

Photonic Reference Signal Generation Based on Precise Optical Modulation

Enabling Technology for Next-Generation Radio Astronomy

Tetsuya Kawanishi
Waseda University / NICT

Outline

Overview of research on convergence of radio and optical technologies

Photonics in ALMA

- Photonic LO
- High-performance optical fiber transmission

Advanced Lightwave modulation for telecommunication

Precise optical modulation

Tetsuya Kawanishi

Kyoto University

- EM-wave scattering theory using stochastic integrals
- Near field optical microscopy

Panasonic

- Lens design

NICT

- Optical modulation and devices
- Optical signal processing, precise Lightwave control for measurement
- Wired and wireless seamless networks

UCSD

- Integrated devices for MWP

Optical soldering machine by Panasonic



Tetsuya Kawanishi, Waseda-U

THz technology

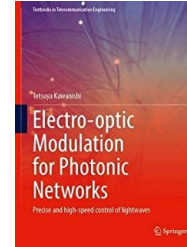
- THz radio comm, THz scattering

Optical modulation

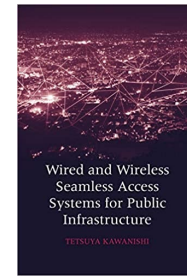
- Precise modulation
- Signal analysis by photonics
- Photonic noise source

Optical fiber communication

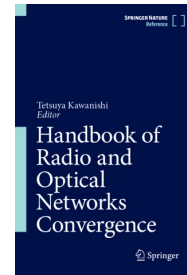
- Multi-mode fiber transmission
- Radio-over-fiber



T. Kawanishi, Electro-optic Modulation for Photonic Networks, Springer Nature, 2022



T. Kawanishi, Wired and Wireless Seamless Access Systems for Public Infrastructure, Artech House, 2020



T. Kawanishi (ed.), Handbook of Radio and Optical Networks Convergence, Springer Nature, 2024



Multi-physics based system design for
future ICT networks

Tetsuya KAWANISHI

Waseda University



WASEDA University
早稲田大学



GIFU UNIVERSITY



千葉工業大学
CHIBA INSTITUTE OF TECHNOLOGY



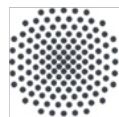
Nagoya Institute of Technology



National Institute of
Information and
Communications Technology



Technische
Universität
Braunschweig



University of Stuttgart
Germany



Fraunhofer
IAF

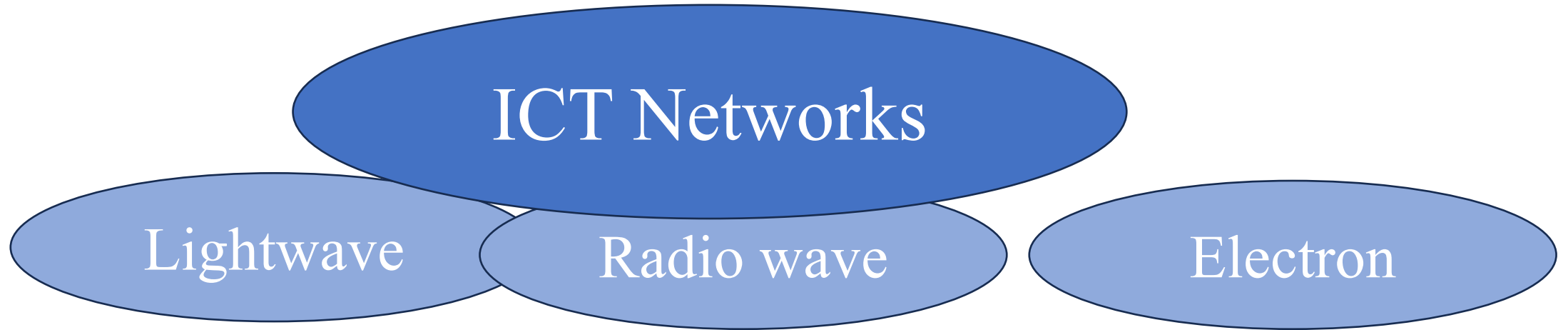


Université
de Lille

Multi-physics based system
design for future ICT networks



Concept of Multi-Physics System Design



Electromagnetism

Meteorology

Mechanics

Thermodynamics

Environmental
Engineering

Etc....



Photonic Computing

Highlighting Ultimate Nature of Light

Grant-in-Aid for Transformative Research Areas (A)

JP / EN



Photon × Computing

-Ultimate Optical System-

Photonic computing highlighting the ultimate
based on deeply intertwined optical science and in

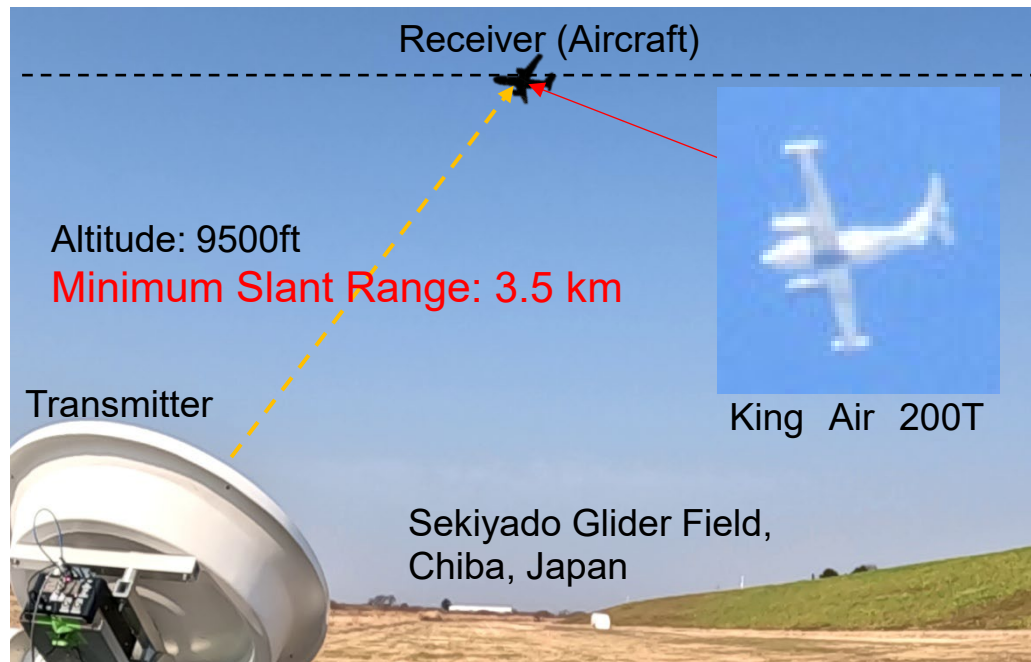


Overview of Ground-to-Air Communication Demonstration

Transmitter: Ground station located at Sekiyado Glider Field, Chiba, Japan
Equipped with a 24 dBm power amplifier and a high-gain antenna (57 dBi)

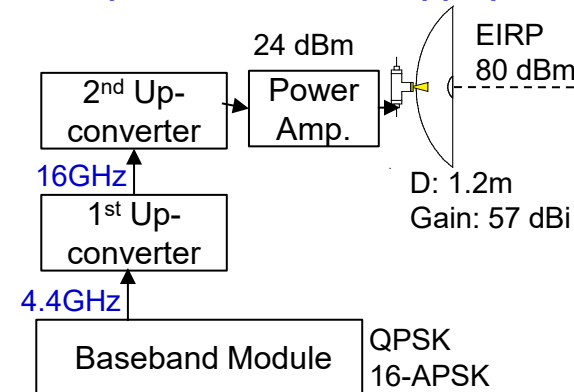
Receiver: Installed on a King Air 200T aircraft

The slant range between the ground station and the aircraft is approximately **3.5 km** at the closest point

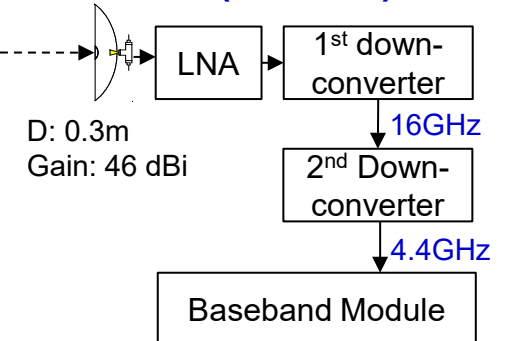


Overview of ground-to-air demonstration

TX (Ground station)(*2)



RX (Aircraft)

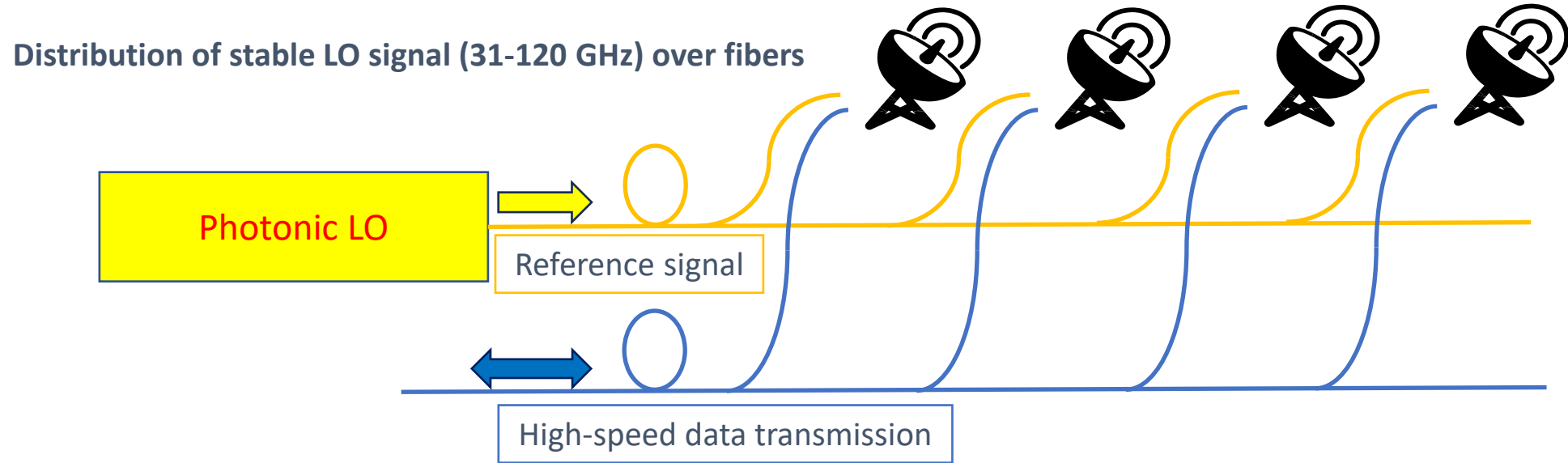


(*2) License of Experimental Radio Station up to 1W of PA is received as 関実 第55701号

System configuration for ground-to-air demonstration

Photonics in ALMA

- Photonic LO
- High-performance optical fiber transmission



In WSU, optical transmission links will be based on 400G-ZR (16-QAM).

