the outside, resulting in an increased rate of evaporation at the edges. This creates an outward current, which can be minimized by the addition of solvents with a higher boiling point and a lower surface tension than the primary ink solvent. This will induce the Marangoni effect [34], in which a surface tension gradient produces an inward current to balance the natural outward current. The simultaneous currents circulate the ink as it dries, thereby creating a more even height. Dimethylformamide (DMF) when mixed with water as a solvent for Ag NPs has been shown to be effective in reducing the coffee-ring phenomenon [35]. Furthermore, printing lines counter to the nozzle direction have

been shown to reduce the coffee-ring effect and create a more uniform lateral profile [31].

3.1.2. Aerosol Jet Printing. Similar to IJP, AJP is also a DW method, but the print head continuously sprays ink that has been either pneumatically or ultrasonically aerosolized into 2–5 μm droplets [36]. A sheath gas flowing along the outside of the atomized ink droplets focuses the beam and prevents nozzle clogging. As a result, inks with much higher viscosities than IJP, which is limited to less than 30 cP, may be used. The desired pattern is produced by closing an electromagnetic shutter to halt the flow of the ink mist until the nozzle is in the correct position. Due to the small size of the aerosol droplets, the printed path begins to dry during deposition [37] which can affect the smoothness of the final print.

Like IJP, AJP also shows the coffee-ring effect [31], indicating that similar evaporation processes take place for both printing methods. However, no work has shown successful mitigation of this effect to date for AJP. Despite the difference in nozzle sizes between IJP and AJP, both methods achieve decreased feature sizes with a decrease in nozzle diameter [31, 36]. AJP demonstrates a splatter effect [31] rather than cleanly defined droplets due to the mist of particles, and this can be detrimental to achieving finer patterns and tighter print spacing.

3.1.3. Direct Ink Writing. DIW operates by using a combination of precision pump and variable size syringes to extrude highly viscous inks. Due to the shear-thinning rheological properties of the ink, it flows while in the nozzle tube but becomes solidified once deposited. This acts as an “instant-cure” process and allows for rapid 3D architecturing [38].

Some of the highest printed conductivities to date have been demonstrated with DIW by Lewis and Walker, who report Ag electrodes with conductivity of $6.25 \times 10^7 \text{ S/m}$, which is as close to bulk Ag conductivity ($6.25 \times 10^7 \text{ S/m}$) as anyone has demonstrated [21]. However, this may be a result of the ink properties rather than the printing mechanism. Adding 2,3-butanediol dilutes the viscosity so that this ink may be used with IJP [21]; however, there have been no widely circulated reports regarding the conductivities using this ink and printing method.

Uniquely, this method is also very versatile as sol-gels, ceramics, waxes, and even silk have been printed. Since DIW affixes to a multiaxis stage, omnidirectional printing is achieved to enable true conformal printing on any surface. Additionally, since the print heads are analogous to IJP printers, multiple heads can be utilized at once at very high printing rates. While this technique is relatively new, it has emerged as a versatile method that will likely play a critical role in high performance antennas and components.

3.1.4. Comparison of Direct Write Methods. While there are a multitude of publications about IJP, however AJP and DIW are relatively newer technologies. Table 1 gives an overview of the different DW printing including their key benefits. A schematic representation of the three DW methods highlighted in this review is shown in Figure 2. AJP is more versatile than IJP for the following reasons. First, AJP

TABLE 1: Comparison of direct write printing techniques.

Print method	Ink viscosity (cP)	Nozzle diameter (μm)	Feature size (μm)	Min. line thickness (μm)	Key benefits
IJP	1–30 [34]	20–60 [31, 39]	20–100 [34]	0.6 [31]	Low cost, multiple heads
AJP	1–1000 [36]	150–300 [40]	10–200 [40]	0.1 [40]	High throughput, thin layers, fine features
DIW	1–1000000 [21, 41]	0.1–1 [21, 42]	1–1000 [42]	0.5 [41]	Most precise, best resolution

FIGURE 2: Schematic representation of direct write (DW) printing methods. (a) Inkjet printing (IJP); (b) aerosol jet printing (AJP). Reproduced with permission from [37]. (c) Direct ink writing (DIW).

produces much finer resolution. Mahajan et al. defined the “focusing ratio” as the flow rate ratio of sheath gas flow rate to carrier gas flow rate [43]; they found that the printed line width decreases as the focusing ratio increases, while the standard deviation from run to run decreases, thus enabling a highly repeatable reduction in feature size. However, DIW with its submicron nozzle diameter enables even finer printing than AJP. Second, because of the vector-based printing approach as opposed to the line-by-line pixel rastering of IJP, a higher level of manufacturing flexibility is afforded to AJP systems. For example, a square may be printed using either a serpentine or a perimeter-fill pattern [31]. The drying rate of the ink affects the smoothness of the final printed structure. Third, the large distance between the nozzle and the substrate allows for printing on nonplanar, conformal substrates. This is especially useful for applications such as 3D RF antennas. Fourth, AJP may be able to produce higher conductivity structures than IJP. Because of the large range of acceptable viscosities, the ink can contain a higher weight percentage of metal, thereby increasing the probability of contact between the metal NPs. Finally, AJP can print much thinner single passes than IJP, therefore leading to increased design flexibility for device manufacturing.

The notable disadvantage of AJP is the resultant morphology of the printed line. Werner et al. found that higher sintering temperatures were needed to achieve the same resistivity within AJP structures versus IJP structures [37]. This is because the contact area with the substrate is increased for IJP, leading to more thermal dissipation and thus more progressed sintering. Also, the AJP structures are more porous, thus leading to a decreased effective cross-

section [37]. However, some interesting methods to combat this increase in resistivity have been proposed, such as the inclusion of carbon nanotubes [44] to enhance conductivity. Electrical sintering, rather than furnace sintering, has also been shown to produce conductivities as high as half that of bulk silver with AJP [37].

