公益財団法人矢崎科学技術振興記念財団
国際交流援助　研究発表　帰国報告書

公益財団法人矢崎科学技術振興記念財団
　理事長 殿

国際学術会議での研究発表を終えて帰国しましたので、下記の通り報告します。

2025 年　 10 月　 20 日
氏名　紙浦 欣輝
所属　九州大学 システム情報科学府
職位　博士課程 3 年

１. 発表論文名

300-GHz Photonic Wireless Link with 5.3 mW Output Power Using Waveguide-Combined UTC-PD/SiC Photomixers

導波管結合型 UTC-PD/SiC フォトミキサを用いた出力 5.3mW の 300GHz フォトニックワイヤレスリンク

２. 国際学術会議の名称

The 51st European Conference on Optical Communication（第 51 回欧州光通信会議）

４. 国際学術会議の開催地（国、地名、会場名など）

国　　:　Denmark（デンマーク）
地名　:　Copenhagen（コペンハーゲン）
会場名:　The Bella Center（ベラセンター）

５. 渡航期間
　2025 年 9 月 27 日 ～ 2025 年 10 月 3 日

６. 国際学術会議発表の要旨

　本研究では、シリコンカーバイド（SiC）基板上に作製したユニトラベリングキャリアフォトダイオード（UTC-PD）モジュールを 2 つ用いて、J バンド導波管内で電力を合成する構成を提案・実証した。これにより、単一素子構成比で約 1.45 倍、絶対値で 5.3 mW（7.23 dBm）の出力を達成し、300 GHz 帯フォトニック送信器として世界最高水準の出力を実現した。また、OOK および QPSK/16QAM/32QAM 変調を用いた無線伝送実験により、50 Gbit/s までの高品質通信を確認した。波形歪みや EVM の劣化は見られず、波導型コンバイナを用いた高出力化が通信品質を損なわないことを実証した。
　現地では、研究者から「SiC モジュールの入手可能性」「使用したシミュレーション環境」「受信器の構成（ダイオードベースか）」「通信距離」「新しい基板材料」等について質問があり、システム全体の設計指針に対する議論が行われた。
また、日本の通信事業者関係者からは「帯域維持を考えると 100 GHz 帯ではアレイでも可能ではないか」「SiC 化の主流性」「InP 比での出力増加率（約 10 倍）」「必要電力量」など、実用化

視点での質疑が寄せられた。特に「コンバイナ結合効率 75 %は非常に優れている」「この内容ならオーラル発表でも良い」との高い評価を得た。

さらに、「300 GHz 帯でこれだけ高い出力は世界的にも稀であり、UTC-PD 技術の成熟度が示された」「電気生成方式はコスト優位だが、フォトミキシング方式は技術的に極めて興味深い」といったコメントもあり、本研究の独創性と技術的完成度が国際的に認められた。

全体として、SiC 基板 UTC-PD の高出力化および波導結合による高効率電力合成技術が、Beyond 5G/6G におけるフォトニック THz 送信機の有力候補であることを強く印象づける成果となった。

7. 国大学術会議の動向

今年の ECOC（European Conference on Optical Communication）は、世界最大規模の光通信国際会議として、例年にも増して高い競争率となりました。採択率は、口頭発表が約 29%、ポスター発表が約 20%、Post-deadline Paper が約 23%と非常に狭き門であり、改めて本会議の難易度とレベルの高さを実感しました。私はポスター発表として採択され、発表当日は多くの研究者や企業関係者から質問やコメントをいただき、非常に有意義な討論の場となりました。

ECOC は、最先端の研究成果の発表に加えて、産業展示が非常に充実している点が特徴であり、研究者・技術者・学生・企業関係者が一堂に会する光通信分野を代表する会議です。今年は世界各国から 2,000 名を超える参加者が集まり、光通信技術の現状と将来展望について活発な意見交換が行われていました。

今年の技術的傾向としては、低損失かつ低遅延で注目を集める Hollow-Core Fiber（HCF）、マルチコアやフューモードファイバによる空間分割多重（SDM）技術、およびシリコンフォトニクスを基盤とした高周波変調器や高シンボルレート伝送が特に目立ちました。また、光アクセスネットワークにおけるコヒーレント通信技術や、光ファイバセンシング・海底ケーブルを用いた地震観測・社会インフラモニタリングといった応用寄りのトピックも注目を集めており、実用化を見据えた研究が一層活発になっている印象を受けました。

