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Aerosol Jet Printing on Kapton for Affordable Millimeter Wave Antenna Prototyping

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Abstract— **In this work, we have examined the feasibility of 3D printed antennas on Kapton for mm-wave applications. Initially, a series-fed patch antenna array at 47 GHz was designed and fabricated on a low-loss Rogers substrate. Subsequently, aerosol jet printing was employed to prototype the antenna on Kapton film, which was adhered to the Rogers substrate. Experimental results showed that the Kapton antenna demonstrated similar performance to the copper etched Rogers antenna. Therefore, this method can be adopted for prototyping high-frequency antennas on expensive low-loss substrates, enabling rapid prototyping and allowing the substrates to be reused by peeling off the Kapton films.**

Keywords—aerosol jet printing, antennas, antenna array, Kapton antenna, millimeter-wave (mm-wave) array, printed antennas, series fed array.

I. Introduction

With the increasing demand for millimeter-wave spectrum in commercial applications, the need for high-performance radio frequency (RF) communication systems at these higher frequencies has become critical [1]. Effective RF communications hinge on innovative antenna design and development. For many millimeter-wave applications, the ideal solution involves cost-effective antenna arrays that can be mass-produced, offering both high gain and broad bandwidth. Consequently, there has been a concentrated effort to enhance antenna gain while keeping manufacturing costs and complexity to a minimum.

Additive Manufacturing (AM) marks a significant evolution in manufacturing processes and materials, making it possible to create innovative concepts that would be impractical or too costly with traditional methods [2]. This advancement greatly influences passive microwave and millimeter-wave components, including RF (radio frequency) components. AM's flexibility in using various materials such as polymers, composites, ceramics, and metals makes it ideal for producing intricate designs that minimize weight and volume, while optimizing lead time, production costs, and RF performance [3, 4]].

AM is increasingly being explored for antenna prototyping and production, becoming a key research area in RF applications. Among the notable technologies is aerosol jet printing (AJP), a non-contact, direct-write additive manufacturing technique that is compatible with a wide array of functional materials. AJP is extensively used in printed and hybrid electronics, especially in healthcare, electronics packaging, and flexible and wearable circuits [5]. In the field of printed electronics (PE), AM typically allows for direct writing of a design onto a substrate, followed by a post-processing stage to achieve a conductive pattern. Inkjet printing has been widely adopted in PE, along with other methods such as direct ink writing and AJP [6,7]. AJP enables rapid prototyping, allowing for quick iterations and faster characterization than traditional production methods. This not only helps keep material costs down but also provides greater flexibility in substrate choice, as no lamination or development stages are required.

Printed array antennas have emerged as a low-cost, low-waste solution and have been demonstrated across various frequency ranges. For instance, He et al. successfully used AJP alongside a 3D-printed dielectric to create a Quasi-Yagi-Uda antenna, which matched well with simulated results [8]. Similarly, Gu et al. printed conformal cross antennas on the interior surfaces of glass hemispheres, although their work only included performance simulations [9]. It is widely recognized that for printed electronics (PE) in RF applications, achieving consistent morphology and good conductivity, which minimizes signal loss, requires optimized ink formulations and precise printing parameters.

In this study, we investigate a series-fed patch array using conductive inkAJP on Kapton, which is then adhered to a Rogers substrate, for the rapid prototyping of millimeter-wave antennas. This paper is organized as follows: Section II discusses the fabrication of the prototype using AJP. Section III presents the design of the proposed series-fed line array. Sections IV discusses the performance of the microstrip line array with measurement results on different substrates . Finally, Section V presents the conclusions

II. Aerosol Jet Printing on Kapton

In this study, an aerosol jet printer Optomec AJ 300 is utilized to print a silver nano particle ink. The high conductivity and resilience to oxidation of silver ink makes it very suitable for this application. The Sigma Aldrich silver dispersion 736365-25g (30-35 wt.%) was diluted with deionized water to prepare silver ink with a final concentration of 11 wt.% silver nanoparticles. At this lower concentration, the conductivity per pass was reduced compared to higher concentrations. However, this dilution significantly decreased over spray. To achieve adequate

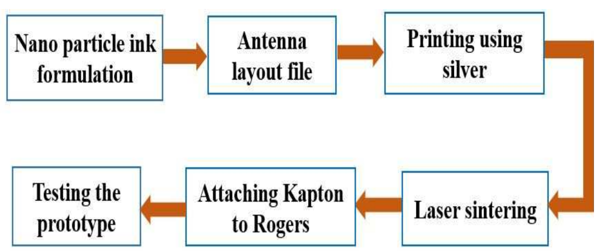

Fig. 1. Aersol jet printing process for fabrication of kapton antenna.