The advantage of DIW in comparison to IJP and AJP is that it can produce much finer resolution prints. However, it is a less mature technology and the intricate process parameters are not as well researched.

3.2. Methods for Additive Manufacturing. Three-dimensional printing of dielectrics is also of interest. Stereolithography (SLA), fused deposition modeling (FDM), and digital light processing (DLP) produce polymers with properties favorable for flexible electronics and RF devices. These methods are all layer-by-layer manufacturing processes which utilize a curing process to turn resins into solid structures via treatment with heat or light. A schematic representation of the three AM methods highlighted in this review is shown in Figure 3.

3.2.1. Fused Deposition Modeling. FDM is the most mature technology in AM of dielectric materials. In this technique, filaments are heated and extruded from the print head and deposited onto the print bed in a shape defined by the CAD file in a continuous flow. As the print progresses, newly extruded polymer fuses with the already printed layer to form the solid structure. Reducing the layer thickness increases the smoothness of the final structure, but it also increases the amount of time needed to form the sample. Since this is a bottom-up approach, structures with overhanging segments

FIGURE 3: Schematic representation of additive manufacturing (AM) printing methods. (a) Stereolithography (SLA), (b) digital light processing (DLP), and (c) fused deposition modeling (FDM).

may require the addition of a support piece, which can either be mechanically broken off, or it can be made with a different resin that dissolves in a chosen solvent [45]. Thus, a significant disadvantage is that FDM-manufactured structures may require some level of postprocessing depending on their complexity, which may include organic acid etching to reduce surface roughness. Also, since there can be voiding between the printed layers, additional postprocessing or annealing to minimize these features is necessary.

For RF applications, low loss within the substrate is desired. Deffenbaugh et al. found that FDM structures exhibit lower loss $\tan\delta$ than SLA [46]. Furthermore, embedding cyclo-olefin polymer (COP) resin with TiO_2 demonstrates low loss $\tan\delta$ of 0.0014 up to frequencies of 17 GHz [18]. However, FDM structures also have lower print resolution ($>200\ \mu\text{m}$) and a rougher surface finish than SLA structures.

3.2.2. Vat Photopolymerization

(1) *Stereolithography*. SLA printing works by exposing a photosensitive liquid polymer resin to a light source, typically a hundred of mW UV laser, since the high-power output is desirable, to solidify the resin. The light source rasters across the surface of the sample in point-by-point or line-by-line fashion and introduces enough energy into the resin to induce photopolymerization resulting in the cross-linking of resin polymer chains to form a cohesive solid structure. Some SLA printers employ a top-down approach, in which the build plate is above the vat of resin and increases in height after each layer is cured [45], while others employ a bottom-up approach in which the build plate is in the resin and moves down after each layer is cured to expose the next layer of resin. The structure is generated from a 3D mesh of triangular elements [47]; the tolerances are specific to the printer used, but the layers are generally 0.05–0.15 mm thick in the z-direction, with accuracies of 0.01–0.02 mm in the xy-plane [48]. Because of the layer-by-layer addition and specific laser raster pattern, smooth surfaces with highly detailed features may be obtained.

SLA-printed substrates demonstrate promising capability to be used for RF and microwave circuits. Some prints show material properties comparable to FR-4 circuit boards [46], with the advantage of being flexible or of arbitrary shape

(FR-4 is planar); however, FR-4 is not the industry standard due to high loss. In applications where a high dielectric constant is desired, such as for waveguides and increasingly miniaturized devices, SLA-printed materials may be better suited than FDM materials [46].

(2) *Digital Light Processing*. DLP is similar to SLA as it uses a projection light source to solidify a liquid resin layer by layer. However, rather than rastering a laser, DLP flashes a digital image of each layer onto the exposed resin; thus, each layer is created at once rather than in a point or line process profile. The build plate then moves down, and the next layer is cured. DLP is a relatively new technology compared to SLA and FDM, but the all-at-once approach means that print time is drastically reduced [49]. Total print resolution depends on the pixel size, which is affected by the projector. Since the projector is limited by a maximum number of pixels, prints approaching the size of a pixel will be increasingly lower resolution. Thus, there is a trade-off between size of print and resolution obtained. This approach also creates striations known as voxel lines along the z-axis of the print and therefore may necessitate some level of postprocessing to obtain a smoother print. To date, there have been few studies on the RF characteristics of DLP-printed dielectrics, although they are anticipated to be comparable to SLA.

Controlled oxygen inhibition enables simpler and faster DLP printing [4]. Printers equipped with an oxygen-permeable membrane below the print window obtain an “oxygen dead zone,” a thin layer of uncured liquid resin between the print window that supplies the digital image and the already-solidified resin. Polymerization begins at the point where oxygen no longer exists but free radicals (produced by photons from the DLP projector) are present. Suction forces result in the continuous renewal of resin as the part is pulled upwards from the vat so the process is continuous rather than stepwise like in SLA and standard DLP processes. Thus, the viscosity and cure rate of the resin are the process-limiting factors, allowing for vastly reduced printing times.

3.2.3. *Emerging Methods*. The ultrasonic wire mesh embedding printing method developed by UTEP researchers combines FDM and ultrasonic thermal embedding to employ

wires and wire meshes into the printed thermoplastic surfaces, which enables nonplanar printed circuit boards and antennas [28, 50]. This method also circumvents sintering; however, it would likely still require some form of printed interconnect. While vat photopolymerization, FDM, and IJP are the most widely used and understood processes to date, we do want to highlight emerging additive manufacturing methods that may play a role in the future for realization of difficult to fabricate RF components. As printed components become increasingly smaller, some higher-resolution techniques such as 2-photon polymerization (2PP) have emerged. 2PP has been popularized by the mechanical engineering community by demonstrating extremely high-yield strength to density ratio, but the authors envision that this technique could meet the high-resolution needs for RF systems [51, 52]. Electrohydrodynamic printing is the high-resolution printing analog to IJP. With this method, researchers have achieved nm-scale resolution and achieve this by changes in voltage potentials between the printer nozzle and the surface to be printed on [53, 54]. While these methods have shown that they can impact future RF systems, there has not been widespread adoption of these techniques to date making a path towards realization of high performance RF components difficult. However, we envision a path towards hybrid additive manufacturing approaches in the future.

