Coupled Line Wilkinson Combiner-Antenna Integrated Design for 300-GHz Arrayed UTC-PDs

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***Abstract*—We designed and analyzed the performance of a 2 by 1 coupled line Wilkinson combiner-antenna device for arrayed photomixers at 300 GHz. Simulation results showed that there is a 2.59 dB increase in total radiated THz-wave power when the coupled line Wilkinson combiner is used to integrate two identical UTC-PDs and feed their output power into an antenna, compared to a single-port feed for a single UTC-PD. Additionally, there is a −21.5 dB isolation between the feed ports and a realized gain of 4.8 dBi in the +z (theta = 0) direction. Furthermore, the quarter wavelength lines for the designed combiner covers a half area of 0.1 × 0.055 mm² compared to the conventional Wilkinson combiner.**

Keywords—coupled lines, Terahertz, UTC-PD, Wilkinson combiner

I. Introduction

With the rapid growth of internet of things, e-commerce, online studying, telemedicine and so on, data traffic is rapidly increasing worldwide. The use of high frequency carrier waves has been proposed as a solution to handle the ultra-high data rates, hence, the upsurge in research on Terahertz (THz) wave technology. THz waves are electromagnetic waves ranging from radio wave to far-infrared (0.1 THz – 10 THz) with potential applications in wireless communication, sensing and imaging because of their unique features like ultra-wide bandwidth and the ability to penetrate many non-metallic materials [1].

One of the key areas of interest is the THz wave generation. To date, several solid-state electronics-based sources like Complementary Metal-Oxide-Semiconductor (CMOS), Monolithic Microwave Integrated Circuits (MMIC), Resonant Tunneling Diodes (RTD) as well as photonic (optoelectronic) sources, have been studied. Although solid-state electronics-based sources have the advantages of flexibility, high-level integration and low cost, there is a problem of drastic power decrement as frequencies go high [2].

Hence, a number of researchers are now exploring the novel photonic (optoelectronic) methods for THz wave generation with a specific interest in the photomixing technique with a uni-traveling carrier photodiode (UTC-PD). With this technique, two lightwaves of different frequencies are combined in an optical coupler to produce an optical beat signal with the required frequency *f*. The UTC-PD converts the optical beat signal into an alternating electric current with the same frequency *f*. The signal is then transmitted by a planar antenna or a waveguide horn. Because only electrons are the active charge carriers in the UTC-PD, the device can operate at a maximum speed that is only determined by the electron velocity, which is significantly greater than the hole velocity. Also, because the UTC-PD has much lower carrier accumulation than a conventional pin-PD, the space charge effect is much smaller. Hence, the UTC-PD is faster and has higher saturation power than the pin-PD [3].

Despite the aforementioned merits, the maximum output power of the UTC-PD is still limited to about 100 µW at 300 GHz [4]. To have more transmitted THz-wave power than what a single UTC-PD can provide, we propose monolithically integrating two UTC-PDs with an on-chip coupled line-based Wilkinson combiner and patch antenna. In this paper, we design and analyze the performance of the Wilkinson combiner and patch antenna for integrating with the UTC-PDs. Because there is always a need for device miniaturization in THz systems, the proposed coupled line combiner, which has a smaller area than the conventional Wilkinson combiner, can be a better choice. Also, during the semiconductor fabrication process, it's always easier to fabricate straight microstrip transmission lines than curved ones.

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II. Power Combining Theory

The terahertz wave power can be enhanced by connecting more than two UTC-PDs in parallel as shown in Fig. 1.

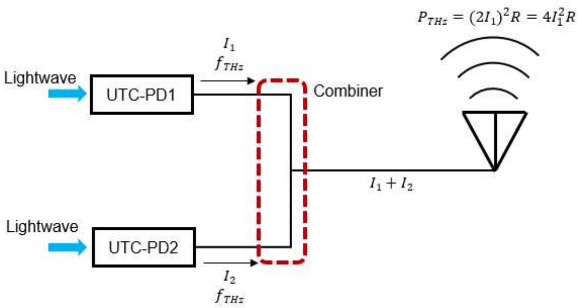

Fig. 1. Two UTC-PDs connected to the antenna by a Wilkinson combiner

The photocurrent I generated by the UTC-PD is proportional to the lightwave intensity incident on it [5]. Considering two UTC-PDs (UTC-PD1 and UTC-PD2) with equal incident lightwave intensity and modulation frequency, photocurrents I_1 and I_2 generated by UTC-PD1 and UTC-PD2 can be expressed as

$$I_1 = I_{dc} + I_{ac}\cos(2\pi f_{THz}t + \varphi_1) \quad (1)$$

$$I_2 = I_{dc} + I_{ac}\cos(2\pi f_{THz}t + \varphi_2) \quad (2)$$

where I_{dc} is the direct current component, I_{ac} is the alternating current amplitude, f_{THz} is the modulation frequency (e. g. 300 GHz), and φ_1 and φ_1 are the phases for I_1 and I_2 respectively.

