Study on On-Chip Antenna Design Based on Metamaterial-Inspired and Substrate-Integrated Waveguide Properties for Millimetre-Wave and THz Integrated-Circuit Applications

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***Abstract*: This paper presents the results of a study on improving the performance parameters such as the impedance bandwidth, radiation gain and efficiency, as well as suppressing substrate loss of an innovative antenna for on-chip implementation for millimetre-wave and terahertz integrated-circuits. This was achieved by using the metamaterial and the substrate-integrated waveguide (SIW) technologies. The on-chip antenna structure comprises five alternating layers of metallization and silicon. An array of circular radiation patches with metamaterial-inspired crossed-shaped slots are etched on the top metallization layer below which is a silicon layer whose bottom surface is metalized to create a ground-plane. Implemented in the silicon layer below is a cavity above which is no ground-plane. Underneath this silicon layer is where an open-ended microstrip feedline is located which is used to excite the antenna. The feed mechanism is based on the coupling the electromagnetic energy from the bottom silicon layer to the top circular patches through the cavity. To suppress surface-waves and reduce substrate loss SIW concept is applied at the top silicon layer by implementing the metallic via-holes at the periphery of the structure that connect the top layer to the ground-plane. The proposed on-chip antenna has an average measured radiation gain and efficiency of 6.9 dBi and 53%, respectively, over its operational frequency range from 0.285-0.325 THz. The proposed on-chip antenna has dimensions of 1.35×1×0.06 mm^3. The antenna is shown to be viable for applications in millimetre-waves and terahertz integrated-circuits.**

***Keywords*: On-chip antenna, terahertz (THz) integrated-circuits, metamaterial (MTM), substrate-integrated waveguide (SIW), silicon process, millimetre-waves (mm-waves), antenna feed mechanism.**

I. INTRODUCTION

This is an era of millimeter-wave (mm-wave) and terahertz (THz) wireless communications, which is necessary to deliver multi-Gbps data rates using standard, low-cost integrated circuit technology. THz regime of the electromagnetic spectrum is located between the microwave and optical frequencies and normally defined as the band from 0.1 to 10 THz [1–3]. Currently, industry is commercializing the unlicensed 60 GHz wireless band (e.g. IEEE 802.11ad/WiGig) for indoor short-range communication networks [1-5]. The atmospheric attenuation property of 60 GHz was one of the driving forces for regulatory agencies such as the U.S. FCC to unlicense the multi-GHz of bandwidth at 60 GHz [6]. Beyond 60 GHz more research is needed on how to design and develop THz on-chip antennas [7-12].

Active components functioning at mm-wave and THz circuits are highly integrated except for the antennas [13, 14]. Antenna integration is of great importance [15, 16]. At these frequencies, the antennas need to be assembled using expensive high frequency ground-signal-ground (GSG) probes, bulky waveguides, and horn antennas, which is not conducive for mass production and future industry application. For high-efficiency and gain, the off-chip antenna in the package design is usually fabricated on either the printed circuit board (PCB) [17], low-temperature cofired ceramic (LTCC) [15], or low-loss materials [17]. At mm-wave and THz frequencies the interconnect loss of the packaging is significant (~2 dB at 60 GHz) because of the incompatibility of the antennas and the silicon based active circuits [18-21].

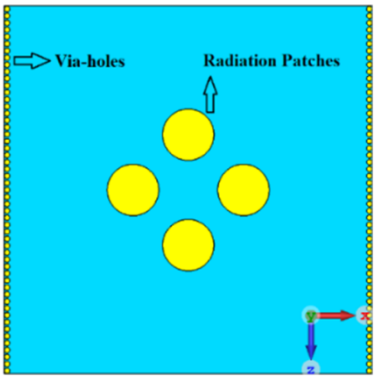
In this paper, an on-chip antenna design is presented for millimetre-wave and THz applications that is constructed from five alternating layers of metallization and silicon. The antenna's performance in terms of impedance bandwidth, radiation gain and efficiency are enhanced by employing the metamaterial (MTM) inspired technology [22-24]. Surface-waves and loss in the silicon substrate are mitigated using substrate integrated

waveguide (SIW) technology [25, 26]. A simple method based on open-ended microstrip-line is employed to excite the antenna. The next section describes the on-chip antenna structure design along with the simulated and measured results, and the paper is finally concluded.