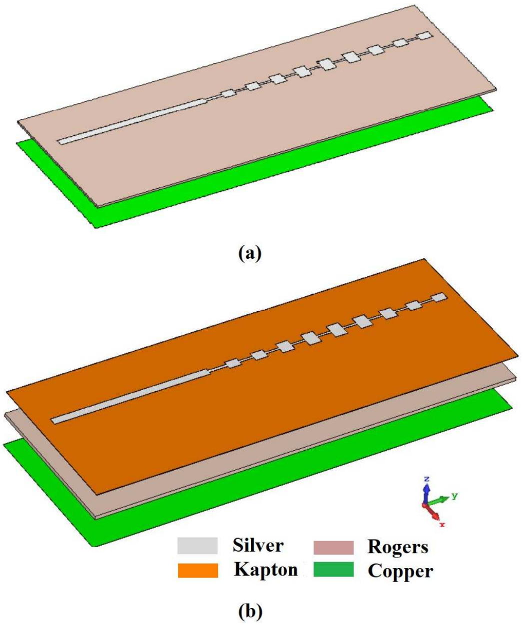

Fig. 2. Configuration of the series fed array: (a) etched antenna array, (b) kapton antenna array.

conductivity, multiple layers of the ink were deposited. Fig. 1 illustrates the fabrication of series fed array by AJP on Kapton. Kapton tape substrate is cleaned prior to printing with isopropyl alcohol followed by acetone. Residue from the adhesive on the top layer of the Kapton would interfere with the printing leading to gaps in the printed traces [10]. Although other studies have utilized ultrasonic or plasma cleaning to enhance wettability and reduce the resistance of printed metal, these methods were not employed in this study [10]. It has been demonstrated that printing onto heated surfaces results in silver lines with higher aspect ratios because the increased rate of solvent evaporation occurs [11, 12]. Higher aspect ratios, when printing patterns comprised of lines, permit reduced line spacing, which enhances the consistency of the printed silver's thickness. This consistency leads to lower resistance with fewer printed layers. In this study, all substrates were heated to 60 °C during printing. Printing at higher temperatures led to dry deposition and wider traces. Normally, thermal sintering on a hot plate was used to create conductive traces on Kapton, though substrate warping significantly affected the RF characteristics, despite achieving low resistance. While laser sintering also causes some warping, its impact on RF characteristics is less pronounced.

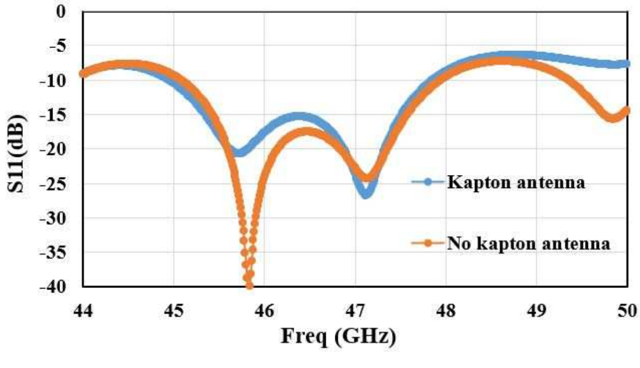

Fig. 3. Simulated reflection coefficient of the series fed antenna array with and without kapton.

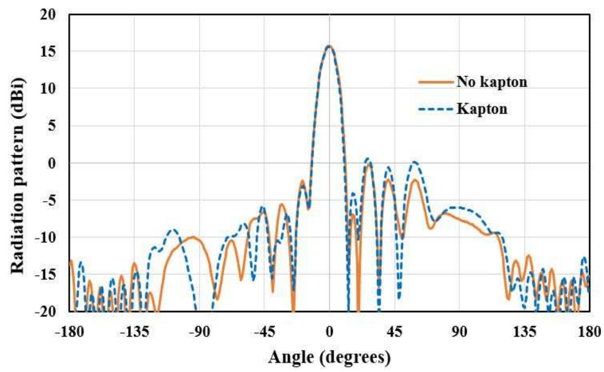

Fig. 4. Simulated E- plane radiation pattern of no kapton (etched) and Kapton array at 47 GHz.

III. Series Fed Patch Antenna Array Design

Microstrip antennas are preferred over other millimeter-wave antennas due to their low profile and cost-effectiveness. Despite these advantages, array feeding techniques pose significant challenges, involving trade-offs among parameters such as bandwidth, side lobe levels (SLL), gain, and desired radiation patterns. Parallel-fed arrays typically suffer from complex design processes, bulky sizes, and additional feeder losses. In contrast, series-fed arrays feature simpler feeding networks and more compact configurations. Thus, series fed patch arrays are important for millimeter wave applications [13]. A circuit model is employed to design series-fed patches for creating the desired patterns in series-fed microstrip antenna arrays [14]. In [15], the amplitudes of the array elements are adjusted by tapering the length of the coupled region between them. In [16], two tapering methods for adjusting the amplitudes are compared: the patch width tapering method and the feed linewidth tapering method. In [17], a design approach for series-fed microstrip arrays is introduced, which uses simulation results of the array elements to minimize the simulation time in the design process.