The Wilkinson combiner adds I_1 and I_2 and thus we will have

$$I_1 + I_2 = 2I_{dc} + 2I_{ac}\left\{\cos\left(2\pi f_{THz}t + \frac{\varphi_1+\varphi_2}{2}\right)\right\} \left\{\cos\left(\frac{\varphi_1-\varphi_2}{2}\right)\right\} \quad (3)$$

If I_1 and I_2 has same phase or $\varphi_1 = \varphi_2$, then

$$I_1 + I_2 = 2\{I_{dc} + I_{ac}\cos(2\pi f_{THz}t + \varphi_1)\} = 2I_1 \quad (4)$$

The intensity of the radiated THz wave P_{THz} can be expressed as

$$P_{THz} = I^2R \quad (5)$$

where R is the antenna radiation resistance.

Hence from (4) and (5), the radiated THz wave intensity from the two UTC-PDs is

$$P_{THz} = (I_1 + I_2)^2R = 4I_1^2R \quad (6)$$

It can therefore be inferred from (6) that when N lightwaves with same phase are introduced to N combined UTC-PDs, the output current is ideally N fold and the radiated wave intensity from an antenna is N^2 fold.

III. Proposed Combiner-Antenna design

Microstrip transmission lines were used to design the proposed combiner and antenna with gold as the conducting metal. The substrate was Silicon Carbide (SiC) with a dielectric constant (ε_r) of 10, a loss tangent (tanδ) of 0.002, and a thickness of 0.032 mm. It is important to note that the high ε_r of SiC causes the antenna to have an increased surface wave power and narrower bandwidth, and, as a result, lower radiation efficiency. Despite this, SiC is a hard semiconductor material with excellent properties such as wide bandgap and high thermal conductivity, which facilitates it's use in the semiconductor fabrication process.

For a Wilkinson combiner/divider, good matching and high isolation can be achieved by using $\lambda/4$ impedance transformers with a characteristic impedance of $\sqrt{2}Z_0$ and a lumped isolation resistor of $2Z_0$ where Z_0 is the characteristic impedance of the input and output ports [6]. The proposed Wilkinson combiner/divider uses coupled line quarter wave transmission lines to combine power. A synthesis method using Akhtarzad's technique of coupled lines design [7]-[8] is adopted for our design. Since our input/output characteristic impedance is 50Ω, and the even mode characteristic impedance Z_{0e} is fixed as $\sqrt{2}Z_0$, we can get the odd mode characteristic impedance Z_{0o} from the approximation that

$$Z_0 \approx \sqrt{Z_{0e}Z_{0o}} \quad (7)$$

The approximation in (7) holds for applications where coupling between the lines needs to be as low as possible which is our case. A thorough analysis on how the even and odd mode impedance (Z_{0e} and Z_{0o}) affect the S-parameters of the combiner is provided in [9].

By using Akhtarzad's technique,

$$W/H = 0.85 \quad (8)$$

$$S/H = 0.25 \quad (9)$$

where W is the width of each of the coupled lines, S is their spacing and H is the substrate height. Since H is fixed as 0.032 mm, then $W \approx 0.0225\ mm$ and $S \approx 0.01\ mm$.

The length of the coupled lines L_c can be calculated as

$$L_c = 2(\lambda_{ge} + \lambda_{go}) \quad (10)$$

whereby

$$\lambda_{ge} \approx \left(\frac{300}{f}\right)\left(\frac{Z_{0e}}{Z_{1e}}\right) mm \quad (11)$$

$$\lambda_{go} \approx \left(\frac{300}{f}\right)\left(\frac{Z_{0o}}{Z_{1o}}\right) mm \quad (12)$$

where f is the frequency (300 GHz) and λ_{ge} and λ_{go} are the free space even mode and odd mode characteristic impedances and can be obtained from Bryant and Weiss' curves applicable to $\varepsilon_r = 1$ [10] as 0.38 and 0.48 mm respectively.

