Light Weight and Conformal 2-bit, 1x4 Phased-Array Antenna with CNT-TFT Based Phase-Shifter on a Flexible Substrate

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Light Weight and Conformal 2-bit, 1x4 Phased-Array Antenna with CNT-TFT Based Phase-Shifter on a Flexible Substrate

Daniel T. Pham, Harish Subbaraman, Maggie Yihong Chen, Senior *Member, IEEE*, Xiaochuan Xu,
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***Abstract*— This paper presents the development and characterization of an ink-jet printed 2-bit, 1x4 phased-array antenna (PAA) system developed on a flexible Kapton polyimide substrate using carbon nanotube thin-film transistors (CNT-TFTs) as switching elements in the phase-shifting network. A multilayer metal interconnection strategy is used to make a complete PAA system with control lines. By appropriately controlling the ON and OFF states of various switches, a 4.99GHz signal is steered from 0^{o} to -27^{o}. The experimental results show very good agreement between the simulated and measured far-field radiation patterns. An experiment to observe the effect of bending on far-field radiation pattern is also performed.**

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

I. INTRODUCTION

FLEXIBLE antenna has become more attractive in recent times due to the development of several interesting flexible circuit components that can be integrated into one system on a light weight, conformal flexible platform. Since different communication tasks require different antenna technologies, a flexible antenna is important for several communication applications. For example, proximity surface activity applications such as 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 (~ 10 m) to medium range (~ 5-10 km) operation [1].

A very important flexible antenna system, namely the phased array antenna (PAA), is formed by combining the flexible antenna elements and electronics involved, such as transmit/receive (T/R) modules for controlling the system, on a single flexible substrate. The PAA plays an important role in the modern radar system since it can electrically scan the beam in a wide angular range without the need for mechanically rotating the antenna [2]. However, embedding the phase shifting chip on a flexible substrate is not an easy task since the fabrication resolution limit of 50μm line widths achievable from the printing technique, and the limitation on the available flexible substrate material/design, render the size of the embedded electronics to be large. The assembly of these components on flexible substrate; therefore, is prone to reliability issues.

Recently, CNT transistor has shown tremendous progress over the last decade due to their excellent mobility characteristics [4]. CNT TFT-based devices on flexible substrates have achieved high field mobilities using ultrapure electronics-grade CNT solutions [5, 6] by ink-jet printing technique. Other techniques such as dielectrophoresis (DEP) [7], spin-coating [8], and spray-coating [9] to form CNT thin-film transistors have also been demonstrated. All of these techniques yield a random network of CNTs on the substrate. To improve CNT transistor device performance, several techniques to align CNTs have been demonstrated [10-14]. Compared with random network of CNTs, aligned CNT improves the drain current (Ion) by decreasing average carriers path length. Most of the reported aligned CNT thin films are deposited on silicon or quartz substrates via the chemical vapor deposition (CVD) technique [10-14]. This deposition technique is unsuitable for flexible substrates because of the high deposition temperature ($400^{o}C$ -$1000^{o}C$, most CVD process is around $900^{o}C$). Other aligned CNT techniques using self-alignment principle in solution, such as dip-coat technique, shows good performance results [13, 14, 18].

In this report, ink-jet printing technique is used to print a 1x4 phased-array antenna with 2-bit CNT-TFT based phase-

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shifter on multilayer flexible substrate. The CNT-TFT is self-aligned and formed by combining printing and stamping techniques [14,18]. Previous research has shown the 2 elements antenna system by fully printing technique [17].

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, which uses a piezoelectric printing cartridge (DMC-11610) consisting of 16 nozzles, wherein, one or multiple nozzles can be used simultaneously. The ink droplets dispensed from the ink cartridge have a nominal volume of 10pL. The machine is suitable for room temperature printing of circuits on any kind of substrate, including flexible substrates, since the non-contact printing is substrate topography independent. This printing technique, therefore, can also fill the contact "via" during multi-layer interconnection fabrication or print multiple layers of different materials on top of each other.