3.3. Ink and Resin Formulation. Inks containing conductive materials must be printed in order to fabricate a conductive path within the RF circuit. Resins are the dielectric that acts as the structural and capacitive medium for RF components. Nanoinks based on van der Waals (vdW), materials and CNTs have been successfully printed, showing promise for the field of conformal and, more specifically, flexible RF electronics based on their propensity to perform under flexing.

3.3.1. Direct Write Metallic Nanoparticle Inks. Metal-containing inks are of great importance as the conductive path in DC circuits and RF devices. The high surface to volume ratio of NPs reduces the necessary thermal cure temperature by up to 90% relative to their bulk counterpart [55]. This is important for use with flexible substrates that are sensitive to high temperatures and also for overall process efficiency. Most metal NPs are fabricated using a bottom-up approach [42], in which crystallization is induced via the addition of a surfactant. The distribution of size and shape results in inks with varying properties, so growth must be carefully controlled. The smaller the NP diameter, the lower the required annealing temperature [56]; therefore, for flexible electronics and other substrates that are incompatible with long heat treatments, achieving smaller NP inks is important. For use with AJP, the NPs must be less than $1\ \mu\text{m}$ or $0.1\ \mu\text{m}$ for pneumatic and ultrasonic atomizers, respectively. To develop an ink for DW, the metal NPs are dispersed within a solution of cosolvents with different vapor pressures. The high vapor pressure solvent ensures that the viscosity of the ink is lowered enough to achieve high rates of atomization. It evaporates out of the ink upon deposition, increasing the effective weight percentage of metal in the printed ink. The low vapor

FIGURE 4: Common high and low vapor pressure solvents for AJP.

pressure solvent ensures that the ink retains its droplet shape, thereby minimizing the amount of overspray. The vapor pressures of some commonly used solvents are shown in Figure 4. Spherical or flake-like NPs have the highest chance of successful printing, since long or rod-like NPs may be damaged by the atomizer or nozzle. An adhesion promoter may need to be added to the ink in order to achieve good adhesion on all types of substrates. This also helps to mitigate the coffee-ring effect.

For IJP, controlling viscosity between 1 and 30 cP will generally prevent nozzle clogging. The viscosity window to obtain good resolution and line profile is typically much narrower at 8–13 cP. NP loading in the IJP-based ink is one example how viscosity may be tuned. For DIW, rheology and high particle loading are most important to control. The viscoelastic properties of the ink can be tailored to allow continuous flow through the nozzle and then “fixing” or setting upon deposition, while the high loading maintains the line shape and profile upon drying.

3.3.2. 2D Material Inks. In addition to metal NPs, 2D vdW materials such as graphene and transition metal dichalcogenides have successfully been implemented as inks [19, 42]. These rely upon a top-down fabrication approach, in which exfoliation of the bulk crystal via ball milling, ultrasonication, or liquid-phase exfoliation is necessary to break the interlayer van der Waals forces [42] and form 2D sheets. Surfactants are added to the ink to stabilize these sheets, as they will preferentially bond or create linkers on the surfaces, thus preventing aggregation. Like metal inks however, it is difficult to control the size and thickness of the sheets during exfoliation [19]. While the performance in RF is orders of magnitude worse than traditional III–V RF electronics, these vdW flextronics are a very promising printable alternative to surpass organic thin film flexible transistors because of their excellent electrical and mechanical properties such as strain to failure ratios [57–59]. These vdW inks will not enable realization of extremely high performance RF actives in the near future;

TABLE 2: Comparison of RF parameters for printed dielectrics [46].

Material	Print method	Characterization frequency range	$\tan\delta$	ϵ
COP w/ 30% TiO ₂ [18]	FDM (then 1100°C)	17 GHz	0.0014	4.56
PC-ABS	FDM	1 MHz–1 GHz	0.0076–0.0055	2.74–2.77
Polycarbonate	FDM	1 MHz–11 GHz	0.0076–0.0066	2.74–2.59
ABS-M30	FDM	1 MHz–11 GHz	0.0069–0.0098	2.63–2.60
Ultem 9085™ [18]	FDM	N/A	0.0040	3.00
DMX-SL 100	SLA	8.2 GHz–11 GHz	0.0115–0.0130	2.97–3.09
Prototherm 12120, thermal-cured	SLA	1 MHz–11 GHz	0.0171–0.0170	3.45–2.71
NanoForm	SLA	1 MHz–11 GHz	0.0131–0.0286	3.75–2.88
Prototherm 12120, UV-cured	SLA	1 MHz–11 GHz	0.0148–0.0368	3.68–2.93

however, they fill a niche to enable completely foldable and deployable RF active circuits that are currently only comparable to CNT-based inks, but with a broader range of properties. These vdW inks can also be utilized to create heterostructures with quite a few materials available including dielectrics, conductors, and semiconductors as more layered materials are being discovered at a near exponential rate [60, 61].

3.3.3. Additive Manufacturing Resin Formulation for Printed Dielectrics. Since FDM relies on polymer extrusion while SLA and DLP rely on resin solidification, the formation of the precursors affords different material properties. For RF applications, a low $\tan\delta$ is ideal, as well as either very high or very low ϵ . Both these properties are correlated to molecular structure by polarity or dipole moments. Since ϵ is the tendency of the material to polarize in an applied electric field, and loss tangent is minimized by how fast the polymer relaxes back to equilibrium after the electric field is turned off, then the more symmetric and smaller chain length a polymer is, that is, cyclic polyolefin, the lower its ϵ and $\tan\delta$. High ϵ may be obtained by choosing the polymer matrix base and adjusting the amount of additive agents to be within the desired ϵ range.