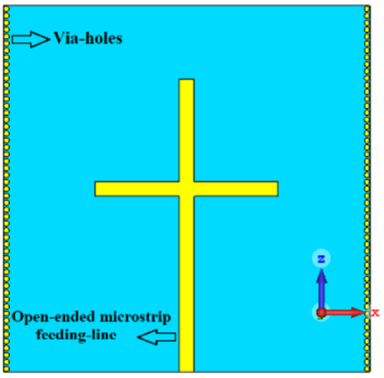
II. High Performance On-Chip Antenna for Applications in MM-Wave and THz Integrated-Circuits

Configuration of the reference on-chip antenna in Fig.1 comprises five layers consisting of metallization-silicon-metallization-silicon-metallization. The silicon layers have a dielectric constant of 11.7 and loss-tangent of 0.00025 [27]. Overall fabrication process used here is based on CMOS technology. Fabricated in the top silicon layer are four conventional circular radiation patches. Conductive material used for the radiation patches and the ground-plane is aluminium. A circular cavity is created in the bottom silicon layer under the four circular patches, and the ground-plane over this region is removed. The patches are excited by an open-ended microstrip-line in the form of a cross shaped line that is constructed on the back side of the bottom silicon layer. In this way, the four circular patches on the top layer are aligned with the feedline to maximise coupling. The feeding mechanism is based on coupling the electromagnetic energy from the bottom silicon layer to the top radiation patches through the cavity whose dominant resonance mode is $TE^{z}_{11\delta}$. The proposed feed mechanism improves the antenna's impedance matching and consequently its impedance bandwidth and radiation characteristics. The periphery of the top silicon layer is punctuated with metallic via-holes to actualize substrate-integrated waveguide (SIW) and thereby suppress surface-waves and minimize substrate loss. Analysis showed that the radius of the metallic via-holes and their spacing from each other are very important to realise low substrates loss and suppress surface-waves. The radius of the via-holes and their separation were 9.0μm and 3.5μm, respectively.

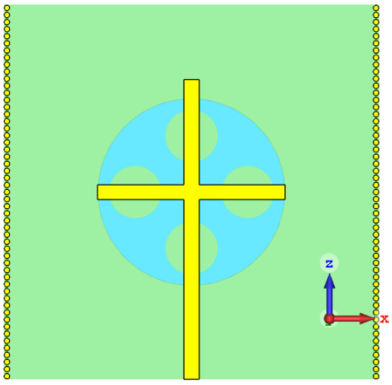
To increase the performance of the antenna its effective aperture area is enlarged without affecting its physical size by applying the metamaterial concept, as illustrated in Fig.2. In this approach, an optimized cross-shaped slot is created inside each circular patch. The periodic array of subwavelength slots act like resonators or scatters that exhibits metamaterial left-handed properties (negative refractive index) when interacting with EM-fields. The resulting structure is referred to as a metasurface, which is a 2D form of a metamaterial [28-30]. The effective permittivity (ε) and effective permeability (μ) of the metamaterials when analysed using retrieval extraction algorithm show the structure exhibits negative permittivity over the frequency range of interest, which is a unique characteristic of metamaterials. The physical parameters of the proposed on-chip antenna for optimum performances over 0.285 THz to 0.325 THz are tabulated in Table I.



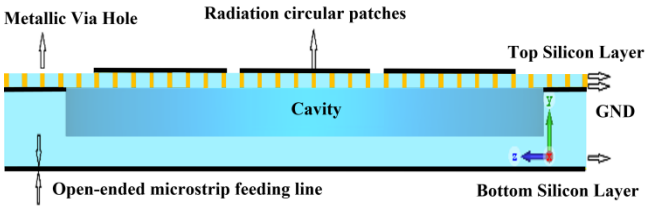
(a) Top-view



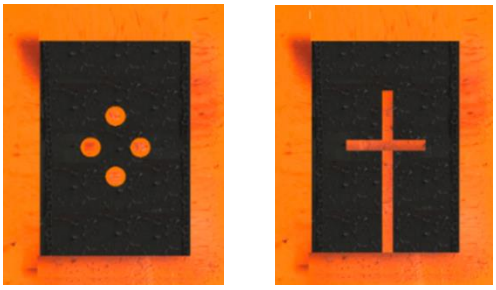
(b) Back-view



(c) View showing relative positions of the feeding line on the bottom layer, the radiation patches on the top layer, and the cavity in the bottom silicon substrate. The cross-shaped feedline is located under the radiation patches to maximise coupling.