The radiator used was the patch antenna known for its low profile and ease of fabrication. It was designed using microstrip antenna design equations given in [11]. The patch antenna was integrated with the coupled line Wilkinson combiner as shown in Fig. 2. The optimized design parameters are given in TABLE I.

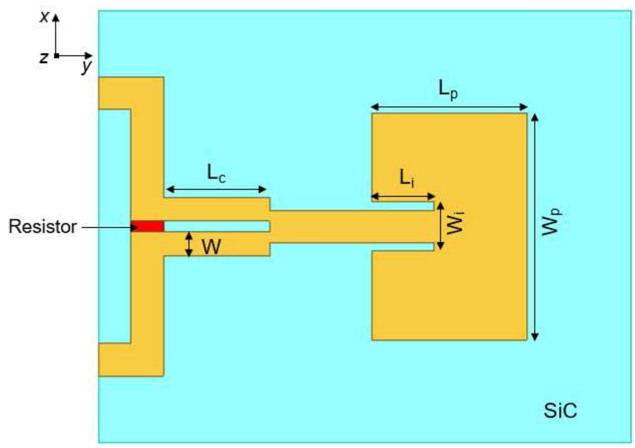

Fig. 2. Coupled line Wilkinson combiner-antenna design

TABLE I. OPTIMIZED DESIGN PARAMETERS

Parameter	Value (mm)
L_p	0.147
W_p	0.2132
L_i	0.059
W_i	0.0459
L_c	0.1
W	0.0225

The input ports were 0.25mm apart which is the fiber pitch. The conventional Wilkinson combiner is illustrated in Fig. 3 as reported in [12].

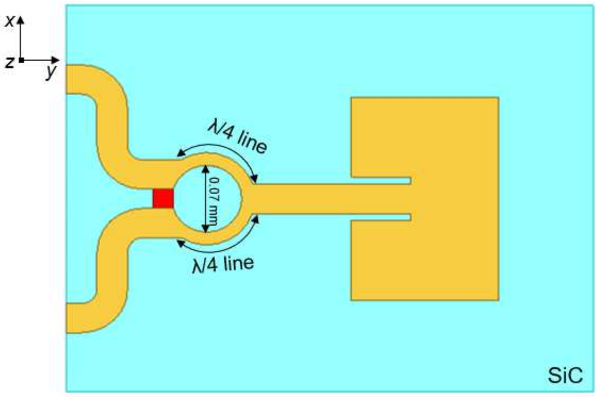

Fig. 3. Conventional Wilkinson combiner-antenna design

IV. Results

The performance of the proposed combiner-radiator structure was assessed in terms of return loss, isolation, radiated power and realized gain (ratio of radiation intensity to incident power). The results for the coupled line-based and the conventional Wilkinson combiner-fed antenna compared well with each other. As depicted in Fig. 4, the simulated return loss at the proposed combiner input ports was −22.2 dB at 300 GHz which is well below the −10 dB requirement. The single port-fed and the conventional Wilkinson combiner-fed antenna had a return loss of −19.3 dB and −35.9 dB respectively.

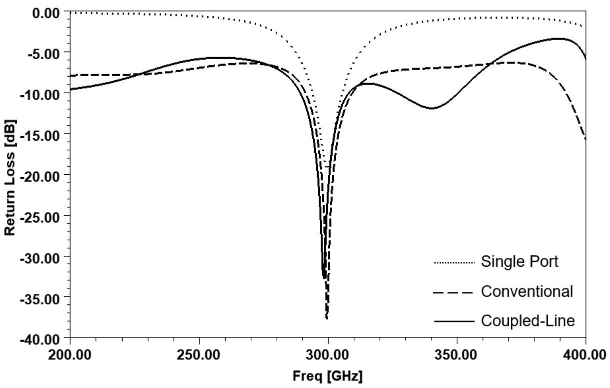

Fig. 4. Return loss

The coupled line combiner also exhibited good isolation of −21.4 dB at 300 GHz as shown in Fig. 5 and this compared well with the conventional design which had an isolation of −21.5 dB between the input ports.

