

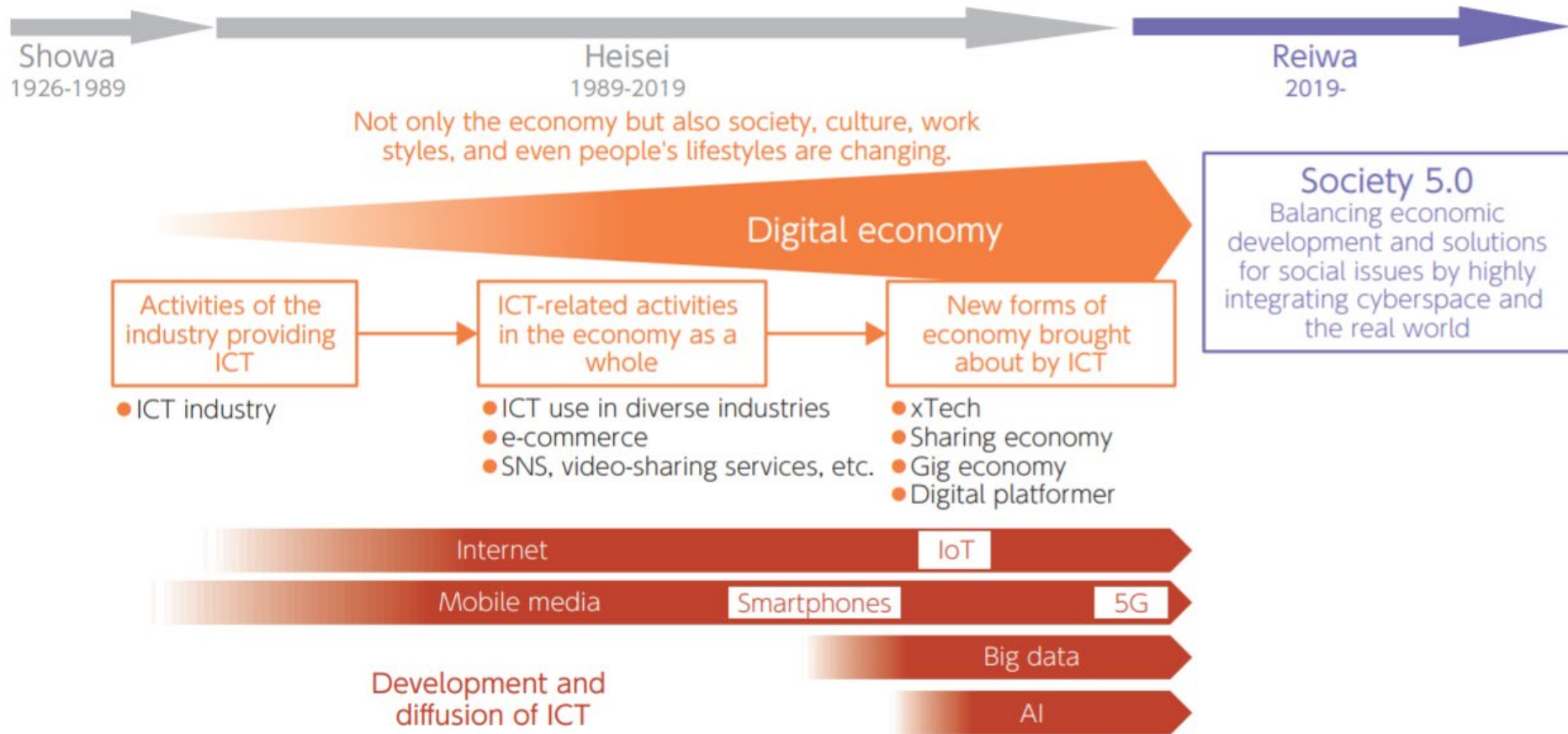
# 分極反転による ミリ波・THz波無線信号処理技術

村田 博司

三重大学 大学院工学研究科  
電気電子工学専攻



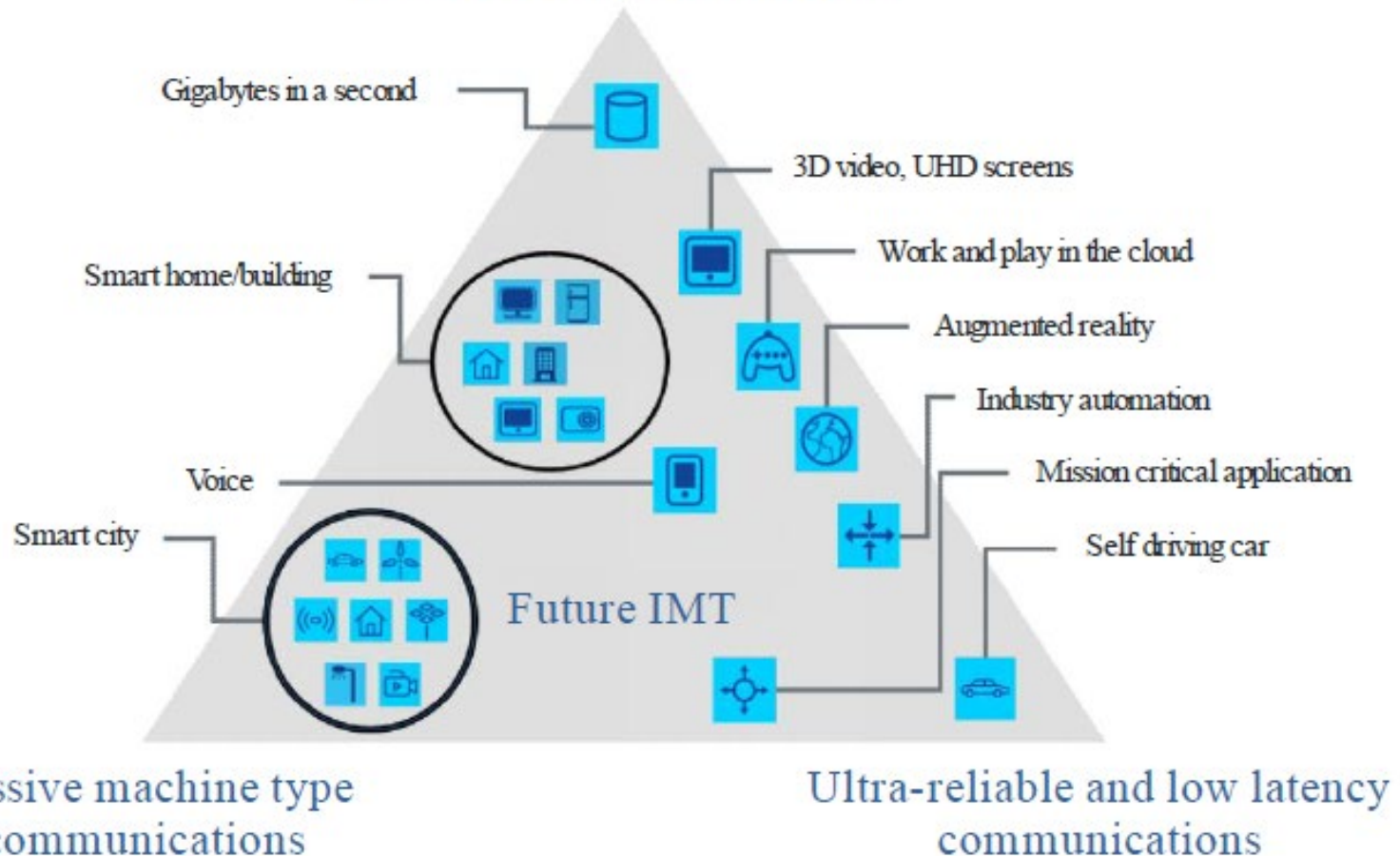
# ICT の進化 - 昭和・平成・令和 -



# 5G Mobile Network

✓ Peak Speed: > 10 Gb/s /ch

Enhanced mobile broadband

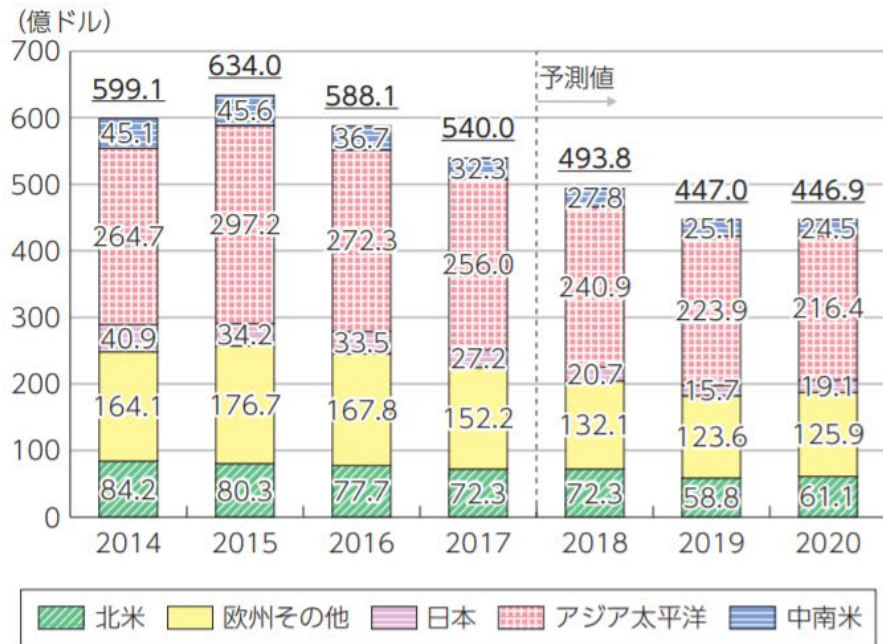


✓ Massive connectivity:  
~10 million/km<sup>2</sup>

✓ Latency: ~ 1ms

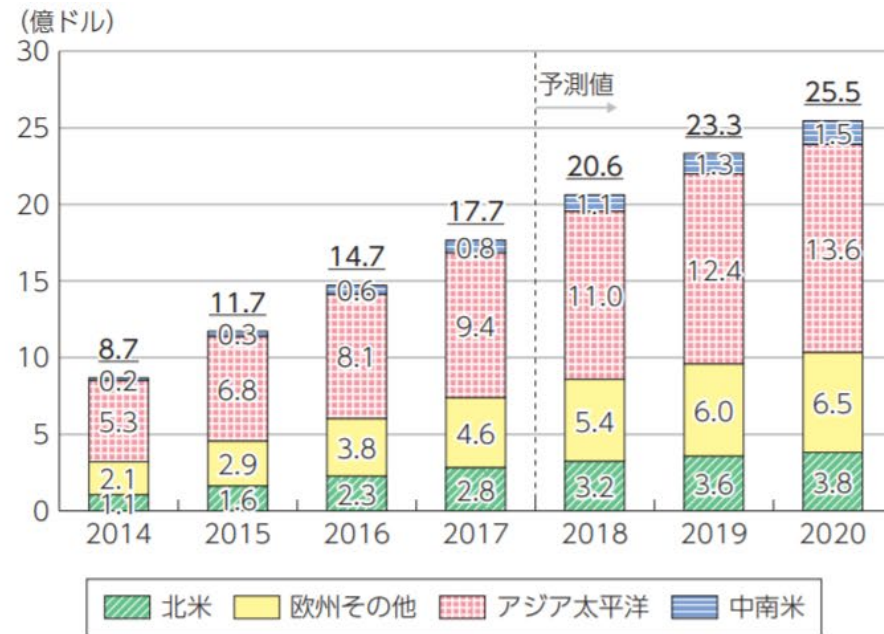
# ネットワーク機器の市場規模

## 世界のマクロセル基地局市場規模の推移



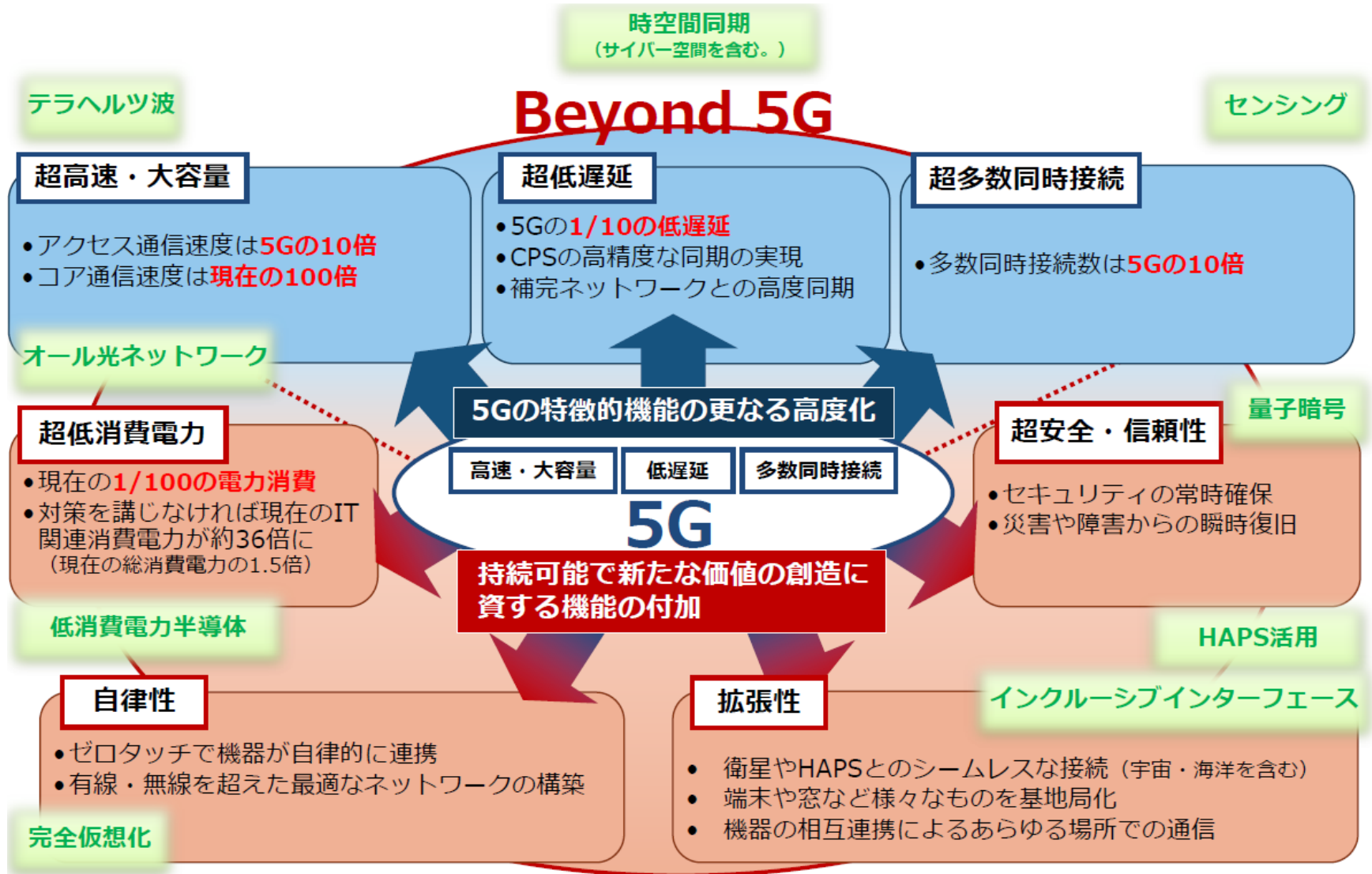
(出典) IHS Technology

## 世界のスモールセル市場規模の推移



(出典) IHS Technology

# From 5G to Beyond 5G/6G



# Beyond 5G 推進戦略ロードマップ（総務省）

社会情勢

COVID-19  
流行

ウィズコロナ／ポストコロナ

大阪・関西万博  
B5G Ready Showcase

Beyond 5G Ready

SDGs  
目標年(年)

2020

2021

2022

2023

2024

2025

2026

2027

2028

2029

2030

第6期科学技術基本計画

移動通信システム  
の進化

初期の5G  
(Non Stand Alone)

機能強化された5G  
(Stand Alone)

B5G  
(6G)

Beyond 5G推進戦略

先行的取組フェーズ

▲Beyond 5G推進コンソーシアム設置

取組の加速化フェーズ

知財・標準化戦略

体制構築・連携強化・国際標準化活動

▲Beyond 5G知財・標準化戦略センター設置

国際標準（技術仕様等）への  
反映に向けた活動の加速

サプライチェーンリスクの低減と  
市場参入機会の創出

順次反映

順次反映

研究開発戦略

要素技術の集中的研究開発

▲Beyond 5G研究開発プラットフォーム構築

要素技術の開発成果の民間展開

世界最高レベルの  
研究開発環境の実現

機能強化された5Gの開発・製造基盤強化

Beyond 5Gの開発・製造基盤強化

- ・超リアルタイム最適化
- ・超自律型セキュリティ
- ・超テレプレゼンス等

連携

連携

展開戦略

多様なユースケースの構築

▲5Gソリューション提供センター構築

Beyond 5G ready な環境実現

Beyond 5G ready  
な環境の実現

社会全体のデジタル化推進

あらゆる活動がデジタル前提に

機能強化された5Gのセキュリティ確保

Beyond 5Gのセキュリティ確保  
(量子暗号システムの社会実装等)

5G・光ファイバ網の社会全体への展開

空、海、宇宙等あらゆる場所で、あらゆる人に届く通信実現へ

# 「Beyond 5G研究開発促進事業」 基幹課題

No	研究開発課題	受託者	予算/年	期間	備考
001	Beyond 5G超大容量無線通信を支える次世代エッジクラウドコンピューティング基盤の研究開発	◎東京工業大学, 岐阜大学, 滋賀県立大学 富士通フティカルコンポネッツ(株) 古河電気工業(株), 古河ネットワークソリューション(株) 日本電気(株), 大阪大学, 東北大学 楽天モバイル(株)	10億円	4年	
