Beyond 5G/6G 無線へ向けた
信号変換・処理技術

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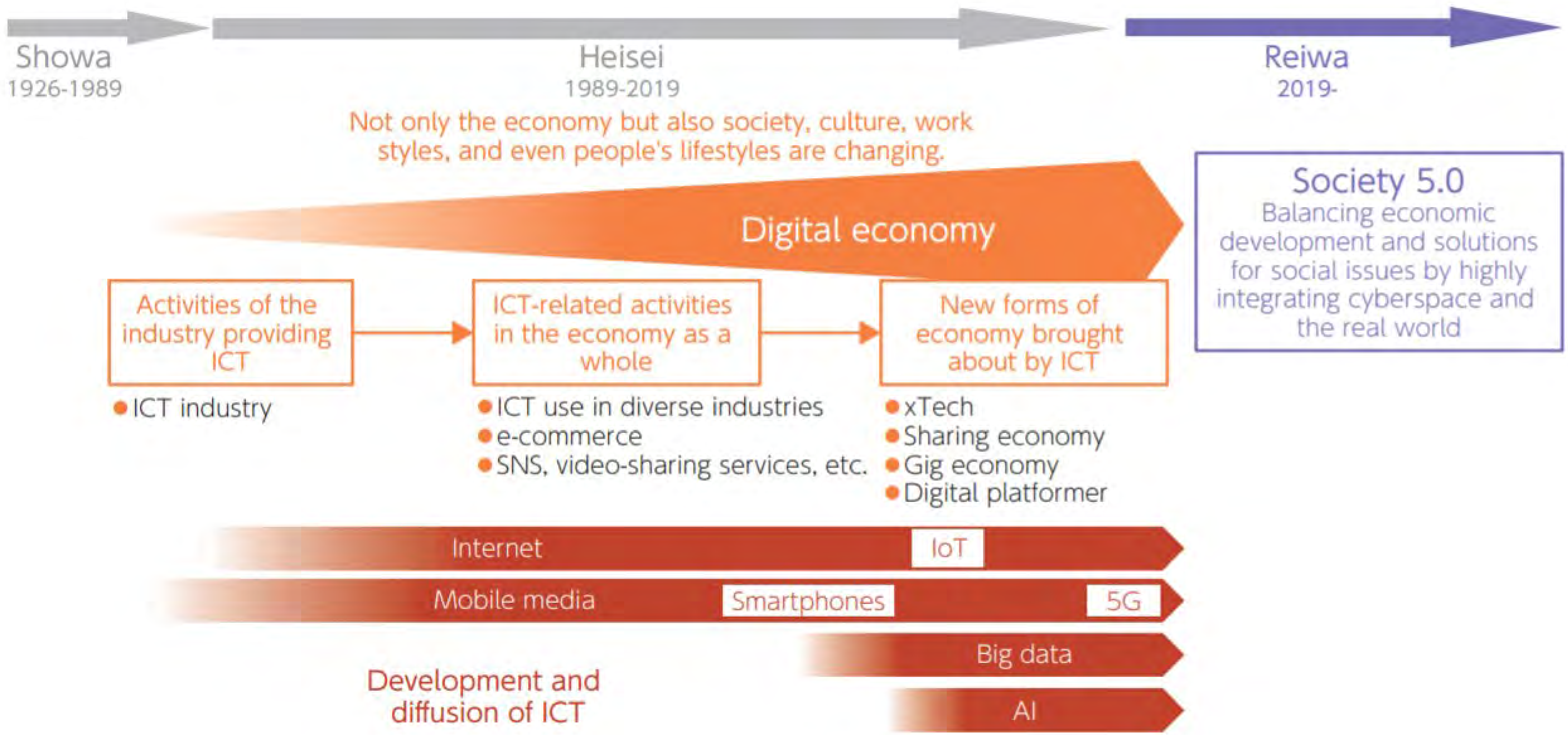
Outline

1. Introduction
   - ✓5G/6G Wireless & Electronic Device
   - ✓Importance of Microwave Photonics for 5G/6G
2. Antenna-Coupled-Electrode EO Modulator
   - ✓Basic structure & operational principle
   - ✓Analysis & design for 5G-band
   - ✓Experiments
     - ✓Data Transfer (PRBS/HD video)
     - ✓Antenna measurement
     - ✓Signal convolution using dispersion effect

3. ACE-EOM for W-band.
   - ✓Analysis & design
   - ✓Experiments
     - ✓IF conversion by photonic technique
4. Conclusion

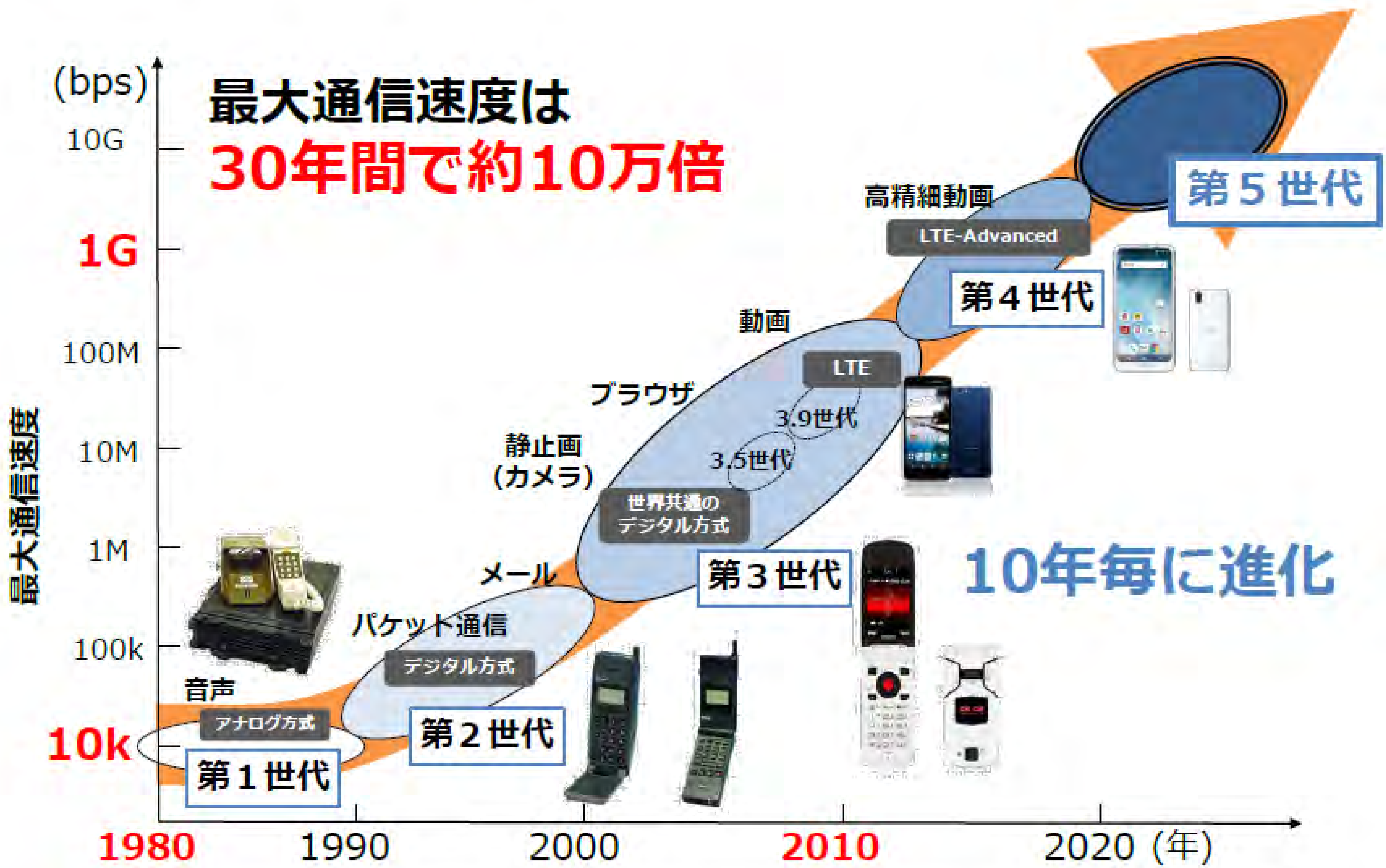
ICT の進化 - 昭和・平成・令和 -



ICT産業・技術は継続的に進化する

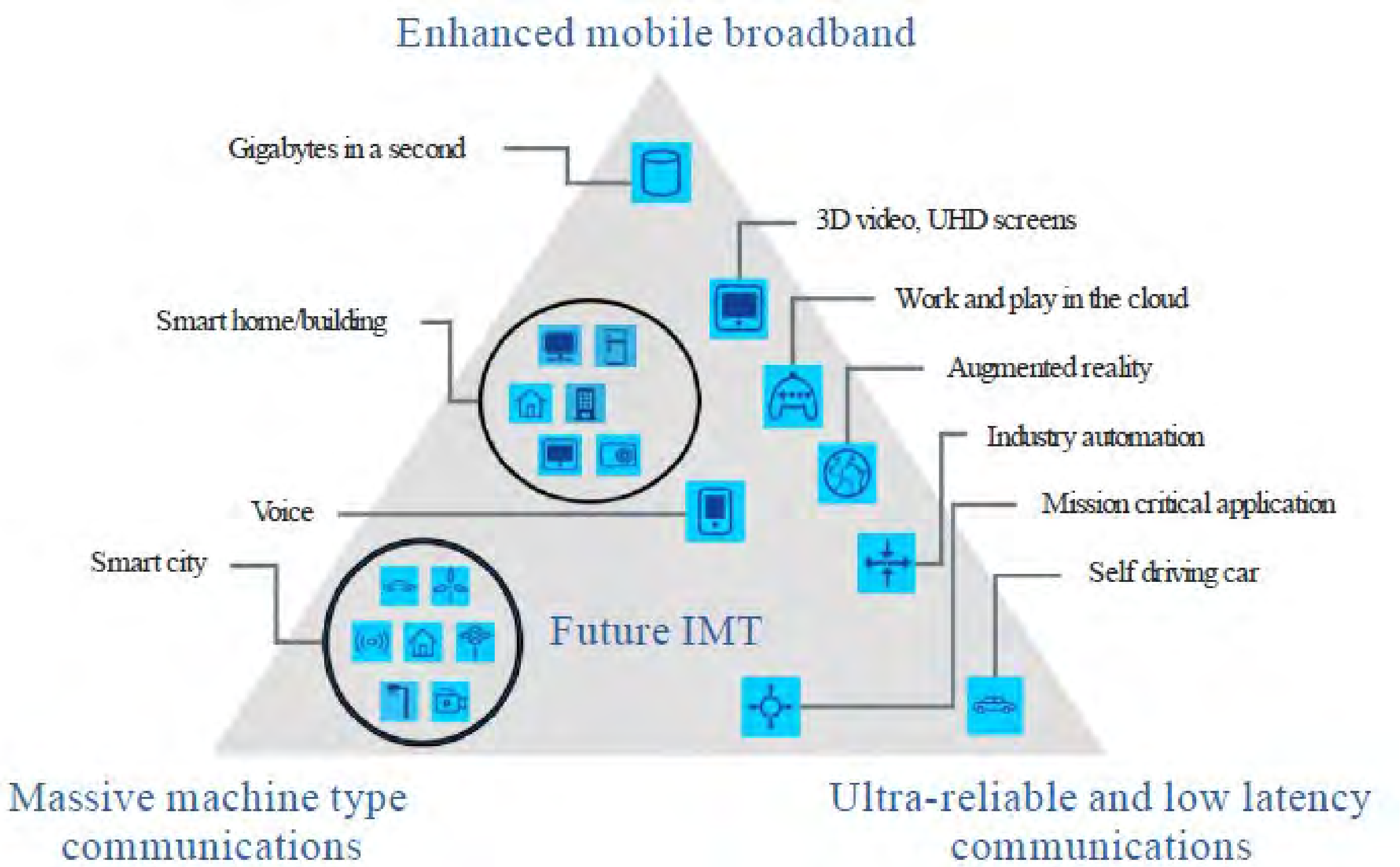
		1970年代	1980年代	1990年代	2000年代	2010年代	2020年代	2030年代
外部環境	経済環境			ニューエコノミー	途上国の成長	エコシステム		
	産業構造	垂直統合			水平分業（グローバルフォーカス）			
ICT産業・技術			GANG OF FOUR (Eric Schmidt 2011)	MS/Intel/Cisco/Dell	Google/Apple/FB/Amazon			
①コンテンツ・アプリ・サービス				EC	SNS	ビッグデータ OTT	超臨場感伝送	
②ICTサービス				検索エンジン	クラウド	IoT/機械学習	深層学習	シンギュラリティ
③インフラ	有線通信	音声通信		インターネット	ブロードバンド	SDN/NFV	NW運用・管理統合・自動化	
	無線通信			2G	3G	4G(LTE)	5G コグニティブ無線	6G 超高周波通信
				デジタル化／IP化／BB化／モバイル化				
	放送	アナログ放送			デジタル放送(HD)		4K・8K	
④端末	電話機	固定電話機			フィーチャフォン	スマートフォン	ウェアラブルフォン	ウェアラブル
	コンピュータ	メインフレーム	ミニコン/WS	デスクトップPC	ノートPC	タブレット	ペーパーPC	IoTデバイス
		ダウンサイジング		パーソナル化／モバイル化／IoT化			量子コンピュータ	
		ハード／ソフト分離						
		OS		WEBブラウザ			UX/音声認識	BMI
	テレビ	CRTテレビ			液晶テレビ		有機ELテレビ	壁紙／立体TV
⑤デバイス	FPD	ブラウン管			TFT液晶		OLED	Embedded D
					プリンタブル化			
	集積回路	バイポーラトランジスタ		CMOS (MOSFET)			Beyond CMOS	
		ムーアの法則（3年で4倍高集積化,トランジスタ当りコストは年率35%減）						
		高集積化／低消費電力化						
⑥材料	半導体	シリコン						