(d) Cross-section view showing the various layers of the on-chip antenna structure.

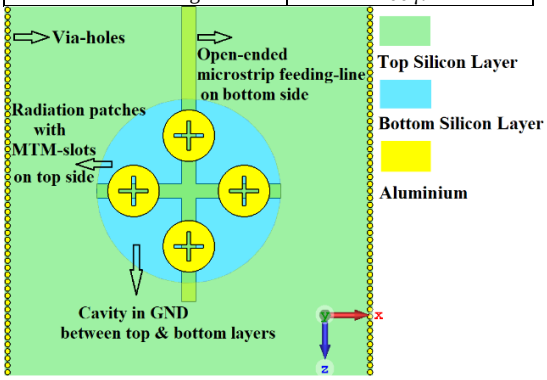


(e) Fabricated prototype, top-view (left-side) and back-view (right-side)

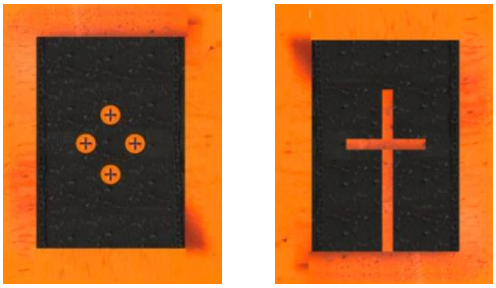
Fig.1. Configuration of the proposed reference on-chip antenna.

TABLE I. Dimensions of Structural Parameters.

On-chip antenna size	1350×1000×60 μm^3
Thickness of top silicon	5 μm
Thickness of bottom silicon	50 μm
Thickness of GND	5 μm
Radius of cavity	400 μm
Radius of via holes	9 μm
Spacing between via holes	3.5 μm
Radius of circular patches	70 μm
Length of MTM slots	85 μm
Width of MTM slots	10 μm
Length of feeding line	1100 μm
Width of feeding line	100 μm



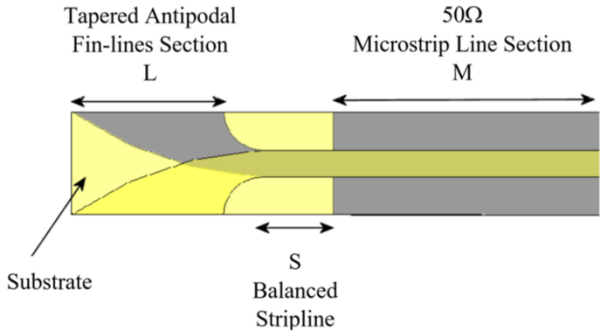
(a) Simulated layout (top-view)



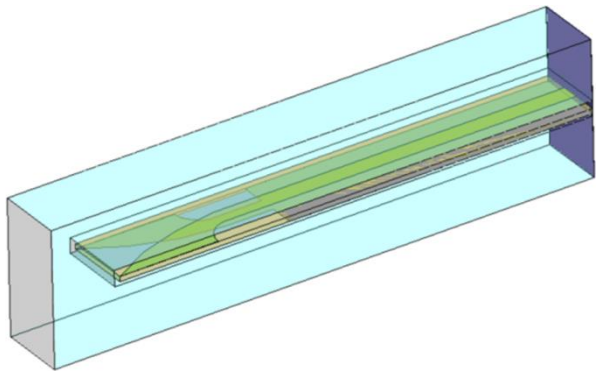
(b) Fabricated prototype, top-view (left-side) and back-view (right-side)

Fig.2. Proposed on-chip antenna with metamaterial-inspired crossed-shaped slot implemented on the radiation patches.

The proposed structure was modelled and simulated using CST Microwave Studio, which is a 3-D electromagnetic solver based on finite integration technique. The antenna was then fabricated to validate its performance. The antenna's feedline was excited using WR3 transition using in-line Fin-lines. By using antipodal Fin-lines, shown in Fig.3, a wide range of impedance values can be realized. The impedance match can be accomplished by tuning the Fin-line dimensions (*L* and *S*) and by tapering the two fins to form microstrip signal line and ground-plane, respectively. The tapered fins gradually allow a change from the rectangular waveguide impedance to the microstrip impedance. Hence, the length and shape of the taper determine reflection and operating bandwidth.