002	Beyond 5G超大容量無線通信を支える空間多重光ネットワーク・ノード技術の研究開発	◎香川大学, (株)KDDI総合研究所 日本電気(株), サンテック(株) 古河電気工業(株)	8億円	4年	
003	テラヘルツ帯を用いたBeyond 5G超高速大容量通信を実現する無線通信技術の研究開発	◎富士通(株), 東京都市大学 ◎早稲田大学, 日本電信電話(株) 宇宙航空研究開発機構, 三菱電機(株)	9億円	4年	項目1 項目2,3
004	Beyond 5Gに向けたテラヘルツ帯を活用した端末拡張型無線通信システム実現のための研究開発	◎(株)KDDI総合研究所, 早稲田大学 千葉工業大学, 名古屋工業大学 (株)日立国際電気	12億円	4年	
005	Beyond 5G超大容量無線ネットワークのための電波・光融合無線通信システムの研究開発	◎三重大学, (株)日立国際電気 (株)京都セミコンダクター (株)KDDI総合研究所, 東洋電機(株)	8億円	4年	

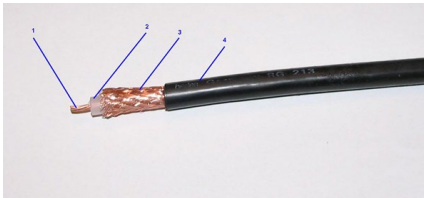
# Challenge in MWP Technology for 5G

## ✓ 4G

$$f_c \sim 1.5 \text{ GHz} \Leftrightarrow \lambda \sim 20 \text{ cm}$$

Loss in coax cable @ 1.5 GHz

$$\mathbf{5D2V} \quad \alpha \sim -0.4 \text{ dB/m}$$



## ✓ A/D Conversion Technique

Sampling frequency

$$f_s \sim 32 \text{ Gsa/s (ADP7000)}$$

## ✓ 5G

$$f_c \sim 30 \text{ GHz} \Leftrightarrow \lambda \sim 1 \text{ cm}$$

Loss in coax cable @ 30 GHz

$$\mathbf{CM06} \quad \alpha \sim -2.5 \text{ dB/m}$$



## ✓ New EOM/EO converter

Antenna-Coupled Electrode

EO modulator

$$f_r \sim 30 \text{ GHz} \Rightarrow \text{field enhance} \sim 8000$$

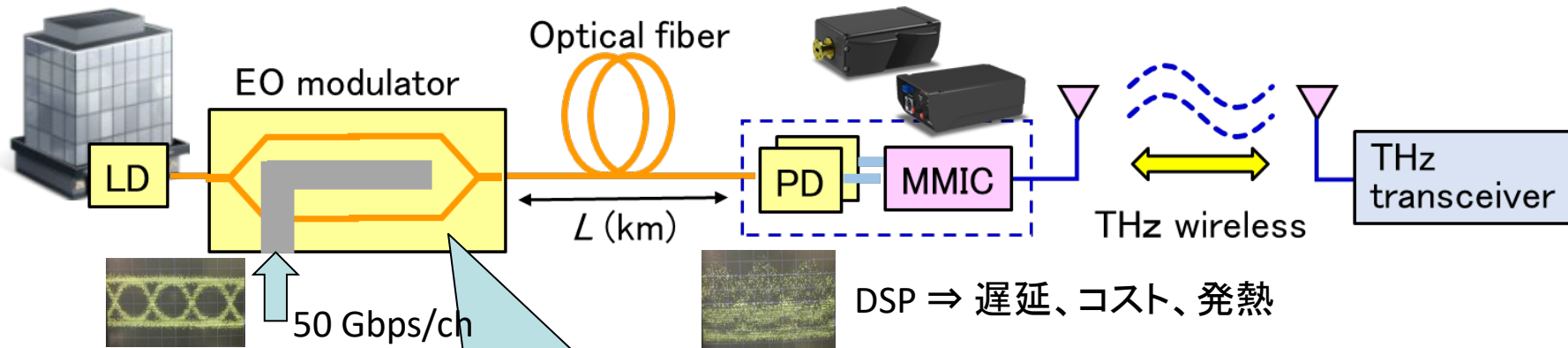
$$f_r \sim 80 \text{ GHz}, 90 \text{ GHz}$$

Optical amplitude/phase modulator

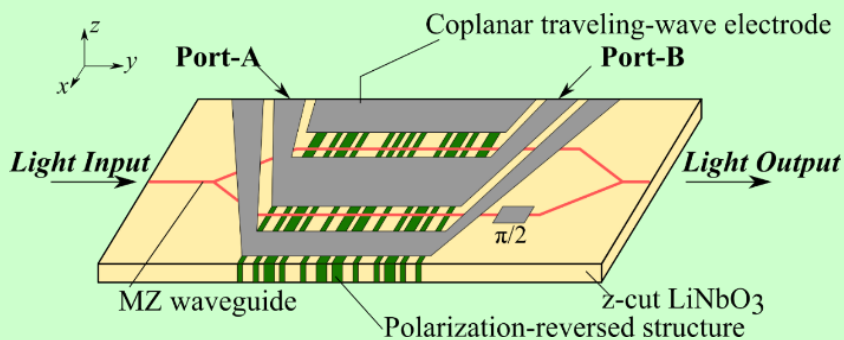
Polarization reversal technique



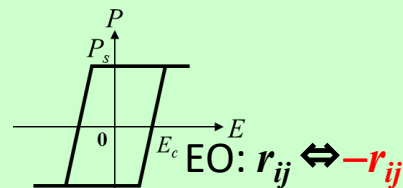
# 低遅延信号配信デバイスの開発



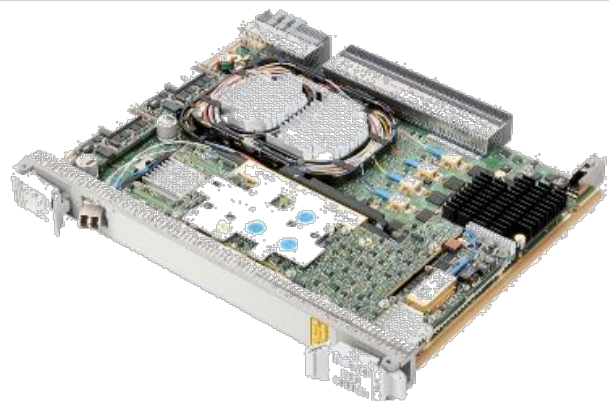
## ▶ プリコライジング高速光変調器



- ✓ 分散補償用伝達関数／インパルス応答
- ✓ 強誘電性 & 進行波型変調 ⇒ 任意伝達関数
- ✓ DSP不要
- ✓ 超低遅延高速信号伝送



# Conventional Dispersion Compensation Techniques



Commercial 40 Gb/s coherent transceiver<sup>[1]</sup>

## ◆ Digital Signal Processing (DSP)

- 😊 Tunable dispersion compensation
- 😊 Wide wavelength range
- 😞 High power consumption
- 😞 Limitation of high-speed operation