Radio-over-Fiber

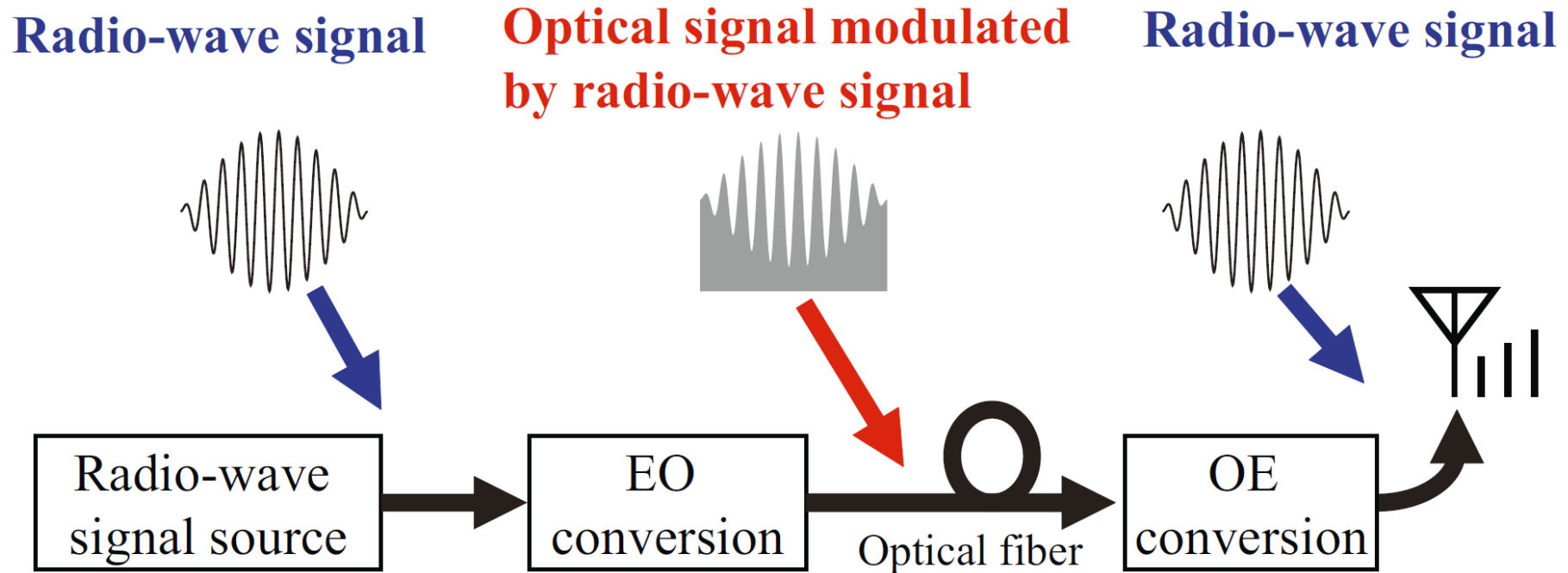
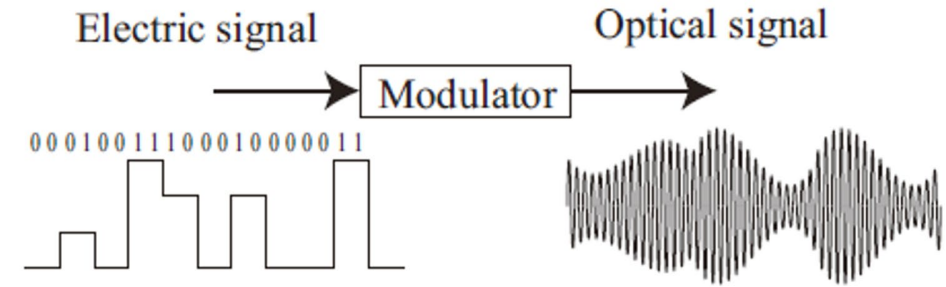


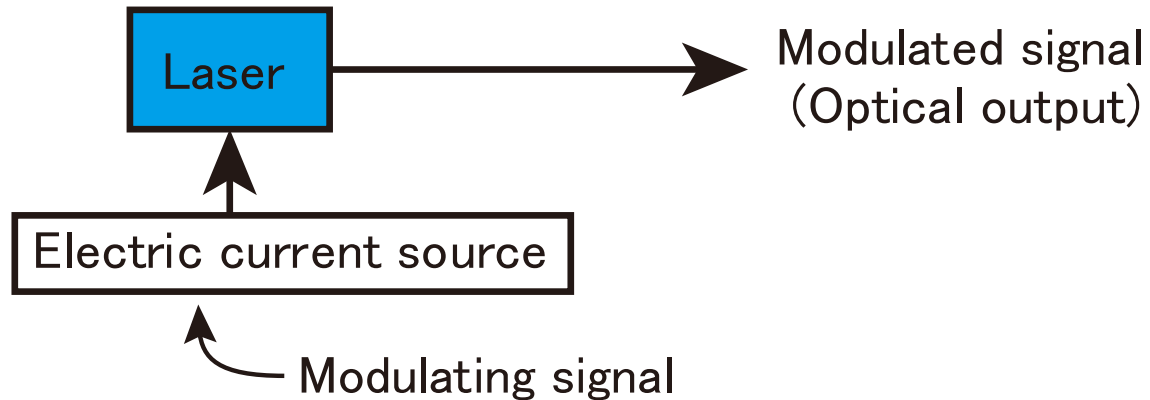
Figure 4.4 Configuration of analog radio-over-fiber.

Simple configuration, low-latency,
low-loss and broadband signal transmission

Optical modulation

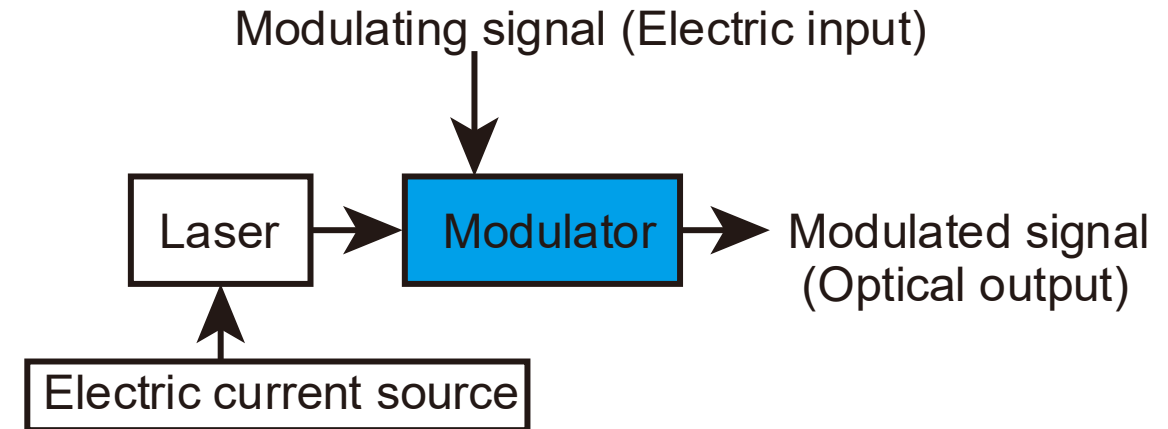


Direct modulation



- Simple configuration
- Modulation speed limited
- Large chirp effect

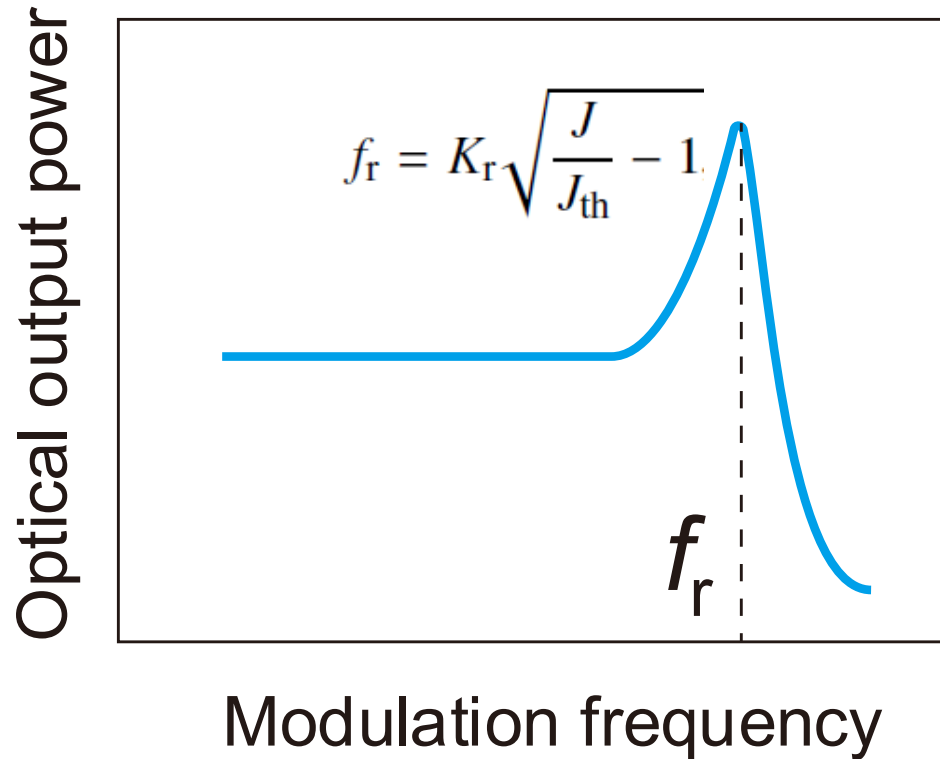
External modulation



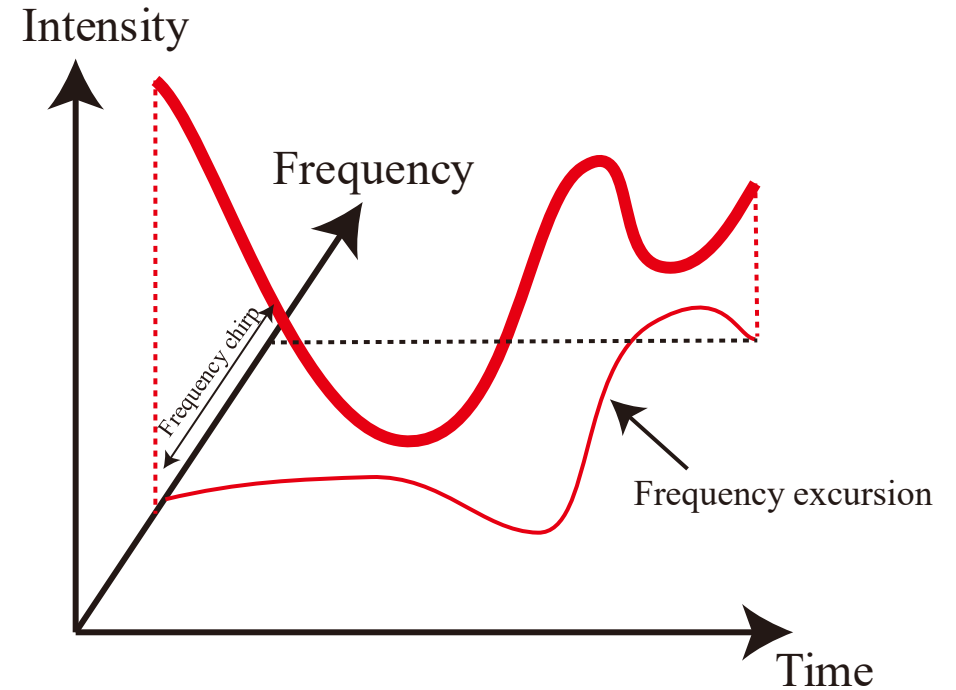
- Needs of external modulators
- High-speed modulation
- Low chirp and precise modulation