総じて、ECOC 2025 は光通信技術の多様化と高機能化を象徴する内容となっており、基盤研究から応用開発までを包括する分野の発展と広がりを強く実感できる貴重な機会となりました。

以上

300-GHz Photonic Wireless Link with 5.3 mW Output Power Using Waveguide-Combined UTC-PD/SiC Photomixers

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Abstract *We demonstrated a record output power of 5.3 mW at 300 GHz band by waveguide-combining two SiC-based InGaAs UTC-PD photomixers, boosting power 1.45-fold. Wireless experiments with OOK and QPSK/QAM confirmed longer transmission distances over free space reflecting higher output power, while preserving consistent signal quality. ©2025 The Author(s)*

Introduction

Terahertz (THz) communications has been extensively researched in recent years as a potential technology for 6th generation (6G) mobile communications systems, which are expected to meet the demand for data rates in excess of 100 Gbit/s [1]. Photonics methods of THz generation have undergone significant developments. Devices based on photonics can take advantage of the benefits of this technology, including a wide operating bandwidth and the ability to transmit and manipulate THz signals with minimal loss, regardless of the frequency [3]. A number of studies on THz-band communications have been reported in the photomixer-based approach using Uni-Traveling Carrier Photodiode (UTC-PD) [4]. Many of them use high-gain antennas and lenses to concentrate the power into the receiver. The major challenge has been an increase of the output power from a single UTC-PD, aiming for practical transmission distances. Recently, as one of ways to increase the saturated output power, a UTC-PD on a silicon carbide (SiC) substrate was developed to improve the thermal management. The UTC-PD/SiC chip was integrated into a rectangular waveguide module, which resulted in the record output power of 4 mW in the 300-GHz band [5]. Current combining from arrayed UTC-PDs is another feasible approach to increase the output power beyond that of a single UTC-PD. The two UTC-PDs were integrated in parallel and combined with an on-chip T-junction power combiner to achieve more than twice the output power at 300 GHz [6]. However, there remains concern about whether such combining methods degrade signal quality, especially under high-speed modulation formats.

This paper reports a record-high output power of 5.3 mW in a 300-GHz photonic wireless link using two InGaAs-UTC-PD/SiC modules integrated with a waveguide combiner. Wireless transmission experiments were conducted using both OOK and QPSK/QAM modulation formats. The results confirmed that the increased power enabled longer transmission distances without significant degradation in signal performance, supporting data rate of up to 50 Gbit/s.

Characteristics of UTC-PD module and combiner

The UTC-PD has a 0.13-μm-thick InGaAs photoabsorption layer consisting of p-type and undoped layers [7] and an area of 12.5 μm^2 (4 μm diameter). In the fabrication process of the UTC-PD, using the substrate transfer technique [8], epi-layers are transferred from an InP substrate to SiC substrate which has excellent thermal conductivity [9] and thus, can flow a larger current without heat retention at the UTC-PD. Figure 1 (a) shows the structure of the UTC-PD chip and a photograph of the module. The new UTC-PD photomixer that includes matching circuit is embedded in a signal line of MSL-based low-pass

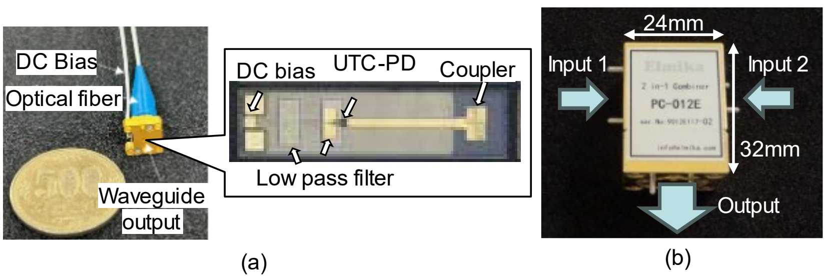

Fig. 1. (a) Compact InGaAs/SiC UTC-PD photomixer module (b)THz waveguide combiner.