Standard DCF module<sup>[2]</sup>

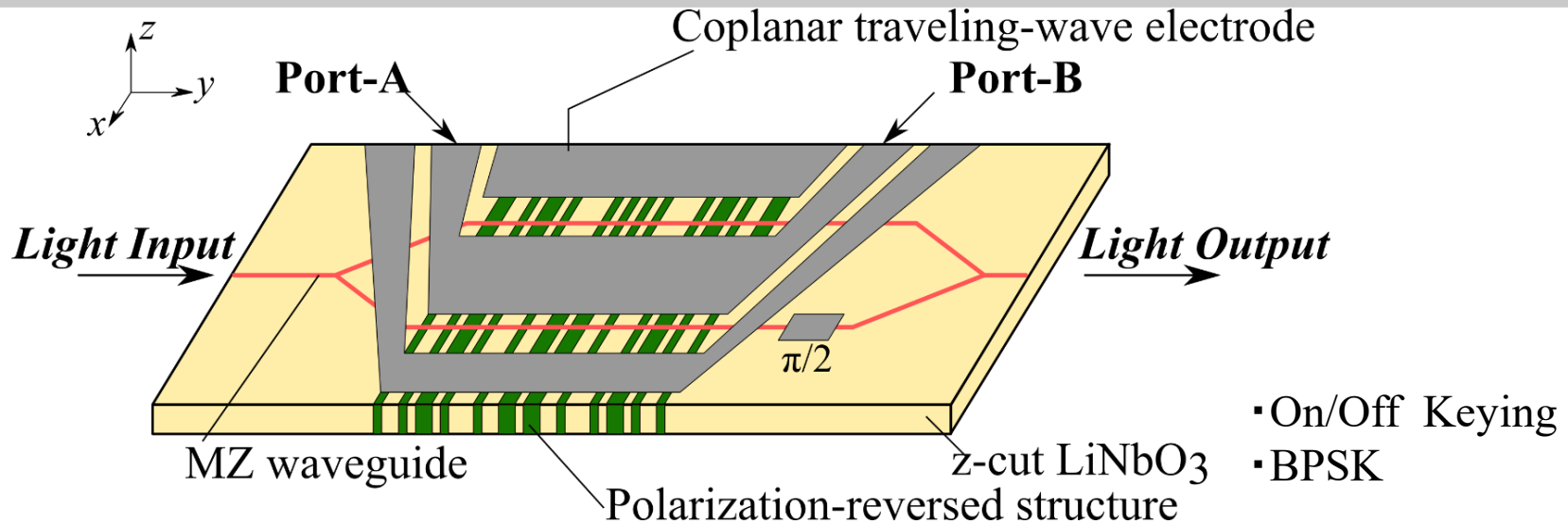
## ◆ Dispersion Compensating Fiber (DCF)

- 😞 Constant dispersion compensation
- 😞 Narrow wavelength range
- 😊 Low power consumption
- 😊 Possible to operate high-speed

[1] K. Roberts, M. O'Sullivan, K.T. Wu, H. Sun, A. Awadalla, D.J. Krause, and C. Laperle, "Performance of dual-polarization qpsk for optical transport systems," *Journal of lightwave technology*, vol.27, no.16, pp.3546-3559, 2009.

[2] L. Gruner-Nielsen, M. Wandel, P. Kristensen, C. Jorgensen, L.V. Jorgensen, B. Edvold, B. Palsdottir, and D. Jakob-sen, "Dispersion-compensating bers," *Journal of Light-wave Technology*," vol.23, no.11, p.3566, 2005.

# Pre-equalizing Electro-Optic (EO) Modulator



**Key point :**

**E/O signal conversion + Pre-equalization**

## Properties

- ☺ High-speed operation ( $\sim 100$  GHz)
- ☺ Wide wavelength range (C-band/ L-band)
- ☺ Low power consumption
- ☺ Fiber length for dispersion compensation ( $\sim 80$  km)
- ☺ Tunable dispersion compensation

# Dispersion of optical fiber

Transfer function of optical fiber

$$H(\omega) = \exp\{-j\beta(\omega)L\}$$

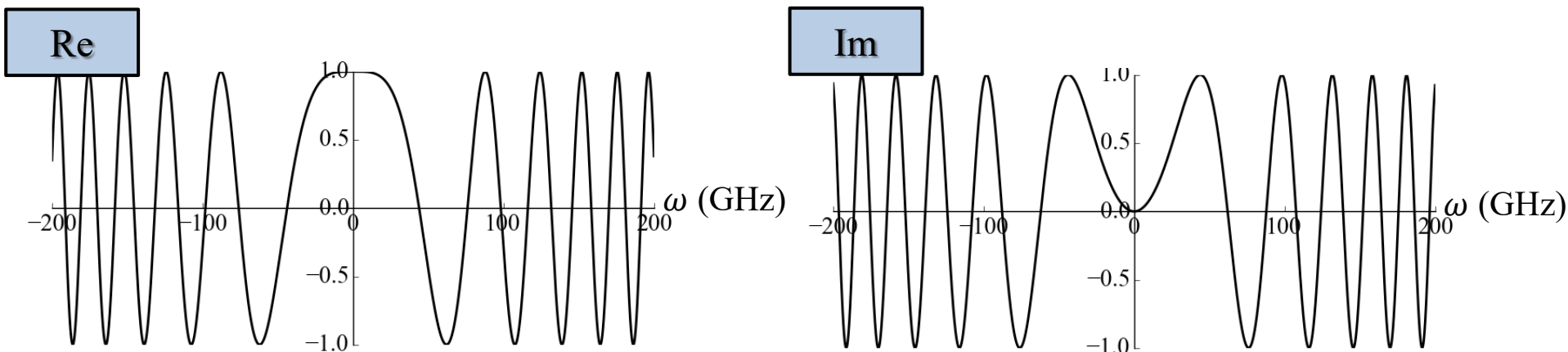
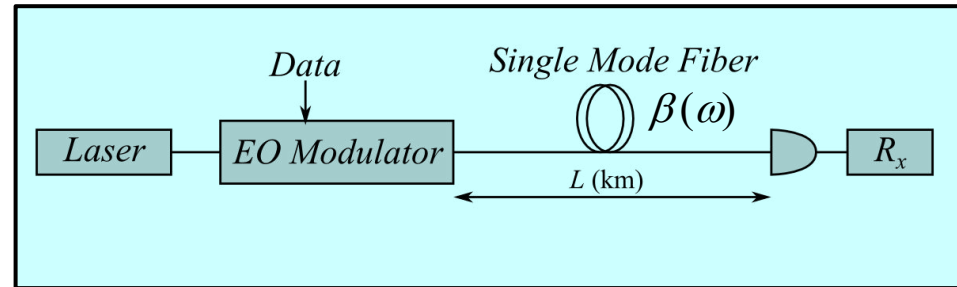
Propagation constant (Taylor expansion)

$$\beta(\omega) = \beta_0(\omega) + (\omega - \omega_0)\beta_1 + \frac{1}{2}(\omega - \omega_0)^2\beta_2$$

Group velocity dispersion

Transfer function of fiber dispersion effect

$$H_{dis}(\omega) = \exp\left\{-j\frac{1}{2}\omega^2\beta_2L\right\}$$



Standard Single-mode glass fiber ( $L=80$  km,  $D=16$  ps/nm $\cdot$ km)

# Principle of pre-equalization

Transfer function of fiber dispersion effect

$$H_{dis}(\omega) = \exp\left\{-j\frac{1}{2}\omega^2\beta_2L\right\}$$

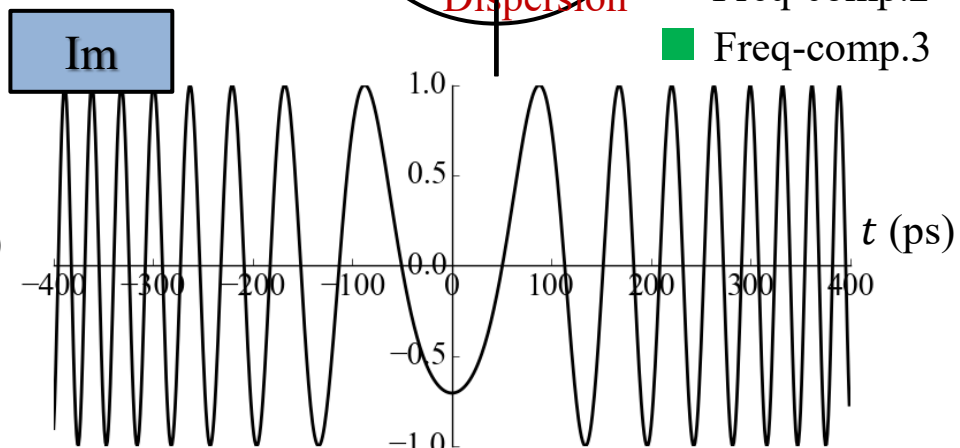
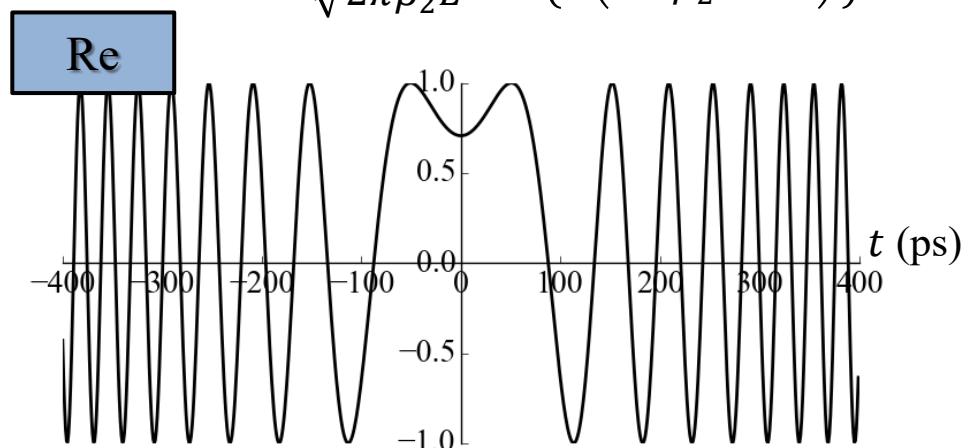
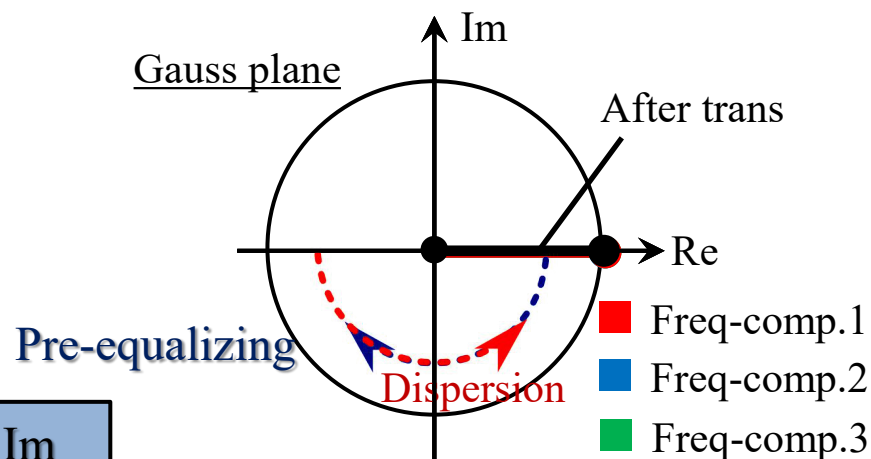
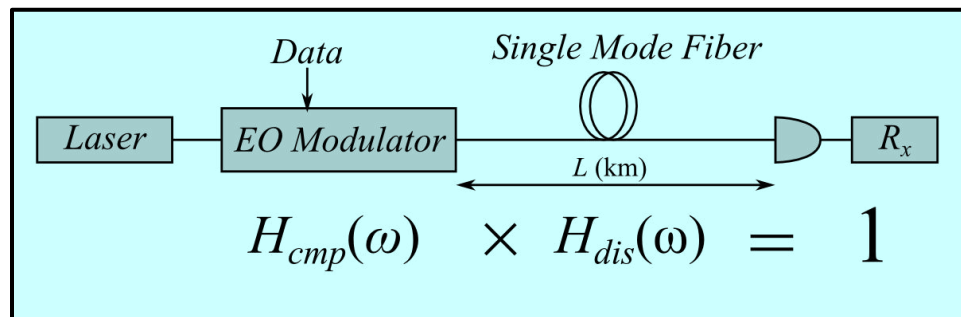
Transfer function for pre-equalization

$$H_{cmp}(\omega) = \frac{1}{H_{dis}(\omega)} = \exp\left\{+j\frac{1}{2}\omega^2\beta_2L\right\}$$