移動体通信システムの進化



5G Mobile Network

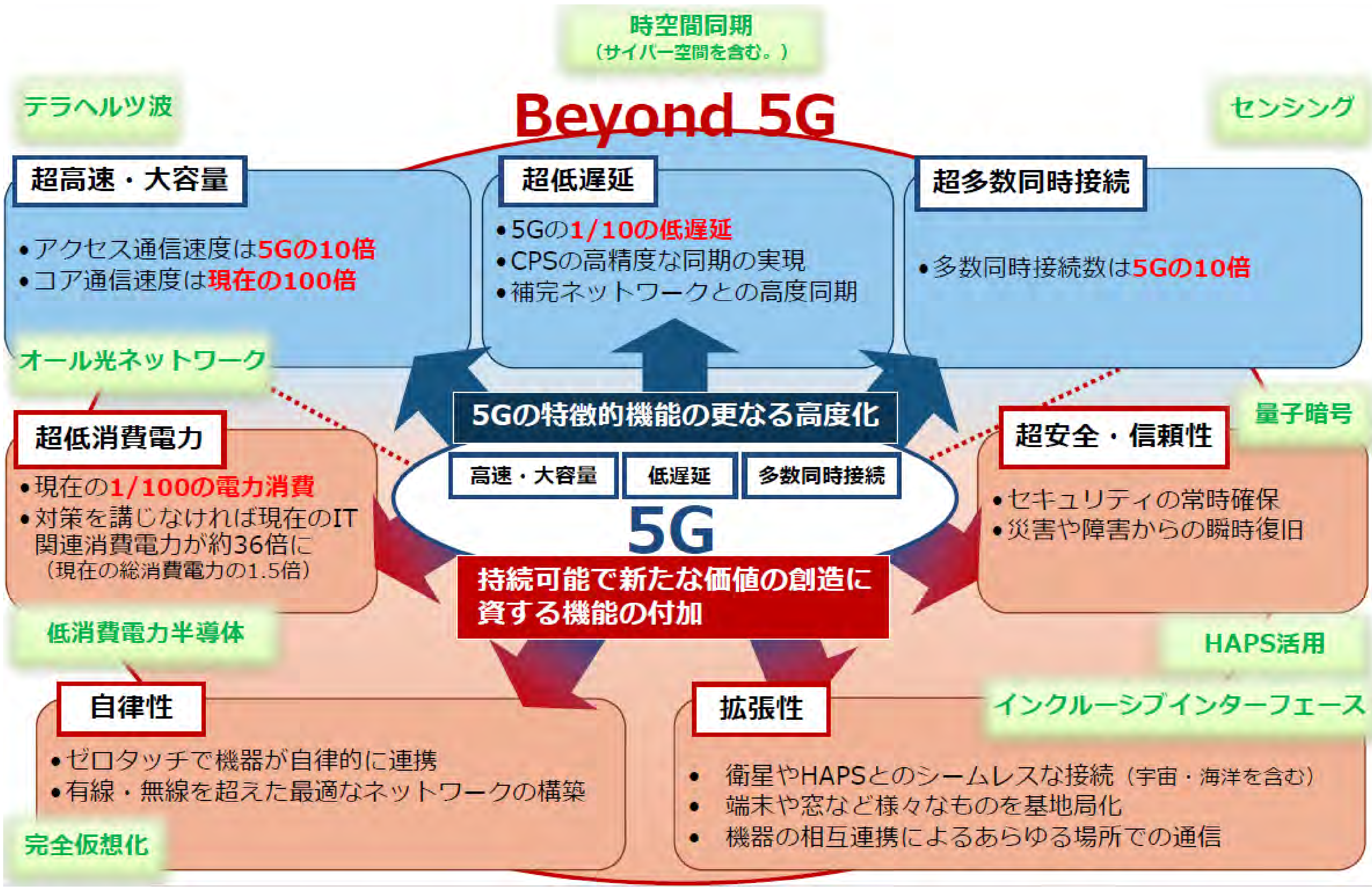
✓Peak Speed: > 10 Gb/s /ch



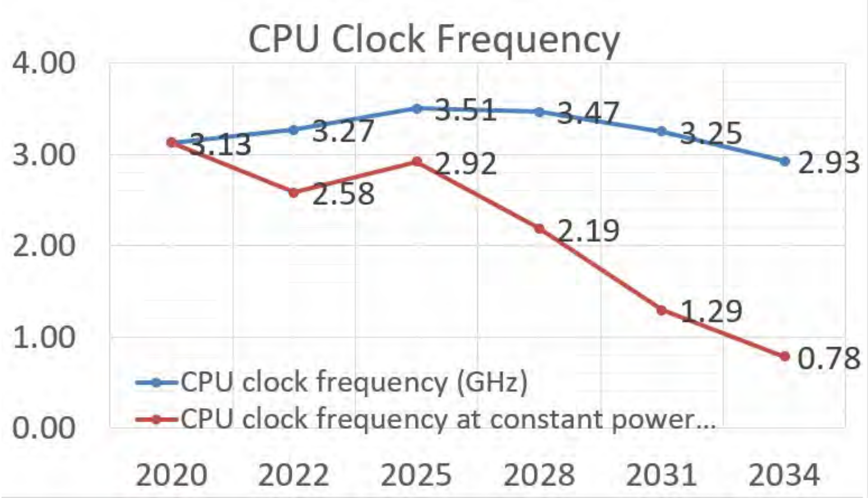
✓Massive connectivity: ~10 million/km^2

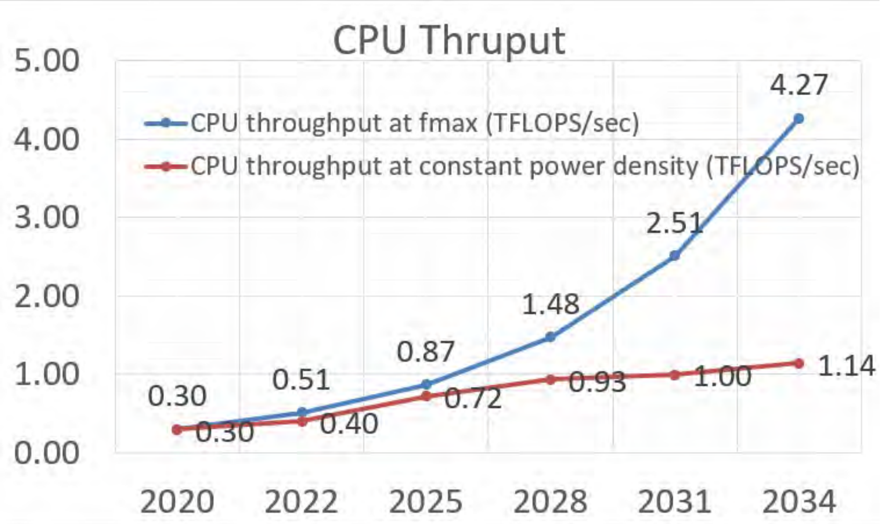
✓Latency: ~ 1ms

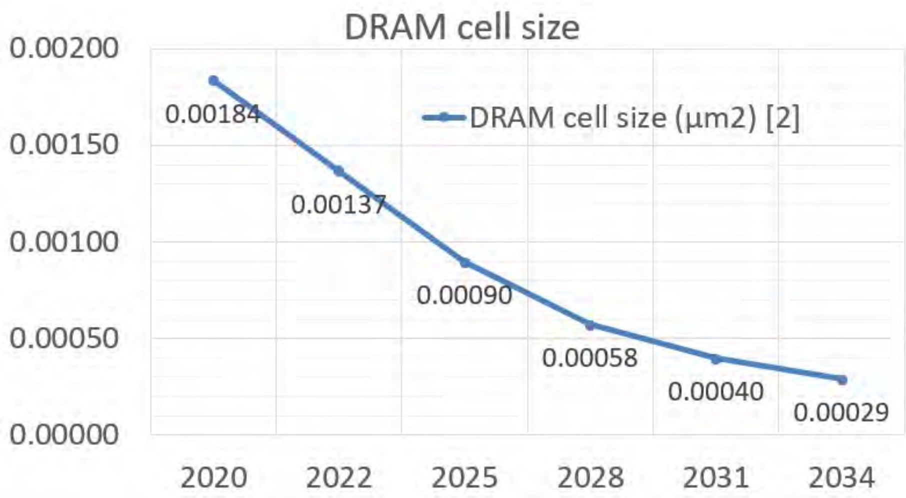
From 5G to Beyond 5G/6G



高速電子デバイスの動向







IEEE THE INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS: 2020

Challenge in MWP Technology for 5G

✓ 4G

f_c ～1.5 GHz ⇔ λ～20 cm

Loss in coax cable @ 1.5 GHz

5D2V α～ -0.4 dB/m

✓ 5G

f_c ～30 GHz ⇔ λ～1 cm

Loss in coax cable @ 30 GHz

CM06 α～ -2.5 dB/m

✓ New EOM/EO sensor

Antenna-Coupled Electrode EO modulator

f_r ～30 GHz ⇒ field enhance ～8000

f_r ～80 GHz, 90 GHz

Optical phase modulator（no-opt bias）

Optical IF conversion technique

✓ A/D Conversion Technique

Sampling frequency

f_s ～32 Gsa/s (ADP7000)

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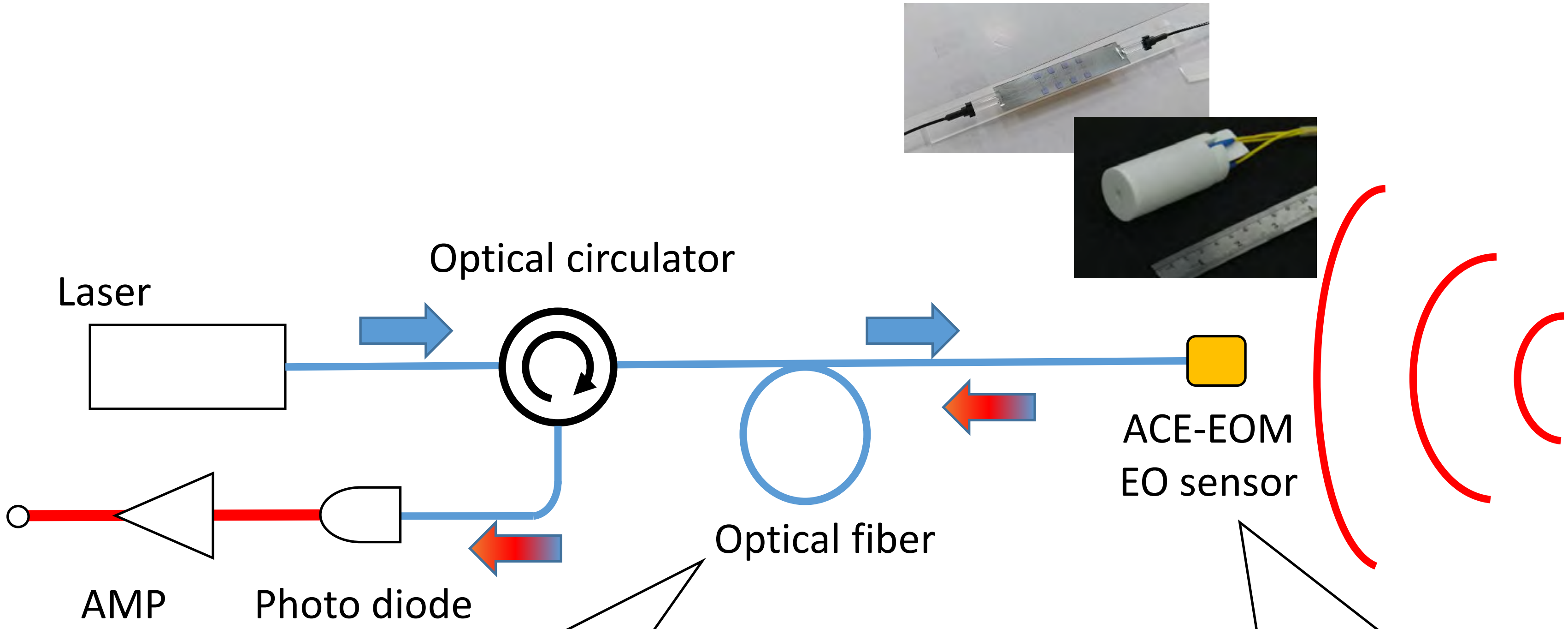
Electromagnetic Field Measurement Using ACE-EOM



✓ Silica optical fiber

Low induction & Low immunity
Ultra-low loss $\alpha \sim$ -0.2 dB/km(1.55μm)
Ultra-wideband $\Delta f > 1$ THz
Dispersion D = 17 ps/nm･km
⇒ Signal processing

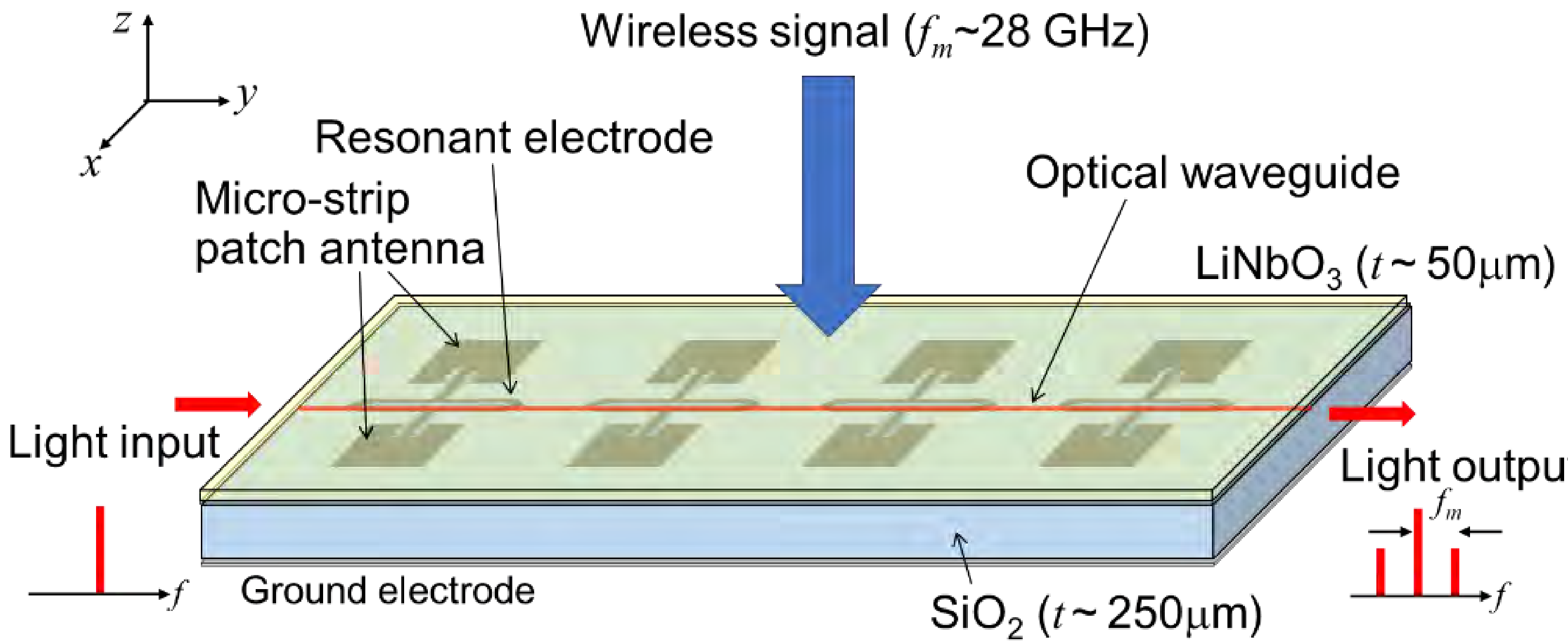
✓ ACE-EOM/EO sensor

Low induction (low immunity), Good linearity
Compact & Light weight ~ cm
Wideband DC ～ THz
High efficiency by antenna-coupled electrode
Advanced function & Signal processing
Stability（Optical PM、No optical bias）