(a)



(b)

Fig.3 Antipodal Fin-line transition(a) consists of three sections: Fin-line tapers *L*, balanced microstrip *S* and microstrip line *M*. The Antipodal Fin-line transition is located at the centre line of the waveguide broad walls (b).

A 3D plot of the E-field relative to the transition mechanism of antipodal Fin-line at 0.305 THz is shown in Fig.4 highlighting the E-field intensity pattern in the three cascaded sections. The waveguide TE_{10} mode, coupled to the structure as its input, splits at the Fin-line taper point and finally converts into the microstrip line mode.

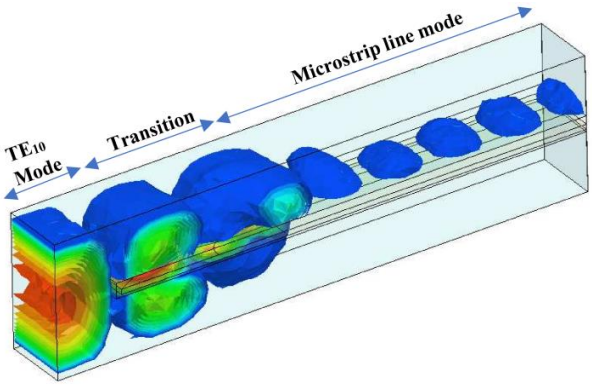


Fig.4 E-field distribution at 0.305 THz. The TE_{10} mode entering the transition from left is split, rotated and finally matched to the microstrip quasi-TEM mode.

The simulated and measured reflection-coefficient response of the reference antenna with no MTM and the proposed antenna with MTM-inspired cross-shaped slots are shown in Fig.5. It is evident that with MTM the impedance match and impedance bandwidth are significantly improved. The proposed structure is shown to effectively operate over the frequency range from 0.285 THz to 0.325 THz for S_{11}<-15dB, which corresponds to a fractional bandwidth of 13.11%.

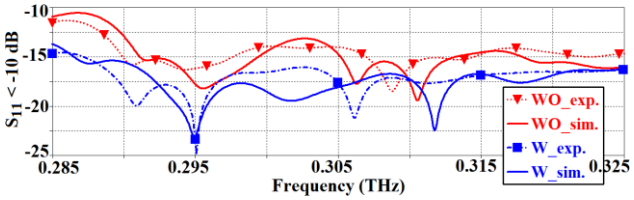
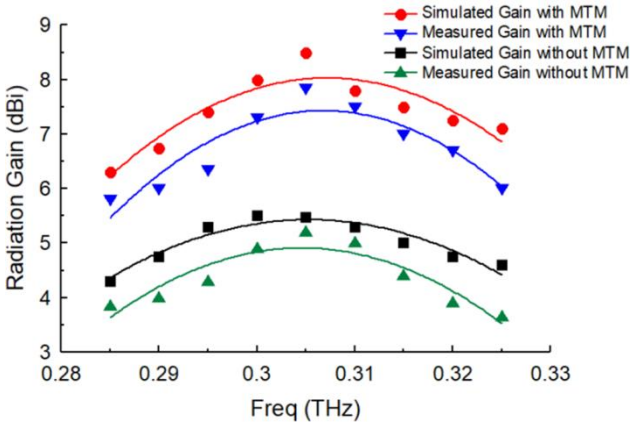


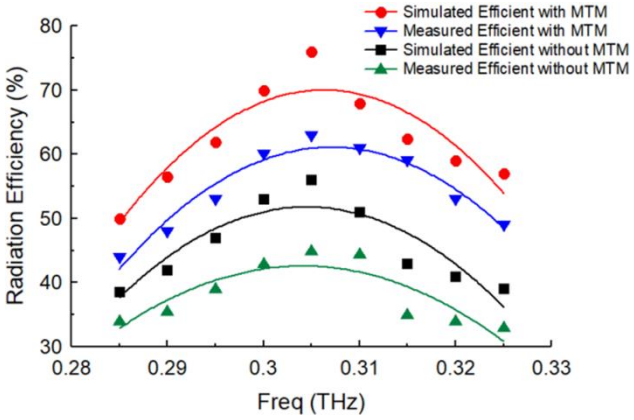
Fig.5. Simulated (sim.) and experimental (exp.) reflection coefficient responses of the reference antenna with no MTM (WO) and proposed on-chip antennas with MTM (W).