Impulse response for pre-equalization

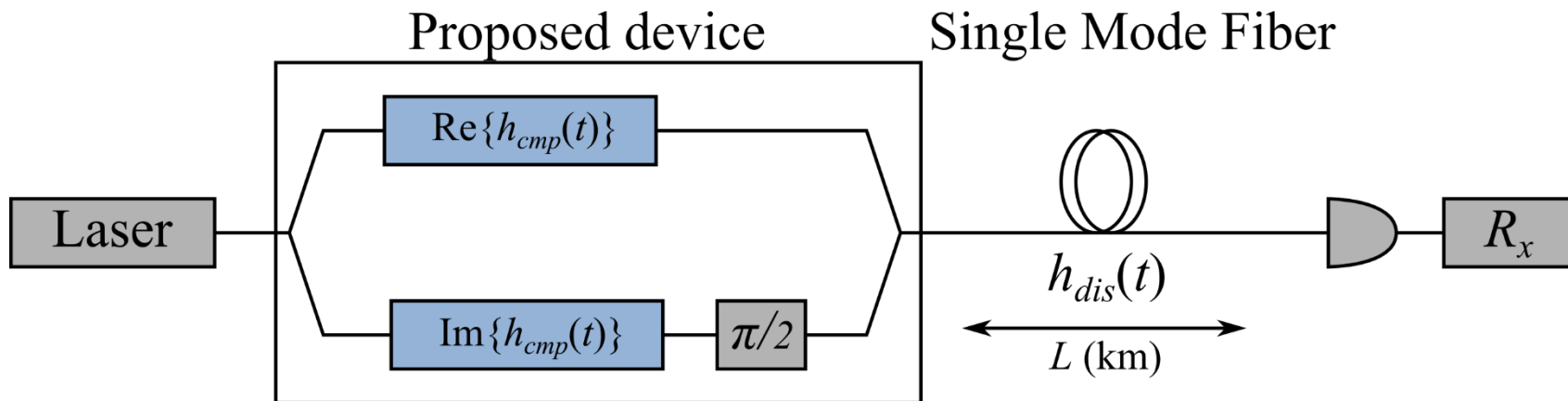
$$h_{cmp}(t) = \frac{1}{2\pi} \int H_{cmp}(\omega) \exp(+j\omega t) d\omega$$

$$= \frac{1}{\sqrt{2\pi\beta_2L}} \exp\left\{j\left(-\frac{t^2}{2\beta_2L} + \frac{\pi}{4}\right)\right\}$$



Standard Single-mode glass fiber ( $L=80$  km,  $D=16$  ps/nm $\cdot$ km)

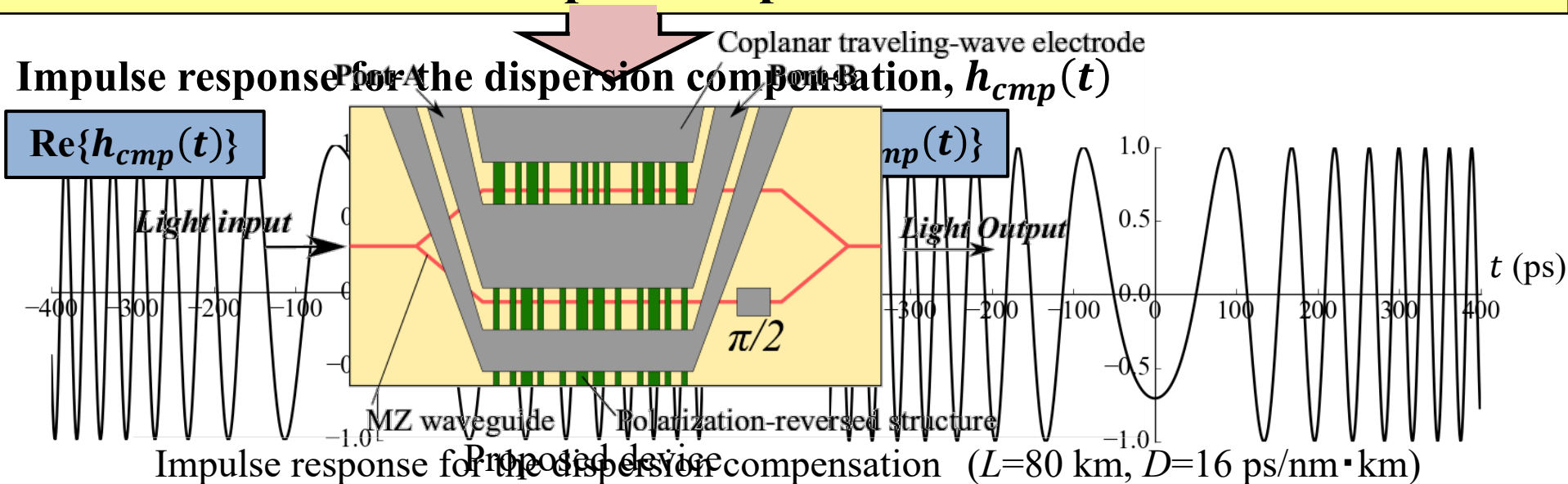
# Operational Principle



Key point :

**How to realize impulse responses in the EO modulator**

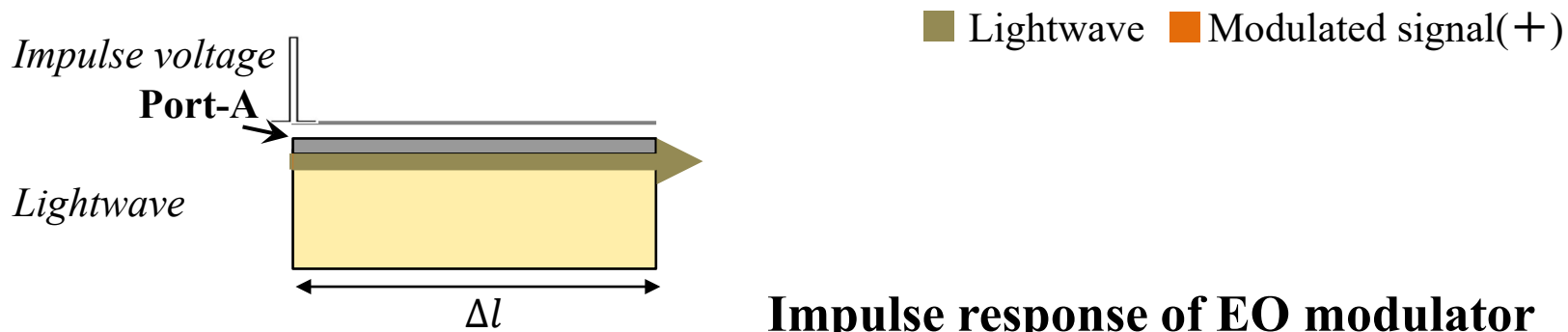
Impulse response for the dispersion compensation,  $h_{cmp}(t)$



# Impulse Response of Traveling-wave EO Modulator

## Conditions

- Velocity mismatching ( $v_g > v_m$ )



## Impulse response of EO modulator

Temporal window in the impulse response

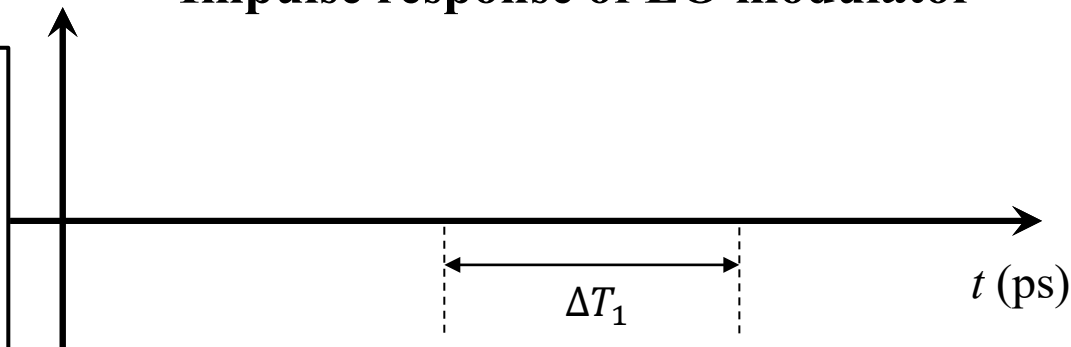
$$\Delta T_1 = \frac{\Delta l}{c} (n_m - n_g)$$

$n_m$  : Effective index of the modulation signal

$n_g$  : Group index of the lightwave

$\Delta l$  : Interaction length

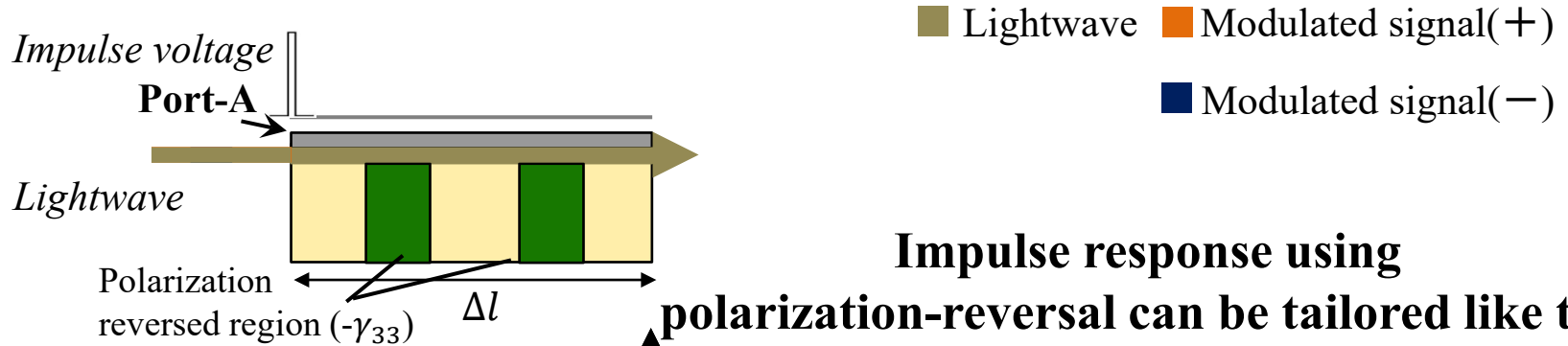
$c$  : Lightwave velocity in vacuum



# Impulse Response of Traveling-wave Modulator

## Conditions

- Velocity mismatching ( $v_g > v_m$ )
- Polarization-reversal ( $\gamma_{33} \Rightarrow -\gamma_{33}$ )



