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Research Article

Performance Investigations of Quasi-Yagi Loop and Dipole Antennas on Silicon Substrate for 94 GHz Applications

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This paper introduces the design and implementation of two high gain Quasi-Yagi printed antennas developed on silicon substrate for 94 GHz imaging applications. The proposed antennas are based on either driven loop or dipole antennas fed by a coplanar waveguide (CPW) feeding structure. For better matching with the driven antennas, a matching section has been added between the CPW feedline and the driven antenna element. To improve the gain of either loop or dipole antennas, a ground reflector and parasitic director elements have been added. Two Quasi-Yagi antenna prototypes based on loop and dipole antenna elements have been fabricated and experimentally tested using W-band probing station (75–110 GHz). The measured results show good agreement with simulated results and confirm that the proposed antennas are working. In addition, a feed and matching configuration is proposed to enable coupling a microbolometer element to the proposed Quasi-Yagi antenna designs for performing radiation pattern measurements.

1. Introduction

In recent years, the printed Yagi-Uda antennas have attracted much interest with many applications in radar, millimeter-wave (MMW) imaging, wireless communication systems, phased arrays, and so forth. This is because they have many advantages such as wide bandwidth, high gain, low cost, end-fire radiation patterns, and ease of manufacturing and integration with other microwave circuits. In 1982, the printed Yagi-Uda antenna was introduced for the first time [1]. It consists of a driven element, a reflector, and one or more directors to create end-fire radiation characteristics. Presently, many researchers have exerted significant efforts to come up with several planar Yagi and Quasi-Yagi antenna designs to improve their performance [2–17]. One key factor to obtain a wide operating bandwidth is the design of a suitable feed structure for these kinds of antennas.

A differentially fed high gain Yagi-Uda antenna with folded dipole feed was introduced in [2]. However, it has a bigger size along with degraded performance because of its complex feeding structure. A Quasi-Yagi antenna with a wide bandwidth of 74% and a gain of 4–8 dBi was proposed [3]. However, the asymmetry of those antennas also deteriorated their radiation performances. The complementary metal-oxide semiconductor transistor (CMOS) technology is used to design a CPW-fed on-chip Yagi-Uda antenna operating at 60 GHz [4]. However, a very low gain of −10 dB was achieved. In order to enhance the front-to-back ratio of the Quasi-Yagi antenna, another design based on a series-fed two-bowtie dipole array is presented [5]. In order to reduce the size of

Quasi-Yagi antenna, the Koch fractals (Sierpinski) shaped dipole elements are introduced [6]. In [7], in order to achieve the multiband operation for Yagi antenna, a driven dipole element is used with derived sections. Another design for a wideband Quasi-Yagi antenna with achievable bandwidth of 46% which is fed by microstrip-to-slot line transition is proposed [8]. In [9], a Quasi-Yagi antenna was designed to achieve a size reduction in the length of driver by using a folded dipole as a driven element. The proposed antenna has an achieved operational bandwidth of 1.3 : 1. A broadband planar Yagi antenna for millimeter-wave and submillimeter detectors has been proposed [10]. Another design for Quasi-Yagi antenna at 60 GHz is based on genetic algorithm (GA) to achieve a bandwidth of 16% [11]. Because of their high gain, an electrooptic (EO) wireless millimeter-wave-lightwave signal converter is proposed using planar Yagi-Uda array antennas coupled to resonant electrodes [12]. In [13], a novel wideband planar Quasi-Yagi antenna with a bandwidth of 48% and a gain of 6.2 dB using x-shaped elements is presented. A 60 GHz differential on-chip Quasi-Yagi antenna fabricated with 0.18 μm CMOS technology is proposed [14]. However, the achieved bandwidth is 33% and the gain is only −2.64 dB.

In this paper, two different Quasi-Yagi antennas utilizing either driven loop or dipole antennas are proposed. Two novel antenna designs, Yagi dipole and Yagi loop antennas, are proposed, manufactured, and measured. The proposed Quasi-Yagi antenna using elliptical loops instead of regular dipole elements is a novel design. The truncated ground plane of the antenna acts as a reflector for the transverse-electric surface wave generated by the driver. The parasitic directors are used to enhance the radiation in the forward end-fire direction. Novel feed and matching configuration to allow coupling a microbolometer element is proposed to enable a simple method for radiation pattern measurement. Two antenna prototypes have been fabricated and tested experimentally using a probing station. We also propose a novel feed and matching configuration to allow coupling a microbolometer element with the proposed Quasi-Yagi antennas for measuring the radiation patterns at 94 GHz. The simulated and measured results show that the antenna gain can reach 4 dBi and 8.1 dBi for prototypes I and II, respectively. The achieved beam width is of approximately 25° and 27° in XY plane ($\theta = 90°$) and approximately 51° and 54° in YZ plane ($\phi = 90°$) for prototypes I and II, respectively. The antenna radiation efficiency can reach 88% and 77% for prototypes I and II, respectively. Compared to other W-band millimeter-wave antennas fabricated on silicon substrates, our antennas are showing relatively higher gains.