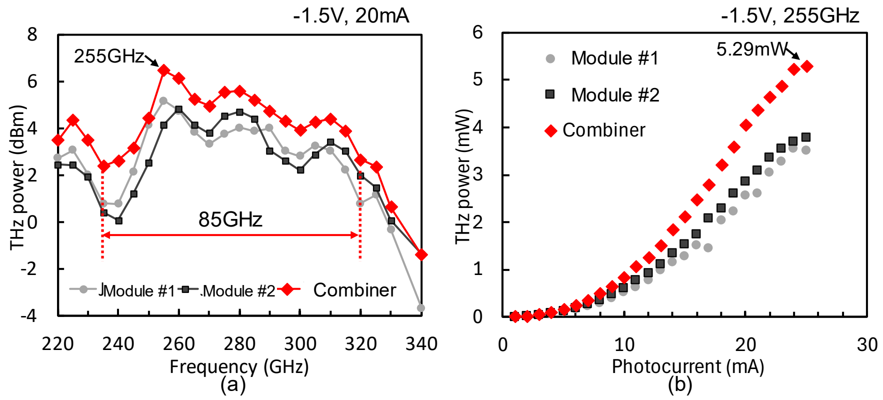

Fig. 2. Comparison of single modules and a waveguide-combined module: (a) frequency dependence of output power and (b) photocurrent dependenceof output power.

Tab. 1: Output-power milestones of UTC-PD photomixer transmitters in 300-GHz band

Year	Power (mW)	Notes	Ref.
2003	0.3	Based InP, Single	[10]
2008	0.54	Based InP, Single	[11]
2012	1.2	Based InP, 2Array	[6]
2023	2.53	Based SiC, Single	[12]
2024	4.03	Based SiC, Single	[5]
2025	5.06	Based SiC, Combiner	[13]
This work	5.29	Based SiC, Combiner	

filter. The module is designed to be 1/10 the volume of a conventional UTC-PD module. An optical fibre and DC bias cable are connected to the module to provide an optical beat signal and DC bias voltage to the UTC-PD, respectively. The generated THz waves are coupled from the radiator to the J-band (220-340GHz) waveguide.

Two laser sources with tunable wavelengths in the 1550-nm band were utilized whose frequency difference was set to be in the J-band. The THz waves outputted from each module were combined by a THz waveguide combiner as shown in Fig.1(b). The single module and combined power were measured with a calibrated power meter (Ericsson Power Meter PM5). Fig. 2(a) shows the measured spectral characteristics of the module with a bias voltage of -1.5 V and a photocurrent of 20 mA. The peak operating frequency and the 3-dB operating bandwidth were 255 GHz and 85 GHz, respectively. Then, the single module and combined power at 255 GHz was measured as a function of the photocurrent. As shown in Fig. 2(b), the power from the two UTC-PD modules increased proportionally to the square of the photocurrent. The output of the single module averaged 3.6 mW (5.61 dBm) at 25 mA, whereas the output combined by the waveguide combiner was 5.29 mW (7.23 dBm). The coupling efficiency of the waveguide combiner was 75.3%, demonstrating the effectiveness. The combined output of the two modules based on SiC substrates increased by a factor of 1.45 (1.62 dB) compared to the single module. Furthermore, it corresponds to approximately 10 times more than a single conventional UTC-PD module using an InP substrate shown in Table 1.

300-GHz band Wireless Transmission

1. OOK 12.5 Gbps Transmission

To investigate the power enhancement achieved using combiners, the transmission system illustrated in Fig. 3(a) was configured. The carrier frequency of the THz wave was set to 255 GHz. First, two lightwaves were intensity-modulated with on-off keying (OOK) at a data rate of 12.5 Gbit/s using an electro-optic modulator (EOM). The data stream consisted of a pseudo-random bit sequence (PRBS) of length 2^7–1. The modulated lightwaves were subsequently amplified by an EDFA and launched into an UTC-PD via optical fiber. A THz wave at 255 GHz was generated by photomixing and radiated into free space by a horn antenna with a gain of 26 dBi. The THz wave was received by a Fermi-level-managed barrier diode (FMBD) [14] connected to a horn antenna having a gain of 21 dBi, positioned at distances ranging from 0 to 23 cm from the transmitting antenna, as shown in Fig. 3(a). The bit error rate (BER) of the received signal was evaluated using a bit error rate tester (BERT).

Fig. 3 (a) shows the BER performance as a function of transmission distance for both a single photomixer module and a power-combined configuration using a THz waveguide combiner, where the optical input power to each photomixer in the combined setup was adjusted to produce the same photocurrent as in the single-module case. When the receiver was placed at distances ranging from 0 to 9 cm, both systems achieved error-free transmission. At a comparable BER level beyond this range, the combined