These mixtures or composite resins represent a large and promising class of materials, as the mechanical characteristics of the resin may be chosen to fit the specifications of the printer by altering the polymer matrix base [62]. The effective permittivity of a composite is dependent on the permittivity of the interfaces within the mixture as well as on the DC conductivity of the composite, expressed in

$$k_{\text{eff}}^* = k^*(\omega) + \sum_i k_{\text{MW},i}^*(\omega) + j \left(\frac{\sigma_{\text{DC}}}{\omega k_0} \right), \quad (1)$$

where $k^*(\omega)$ is the permittivity of all composite components, $k_{\text{MW}}^*(\omega)$ is the permittivity of the composite interfaces, σ_{DC} is the DC current, and k_0 is the permittivity of free space. Ceramic fillers afford naturally high ϵ and low $\tan\delta$, but they may alter the mechanical or electrical properties of the printed part, which needs to be considered in advance. At high ceramic loading concentrations, a postprint high temperature firing step may need to occur causing densification or shrinkage of the printed component. A summary of key

printed dielectric materials properties for RF can be found in Table 2.

Environmental stability is also required for a high performance printed dielectric. Materials such as polylactic acid (PLA) are commonplace in printing and satisfy many of the parameters previously listed. However, PLA absorbs moisture readily at ambient conditions causing unwanted warpage, thus rendering it an impractical material for high performance RF components.

4. Structure-Property Relationships

In this section, we will review the postprint sintering and curing approaches for DW and AM methods, respectively. We will also discuss the methods used to characterize DC and RF properties that are critical to obtaining high performance printed RF materials. The material properties such as ϵ , metal σ , $\tan\delta$, and μ will also be covered. It should be noted that bulk conductor conductivity acquires a major importance as the operation frequency is increased. Indeed, due to the skin-depth effect, the electromagnetic field can only penetrate inside the conductor by a thickness on the order of a few skin depths, expressed in

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}, \quad (2)$$

where δ is the skin depth, ρ the bulk resistivity of the conductor, μ is the permeability of the conductor, and f is the operating frequency. As a consequence, the effective thickness of a printed conductor cannot exceed the skin depth ($2\mu\text{m}$ in bulk silver at 10 GHz). Therefore, a low bulk conductivity cannot be compensated by printing thicker, as it could for DC.

RF microstrip and stripline test structure fabricated with DW and AM methods can be used to determine the RF properties of printed metal lines and dielectric substrate materials [63]. S-parameter measurements obtained from the RF test structures over the desired frequency range combined with modeling can be used to extract ϵ , σ , $\tan\delta$, and μ [64]. Correlating the electrical parameters from both DC and RF measurements with microstructural characteristics of the printed thin film materials is essential to provide a more complete and in depth understanding of key parameters

optimization in the thin film printing and sintering process for more optimal DC and RF performance as a path forward to obtain high performance RF components.

4.1. Postprint Sintering of Metal NP Inks. Sintering processes play a key role in microstructure formation of printed metal thin film lines. Correlations in electrical, mechanical, and thermal properties of the printed thin film lines relate directly to microstructure. In the following sections, we will discuss the sintering of NP printed inks; however, similar mechanisms and characterization methods are applicable to the study of non-NP reactive inks. These reactive inks either require mixing within deposition or a two-step printing process of depositing metal precursors followed by reducing reactants to create the thin film metal line [65].

In order to create a conductive path, metal NPs must be in contact with each other in the printed metal line. Since nanoinks require a liquid carrier such as organic or aqueous solvents with surfactants to prevent agglomeration, these must be removed to have optimal contact of the metal NPs. Furthermore, NPs may be understood as many distinct grains, of varying sizes. Growth of large grains by the consumption and coalescence of smaller ones will occur during the sintering process as predicted by the Gibbs-Thompson effect [66]. Optimizing the thermal coalescence process to completion during sintering to overcome the activation barrier to diffusion without introducing large thermal gradients within the growing film plays a critical role in forming fully dense and conductive metal film microstructures [67, 68]. The phenomenon of necking, in which NPs come into contact with each other, is also important to facilitate a more conductive path. Necking has been observed to initiate at various sintering temperatures and scales nonlinearly with particle size. This has been more thoroughly discussed in the Ag system by Seifert et al. at 200°C and above for >30-minute intervals [31]. Numerous publications [31, 55, 69–71] have shown that increased annealing temperature or time leads to increased densification of the metal film, which is consistent with well-known ripening phenomena in crystal grain growth.

High performing electrical conductivity values have been achieved by printed Ag films at 50–70% of bulk Ag [72]. Zhao et al. have seen conductivity 57% of bulk Ag by including 0.15 weight percent carbon nanotubes [44]. These highly conductive structures are reported to act as bridges across defects and grain boundaries. Similarly, Li et al. have recorded thermal conductivity 65% of bulk Ag by utilizing ink with a 2:1 ratio of 10 nm Ag NPs to 50 nm Ag NPs to decrease the porosity [73]. Separately, for Au, half of the bulk conductivity has been demonstrated on carefully tailored ligand chemistry and particle sizes at 150°C; however, this was in a thin film ink and not printed [22]. There have been a number of mechanistic explanations proposed for the decrease in DC resistivity observed during sintering. First, increasing sintering time leads to grain agglomeration via Ostwald ripening, thereby decreasing the amount of grain boundaries in the structure. Furthermore, the dislocation density decreases with annealing [74]. Finally, decreases in porosity have been observed with increased sintering time,

which increases the effective cross-sectional area. All of these phenomena decrease the hindrance to the conductive path of electrons, thereby increasing conductivity.