The simulated and measured radiation gain and efficiency performances of the reference antenna with no MTM and the proposed antenna with MTM are shown in Fig.6. It is evident that the proposed antenna structure with MTM properties exhibits improvement in the measured gain by 2.4 dBi and radiation efficiency by 14%, which is achieved with no increase in antenna's physical dimensions. The measured average radiation gain and efficiency of the proposed on-chip antenna operating between 0.285 THz to 0.325 THz are 6.9 dBi and 53%, respectively. Performance characteristics of the reference and proposed antenna are summarized in Table II. There is good coherence between the simulation and the measurement in results presented in Figs. 5 & 6, and the discrepancy can be attributed to several factors, namely, imprecise simulation models at terahertz, fabrication tolerances and unwanted signal reflections from surrounding objects during measurements.

The simulated and measured E-plane and H-plane radiation patterns of the proposed metamaterial on-chip antenna at spot frequencies of 0.285, 0.305, and 0.325 THz are shown in Fig.7. This figure shows that in the E-plane the 3-dB beamwidth narrows at the mid-band frequency of 0.305 THz. It also shows the radiation in the E-plane rotates by 90° in the clockwise direction from 0.285 THz to 0.305 THz, and again from 0.305 THz to 0.325 THz. In the H-plane the beamwidth narrows significantly in the mid-band frequency of 0.325 THz.



(a) Radiation gain



(b) Radiation efficiency

Fig.6. Simulated and measured radiation gain and efficiency over the operating frequency range of the proposed on-chip antenna with and without MTM properties.

TABLE II. Measured Radiation Gain & Efficiency Performance of the On-Chip Antennas With and Without MTM-Inspired Technology

Reference on-chip antenna without MTM properties

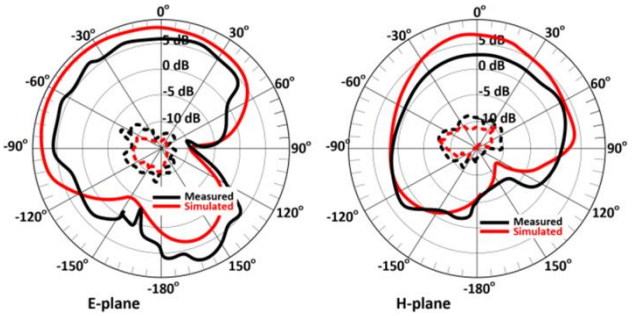
Min. Gain & Efficiency @ 0.325 THz	3.65 dBi & 33.12%
Max. Gain & Efficiency @ 0.305 THz	5.33 dBi & 46.43%
Ave. Gain & Eff.(0.285 THz – 0.325 THz)	4.5 dBi & 39%

Proposed on-chip antenna with MTM properties

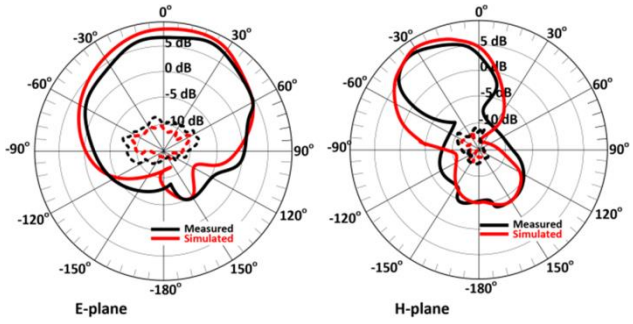
Min. Gain & Efficiency @ 0.285 THz	5.86 dBi & 44.10%
Max. Gain & Efficiency @ 0.305 THz	8.05 dBi & 62.95%
Ave. Gain & Eff. (0.285 THz–0.325 THz)	6.9 dBi & 53%

Improvements after applying MTM properties

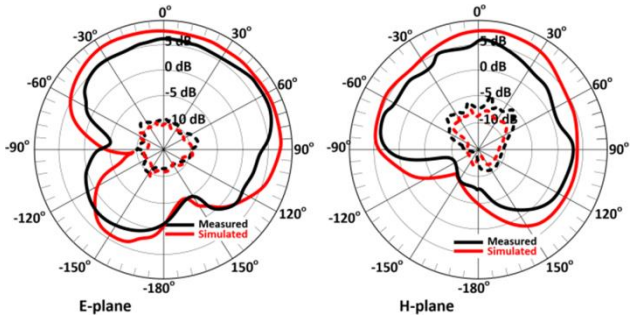
Min. Gain & Efficiency	2.21 dBi & ~11%
Max. Gain & Efficiency	2.72 dBi & 16.52%
Ave. Gain & Efficiency	2.4 dBi & 14%