2. The Proposed High Gain Quasi-Yagi Loop Antenna Prototype I

2.1. Antenna Geometry and Design. The geometrical configuration and seen structure of the proposed Quasi-Yagi loop antenna prototype I are introduced in Figure 1. The top view and side view of the proposed antenna are shown in Figures 1(a) and 1(b), respectively. The antenna is built on a silicon dioxide (SiO_2) layer ($\varepsilon_r = 4.84$) above a silicon (Si) substrate with $\varepsilon_r = 11.7$. It consists of a driven elliptically shaped loop antenna, ground reflector (bigger in size), and two elliptically shaped parasitic loop directors (smaller in size) in front of the driven antenna. The antenna is fed using a coplanar waveguide (CPW) feeding structure. To improve the impedance matching between the driven antenna and the CPW feedline, a matching section has been utilized. Figure 1(c) presents the detailed view for matching section and CPW feedline. The optimized antenna parameters are calculated using extensive parametric studies and optimization techniques done in the full wave Computer Simulation Technology Microwave Studio (CST MWS) software program [18]. Table 1 summarized the optimized dimensions for the proposed Quasi-Yagi loop antenna prototype I.

Table 1: Optimized Quasi-Yagi loop antenna prototype I dimensions.

Parameter	Quantity	Value
A_1	Driven ellipse major radius	928 μm
B_1	Driven ellipse minor radius	430 μm
T_1	Driven ellipse thickness	72 μm
S_1	Spacing between the driven antenna and director 1	1302 μm
A_2	Director 1 ellipse major radius	480 μm
B_2	Director 1 ellipse minor radius	280 μm
T_2	Director 1 ellipse thickness	72 μm
S_2	Spacing between director 2 and director 1	802 μm
A_3	Director 2 ellipse major radius	480 μm
B_3	Director 2 ellipse minor radius	280 μm
T_3	Director 2 ellipse thickness	72 μm
W_G	Ground reflector width	302 μm
L_G	Ground reflector length	1520 μm
W	Substrate width	3502 μm
L	Substrate length	5002 μm
W_M	Matching section width	564 μm
L_M	Matching section length	268 μm
W_1	Interdigital capacitor width	294 μm
L_1	Interdigital capacitor length	1052 μm
W_F	CPW feedline width	32 μm
G	CPW feedline gap	27 μm
H_{Si}	Si substrate thickness	380 μm
H_{SiO_2}	SiO_2 layer thickness	1.2 μm
H_{Al}	Al thickness	0.2 μm

2.2. Antenna Fabrication. The designed antennas are fabricated on a 385 μm thick high resistivity ($\rho > 5000\,\Omega$ cm) Si substrate. The Si substrate is coated on both sides with a 1.2 μm layer of SiO_2 for the purpose of electrical isolation. The following steps were performed for fabricating the printed antenna structures. First, a 200 nm layer of aluminum (Al) was deposited on the Si/SiO_2 substrate using direct current (DC) magnetron sputtering at 150 Watts of power, a chamber base pressure of 1.5×10^{-6} Torr, and an argon (Ar) pressure of 3 mTorr. Rohm & Haas S1813 photoresist was then spun at 4500 rpm for 60 sec. The photoresist was exposed for 4 sec at 175 Watts of ultraviolet power at a wavelength of

