Meteracom Workshop
At the IRMMW-THz 2025

Effects of Phase Noise and Nonlinearity on Signal Integrity in Photonics-Enabled THz Links

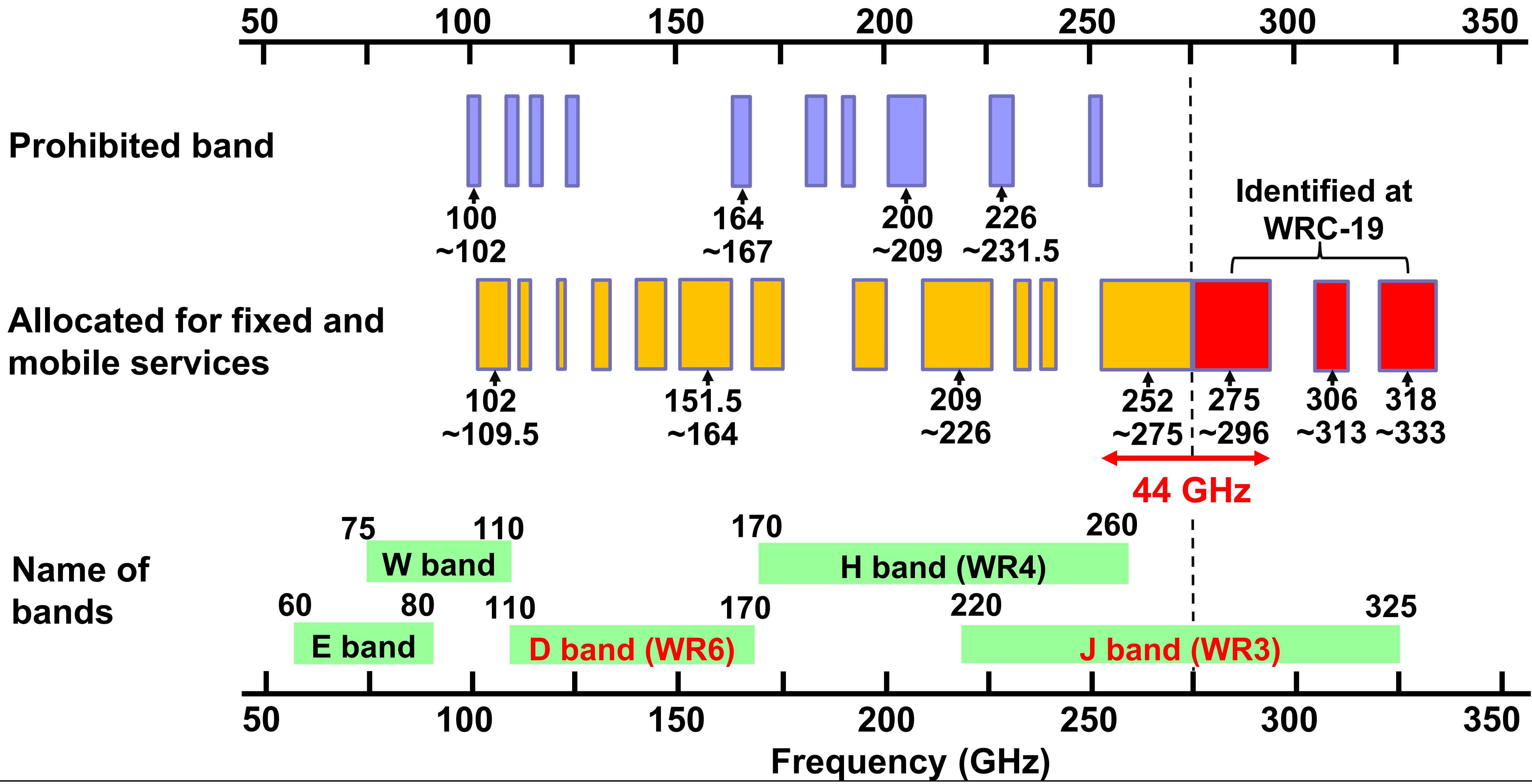
Tadao Nagatsuma

Graduate School of Science, The University of Tokyo

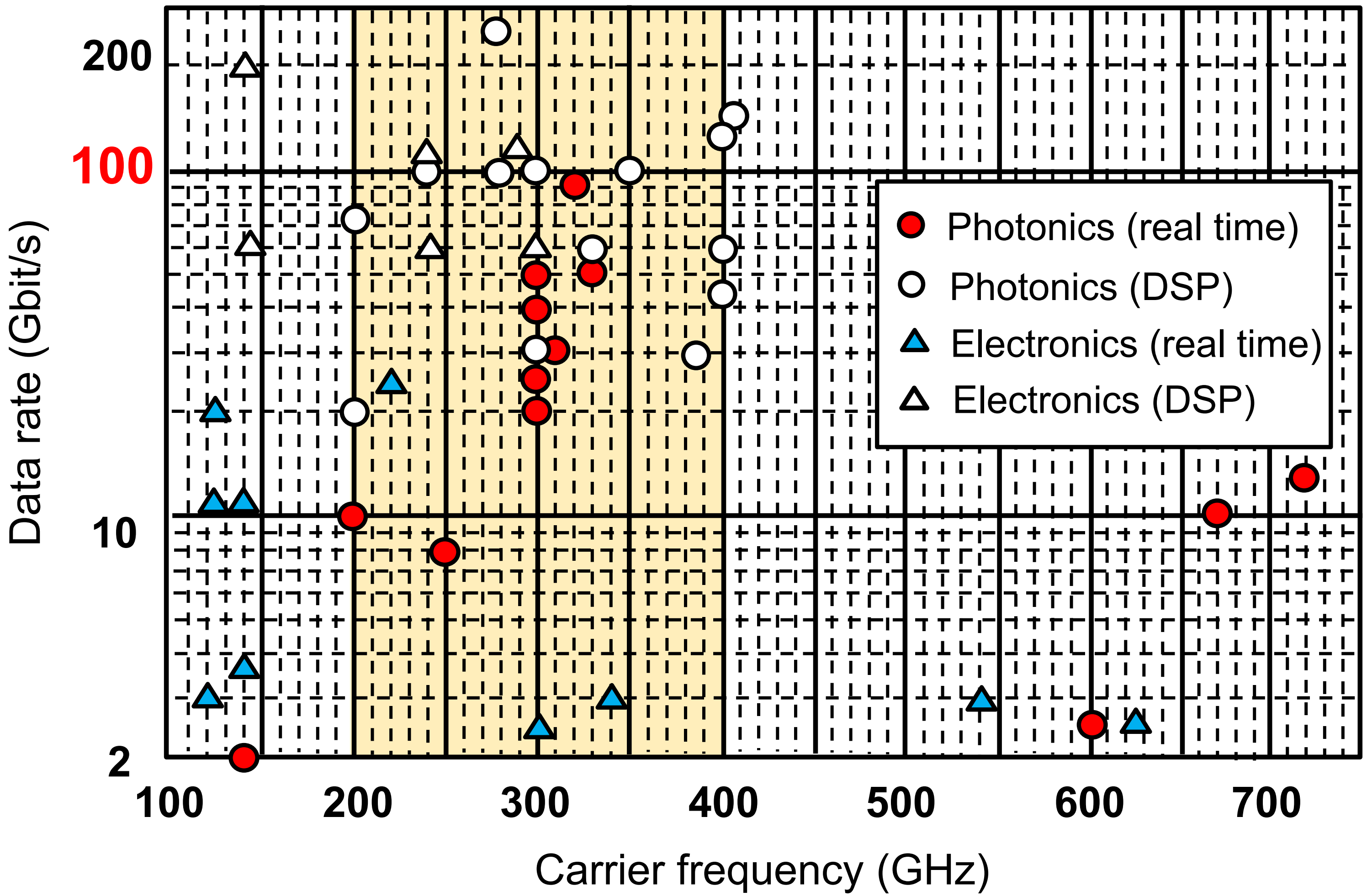
Outline

1. **Background and motivation**
2. **Effect of phase noise**
3. **Effect of nonlinearity**
4. **Conclusion**

Frequency Selection: International Consensus

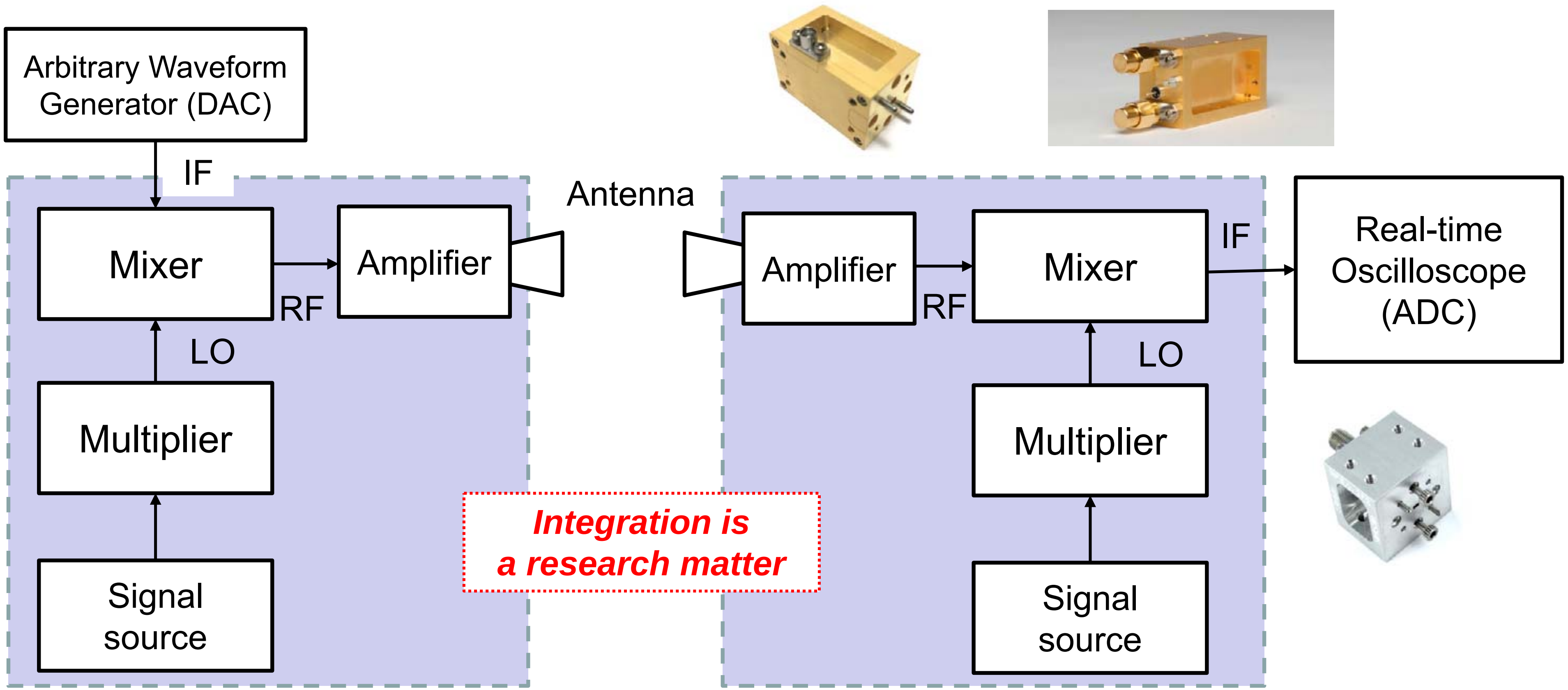


Recent Developments in THz Wireless: Single Channel Transmission Speed

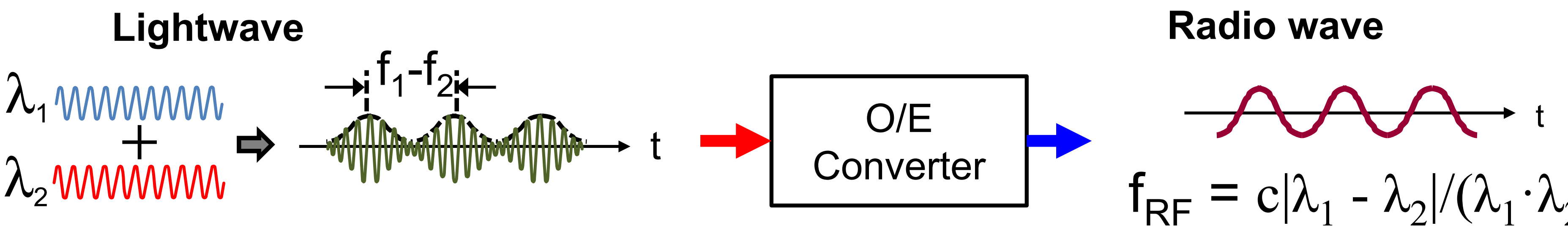


Basic Configuration of a Wireless Communication System

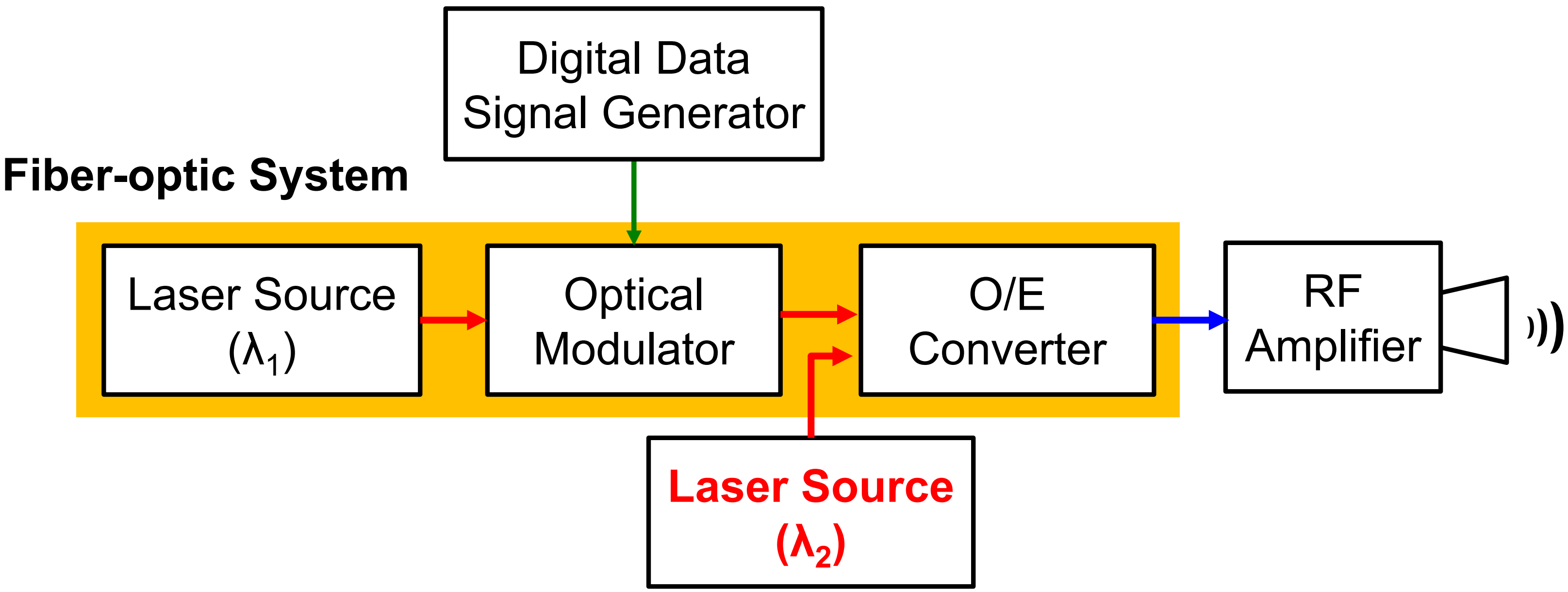
All components (discrete) are now commercially available up to 300 GHz



Photonics-based Approach: Transmitter

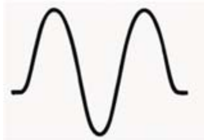


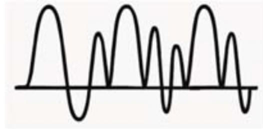
$$f_{RF} = c|\lambda_1 - \lambda_2|/(\lambda_1 \cdot \lambda_2)$$



Photonics-based Approach: Mertis

Signal Generation and Modulation





Photonics technology offers broader bandwidth and potentially higher stability and integrity than electronic technology.