In this work, a series fed patch array is designed at 47 GHz with 9 patch elements. The spacing between adjacent patch elements is roughly λg, the wavelength in the substrate at 47 GHz, ensuring that all elements are nearly in phase. As a result, both the patch and feedline lengths are 0.5λg. The length and width of the middle element is initially designed using the standard patch antenna design method. Then, eight elements with symmetrical dimensions around the central element (e.g., element 1 is identical to element 9, element 2 is identical to element 8, and so on) are designed. For improving the side lobe level performance of this antenna array, an amplitude tapering of patch elements is considered in this design. Dolph-Chebyshev weighting values, are multiplied by the width of the middle element to implement the Dolph-Chebyshev taper, resulting in a set of elements with tapered widths, as shown in Fig. 2. To achieve a 50-ohm array input impedance, a quarter-wavelength transformer is employed. The antennas are designed and optimized in CST, a finite-difference time-domain electromagnetic solver. A Rogers RO4003C substrate with dielectric constant εr = 3.55, substrate thickness, h = 0.5 mm and loss tangent tan δ =

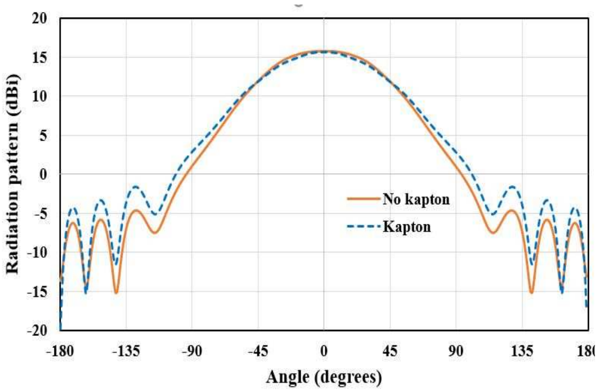

Fig. 5. Simulated H- plane radiation pattern of no kapton (etched) and Kapton array at 47 GHz.

0.0027 is utilized in this design. The copper used for the antenna traces and ground has a conductivity of 5.96×10^7 S/m.

The simulated reflection coefficient of the series fed array with and without Kapton is shown in Fig. 3. It can be observed that more than 10 dB return loss has been achieved over a 3GHz bandwidth from 45 to 48GHz. The conventional etched antenna and AJP on Kapton antenna have similar bandwidth performance. Fig. 4 represents the simulated E-plane radiation pattern of both designs at 47 GHz. A narrow beam is obtained in both designs and SLL is around 15 dB, though the SLL is slightly better in the etched array design. The simulated H-plane radiation pattern of etched and Kapton array at 47 GHz is shown in Fig. 5. It can be observed that the radiation patterns are very similar in both designs.

IV. RESULTS

To validate the feasibility of the proposed idea, two series fed patch antenna array prototypes are fabricated with 9 elements, as shown in Fig. 6. An etched array on Rogers 4003C is initially fabricated. The antenna prototype is connected to a 2.4 mm edge launch connector (ELF50). Then, the same layout is silver printed on Kapton film using an AJP

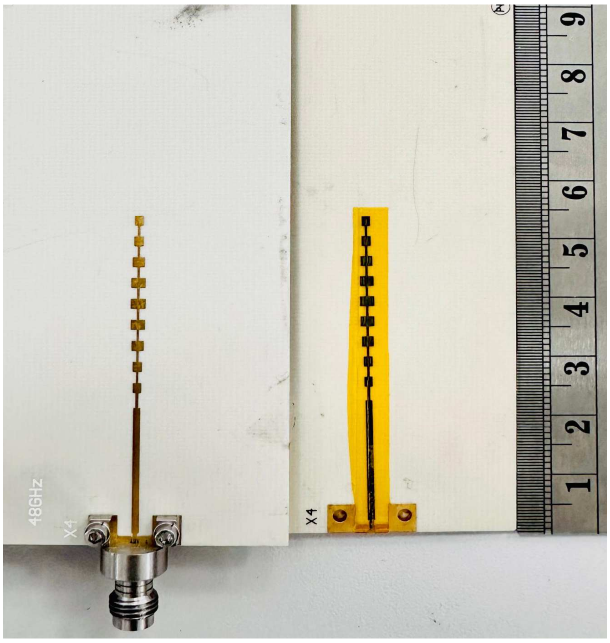

Fig. 6. Fabricated etched series fed antenna array and AJP on Kapton array.