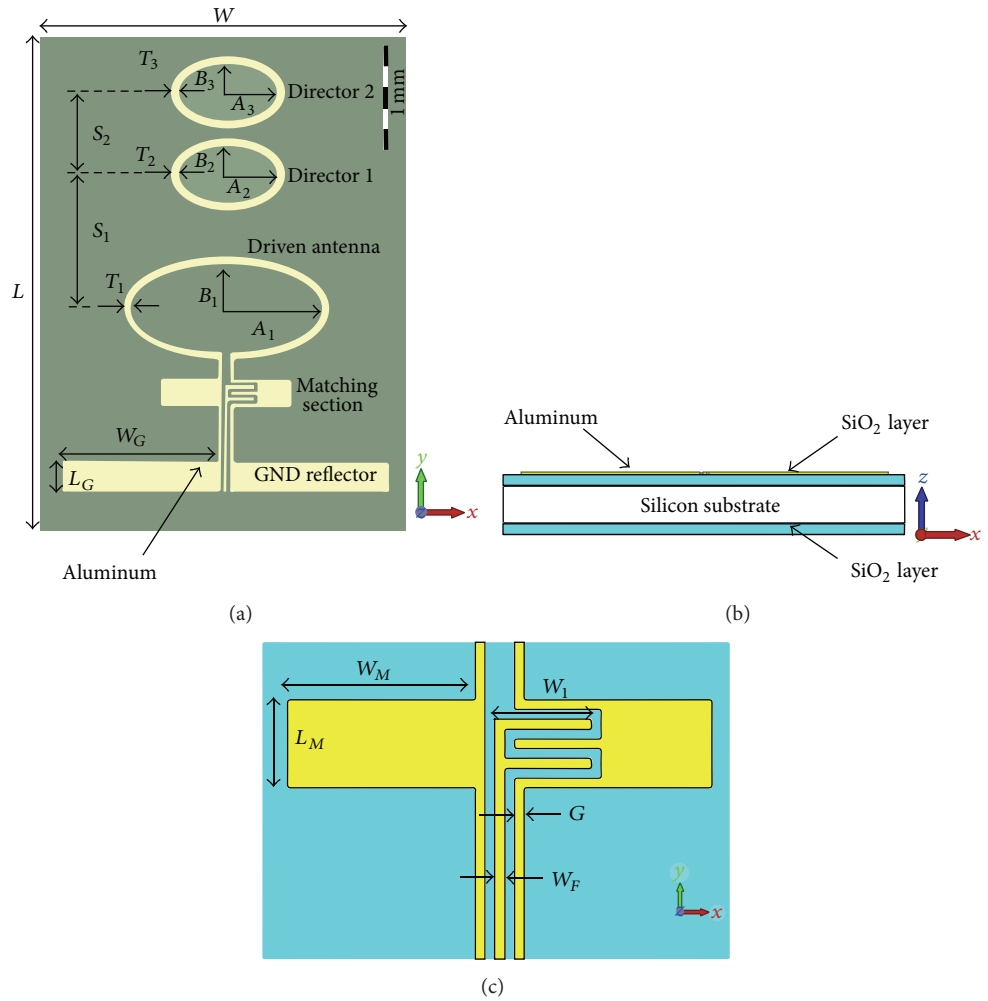

FIGURE 1: Geometrical configuration and photograph of the fabricated Quasi-Yagi loop antenna prototype I: (a) top view, (b) side view, and (c) detailed view for matching section and CPW feedline.

365 nm using an NXQ 4004 contact mask aligner. Next, a combined photoresist development and Al etching process was performed using Rohm & Haas MIF 319 developer. Aluminum was found to be etched by Rohm & Haas MIF 319 developer at an etch rate of 0.51 nm/s and so it was more practical to use Rohm & Haas MIF 319 developer for both photoresist development and Al etching processes. Rohm & Haas MIF 319 developer was applied for 9 minutes yielding resist-free and Al etched areas. Finally, the remaining photoresist was then removed using acetone. The fabricated Quasi-Yagi loop and dipole antennas are shown in Figures 1(a) and 6(a), respectively.

2.3. S-Parameter Measurement and Simulation. The $|S_{11}|$ versus frequency measurements were performed using Cascade Microtech's PM8 probe station in conjunction with Agilent E8361C network analyzer attached with N5260 frequency extender module, 67–110 GHz. Ground-signal-ground (GSG) infinity probes with a probe pitch of 75 μm, connected to the frequency extender module, were accurately positioned on the CPW structures and then the $|S_{11}|$ versus frequency measurements were performed at a frequency sweep from 80 to 110 GHz.

All simulations were carried out using Computer Simulation Technology Microwave Studio (CST-MWS) [8], which is considered a commercial and industry-standard full wave software program based on numerical analysis of electromagnetic problems. The measured and simulated $|S_{11}|$ curves versus frequency for the proposed Quasi-Yagi loop antenna prototype I are shown in Figure 2.

It can be seen that the shift in frequency between the simulated and measured cases is maybe because the substrates are not perfectly diced to the exact dimensions. Moreover, there may be some fabrication tolerance and calibration errors. In addition, the substrate dielectric properties are not correctly modeled in CST at those higher frequencies.

2.4. Radiation Pattern Measurement and Simulation. In this work, we propose coupling a microbolometer to the feed of the developed Quasi-Yagi loop antenna for performing radiation pattern measurements. For this purpose, a novel feed and matching section configuration is presented to permit

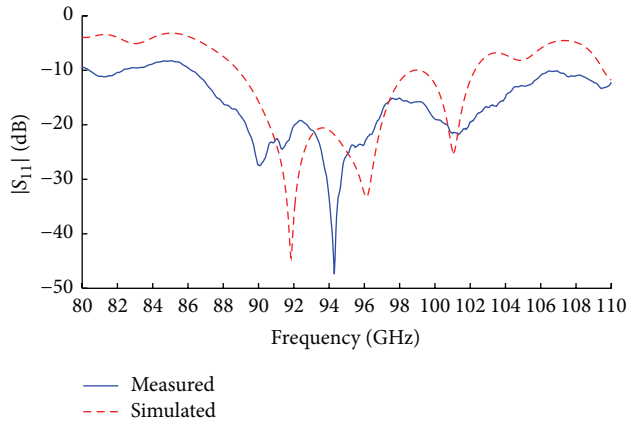

Figure 2: Measured and simulated reflection coefficient $|S_{11}|$ versus frequency of the proposed Quasi-Yagi loop antenna prototype I.