There are many different methods to achieve the sintering of metals after they have been printed with DW techniques. The sintering method will highly depend upon the glass transition temperature (T_g) of the dielectrics or substrate present, the temperature required for sintering the metal (dependent upon particle size), and the form factor of the component. Environmentally controlled oven treatments are commonly utilized for sintering NP-based inks to rid the metal of solvents, binders, and surfactants if they exist in the native ink. The smaller the particle size the lower the sintering temperature can be; however, care has to be taken to design the ink sintering not to exceed temperatures of the other materials printed to. Photonic sintering is an approach that can circumvent this issue by flooding quick flashes of light at high powers so there is only surface effect [75]. Under the right conditions, the energy is absorbed by the surface and quickly dissipates as a function of depth so the materials below the surface are selectively cooler. This enables printed high σ metals with sintering temperatures > 150°C to be sintered on substrates with $T_g < 100^\circ\text{C}$. The mechanism of this local heating effect is due to the surface plasmon resonances within the range of the light source, with the main variables to consider being the layer thickness and specific heat capacity. This method also allows for rapid sintering and in-process sintering at potentially large areal domains since the timescales are on the order of ms or less. The drawback to photonic sintering approaches is that because they are surface mediated, it may cause nonuniform sintering or even preclude applications with nonplanar surfaces. Another interesting sintering approach is electrical. Current (DC or AC) is applied to the printed metals, and local resistive heating can rapidly increase enough to sinter NP printed inks [76]. With this approach, there needs to be some initial treatment of the printed metal to go from insulator to resistor in order for current flow to cause heating. This method can be contact (DC) or contactless (AC) and can achieve reasonably high conductivity values; however, further work in this area is required. Both microwave and plasma sintering approaches are emerging but have only been demonstrated at small scales to date.

4.2. Postprint Curing of Dielectrics. Curing of printed dielectric materials may not be compatible with methods and annealing conditions used to sinter printed metal lines due to the lower glass transition temperatures of the printed dielectric materials. Therefore, multiple steps may be required to obtain optimal dielectric properties in conjunction with high conductivity metal lines for RF structures [77]. Polymeric dielectrics can be cured using several methods. UV irradiation is one of the most common methods. UV curable dielectrics consist of chemical mixtures of oligomers (long molecules), monomers (short molecules), photoinitiators, and other fillers. Upon exposure to UV light, the photoinitiators break apart reacting with the oligomers and monomers to form a thermoset that cannot be returned to a liquid state. Optimization of dielectric curing conditions

TABLE 3: Summary of prior work on metallic nanoparticle conductive inks.

Metal	Particle size (nm)	Solvent	Conc. (wt%)	Curing	Print method	Width (μm)	Thickness (nm)	ρ ($\Omega \text{ cm}$)	Ref
Ag	N/A	NH_4OH , formic acid	22	15 min at 90°C	DIW	5	—	1.6×10^{-8}	[21]
Ag/CNT	—	Alcohol-based	—	30 min at 350°C	AJP	13.5	700	2.8×10^{-6}	[44]
Ag	5–7	Alpha-terpineol	10	$100\text{--}300^\circ\text{C}$	IJP	80	100	3×10^{-6}	[80]
Ag	10–50	Water-DEG	25	$150\text{--}260^\circ\text{C}$	IJP	130	532	1.6×10^{-5}	[81]
Ag	1–10	Toluene	30–35	300°C	IJP	120	1000	3.5×10^{-5}	[82]
Au	2–4	Toluene	30	$300\text{--}400^\circ\text{C}$ (laser)	IJP	20	50	1.4×10^{-5}	[83]
Au	2–4	Toluene	30–35	200–500 mW (laser)	IJP	123	250	4.5×10^{-6}	[84]
Au	2–5	Toluene	30	200–1000 mW (laser)	IJP	17	20–200	1.4×10^{-5}	[85]
Au	5–20	Toluene	30	300°C	IJP	1000	600	1×10^{-5}	[86]

such as power, wavelength, temperature, and time is essential to minimize the occurrence of pinholes in the post cured dielectric materials. In addition to pinholes, contaminants must be eliminated as they will also affect the film quality and electrical/mechanical integrity.

Roughness of printed dielectric materials after curing can be the order of several micrometers, which is much greater than the typical printed metal lines thickness of a micron per layer. Printed dielectric substrates with roughness of several microns will attenuate the RF signal to degrade circuit performance. One approach to reduce roughness of printed dielectric substrates is to follow with printing a more conformal dielectric material, which spreads over the rough substrate surface before UV cure. After UV curing, the conformal dielectric material substrate surface roughness can be reduced to a few submicron RMS roughness [78].

4.3. Materials for DC and RF: Structure-Property Relationships. The baseline metal deposition focuses on electrical and structural properties. While the electrical resistivity is an important operational parameter, it is the microstructural features of the lines that determine the resistivity. The electrical resistivity of a metal line is determined by measuring the resistance [79]. The resistivity then can be calculated if the cross-sectional area of the line and length of the line is known. The resistivity is expressed in 3 for 3D and 4 for 2D below.

$$\rho = R * \frac{A}{l}, \quad (3)$$

$$\rho = R_{\text{sq}} * h, \quad (4)$$

where A is the cross-sectional area of the sample, l is the length of the structure, and h is the height of the stripline. For AJP- or IJP-deposited metal lines, the lines are highly resistive after deposition. The AJP deposit consists of nano-sized particles. After annealing, the NPs agglomerate into larger grains and become more conductive after postdeposition annealing. Table 3 summarizes measured resistivity values for Ag and Au NPs with varying particle sizes, solvents, concentrations, and curing conditions. Upon annealing, the deposited thin film resistivity values remain a factor

of $2\text{x--}10\text{x}$ greater than the bulk values, showing that a better understanding of the annealing process is necessary.