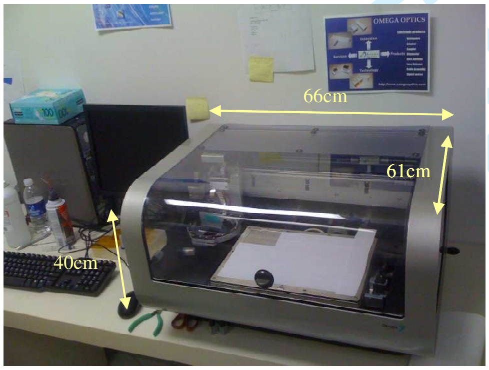


Figure 1: Fujifilm Dimatix Materials Printer

For complicated printing area consisting of small and large structures or closely spaced lines next to each other, as in the case of the PAA system, the orientation of the PAA system needs to be considered such that the printing material can be deposited everywhere uniformly. In our case, printing our PAA system in horizontal position, as shown in figure 1, provides the best result. It is found that in printing small lines and large areas that are located next to each other, the nozzle has a problem of printing uniformly. While printing large areas, the nozzles operate continuously in a long endurance time mode. The printing material wets the nozzle surface, which while printing on small area or small line, could cause a problem. Also, at the beginning of the printing cycle, the nozzle provides uniform deposition, and after printing a large area (long operating time), the performance is degraded. Therefore, breaking the printing area down to several small parts is a good way to have better uniform printing. Figure 1 shows the PAA system architecture formed by connecting two parts. The first part contains narrow width (~300micron) transmission lines. This part can be printed by using a single nozzle on the cartridge for better precision. The second part consists of the large antenna elements, which can be printed using multiple nozzles. Using this type of combination printing, the printed product has better precision 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 the figure 2.

B. Principle of operation of Phased-Array Antenna subsystem

Figure 2 shows the layout of the 2-bit 1x4 element phased array antenna subsystem. Standard microstrip antenna design techniques are followed to design the transmission lines, antenna elements and coplanar waveguide to microstrip line transition sections [19-23]. First, the RF signal is applied through the RF input coupling section. This 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). Each of the 4 branches feed a phase shifting network. A schematic of a 2-bit phase shifter is shown in Figure 3. Each of the switches in the phase shifter is a CNT-TFT. Table 1 shows the switching pair selection for the phase shifter versus steering angle for the designed PAA system. Switch numbers are shown on figure 4 for reference. By controlling the ON/OFF ratio of the switch pairs as indicated in Table 1, beam steering at -27 °, 0 °, 27 °, and 45° is achieved. This PAA system is designed for operation at 5GHz (C-band).

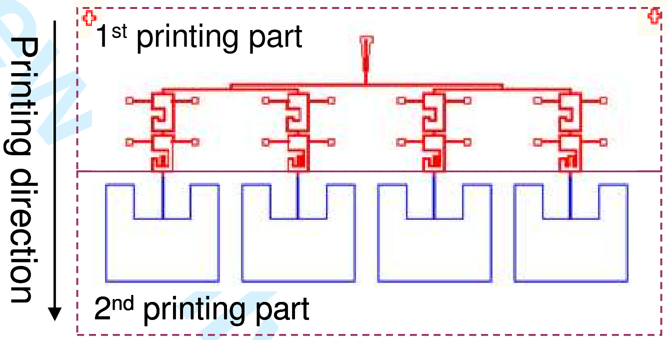


Figure 2: Schematic of a 2-bit, 1x4 Phased-Array Antenna. Printing transmission lines and antenna elements separately provides good printing coverage.

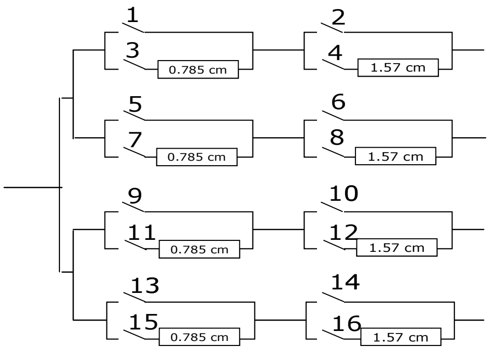


Figure 3: 2-bit, 1x4 array phase shifter design

Switch Pair Selection	Length difference between adjacent elements	Steering Angle
1, 2 6, 7 9, 12 15, 16	0.785cm	27°
3, 4 5, 8 10, 11 13, 14	-0.785cm	-27°
1, 2 5, 6 9, 10 13, 14	0	0°
1, 2 5, 7	2.355cm	45°