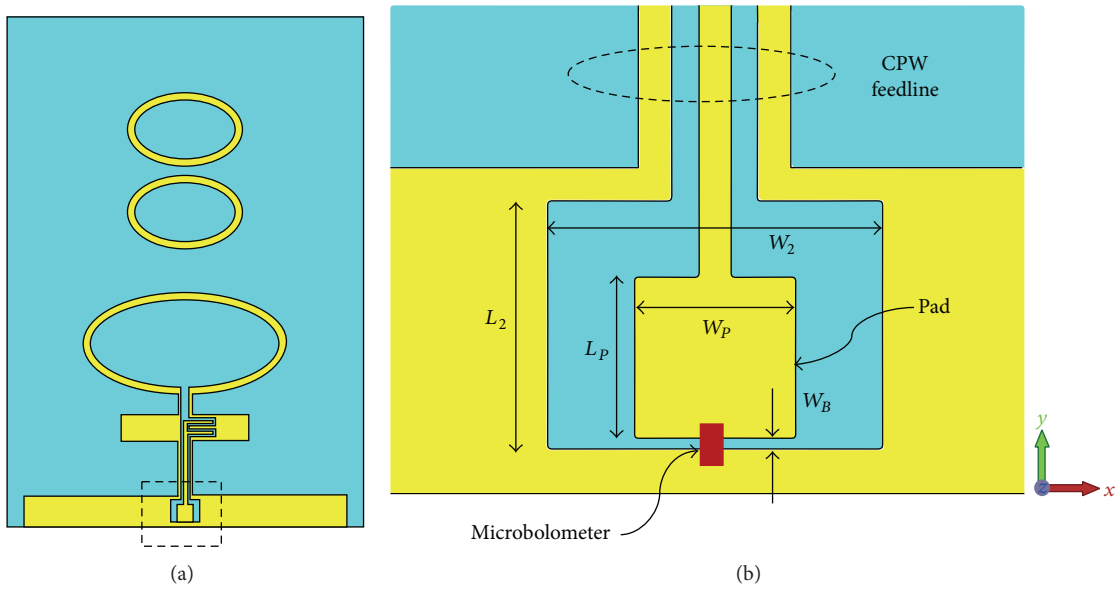

Figure 3: Geometrical configuration of the proposed Quasi-Yagi loop antenna prototype I with added microbolometer for radiation pattern measurements: (a) top view and (b) detailed view for bolometer.

coupling the microbolometer to the developed Quasi-Yagi loop antenna. In the meantime, the proposed design maintains similar radiation pattern characteristics to the original microbolometer-less Quasi-Yagi loop antenna design; this enables a proper comparison between both designs. The presented design in Figure 3 shows the developed antenna-coupled microbolometer configuration. The optimized parameters for the developed microbolometer are found to be as follows: W_P (= L_P) = 152 μm, W_2 = 312 μm, L_2 = 232 μm, and W_B = 10 μm. In the presented design, the CPW feedline, feeding the antenna signal to the microbolometer, is modified to include a square pad to permit biasing the microbolometer. This square pad allows connecting to one microbolometer terminal. The second microbolometer terminal will be connected to one section of the ground reflector. Bond wires will be connecting the square pad and the ground reflector to an external chip carrier.

The microbolometer material will be either niobium (Nb) or titanium (Ti) as they both possess the proper electrical resistivity for producing impedance matched loads within the constraints of the 10 μm feed gap (W_B) which will represent the length of the microbolometer. The width and thickness of the microbolometer structure will be exactly determined subsequent to a precise characterization of the electrical resistivity of the available material at the time of fabrication. The antenna resonant currents will be dissipated in the microbolometer located at the feed of the antenna causing joule heating in the microbolometer element. This joule heating will cause a resistance change in the microbolometer. A PIN switch will be used to modulate the MMW radiation incident on the microbolometer. The resistance change will be sensed by biasing the microbolometer element with a constant current and monitoring the voltage change. The voltage change will be monitored using a lock-in amplifier

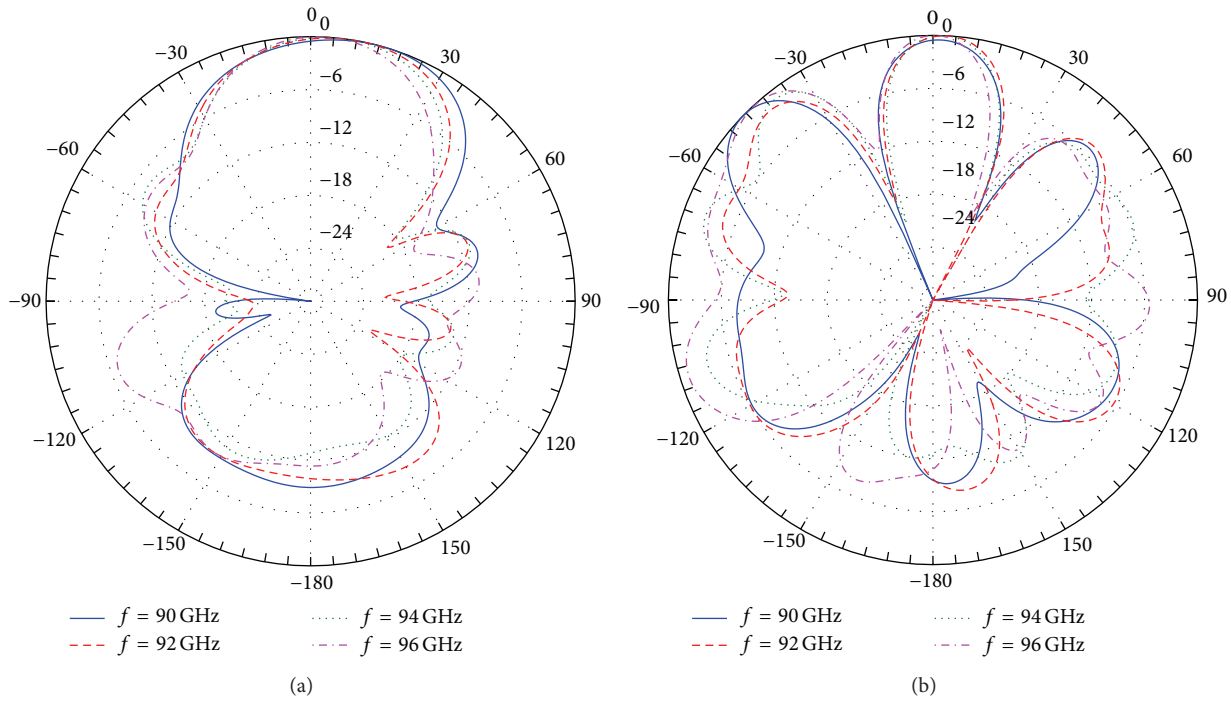

FIGURE 4: Simulated radiation patterns in (a) YZ plane and (b) XY plane at different frequencies $f = 90, 92, 94$, and 96 GHz for the Quasi-Yagi loop array antenna prototype I.

referenced at the modulation frequency of the incident radiation.