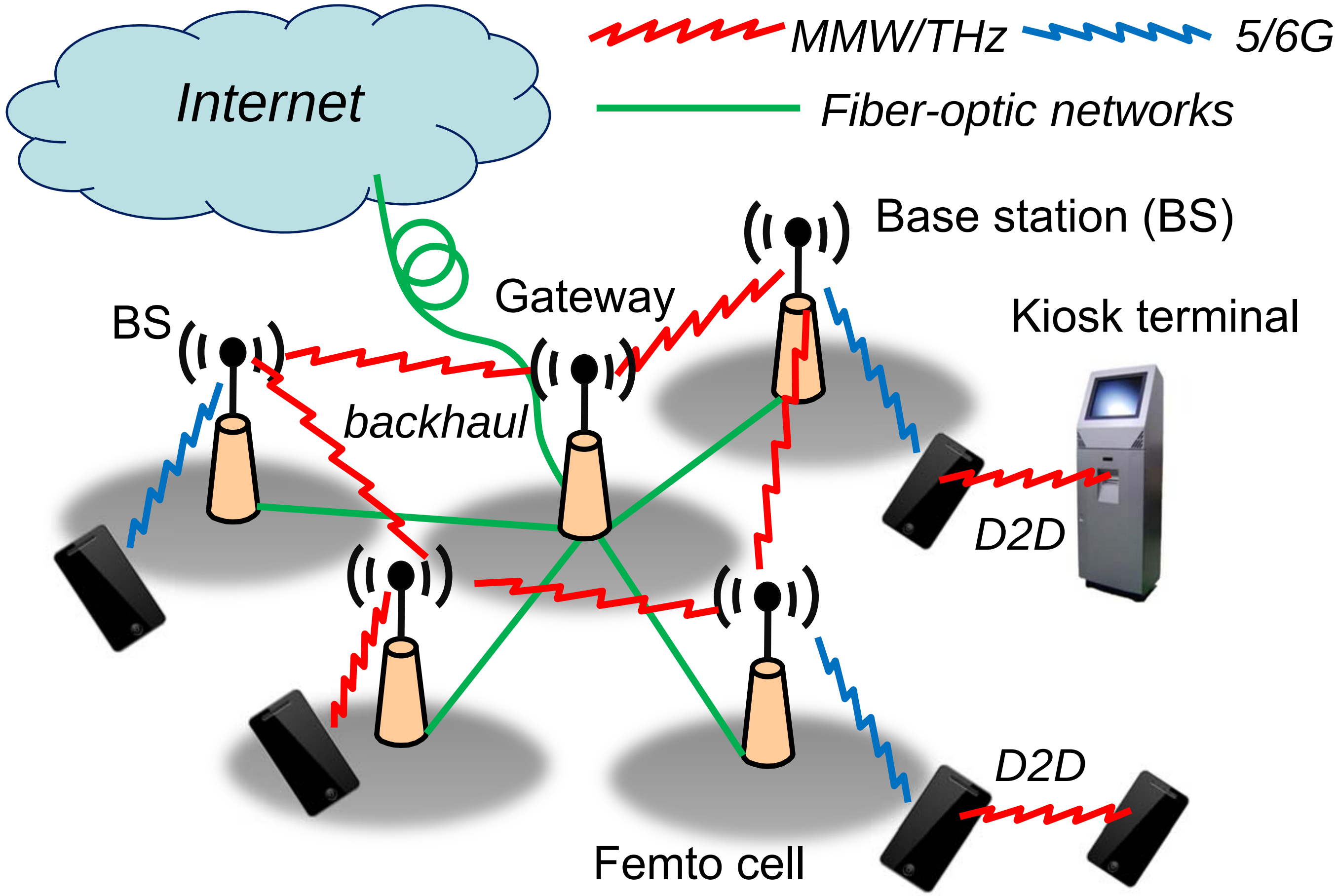
e.g., J. Dittmer *et al.*, "Comparison of electronic and optoelectronic signal generation for (sub-)THz communications," *International Journal of Microwave and Wireless Technologies*, vol. 17, no. 2, pp. 246–256, 2025.

Signal Transmission

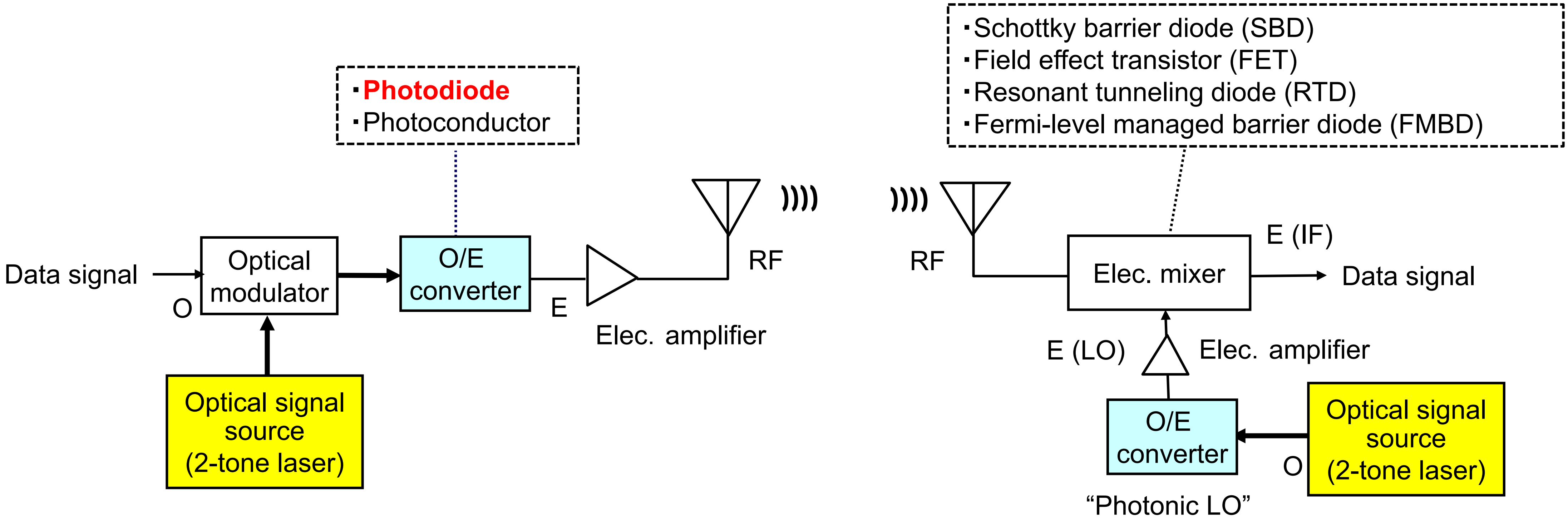
Direct combination with fiber-optic transmission technology makes it easy to be deployed in converged wireline-wireless networks.

Convergence of Wireless and Fiber-optics

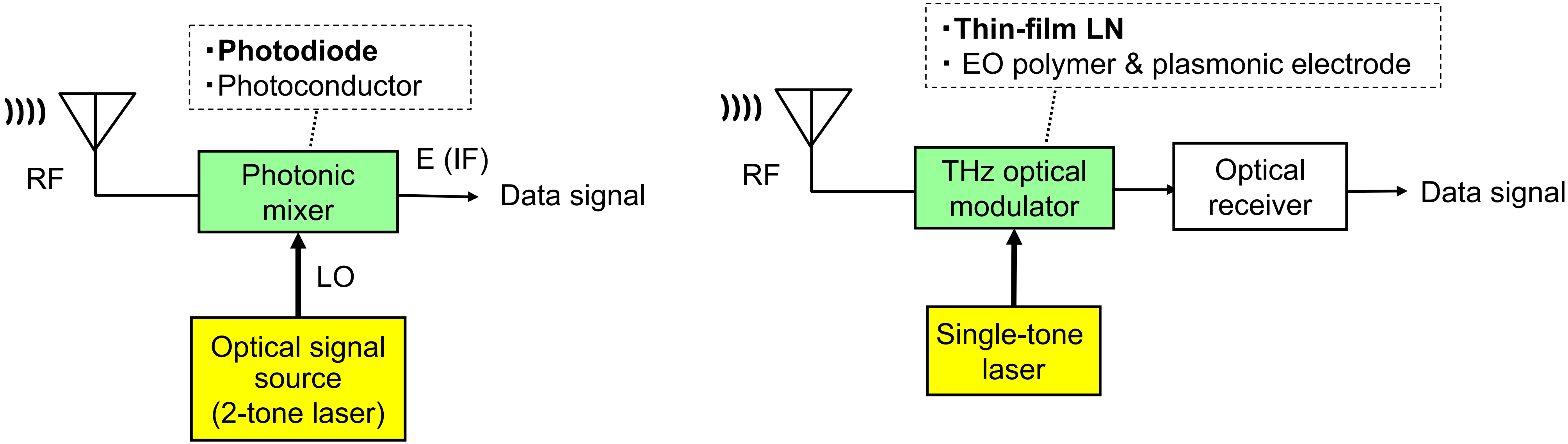
T. Nagatsuma et al., Nature Photonics, vol. 10, 371(2016).



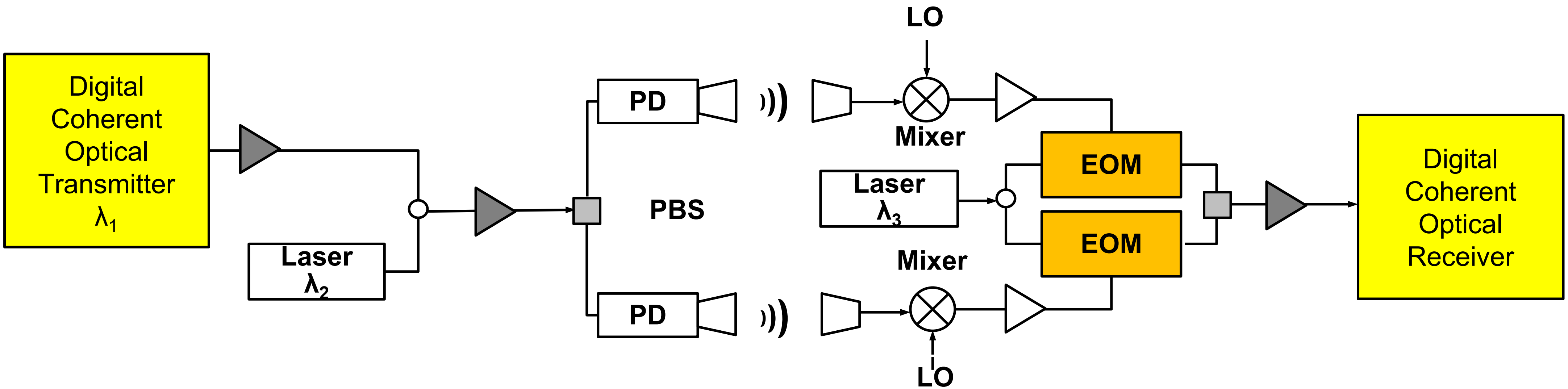
Photonics-assisted Systems



Photonics-based Receivers

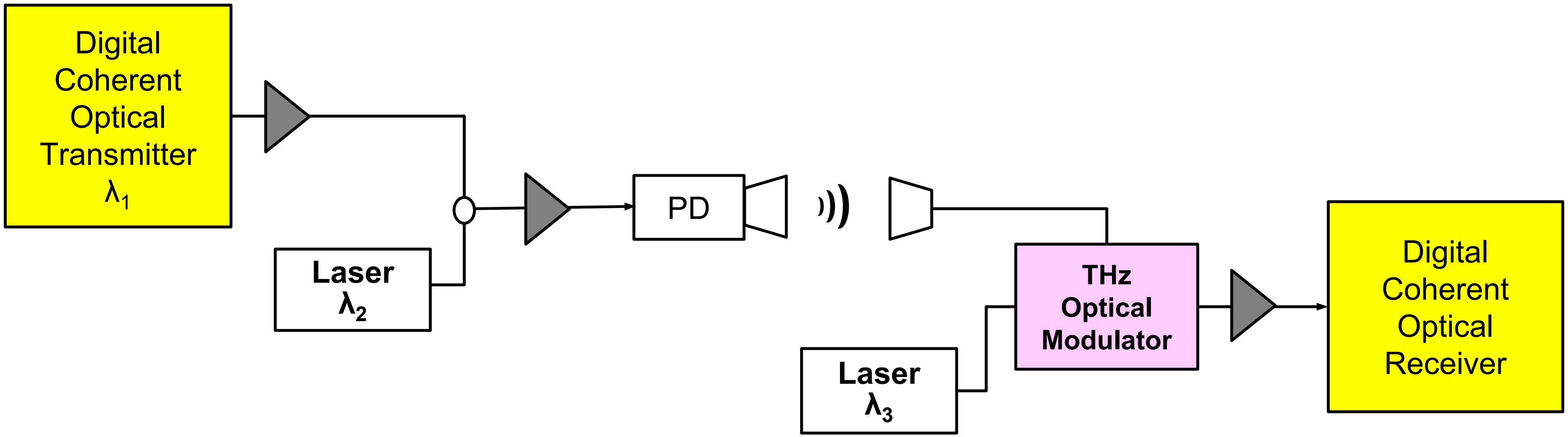


Real Optical-THz-Optical Link



J. Zhang, M. Zhu, M. Lei, B. Hua, Y. Cai1, Y. Zou, L. Tian, A. Li, Y. Huang, J. Yu, and X. You1, "Demonstration of real-time 125.516 Gbit/s transparent fiber-THz-fiber link transmission at 360 GHz~430 GHz based on photonic down-conversion," Tech. Dig. Optical Fiber Communication Conference, M3C. 2, 2022.

All Photonic Receiver

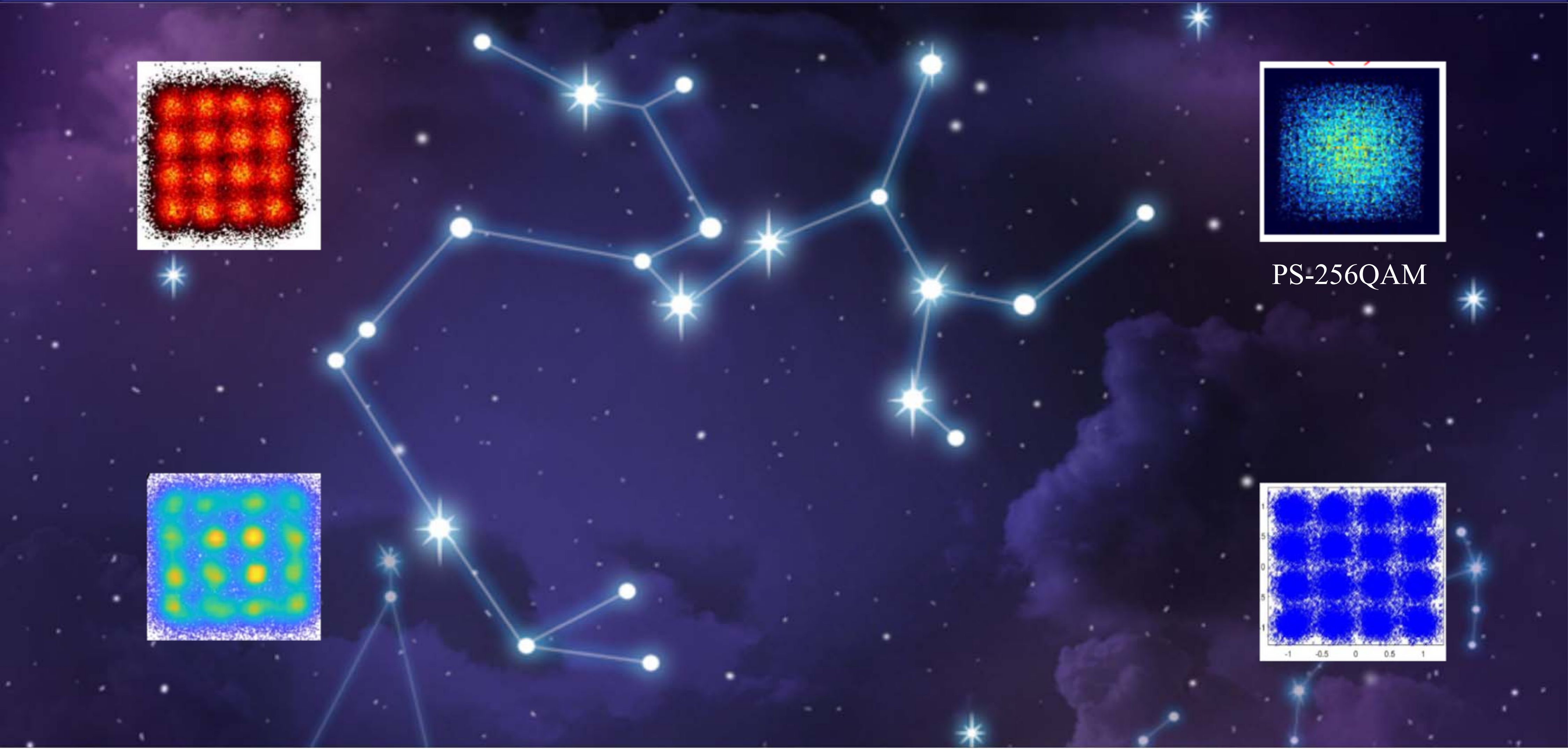


Y. Horst, T. Blatter, L. Kulmer , B. I. Bitachon , B. Baeuerle, M. Destraz, W. Heni , S. Koepfli, P. Habegger, M. Eppenberger, E. D. Leo, C. Hoessbacher, D. L. Elder, S.R. Hammond, L. E. Johnson, L. R. Dalton, Y. Fedoryshyn, Y. Salamin, M. Burla, and J. Leuthold, “Transparent optical-THz-optical link at 240/192 Gbit/s over 5/115 m enabled by plasmonics,” J. Lightwave Tech., vol. 40. no. 6, pp. 1690-1697, 2022

Outline

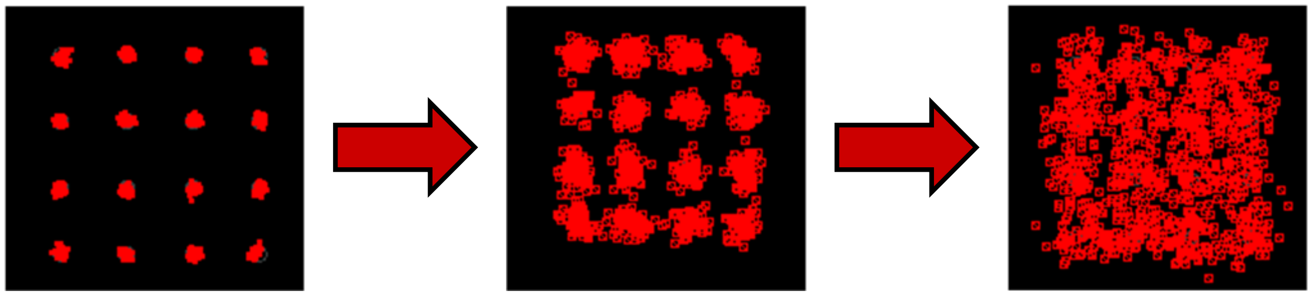
1. Background and motivation
2. **Effect of phase noise**
3. Effect of nonlinearity
4. Conclusion

