Inkjet-Printed Two-Dimensional Phased-Array Antenna on a Flexible Substrate

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***Abstract*—In this letter, we present a two-dimensional 2-bit 4×4 phased-array antenna on a flexible Kapton substrate fabricated using inkjet printing. Printed carbon nanotube thin-film transistors (CNT-TFTs) form the switching elements in the phase-shifting network. A multilayer interconnection scheme has been utilized to fully package the subsystem and enable convenient access of the control lines to the 64 CNT-TFTs. By appropriately controlling the ON and OFF states of the TFT switches using a computer mainframe, beam steering of a 5-GHz RF signal at four steering angles of $\theta = 0°$, $\varphi = 0°$; $\theta = 14.5°$, $\varphi = 0°$; $\theta = 20.7°$, $\varphi = -45°$; and $\theta = 34°$, $\varphi = -26.5°$ are experimentally demonstrated. The insertion loss and the power consumption by the switch array are measured to be 8.17 dB and 11.2 mW, respectively.**

***Index Terms*—Beam steering, carbon nanotube, flexible antenna, inkjet printing, phase shifters, phased arrays, thin-film transistors.**

I. Introduction

PHASED-ARRAY antenna (PAA) systems have many advantages over mechanically steered antenna arrays in terms of speed, sensitivity, and size [1]. They have become critical components for modern military and commercial radar and wireless communication systems. Traditional antenna arrays are bulky, heavy, and extremely expensive due to the nature of the rigid substrate and complex manufacturing processes that limit their applications.

On one side, flexible electronics has emerged as a multibillion dollar industry [2], [3] over the last decade, owing to a large demand for low-cost, lightweight electronics fueled by progress in room-temperature solution processable fabrication technologies in the areas of displays, sensors, lighting, etc. [4]–[8]. On the other side, conformal antennas have also been gaining widespread interest in both military and commercial applications [9]–[12]. For the latter, while the interest is partially due to the availability of potentially useful large-area nonplanar real estate on aircrafts, ships, automobiles, etc., there has also been interest in developing rollable antenna systems for easy storage and deployment—for example, near a campsite, in a battlefield, or on extraterrestrial surfaces such as the Moon and Mars [13], [14]. Due to the low profile of the antenna, the local networks for flexible antennas are expected to provide coverage for short- ($\sim$10 m) to medium-range ($\sim$5–10 km) wireless operation [15]. Conventional conformal antenna systems rely on direct fabrication of antenna elements on a curved surface [16]–[18], or attaching individual components directly on a flexible surface [14]. However, such systems tend to be heavy, difficult to fabricate, and unreliable. Using multilayer solution processing techniques, such as inkjet printing, screen printing, offset printing, etc., it is possible to wed flexible electronics manufacturing with antenna circuit design in order to develop low-cost, lightweight, easy-to-fabricate conformal antenna systems on flexible substrates such as paper, plastic sheets, etc.

We have previously developed and demonstrated inkjet-printed one-dimensional 1×2 and 1×4 PAA subsystems on flexible substrate [19]–[21]. In this letter, we extend the complexity to two dimensions and present the development and demonstration of a two-dimensional 2-bit 4×4 flexible PAA system. Multilayer interconnection scheme is used to fully package the fabricated system [19], [20]. The ON–OFF states of the 64 carbon nanotube thin-film transistors (CNT-TFTs) forming the phase shifter are controlled using a switching mainframe computer, and beam steering of a 5-GHz RF signal at four angles of $\theta = 0°, \varphi = 0°$; $\theta = 14.5°, \varphi = 0°$; $\theta = 20.7°, \varphi = -45°$; and $\theta = 34°, \varphi = -26.5°$ are experimentally demonstrated. From measurements, the insertion loss of CNT-TFT switch array is 8.17 dB, and the switch array consumes a low power of 11.2 mW for steering. The gain of the antenna array is measured to be 14.6 dBi, and the efficiency is 58%, excluding the transmission line loss at $\theta = 0°, \varphi = 0°$. Such a demonstration paves the way for the development and deployment of large-area, conformal antenna systems for several future applications.

II. Design and Printing of 2-Bit 4×4 Phased-Array Antenna

A schematic of a 2-bit 4×4 phase shifter is shown in Fig. 1. Each of the switches in the phase shifter, numbered from 1 to 64, is an active TFT that can be formed by printing the gate-dielectric-active layer-source/drain material stack on the flexible substrate.