The simulated antenna radiation patterns in both YZ plane ($\phi = 90^{\circ}$) and XY plane ($\theta = 90^{\circ}$) at different frequencies of 90, 92, 94, and 96 GHz are shown in Figures 4(a) and 4(b), respectively. In addition, the copolarization and cross-polarization components of the radiation patterns at 94 GHz in both planes Quasi-Yagi loop array antenna prototype II with and without microbolometer are calculated and presented in Figure 5. As shown from the simulated results, a good radiation pattern is achieved having a maximum gain of 6.5 dBi and side lobe level of −7.4 dB in YZ plane at frequency of 94 GHz. The 3 dB beam width is found to be approximately 51.2°; furthermore, the antenna front-to-back ratio of 12.1 dB is achieved. The radiation characteristics in the XY plane are not as expected and they will be improved using the proposed Quasi-Yagi dipole antenna prototype II. The antenna peak-realized gain and radiation efficiency are calculated throughout the frequency band of interest. The results are given in the next section with a detailed comparison between the two antenna prototypes.

3. The Proposed High Gain Quasi-Yagi Dipole Antenna Prototype II

3.1. Antenna Configuration. The schematic diagram of the Quasi-Yagi dipole antenna prototype II is shown in Figure 6. In this case, the driven element is a printed dipole with two rectangular shaped directors in front of it. The optimized antenna parameters are tabulated in Table 2. The schematic diagram of the designed antenna with a microbolometer is presented in Figure 6(c). The optimized dimensions for the microbolometer are the same as the previous design.

TABLE 2: Optimized Quasi-Yagi dipole antenna prototype II dimensions.

Parameter	Quantity	Value
A_1	Driven dipole length	900 μm
B_1	Driven dipole width	400 μm
S_1	Spacing between driven antenna and director 1	1476 μm
A_2	Director 1 rectangular length	700 μm
B_2	Director 1 rectangular width	550 μm
S_2	Spacing between director 1 and director 2	1000 μm
A_3	Director 2 rectangular length	700 μm
B_3	Director 2 rectangular width	550 μm
W_G	Ground reflector width	300 μm
L_G	Ground reflector length	1520 μm
W	Substrate width	3500 μm
L	Substrate length	5000 μm
W_M	Matching section width	560 μm
L_M	Matching section length	250 μm
W_1	Interdigital capacitor width	290 μm
L_1	Interdigital capacitor length	1040 μm
W_F	CPW feedline width	30 μm
G	CPW feedline gap	25 μm
H_{Si}	Si substrate thickness	380 μm
H_{SiO_2}	SiO_2 layer thickness	1.2 μm
H_{Al}	Al thickness	0.2 μm