(a) 0.285 THz



(b) 0.305 THz



(c) 0.325 THz

Fig.7. Simulated and measured E-plane and H-plane radiation patterns of the proposed metamaterial on-chip antenna at various spot frequencies in the antenna's operating frequency range. Solid lines represent co-polarization, and dotted lines cross-polarization.

Table III compares the characteristics of the proposed on-chip antenna with other techniques. With the proposed technique a better factional bandwidth can be achieved. The gain and efficiency of the proposed antenna is comparable to other techniques and in some cases better. In addition, compared to previously reported on-chip antenna designs the proposed design is of a simpler structure and easy to fabricate at low cost, which makes it viable for mass production.

TABLE III. COMPARISON OF THE PROPOSED ON-CHIP ANTENNA WITH THE RECENT PUBLICATIONS

Ref.	Antenna Type	Operation Mode	Freq. / BW (GHz / %)	Gain (dBi)	Eff. (%)	Fab. Process	DR Material εr	DR Type	Size (mm^2)	Height (mm)
[7]	Patch fed higher order mode DRA	$TE_{\delta 17}$	341 / 7	7.9	74	0.18-μm SiGe	11.9	Rectangular	0.2	0.5
[8]	On-chip 3D (Yagi like concept)	$TE_{11\delta}$	340 / 12	10	80	0.13-μm SiGe	10	Rectangular	0.49	0.43
[10]	Slot loaded magnetic loop on SIW	-	340 / 7	3.3	45	0.13-μm SMOS	NA	NA	0.49	-
[31]	Patch	-	280 / 2.5	–1.6	21	0.13-μm CMOS	NA	NA	0.2	-
[32]	Ring antenna	-	296 /-	4.2	-	65-nm CMOS	NA	NA	0.3	-
[33]	Slot ring antenna + superstrate	-	375 / 8	1.6	35	45-nm CMOS SOI	NA	NA	0.05	-
[34]	Ring antenna with silicon lens	-	288 / NA	18.3	65	65-nm CMOS	NA	NA	12.56	2.55
[35] - a	Half-mode cavity fed DRA	$TE_{\delta 11}$	135 / 13	3.7	62	0.18-μm CMOS	10	Rectangular	0.63	0.25
[35] - b	Half-mode cavity fed higher order mode DRA	$TE_{\delta 13}$ / $TE_{\delta 15}$	135 / 7	6.2 / 7.5	46 / 42	0.18-μm CMOS	10	Rectangular	0.72	1.3/2.2
[36]	Slot fed stacked DRA	$TE_{\delta 11}$	130 / 11	4.7	43	0.18-μm CMOS	10	Rectangular	0.72	1.5
[37]	DRA	$TE_{\delta 11}$	135 / 11	2.7	43	0.18-μm CMOS	10	Rectangular	0.72	0.6
This Work	MTM & SIW	$TE_{11\delta}$	305 / 13.11	8.05	62.95	0.13-μm CMOS	NA	NA	2.35	0.06

Note: DR represents Dielectric Resonator, and NR is not applicable.

III. Conclusion

The feasibility of the proposed metamaterial-inspired antenna is demonstrated for on-chip applications at the lower end of the THz region. The novelty introduced includes: (i) the feed mechanism for effective coupling of electromagnetic energy from bottom layer to the top radiation patches; (ii) combining metamaterial-inspired and SIW technologies to improve the antenna's performance parameters while preserving its physical dimensions; and (iii) using stacked layers to create a highly compact on-chip antenna structure. The proposed silicon-based antenna structure provides low integration loss and is relatively simple to design and fabricate and therefore a promising candidate in the millimeter-wave and terahertz integration applications.

Acknowledgements

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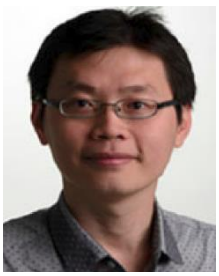

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