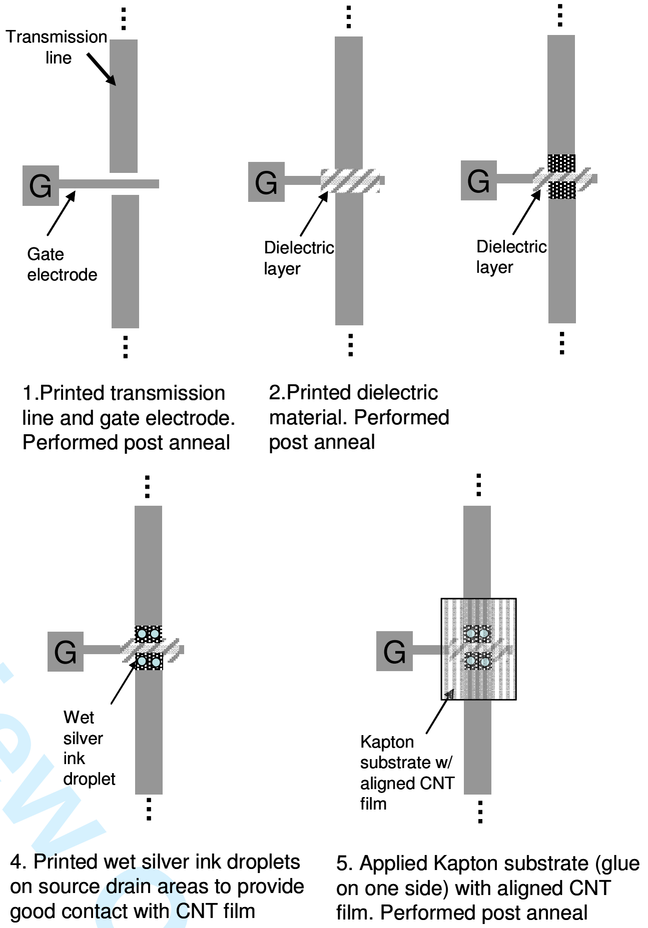
Table 1: Switching selection versus steering angle.

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

Carbon nanotube thin-film transistors (CNT-TFTs) are formed by a combination of printing and stamping techniques on a 125μm thick Kapton Polyimide substrate [14,18]. Figure 4 shows a schematic of the bottom gate integration process flow for the CNT-TFT. At first, the silver gate electrode is printed together with the silver transmission lines and antenna elements by utilizing Silver nanoparticle ink from Cabot Corp. 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 annealed. Then, the silver source and drain (same width as transmission line which is 300 μm) electrodes are printed with the gate length of 100μm. After annealing, wet silver droplets are printed on the source drain areas to provide a good contact between source drain electrodes with CNT film which is captured by a special thin Kapton layer with glue on one side. The CNT is aligned by using dip-coat technique on sacrificial silicon substrate [12-16]. Detailed process integration, electrical data and bending test results of our CNT-TFT are reported in reference [14,18].

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 packaging the system. A thin Kapton (25μm) substrate with adhesive coating on one side is bonded on top of the first substrate containing the printed PAA subsystem. Contact vias are formed prior to attaching in order to obtain metal contacts with the gate contact pads on the first substrate. A pressurized annealing process on a heat chuck at 100°C is used to bond these layers together. Then, silver ink is printed on the top 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 in order to evaporate the remaining solvent in the silver solution to form solid silver filled contact vias. Detail of this multilayer metal interconnection is also reported in reference [18].



1.Printed transmission line and gate electrode. Performed post anneal

2.Printed dielectric material. Performed post anneal

4. Printed wet silver ink droplets on source drain areas to provide good contact with CNT film

5. Applied Kapton substrate (glue on one side) with aligned CNT film. Performed post anneal

Figure 4: Schematic of bottom gate integration for our CNT-TFT which acts as a switch for the phased shifter.