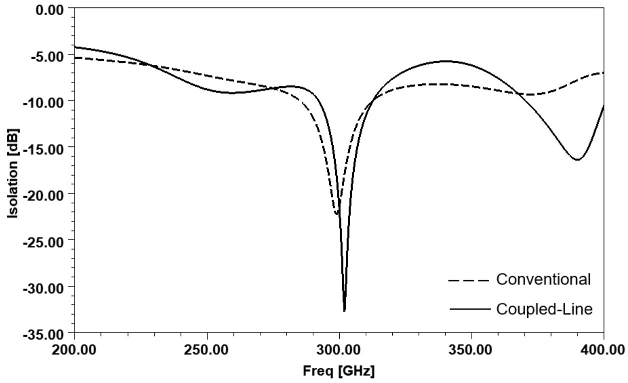

Fig. 5. Isolation between the input ports

To assess the design performance in terms of radiated THz power, one milliwatt (0 dBm) was fed to the single port-fed antenna and then to each port of the combiner-fed antenna. At 300 GHz, as shown in Fig. 6, simulation results showed that the single port-fed antenna radiated −0.71 dBm of the 0 dBm (1 mW) fed to it with a 3-dB bandwidth of 34.99 GHz, whereas the coupled line and the conventional Wilkinson combiner-fed antenna radiated 1.88 dBm and 1.83 dBm of the 3 dBm (2 mW) fed to the input ports with 3-dB bandwidths of 24.75 GHz and 24.12 GHz, respectively. The difference of 0.05 dBm in total radiated power between the two combiner-antenna devices suggests that coupled line Wilkinson combiner has a slightly better but comparable performance with the conventional Wilkinson combiner.

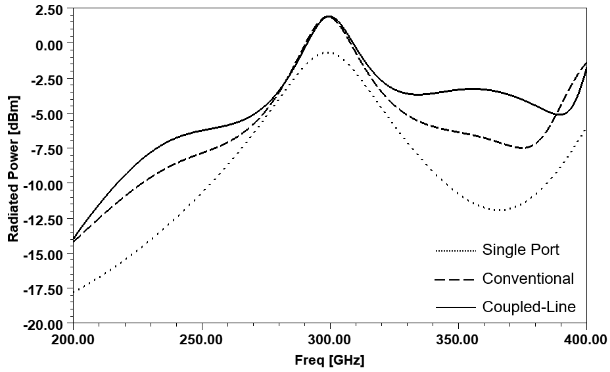

Fig. 6. Radiated power

The simulated realized gain for both the coupled line combiner-fed and the conventional combiner-fed antenna in the +z (theta = 0) direction was 4.8 dBi with a 3-dB bandwidth of 24.77 GHz for the former and 23.72 GHz for the latter, as shown in Fig. 7. Hence, the peak power in the +z direction for both *xz* and *yz* planes can be increased by more than three times (4.8 dBi). Moreover, the single port-fed antenna's realized gain was 5.04 dBi with a 3-dB bandwidth of 34.8 GHz. The difference in the realized gain between the combiner-fed antenna and the single-port fed antenna is because of the different radiation efficiencies of 77% and 86% respectively. Additionally, the realized gain antenna bandwidths demonstrate the possibility of high-capacity wireless communication.

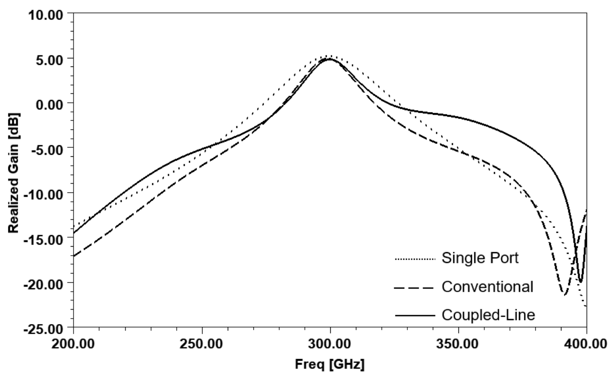

Fig. 7. Realized gain

The radiation patterns are illustrated in Fig. 8 and TABLE II summarizes the simulated half-power beam widths (HPBW) in the xz-plane and yz-plane. The simulated half-power beamwidths suggest that the designed antenna has the potential of radiating a relatively higher amount of power over a wider area.

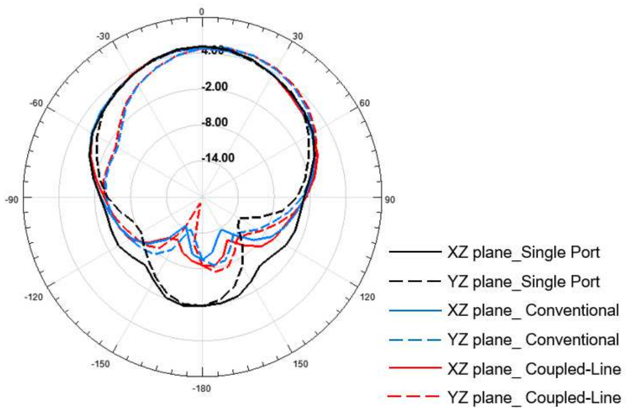

Fig. 8. Radiation patterns

TABLE II. HALF-POWER BEAM WIDTHS

Antenna feed type	HPBW (degrees)	
	XZ plane	*YZ plane*
Single port	97	96
Conventional Wilkinson combiner	106	79
Coupled line Wilkinson combiner	103	83