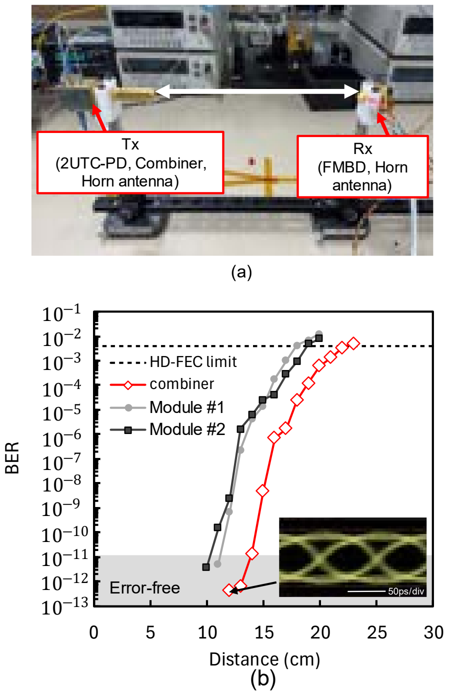

Fig. 3: BER vs distance for a 12.5 Gbit/s 255-GHz wireless link with and without power combining

configuration enabled approximately 1.25 times longer communication distance than the single-module system.

Since transmission distance scales with the square root of the received power. The experimentally observed distance gain of 1.24 times is in good agreement with this theoretical prediction, validating the effectiveness of power combining using a waveguide combiner. Beyond 10 cm, the steeper BER slope of the combined system suggests that power-combining improves receiver SNR, thereby extending range and bolstering robustness under moderate attenuation.

2. QPSK/QAM Transmission

Single module and combiner-based communication systems were also compared in experiments with 300 GHz QPSK and QAM transmission. In the transmitter, one of two laser diodes (LDs) was modulated with an arbitrary waveform generator (AWG) and an IQ modulator. Each module was biased to yield a photocurrent of -4 mA. The output signals were received via a waveguide-connected sub-harmonic mixer. By setting the local oscillator (LO) frequency for heterodyne detection, the signal was down converted to an intermediate frequency (IF).

Constellation diagrams obtained via real-time oscilloscope signal processing illustrate the performance of both single-module and combiner-based communication systems under QPSK, 16QAM, and 32QAM modulation formats at 10 Gbaud. As shown in Fig. 4, comparable communication quality was achieved using the combiner module relative to the single module. Furthermore, for 32QAM at 10 Gbaud, an error vector magnitude (EVM) level below the SD-FEC threshold was observed, enabling successful transmission at up to 50 Gbit/s. For 16QAM at 10 Gbaud, the EVM was below the HD-FEC threshold, supporting transmission rates of up to 40 Gbit/s. Despite the integration of the combiner, EVM degradation was minimal, indicating that the combiner can be effectively used without significantly compromising signal quality.

Conclusions

We demonstrated a 300-GHz photonic wireless transmission system using two InGaAs/SiC UTC-PD photomixer modules combined with a J-band waveguide. The system achieved a record output power of 5.3 mW (7.23 dBm), which is 1.45 times higher than that of a single module. Wireless transmission experiments using both OOK and QPSK/QAM modulation formats were conducted to evaluate the performance of the combined system. The resulting increase in output power enabled long-distance transmission as predicted based on Friis. In long-distance OOK transmissions, BER was measured at photocurrents of up to 15 mA, confirming stable operation even at high currents. No significant signal degradation was observed for QPSK and QAM at data rates up to 50 Gbit/s.

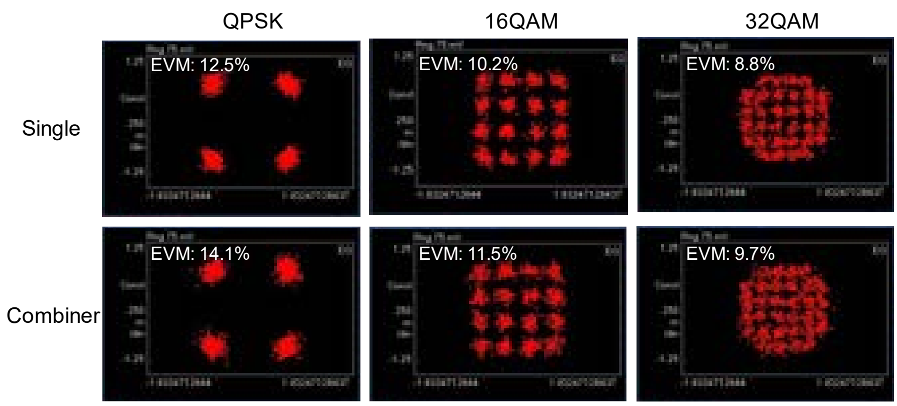

Fig. 4. Constellation quality of 10 Gbaud QPSK/16QAM/32QAM at 320 GHz using single vs. combined transmitters.

Acknowledgements
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