Figure 5 shows a picture of a fabricated 2-bit, 1x4 PAA system on a Kapton substrate. Notice that a third thin Kapton layer is applied on top of the second layer to protect the metal interconnection lines and vias. Probing pads are formed using double-sided copper tape.

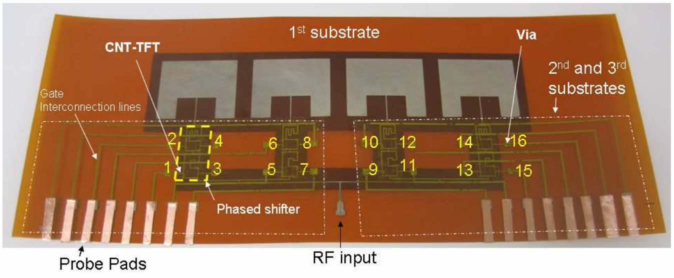


Figure 5: Picture of a complete 2-bit 1x4 PAA system containing CNT-TFTs as switches in the phase shifting network. Multilayer metal interconnection produces a fully packaged system with metal interconnection lines.

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 figure 6. It can be seen from the figure that the antenna radiates well around 4.99GHz.

The next step is to measure the PAA far-field pattern. Figures 7 (a) and (b) show the entire measurement setup with the network analyzer, receiving horn and microwave spectrum analyzer (MSA). The RF signal from a HP8510C network analyzer is applied at the input of the 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 CNT-TFT switch network is controlled using a mainframe computer with a switch control module. As shown in Table 1, 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 multi-path 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 4.99GHz signal is collected using the above setup. We measure all the four azimuth steering angles. Figure 8 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.

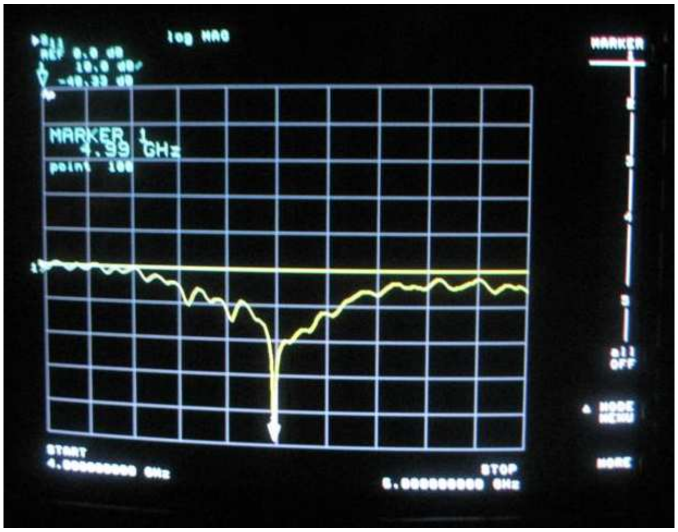


Figure 6: S11 parameter of the 1x4 PAA system.

