Light Weight and Conformal 2-Bit, 1×4 Phased-Array Antenna With CNT-TFT-Based Phase Shifter on a Flexible Substrate

Daniel T. Pham, Harish Subbaraman, Maggie Yihong Chen, Xiaochuan Xu, and Ray T. Chen

***Abstract*—This paper presents the development and characterization of an ink-jet printed 2-bit, 1×4 phased-array antenna (PAA) system on a flexible Kapton polyimide substrate utilizing carbon nanotube thin-film transistors (CNT-TFTs) as switching elements in the phase-shifting network. A multilayer metal interconnection strategy is used to fabricate a complete PAA system with control lines. By appropriately controlling the ON and OFF states of various switches, a 4.99 GHz signal is steered from 0° to -27°, and the measured far-field radiation patterns agree very well with the simulated data. Bending tests performed on the fabricated system at bending radii of 6.5 cm, 9.5 cm, 12 cm, and 24 cm also demonstrate good agreement with the simulations.**

***Index Terms*—Beam steering, carbon nanotube, flexible antenna, phased-array antenna, phase shifter, thin-film transistor.**

I. Introduction

FLEXIBLE antenna has become very attractive in the last decade due to the development of several interesting flexible circuit components that can be integrated into one system on a light weight, conformal flexible platform. Such flexible antenna components are being considered for several applications including communication, sensing, RFID, etc. For example, proximity surface activity applications for use on robotic devices or on human clothes, mandate a small size, light weight, and low power antenna system that can be used in a desired frequency band for certain data services. Due to the low profile of conformal antenna designs, the local networks for flexible antennas are expected to provide coverage for short ($\sim$10 m) to medium range ($\sim$5–10 km) operations [1].

An important system utilizing such flexible antenna elements, such as a conformal phased array antenna (PAA), is formed by combining the flexible antenna elements and electronics involved in transmit/receive (T/R) modules, on a single flexible substrate. The PAA plays an important role in the modern radar systems since large angle electronic beam steering can be achieved without mechanically rotating the antenna array [2]. Although, it is possible to develop flexible antenna elements using ink-jet printing, embedding the phase shifting chip for the T/R modules on a flexible substrate is not an easy task. Due to the fabrication resolution limit of the printer, line widths smaller than 50 μm for the metal lines are difficult to achieve. Additionally, the material and physical properties of the available flexible substrates lead to large feature sizes on the phase shifter in order to achieve 50 Ohm impedance matching with the printed antenna elements. Thus, the phase shifter and associated electronics take up a lot of space due to their large size. The assembly of these components on flexible substrates, herefore, is prone to reliability issues.

Recently, CNT transistor has shown tremendous progress due to their excellent mobility characteristics [3]. CNT TFT-based devices on flexible substrates have achieved high carrier mobilities using ultrapure electronics-grade CNT solutions [4], [5] by ink-jet printing technique. Other techniques such as dielectrophoresis (DEP) [6], spin-coating [7], and spray-coating [8] to form CNT thin-film transistors have also been demonstrated. All of these techniques yield a random network of CNTs on the substrate. Utilizing ink-jet printing technique, we previously developed and demonstrated the working of a 2-element phased array antenna system that utilizes CNT-TFT containing random network of TFTs [9]. Further improvement in the CNT transistor device performance has been demonstrated through the use of aligned CNTs [10]–[14]. In comparison with a random network of CNTs, aligned CNTs improve the drain current $(\mathrm{I_{on}})$ by decreasing the average carrier path length. A majority of the reported aligned CNT thin films utilize direct deposition on silicon or quartz substrates via chemical vapor deposition (CVD) technique [10]–[14]. This deposition technique is unsuitable for flexible substrates due to high deposition temperatures (400 °C–1000 °C) involved. Among the flexible substrate compatible methods for achieving self-aligned CNTs, dip-coat technique has shown good performance results [13]–[15].

In this paper, a combination of ink-jet printing and stamping technique is used to fabricate a fully functional 1×4 phased-array antenna with 2-bit CNT-TFT based phase-shifter on a flexible Kapton polyimide substrate. The self-aligned CNTs are formed on a silicon substrate using a dip-coat method, and a stamping technique is used to form the CNT-TFTs in the phase shifter [14], [15].