THz constellations diagrams are generally poor



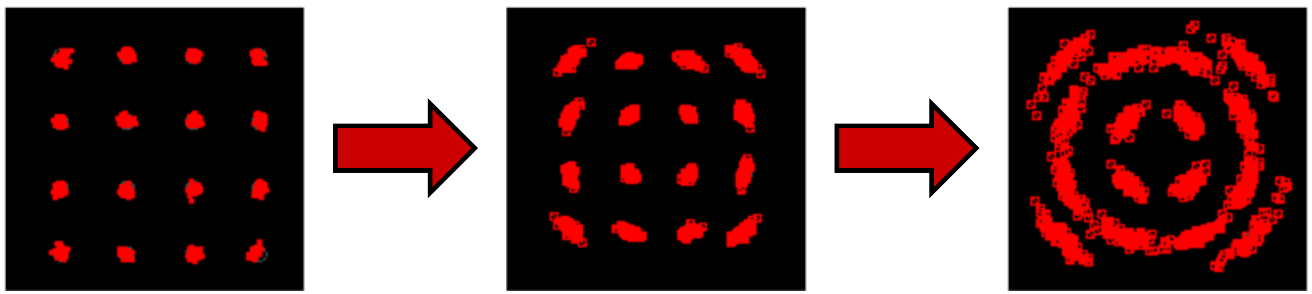
Impact of Noises on Constellation Diagrams

Effect of Intensity Noise



Causing symbols fluctuation

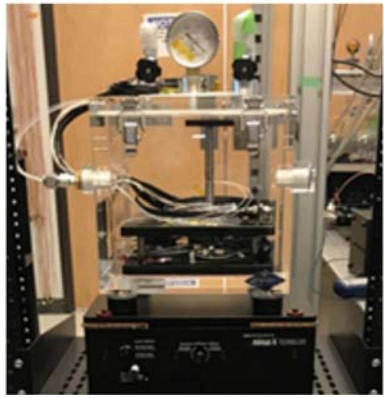
Effect of Phase Noise

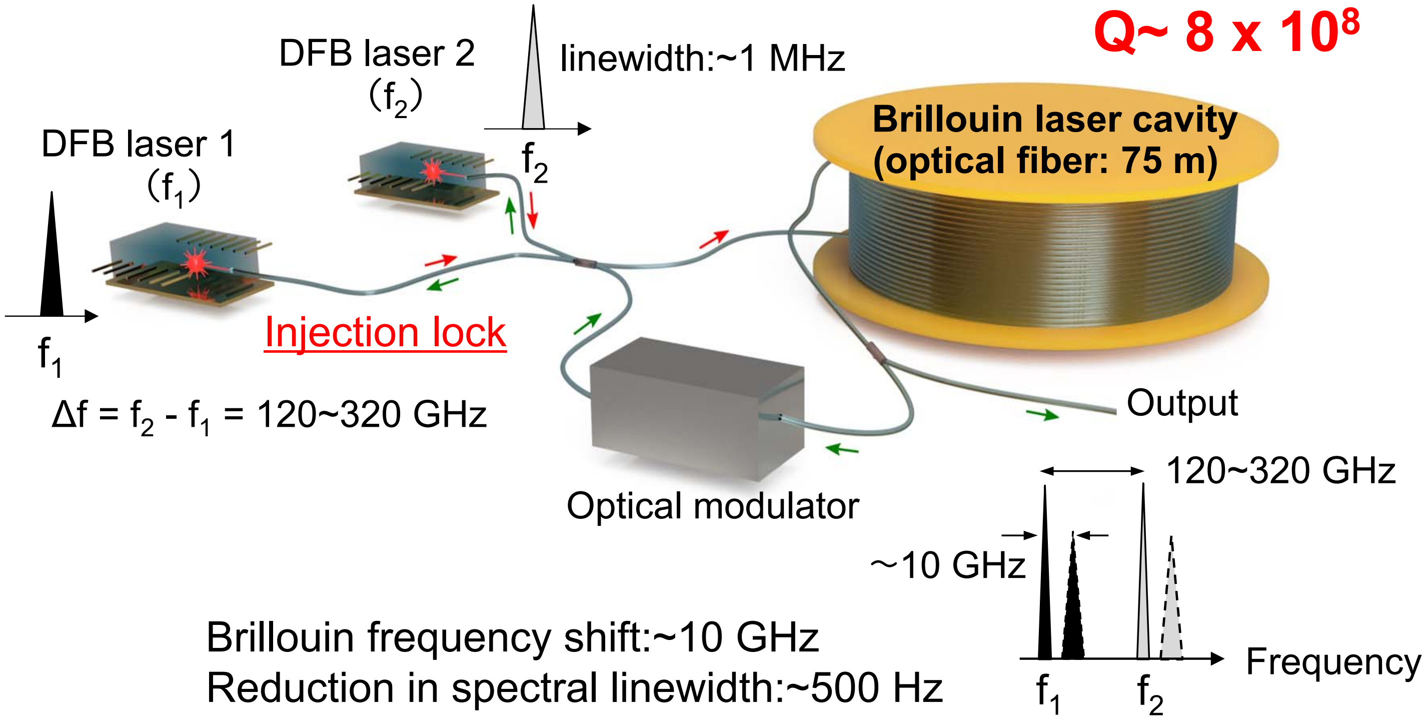


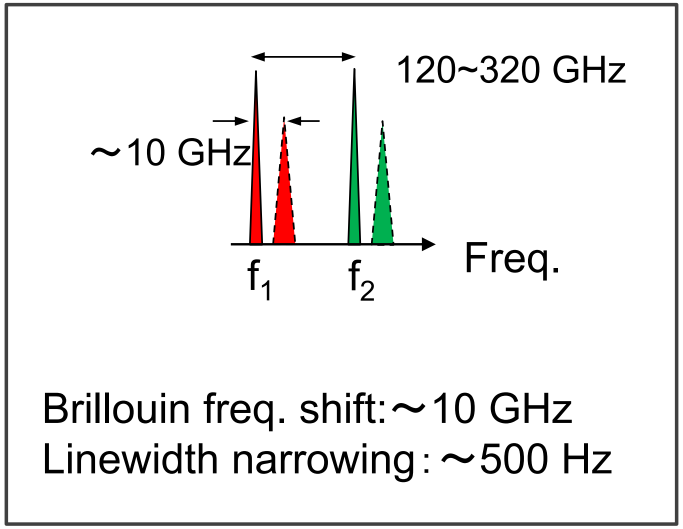
Causing symbols rotation

Ultralow-phase Noise Reference: Dual-wavelength Brillouin Laser (DWBL)

B. Heffernan, J. Greenberg, T. Hori, T. Tanigawa, and A. Rolland, “Brillouin laser-driven terahertz oscillator up to 3 THz with femtosecond-level timing jitter, ” Nature Photonics, 18 (12), pp. 1263-1268 (2024).

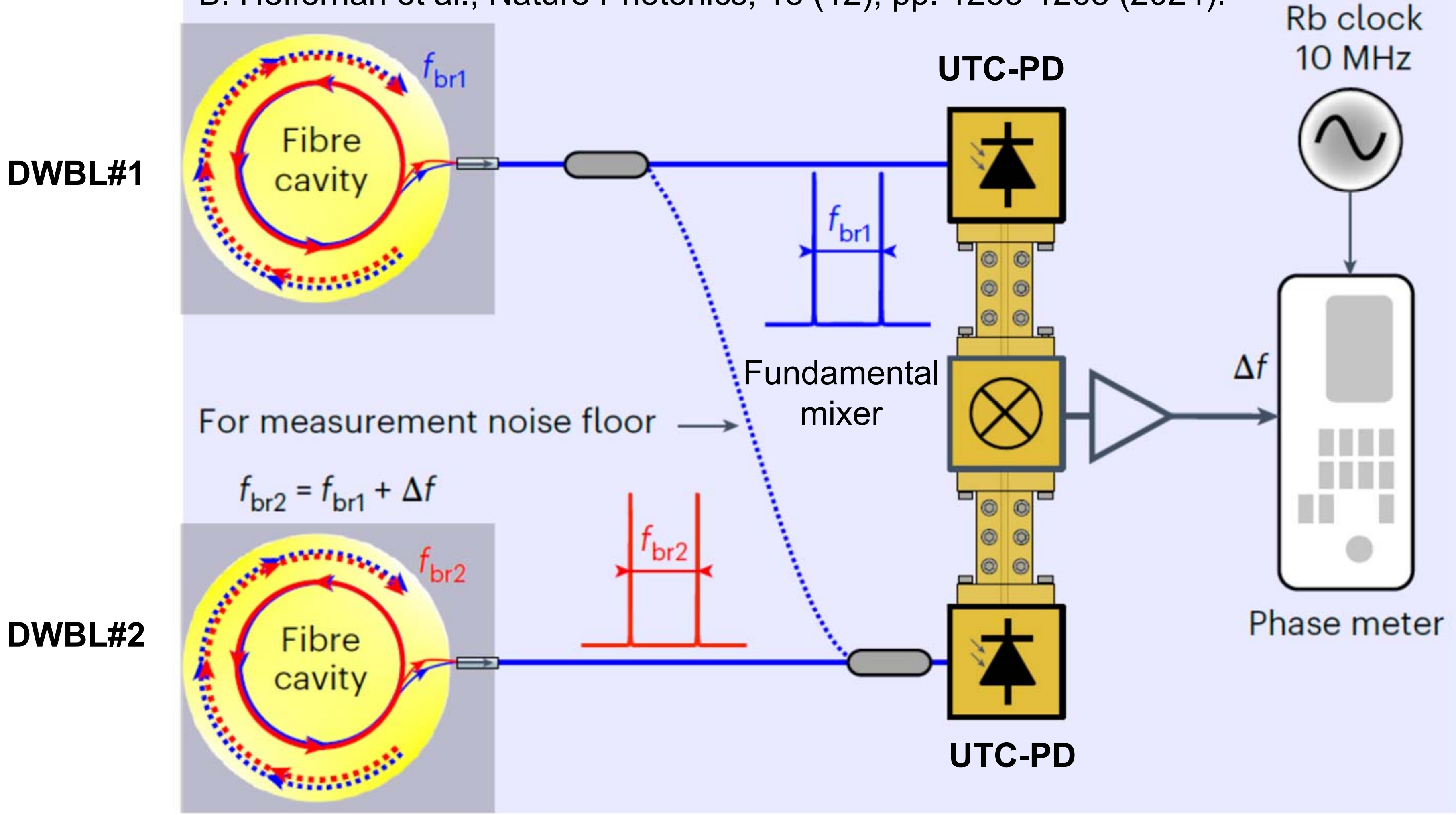






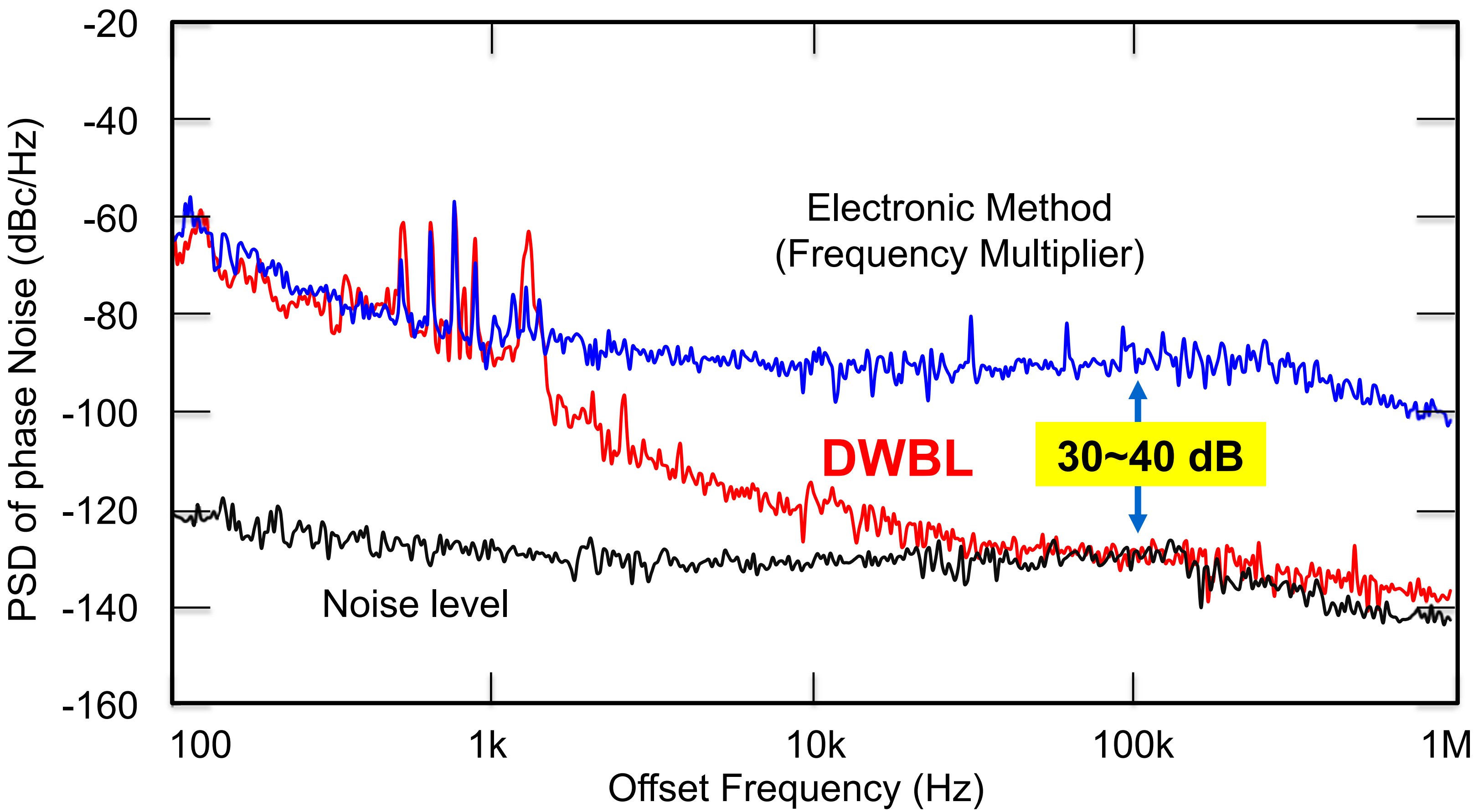
Phase-noise Measurement Method at 300 GHz

B. Heffernan et al., Nature Photonics, 18 (12), pp. 1263-1268 (2024).

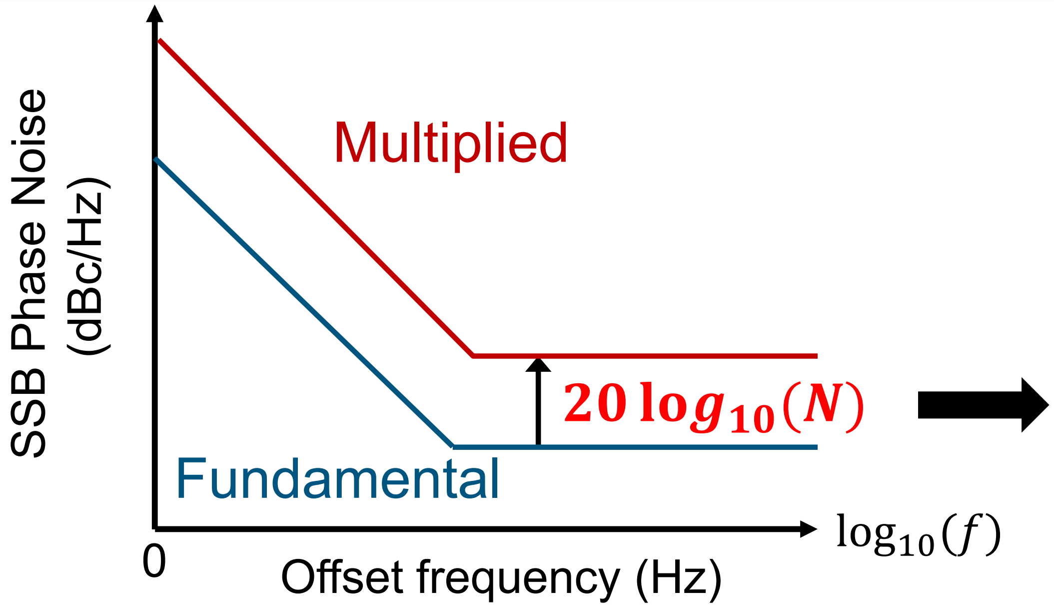


Measured Phase Noise of DWBL at 300 GHz

B. Heffernan et al., Nature Photonics, 18 (12), pp. 1263-1268 (2024).

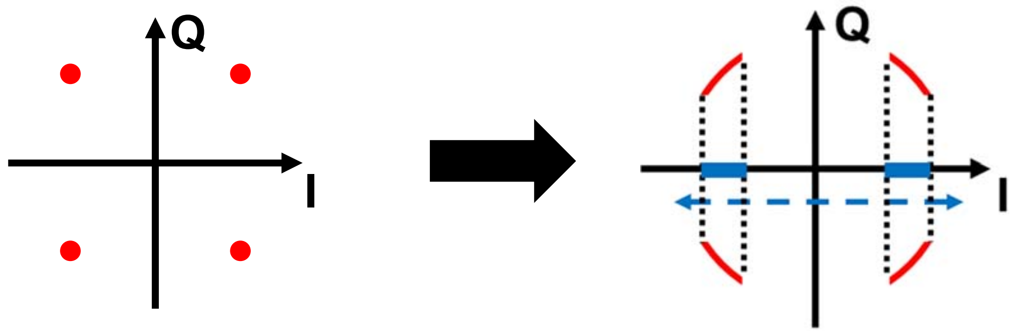


Phase Noise Increase by Frequency Multiplication



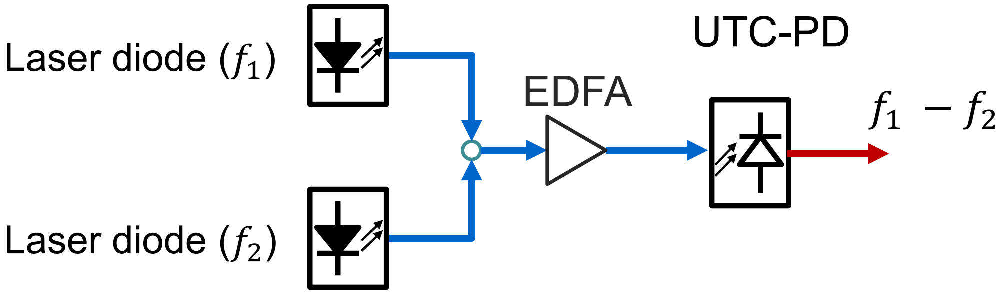
20.0 dB (N = 10)
26.0 dB (N = 20)
29.5 dB (N = 30)