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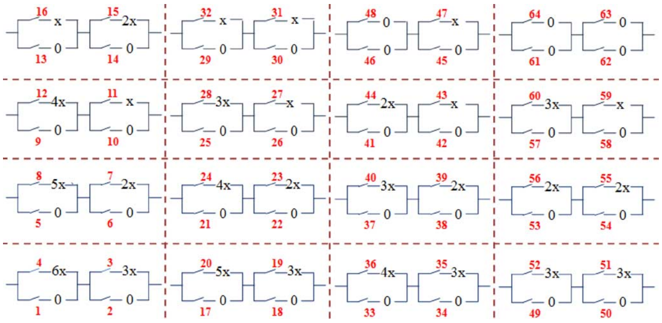

Fig. 1. 2-bit, 4×4 array phase shifter design. The light numbers indicate CNT-TFT switch number in the array, and black text denotes the length of transmission line in that region. The step x is chosen as 0.785 cm in order to achieve a maximum steering angle of $\theta = 34^\circ, \varphi = -26.5^\circ$.

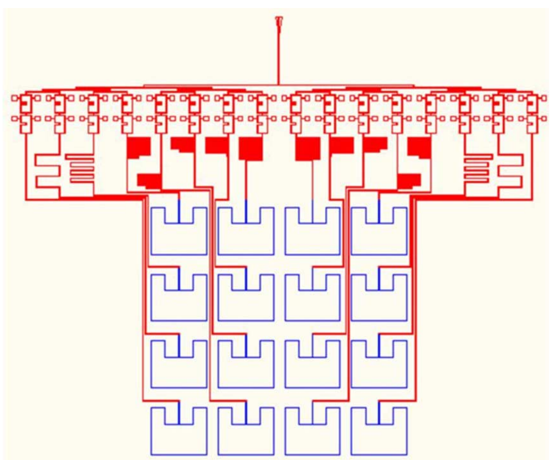

Fig. 2. Schematic layout of a 2-bit, 4×4 phased-array antenna. Each of the 16 antenna elements is controlled by a 2-bit phase shifter consisting of four CNT-TFT switches.

The text indicated in black color denotes the length of transmission line in that section. In our design, the length step "x" is chosen to be 0.785 cm in order to achieve a maximum steering angle in elevation (θ) of 34°, and in azimuth (φ) of -26.5°. Note that this maximum angle can arbitrarily be chosen to any value and is not limited by the design. Since the Fujifilm Dimatix DMP-2800 inkjet printer used in this letter can print an area as large as 8×11 in^2, a maximum θ of 34° was chosen since it greatly simplified the phase-shifter design and kept the area of the PAA within the printable limit. Each of the 16 phase-shifter outputs are connected to 16 patch antennas arranged in a 4×4 array with an interelement spacing of 3 cm (for 5-GHz operation) in both x and y dimensions, as shown in Fig. 2, to form a two-dimensional phased-array antenna system. By controlling the ON/OFF states of the switch pairs within each of the 16 sectors in Fig. 1, beam steering in four directions can be achieved.

The 2-bit 4×4 PAA comprising of silver transmission lines, antenna elements and carbon nanotube TFT (CNT-TFT) switches are printed using a Fujifilm Dimatix Materials Printer (DMP-2800) using method outlined in [20].

III. Device Packaging and Testing

Upon fabricating the 2-bit 4×4 PAA system, it is fully packaged utilizing the multilayer interconnection scheme [21]–[23].

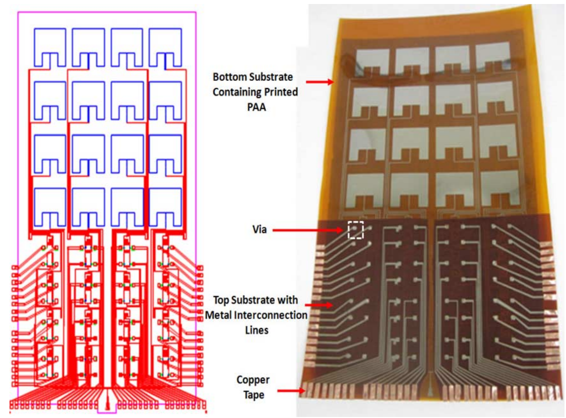

Fig. 3. *(left)* Schematic layout of a 4×4 PAA subsystem with multilayer interconnection scheme. *(right)* Photograph of a fully developed 4×4 PAA system consisting of a three-layer circuit (bottom substrate/CNT stamp/metal interconnection).

