Design and Fabrication of A Sub-THz Co-Reflectively Curved Patch-Reflector Antenna Array for Gain Enhancement and Near Field Focusing

Ching-Jen Lee
Institute of Electronics Engineering, National Yang Ming Chiao Tung University, Hsinchu, Taiwan
xxdd.hahaha1124@gmail.com

Pin-Cheng Tseng
Institute of Electronics Engineering, National Yang Ming Chiao Tung University, Hsinchu, Taiwan
e0710186.ee07@nctu.edu.tw

Wei-Chian Wang
Institute of Electronics Engineering, National Yang Ming Chiao Tung University, Hsinchu, Taiwan
wonging666@gmail.com

Yun-Hao Liou
Institute of Electronics Engineering, National Yang Ming Chiao Tung University, Hsinchu, Taiwan
tripleman01@gmail.com

Yu-Ting Cheng*
Institute of Electronics Engineering, National Yang Ming Chiao Tung University, Hsinchu, Taiwan
ytcheng@nycu.edu.tw

Chien-Nan Kuo
Institute of Electronics Engineering, National Yang Ming Chiao Tung University, Hsinchu, Taiwan
cnkuo@nycu.edu.tw

Abstract—This paper presents a sub-THz co-reflectively curved patch-reflector antenna array, which is a co-reflecting surface stage made by 3D stereolithography-SLA printing technology to integrate a 160 GHz, 1x4 curved patch antenna array. The co-reflecting surface stage is applied for supporting the patch antenna array made of a micromachined flexible Kapton substrate to achieve gain enhancement and near-field focusing functions. In the near-field measurement of the antenna array, -9.34 dBm @ 160 GHz signal power is measured at a 3 mm distance to the patch array, which is consistent with the simulation results. According to the simulation results, the co-reflecting antenna can accomplish an antenna gain of 13.3 dB, an increase of 2.4dB as compared to that without co-reflection surface design for far-field radiation. In addition, for a -19dBm power input into the antenna array, a maximum radiated energy of -11.95 dBm with 82% half-radiated energy area reduction at a distance of 4 mm to the patch array and depth of focus (DOF) of 3.05 mm can be obtained indicating the proposed antenna scheme can exhibit near-field focusing ability.

Keywords—Near field focus, Reflector antenna, Patch antenna array, Co-reflecting Surface

I. INTRODUCTION

Recent technology development in wireless communication systems towards ultra-high speed and data rate specifications is aimed at facilitating the applications of artificial intelligence (AI), virtual reality/augmented reality (AR/VR), unmanned vehicles, etc. [1-3]. For example, the present 5G wireless network communication system designated for data-centric and automated systems is still incapable of handling the future convergence of the communication, intelligence, sensing, control, and computing functionalities, which are required for the realization of beyond 5G (B5G) system [3]. Satellite-to-satellite links in low earth orbit (LEO) satellite systems are necessities to intensify various industrial applications ranging from the far from terrestrial coverage communication, earth observation, signal monitoring to scientific missions. Currently, there are two approaches to realizing high data rate communication, which are the utilization of wider bandwidth and higher carrier frequency schemes, respectively. However, for obtaining bandwidth above 100 GHz, the scheme using the carrier frequency in sub-THz, i.e. 0.1-0.3 THz has been recognized as an essential mean in the 6G wireless communication system [4-6].

Meanwhile, THz-wave imaging or sensing systems have become interesting research objects for many applications such as environment detection, biomedicine, homeland security, etc. For THz imaging, the characteristics of nonionizing and good penetration through nonmetallic and nonpolar material make the imaging system more attractive with the capability of “see through” without harming the object or live tissue interrogated. For THz sensing, the characteristics of resonance related to both macro- and bio-molecular interactions in the THz regime like resonant absorptions of binding states can be used for label-free biomolecule analysis based on corresponding material-specific spectral fingerprints [7].