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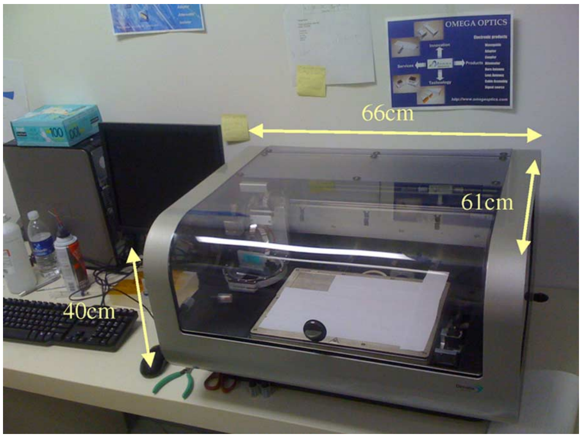

Fig. 1. Fujifilm Dimatix Materials Printer.

II. Fabrication Process

A. Ink-Jet Printing

The ink-jet printer used in this work is a Fujifilm Dimatix Materials Printer (DMP-2800) as shown in Fig. 1. The printer uses a piezoelectric printing cartridge (DMC-11610) consisting of 16 independently controllable nozzles. The ink droplets dispensed from the nozzles have a nominal volume of 10 pL. The machine is suitable for room temperature printing of circuits on any kind of substrate, including glass, plastic, rubber, textile, etc., since the noncontact printing is substrate topography independent.

In order to print a complicated pattern consisting of small and large structures or closely spaced lines next to each other, such as in the PAA system, the orientation of the PAA system needs to be considered in order to achieve uniform deposition of material ink at all locations. Several orientations of the PAA system were investigated, and it was found that the PAA system in horizontal position, as shown in Fig. 2, provides the best result. While printing large areas, the nozzles operate continuously in a long endurance time mode. In this mode, the printing material wets the nozzle surface. This wetting causes a problem, especially while printing on small area or printing small lines. Therefore, in order to print small features, a single nozzle is utilized. Another problem which requires consideration is the deposition uniformity. For example, during the beginning of the printing cycle, the nozzles provide uniform deposition, and after printing a large area (long operating time), the performance slowly degrades. Therefore, breaking the printing area down to several small parts is a good way to have better uniform printing. Fig. 2 shows the PAA system architecture formed by connecting two parts. The first part contains narrow width (~300 micron) transmission lines. This part is printed using a single nozzle on the cartridge for better precision. The second part consisting of the large antenna elements, is printed using multiple nozzles. Using this type of combination printing, the printed product has better quality and is performed with an optimal printing time. Please note that alignment marks are used to precisely align the two printing steps, which are also shown in Fig. 2.

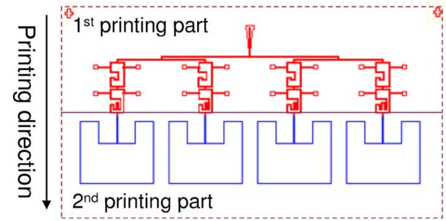

Fig. 2. Schematic of a 2-bit, 1×4 phased-array antenna. Printing transmission lines and antenna elements separately provides good printing coverage.

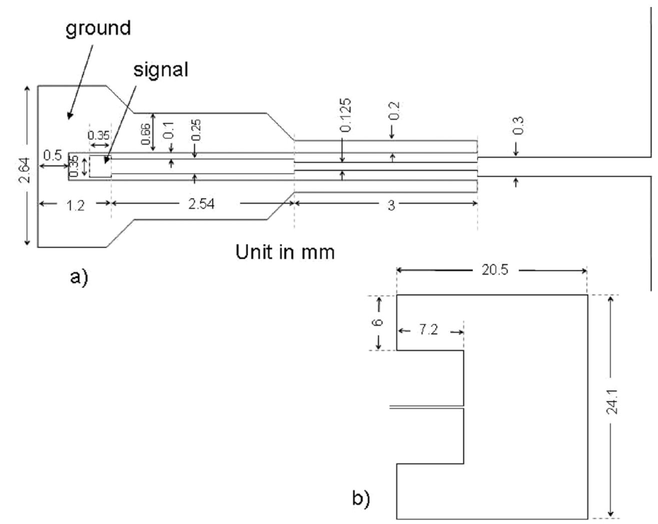

Fig. 3. (a) microstrip transmission line, co-planar waveguide and coupler design; (b) microstrip antenna design.