Change in constellation: QPSK

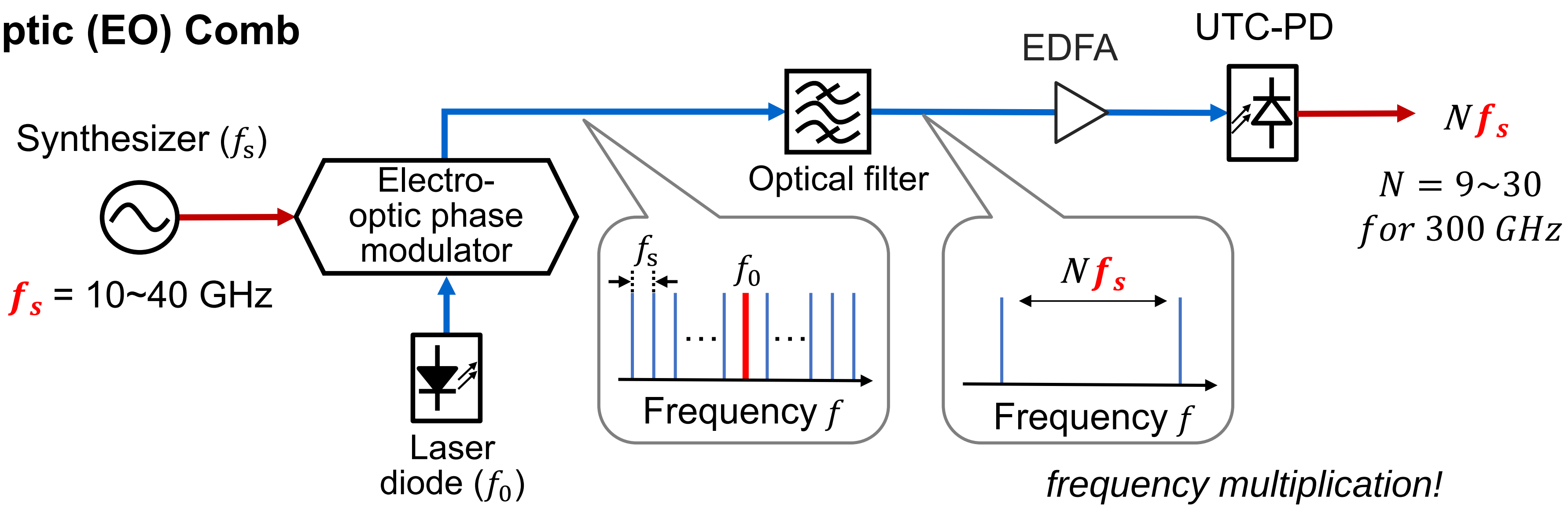


Comparison with Two Major Photonic Sources

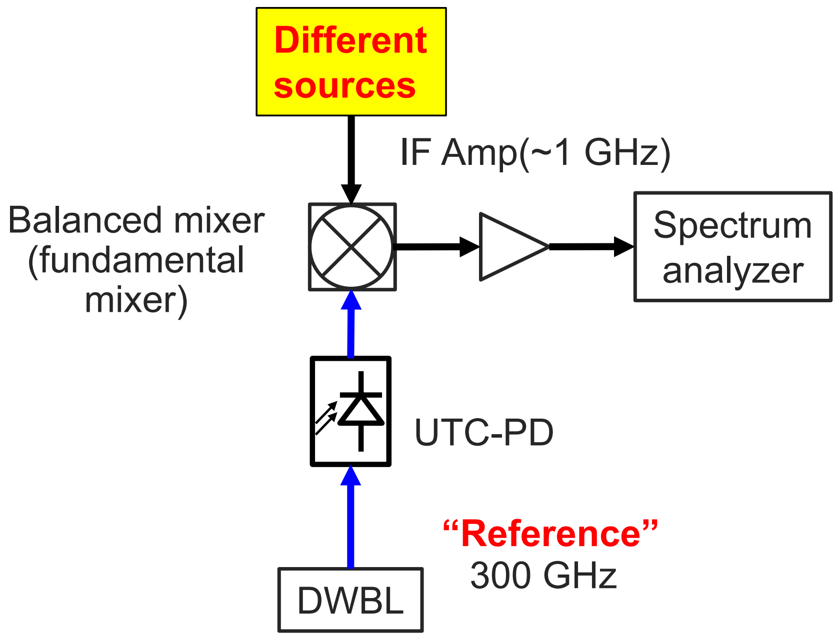
Two Laser Pairs (free-running)

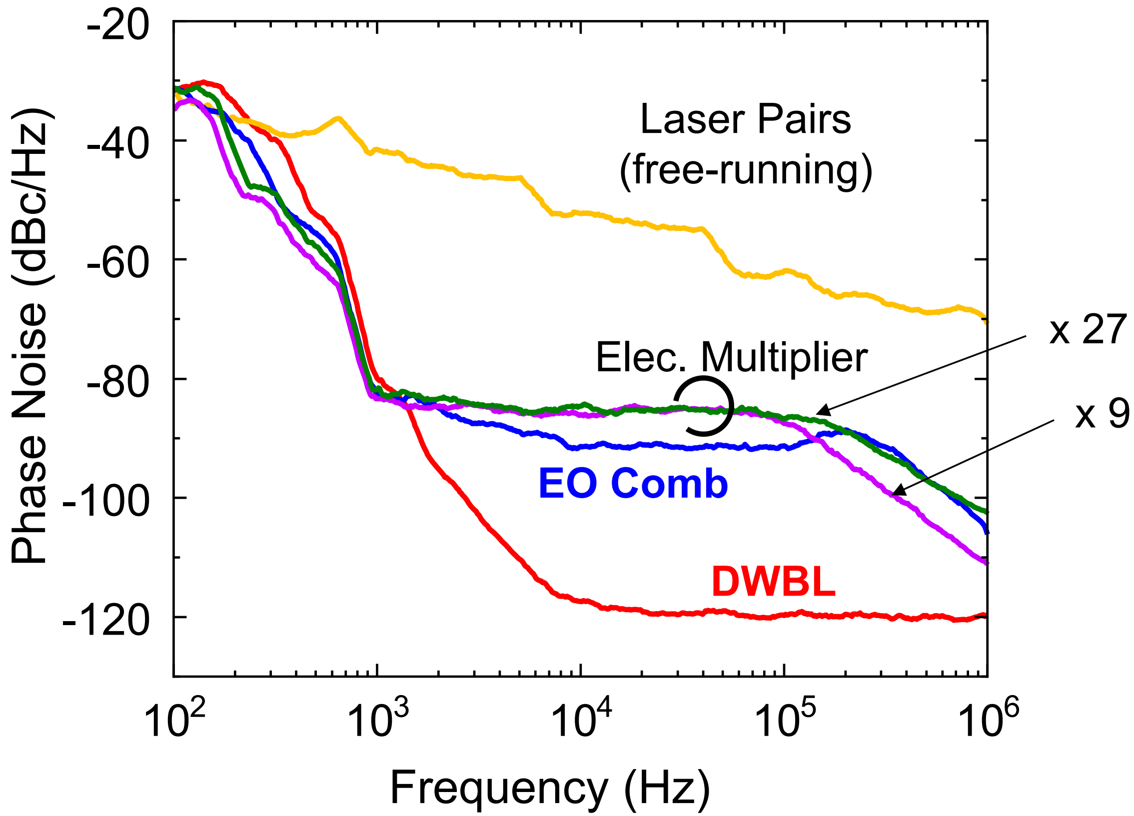


Electro-optic (EO) Comb

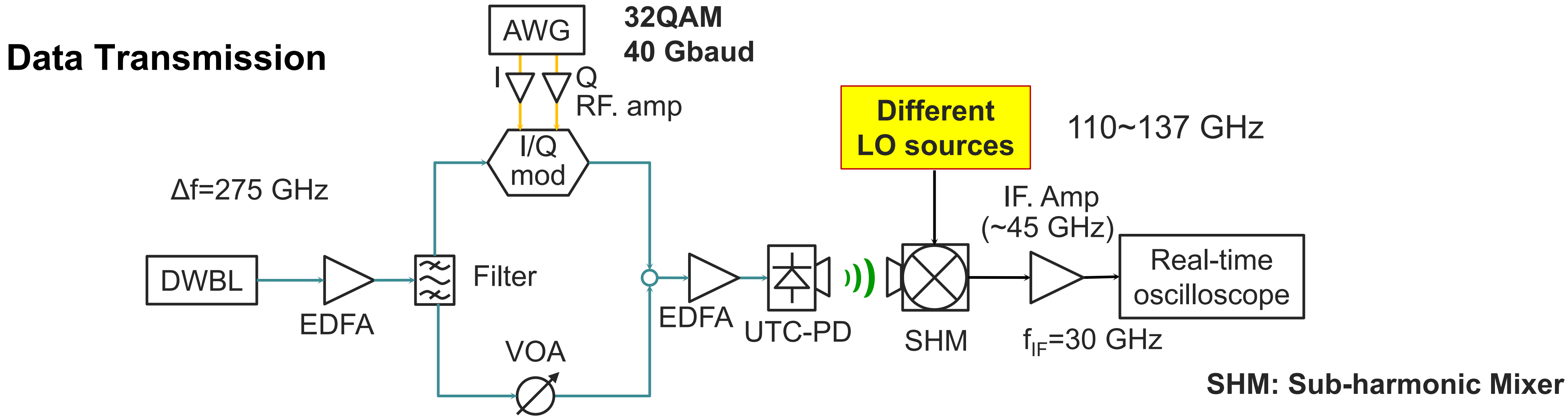


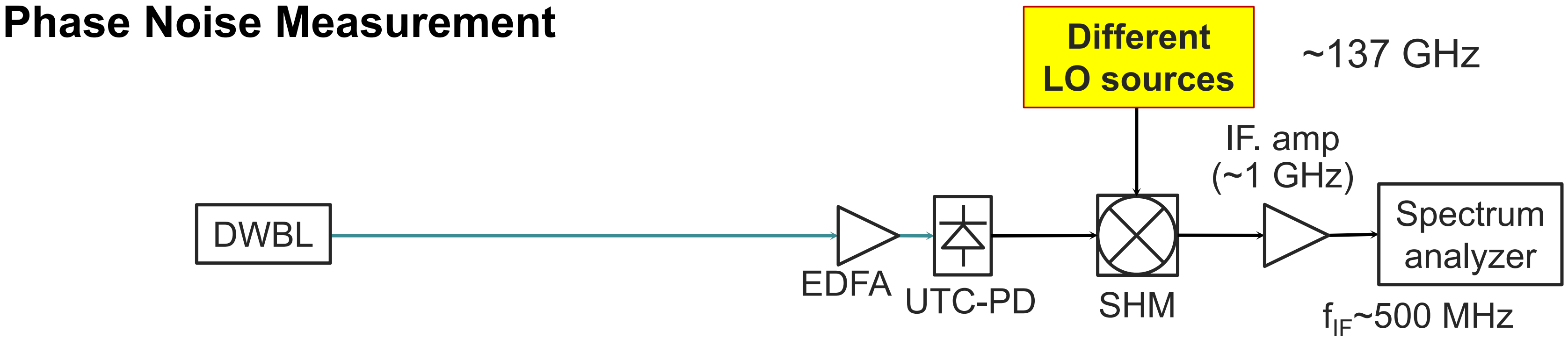
Phase Noise Comparison at 300 GHz





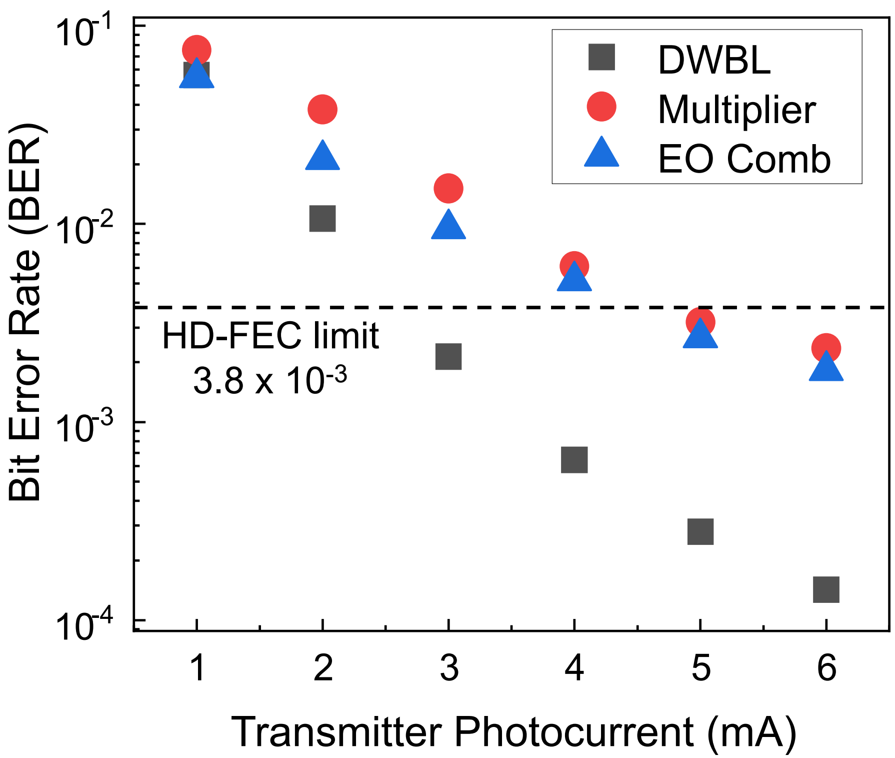
Transmission Test with Different LO Sources