Limitation of direct modulation

Laser frequency response

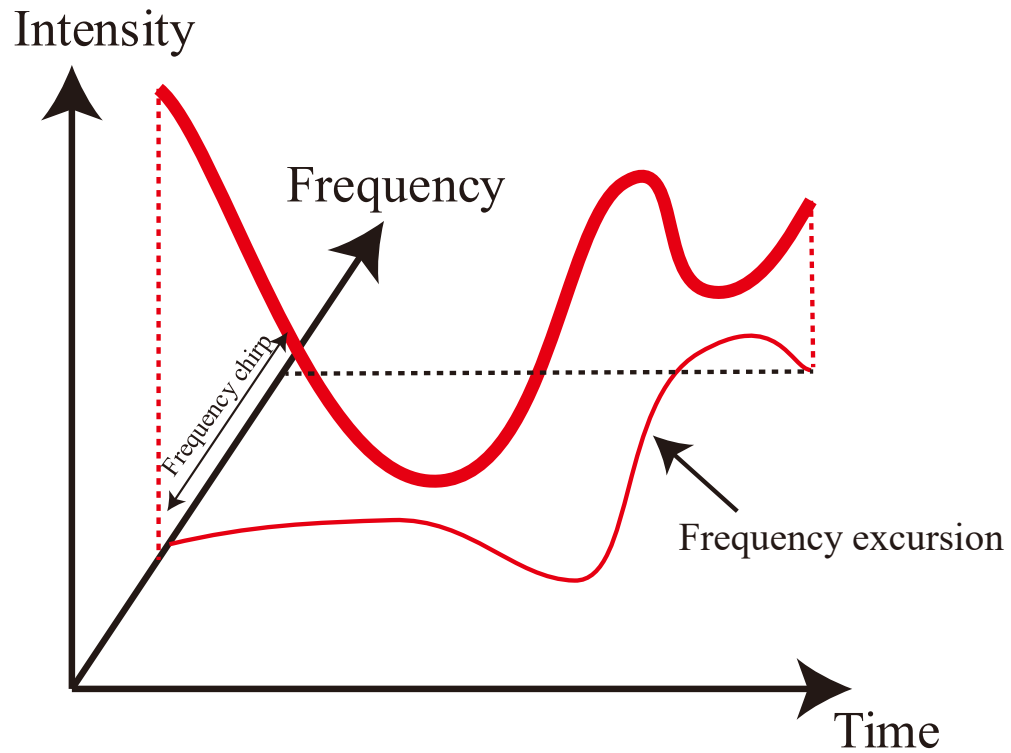


Parasitic frequency/phase excursion (chirp)