For metal lines, the cross-sectional area is determined by two key factors. First, the spray deposition process does not typically produce a circular or rectangular cross section. Instead, the cross section depends on deposition parameters [31]. Second, the deposited metal lines are not fully dense. The agglomeration of the metal NPs after deposition and annealing determines the final density. Focused ion beam (FIB) techniques can be used to determine that the actual cross section is the porosity of the deposited metal lines. Determining the cross-sectional area using FIB of the irregular shape provides a more accurate determination of the resistivity. However, this difference does not account for the 2x or greater difference is the deposited line resistivity and bulk resistivity.

A second important issue relates to the porosity and microstructure of the metal line. Figure 5 shows SEM images of Ag-printed lines after different annealing temperatures from 70 to 260°C [81]. Several features stand out in the SEM images in Figure 5(a). The dark regions represent pores, confirming that the layers are not fully dense after the 70°C -curing condition. The small, spherical particles are those originally deposited in the AJP process and are on the order of $10\text{--}50 \text{ nm}$. NP coalescence and grain formation occurs at the 150°C -annealing conditions (Figure 5(b)). Observations of grains on the order of $0.2\text{--}0.4 \mu\text{m}$ can be seen in Figures 5(c) and 5(d) at 200°C - and 260°C -annealing temperatures. These are the results of the fusion of many of the original $10\text{--}50 \text{ nm}$ particles. Cross sections of the microstructure taken at different curing conditions are the key to understanding the sintering process of the metal (and other NP-deposited materials). As seen in Figure 5, higher annealing temperatures after deposition would be expected to produce larger grains and consume the remainder of the small NPs into the larger grains.

Work by Werner et al. investigated microstructural changes in AJP Ag lines upon annealing temperatures of 150 and 250°C and times for $30\text{--}120$ minutes [37]. As seen in Figure 6, 150°C -annealing temperature did not lead to significant changes in the microstructure structure, even for extended annealing times up to 120 min (Figures 6(a)–6(c)). The 50 nm Ag NPs are still visible and are in contact, and

FIGURE 5: SEM images of IJP-printed Ag lines after different curing temperatures. Reproduced with permission [81].

FIGURE 6: SEM images of AJP printed Ag lines taken at different temperature and time sintering conditions. Reproduced with permission [37].

sintering neck formation between these particles is only partially observable after 60 and 120 min. However, as sintering temperature is increased to 250°C, they observe coalescence

of the particles for 30 min-annealing times (Figure 6(d)). With the coalescence occurring at 250°C, there is no observation of 50 nm Ag NPs. 250°C-annealing temperatures allow for NPs

TABLE 4: Thin film microstructure analysis.

Characterization methods	AFM	XRD	Optical profilometer	SEM & TEM	Nanoindentation
Figures of merit	Surface roughness, line shape	Lattice parameter, crystal structure, phase analysis, residual stress, preferred orientation	Line shape, line widths, line thickness	Grain size, grain orientation, crystal defects, voids	Hardness, fracture toughness

TABLE 5: Thin film electrical characterization.

Characterization methods	DC van der Pauw	RF through line
Figures of merit	Sheet resistance, conductivity	Impedance, RF loss tangent, dielectric constant, permeability

to neck and form grain boundaries (Figures 6(e) and 6(f)). Pores in the sintered Ag films can be observed with each of the annealing conditions. The authors noted that small spherical structures containing both Si and O are observed on the Ag surfaces sintered at 250°C. It was mentioned that the probable cause for the Si and O was from thermal decomposition of silanes in the ink.

Studies by Rahman et al. correlated microstructural-electrical properties of AJP Ag NP thin films at high temperatures [87]. They determined that optimization of sintering conditions could provide efficient means to control the temperature stability and oxidation resistance of the Ag NP thin films up to a temperature of 500°C.

4.4. Characterization Methods and Figures of Merit. Studies to date have leveraged a limited set of characterization methods to correlate printed thin film electrical performance with microstructure [72, 74, 87–89]. A more comprehensive set of characterization methods shown in Tables 4 and 5 must be employed to establish a better understanding of the kinetics and growth mechanisms during sintering to achieve thin film conductivities near-bulk values for AM-printed metal film lines.

Optical profilometry and atomic force microscopy (AFM) are essential characterization methods to provide valuable insights on the printed metal line shape, width, thickness, and dielectric substrate surface roughness as discussed in Sections 3.2 and 3.3 to further optimize printed electronic circuit RF performance. X-ray diffraction (XRD) can be leveraged for nondestructive quick turnaround analysis of the printed thin film metal lattice parameter, crystal structure, phase analysis, texturing, and evidence of residual stress in the thin film [90]. XRD analysis can be used to tune and guide annealing conditions in a design of experiments to better understand microstructure evolution during the various stages of thin film sintering as outlined in Section 4.1. SEM measurements combined with transmission electron microscopy (TEM) for higher-resolution analysis of the printed metal thin film enable more critical insights on the stages of NP ink necking, grain growth kinetics, and microstructure evolution during the sintering. SEM and TEM will also provide more insights on the metal defects, voiding, and overall assessment of printed metal film density as these parameters will be important in achieving near-bulk conductivity values. Nanoindentation provides an assessment of

printed film microhardness and fracture toughness properties as these parameters will be important to understand the overall mechanical integrity of the printed thin films for various RF circuit applications.

Table 5 summarizes electrical characterization methods and test structures for printed dielectric substrates and metal thin films. DC van der Pauw measurements can be used to study the printed metal sheet resistance and conductivity as samples are annealed at different conditions. Stripline and microstrip RF test structures can be used, preferably after obtain desired conductivities, to further analyze the impedance, loss tangents, permeability, and dielectric constant of the printed substrate and metal line structures.

Integrating the information obtained from microstructural analysis with electrical characterization of printed substrates and metal thin films provides a more complete study to further drive experiments and process optimization to fully realize the potential of printed electronic circuit performance at the desired frequencies.