2. Antenna-Coupled-Electrode EO Modulator

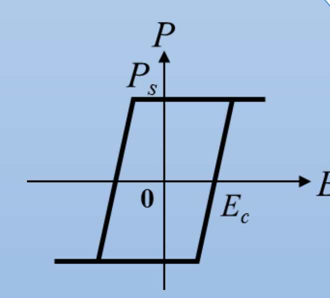
- ✓ Basic Structure & Operational principle
- ✓ Analysis & Design for 5G-band
- ✓ Experiments
  - ✓ Data Transfer (~ 2.5 Gb/s PRBS Signal, HD Video Stream)
  - ✓ 5G Antenna Measurement
  - ✓ Signal Convolution

Antenna-Coupled-Electrode Electro-Optic Modulators



Advantage

- ○ Direct MW/MMW => LW conversion
- ○ No external power supply
- ○ Stable operation (optical PM modulation)
- ○ No re-emission of MW/MMW signals
- ○ Advanced functions (Directivity control, SSB mod. by Pol.-reversal)



EO: $\boldsymbol{r_{ij}} \Leftrightarrow -\boldsymbol{r_{ij}}$

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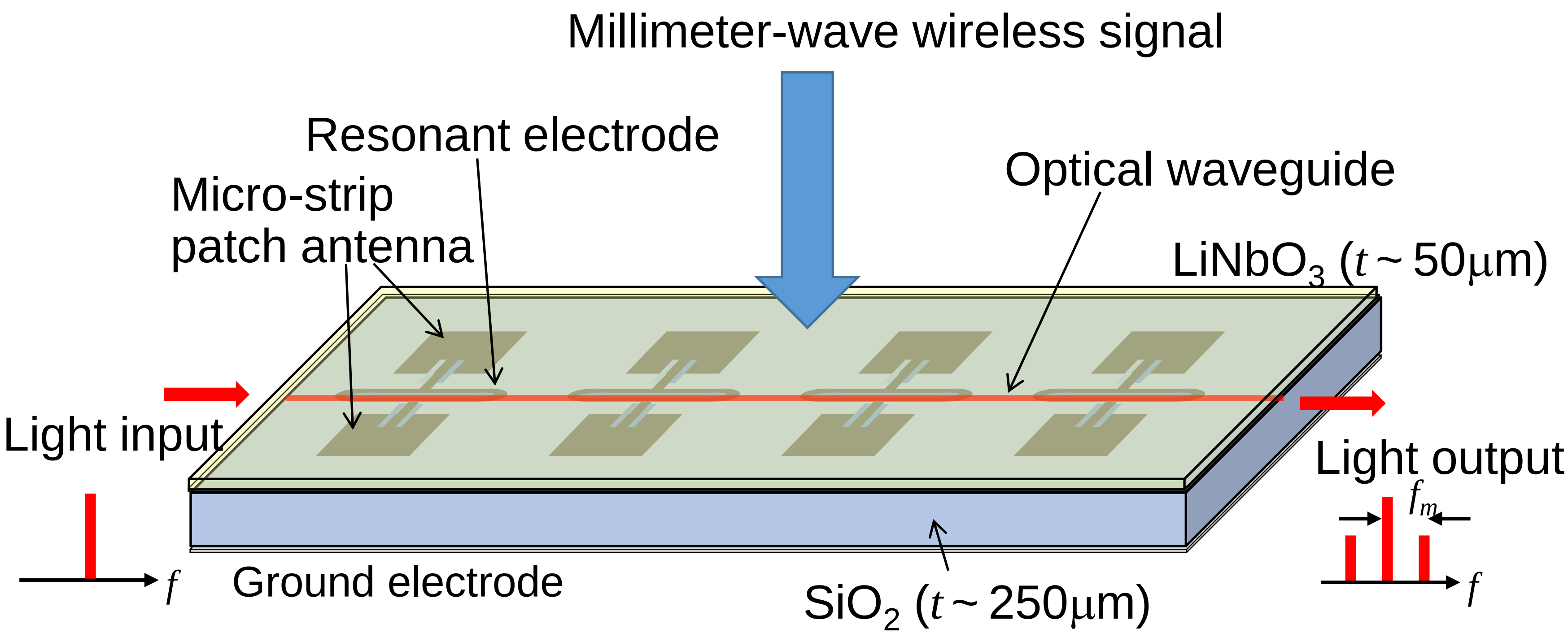
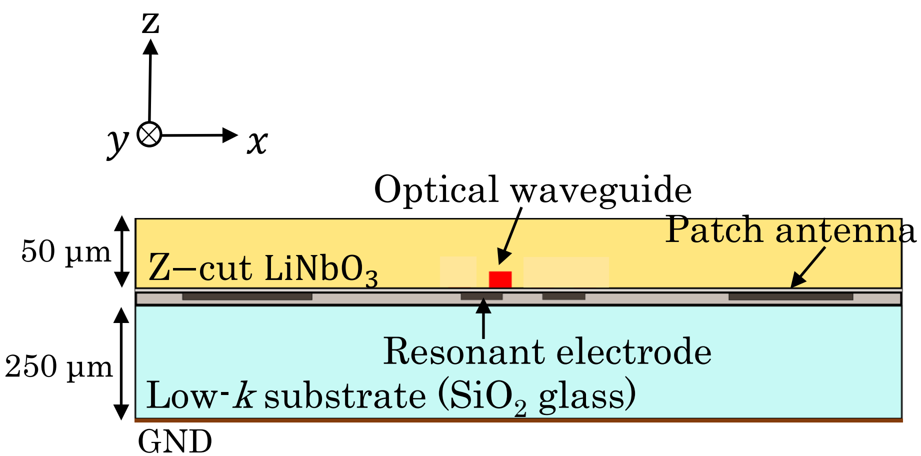
Antenna-Coupled-Electrode Electro-Optic Modulators

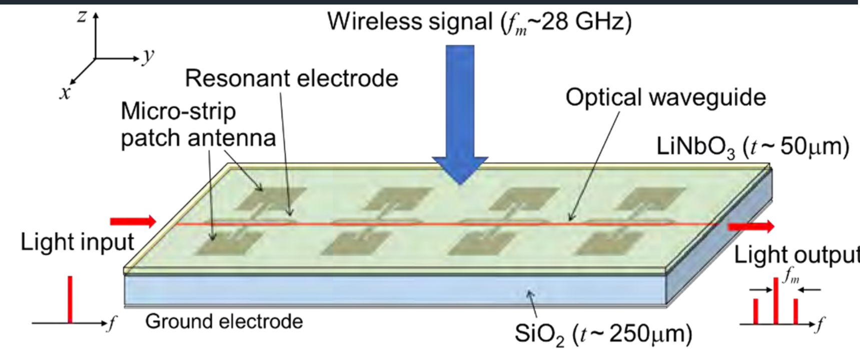


Key point

- ☆ Stacked substrate structure
- ☆ Critical coupling between two-antenna & electrode
  - ✓ Field enhancement of ~8,000 times
  - ✓ Elimination of unwanted substrate mode

Stacked Substrate Structure

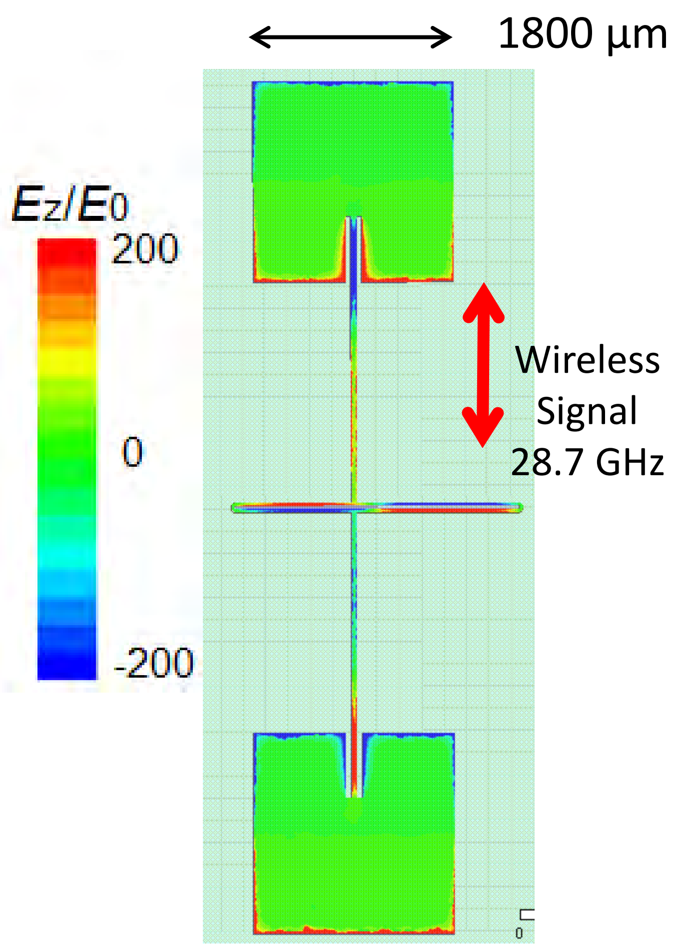




$$\varepsilon_{\mathrm{reff}} = \frac{t_{\mathrm{SiO_2}} + t_{\mathrm{LN}}}{\frac{t_{\mathrm{SiO_2}}}{\varepsilon_{\mathrm{rSiO_2}}} + \frac{t_{\mathrm{LN}}}{\varepsilon_{\mathrm{rLN}}}}$$

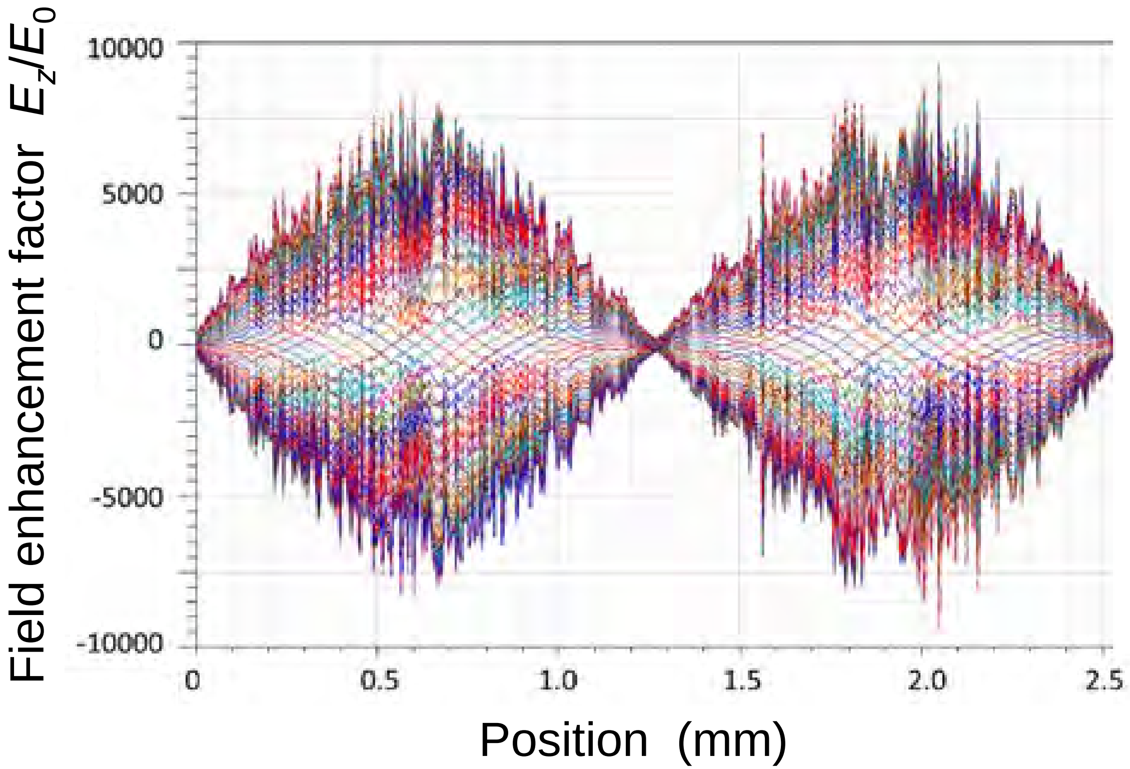
	ε_r	$\tan\delta$	thickness
$LiNbO_3$	(43, 43, 28)	~0.001	50 µm
SiO_2 glass	4.0	0.0007	250 µm
Fluorine-based resin	2.28	0.0008	100/250 µm

Analysis of Antenna-Coupled Electrode for 5G



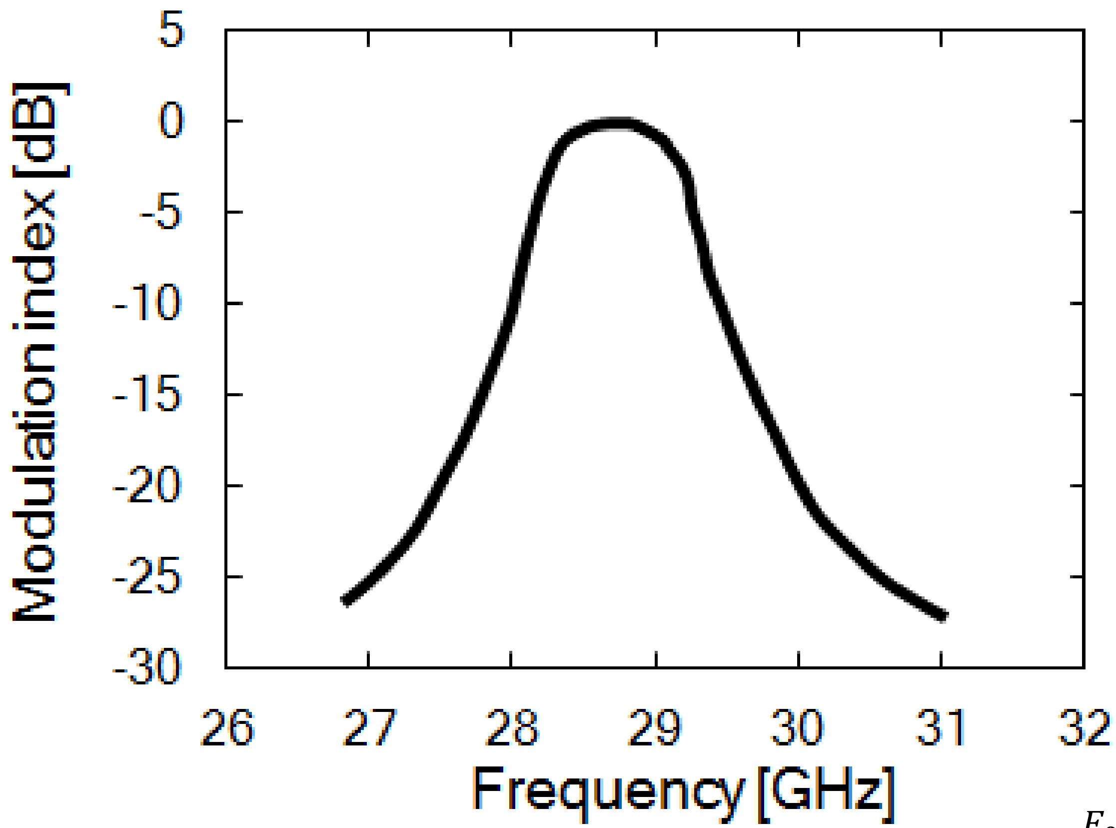
Surface electric field distribution
under 28.7 GHz plane-wave irradiation