Conclusion

A 2 by 1 coupled line Wilkinson combiner-antenna device for THz-wave power enhancement has been designed and analyzed at 300 GHz. Simulation results with ANSYS HFSS show that, compared to a single-port fed antenna, the total radiated power can be enhanced by 2.59 dB when a 2 by 1 coupled line Wilkinson combiner is used to feed the patch antenna. Hence, when two identical UTC-PDs are integrated with the designed combiner, the radiated power from the antenna will almost be doubled compared to the power radiated when a single UTC-PD is used. Furthermore, the simulated return loss is -22.2 dB which is well below the -10 dB requirement. This suggests that for UTC-PDs with 50Ω output lines, almost all the photocurrent will be accepted by the combiner. Results further show a good isolation between the input ports and an antenna realized gain of 4.8 dBi. It's also important to note that the combiner is easier to fabricate than the conventional Wilkinson combiner and it's $\lambda/4$ lines cover a half area of 0.1×0.055 mm^2 compared to the conventional Wilkinson combiner. Thus, the coupled line Wilkinson combiner can be a better choice for monolithic integration of components at THz frequencies.

References

[1] H. -J. Song, K. Ajito, Y. Muramoto, A. Wakatsuki, T. Nagatsuma and N. Kukutsu, "Uni-Travelling-Carrier Photodiode Module Generating 300 GHz Power Greater Than 1 mW," IEEE Microwave and Wireless Components Letters, vol. 22, no. 7, pp. 363-365, July 2012.

[2] J H. Elayan, O. Amin, B. Shihada, R. M. Shubair, M. S. Alouini, "Terahertz band: The last last piece of RF spectrum puzzle for communication systems," IEEE Open J. Commun. Soc., vol. 1, no. 1, pp. 1–32, November 2019.

[3] A. Wakatsuki, Y. Muramoto and T. Ishibashi, "Development of Terahertz wave Photomixer Module Using a Uni-traveling-carrier Photodiode," Feature Articles: Imaging and Sensing Technologies for Safety and Security, vol. 10, no. 2, February 2012.

[4] A. J. Seeds, H. Dhams, M. J. Fice, and C. C. Renaud, "TeraHertz Photonics for Wireless Communications" Journal of Lightwave Technology, vol. 33, no. 3, pp. 579-587, February 2015.

[5] Y. Matsuo, M. Che, H. Kanaya and K. Kato, "THz-Wave Power Multiplication by Parallel-Connection UTC-PDs," 2020 Opto-Electronics and Communications Conference (OECC), Taipei, Taiwan, October 2020.

[6] E.J. Wilkinson, "An N-way Power Divider", IRE Trans. on Microwave Theory and Techniques, vol. 8, p. 116-118, January 1960.

[7] T. C. Edwards and M. B. Steer, Foundations for Microstrip Circuit Design, 4th Edition, West Sussex: J. Wiley & Sons, 2016.

[8] S. Akhtarzad, T. Rowbotham, and P. Johns, "The design of coupled microstrip lines," IEEE Trans. on Microwave Theory and Techniques, vol. 23, no. 6, pp. 486–492, Jun. 1975.

[9] X. Tang and K. Mouthaan, "Analysis and design of compact two-way Wilkinson power dividers using coupled lines," 2009 Asia Pacific Microwave Conference, Singapore, December 2009.

[10] T. Bryant and J. Weiss, "Parameters of microstrip transmission lines and of coupled pairs of microstrip lines," IEEE Trans. on Microwave Theory and Techniques, vol. 16, no. 12, pp. 1021–1027, Dec. 1968.

[11] D.M. Pozar, Microwave Engineering, Third Edition, John Wiley & Sons: New York, 2005.

[12] H. Ssali, M. Che and K. Kato, "Performance Analysis of a Wilkinson Power Combiner-Fed Patch Antenna for 300-GHz Arrayed Photomixers," 2022 10th International Japan-Africa Conference on Electronics, Communications, and Computations (JAC-ECC), Alexandria, Egypt, December 2022.