With the advance of nm-CMOS technology same as the SiGe one, the ft and fmax of the silicon-based transistors can be greater than 300 GHz, which makes them ideal for sub-THz circuit design. Although the output power of the THz signal generated by the CMOS-based chips is relatively small in comparison with the typical solid-state THz sources generated by ultrafast optoelectronics [4], microwave tube [5], quantum cascade laser [6], nonlinear crystal [8], etc., small form factor and low manufacture cost have shown the applicability in THz microsystems for portable applications. Combined with the inherent characteristics of THz signals such as high path loss and molecular absorption loss, the newly CMOS-based THz microsystems require high gain design and implementation for better system performance.
Antenna design typically depends on its application. For example, a high antenna gain and directivity design conflicts with the broadband one. It is difficult for an antenna to exhibit these characteristics at the same time without changing its size [9]. Due to the wide applications of near-field focusing in biomedical image and sensing and 6G communication systems [10,11], varieties of near-field focusing antennas optimized with specific algorithms, such as Levenberg–Marquardt algorithm [4], Steepest Descent Method (SDM) [5], etc. have been proposed in recent decades. These antennas are reflector antenna [6], horn antenna [8], disk-like patch array antenna [12] imitation surface patch array antenna, patch array antenna [13], respectively. Among these antennas, reflector antenna and patch array antenna can exhibit the advantages of high gain, low profile and easy fabrication [14]. The higher the signal frequency is, the smaller the wavelength will be, thereby facilitating the sub-THz antenna miniaturization using silicon micromachining technology. For example, Lisa et al demonstrated the fabrication process of the THz reflector based on silicon-on-wafer technology [15].

Previously, we demonstrated a disk-like patch antenna array for generating a focused THz source and also a silicon-based parabolic reflector antenna integrated with monolithic microwave integrated circuit sources, i.e. 40 nm CMOS triple-push oscillator, for achieving an excellent near field focus characteristic with a 28.5 mm depth of field (DOF). Both of the antennas adapted the fabrication process of patterned Kapton on a micromachined silicon substrate to realize spherical microstructures, i.e., hemispherical shell and parabolic reflector. In this paper, we will apply the stereolithography-SLA (laser) printing technology to realize smoother and smaller 3D curved microstructures for the fabrication of a co-reflectively curved patch-reflector antenna array as shown in Figure 1. There are four in-parallel patch antennas locating on a co-centered curved surface on which each patch antenna is devised on the focus point of a parabolic reflector. Combining the characteristics of the antenna array and reflector antenna, better sub-THz source gain enhancement can be expected.

II. ANTENNA ARRAY DESIGN AND FABRICATION AND MEASUREMENT SETUP

The proposed antenna comprises two major components, which are 1x4 patch-reflector antenna array and co-centered curve structure, respectively. For the patch antenna array design, we utilized the full-wave electromagnetic Ansoft High Frequency Structure Simulator (HFSS) to design a single 160 GHz patch antenna on a Kapton substrate fed with a 100 Ω microstrip line as shown in Figure 2. The microstrip line is designed based on the following equations [16]:

\[
W = \frac{c}{2f_0 \sqrt{\frac{\varepsilon_f}{2}}}, \quad \varepsilon_{eff} = \frac{\varepsilon_f + 1}{2} + \frac{\varepsilon_f - 1}{2} \sqrt{1 + 12 \left(\frac{h}{w}\right)^2}
\]  
(1)

![Figure 2: A single patch antenna design with corresponding geometric parameters for a resonant frequency of 160 GHz.](image)

![Figure 3: Simulation results of the patch antenna: (a) S11 (b) 3D radiation pattern](image)
where \( f_0, W, L, h, \) and \( \varepsilon_R \) are the resonant frequency, the width, length and substrate thickness of the patch, and the dielectric constant, respectively. Figure 3 shows the simulated reflection coefficient, \( S_{11} \), and 3D radiation pattern of the signal patch antenna indicating the antenna can exhibit a maximum antenna gain of 6.68 dB@158 GHz. The antenna is then used for the 1x4 array design where the pitch of the antenna array is set with \( \lambda/2 \), i.e. ~938 \( \mu \)m to suppress the generation of grating lobes from adjacent antennas as shown in Figure 4. Every two patch antennas are firstly connected in parallel and fed with a 3/4, 70.7 \( \Omega \) microstrip line, and then two identical sets of the connected antennas are connected and fed with a 50 \( \Omega \) microstrip line. From the simulated reflection coefficient, \( S_{11} \), and 3D radiation pattern of the 1x4 patch antenna array as shown in Figure 5, the array can accomplish a gain enhancement of 1.4 dB@162 GHz, thereby increasing the maximum antenna gain up to 8.08 dB.