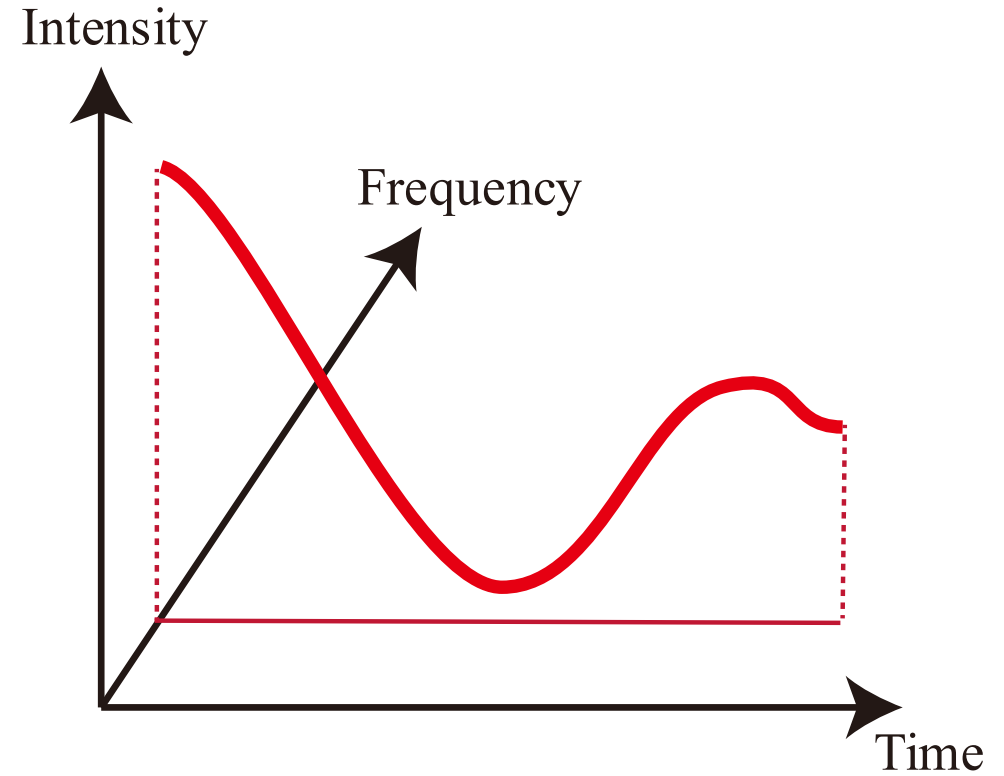


Chirp

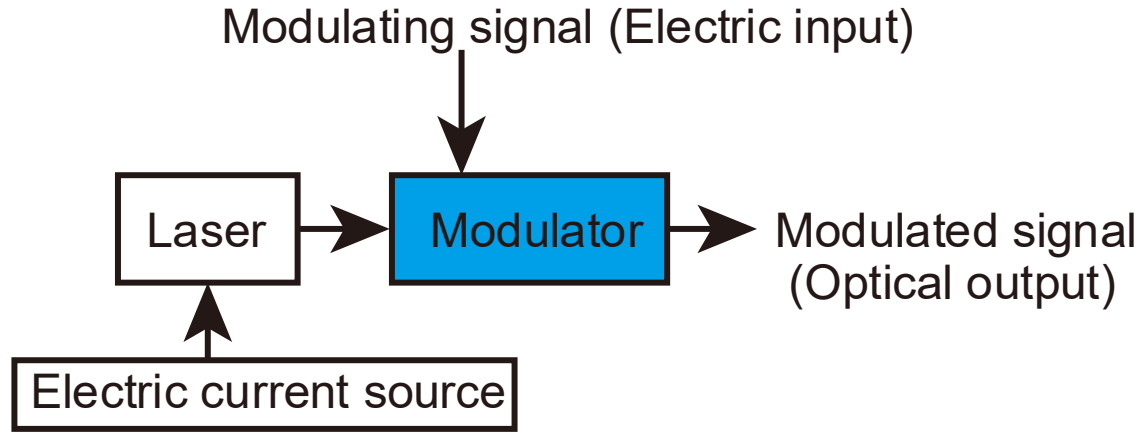
Intensity modulation with chirp



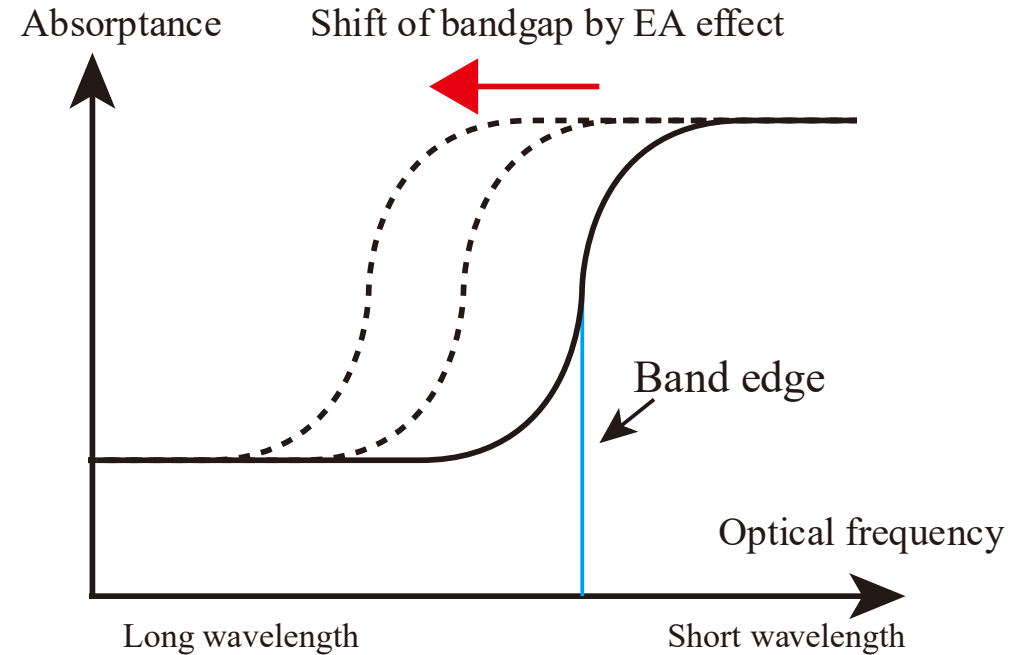
Intensity modulation without chirp



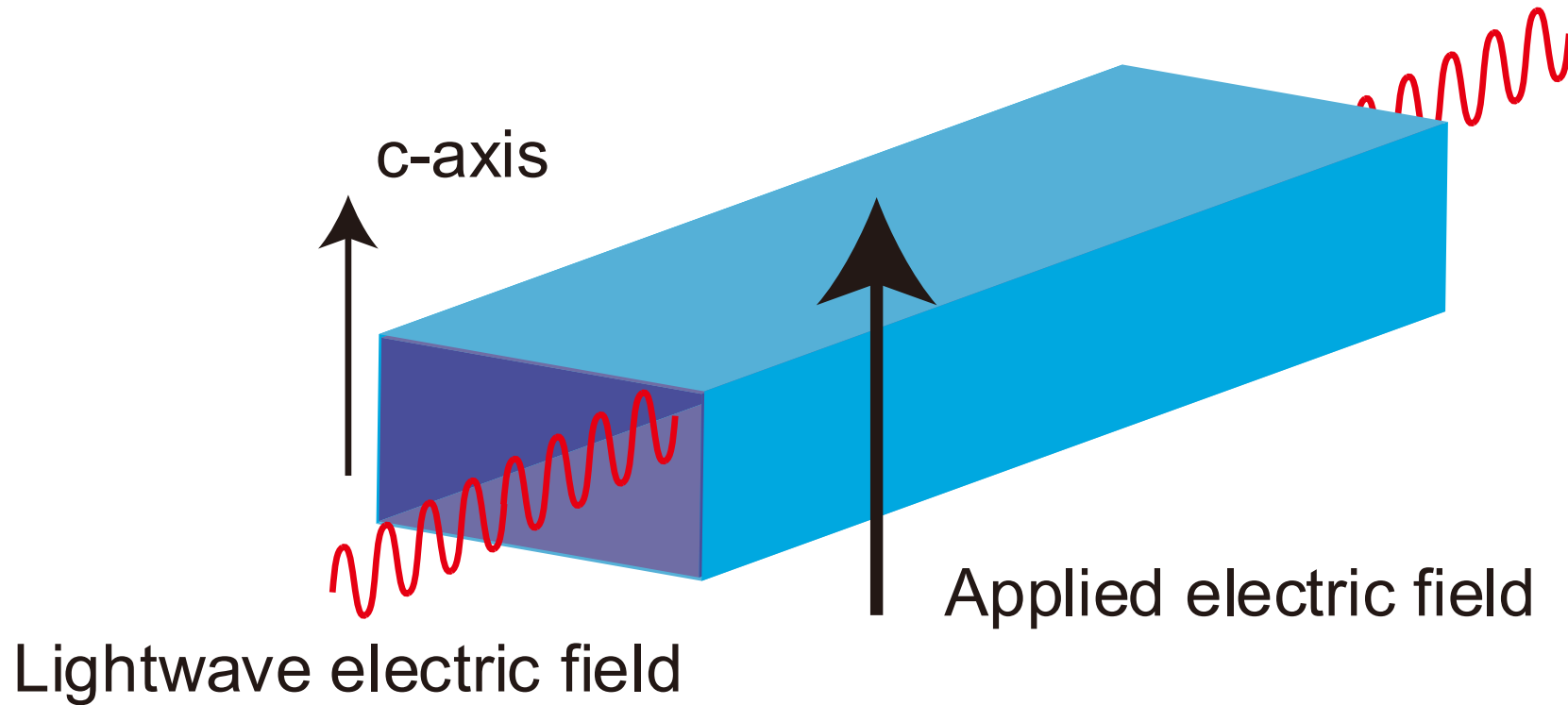
External modulation



- **Electro absorption (EA) effect**
- **Electro optic effect (EO) effect**



EO effect



EO coefficient

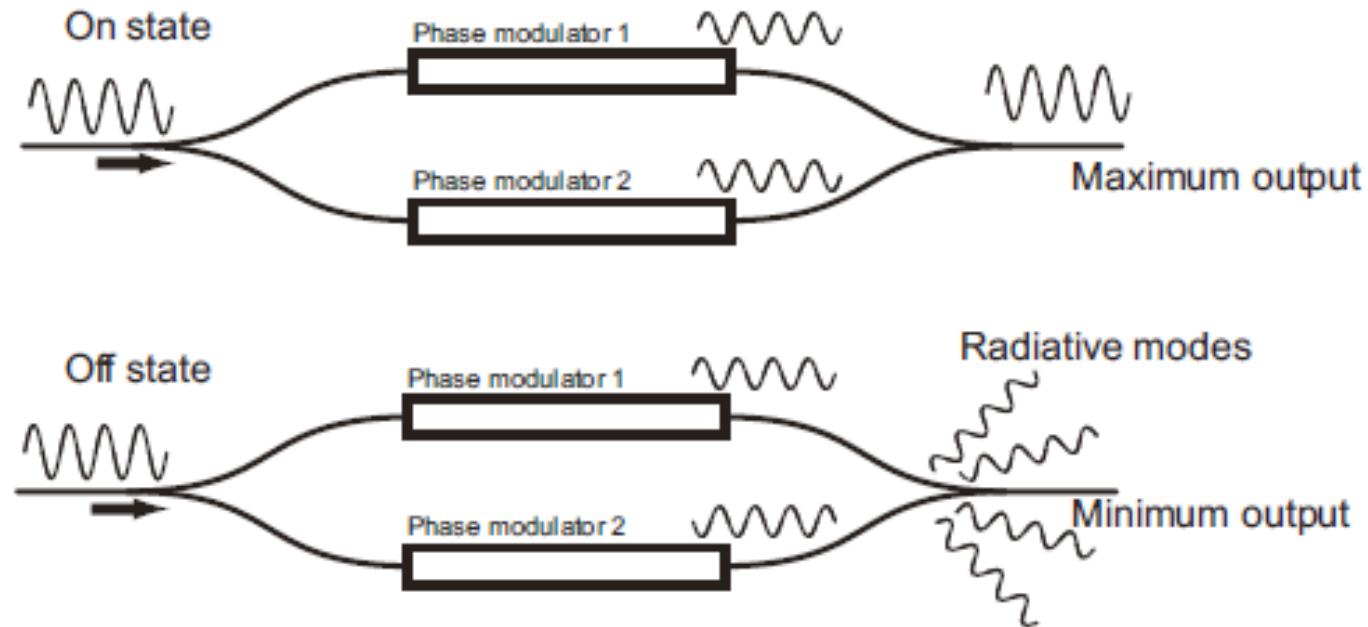
$$\Delta \frac{1}{n_i^2} = r_{ij} E_j$$

$i, j = x, y \text{ or } z$

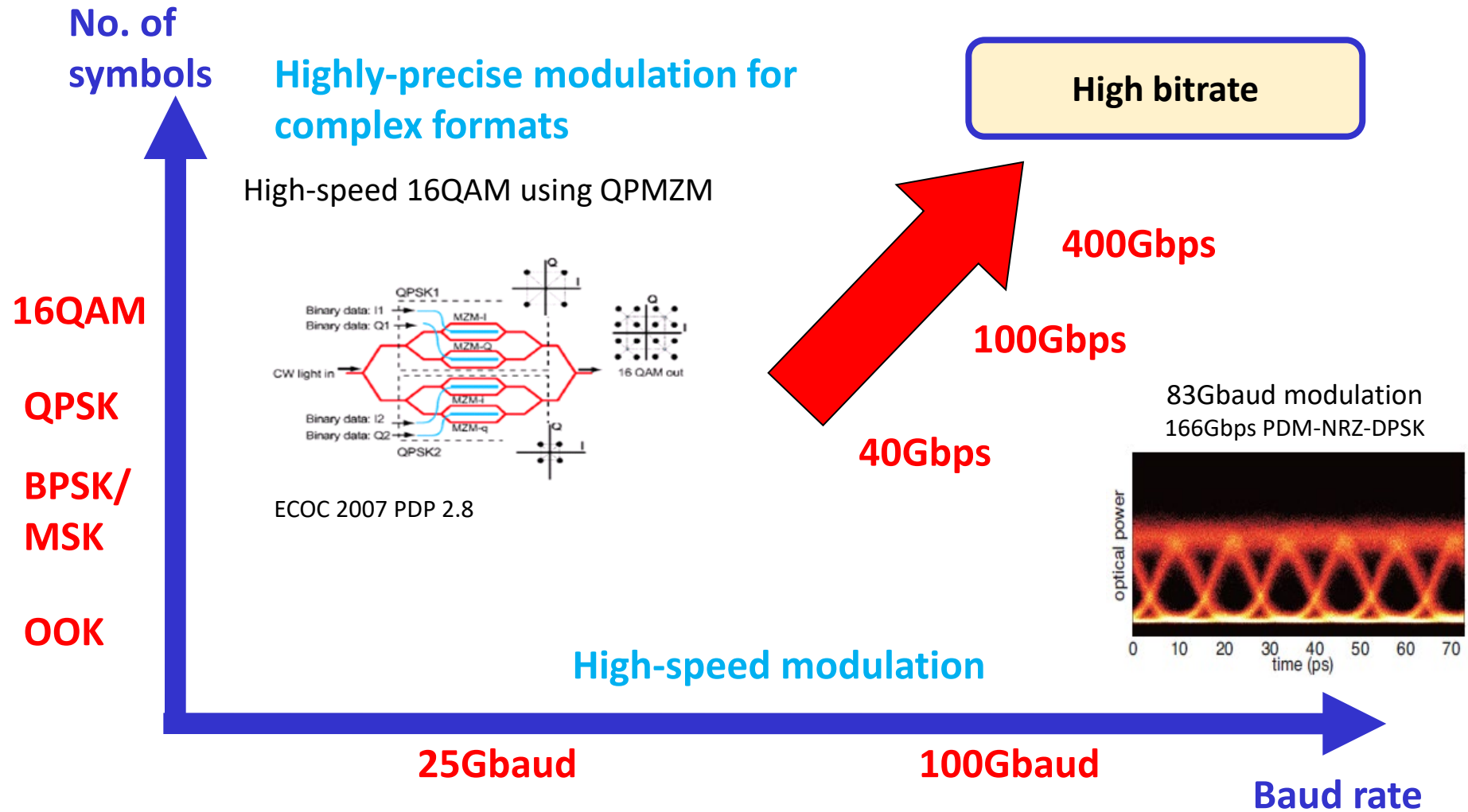
Lithium Niobate: LN (LiNbO_3)

$$r_{33} = 30.8 \times 10^{-12} \text{ m/V}$$

Optical Mach-Zehnder Modulator



Evolution of optical modulation technologies



Now, we have high-speed and precise lightwave control !

Presentations – Wed, Mar 19 (Track 1)

Time	Presenter	Affiliation	Title	File Name
8:00 AM			Opening Comments	
8:05 AM	Paul Kolesar	Commscope	Channel Coverage in Data Centers	kolesar_01_0308.pdf
8:20 AM	Jack Jewell	JDSU	Conditions for 100m and >100m reaches on OM3 and OM4 MMF at 10Gb/s/ch	jewell_01_0308.pdf
8:40 AM	Robert Lingle	OFS	Performance of OM3 and OM4 fibers with Relaxed Transceivers	sun_01_0308.pdf
9:00 AM	John Petrilla	AvagoTechnnologies	Multilane MM Optics: Considerations for 802.3ba	petrilla_01_0308.pdf
9:30 AM	John Petrilla	AvagoTechnnologies	Multilane MM Optics: Eye Safety Categories	petrilla_02_0308.pdf
9:50 AM			Break	
10:05 AM	Jorg Kropp	V-I-Systems Gmbh	1x40Gbit/s and 4x25Gbit/s Transmission at 850nm on Multimode Fiber	kropp_01_0308.pdf
10:35 AM	Petar Pepeljugoski	IBM	Proposal for a Limiting, Non-retimed PMD for 100Gb/s and 40 Gb/s Ethernet and Related Specifications	pepeljugoski_01_0308.pdf
11:05 AM	Tetsuya Kawanishi	NICT, Japan	High-speed 16-QAM for serial PMDs	kawanishi_01_0308.pdf
11:25 AM	Pete Anslow	Nortel	Polarisation Mode Dispersion in 100GbE links	anslow_01_0308.pdf
12:00 PM			Lunch	
1:00 PM	Chris Cole	Finisar	100GE 10km SMF WDM Grid Alternatives	cole_01_0308.pdf
1:55 PM	Chris Cole	Finisar	100GE SMF WDM Grid Q&A	cole_02_0308.pdf
1:30 PM	Matt Traverso	Opnext	Uncooled CWDM 25-Gbps EA/DFB Lasers for Cost-Effective 100GbE transceiver for 10km SMF	traverso_02_0308.pdf
2:25 PM	Matt Traverso	Opnext	Merits of Selecting CWDM for 10km SMF PMD - Impact of Wavelength Grid on Optical MUX/DMUX	traverso_03_0308.pdf
2:55 PM	Matt Traverso	Opnext	Merits of Selecting CWDM for 10km SMF PMD	traverso_01_0308.pdf
3:20 PM			Break	
3:35 PM	Youichi Akasaka	Fujitsu	25Gb/s 10km Transmission performance Using 1.3-um DML	isono_01_0308.pdf
4:00 PM	WB Jiang	Huawei	PHY Layer Monitoring	jiang_01_0308.pdf
4:30 PM	Hidenori Takahashi	KDDI Labs	Comments on Multi-Lane PMD Reliability	takahashi_01_0308.pdf
4:45 PM	Piers Dawe	AvagoTechnnologies	Eye mask statistical significance and practicality	dawe_01_0308.pdf
5:15 PM	Frank Chang	Vitesse	Considering 40GbE MMF and SMF Reach Objectives	chang_01_0308.pdf
5:30 PM	Chris Cole	Finisar	40GE 10km SMF PMD Technical & Economic Feasibility	cole_03_0308.pdf
5:40 PM	Jesse Simsarian	Alcatel-Lucent	40GbE SMF for Carrier Applications	simsarian_01_0308.pdf
5:50 PM	Matt Traverso	Opnext	40 GbE SMF Technical & Economic Feasibility	traverso_04_0308.pdf