Enhanced 28.7 GHz field for optical modulation

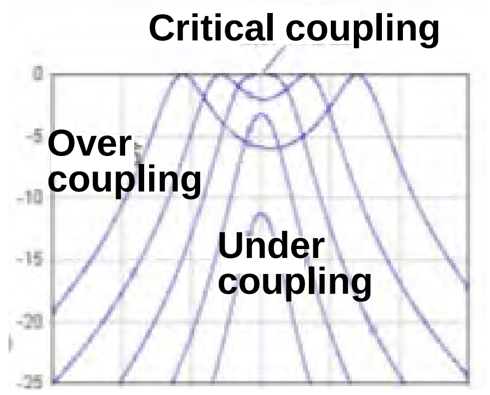


Tuning of f_m, Z_{in} & Q-params

Calculated Frequency Response



Critical coupling-like characteristics



$$D(\theta) = \frac{\pi r_{33} n_e^3}{\lambda} E_0 \Gamma \int_0^{L_e} \underbrace{\sin(n_m k_m y)}_{\text{Spatial oscillation}} \underbrace{\cos(n_g k_m y + \varphi)}_{\text{Temporal oscillation}} dy$$

E_0 : Amplitude of MMW electric field

n_m : MMW signal effective index

k_m : MW signal wave number

λ : Light wavelength

r_{33} : EO coefficient

Γ : Overlapping integral

n_g : Light group index

$\emptyset = n_g k_m t$: Initial phase

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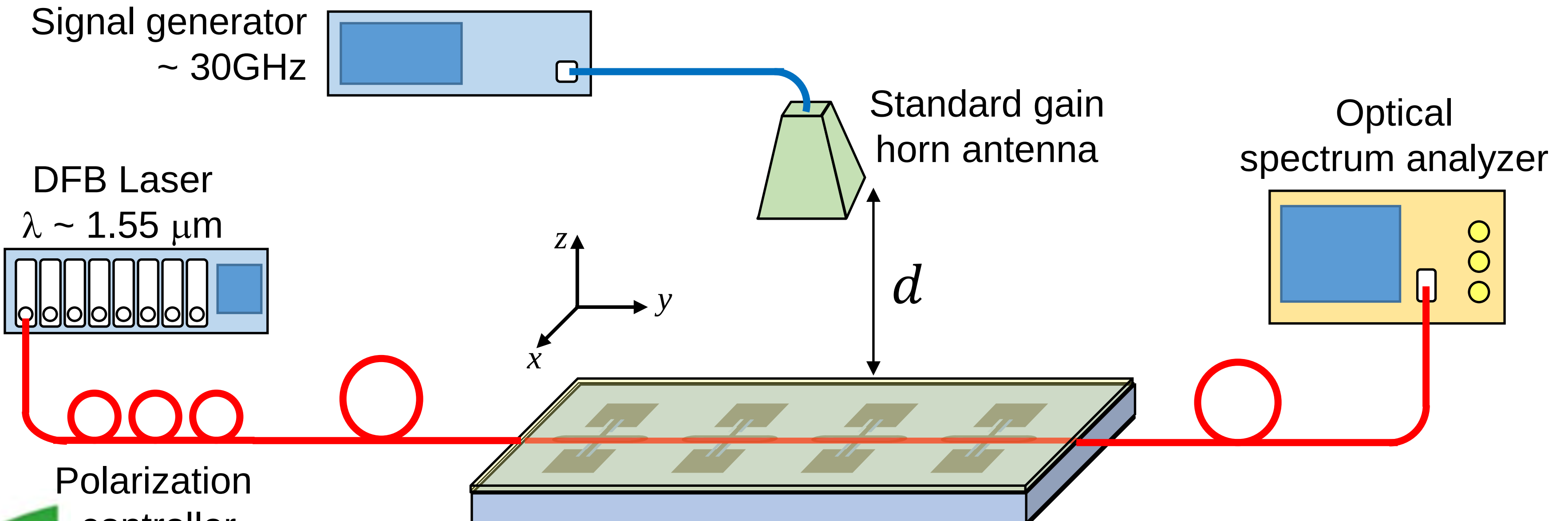
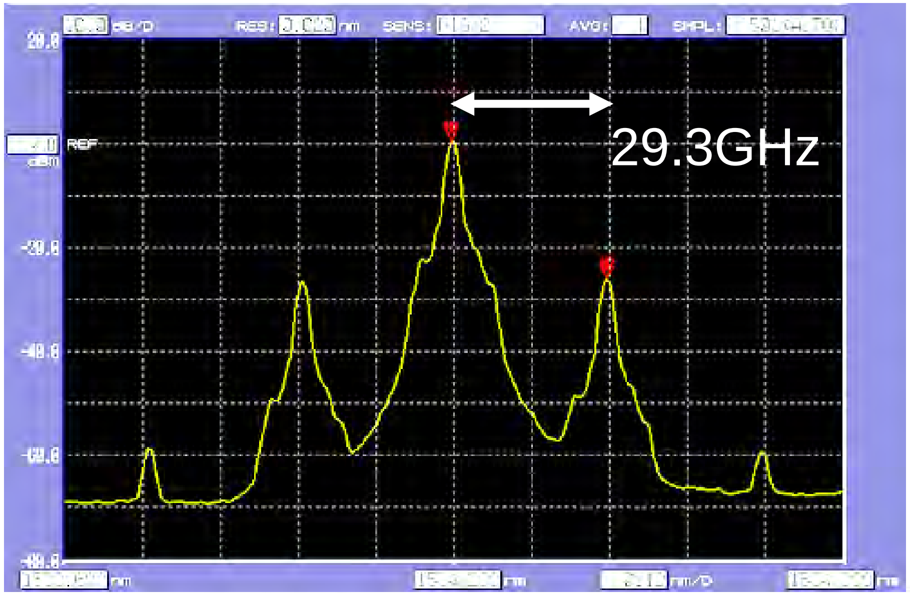
Fabricated ACE EO-modulator

1-/2-/4-Element Array
（Optical insertion loss ～ 6 dB）

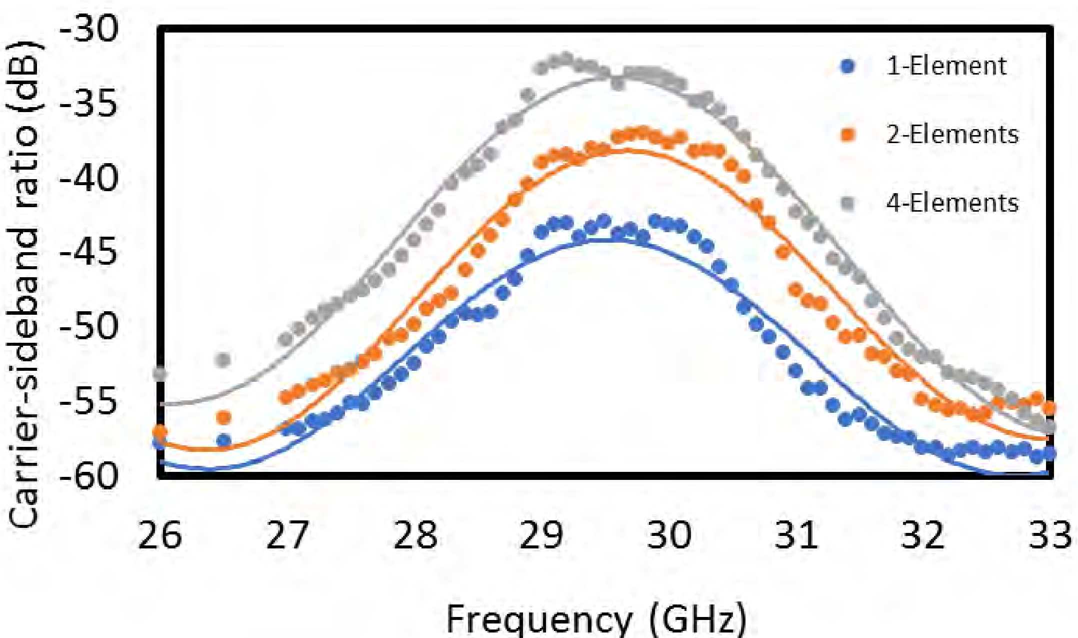


Measured Spectrum & Frequency Dependence



- ✓ 4-element array
  - 29.3 GHz of 13 dBm
  - *d* = 100 mm
- => Optical mod. index $\Delta\theta$=90 mrad.

- ✓ MMW pol.-selectivity
  - > 20 dB (optical)
  - > 40 dB (re-conv. MMW)



- ✓ Critical-coupling-like response
  - BW > 2 GHz
- ✓ Almost same BWs
  - Not limited by array

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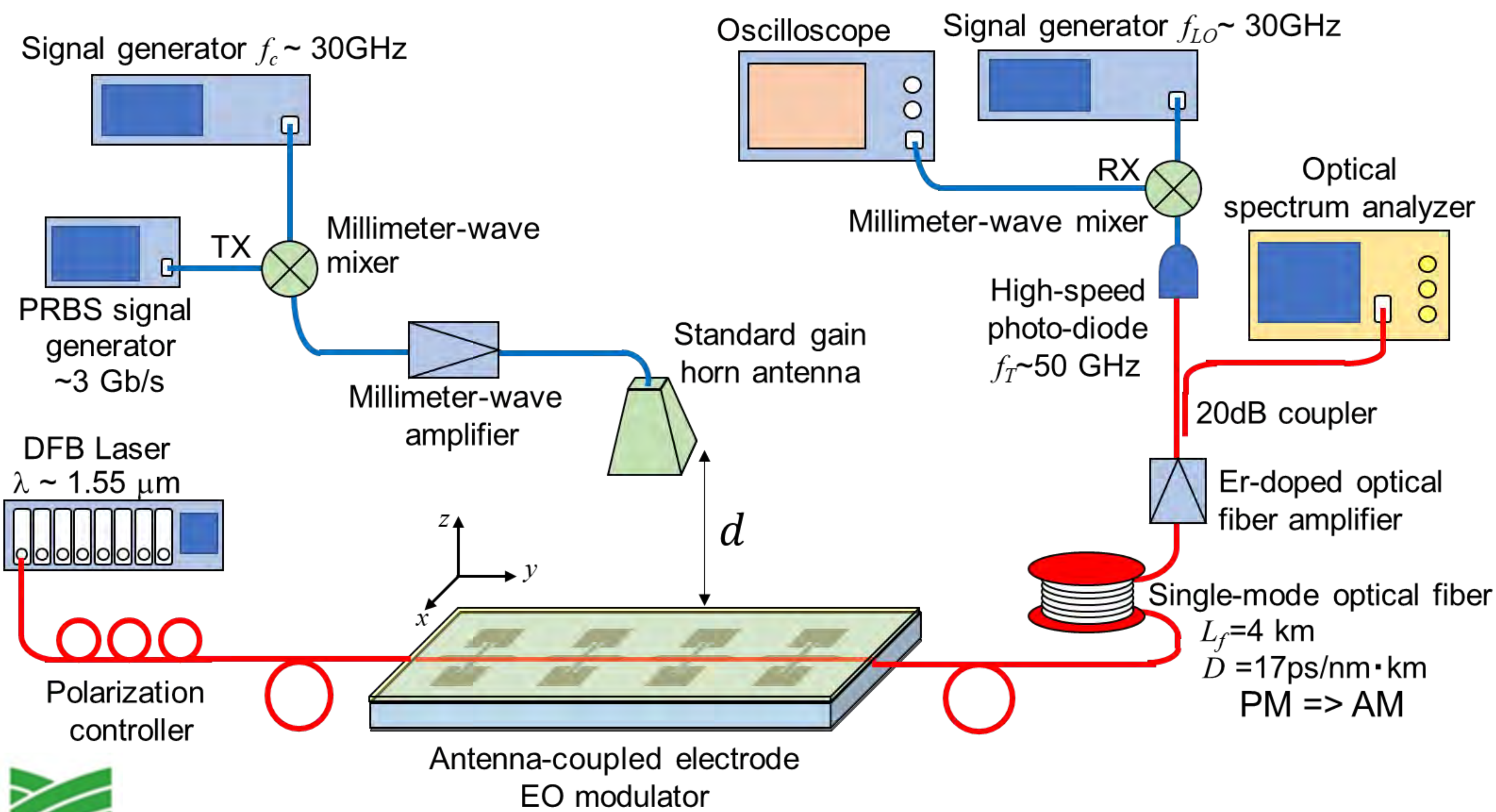
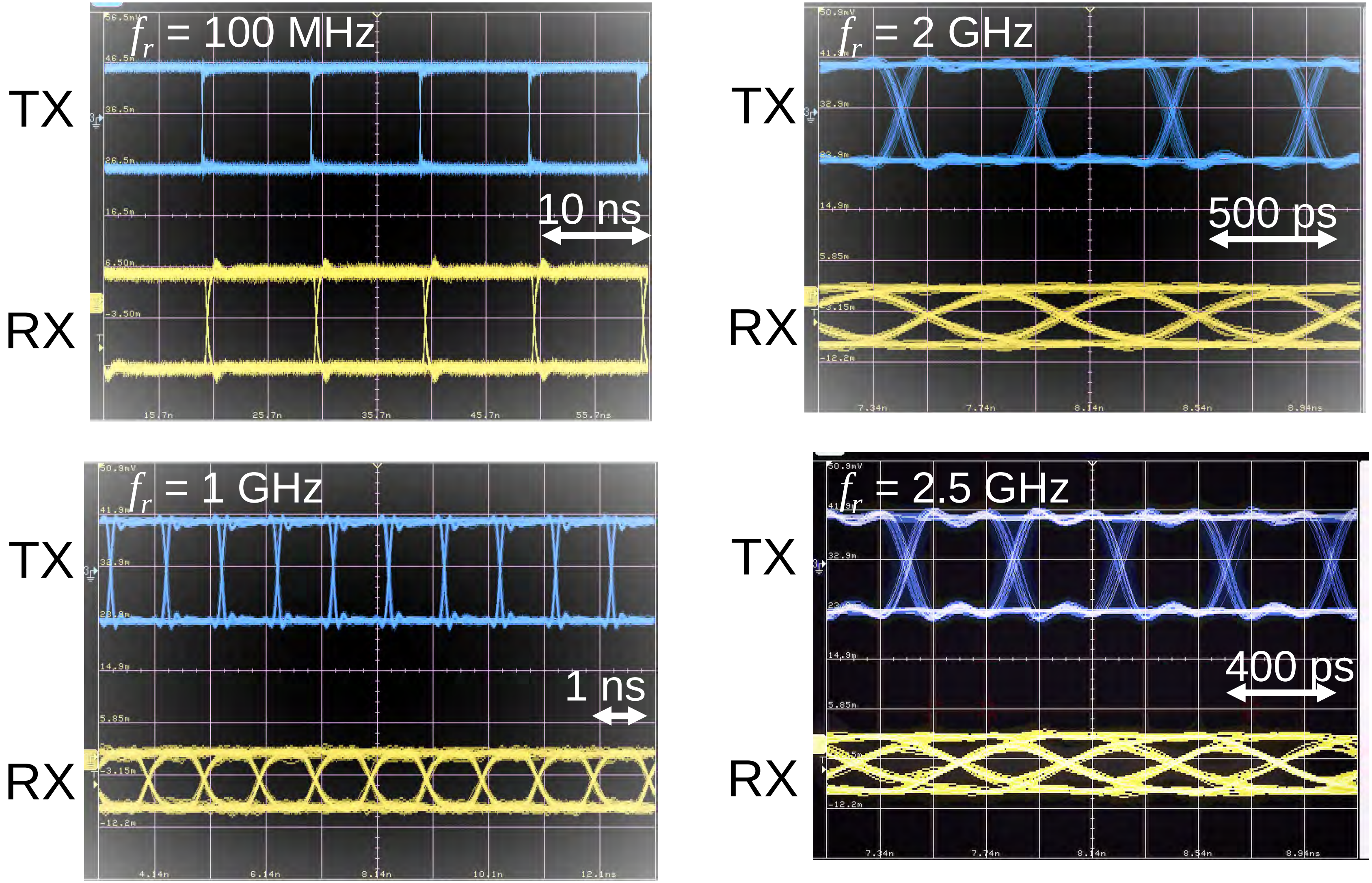
Data Transfer Experiments