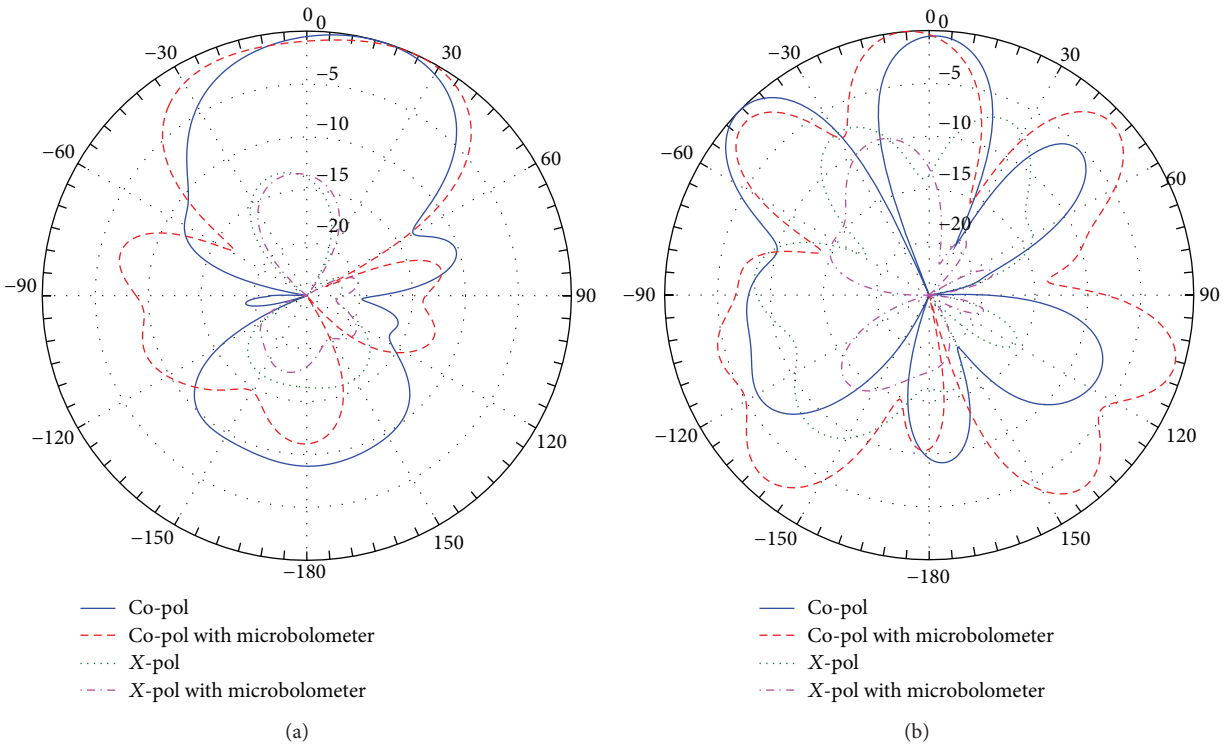

FIGURE 5: Simulated copolarization and cross-polarization radiation patterns in (a) YZ plane and (b) XY plane at $f = 94$ GHz for the Quasi-Yagi loop array antenna prototype I with and without microbolometer.

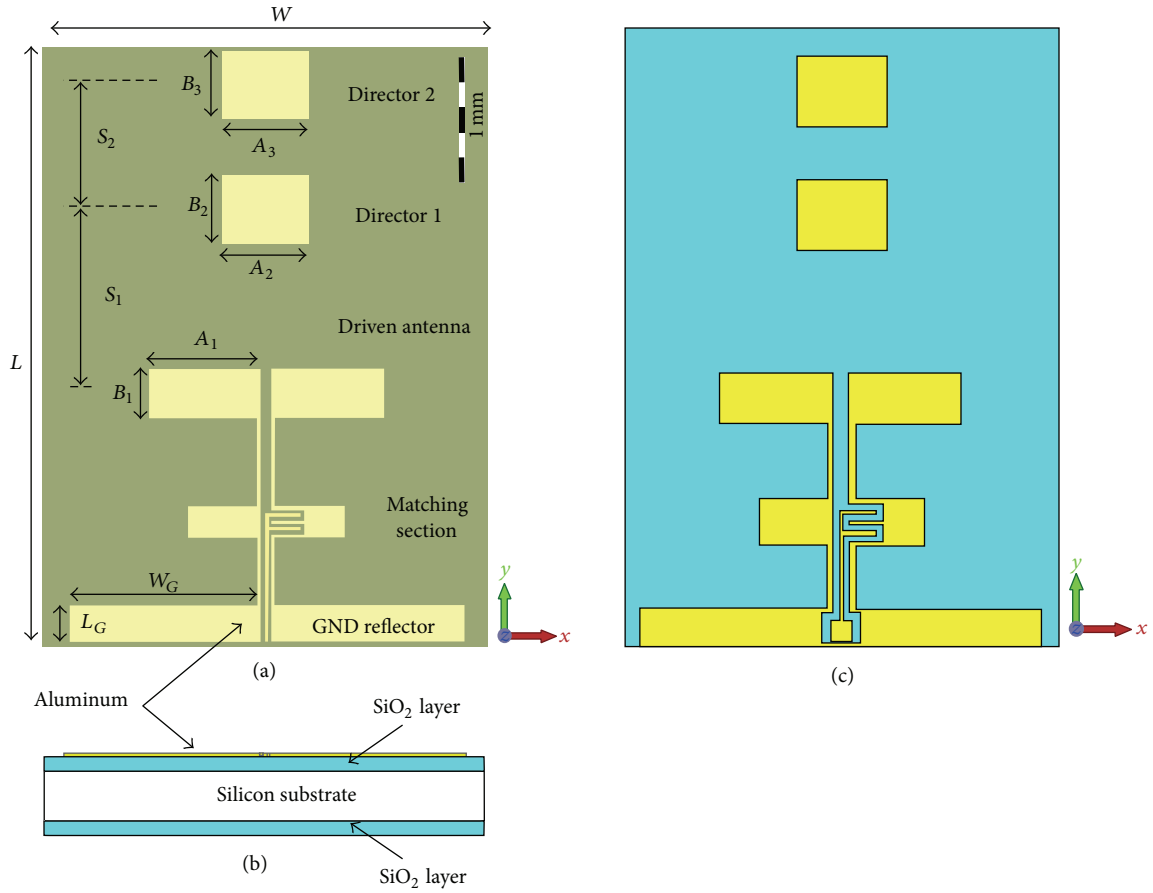

FIGURE 6: Geometrical configuration and photograph of the fabricated Quasi-Yagi dipole antenna prototype II: (a) top view, (b) side view, and (c) schematic diagram of the designed antenna with a microbolometer.

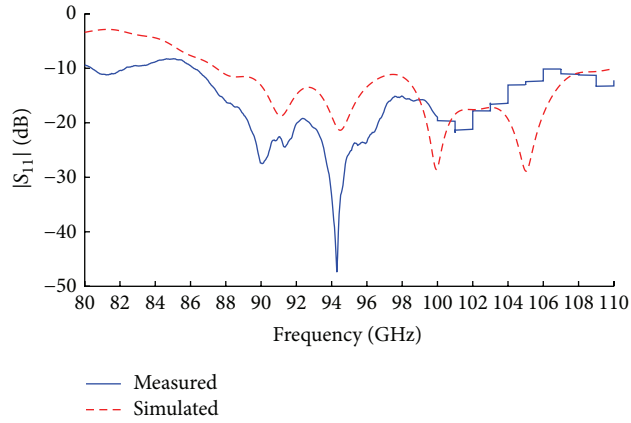

FIGURE 7: Measured and simulated reflection coefficient $|S_{11}|$ versus frequency of proposed Quasi-Yagi dipole antenna prototype II.