Note – Order of presentations and times listed are subject to change.

Over 10000 QAM

16384-QAM TRANSMISSION AT 10 GBD OVER 25-KM SMF USING
POLARIZATION-MULTIPLEXED PROBABILISTIC CONSTELLATION SHAPING
ECOC2019 PD.3.3

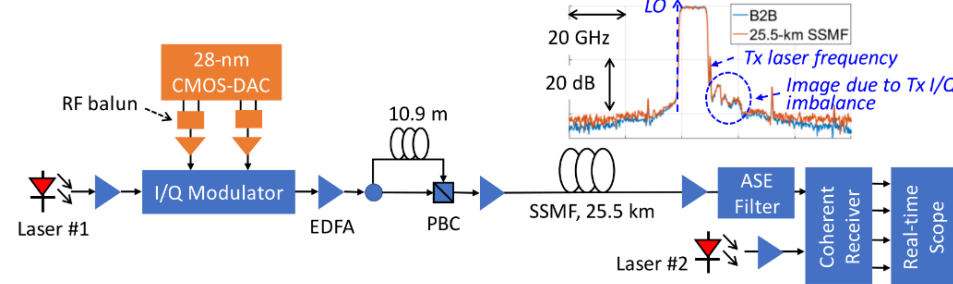


Fig. 2 Experimental setup for the transmission of 10-GBd PS-16384-QAM. Inset: Optical spectra before and after 25.5-km SSMF.

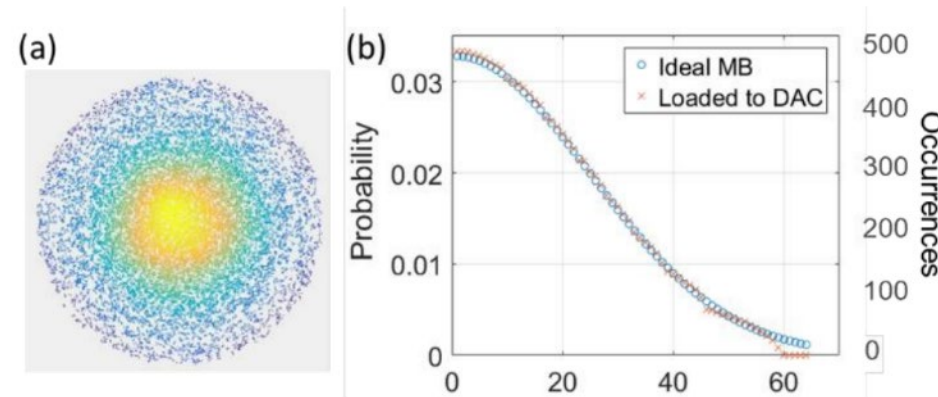
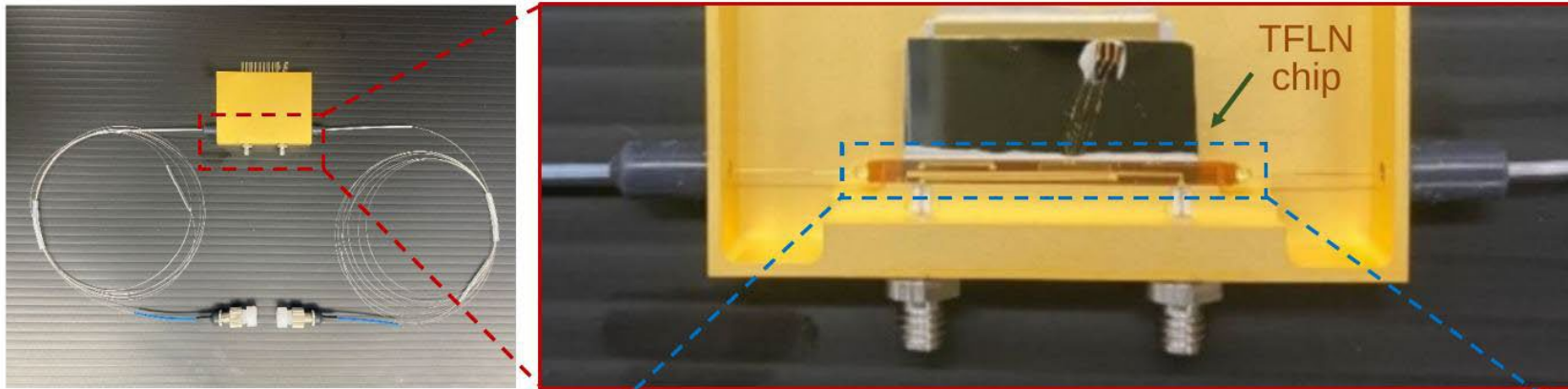
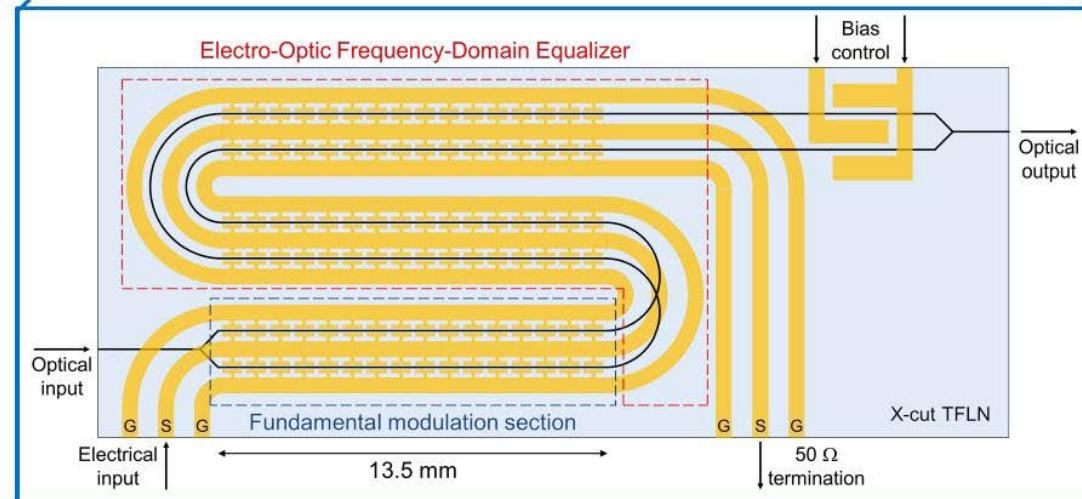


Fig. 6 (a) Recovered PS-16384-QAM constellations with $\beta=5.597$; (b) Histogram of the positive-amplitude portion of real-part of the transmitted PS-16384-QAM signal with $\beta=5.597$.

Ti-diffused LN Modulator Integrated with Equalizer

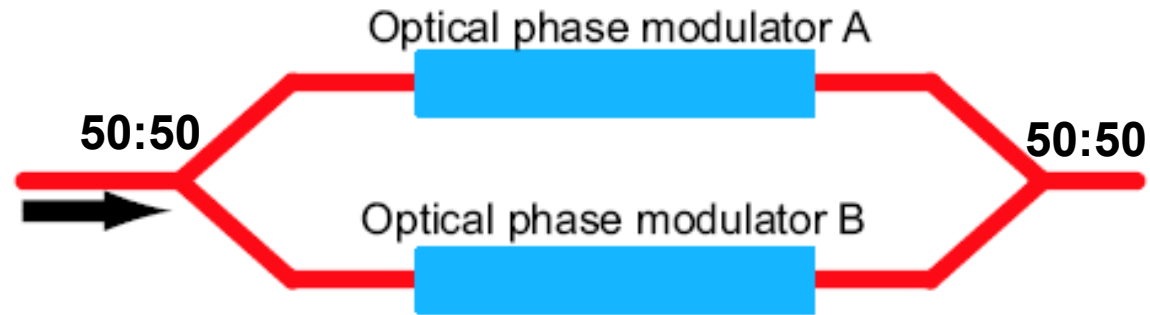


V_π (half-wave voltage)	2.0 V
1dB bandwidth (chip)	100 GHz
3dB bandwidth (packaged)	100 GHz
Total optical loss including fiber-coupling	9.2 dB

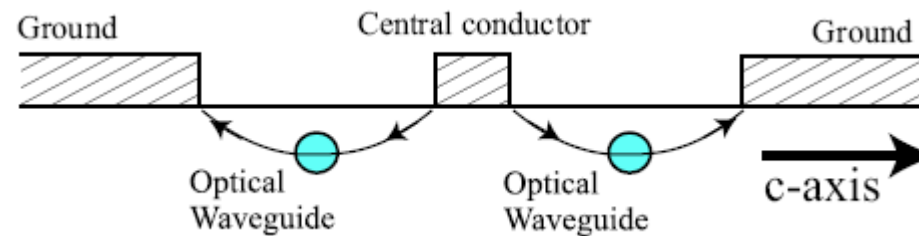


Y. Yamaguchi *et al.*, "Fully Packaged 100-GHz-Bandwidth EO-Equalizer-Integrated TFLN Modulator with Record-High Slope Efficiency Enabling 200-GBaud Signaling," 2025 *Optical Fiber Communications Conference and Exhibition (OFC)*