Regarding the design of parabolic reflectors for the patch antenna array, the ratio of focus length \( (F) \) and the aperture size \( (D) \) of the reflector, i.e., \( F/D \), is set at 0.33, which is a trade-off between the antenna size and radiation efficiency. The smaller the aperture of the reflector is, the lower the radiation efficiency of the antenna will be as result of excessive radiated power leakage. Nevertheless, the aperture size and focal length can be two design parameters to be used for optimizing the antenna performance with the patch antenna size, while the \( F/D \) ratio is kept constant. In this work, the aperture size and focus length of the reflector are designed as 5 mm and 1.5 mm, respectively.

In order to create a focused source, the four patch-reflector antennas are designed on the same spherical surface. As a result, while the overall size of the antenna array is miniaturized, the four parabolic reflectors will inevitably overlap with each other to form a merged co-reflector. Figure 6 shows the proposed schematic 3D exploded graph of the co-reflectively curved patch-reflector antenna array where the patch antenna array is supported by a photo-sensitive polymer-based overhang on the top of the substrate with a co-reflector, which is curved and merged by the four parabolic reflectors. Both the overhang and the co-reflector substrate are fabricated using the stereolithography laser (SLA) printing technology, which can realize smoother and smaller 3D curved structures [17]. The inset of Figure 6 is the as-fabricated co-reflector substrate metalized by the Cu deposition.

Figure 7 depicts the fabrication processes of the antenna array: (a) Laminating A 75\( \mu \)m thick Kapton film on a silicon carrier substrate, (b) Depositing a layer of (Ti\_50 nm/ Cu\_500 nm) on the Kapton, (c) Spin-coating and photo-patterning a layer of AZ-4620 as an etching mask (d) Etching Ti/Cu in the solution of HAc:HO\_2:H\_2O = 5:5:100, and then in the solution of buffered oxide etchant (BOE) (e) detaching the Kapton from the silicon substrate, (f) flipping over and then re-laminating the...
Kapton on another silicon substrate followed by sputtering another layer of Ti/Cu, (g) removing the Kapton from the silicon substrate, (h) laser cutting Kapton substrate to form a patch antenna array, and (i) dispensing silver paste to electrically connect the top and backside metal layers. Once the flexible antenna array is fabricated, it will be bonded to the printed overhang structure and co-reflector substrate to form the final co-reflectively curved patch-reflector antenna array. Figure 8 shows the photographs of the laser-cut patch antenna array bonded to the overhand (Figure 8(a)) and the as-fabricated patch-reflector antenna array mounted on a PCB board (Figure 8(b)). Noted that the overhand interlocked onto the co-reflector substrate is designed to ensure that the patch antenna array locates precisely on the focal points of the co-reflector.

For the antenna measurement, we used Agilent E8257D function generator to generate a 40GHz signal with an input power of 10 dBm. The 40GHz signal was fed into an in-lab frequency multiplier CMOS chip [18], which can double the signal frequency up to 160 GHz and be delivered to the antenna array via bonding wires. The signal detector was a horn antenna (WR5.1 horn antenna) connected to a power meter (PM5). Lastly, we set both the DUT, i.e., the antenna array, on a positioner with a motion controller (ESP301) and the detector on an optical table to measure the XYZ energy distribution as shown in Figure 9.