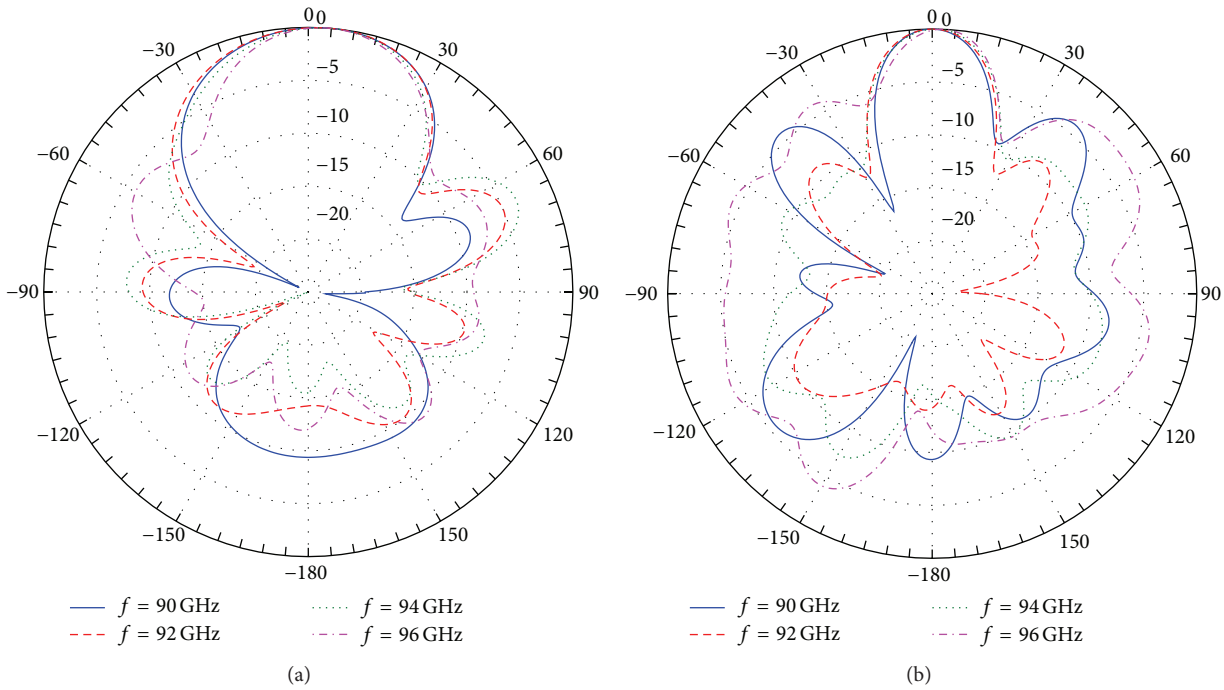

FIGURE 8: Simulated radiation patterns in (a) YZ plane and (b) XY plane at different frequencies $f = 90, 92, 94$, and 96 GHz for the Quasi-Yagi dipole array antenna prototype II.

3.2. Measured and Simulated Results. Figure 7 presents the measured and simulated $|S_{11}|$ results for the antenna prototype II. The results show that there is a good agreement between the measured and simulated one. The antenna exhibits a good −10 dB impedance matching bandwidth starting from 86 GHz to beyond 110 GHz with $|S_{11}|$ value better than −48 dB at 94 GHz.

The simulated antenna radiation patterns are also calculated and presented in Figure 8. The copolarization and cross-polarization components in both XY ($\theta = 90^\circ$) and YZ ($\phi = 90^\circ$) planes at 94 GHz are presented in Figures 8(a) and 8(b), respectively. As shown in the figure, good radiation patterns are achieved with maximum cross-polarization levels of −14.2 dB and −14.8 dB at 94 GHz in both XY and YZ planes, respectively. The antenna also exhibits a maximum gain of 7.5 dBi and side lobe level of −8.8 dB at frequency of 94 GHz. The 3 dB beam width is found to be approximately 53.8°; furthermore, the antenna front-to-back ratio of 15.74 dB is achieved.

The simulated copolarization and cross-polarization radiation patterns in both YZ plane and XY plane at $f = 94$ GHz for the Quasi-Yagi dipole array antenna prototype II with and without microbolometer are shown in Figure 9.

Figure 10 presents the peak-realized gain of the two proposed antenna designs. The peak-realized gain of the proposed antenna II is higher than that of the proposed antenna I for the whole frequency band of operation. The calculated antenna radiation efficiencies are found to be