“Balanced” Optical Mach-Zehnder Modulator



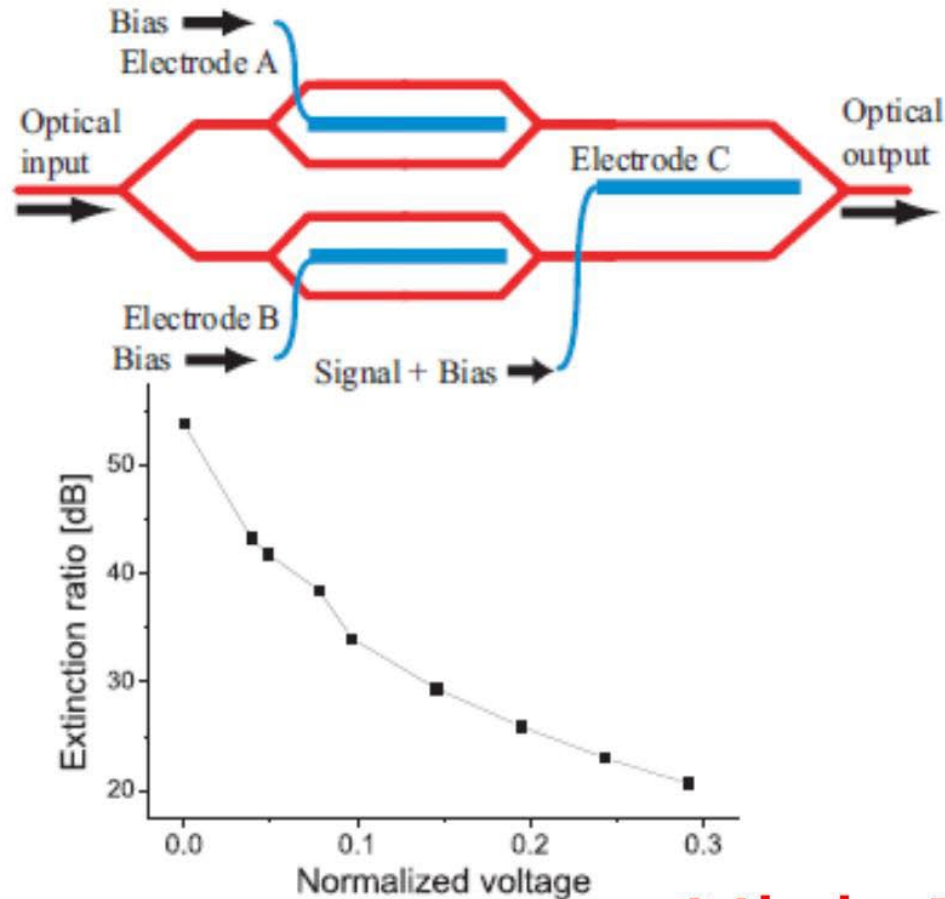
Balance in photonic circuit: **high extinction ratio.**



Balance in electric circuit: **zero chirp ($\alpha=0$)**
(modulation index)

Typ. ER: 20-30dB, α : 0.1-0.2

Sub MZ structures for trimming



ECOC 2005, Th1.6.6

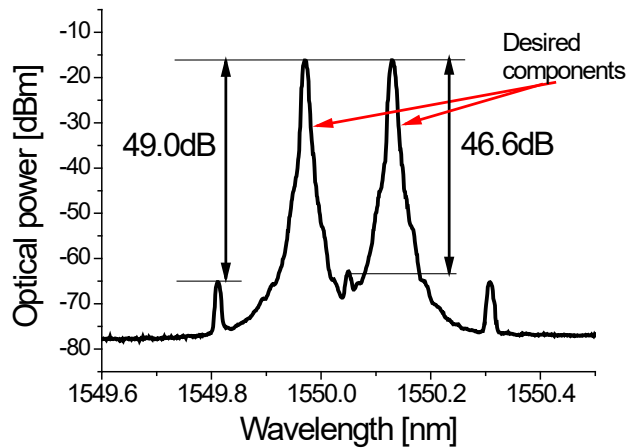
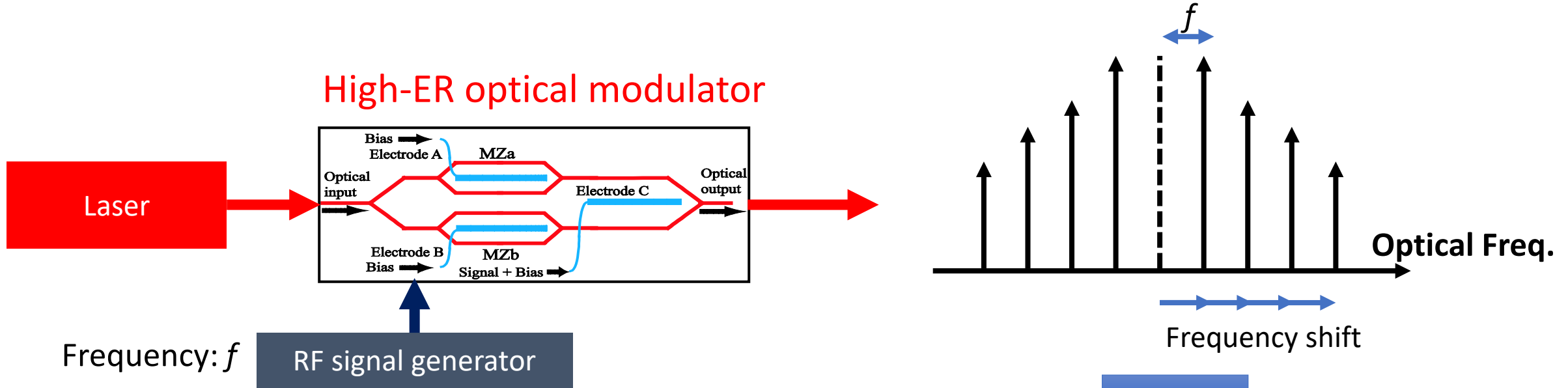
ER > 75dB

**Imbalance
between arms
can be
compensated
by trimmers.**

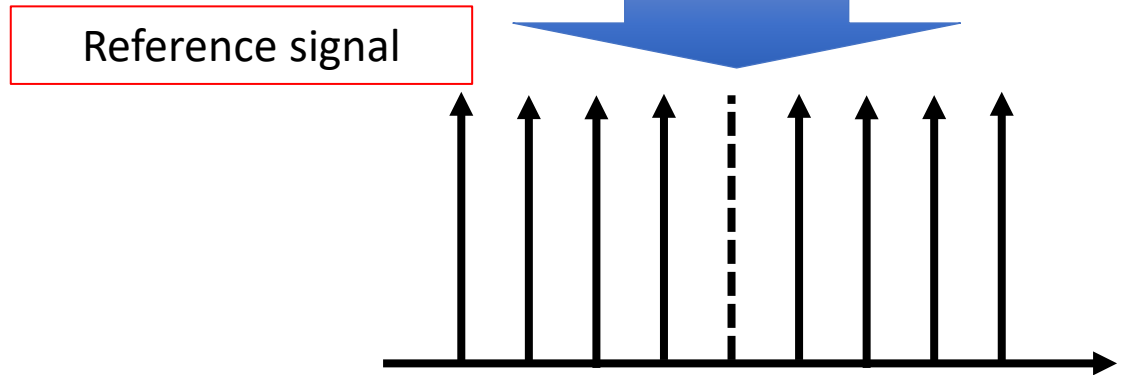
High-ER and ER-tuning



Two-tone signal generation by optical modulation



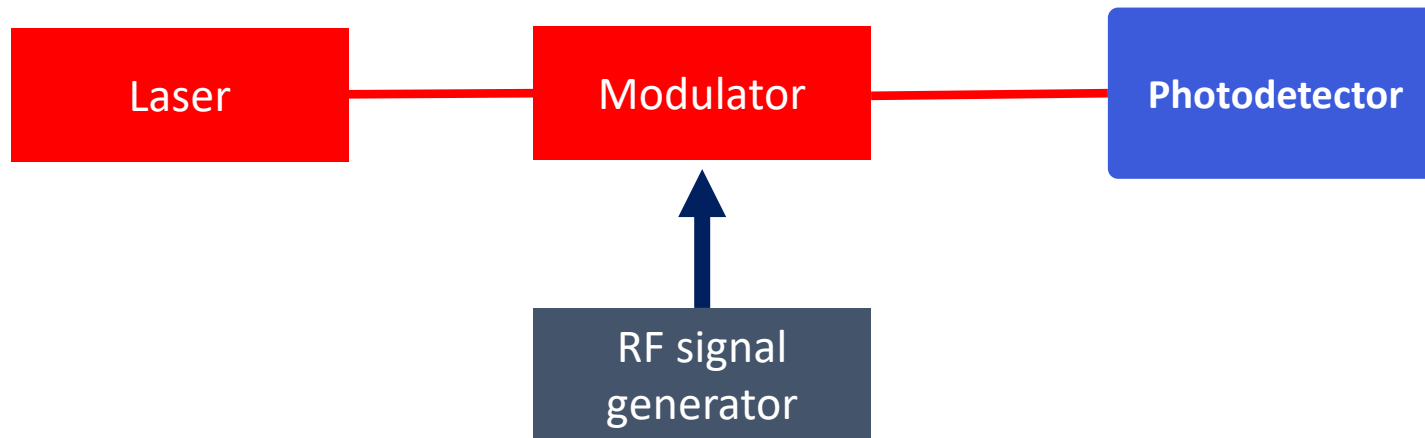
Extinction ratio (balance in photonic circuit): 66dB
Alpha parameter (balance in electric circuit): 0.0099



Amplitude ripple due to the modulator frequency response can be compensated by optical amplifiers or variable attenuators. Frequencies and relative phase are unaffected.

Principle: Two-Tone Generation by Precise Optical Modulation

- Single laser + MZM at null bias → carrier-suppressed ± 1 st-order sidebands: two tones separated by exactly $2 \cdot f$
- Photomixing beat: laser phase noise cancels as common mode — correlation guaranteed by structure, not by a lock loop
- Frequency difference = modulation frequency, exactly — set by the microwave reference, no control loop, no unlock
- Spectral purity of the beat is decoupled from the modulator's own frequency response — response ripple changes tone amplitude, not tone frequency or relative phase
- Intensity noise: single source → removed as common mode by total optical power stabilization
- Trade-off: sideband power < full laser power → weaker beat signal



Photodetector measurement by optical reference (two-tone)