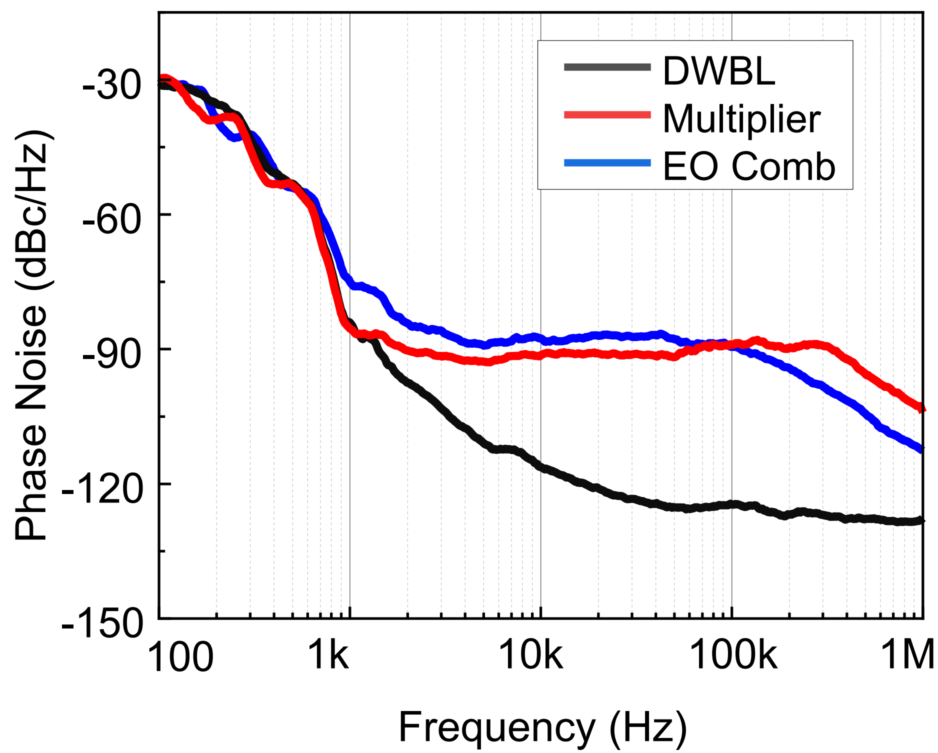


Effect of Phase Noise on BER at 200 Gbit/s

Data Transmission



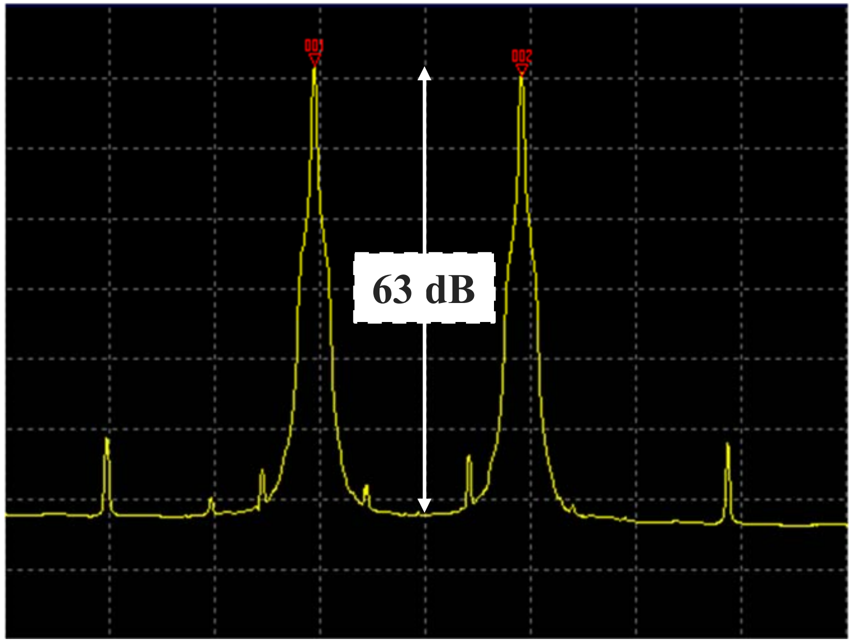
Phase Noise Measurement



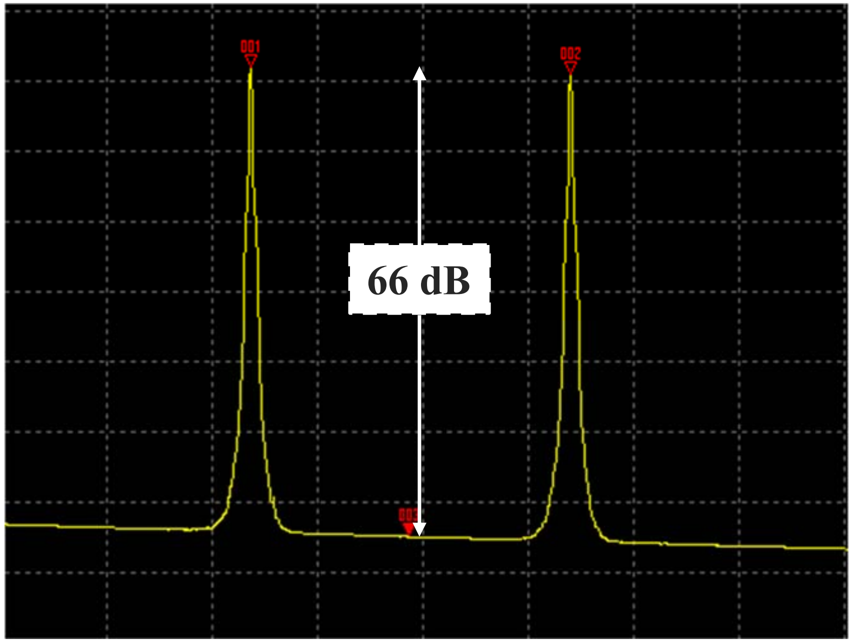
Difference in Optical CNRs for Los at ~130 GHz

Optical Spectrum Dual-wavelength Lasers → Amplitude Noise

EO Comb

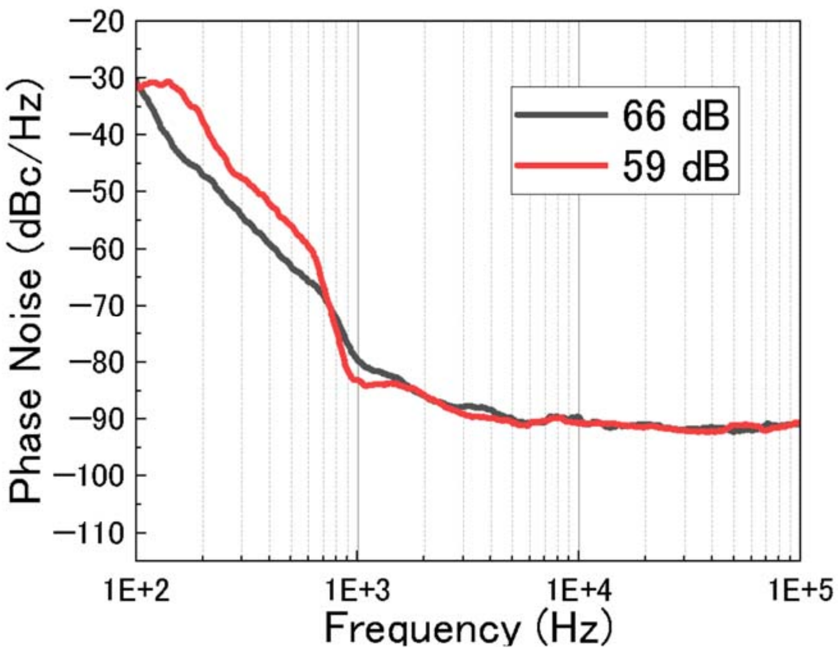


DWBL

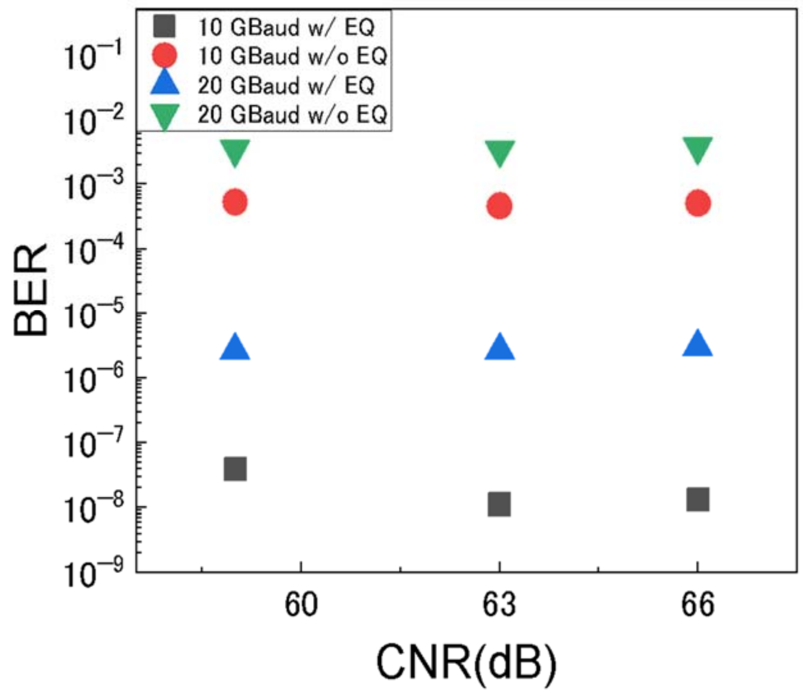


Effect of CNR on Bit Error Rate: EO Comb

Phase Noise of EO comb

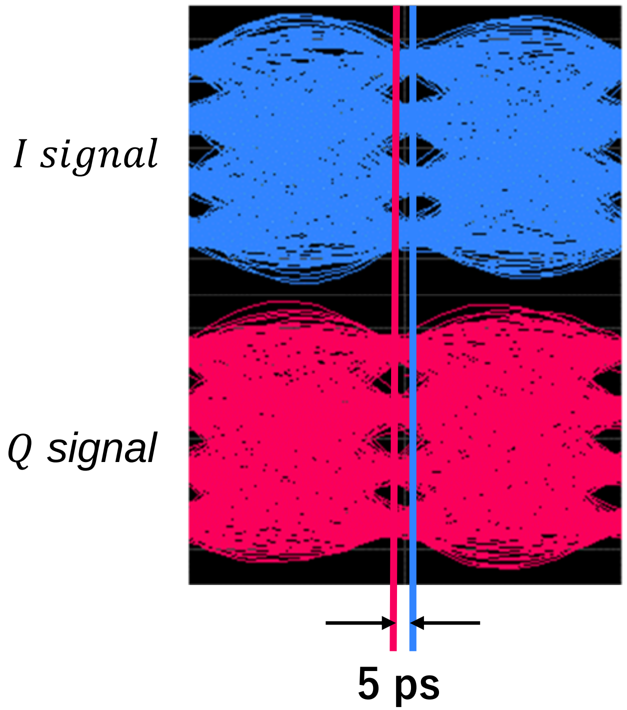


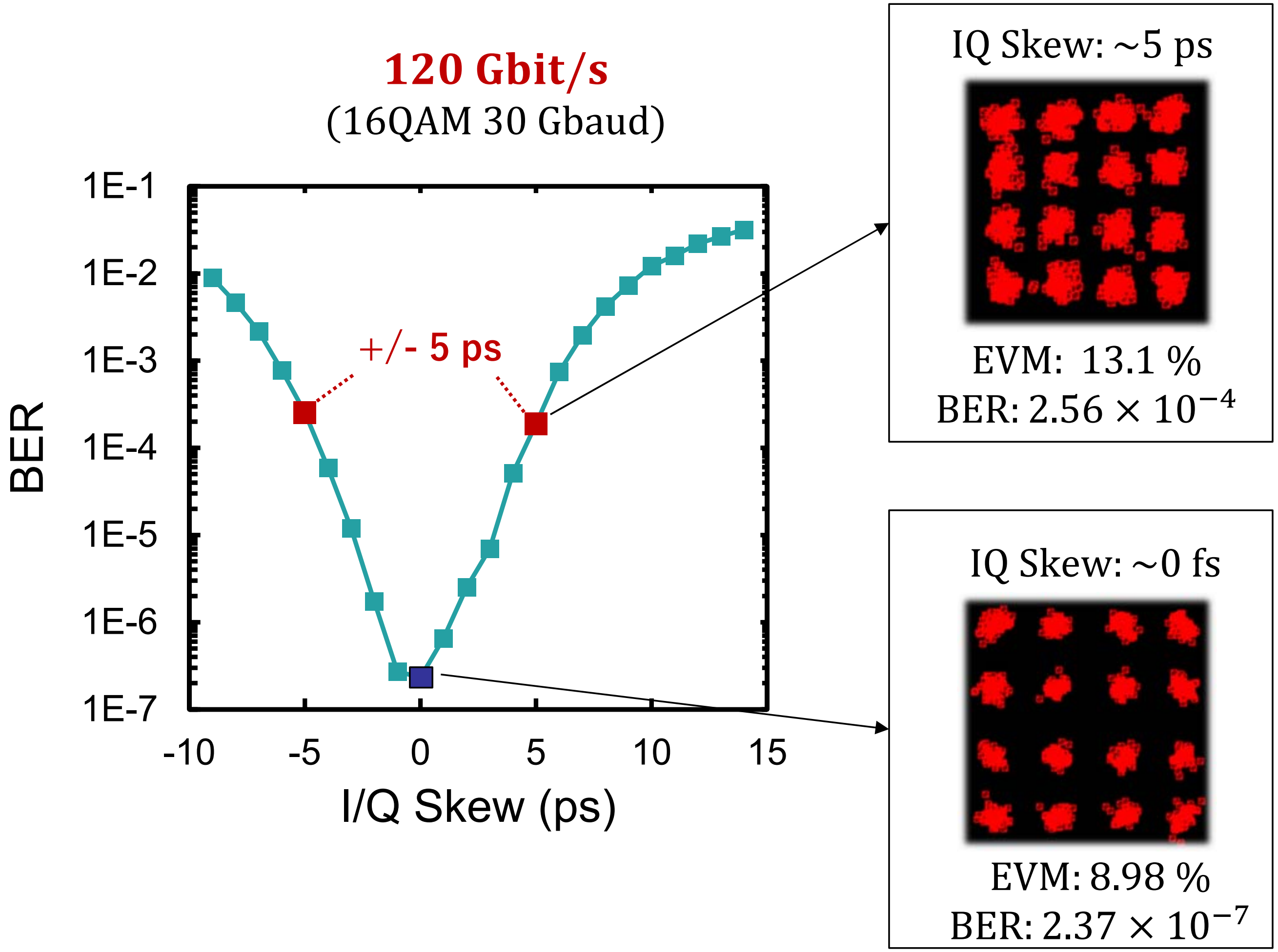
BER on CNR of EO comb



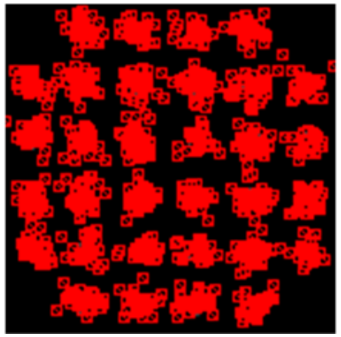
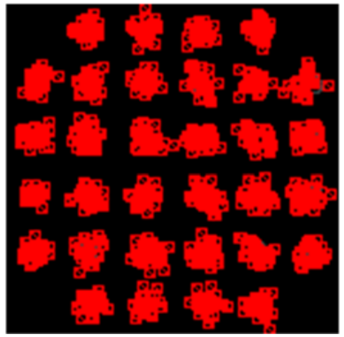
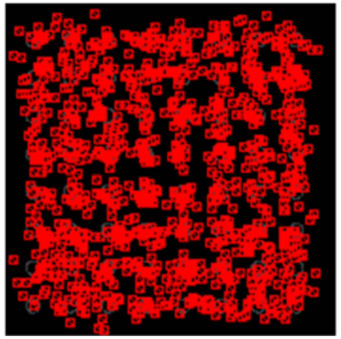
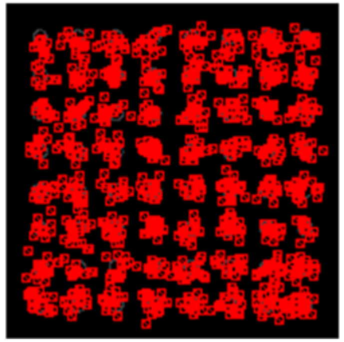
Almost *No* effect of optical CNR on phase noise and BER when CNR is > 59 dB

Other “Common” Crucial Factor: IQ Skew



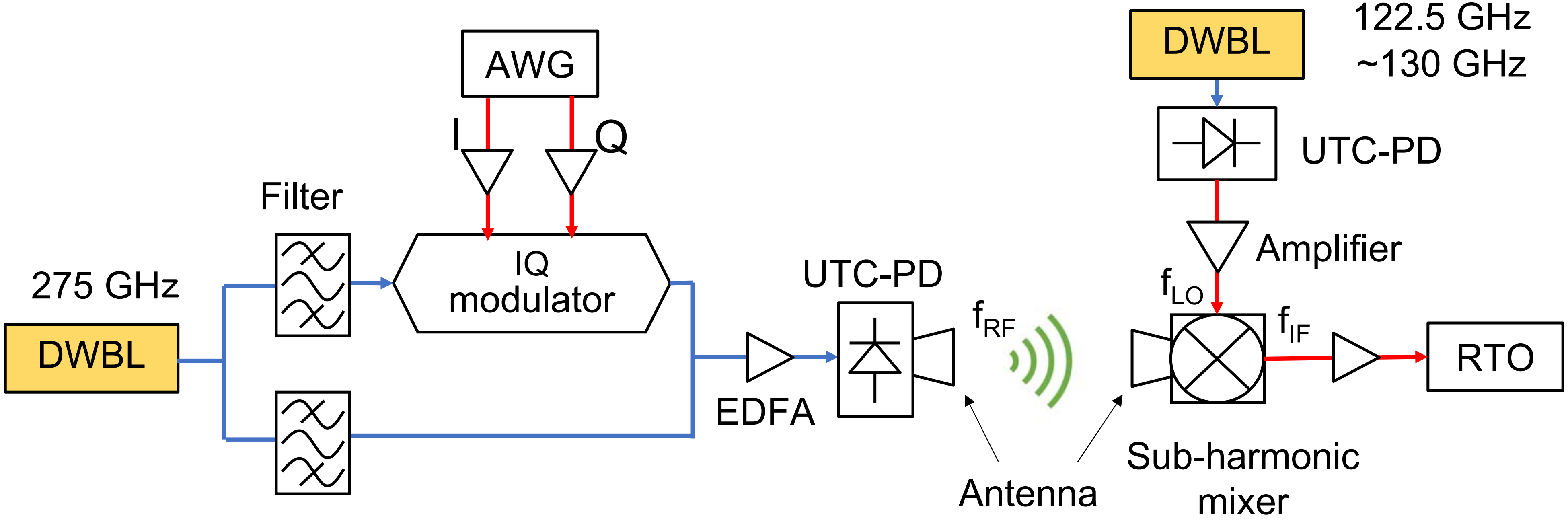


Comparison of Constellations: EO Comb vs. DWBL

	EO Comb	**DWBL**
32QAM 42 Gbaud 210 Gbit/s	 $\mathbf{BER = 1.7 \times 10^{-3}}$	 $\mathbf{2.8 \times 10^{-4}}$
64QAM 40 Gbaud 240 Gbit/s	 $\mathbf{BER = 1.4 \times 10^{-2}}$	 $\mathbf{3.4 \times 10^{-4}}$