Fig. 7. NSI spherical antenna measurement sytem for radiation pattern measurement [18].

and glued on top of the roger's substrate. The radiation pattern and gain performance of the proposed antenna array was evaluated using the NSI-MI 700S-360 antenna spherical measurement system in The University of Sheffield mm-wave Lab as shown in Fig. 7 [18]. Fig. 8 represents the measured 3-D radiation pattern of the etched series fed antenna array with no Kapton film. The antenna array is in the X-Y plane and the peak radiation is in Z direction. This series fed antenna array has a broadside radiation pattern, as expected. It can be observed that the side lobe levels are 12 dB lower than the major lobe, agreeing with Fig. 4. A narrow beam in the E-plane (φ = 90◦) and fan shape pattern in the H-plane (φ = 0◦) is observed. Similar radiation patterns were also measured at 45, 46 and 48 GHz frequency bands without any significant side lobes.

Fig. 9 shows the measured 3D radiation pattern of the AJP series fed patch antenna array with Kapton at 47 GHz. The radiation pattern is very similar to that of the etched antenna at 47 GHz. It can be observed that the side lobe levels (SLL) are slightly inferior compared to etched array with no Kapton, however the SLL values are still better than 10 dB. Moreover, stable fan shaped radiation patterns are observed from 46 to

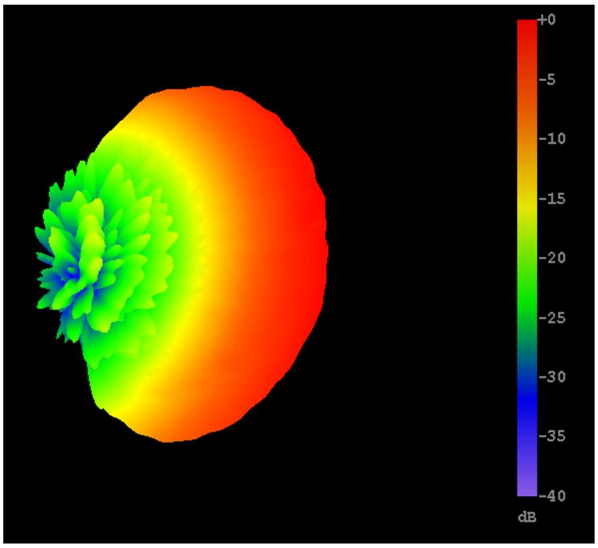

Fig. 8. Measured 3D radiation pattern of the etched antenna array (no kapton) at 47 GHz.

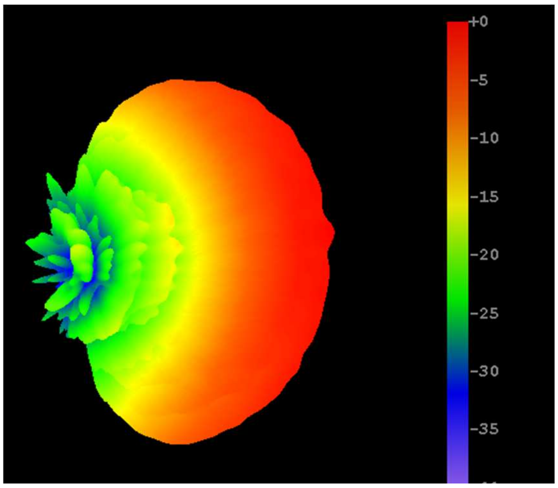

Fig. 9. Measured 3D radiation pattern of the AJP antenna array with Kapton at 47 GHz

49 GHz, compared to 45 to 48GHz of etched array. This can be due to the small discrepancies from gluing of the Kapton film to Rogers. Moreover, the layout design is optimised only for the etched design.

Considering the similar performance of conventionally fabricated etched antenna arrays and AJP on Kapton antenna arrays, it can be suggested that silver printed on Kapton is an effective method for prototyping millimeter wave antennas. This approach allows for rapid prototyping and easy design modifications by simply peeling off the Kapton film and replacing it with another printed Kapton. Consequently, this method enables the reuse of expensive low-loss substrates in millimeter wave antenna designs

V. Conclusions

In this work, our study demonstrated the feasibility of 3D printed antennas on Kapton for millimeter-wave applications. By designing and fabricating a series-fed patch array at 47 GHz on a low-loss Rogers substrate and then prototyping the antenna on Kapton film using aerosol jet printing, we found that the Kapton antenna exhibited similar performance comparable to the etched copper Rogers antenna. The measured 3D radiation pattern of the etched antenna and the Kapton antenna were similar at 47 GHz and the side lobe levels were better than -10dB. This method facilitates rapid prototyping of high-frequency antennas on expensive low-loss substrates and allows for the reuse of these substrates by simply removing the Kapton films.

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