5. Demonstrations of Printed RF Passive and Active Components

There have been a number of printed RF components produced to date using different techniques, as indicated in Figure 7; however, the most common AM method is FDM and the most common DW method is IJP. While active RF components such as transistors, tunnel diodes, integrated circuits, and thyristors are beginning to be demonstrated via printing methods, these printed actives are still in their infancy as far as realization for high performance RF demonstrations. Indeed, printed semiconducting films only display carrier mobilities of up to a mere $10 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ [97, 98] compared to the $8500 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ of a III–V semiconductor like GaAs. Conversely, RF passives may be printed with good performance compared to their subtractively manufactured counterparts; however, as previously described, control over the electromagnetic properties in the raw materials along with the feature size, resolution, and surface topology requires further innovations. In this section, we will review unique RF structures that have been demonstrated via printing and the different types of passive components that are enablers to the realization of printed RF systems.

FIGURE 7: Demonstrations of 3D printed RF components. (a) All-dielectric frequency selective surface under C-band testing. Reproduced with permission from [91]. (b) SEM image of postreliability tested printed gold wire interconnect. Reproduced with permission from [13]. (c) IJP-printed mm-wave Yagi-Uda antenna on flexible substrate. Reproduced with permission from [92]. (d) Multifunctional embedded electronics for a cubesat demonstration. Reproduced with permission from [93]. (e) IJP-printed phased array on a flexible substrate. Reproduced with permission from [94]. (f) Hybrid AM and DW demonstration of 3D-embedded structural electronics. Reproduced with permission from [95]. (g) A controllably folded inverted F antenna smart structure. Reproduced with permission from [96].

5.1. Printed Metamaterials and Frequency Selective Surfaces.

RF metamaterials are a relatively new arena in electromagnetics that are typically composed of subwavelength unit cells that get their unique properties by a careful design of dielectric or metal-dielectric building blocks which are not exhibited in their bulk counterparts (i.e., negative index of refraction). There have been recent demonstrations of complex printed metamaterials that have been enabled by advancements in printing techniques which would otherwise be impossible to fabricate with conventional techniques [99, 100]. Additionally, frequency selective surfaces are periodic structures with elements that can act as band stops or band passes. These structures can be complicated to design and often require multiple design/fabricate/test loops in order to tune to the desired frequency. The fabrication piece of this cycle has been demonstrated with a printed all-dielectric frequency selective surface, which shows the utility and expediency of these techniques [91].

5.2. Printed Transmission Lines and Interconnects. Reports in the recent literature have shown that transmission lines can be fabricated by printing with competitive performance to standard copper lithographic-based processes in impedance, ϵ , and $\tan\delta$ in the microwave regime, which enables flexibility in the design parameter space [64, 95, 101, 102]. Further improvements in these RF parameters will increase the

overall system efficiency, as indicated by the use of AJP, and the transmission lines showed an order of magnitude reduction in insertion losses when compared against IJP.

RF interconnects are abundant, in high density (analogous to the body's nervous system), and can become incredibly complex within RF systems as evidenced by the different types of vias that exist. Interconnect parasitic losses can quickly add up to degrade the overall system performance. Therefore, it is critical to have near-bulk metal conductivity, while maintaining reliable conductivity over temperature and environmental excursions [13, 93, 103, 104]. While there are many different techniques that have been investigated for interconnects in DW processes, the current best performers are AJP and wire mesh embedding. RF waveguides, such as a metal pipe rectangular waveguide, direct the electromagnetic waves in one direction to prevent inverse square law losses. Interestingly, these waveguides have been printed using FDM for use in the microwave regime, and SLA in the mm-wave regime and subsequently Cu plated [105]. By these methods, similar attenuation values and return losses were obtained when compared to traditional manufacturing approaches. Surface roughness scattering tends to dominate the losses, and a chemical polishing step is needed to reduce the roughness below 300 nm RMS. RF filters are necessary to select desired frequency bands and eliminate others similar to the aforementioned

frequency selective surfaces; however, these can also include low-pass or high-pass cutoffs. Using Polyjet printing, a few types of RF filters have been demonstrated with very high performance including return loss and unloaded quality factor [106, 107].

5.3. Printed Antennas. There have also been many different types of demonstrations of printed antennas in the recent literature. Liang et al. fabricated a microwave patch antenna with a $50\ \Omega$ microstrip line on a printed polyethylene substrate 2.4 mm thick ($\epsilon=2.4$) via FDM and ultrasonic wire mesh embedding with a 5.5 dB gain at 7.5 GHz [50]. MSU researchers demonstrated a rectangular patch antenna using a multijet printer loaded with Vero White ($\epsilon=2.4$, $\tan\delta=0.02$) with $-20\ \text{dB}$ S_{11} reflection coefficient at 5.5 GHz and a simulated 6.94 dB gain [108]. The first demonstration of a fully printed patch antenna at 2.4 GHz also using Vero White with a measured $\epsilon=3.13$ and a tailored resistivity as a function of Ag layers printed to compensate for losses was shown by Nate et al [109]. Ghazali et al. have demonstrated an ultrawide band (4–18 GHz) Vivaldi notch antennas with a measured 12 dB gain; however, this was fabricated with 3D printed ABS plastic and sputtered Cu metal [110]. Georgia Tech researchers were the first to demonstrate a printed log-periodic Koch-Dipole array antenna that has a much reduced areal footprint owing to its design [111]. An interesting dipole antenna was printed with a carbon nanotube (CNT) ink with a resonance at 2 GHz; however, a $10\ \Omega/\square$ sheet resistance was required to give a $-10\ \text{dB}$ S_{11} [112]. A Yagi-Uda antenna was aerosol jet printed using Ag ($5.13 \times 10^6\ \text{S/m}$) on a printed Vero White Plus ($\epsilon=2.8$, $\tan\delta=0.04$) by He and coworkers which shows a low profile at 24 GHz with a 26.4 dB return loss with a 3.3 dBi [113]. These authors also showed a 14.6 dB return loss at 25.8 GHz. The first demonstration of a Yagi-Uda antenna was done a year earlier using IJP Ag ($1.1 \times 10^7\ \text{S/m}$) and SU-8 dielectric ($\epsilon=3.2$, $\tan\delta=0.04$) on a liquid crystalline polymer laminate substrate that has a high 8 dBi gain at 24.5 GHz with a $>33\ \text{dB}$ S_{11} [92]. Several horn-type antennas have also been demonstrated with the best performance going to a hybrid printing and plating process [114, 115]. An SLA process based on epoxy was used to generate the structure, and then a Cu-plating step was added. While the return loss was not verified in [114], the authors reported $>25\ \text{dBi}$ peak directivity at 12 GHz. In [115], a 2×2 horn antenna array utilized the design freedom of SLA to minimize insertion losses to 34 dB along the main radiation axis, while demonstrating a 24 dBi directivity from 26 to 40 GHz.