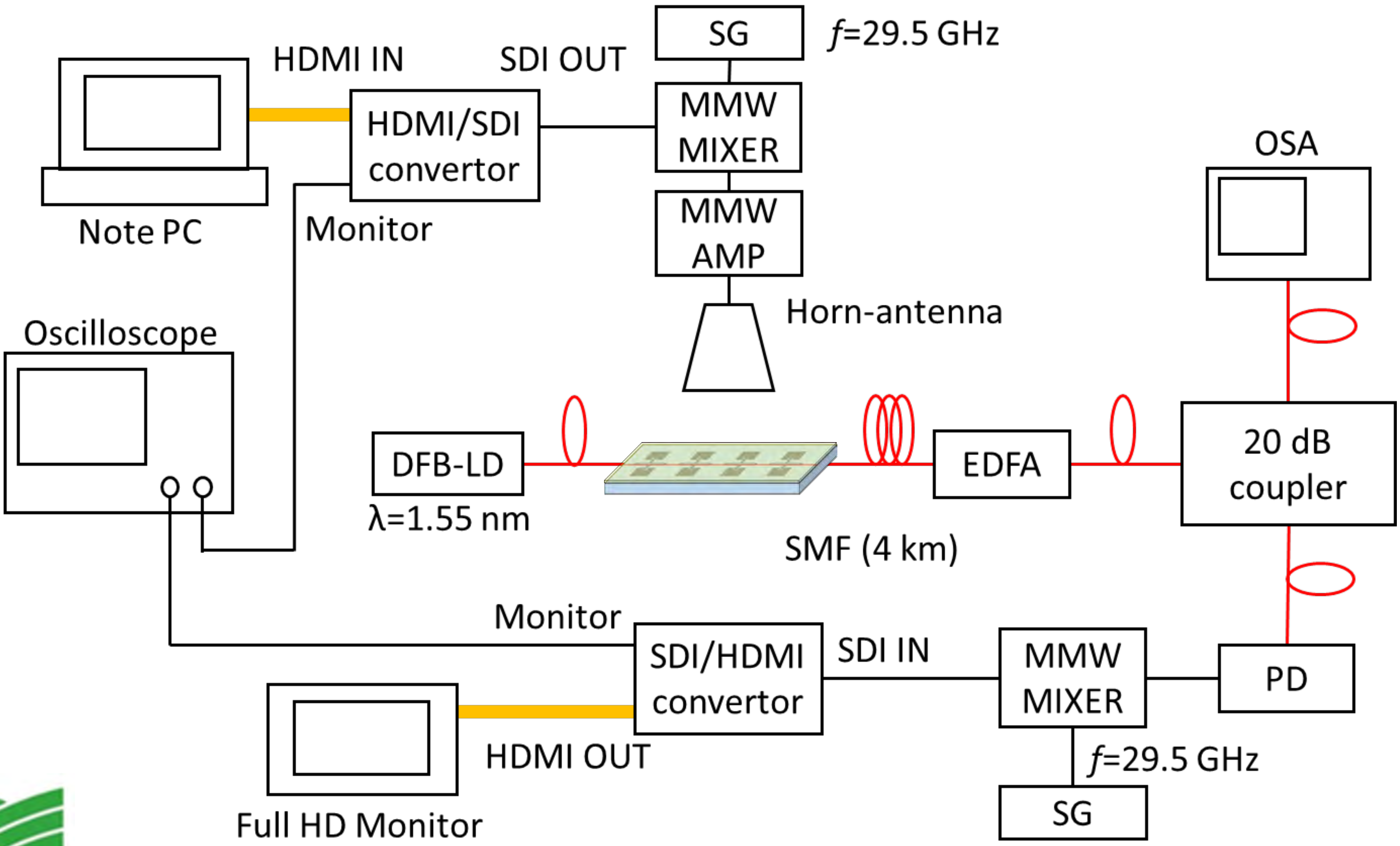


Data Transfer Experiment Results

ASK Signal (On/Off-Keying) (MMW 16 dBm, d = 100 mm)



HDMI Movie Transfer Using Antenna-Coupled Electrode EO Modulator



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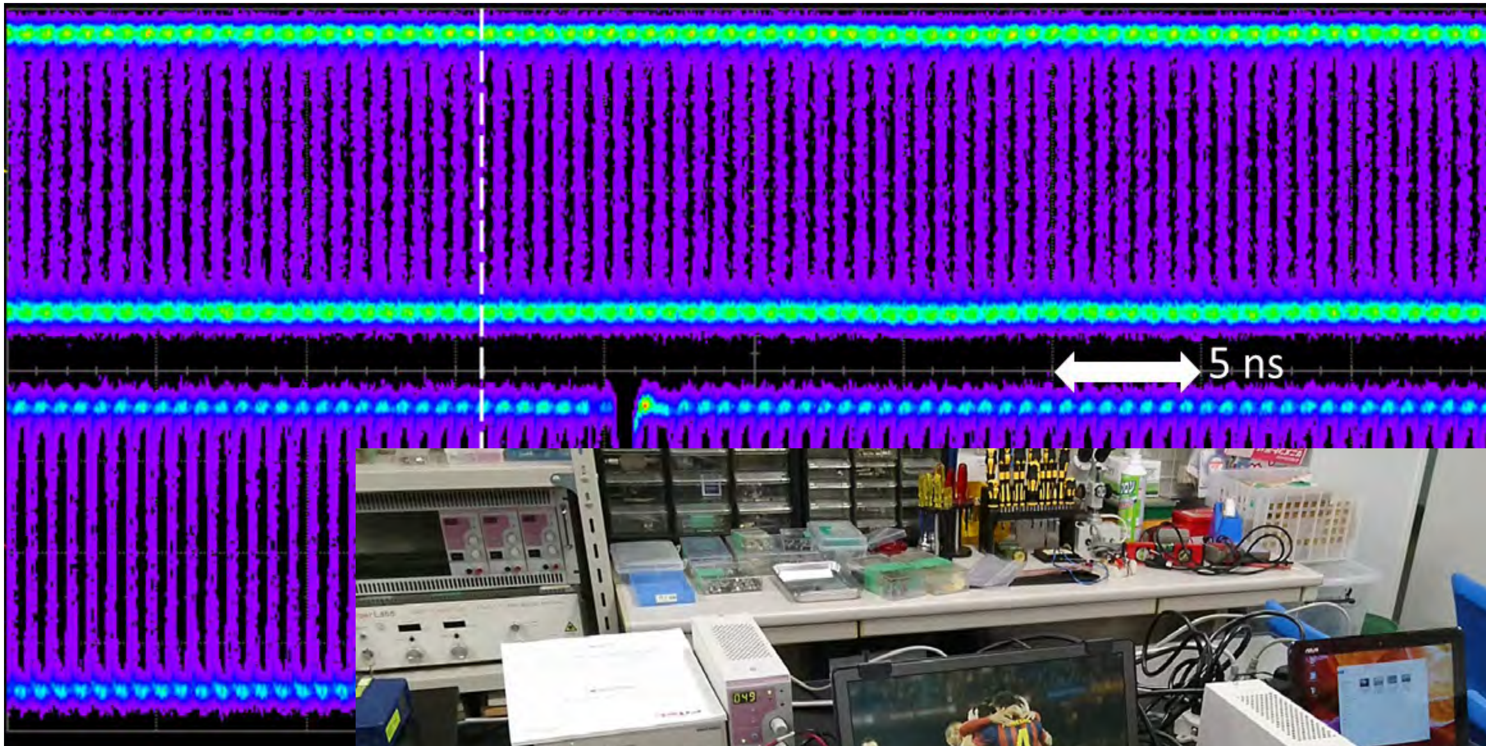
HDMI Movie Transfer Using Antenna-Coupled Electrode EO Modulator

Tx

Rx



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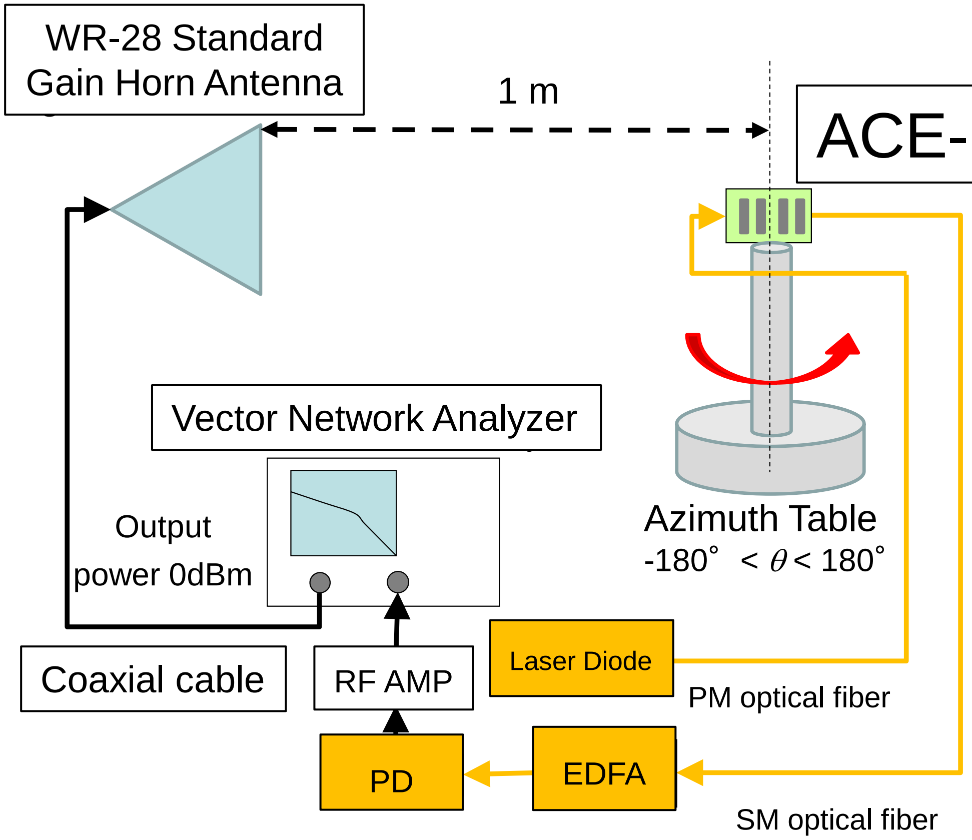
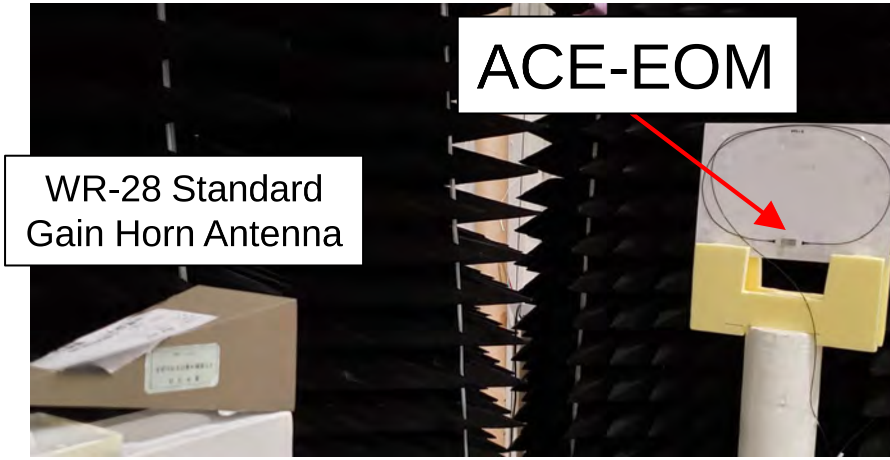
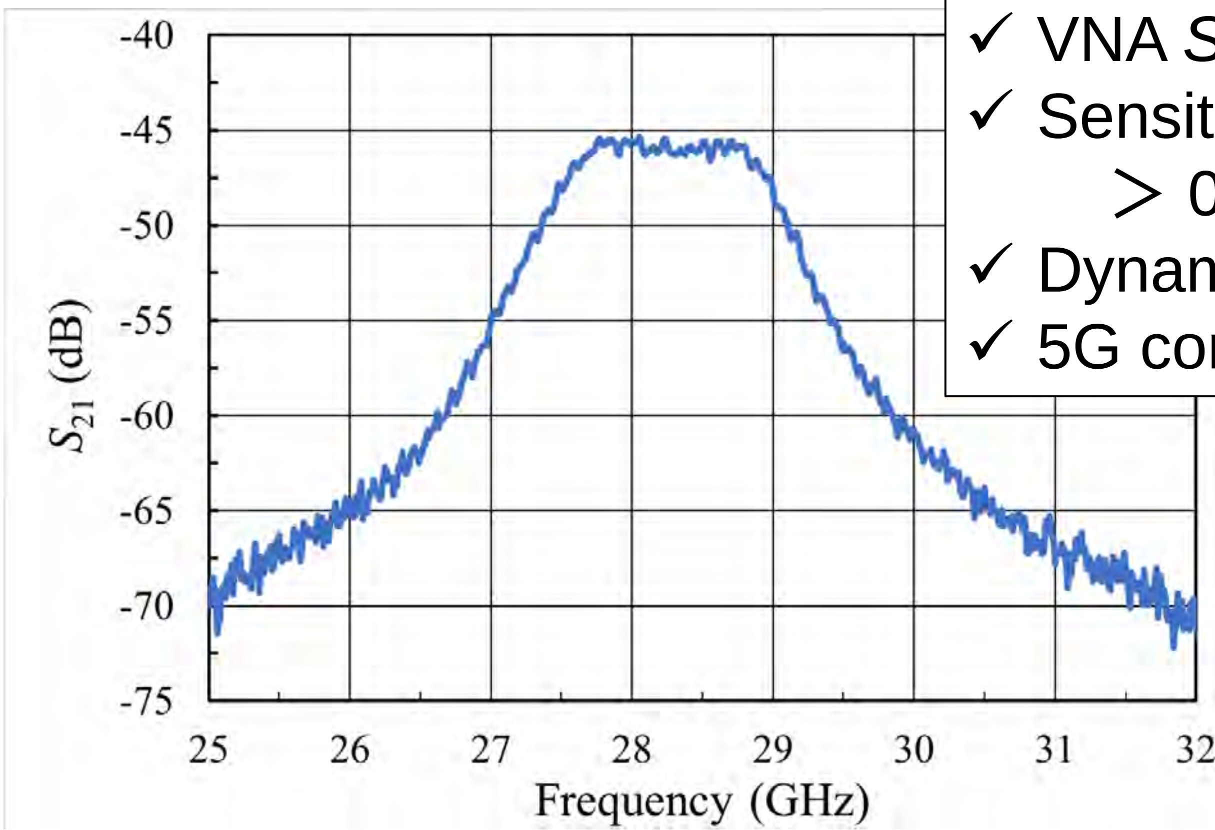
Precise Antenna Measurement