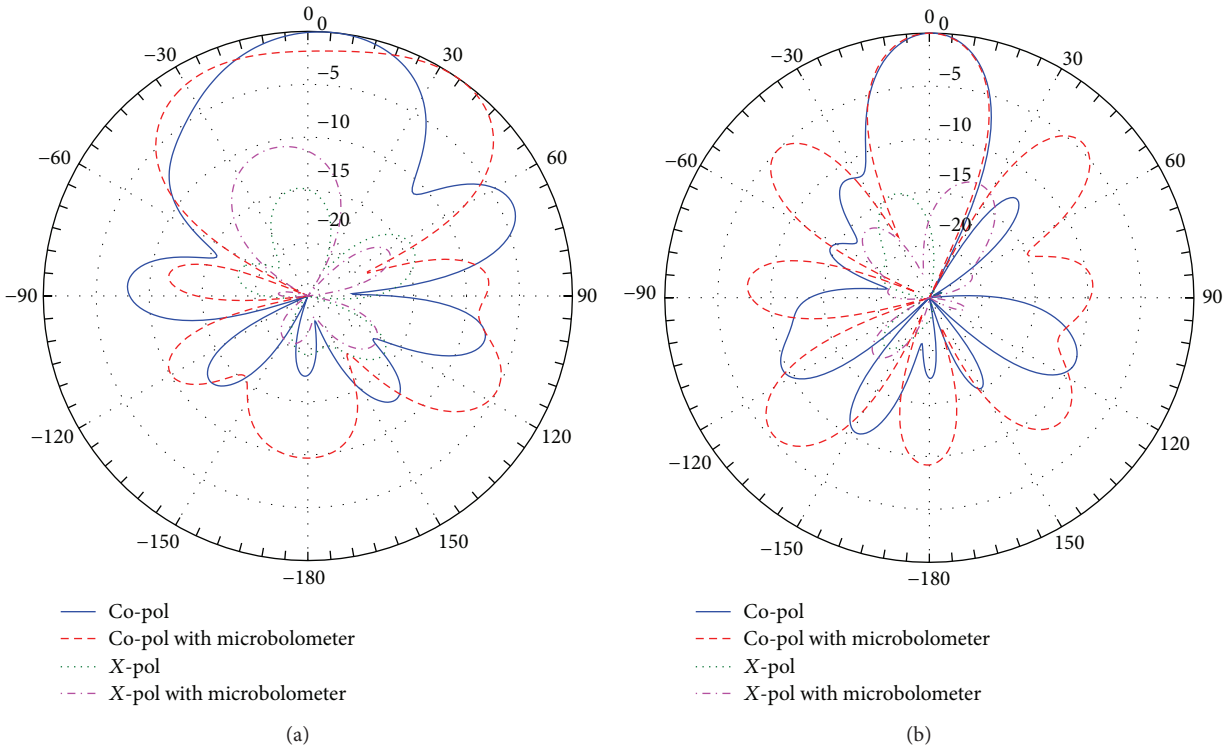

FIGURE 9: Simulated copolarization and cross-polarization radiation patterns in (a) YZ plane and (b) XY plane at $f = 94$ GHz for the Quasi-Yagi dipole array antenna prototype II with and without microbolometer.

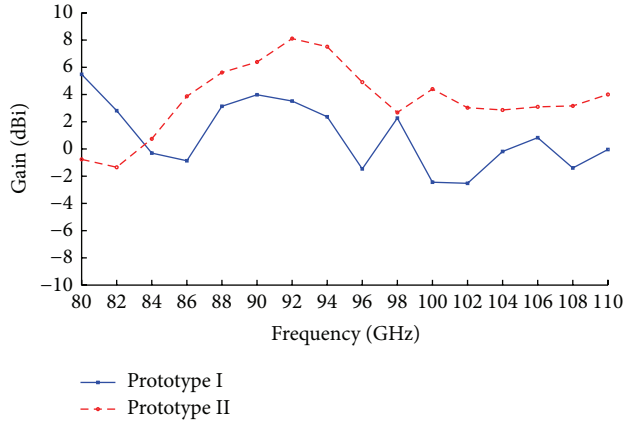

FIGURE 10: Simulated peak-realized gain versus frequency of the proposed Quasi-Yagi antenna prototypes I and II.

approximately ranging from 59% to 88% for the proposed antenna I and from 52% to 77% for the proposed antenna II throughout the band of interest.

3.3. Comparison with Other Related Work. Table 3 presents the performance comparison of other related on-chip Yagi antenna designs reported in the literature. The proposed antenna designs have good performance compared to the other work.

4. Conclusion

Two Quasi-Yagi antenna designs on silicon substrates at 94 GHz for imaging applications have been designed, fabricated, and then tested. The first design uses a driven element of an elliptical shaped loop antenna with elliptical shaped loop directors in front of the driven antenna. The other design utilizes dipole antenna with rectangular shaped patch directors in front of it. The paper also introduces a novel antenna-feed and matching configuration that facilitates

Table 3: Performance comparison with other related work in the literature.

Reference	Process technology	Frequency	Gain	Efficiency
[4]	0.18 um CMOS	60 GHz	−10.6 dBi (measured)	10%
[14]	0.18 um CMOS	60 GHz	−2.64 dBi (simulated)	16.8%
[16]	Post-back-end-of-line	65 GHz	−12.5 dBi (measured)	5.6%
[17]	Silicon substrate	100 GHz	5.7 dBi (measured)	—
This work	Silicon substrate	94 GHz	7.5 dB (simulated)	59%

coupling a microbolometer element to the developed Quasi-Yagi antenna designs. The proposed antenna-coupled microbolometer design will permit carrying out radiation pattern measurements for the proposed Quasi-Yagi antennas. The impedance bandwidth of more than 24 GHz is achieved at center frequency of 94 GHz with a very reasonable gain of above 4 dBi and 8.1 dBi for prototypes I and II, respectively, throughout the whole band of operation. The antenna radiation efficiencies are found to be between 59% and 88% for the proposed antenna I and 52% and 77% for the proposed antenna II.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

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