B. Principle of Operation of Phased-Array Antenna Subsystem

Fig. 2 shows the layout of the 2-bit 1×4 element phased array antenna subsystem. In order to design the full PAA system, standard microstrip antenna design techniques are used [16]–[20]. Schematic drawings of RF coupler, microstrip transmission line, coplanar waveguide to microstrip line coupler, antenna elements designed for operation at 5 GHz are shown in Fig. 3. In order to achieve beam steering using the PAA, first, the 5 GHz RF signal is applied through the input RF port. The coupling section transitions the signal from the coplanar waveguides to the microstrip line. The signal is then split into two branches, with each branch split further into two more branches, thus giving 4 branches with equal length (for 4 elements). The 4 branches feed a 2-bit phase shifting network, schematically shown in Fig. 4. Each of the switches (numbered from 1 through 16) in the phase shifter is a CNT-TFT. By controlling the ON/OFF ratio of the switch pairs as indicated in Table I, beam steering at $-27°$, $0°$, $27°$, and $45°$ is achieved.

C. Formation of Carbon Nanotube Thin-Film Transistor (CNT-TFT)

In this work, Carbon nanotube thin-film transistors (CNT-TFTs) are formed by a combination of printing and stamping techniques on a 127 μm thick Kapton Polyimide substrate [14], [15]. Fig. 5 shows a schematic of the bottom gate integration process flow for the CNT-TFT. At first, the gate electrode is printed along with the transmission lines and

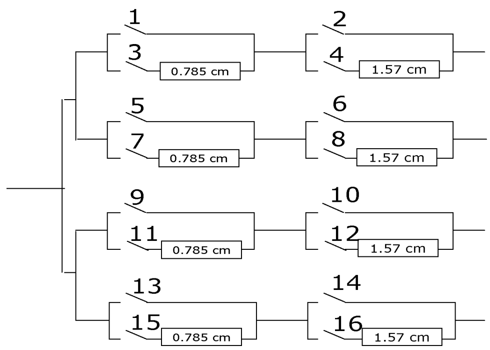

Fig. 4. Schematic of a 2-bit, 1 × 4 phase shifter. CNT-TFTs are numbered from 1 through 16. Lengths indicated within boxes denote additional lengths of microstrip line.

TABLE I
SWITCH PAIR SELECTION VERSUS STEERING ANGLE

Switching Pair Selection	Length difference between adjacent elements	Steering Angle
1,2 6,7 9,12 15,16	0.765cm	27°
3,4 5,8 10,11 13,14	-0.765cm	-27°
1,2 5,6 9,10 13,14	0	0°
1,2 7,8	2.355cm	45°

antenna elements by utilizing Silver nanoparticle ink from Cabot Corporation. After annealing the printed lines at 160 °C for 10 minutes, a spin-on glass dielectric material is printed on top of the gate electrode and cured. Then, the silver source and drain (same width as transmission line, which is 300 μm) electrodes are printed with the gate length of 100 μm. After annealing, wet silver droplets are printed on the source-drain regions in order to provide a good contact between source drain electrodes with CNT film. The CNT is aligned using dip-coat technique on sacrificial silicon substrate [12]–[14], [22], [23], and the film is lifted-off of the silicon substrate using a special thin Kapton substrate (25 μm thick) with an adhesive on one side. This Kapton substrate containing the CNT film is bonded on top of the printed source-drain regions containing wet silver droplets and the entire structure is annealed to form the CNT-TFT. Detailed process integration, electrical data and bending test results of our CNT-TFT are reported elsewhere [14], [15].

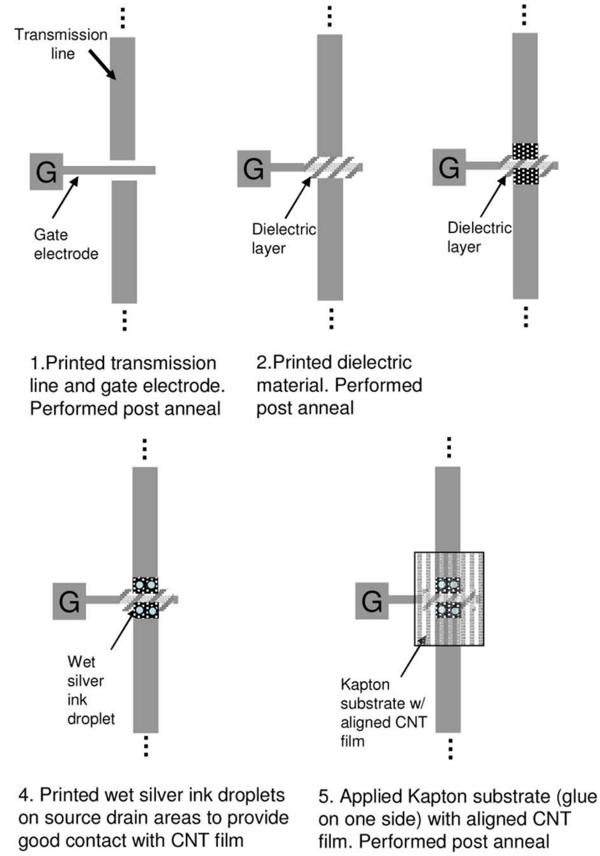

Fig. 5. Schematic of bottom gate integration for our CNT-TFT which acts as a switch in the phase shifter.