Tokyo / 6月 10, 2021

ローデ・シュワルツ・ジャパンがシンクランド社と
協業して光計測市場に参入

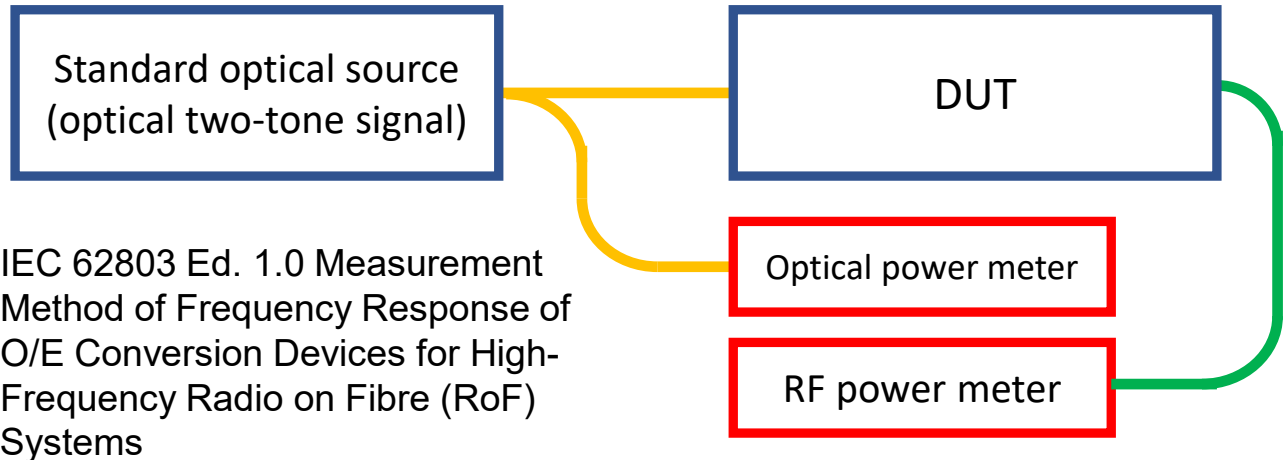
ローデ・シュワルツは、R&S ZNAベクトル・ネットワーク・アナライザを、シンクランド株式会社（本社 神奈川県横浜市）のPFDA-288シリーズと組み合わせることで、従来の製品では対応できなかった高速通信用光デバイスや受光器の周波数特性を、これまでにない高精度・高感度での測定を実現しました。

Think Lands press release



VNA (R&S)

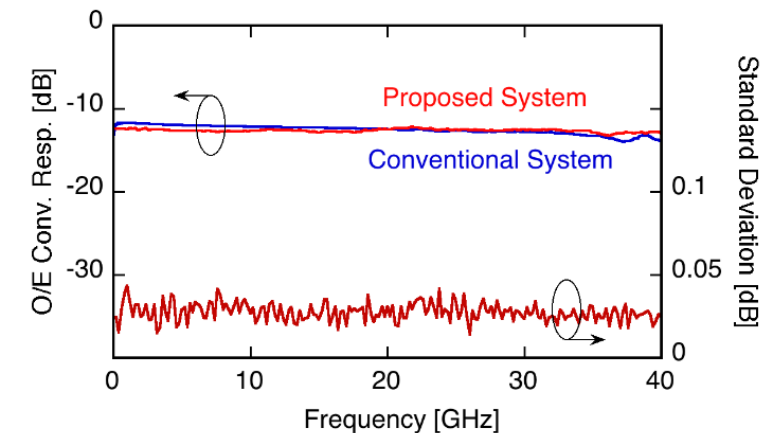
Think Lands
(Optical module)



IEC 62803 Ed. 1.0 Measurement
Method of Frequency Response of
O/E Conversion Devices for High-
Frequency Radio on Fibre (RoF)
Systems

APT Report on Characteristics and
Requirements of Optical and Electric
Components for Millimeter-wave Radio
on Fiber systems ASTAP/REPT 3

K. Inagaki, et al., IEICE Electronics
Express, Vol. 9, 220 (2012)



Current ALMA Photonic LO: Strengths First, Then Blind Spots

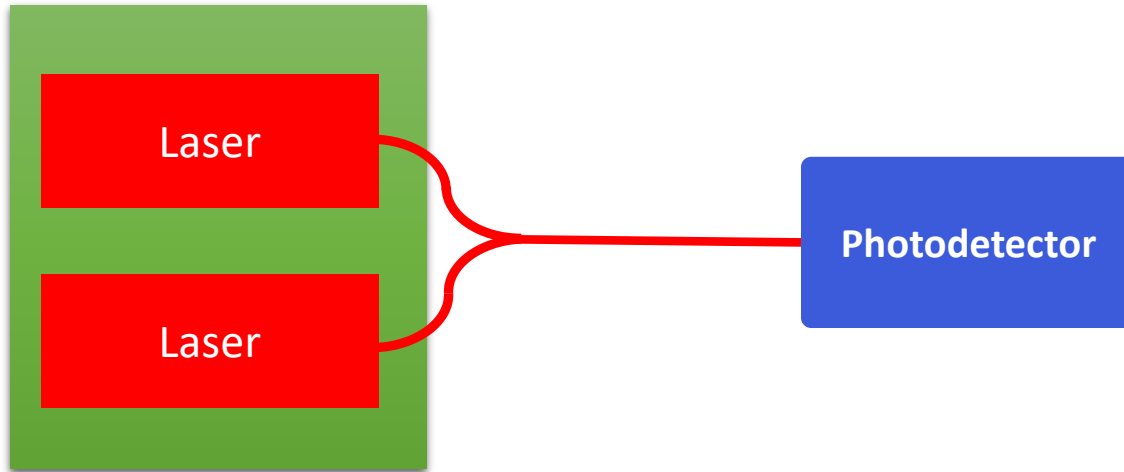
Two-laser offset lock (master/slave + PLL) + Line Length Corrector (round-trip fiber compensation)

Its real strength: best beat SNR — beat amplitude, each tone at full laser power

Residual PLL phase error, unlock events, system complexity; tighter margins at high-multiplication bands

Intensity-noise:

- RIN of two independent lasers adds uncorrelated → beat amplitude noise (PLL fixes phase, not this)
- Relative polarization drift between the two lasers → photomixing-efficiency fluctuation



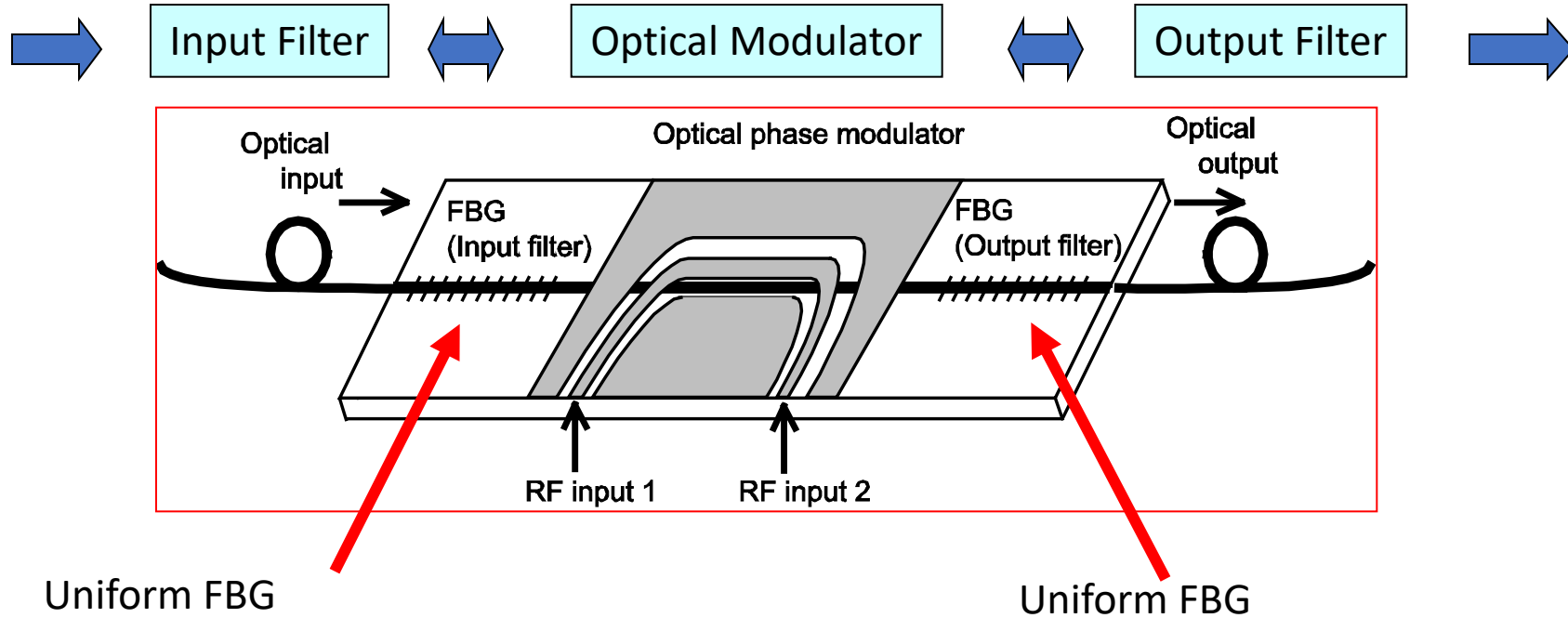
PLL

The Core Comparison: SNR × Stability

Method	Beat SNR	Frequency-difference stability	Intensity noise	Complexity
Two lasers + PLL	Best — each tone at full laser power	Control-loop dependent (residual error, unlock risk)	RIN adds uncorrelated; relative polarization drift	High (OPLL)
Modulator two-tone	Moderate — sideband power; recoverable (EDFA, UTC-PD)	Exact: difference = $2 \cdot f_m$, set by RF reference	Common mode → solved by total-power stabilization	Simple, no locking
EO comb	Weak — power divided over N lines	Exact (same principle)	Common mode	Moderate

The asymmetry that decides it:
an SNR deficit can be recovered by engineering — a frequency-difference instability cannot.

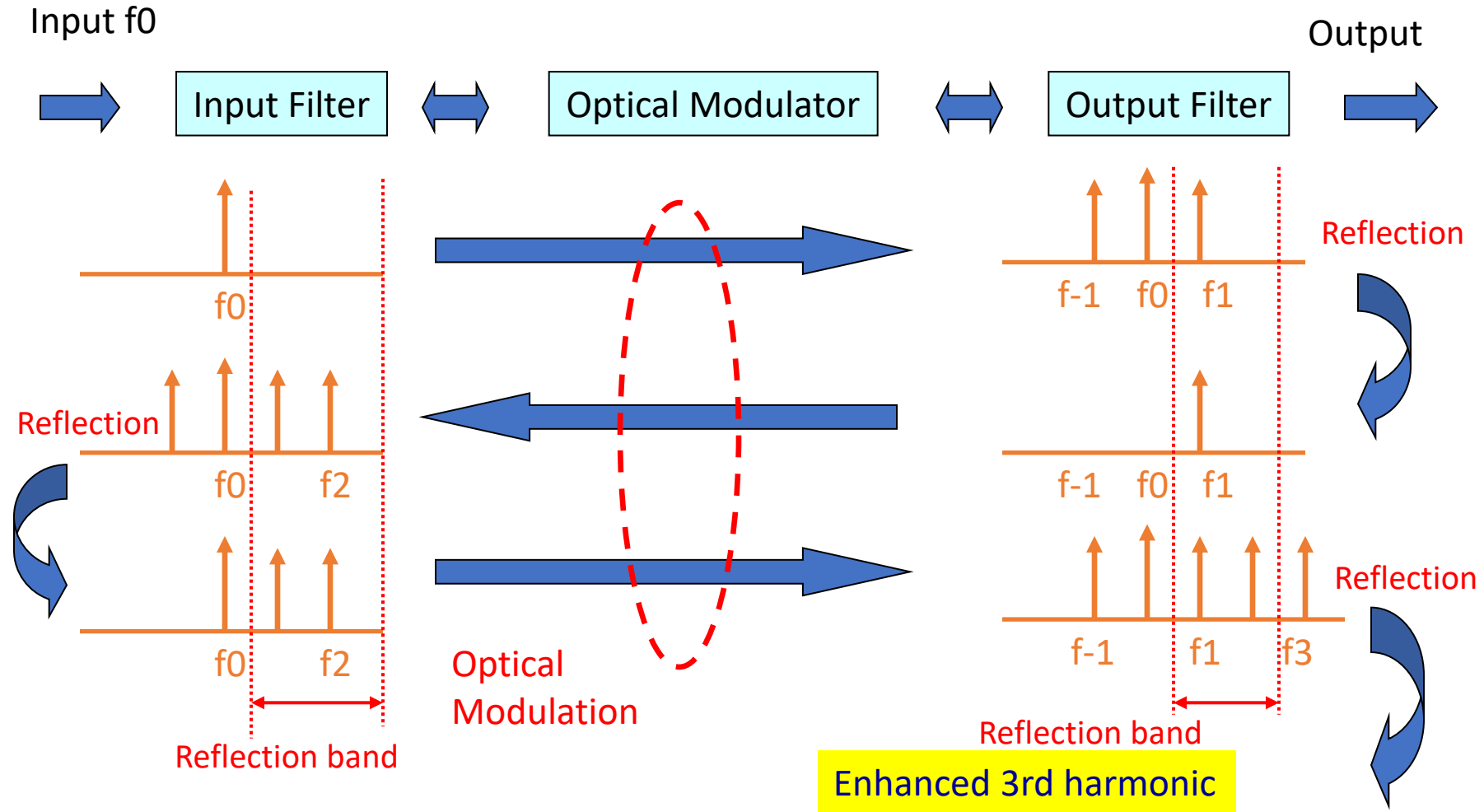
Integrated reciprocating optical modulator