Transmission Test Using DWBLs for Tx and Rx

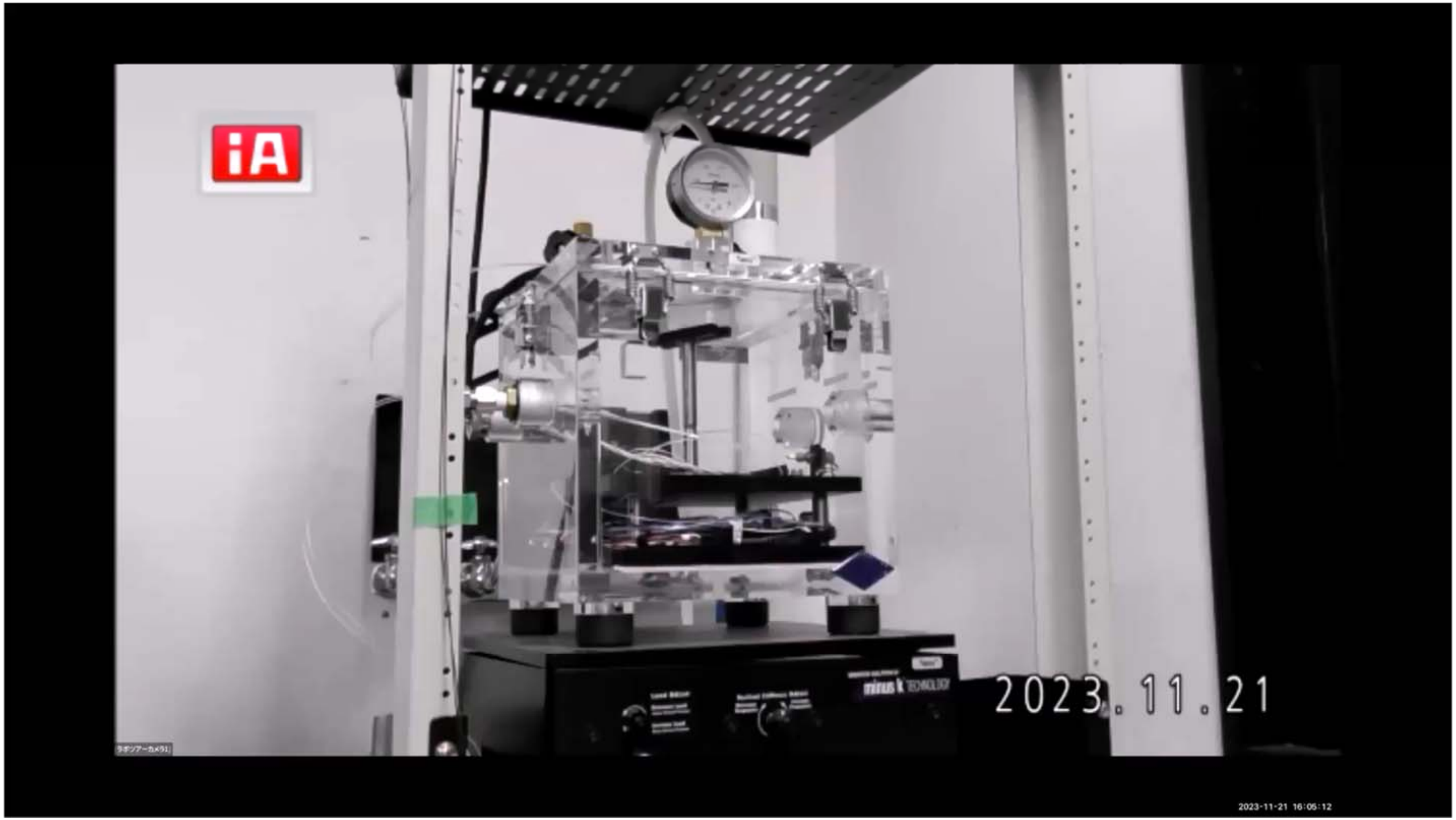
K. Maekawa et al., “Single-channel 240-Gbit/s sub-THz wireless communications using ultra-low phase noise receiver,” IEICE Electronics Express, vol. 21, Issue 3, 2024.



Our Evaluation Criteria

HD (Hard decision) FEC limit: bit error rate (BER) < 3.8×10^{-3} instead of SD (Soft decision) limit (BER<2.2×10^{-2})

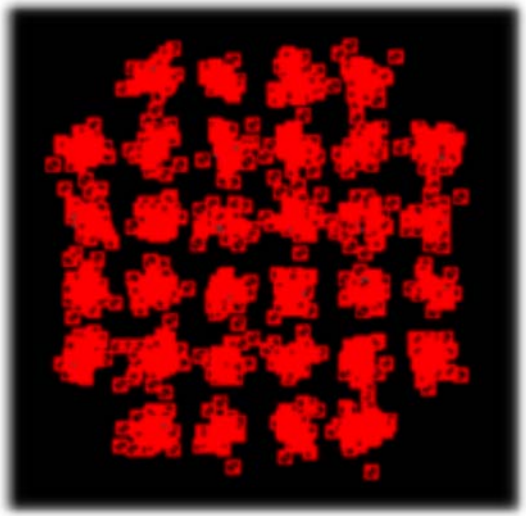
On-line digital signal processing (DSP) based on common software equipped in real-time oscilloscopes (RTO) to allow reasonable comparison and reproducibility


iA
2023.11.21
2023-11-21 16:05:12

Best Results: Short-distance (15 mm; B-to-B) Communication

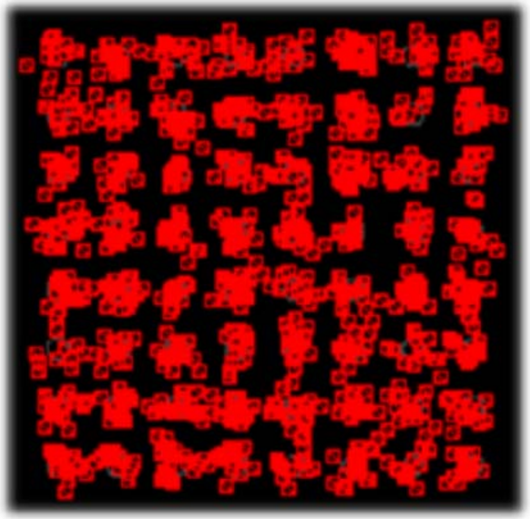
Max. data rates with higher-order modulation（HD-FEC limit）

32QAM/47Gbaud
235 Gbit/s



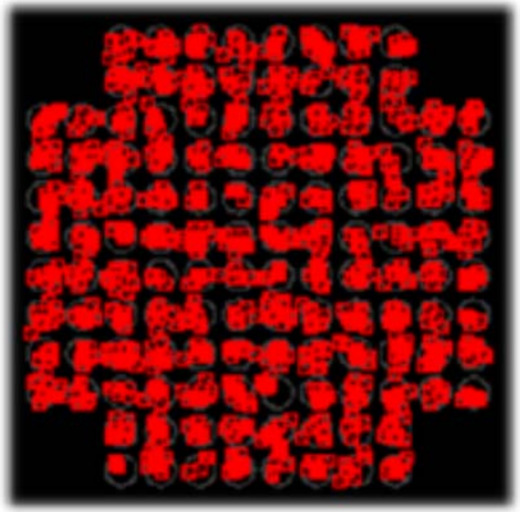
EVM: 11.1%
BER: 1.7×10^{-3}

64QAM/42Gbaud
252 Gbit/s



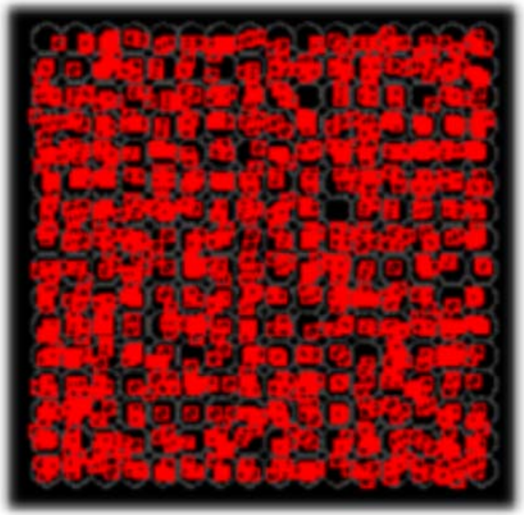
EVM: 11.1%
BER: 3.22×10^{-3}

128QAM/25Gbaud
175 Gbit/s



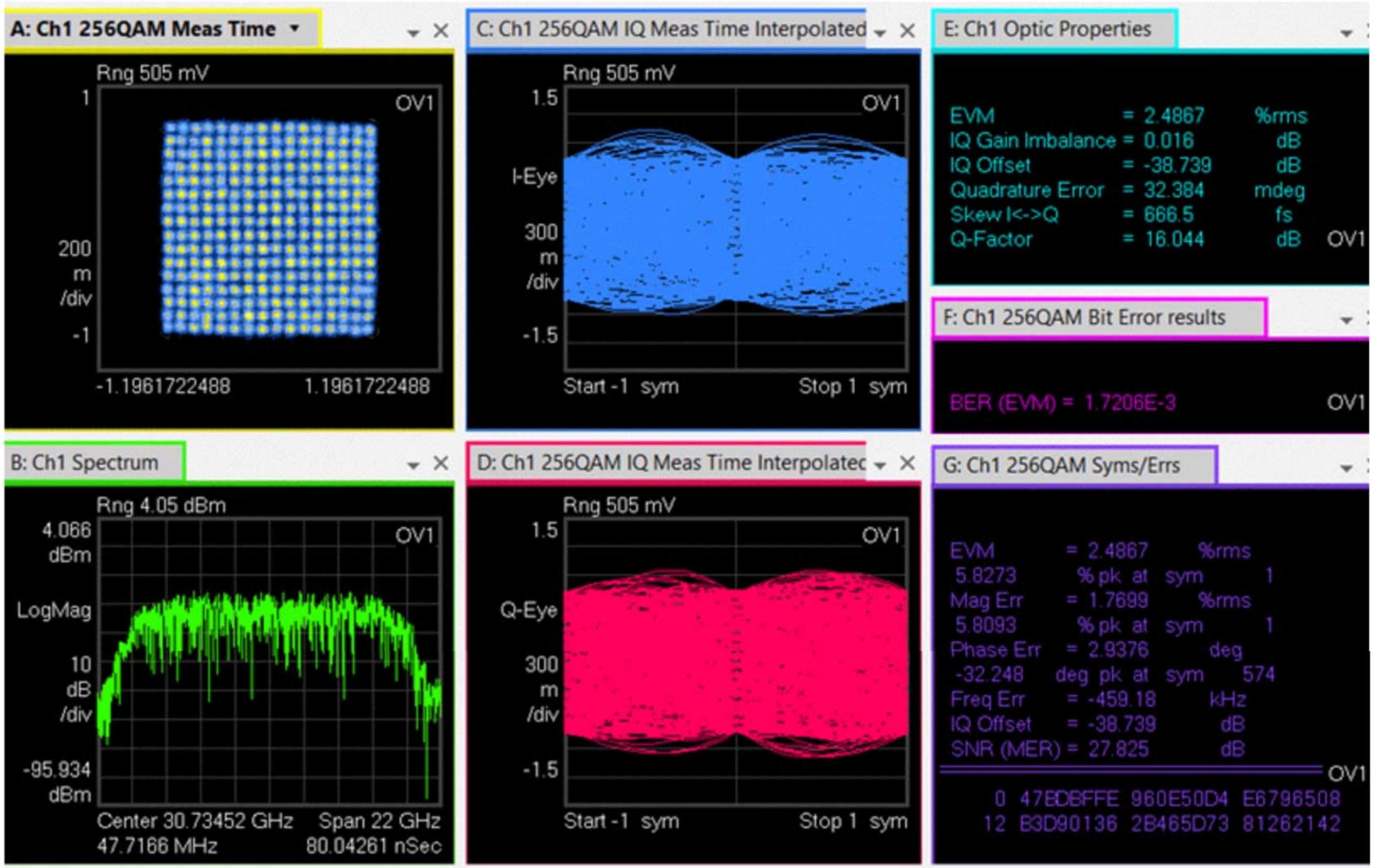
EVM: 3.33%
BER: 1.87×10^{-3}

256QAM/15Gbaud
120 Gbit/s



EVM: 2.47%
BER: 1.62×10^{-3}

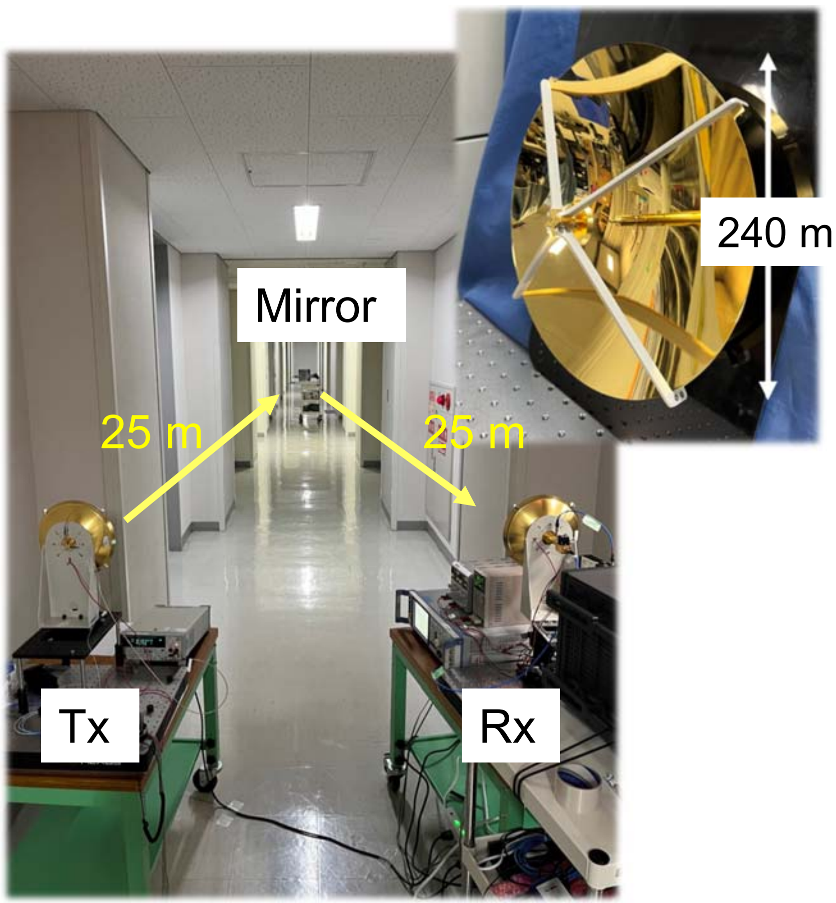
Details:120 Gbit/s@256QAM

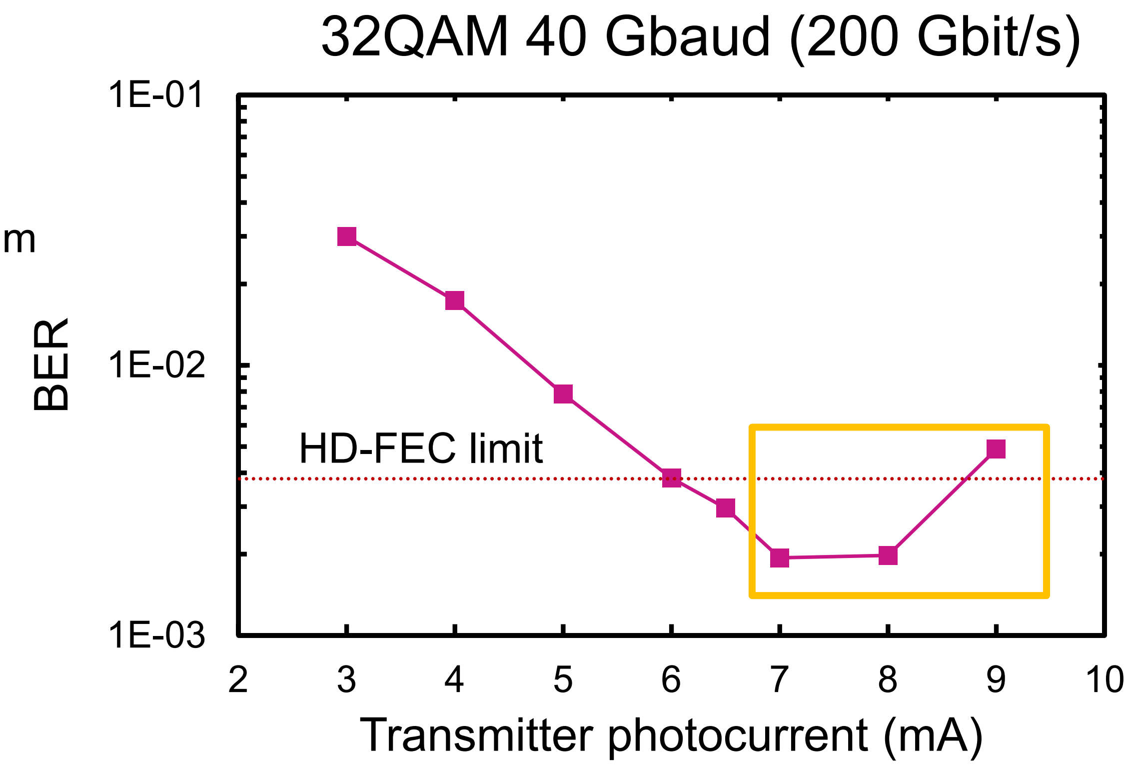


Outline

1. Background and motivation
2. Effect of phase noise
3. **Effect of nonlinearity**
4. Conclusion

50-meters Transmission Test



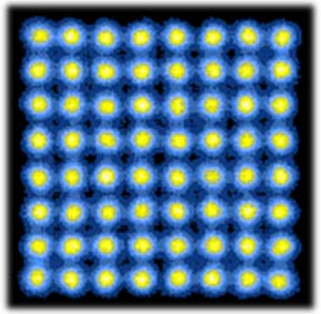


→ Saturation effect of Tx UTC-PD

Distortion of Constellation Diagram

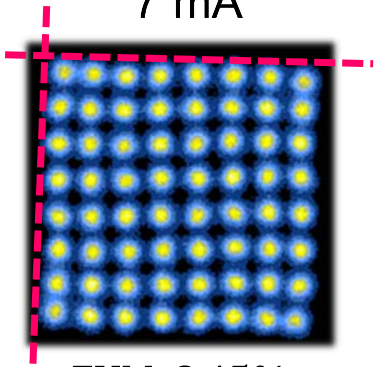
64QAM 25Gbaud
(150 Gbit/s)