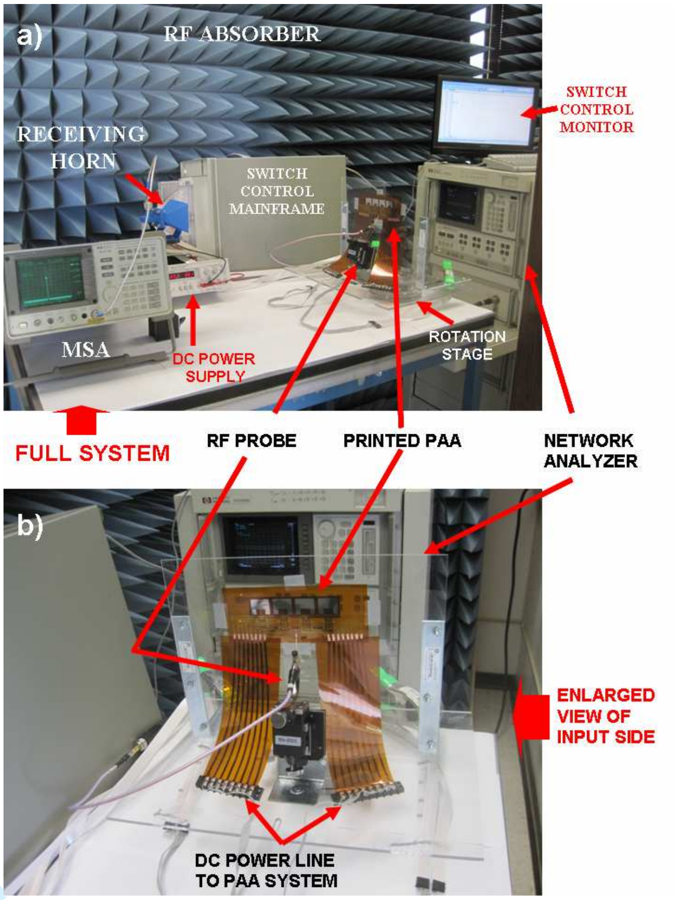


Figure 7: a) Experimental setup to measure the far-field radiation pattern of the printed 1x4 PAA system, b) Close up picture showing the 1x4 PAA system laid flat on a flexi-glass substrate holder.

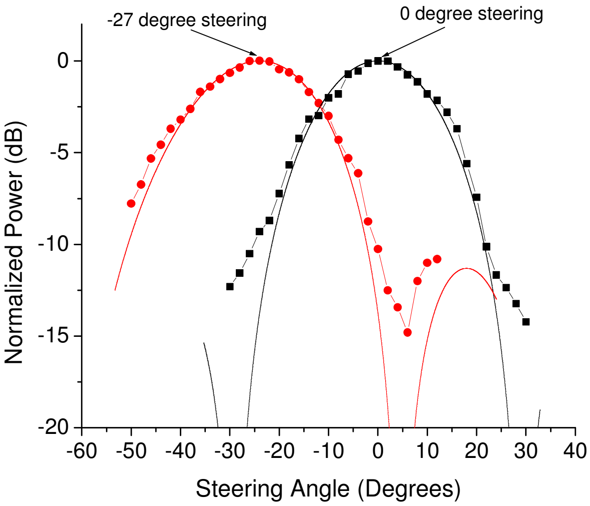


Figure 8: Measured and Simulated Far-Field Radiation Patterns of the Printed PAA system for 4.99GHz signal at 0 degree (indicated by black curves) and -27 degrees (indicated by red curves).

IV. BENDING EXPERIMENT

We also performed an experiment to observe the effect of bending on the far-field radiation pattern of the PAA system. Three PAA 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 Figure 7.

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. Figure 9 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 θ_{3dB} as a function of bending radius of curvature is shown in Figure 10 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.

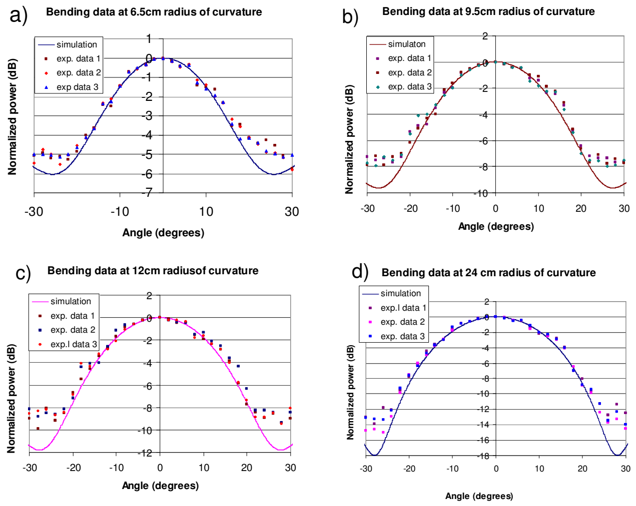


Figure 9: Theoretical (solid) and measured (dots) far-field radiation pattern for (a) 6.5cm bending radius, (b) 9.5cm bending radius, 12cm bending radius, and (d) 24cm bending radius.