D. *Multilayer Metal Interconnection*

Multilayer metal interconnect is also developed to provide connection to the gate electrodes from an external power supply and aid in the packaging of the system. A thin Kapton (25 μm) substrate with adhesive coating on one side (same as the one used to develop the CNT-TFTs) is bonded on top of the first substrate containing the printed PAA subsystem. Contact vias are formed on the thin substrate prior to attaching. A pressurized annealing process at 100 °C is used to bond these layers together. After bonding, silver ink is printed on the thin Kapton layer to form the metal connection lines. The liquid silver ink is printed one or multiple times to fill the contact vias, which makes contact between the bottom gate contact pads and top interconnection lines. Another anneal process is performed to complete the contact. Details of this multilayer metal interconnection are also reported in [15].

Fig. 6 shows a picture of a fully fabricated 2-bit, 1 × 4 PAA system on a Kapton substrate. Notice that a third thin Kapton layer is used on top of the second layer to protect the metal interconnection lines and vias. Probing pads are formed using double-sided copper tape.

III. EXPERIMENTAL SET UP AND DATA

The S_{11} parameter of the printed thin film antenna is measured first to confirm the radiation of the patch antenna, as shown in Fig. 7. It can be seen from the figure that the antenna

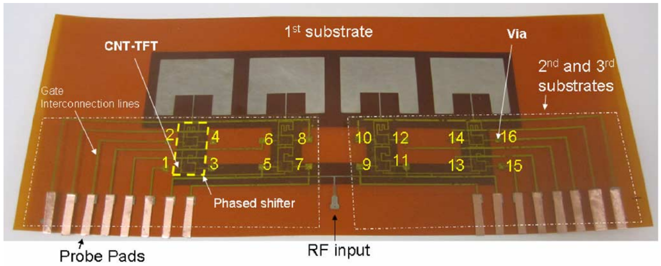

Fig. 6. Picture of a complete 2-bit 1 × 4 PAA system containing CNT-TFTs as switches in the phase shifting network. Multilayer metal interconnection produces a fully packaged system with metal interconnection lines.

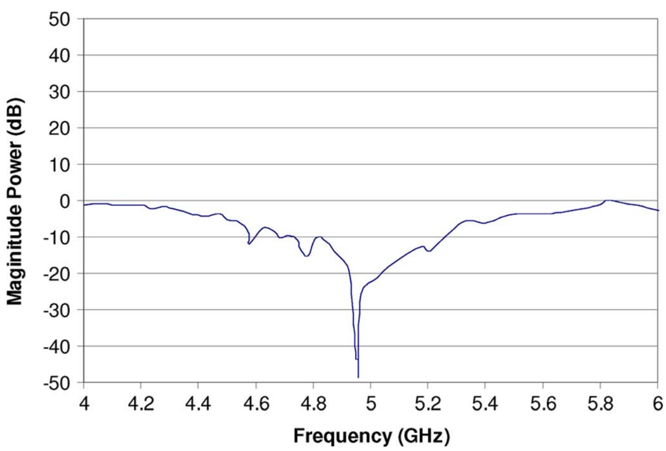

Fig. 7. S_{11} parameter of the printed antenna element. The antenna shows good radiation around 4.99 GHz.