Temporal window in the impulse response

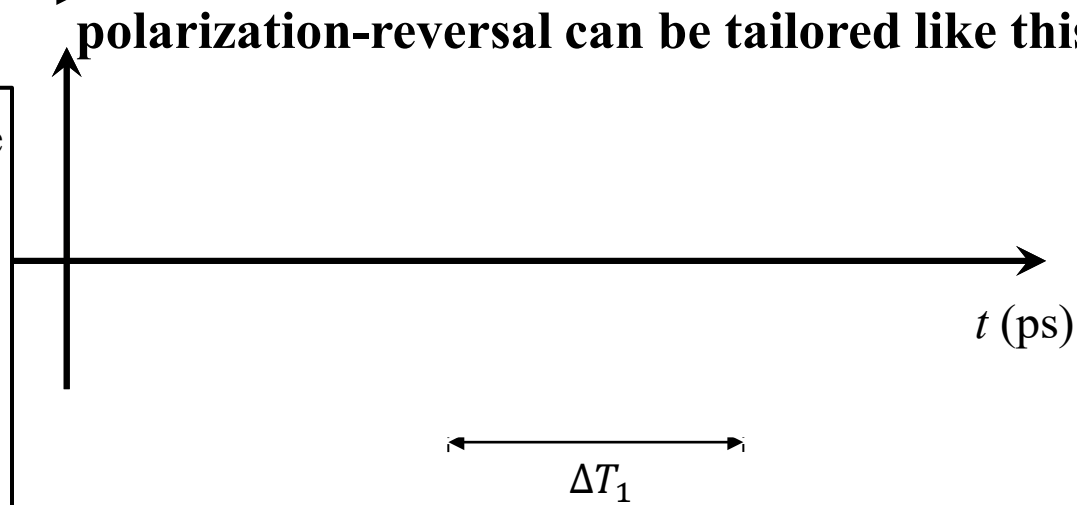
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$n_g$  : Group index of the lightwave

$\Delta l$  : Interaction length

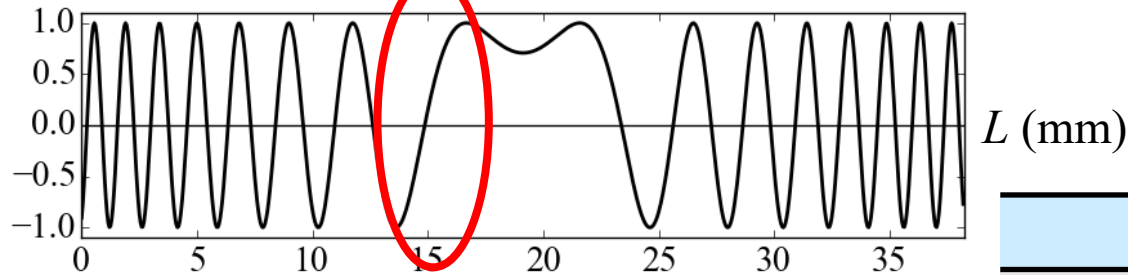
$c$  : Lightwave velocity in vacuum





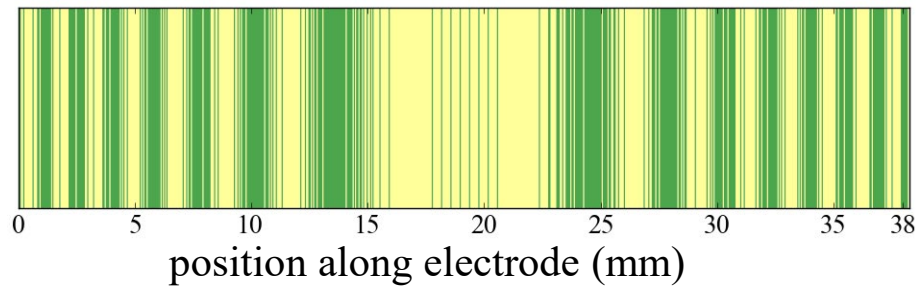
# Design of polarization reversal patterns

Re

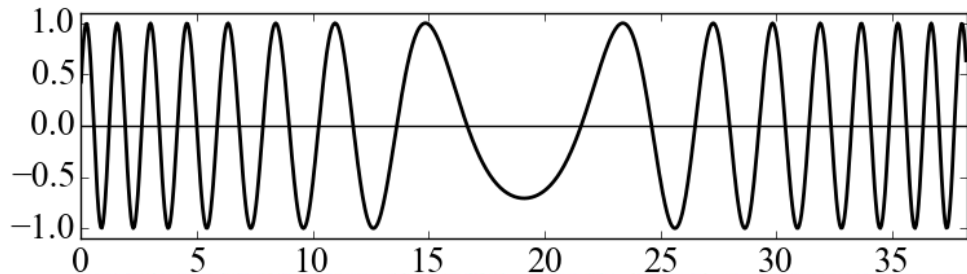


$L$  (mm)

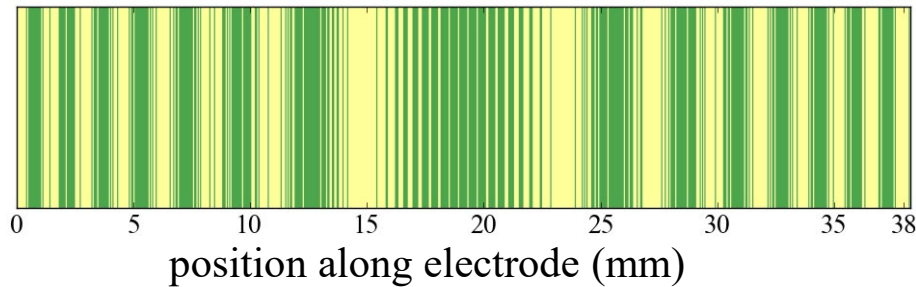
Reversal  
pattern



Im



Reversal  
pattern



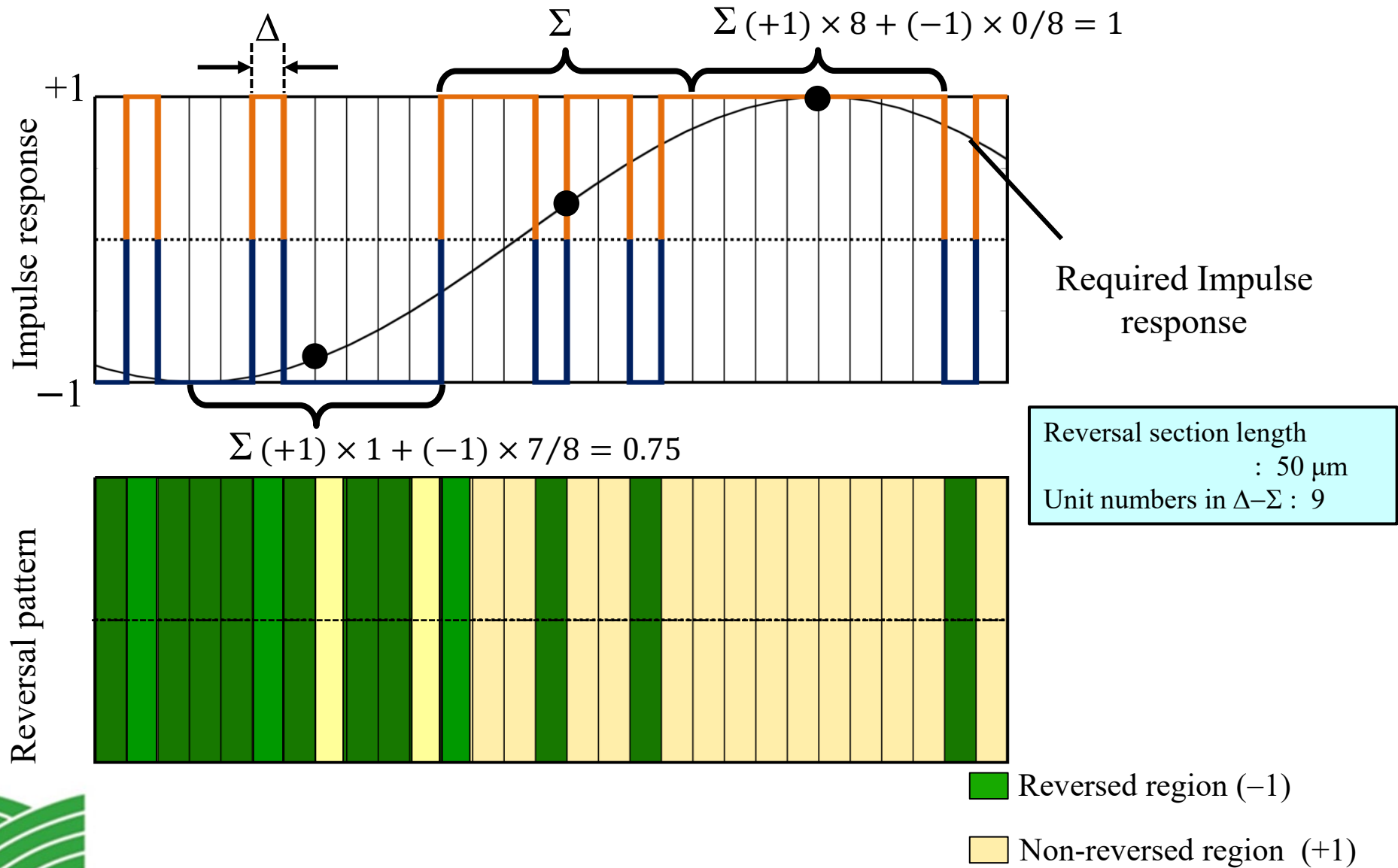
## Designed parameters

LW wavelength	1.55 $\mu\text{m}$
Fiber length	80 km
Symbol rate	40 GS/s
Dispersion	16 ps/nm $\cdot$ km
LW group index	2.193
Electrode length	38.25 mm
Reversal section length	50 $\mu\text{m}$
Unit numbers in $\Delta$ - $\Sigma$	9

■ Reversed region (-1)

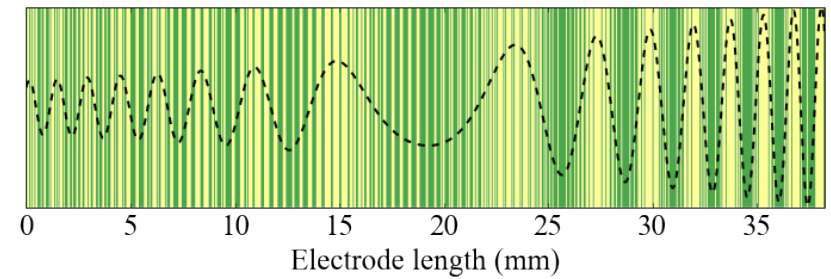
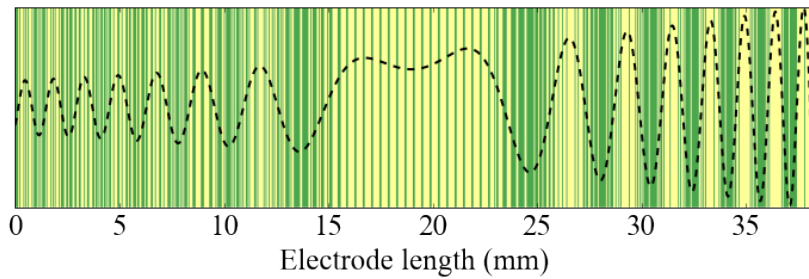
■ Non-reversed region (+1)