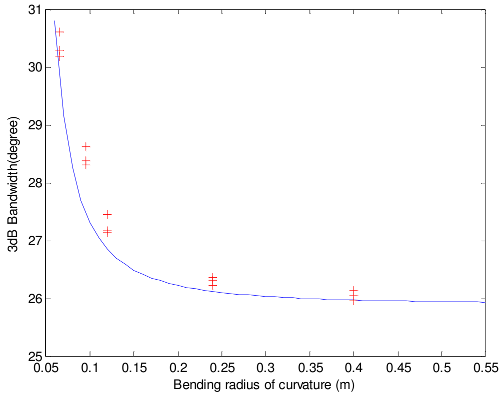


Figure 10: Theoretical (solid) and measured (crosses) 3dB bandwidth of the far-field radiation pattern as a function of bending radius of curvature

V. CONCLUSION

A light weight, flexible 2-bit, 1x4 phased-array antenna system on Kapton substrate has been presented. CNT-TFT is used as a switch in the phase shifting network. Multilayer metal interconnect is also implemented for packaging the full system. By controlling the ON/OFF states of the transistors, beam steering of a 4.99GHz signal from 0^{o} to -27^{o} 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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Maggie Yihong Chen. Dr. Chen received her Ph.D. degree of Electrical Engineering in optoelectronic interconnects from the University of Texas at Austin, Texas (2002). She is an Assistant professor at Electrical Engineering at Texas State University-San Marcos. Dr. Chen's research work in the past ten years has been focused on optical true-time delay feeding networks for phased-array antennas, planar waveguide devices, optoelectronic interconnects, and diffractive optical elements. Dr. Chen has over 50 publications in refereed journals and conferences. She is a senior member of IEEE and SPIE.

Xiaochuan Xu. He received the B.S and M.S. degrees in Electrical Engineering from Harbin Institute of Technology, China. He is currently pursuing Ph.D in Electrical and Computer Engineering department at University of Texas at Austin

Ray T. Chen holds the Cullen Trust for Higher Education Endowed Professorship at UT Austin and the director of nanophotonics and optical interconnects research lab within the microelectronics research center. He is also the director of a newly formed AFOSR Multi-disciplinary Research Initiative (MURI) Center for Silicon Nanomembrane involving faculty from Stanford, UIUC, Rutgers and UT Austin. He received his BS degree in Physics from National Tsing-Hua University in 1980 in Taiwan and his MS degree in physics in 1983 and his PhD degree in Electrical Engineering in 1988, both from the University of California. He joined UT Austin as a faculty to start optical interconnect research program in the ECE Department in 1992. Prior to his UT's professorship, Chen was working as a research scientist, manager and director of the Department of Electrooptic Engineering in Physical Optics Corporation in Torrance, California from 1988 to 1992. Chen also served as the CTO/founder and chairman of the board of Radiant Research from 2000 to 2001 where he raised 18 million dollars A-Round funding to commercialize polymer-based photonic devices involving over 20 patents, which was acquired by Finisar in silicon valley(NASDAQ: FNSR). He also serves as the founder and Chairman of the board of Omega Optics Inc. since its initiation in 2001. Over 5 million dollars of research funds were raised for Omega Optics. His research work has been awarded with 99 research grants and contracts from such sponsors as DOD, NSF, DOE, NASA, the State of Texas, and private industry. The research topics are focused on three main subjects: 1. Nano-photonic passive and active devices for optical phased array and interconnect applications, 2. Thin film guided-wave optical interconnection and packaging for 2D and 3D laser beam routing and steering, and 3. True time delay (TTD) wide band phased array antenna (PAA). Experiences garnered through these programs in polymeric material processing and device integration are pivotal elements for the research work conducted by Chen's group.

Chen's group at UT Austin has reported its research findings in more than 540 published papers including over 60 invited papers. He holds 20 issued patents. He has chaired or been a program-committee member for more than 100 domestic and international conferences organized by IEEE, SPIE (The International Society of Optical Engineering), OSA, and PSC. He has served as an editor or co-editor for eighteen conference proceedings. Chen has also served as a consultant for various federal agencies and private companies and delivered numerous invited talks to professional societies. Dr. Chen is a Fellow of IEEE, 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. We is also the recipient of 2008 IEEE teaching award. Back to his undergraduate years in 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 received the EE PhD degree in Chen's research group at UT Austin.