### III. RESULTS AND DISCUSSION

Table 1 and 2 list the comparison of simulated radiated maximum power and corresponding -3 DB positions with respect to z-axis of the patch-reflector antenna array with/without the curved co-reflector, respectively. The results indicate the patch antenna array fed with -19 dBm power input can exhibit a radiated 160 GHz pattern with a maximum power of -10.79 dBm and a -3 dB spot size of 0.99 mm², while being incorporated with the curved co-reflector with a radius curvature of 3 mm. Figure 10 shows the simulated near-field radiation of the co-reflectively curved patch-reflector antenna array: (a) radiated energy density map in the Y-Z plane, (b) normalized radiation power density vs. the distance from aperture along the Z-axis, (c) the maximum energy profile in the X-Y plane of the patch-reflector antenna array with the co-reflector, and (d) the maximum energy profile in the X-Y plane of the patch-reflector antenna array without the co-reflector.

**Figure 10:** Simulated near-field radiation of the co-reflectively curved patch-reflector antenna array: (a) radiated energy density map in the Y-Z plane, (b) normalized radiation power density vs. the distance from aperture along the Z-axis, (c) the maximum energy profile in the X-Y plane of the patch-reflector antenna array with the co-reflector, and (d) the maximum energy profile in the X-Y plane of the patch-reflector antenna array without the co-reflector.

**Figure 11:** 3D far-field radiation patterns of the co-reflectively curved patch-reflector antenna array (a) with (b) without the co-reflector.
focus radiation distribution pattern of the co-reflectively curved patch-reflector antenna array designed with an aperture size and focus length of 5 mm and 1.5 mm for the reflector and a radius curvature of 4 mm for the co-reflectively curved structure. The energy profile in the Y-Z plane @ X=0 shows there is a region where the radiation energy converges between the distance of 1.6 mm and 4 mm away from the antenna (Figure 10 (a)). According to the normalized power density distribution of the reflector antenna array along the Z-axis, the near-field focusing capability can be realized with the depth of focus DOF of ~3.05 mm@ Y=0 mm (Figure 10(b)). Figure 10(c) and (d) juxtapose the maximum energy profile in the X-Y plane of the patch-reflector antenna array with/without the co-reflector indicating the co-reflector can result in a smaller near-field focused spot with higher radiated energy where the maximum power of the antenna with the co-reflector is -11.95 dBm, and the one from the antenna without co-reflector is -17.12 dBm. In addition to the 5.71 dB power enhancement, there is 82% size reduction of the near-field focused spot from 5.71 mm² to 1.02 mm².  

Figure 11 shows the simulated far field radiation patterns of the co-reflectively curved patch-reflector antenna array designed with an aperture size and focus length of 5 mm and 1.5 mm for the reflector and a radius curvature of 4 mm for the co-reflectively curved structure, respectively. As compared to the patch-reflector antenna array without the co-reflector, the co-reflecting design can enhance the maximum gain of the antenna array from 10.9 dB to 13.3 dB, i.e., 2.4 dB gain increase.

In this work, we utilized an in-lab CMOS frequency multiplier chip whose high frequency signal I/Os were wire-bonded to corresponding ports of the antenna and function generator to generate a 160 GHz signal for the verification of the antenna performance. As a result, we can only characterize the antenna based on the structure with a flipped-over overhang where the co-reflector can only enhance the backfire side lobe signals. About -9.3 dBm, 160GHz signal power was measured at a distance of 3 mm to the patch array in the power measurement. Figure 12 shows the near-field measurement of the normalized signal power vs. the distance from the center of the antenna array, which is close to the simulation results after considering the transition loss from the PCB to the chip and the chip to the antenna waveguide. These losses can be effectively resolved using through substrate via (TSV) and flip-chip bonding technology [19,20]. Although further research development is underway, these results still infer that the proposed antenna scheme should be able to exhibit excellent source-focusing capability.

IV. CONCLUSIONS

We have demonstrated a co-reflectively curved patch-reflector antenna array, which is a 1x4 patch antenna array on a curved co-reflector substrate. Simulation results show that the antenna array can accomplish gain enhancement and near-field focusing functions. Meanwhile, the near-field measurement shows -9.3 dBm, 160 GHz signal power was measured at a 3 mm distance to the patch array in the power measurement, which is consistent with the simulation results after considering the transition loss from the PCB to the chip and the chip to the antenna waveguide.

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