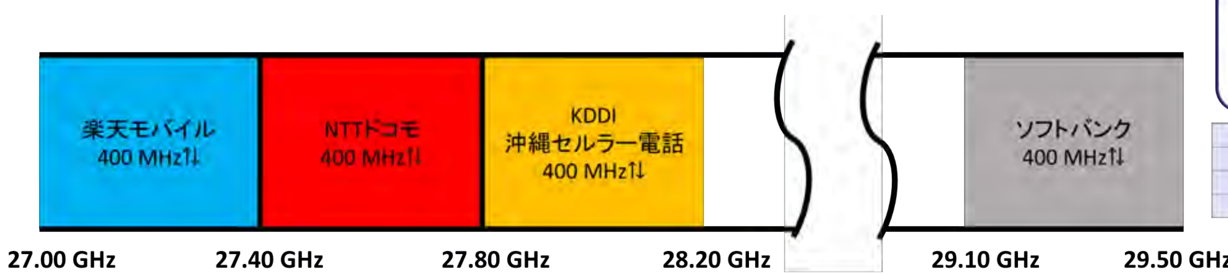




Measured S_{21} Characteristics



- ✓ VNA S_{21}
- ✓ Sensitivity
  - > 0.1V/m @28.2 GHz
- ✓ Dynamic Range > 30 dB
- ✓ 5G commercial band



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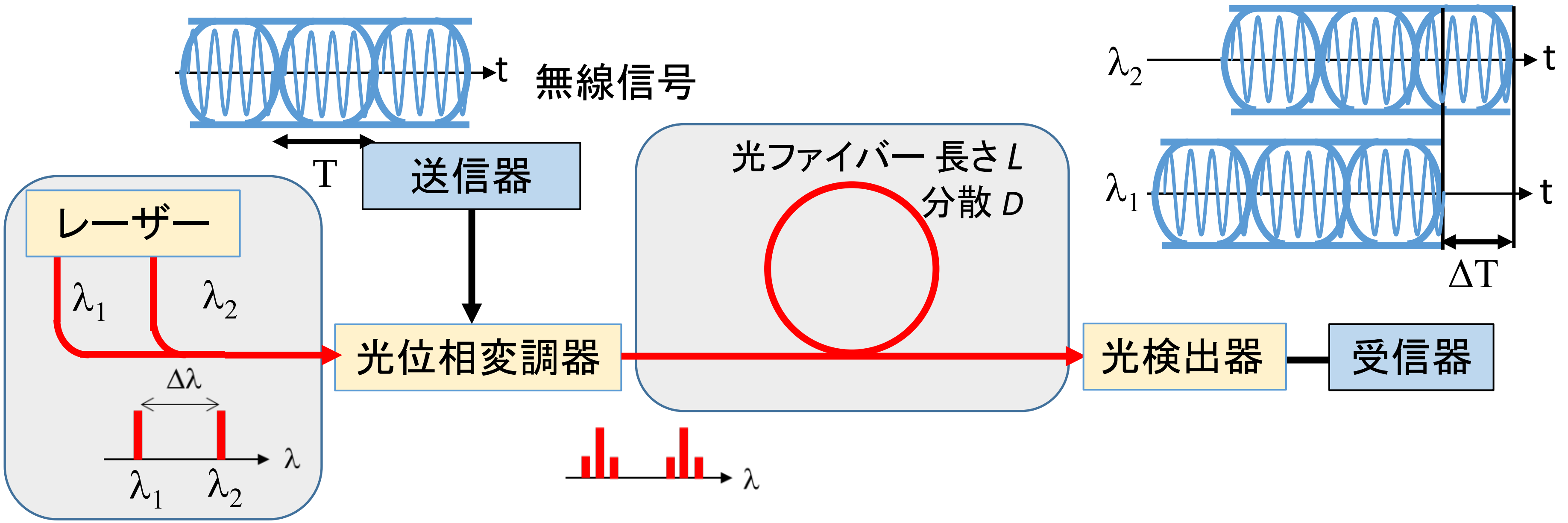
Wireless signal convolution using ANT-EOM & fiber dispersion effect



✓ <u>**光位相変調器(アンテナ電極変調器)**</u>

複数の光波を無線信号で同時に変調可能

✓ <u>**波長分散と受信端での遅延**</u>

光ファイバー中の伝搬速度が波長により若干異る

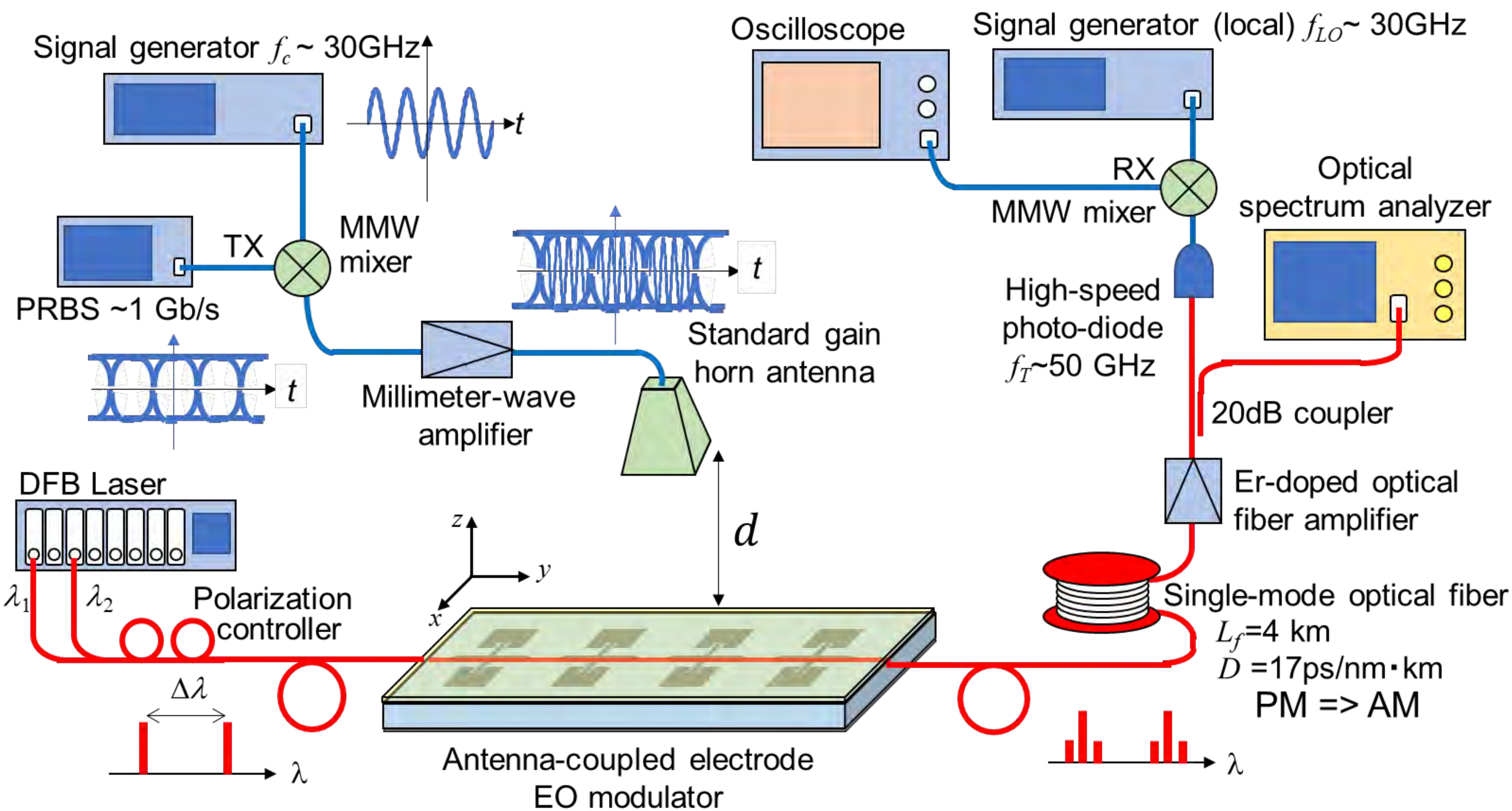
⇒ 遅延時間 : $\Delta T = D\,L\,\Delta\lambda$

ファイバ長 : L、波長差 : $\Delta\lambda$、分散 : D

↓

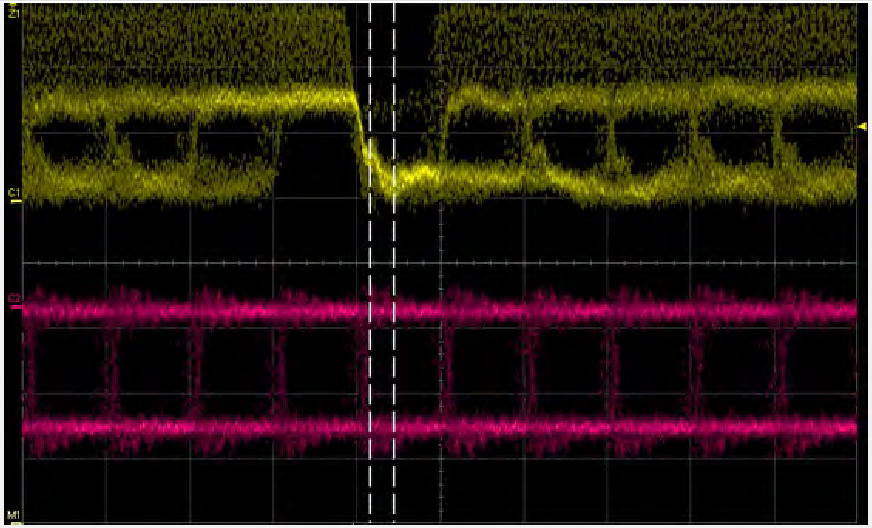
無線信号の自己相関(たたみ込み)

Experimental set-up



Measured signals 1: single laser

レーザー光波長　λ＝1545 nm

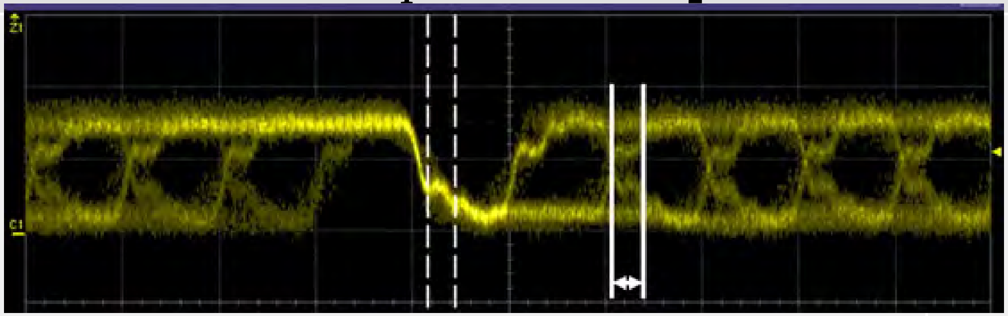


Detected Signal

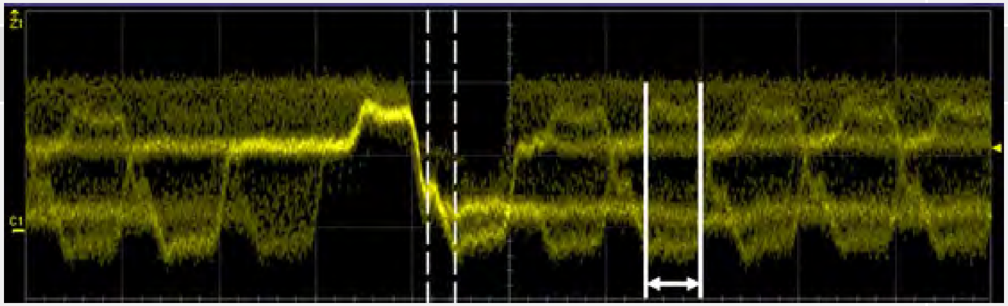
Back-to-Back　1 Gb/s PRBS

Measured signals 2: two lasers

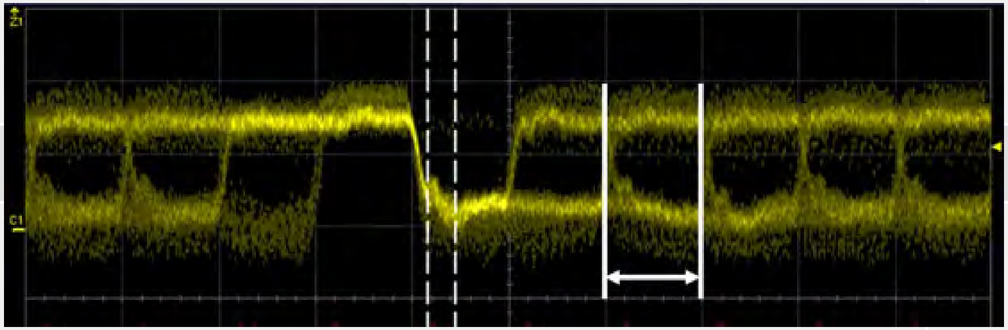
レーザー光波長 $\lambda_1 = 1545$ nm, $\lambda_2 = 1540$ nm