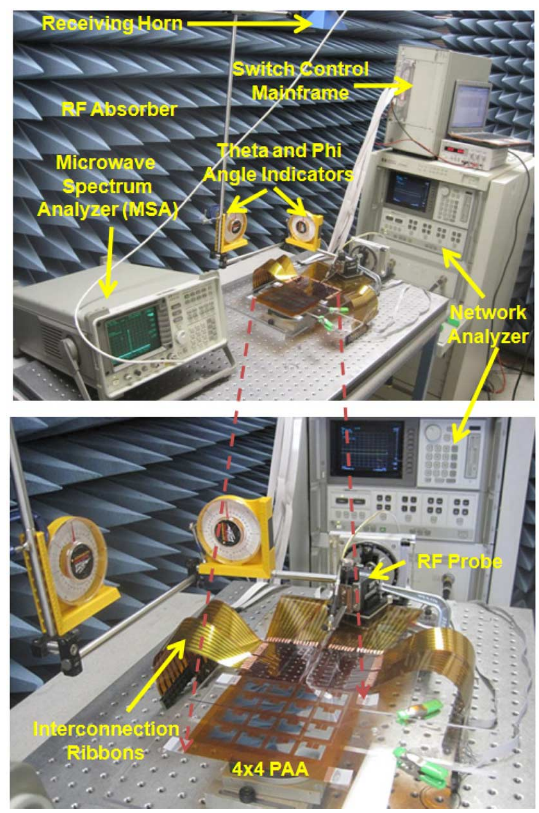

Fig. 4. *(top)* Entire experimental setup to measure the far-field pattern of the fabricated 4×4 PAA system. *(bottom)* Close-up of the section of the measurement setup showing the 4×4 PAA and interconnection ribbons.

The layout of the interconnection pads, as well as a photograph of the fully packaged 4×4 array are shown in Fig. 3, left and right, respectively. In order to enable testing of the fabricated system, probing pads are formed using double-sided copper tapes. Once packaged, the array is ready for testing.

Fig. 4, top and bottom, shows the experimental setup used to measure the far-field pattern of the fully packaged 2-bit 4×4 PAA. The 8510C HP network analyzer provides a 5-GHz RF signal with a power of 1 mW to the flexible PAA through an

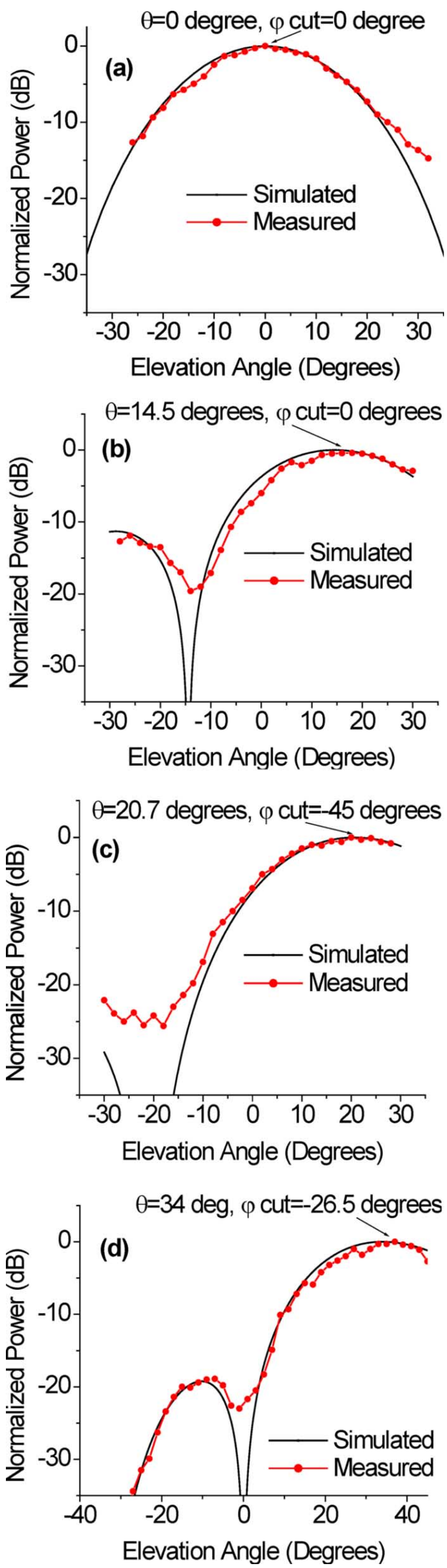

Fig. 5. Measured and simulated far-field radiation patterns of the printed 2-bit 4×4 PAA system for 5-GHz signal showing peak at (a) $\theta = 0°, \varphi = 0°$, (b) $\theta = 14.5°, \varphi = 0°$, (c) $\theta = 20.7°, \varphi = -45°$, and (d) $\theta = 34°, \varphi = -26.5°$.