6 mA



EVM: 8.97%
BER: 4.39×10^{-3}

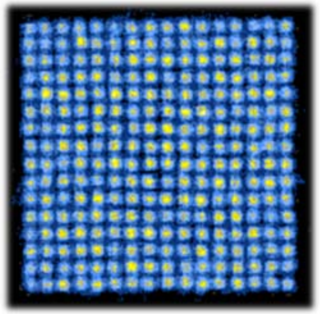
7 mA



EVM: 8.45%
BER: 2.86×10^{-3}

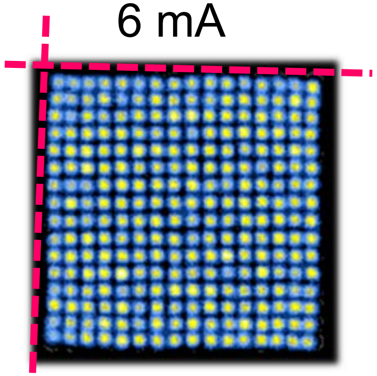
256QAM 10Gbaud
(80 Gbit/s)

5 mA



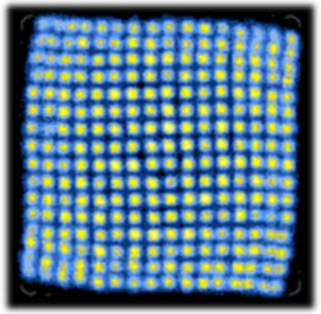
EVM: 2.30%
BER: 8.85×10^{-4}

6 mA



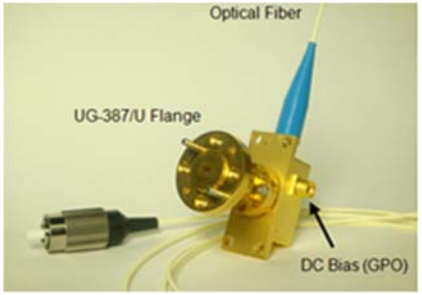
EVM: 2.18%
BER: 5.30×10^{-4}

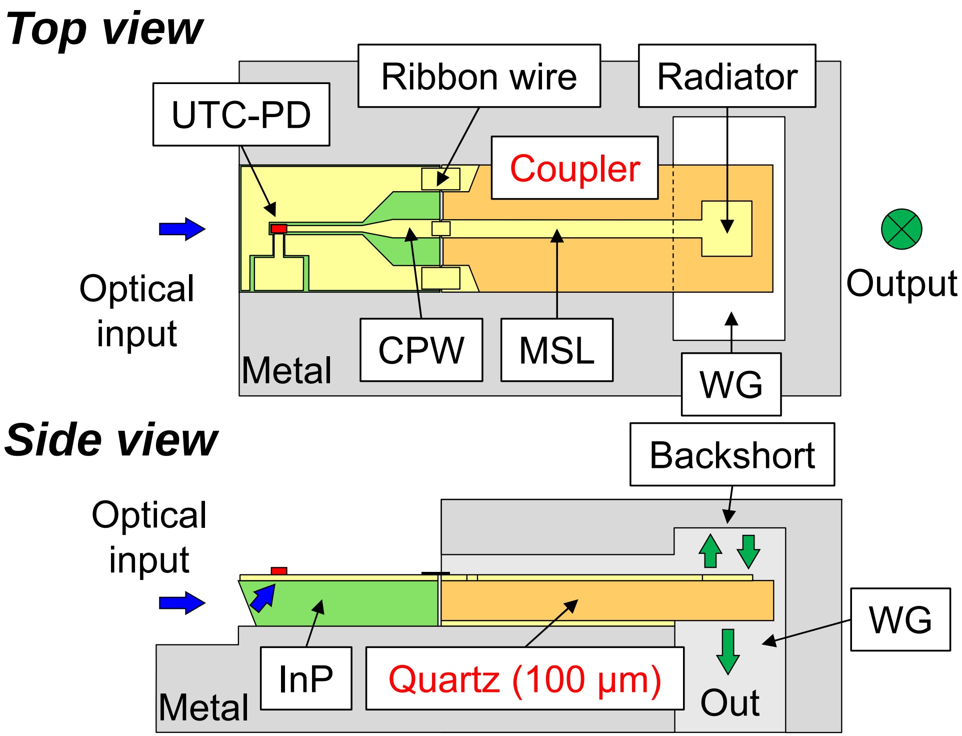
7 mA

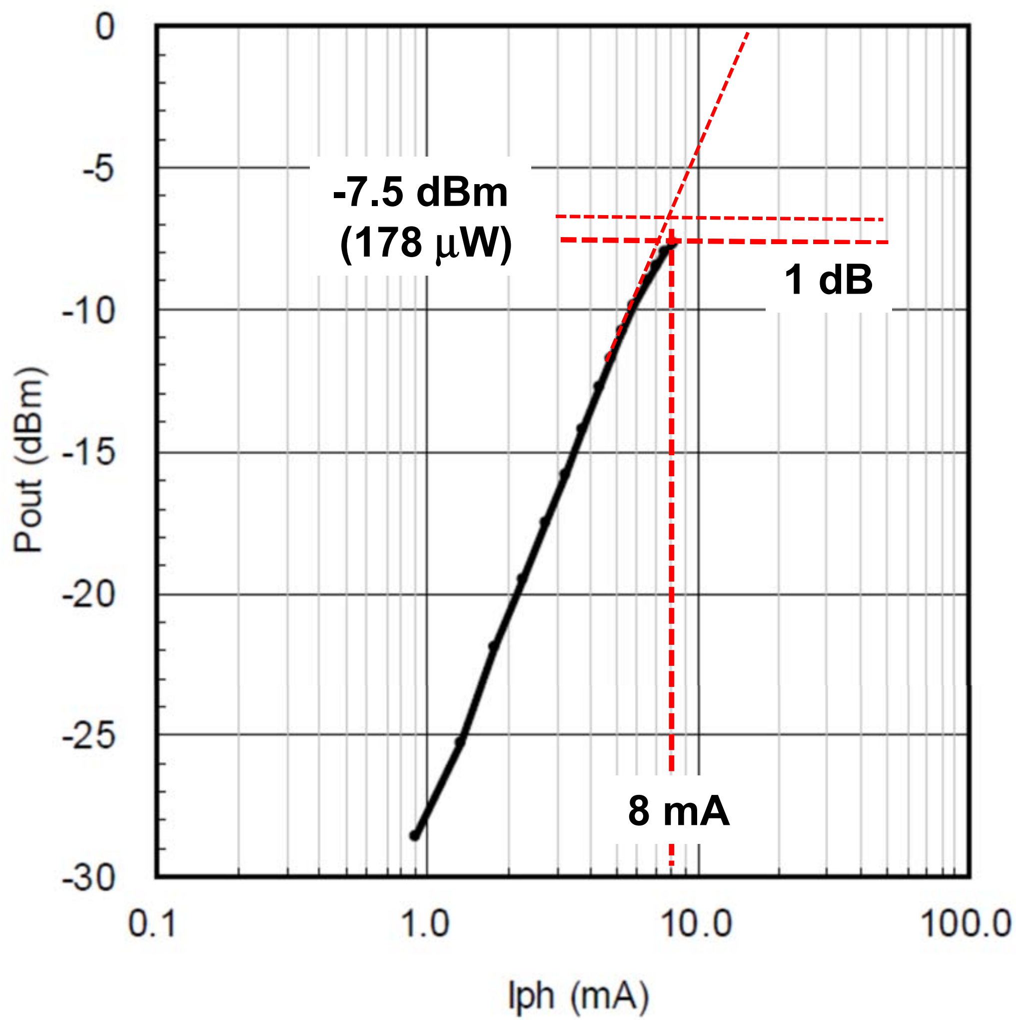


EVM: 3.17%
BER: 8.30×10^{-3}

Performance of NTT Innovative Devices' UTC-PD (Commercial)

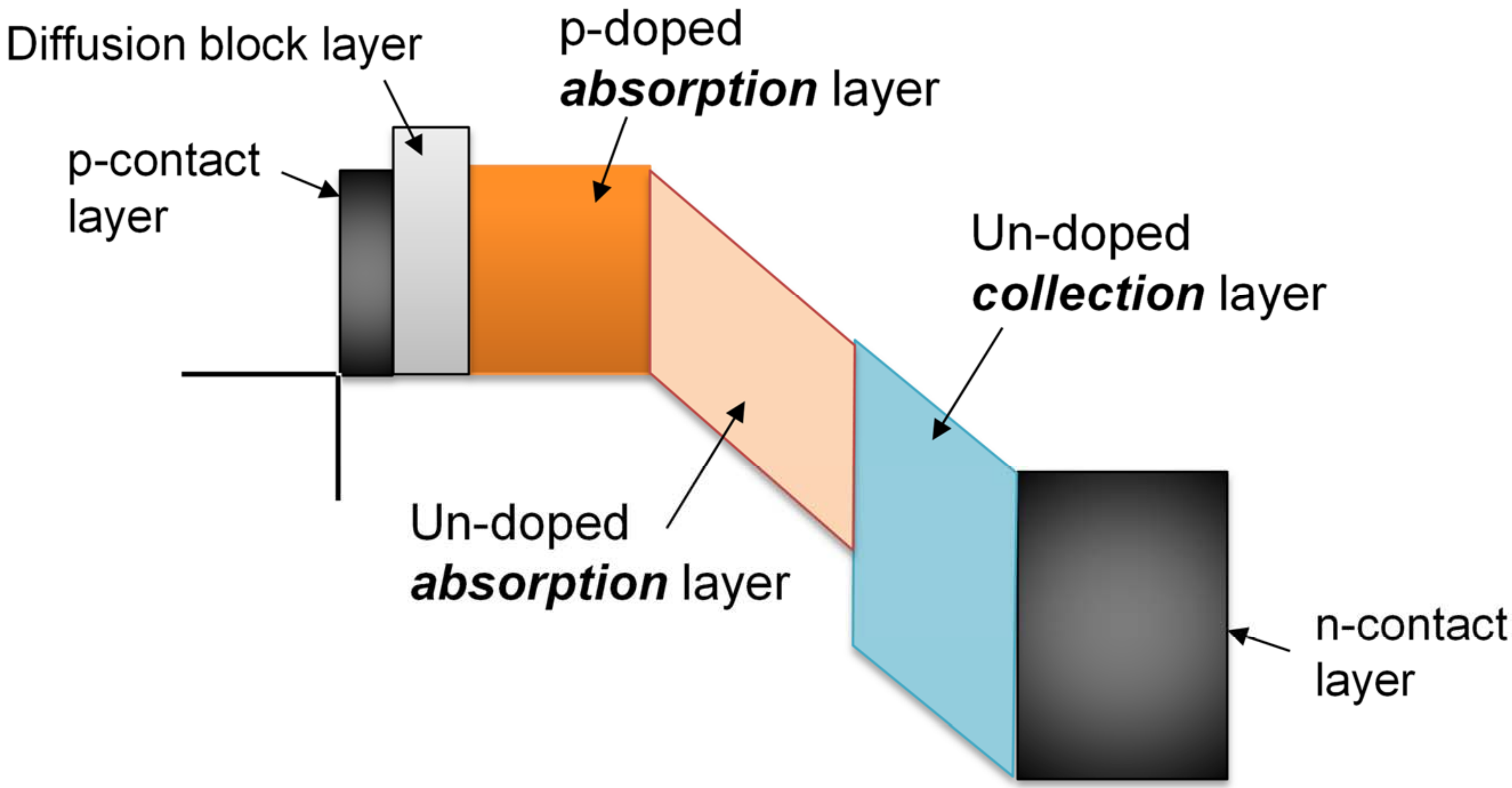






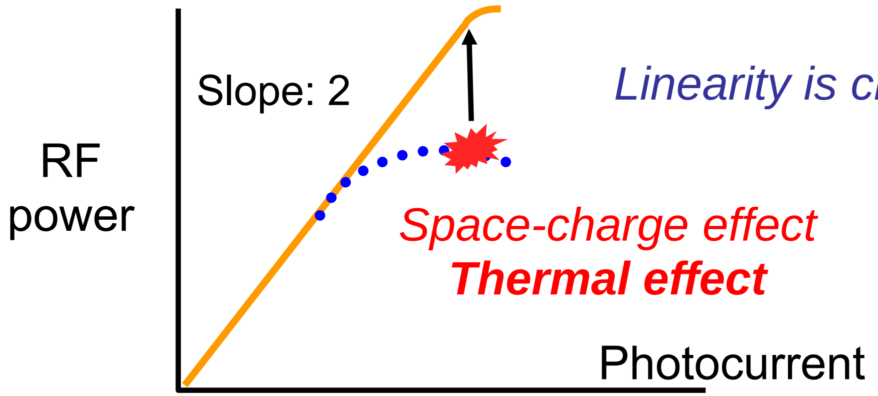
Modified Uni-Travelling-Carrier Photodiode (UTC-PD)

T. Ishibashi et al., “Unitraveling carrier photodiodes for terahertz applications,” IEEE J. Selected Topics in Quantum Electron., vol. 20, no. 6, pp. 79-88, Nov.-Dec. 2014.

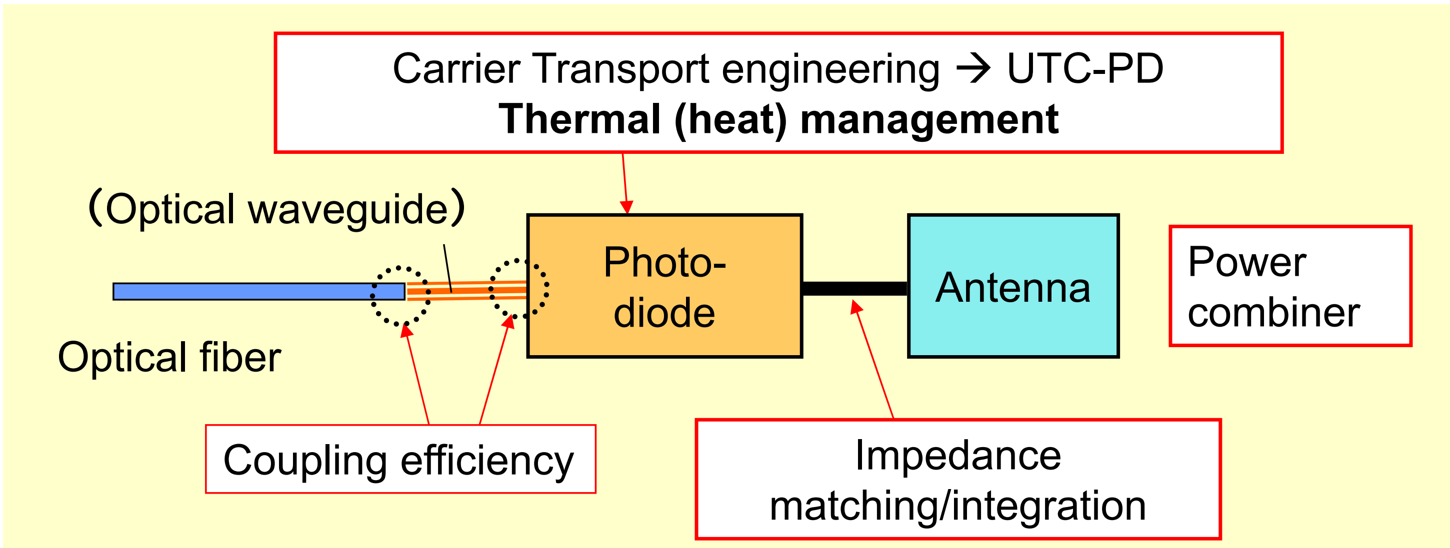


Photodiode Problems: Output Power & Linearity

RF power vs. Photocurrent (log-plot)