波長差 Δλ= 5 nm
時間幅 Δt= 360 ps

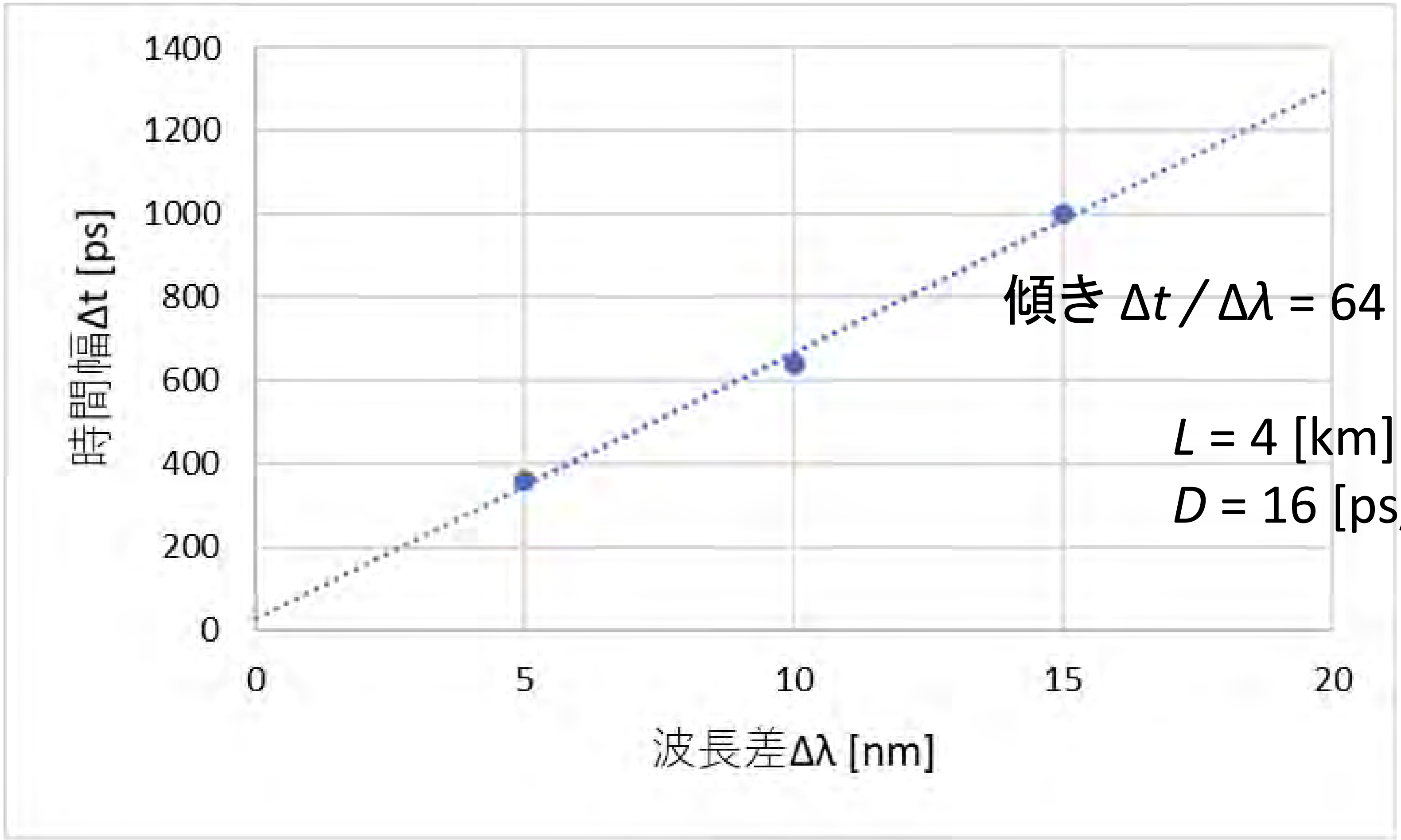


Δλ= 10 nm
Δt= 640 ps



Δλ= 15 nm
Δt= 1000 ps

Measured results



傾き $\Delta t / \Delta\lambda$ = 64 [ps/nm]

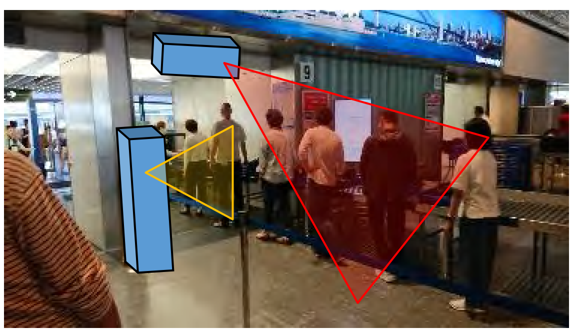
L = 4 [km]

D = 16 [ps/nm*km]

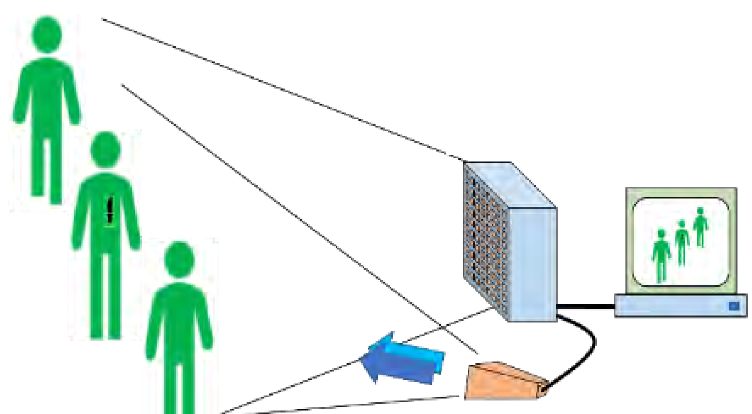
3. ACE-EOM for W-band

- ✓ Design & Experiments
- ✓ IF conversion by use of photonic technique

Security checking system for dense user environment



- ✓ **Big event & public transportation**
  ⇒ Security requirement
- ✓ **Current security check system**
  ⇒ Static / long checking time
- ✓ **Long cue for many people**
  ⇒ Limited application only
  (Airport, etc.)
- ✓ **Check during walking/moving**
  ⇒ Brief check time, High throughput



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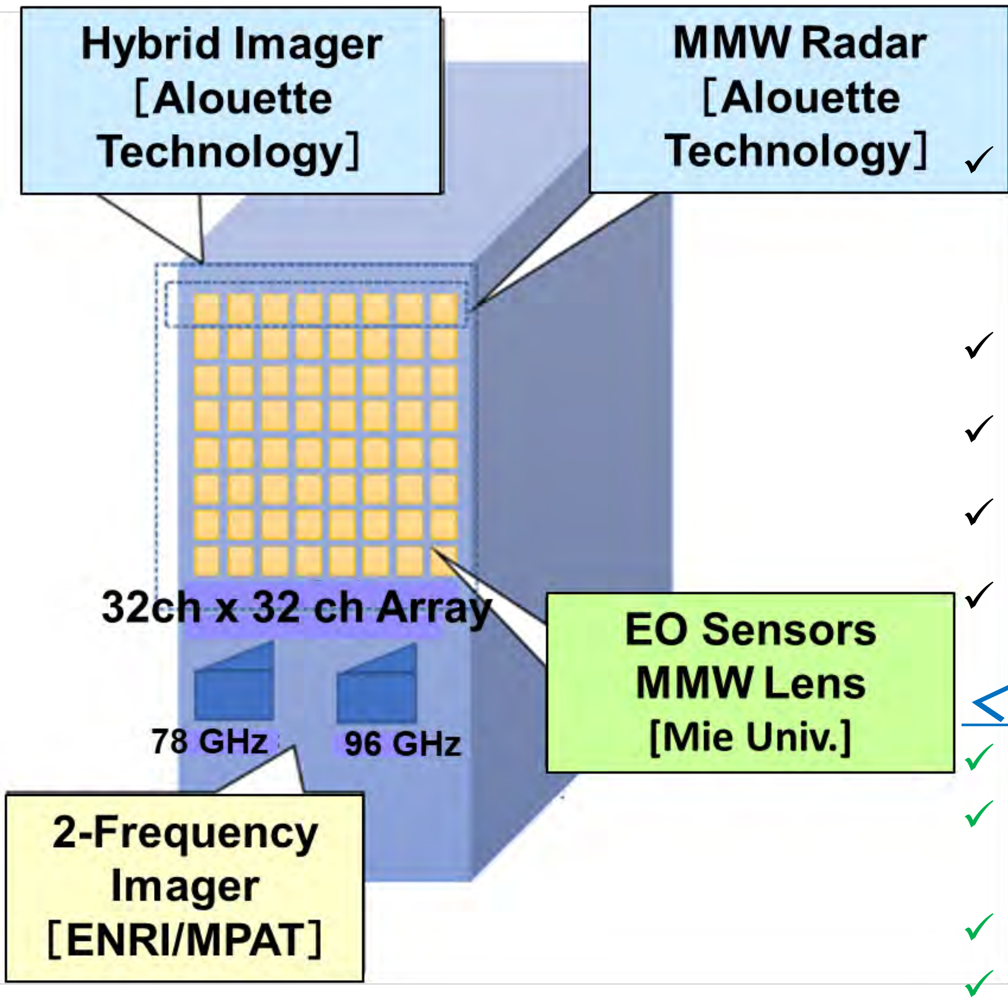
Project for Sensing/Imaging Using W-band MMW

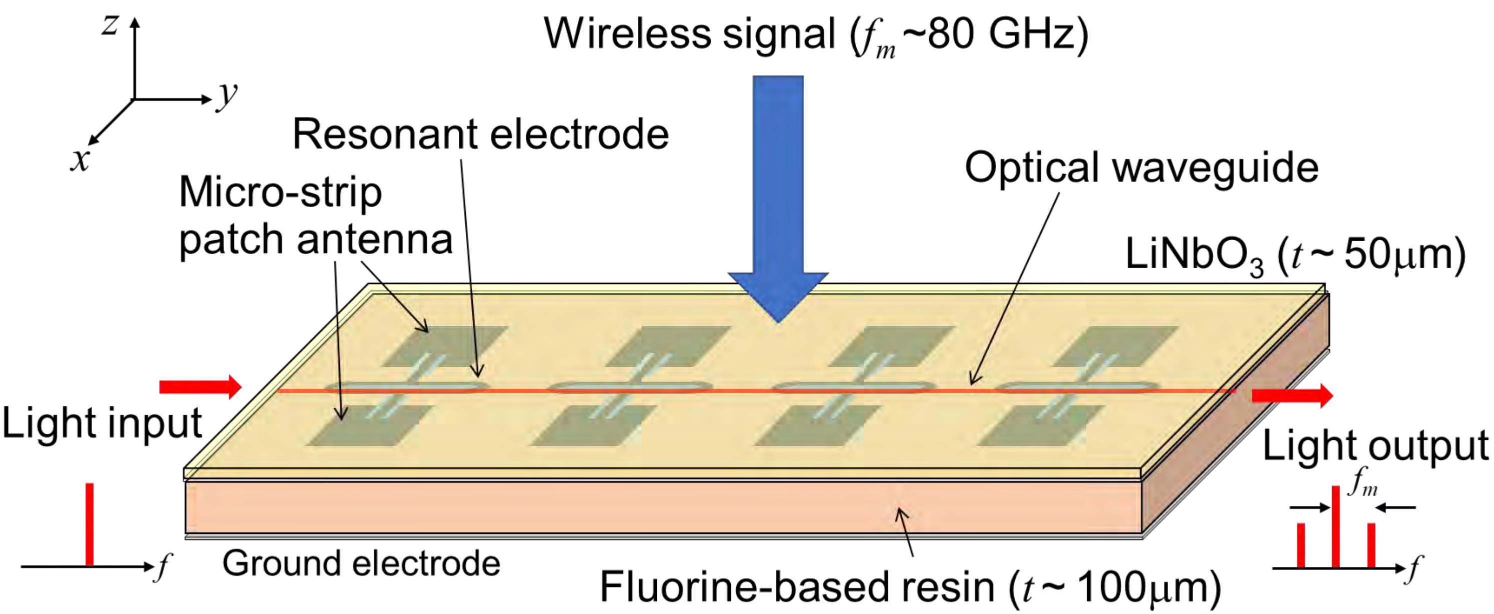


- ✓ MMW field measurement emitted from human body & other items
  ⇒ Passive Imager
- ✓ MMW field measurement reflected from human body surface & other items
  ⇒ Active Imager
- ✓ Hybrid image (Passive & Active)
- ✓ Calibration of sensors using EO sensors
- ✓ Measurement distance expand by lens
- ✓ 2-frequency MMW imaging technique