RF probe. A 6-dBi standard gain horn, placed at a distance of 1.5 m from the PAA, is used as the receiving antenna, with the receiving power measured by a microwave spectrum analyzer (MSA). The gain of the antenna array is first measured for a $\theta = 0°, \varphi = 0°$ configuration. In this measurement, the 64 FET switches corresponding to 0°, 0° steering are biased at $V_{DS} = -1.0$ V and $V_G = 0$ or -3 V for OFF and ON states, respectively. On average, each switch in the ON state has a dc current of 0.35 mA, resulting in power consumption of 11.2 mW by the entire array. The received RF power as a function of angle is measured in order to obtain the far-field pattern shown as a dotted curve in Fig. 5(a). In order to estimate the insertion loss of the CNT switches, we measured the difference in gain of two 4×4 arrays in 0°, 0° steering configuration—one with the active CNT switches and another in which the CNT switches with S and D are short-circuited by a microstrip line. The gain difference was measured to be 8.17 dB, which is attributed to the insertion of CNT switches in the path. The gain of the 4×4 antenna array is measured to be 14.6 dBi. The efficiency is calculated to be 58%, excluding the loss of the transmission line.

Next, we demonstrate beam steering using our 4×4 array. As mentioned earlier in Section II, the 2-bit, 4×4 design can achieve beam pointing in four directions. By appropriately configuring the ON/OFF states of the 64 CNT-TFTs, we measure the far-field patterns for all the other steering angles. Fig. 5(a)–(d) shows the measured (dotted curves) and simulated (black curves) far-field radiation patterns of the PAA system for four switching conditions, indicating peak power at $\theta = 0°, \varphi = 0°, \theta = 14.5°, \varphi = 0°, \theta = 20.7°, \varphi = -45°$, and $\theta = 34°, \varphi = -26.5°$ steering angles, respectively. Simulations are performed using a MATLAB code. The measured data is indicated by dots, whereas the simulated patterns are shown as black curves. It can be seen from the results that the measured and simulated far-field patterns agree well with each other. The gain values of the antenna in the other angles are also measured and are found to be within 2 dB of that in 0°, 0° steering configuration.

Due to the high mobility of CNT, ultrafast steering in the range of gigahertz can easily be achieved by carefully designing the FET [19]. According to the power rating of the polyimide substrate, thin-film silver, and CNT, the possible maximum radiated power is estimated to be ~1 W. Moreover, the scalability of the manufacturing technique can be used to realize very large aperture antenna arrays that can find useful applications in deep space, as well as airborne wireless communication. The unique inkjet printing technique can find useful commercial applications in logic/memory, radio frequency identification (RFID), large-area flexible displays, electronic paper, bio-sensors, large-area conformal and flexible antennas, smart and interactive textiles, lighting, photovoltaics, etc.

IV. Conclusion

In conclusion, a lightweight, flexible 4×4 phased-array antenna system was successfully fabricated on a flexible kapton substrate. The 64 CNT-TFTs that serve as switches in the 2-bit, 4×4 phase-shifting network were formed using a combination of inkjet printing and stamping techniques. The entire circuit was packaged using a multilayer metal interconnection scheme, which also enabled easy access to the 64 switches from an external switch control mainframe. By controlling the ON/OFF states of the transistors, beam steering of a 5-GHz signal at $\theta = 0°$, $\varphi = 0°$; $\theta = 14.5°$, $\varphi = 0°$; $\theta = 20.7°$, $\varphi = -45°$; and $\theta = 34°$, $\varphi = -26.5°$ was demonstrated experimentally. The insertion loss and the power consumption of the array were measured to be 8.17 dB and 11.2 mW, respectively. Compared to traditional antenna design, this lightweight, flexible, and conformal PAA is a promising candidate for flexible portable wireless systems, as well as other airborne communication systems, to meet challenging requirements.

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