# Precise design of reversal patterns: $\Delta - \Sigma$ method



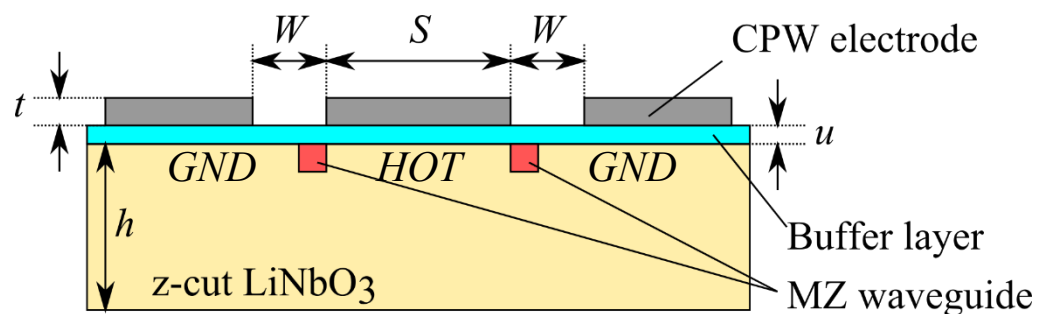
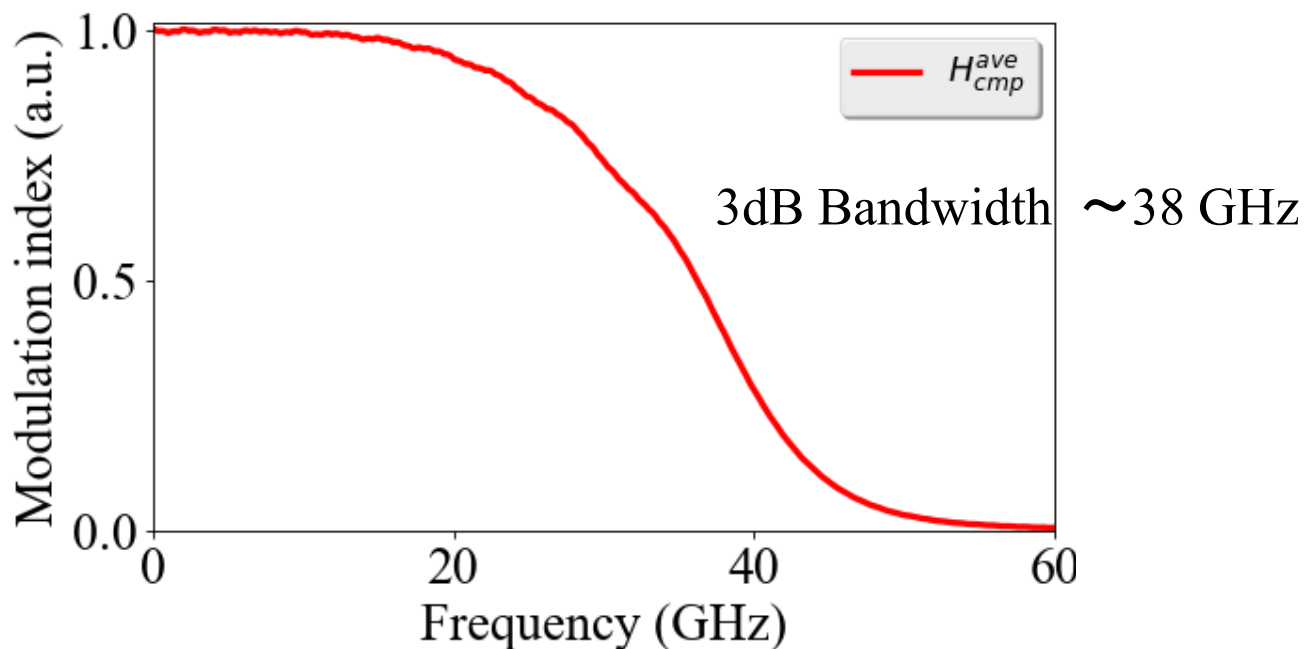
# Polarization-Reversed Patterns for Equalization

<i>Design Parameters</i>	
Optical wavelength	1.55 $\mu\text{m}$
Fiber length	80 km
Data transmission rate	40 Gb/s
Dispersion value, $D$	16 ps/nm $\cdot$ km
Group index of lightwave, $n_g$	2.193
Electrode length	38.25 mm
Minimum length of polarization-reversed region	50 $\mu\text{m}$
Number of quantization levels	9



New polarization-reversed patterns compensating for electrode loss effect for equalization

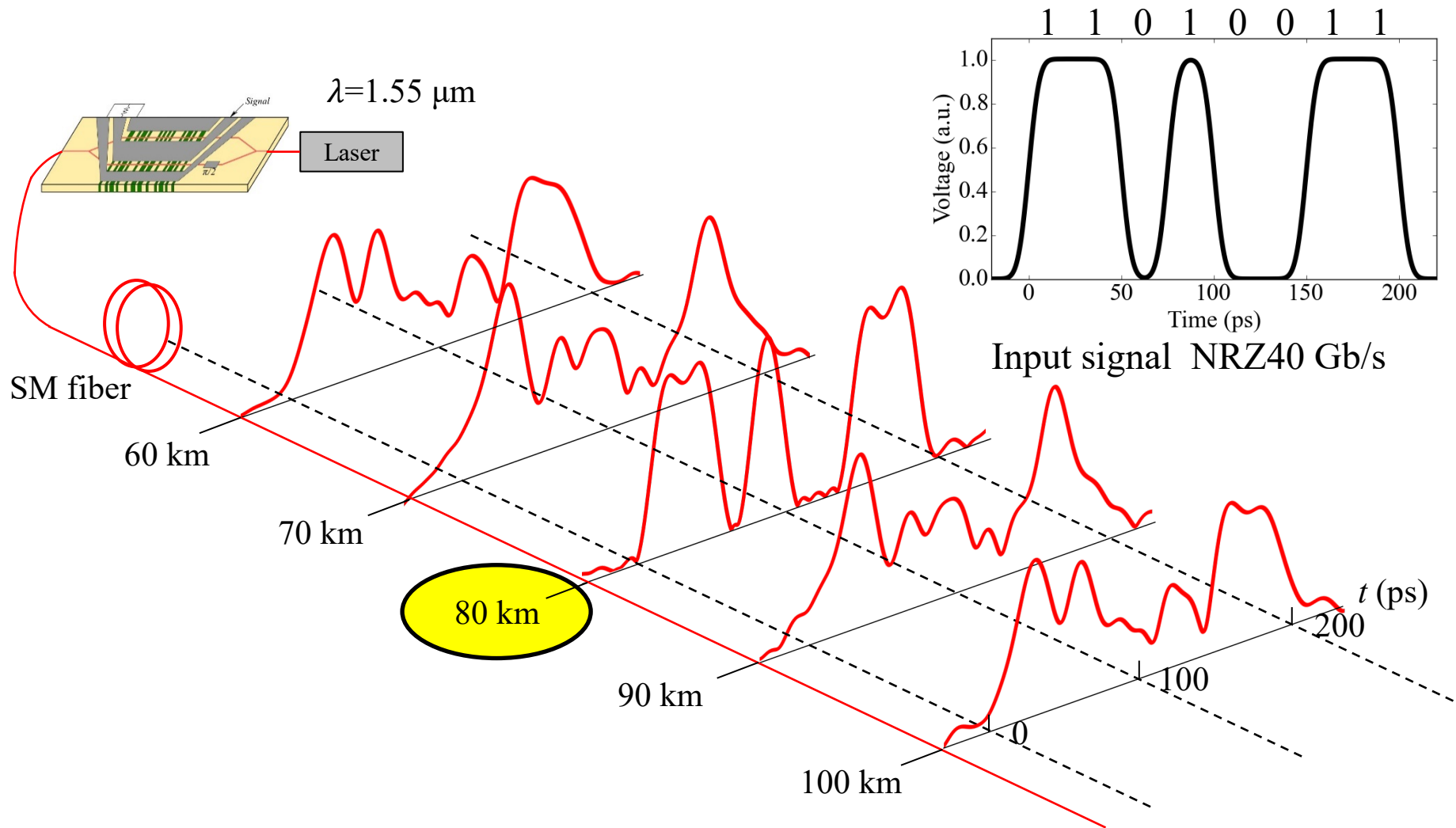
# Modulation Frequency Dependence



## Design parameters for CPW

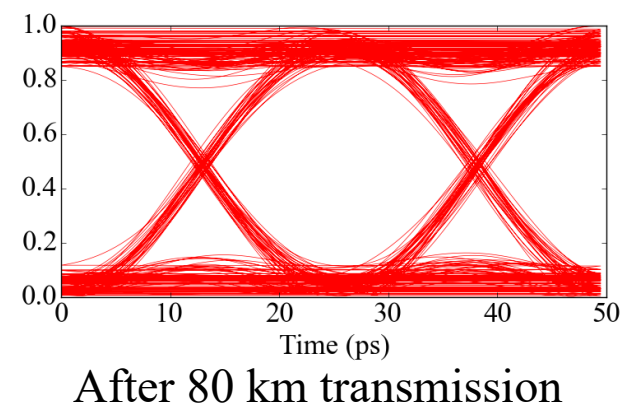
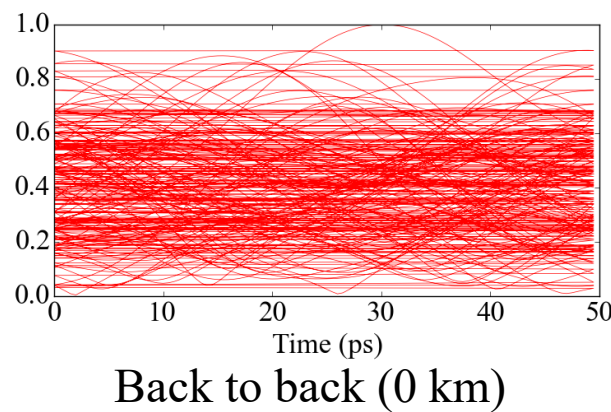
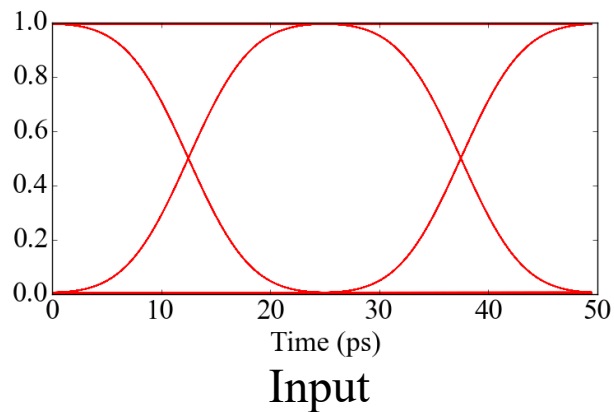
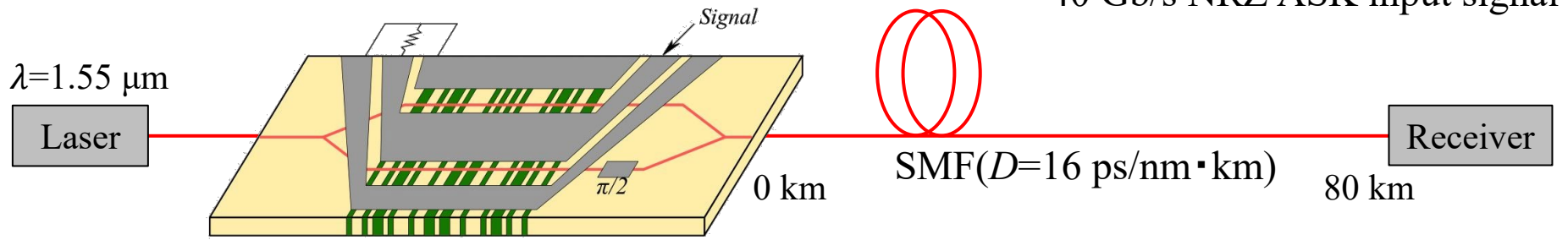
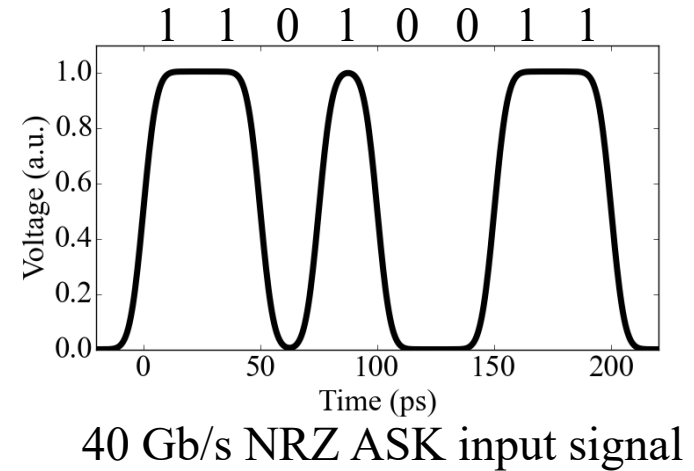
Hot electrode width, $S$	33 $\mu\text{m}$
Gap between electrodes, $W$	46.5 $\mu\text{m}$
Al thickness, $t$	3 $\mu\text{m}$
Buffer layer thickness, $u$	0.2 $\mu\text{m}$
Substrate thickness, $h$	250 $\mu\text{m}$