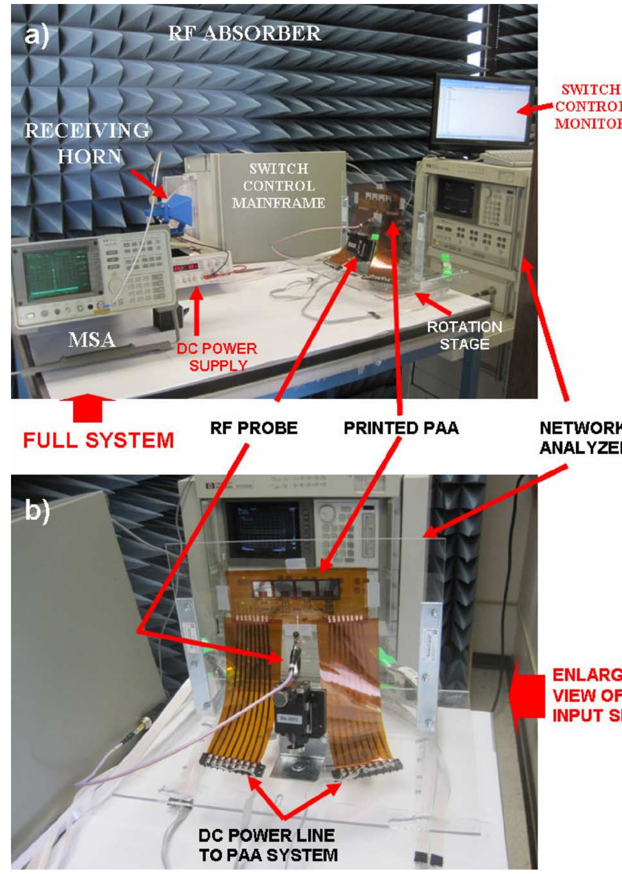

Fig. 8. (a) Experimental setup to measure the far-field radiation pattern of the printed 1 × 4 PAA system; (b) close up picture showing the 1 × 4 PAA system laid flat on a flexi-glass substrate holder.

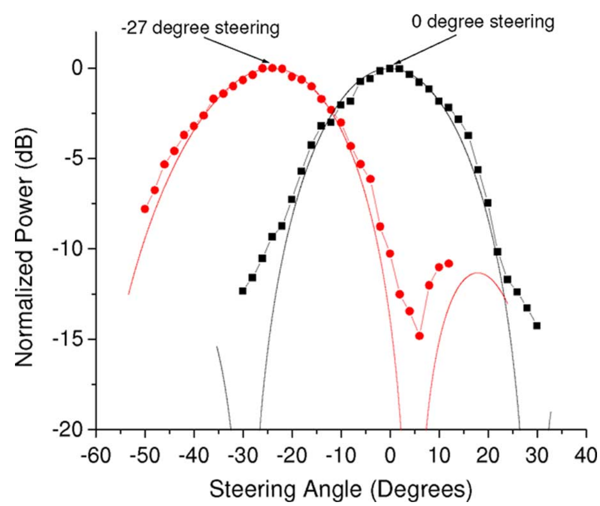

Fig. 9. Measured (indicated by data points) and simulated (indicated by smooth curves) far-field radiation patterns of a 4.99 GHz signal at 0 degree (indicated by black curves) and -27 degrees (indicated by red curves).

radiates well around 4.99 GHz, agreeing well with the designed frequency of 5 GHz.

Figs. 8(a) and (b) show the entire measurement setup for far-field pattern measurement of the fabricated PAA system. The PAA system is spread out flat on a thick flexi glass substrate. We designed the stage such that the flexi glass can also be used to perform bending experiments and study the influence of bending on far-field patterns. The entire circuit is mounted vertically on a precision rotation stage along with the DC and RF probes. The RF signal from a HP8510C network analyzer is applied at the input of the PAA system. The CNT-TFT switch network is controlled using a mainframe computer with a switch control module. As shown in Table I, for each steering angle, 8 CNT-TFT switches are controlled corresponding to each desired steering angle. RF absorbers are arranged around the PAA setup in order to eliminate multipath effects. The radiated signal is received by a receiving horn antenna which is connected to a microwave spectrum analyzer (MSA). The received power is measured on the MSA as a function of the rotation angle, thus producing the far field patterns.

The radiation pattern for a 4.99 GHz signal is measured using the above setup. We measure all the four azimuth steering angles. Fig. 9 shows the measured and simulated far field radiation patterns of the PAA system at 0 degree (black curves) and -27 degree (red curves) steering angles. The measured points are indicated by data points whereas the simulated patterns are shown as smooth curves. It can be seen from the results that the measured and simulated far field patterns agree very well with each other.