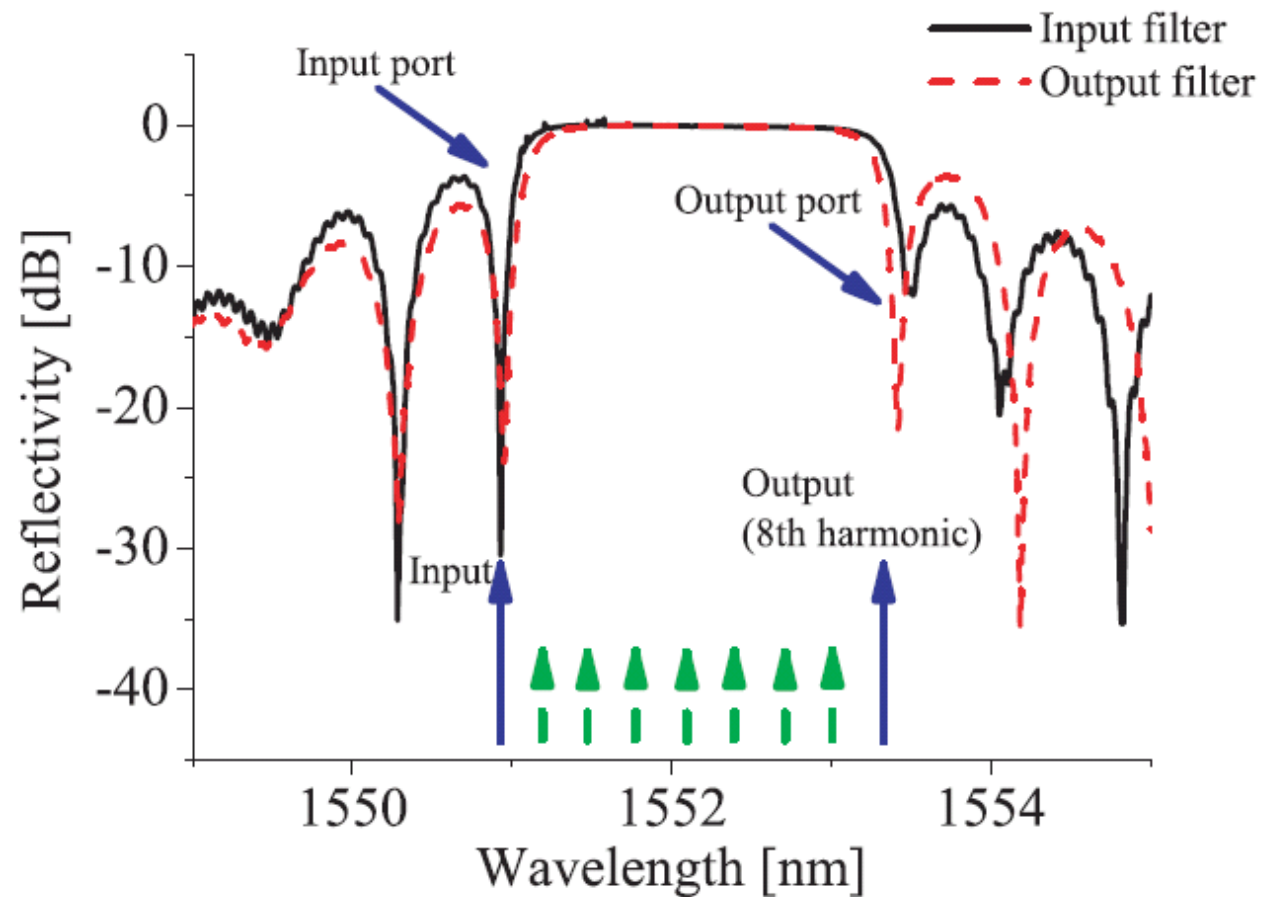
Halfwave voltage of the phase modulator
4.1 V at dc and 7.8 V at 40 GHz

T. Kawanishi, T. Sakamoto and M. Izutsu, "470GHz Optical Clock Signal Generation Using Reciprocating Optical Modulation," *2006 European Conference on Optical Communications*

Principle (3rd harmonic)



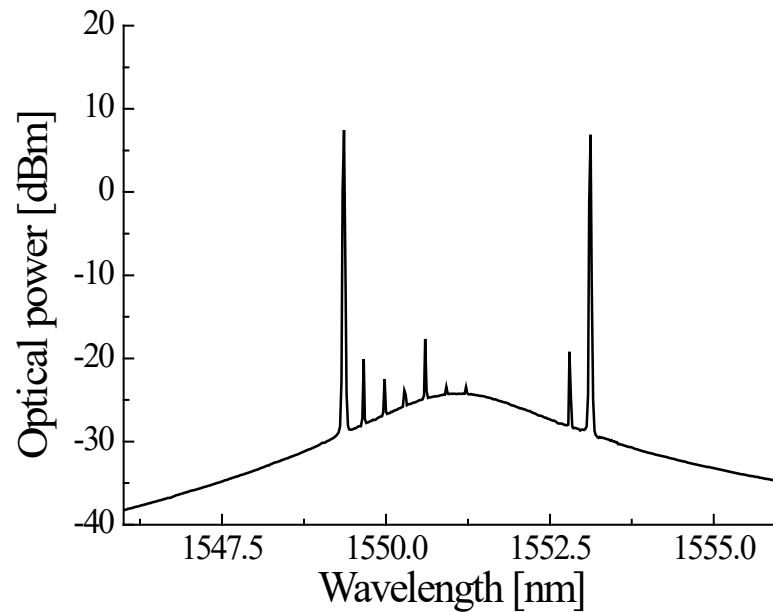
Input/output filters



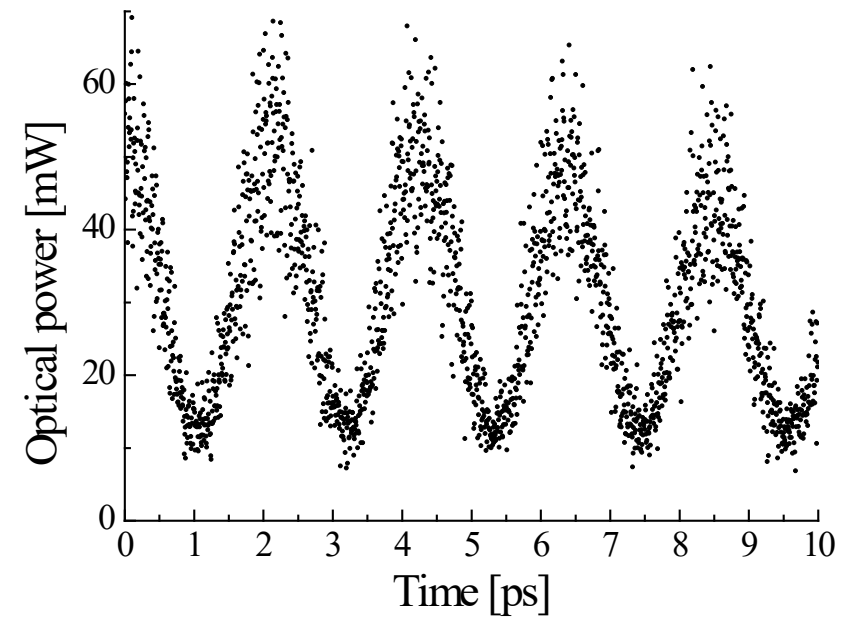
T. Kawanishi, T. Sakamoto and M. Izutsu, "470GHz Optical Clock Signal Generation Using Reciprocating Optical Modulation," *2006 European Conference on Optical Communications*

470GHz optical clock

Spectrum



Time domain



468.84GHz

T. Kawanishi, T. Sakamoto and M. Izutsu, "470GHz Optical Clock Signal Generation Using Reciprocating Optical Modulation," *2006 European Conference on Optical Communications*

Toward 2040: Fiber Plant — Survey Needs, and Life with WSU Coherent Transport

Generation is maturing — the bottleneck moves to the fiber plant

- Thermal delay ~ 40 ps/km/K, acoustic & vibration, polarization drift
- Two-tone specific: dispersion-induced inter-tone delay; polarization fading at the photomixer

WSU puts coherent Ethernet on the same plant

- 400G-ZR corrects dispersion/phase/polarization in DSP, after detection — the LO reference must not fluctuate before the fact: simple technology reuse is not enough

Opportunity: coherent DSP internal state (carrier phase, SOP tracking) = a distributed fiber-fluctuation sensor

- Survey items: (1) site-fiber environmental statistics (2) DSP-telemetry-assisted stabilization

Summary

- Method choice is SNR $\times$ stability — and the asymmetry decides: SNR deficits are recoverable by engineering; frequency-difference instability is not.
- Extinction ratio governs precision — high-ER modulation (>75 dB), field-trimmable and bias-controlled, verified via IEC-standardized measurement: an infrastructure-grade technology.
- Toward 2040, the bottleneck moves to the fiber plant — site-measured fluctuation statistics and WSU-coherent coexistence are the next work, with DSP telemetry as an unexpected ally.

Prospects for East Asian Collaboration

- Device qualification via IEC-standardized measurement
- Co-definition of ALMA2040 reference-signal requirements — written jointly in astronomy and photonics languages
- People: student & postdoc exchange around field demonstrations
- Happy to continue these conversations during the workshop and beyond