When an area becomes a constraint, researchers have typically turned to printing fractal-based antennas [116, 117]. These fractals also tend to have growing popularity for wireless sensing and communications in commonly used commercial bands and have been demonstrated via AJP Ag with a conductivity of $1.1 \times 10^7\ \text{S/m}$. Inverted F antennas that have been aerosol jet printed using Ag have also recently demonstrated by several groups [96, 118]. Deng et al. have shown that by tailoring the Ag ink trace resistivity and using electrical bias as external stimuli that self-folding inverted F antennas can be generating, which

can be discretely delivered and subsequently deployed based on the usage requirements; however, no antenna measurements were taken. Harle et al. demonstrated return losses of 17.8 and 20.4 dB and gain of 2 dBi and 0 dBi at 36.5 and 74.5 GHz, respectively.

Printed, flexible, and conformal-phased array antennas have also emerged, which are becoming increasingly popular for radar communications [94, 119, 120]. These antennas utilize printed CNT thin film transistors and multilayer interconnects to generate a fully packaged system that allows nonmechanical beam steering with an 8.2 dB insertion loss and 11.2 mW power consumption operating at 5 GHz. Finally, Adams et al. have shown that concepts generated in planar structures can also be considered in full 3D by utilizing DIW techniques to print an electrically small antenna on a hemispherical dielectric, which shows much potential and promise for designing in 3D for future antenna systems [16].

6. Opportunities and Conclusion

There is much to look forward to within the arena of printed RF components and their realization as the community moves from rapid prototyping towards manufacturing. Additionally, there are a number of fascinating new fully 3D RF component concepts in the recent literature that can only be fabricated using AM techniques [121–124]. These RF components in full 3D outperform their planar counterparts and give an extra degree of freedom for designing new structures that additionally have function or could potentially be embedded into structures. Hester et al. have demonstrated that by cleverly designing in the 3rd dimension, a 43 dB increase in maximum rejection of the S-parameters can occur over a much broader range (5–14 GHz) than its planar counterpart.

There is a need to establish an upper bound on what can reproducibly be achieved for environmentally robust DW metals, but first, a baseline understanding of the process-structure-property relationship must be achieved. This will become more evident as fully 3D printed RF systems are necessary, which require near-bulk printed metal conductivity on printed dielectrics. A systematic experimental approach is necessary, in which the conductivity of the prints is compared against their morphology, aspect ratio, and processing conditions. Since these structures differ from their bulk counterparts in terms of porosity and grain size, it will be necessary to determine the maximum possible conductivity for different printed metal inks and subsequently work towards achieving such a threshold. Understanding these material effects will allow for dramatically improved material engineering.

For dielectrics, there is a large window of process space to take advantage of the low loss (<0.005) and permittivity (<2.5 or >10) regime. Short-chain polymers are an exciting class of materials due to their small dielectric constant. Tuning their permittivity with small, low-loss additives may be a means to decrease the overall loss of the final RF component. The crucial step here is to ensure that these polymer composites are indeed printable.

Here, we have focused on the main RF building blocks including metals and dielectrics. If DW is to impact RF circuits, then switches will need to be developed, such as MEMS or phase change materials that can act as reconfigurable electronics for phased array applications [125, 126]. Moreover, some new works are coming out on printed magnetic materials that could be viable for use as inductors or circulators that will enable further miniaturization of printed microelectronics since these have been difficult to fabricate with traditional thin film growth techniques with high permeability (μ) over high frequencies [127]. Additionally, there have been some good advancements in printed barium strontium titanate (BST) for tunable capacitors; however, their turn on voltages is currently considerably high [128, 129]. The tunability offers another degree of freedom for design and operation; however, a drastic reduction in voltage will be necessary for realization in many applications.

Looking ahead even further for realization, we anticipate that smart structures, or 3D printed structures that can be actuated via an external mechanism over time, will become increasingly important in applications where compaction is critical. These printed smart components have small form factor for storage, but during usage or deployment, the structure is able to unfold into a fully functioning and truly 3D product [130]. Some antenna examples using this type of “4D” printing have been demonstrated and show an interesting future path [96]. We also wish to highlight that rapid advancements are needed in the design of experiments necessary to address the challenges we have outlined. Here, machine learning and autonomous experimentation could be integrated into the current research field as they have shown great promise for carbon nanotube synthesis [131]. Ultimately, we envision processes associated with AM to be highly automated during the full-scale production workflow with robotics, especially when needed to go between instruments to print at different scales (nm to cm) and final system assembly. Again, borrowing from the semiconductor manufacturing industry, this would reduce unknown variables and increase speed of production once the challenges in this field have been addressed.

In this review, we have identified the major material’s challenges facing realization of AM and DW for RF antennas and components. We have also suggested how to approach solutions to reduce the loss correlated with current materials and processes pertaining to printing that preclude wide usage in the current state-of-the-art. We also envision that additional inks and resins still need to be developed that have tailorable properties for RF applications, so this is an exciting arena to be in moving forward. The realization of high performance RF antennas and components will take a multi-disciplinary effort moving forward in order to result in demonstrations of conformally printed antennas that could be considered robust and reliable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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