# Transmission Simulation

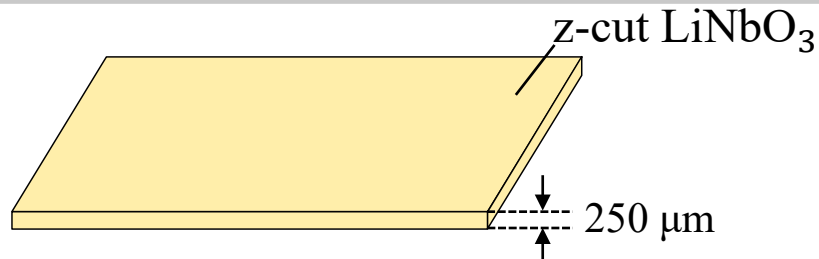


# Simulation

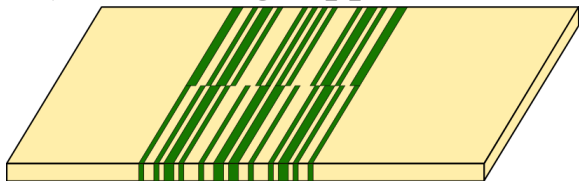
Evaluation of equalizing characteristics by using eye diagrams and BER



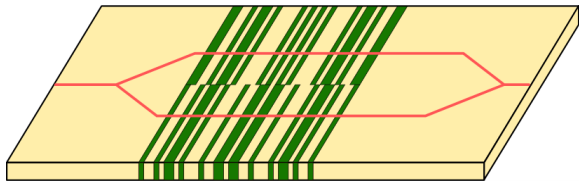
# Device fabrication



**1. Polarization-reversed structure  
(Pulse voltage applied method)**

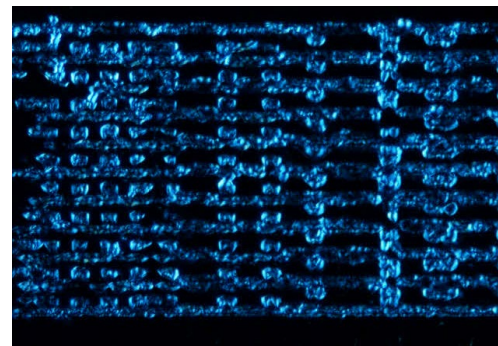
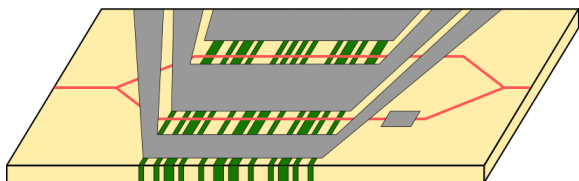


**2. Optical waveguide  
(Annealed proton exchange method)**

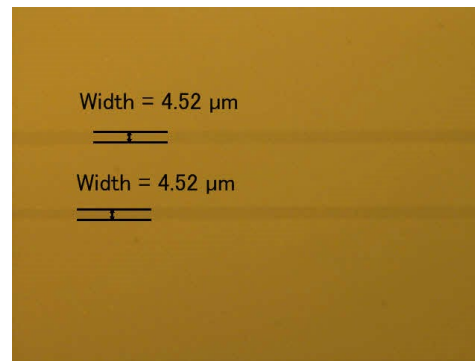


**3. Buffer layer ( $\text{SiO}_2$  sputtering)**

**4. Modulation electrode (Lift off)**



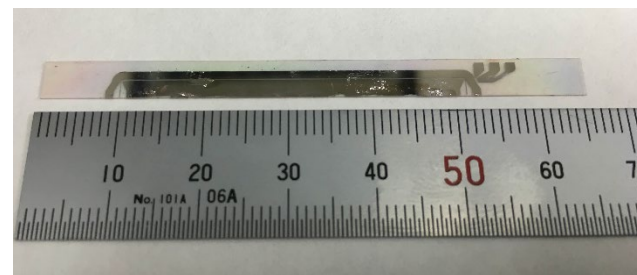
Polarization-reversed patterns



MZ waveguide



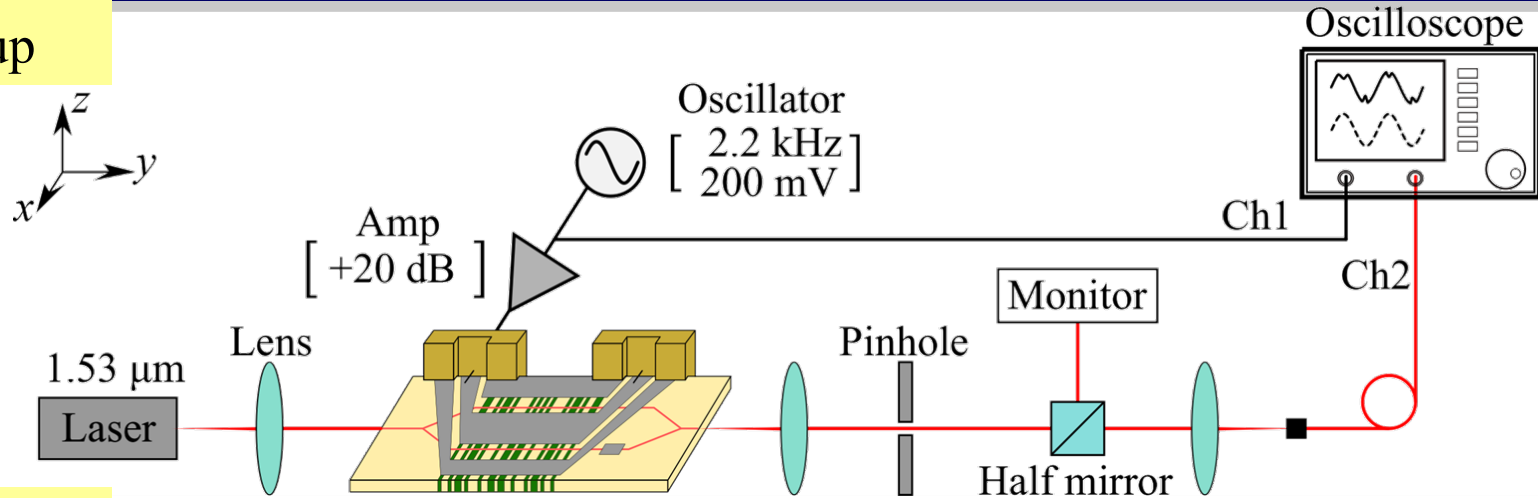
Modulation electrode



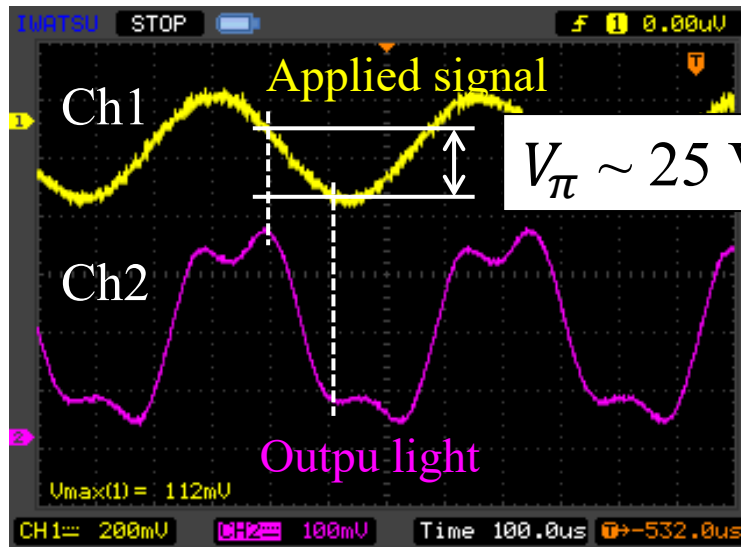
Fabricated device

# Experiment-1: low frequency operation

## Set-up



## Results

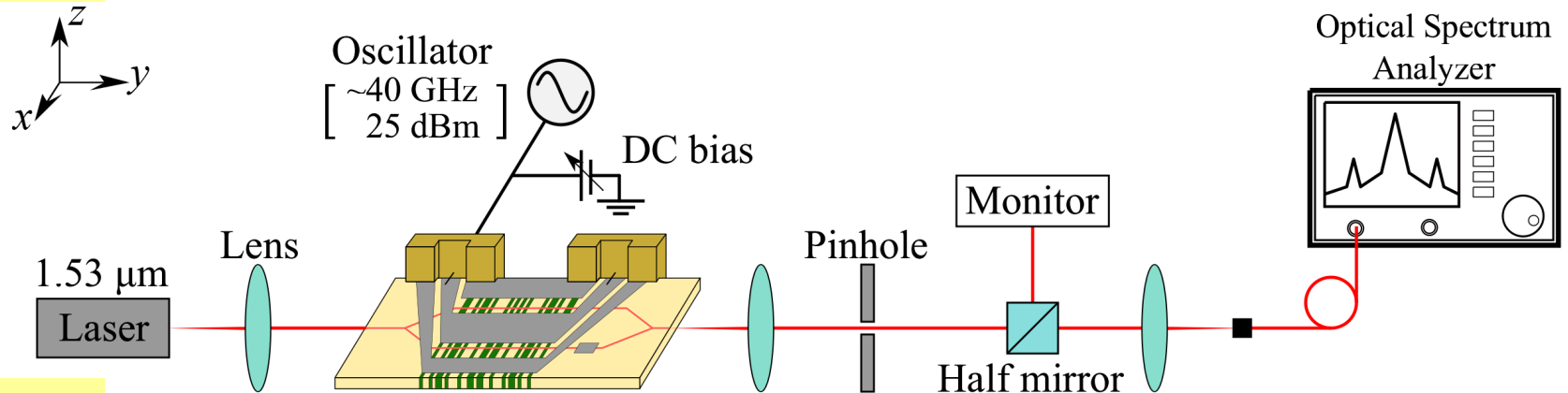


➔ DC voltage for  $\pi/2 \sim 16 \text{ V}$

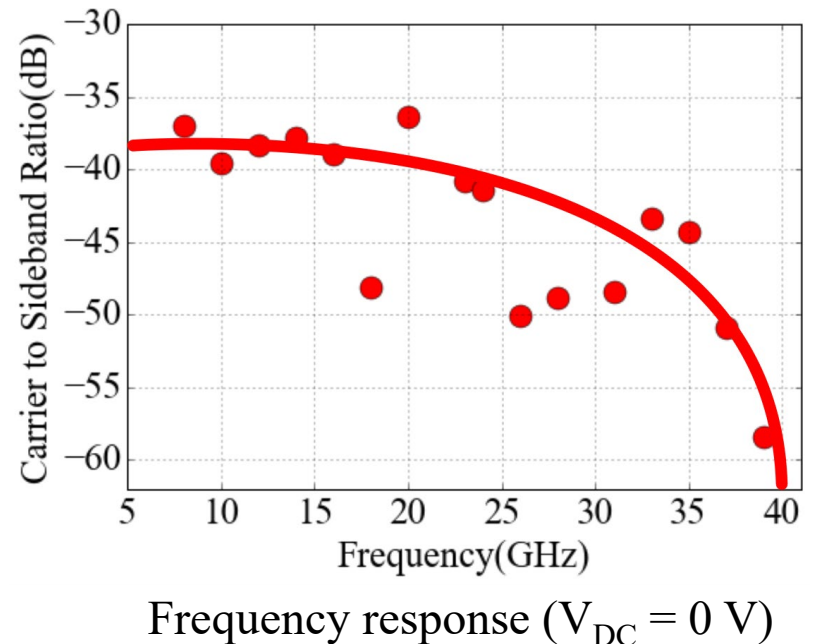
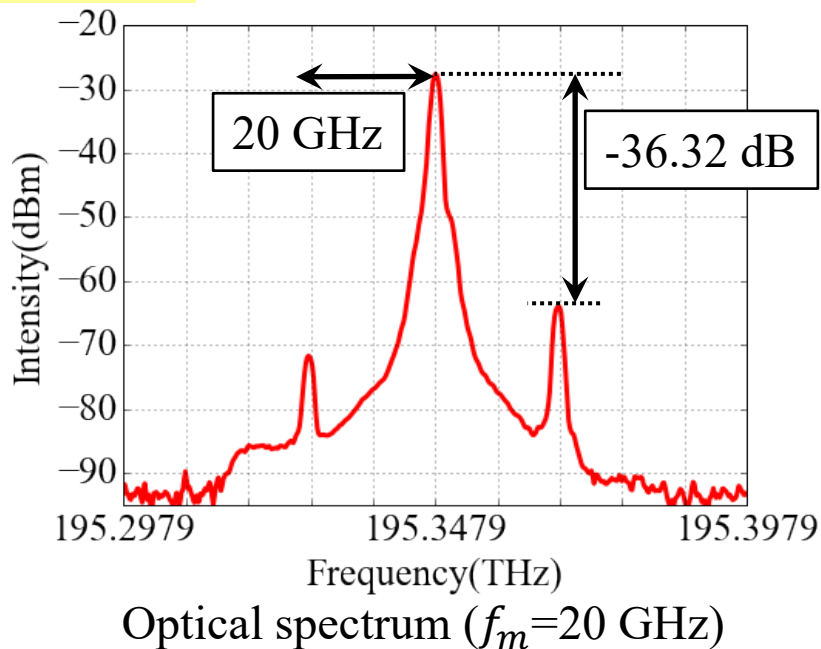