*Linearity is crucial for **multi-value modulation***

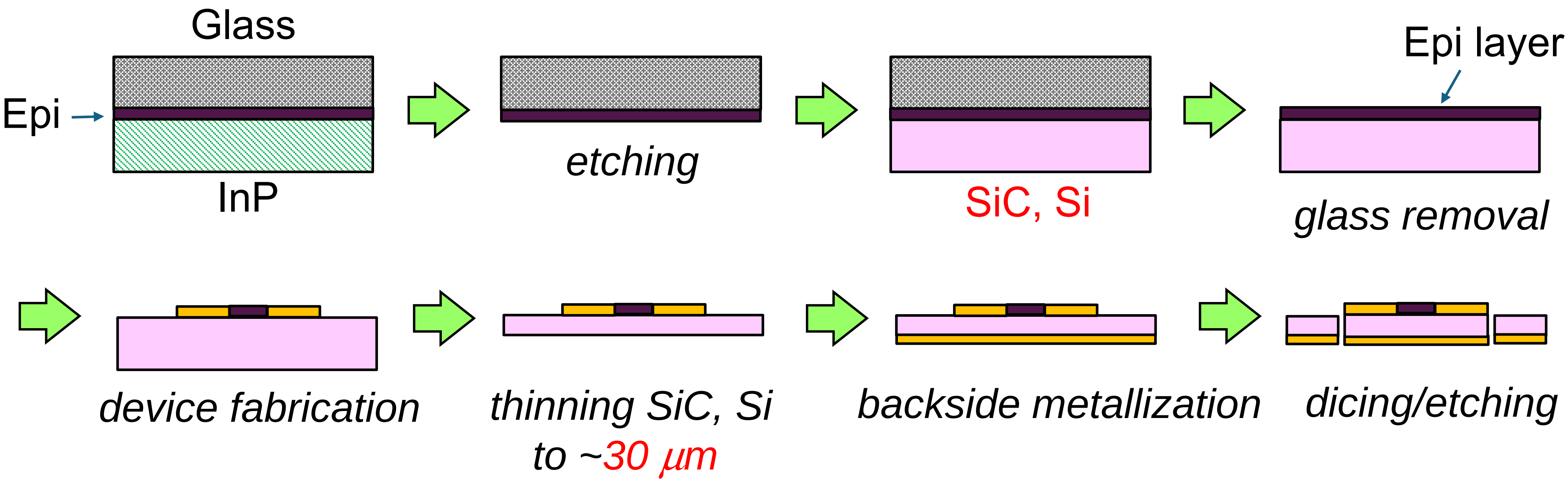


Material Properties of SiC and Si

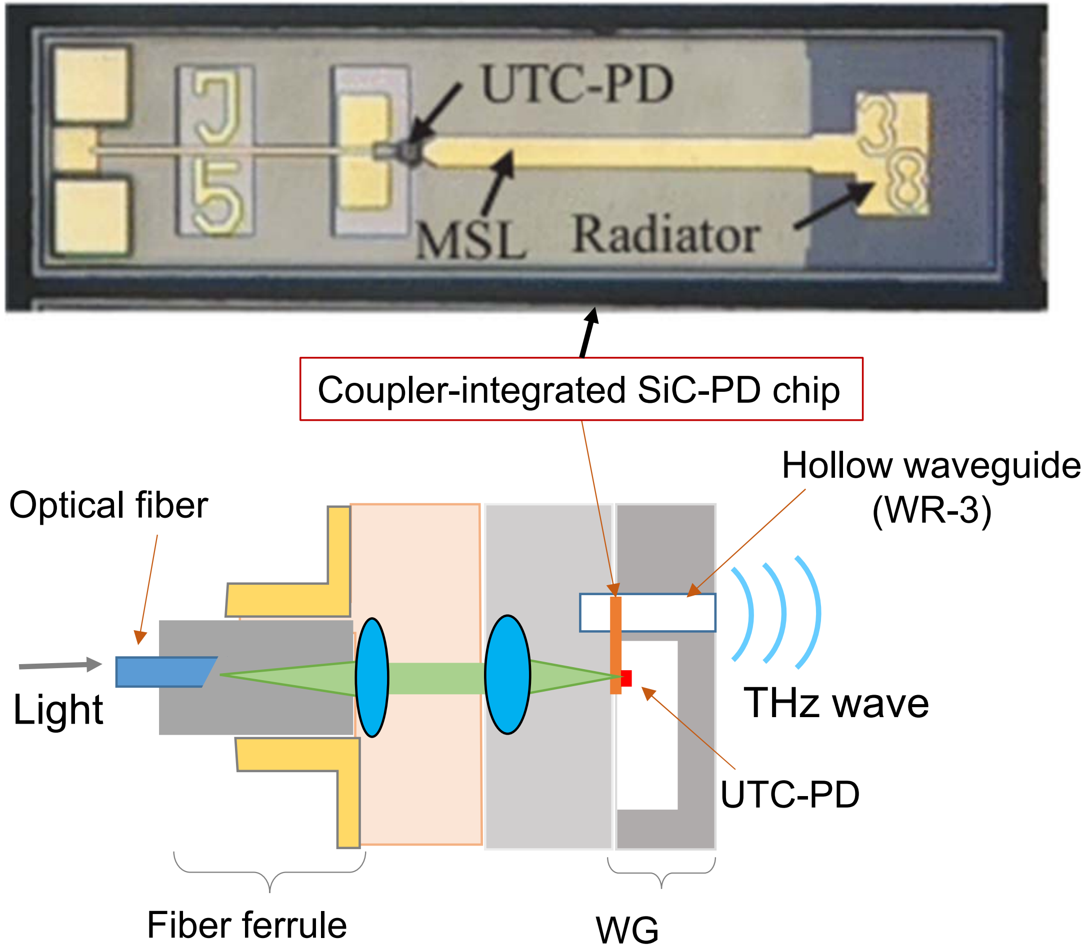
Properties	**SiC (4H-SiC)**	**Si**	InP
Loss tangent	< 1×10^{-3}	7.6×10^{-4}	9×10^{-3}
Thermal conductivity	**490 W/(m·K)**	150 W/(m·K)	68 W/(m·K)
Relative permittivity	9.8	11.7	12.4
Other remarks	**high Young's modulus** (700 GPa)	**arbitrary chip shaping by RIE**	original substrate for lasers, photodiodes, transistors, etc.

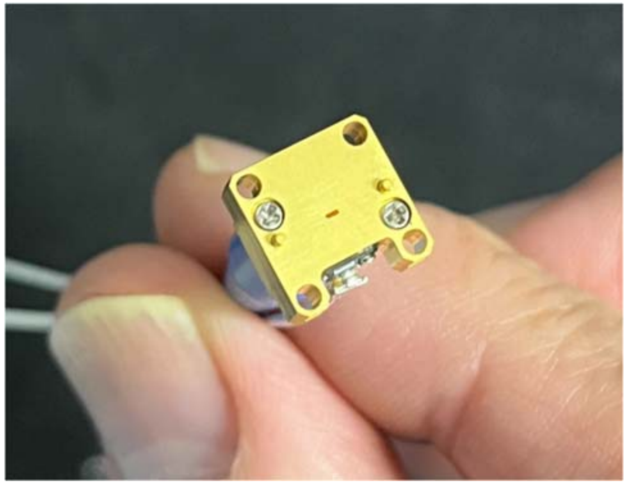
Device Fabrication Process: Epi-layer Transfer

T. Nagatsuma, et al., "InP-based Integrated Circuits on SiC/Si Substrates for Terahertz Communications," Journal of Lightwave Technology, 2025.

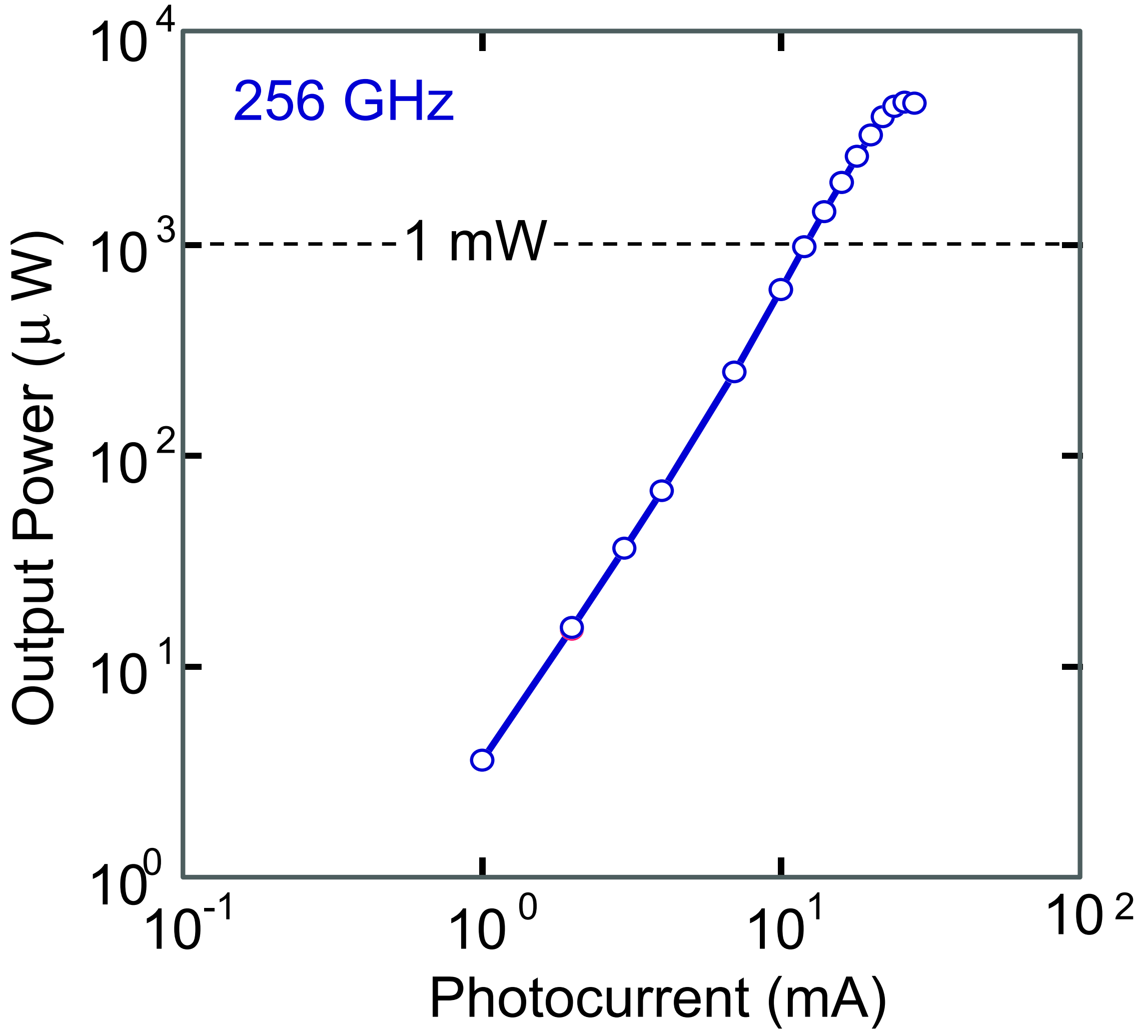


Newly Developed SiC-UTC-PD WG-Output Module





Record Performance for J-band UTC-PD Modules

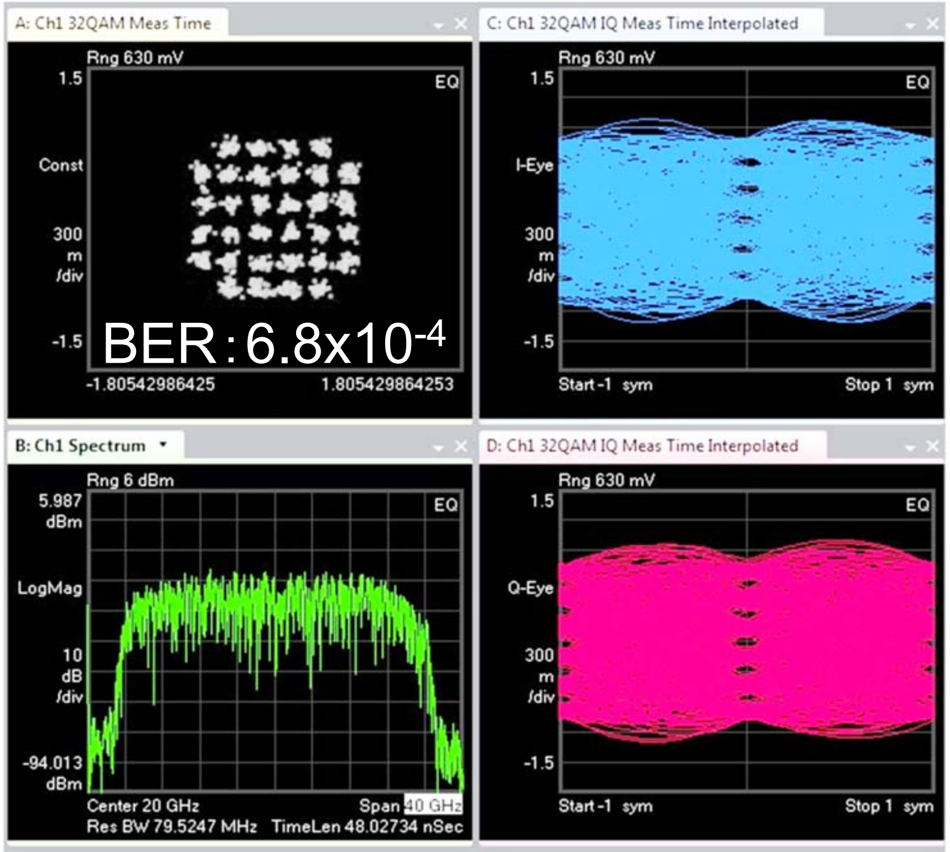


Maximum:
4.75 mW at 256 GHz
with 26 mA (DC bias: 1.8 V)

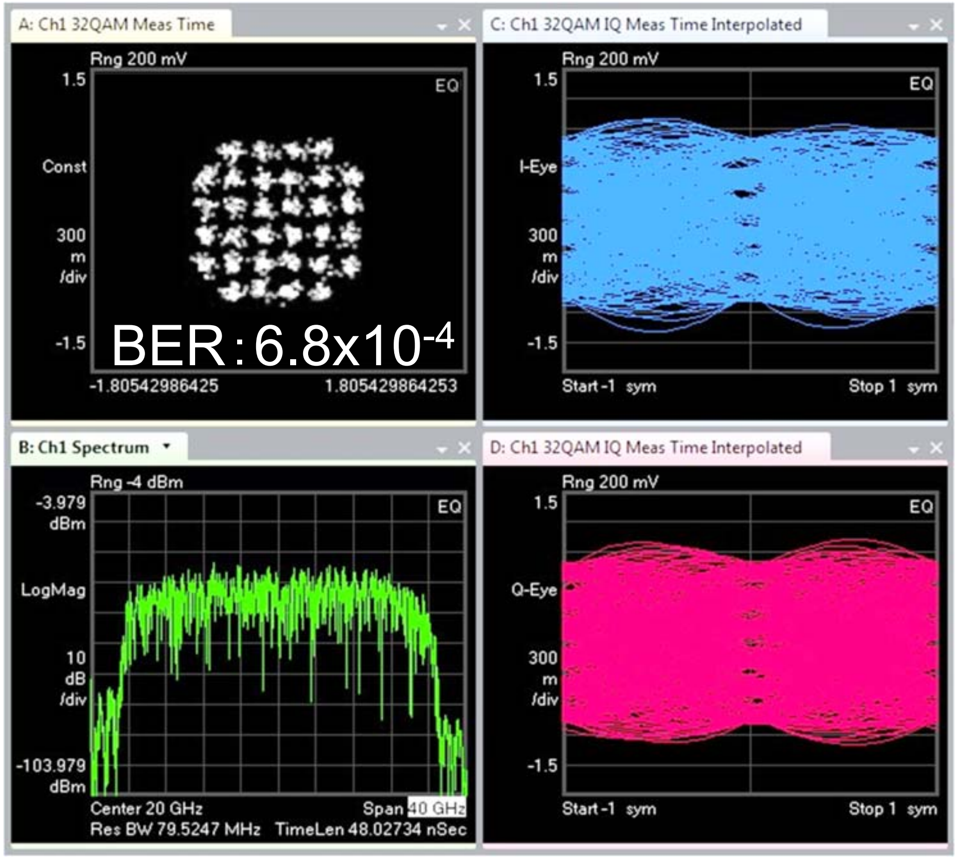
Comparable to RF amplifier!!

Transmission Test: 32QAM, 25 Gbaud at 270 GHz

3 mA (output power: −12 dBm)
link distance: 14 mm



14 mA (output power: 2 dBm)
link distances: 500 mm.



Conclusion (1)

- Commercially available sub-terahertz spectrum analyzers, which use frequency multipliers as LOs, lack sufficient performance for evaluating phase noise in the sub-THz band.
- We experimentally compared the phase noise of frequency multipliers, EO-comb-based signal generators, and free-running lasers, by using a **two-wavelength Brillouin oscillator** (based on the principle of frequency locking to a high-Q optical fiber resonator) as a reference.
- Furthermore, we experimentally clarified the relationship between phase noise and wireless communication quality.

Conclusion (2)

- Using a system using a two-wavelength Brillouin oscillator for both transmission and reception, we experimentally investigated the **impact of nonlinearity due to photodiode saturation** on communication quality during ultra-high-level modulation, such as 256QAM.

- To improve the photodiode output saturation by **more than one order** of magnitude, we developed a photodiode using **SiC substrate as a heat sink**, and demonstrated its effectiveness through communication experiments.

- It is expected that these developments will enable transmission characteristics **exceeding 200 Gbit/s over distances of over 500 m** while **maintaining high communication quality**.

Thank you for your kind attention.

Acknowledgment

Part of this work is supported by the Beyond 5G R&D Promotion Program (JPJ012368C-00901) from the National Institute of Information and Communications Technology (NICT), and JSPS KAKENHI (JP 24K00887).

Special thanks to Mr. **Toki Yoshioka**, Mr. **Tomoya Nakashita**, and Dr. **Keisuke Maekawa** for their dedicated effort on this work, and to a research team of **IMRA America** for providing Brillouin lasers