IV. Bending Experiment

We also performed an experiment to observe the effect of bending on the performance of the PAA system. Three PAA

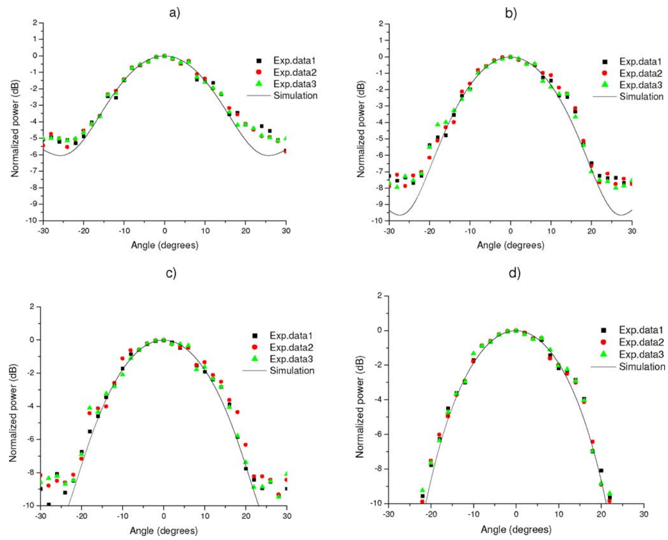

Fig. 10. Theoretical (solid) and measured (dots) far-field radiation pattern for (a) 6.5 cm bending radius, (b) 9.5 cm bending radius, 12 cm bending radius, and (d) 24 cm bending radius.

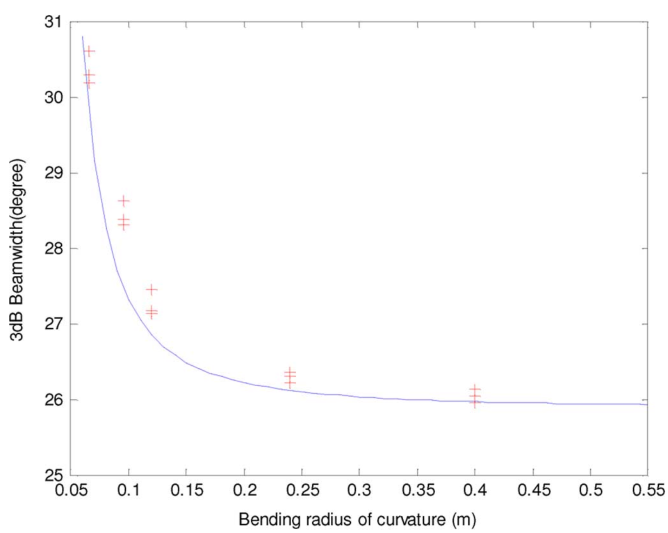

Fig. 11. Theoretical (solid) and measured (crosses) 3 dB beamwidth of the far-field radiation pattern as a function of bending radius of curvature.

samples were fabricated to evaluate their bending characteristics. The PAA system is spread out on circular tube or on bent flexi glass substrate. The entire measuring setup is similar to that shown in Fig. 8.

In order to evaluate the effect of bending on far-field radiation pattern, we first developed a code to simulate the PAA patterns. Using the results from this simulation code, we evaluated the bending performance of our system. Fig. 10 shows the measured (indicated by data points) and simulated (indicated by smooth curves) far-field radiation patterns for four different bending radii. A summary plot showing the calculated and measured 3 dB beamwidth ($\theta_{3\ \mathrm{dB}}$) as a function of bending radius of curvature is shown in Fig. 11 for all three PAA systems. It can be seen that the measured and calculated curves agree well with each other, thus confirming good operation for conformal operations.

V. Conclusion

A light weight, flexible 2-bit, 1×4 phased-array antenna system on Kapton substrate has been presented. CNT-TFT is used as a switch in the phase shifting network. Multilayer metal interconnection is implemented for packaging the full system. By controlling the ON/OFF states of the transistors, beam steering of a 4.99 GHz signal from 0° to −27° has been demonstrated. The antenna system also shows good stability and tolerance under different bending radii of curvature. Compared to traditional antenna design, this light weight, flexible and conformal PAA is a good candidate for portable wireless system to meet challenging requirements.

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Dr. Chen has chaired or been a program-committee member for more than 100 domestic and international conferences organized by the IEEE, SPIE (The International Society of Optical Engineering), OSA, and PSC. He has served as an editor or co-editor for 18 conference proceedings. He is a Fellow of OSA and SPIE. He was the recipient 1987 UC Regent's dissertation fellowship and of 1999 UT Engineering Foundation Faculty Award for his contributions in research, teaching, and services. He is also the recipient of 2008 IEEE teaching award. During his undergraduate years at National Tsing-Hua University, he led a university debate team in 1979 which received the national championship of national debate contest in Taiwan. There are 33 students who have received the electrica engineering Ph.D. degree in Dr. Chen's research group at UT Austin.