# Experiment-2: Single-tone operation

## Set-up

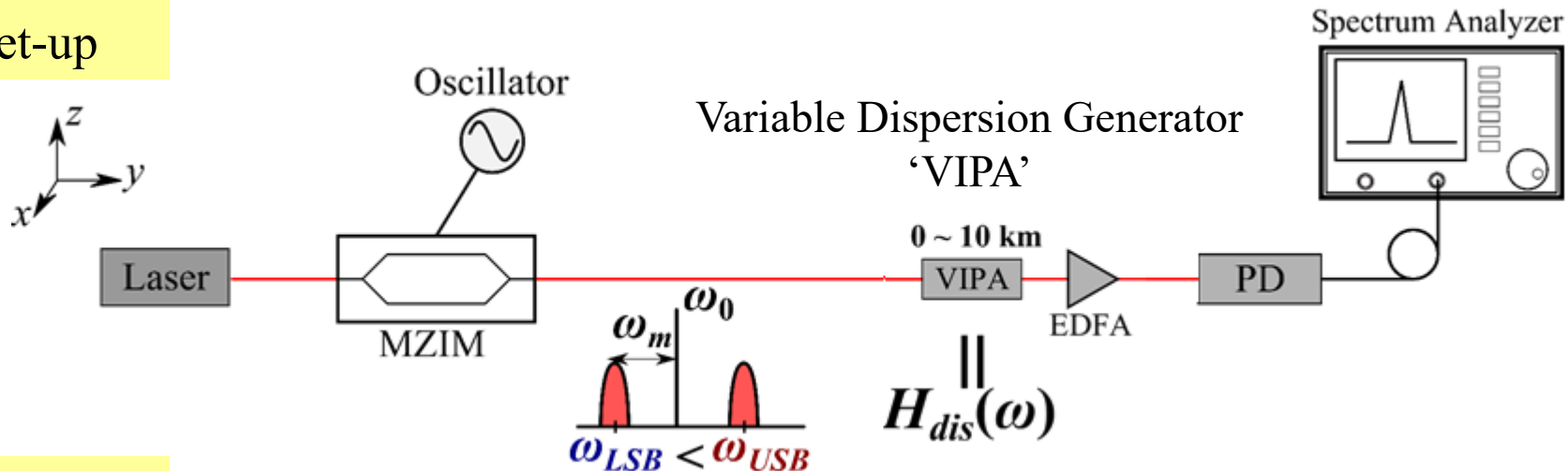


## Results

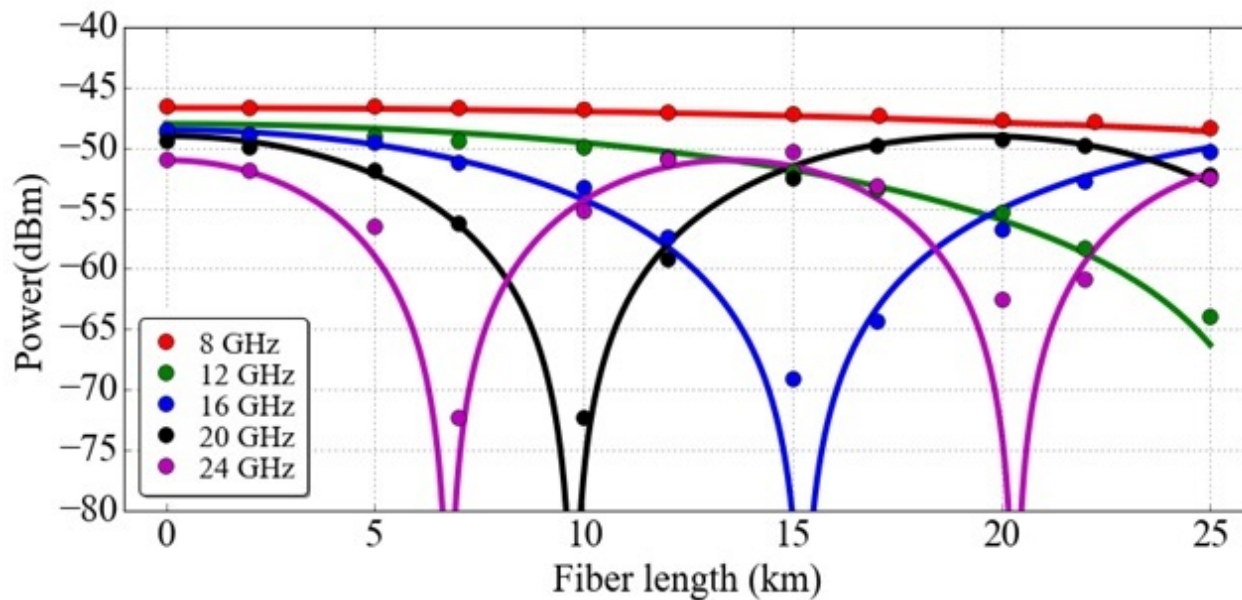


# Experiment: Standard MZM case

## Set-up

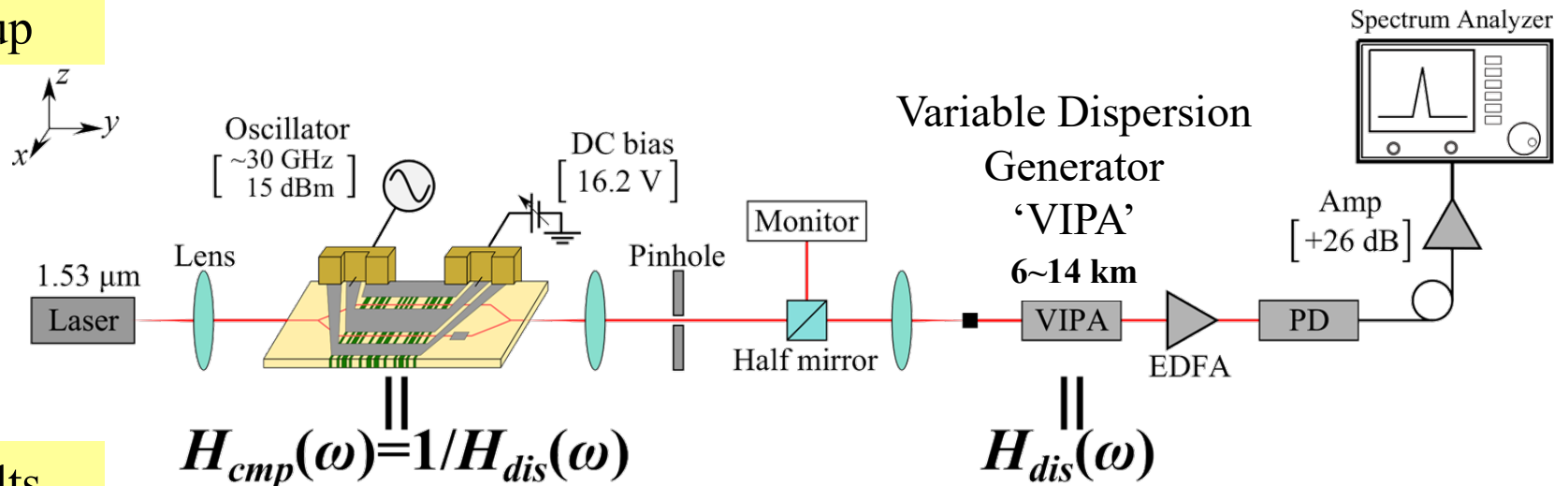


## Results

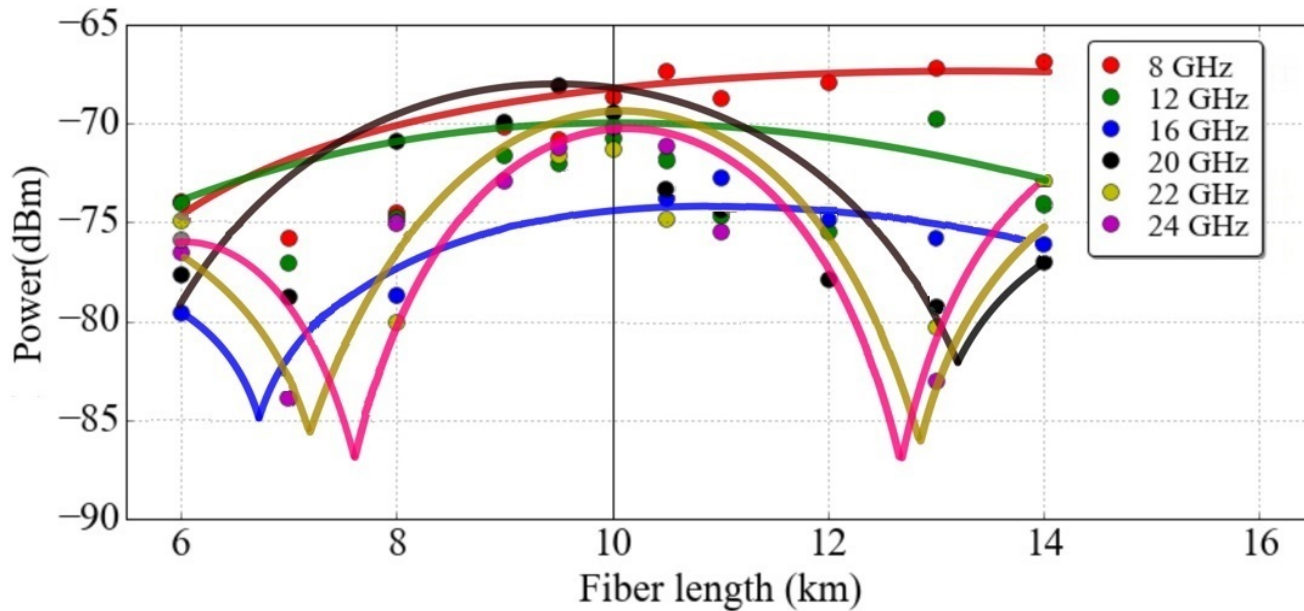


# Experiment: Pre-equalizing EOM case

## Set-up



## Results



# Conclusions

## Pre-Equalizing EO Modulator Utilizing Polarization-Reversed Structures

- ✓ **Pre-equalizing utilizing velocity-mismatch & polarization-reversed structures**
  - New scheme for counter-propagation between lightwave and electrical signal.
    - ⇒ Fiber length for the dispersion compensation (~80 km)
  - Able to compensate for electrode loss effect
  
- ✓ **Simulation**
  - Evaluation of equalizing characteristics by EYE diagrams & BER
    - ⇒ Good agreement with the designed characteristics
  
- ✓ **Device fabrication**
  - Optical extinction ratio ~ 30 dB
  - Transfer function measurement
  
- ✓ **Next Step**
  - Design for THz wireless applications
  - Tuning of fiber length for compensation
  - Assembling & demonstration