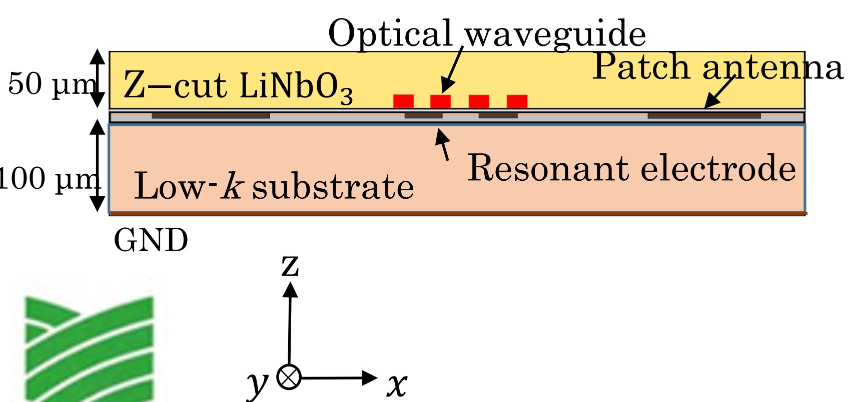
<Key points>

- ✓ High S/N imaging using complex integral
- ✓ Digital signal processing using MMIC
  (IQ-detection for complex integral)
- ✓ High channel isolation by digital technique
- ✓ Multiple imagers operation
- ✓ Image conversion using signal processing

Antenna-Coupled-Electrode EO Modulator/Sensor for W-band



Cross Sectional View



Advantage

- Direct MMW => LW conversion
- No external power supply
- Synthesis of MMW signals by photonics
- Suitable for imager calibration

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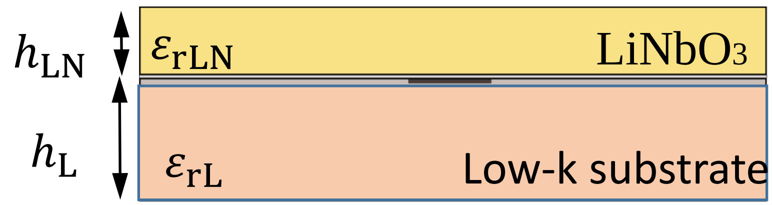
Effect of Low-k Substrate in W-band

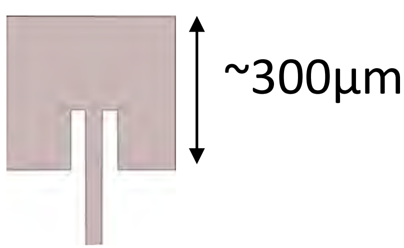
	ε_r	tanδ
$LiNbO_3$	(43,43,28)	~0.001
SiO_2 Glass	4.0	0.0007
Florine-based Resin	2.28	0.0008

$$\varepsilon_{\mathrm{reff}} = \frac{h_{\mathrm{L}} + h_{\mathrm{LN}}}{\frac{h_{\mathrm{L}}}{\varepsilon_{\mathrm{rL}}} + \frac{h_{\mathrm{LN}}}{\varepsilon_{\mathrm{rLN}}}}$$

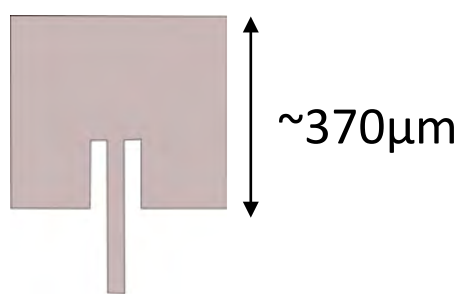


Patch antenna for 80GHz operation

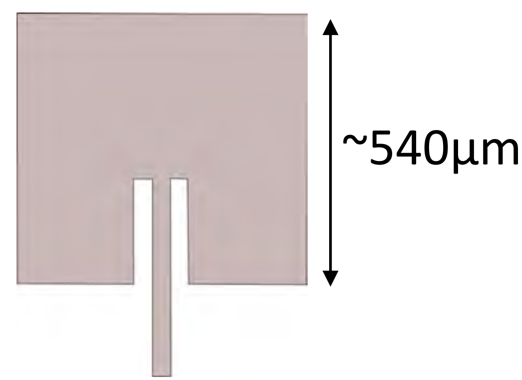
SiO_2 (t=250μm)



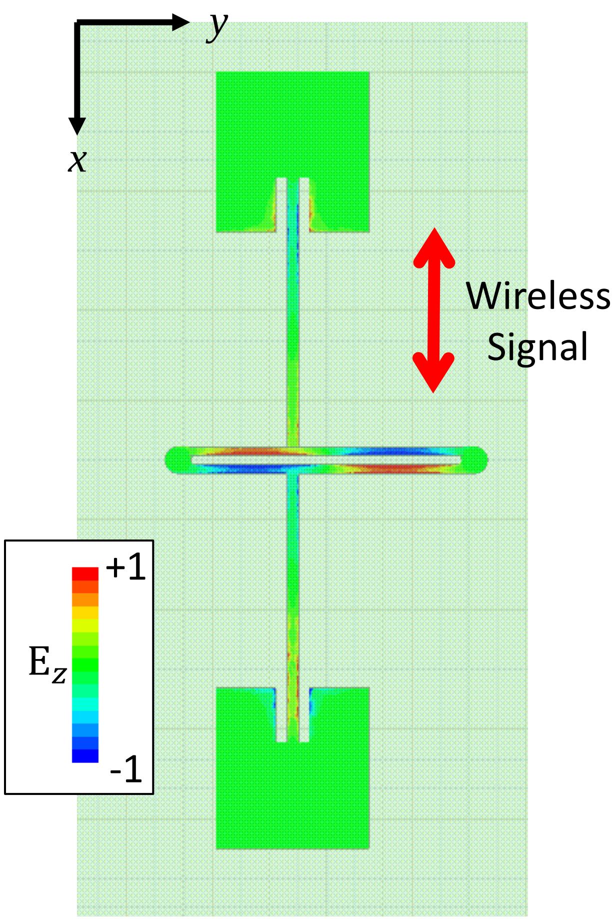
Florine-based Resin
(t=250μm)



Florine-based Resin
(t=100μm)

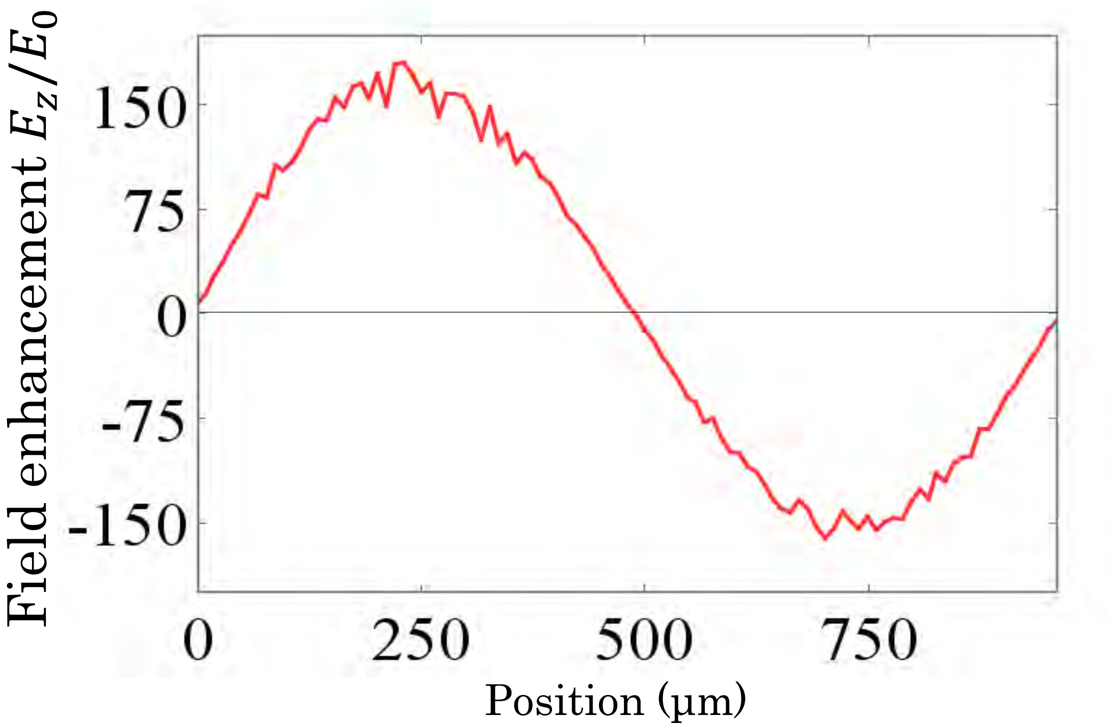


Design for W-band EO sensor

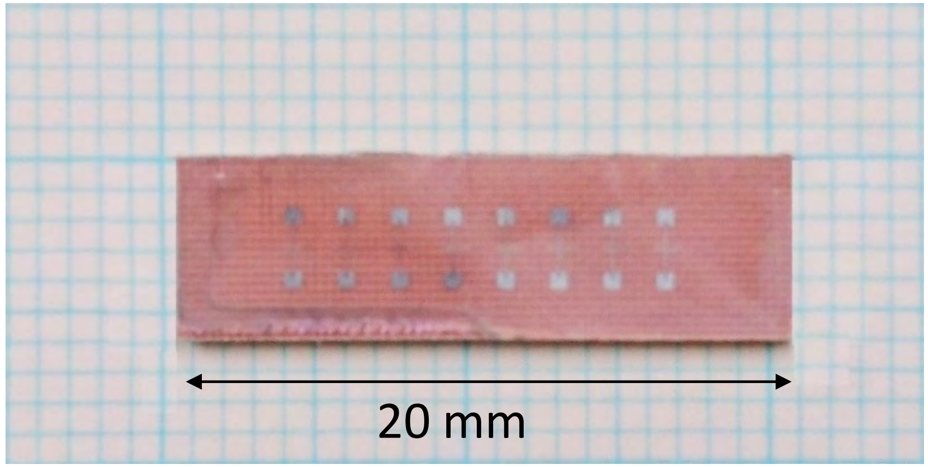


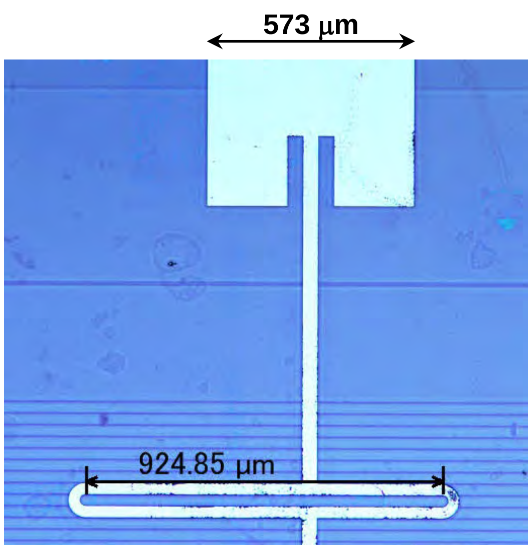
Surface electric field distribution
under 79 GHz MMW irradiation

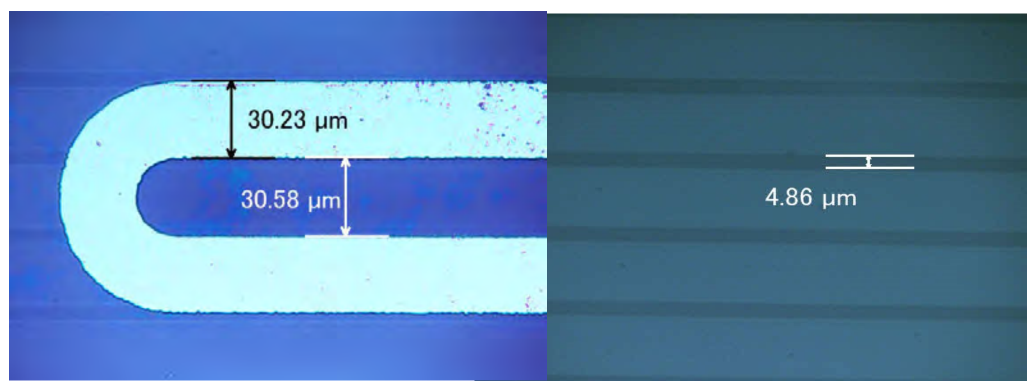
Enhanced MMW field for optical modulation (79 GHz)



Fabricated Device for W-band

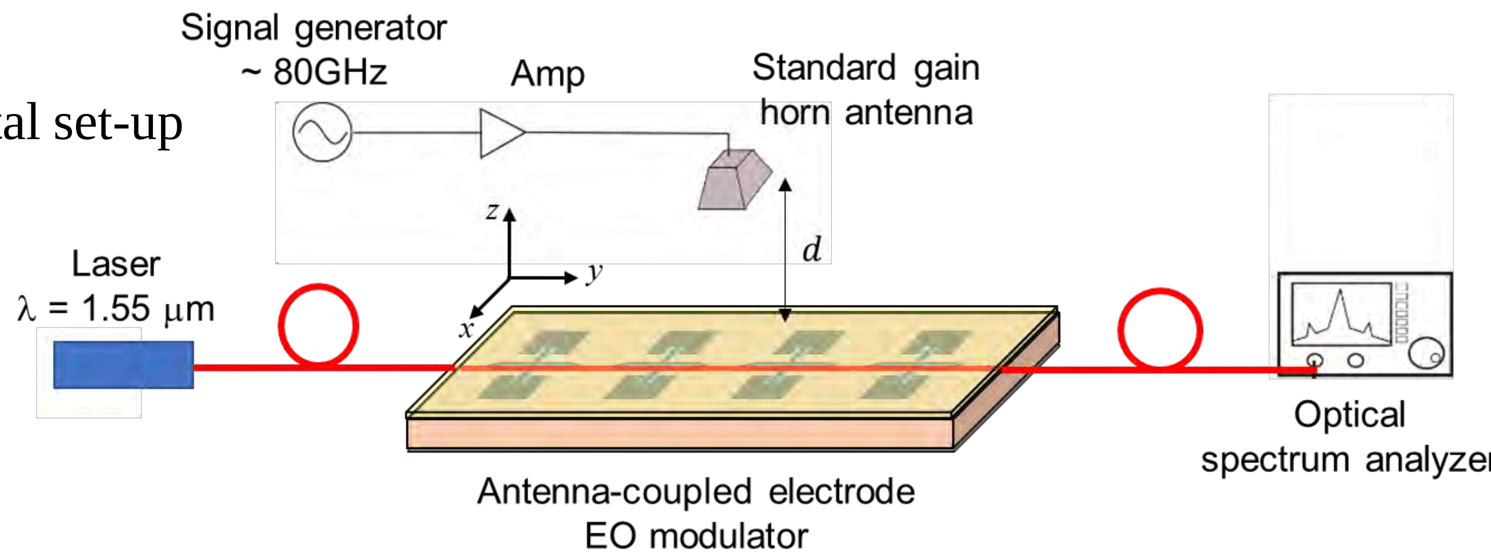




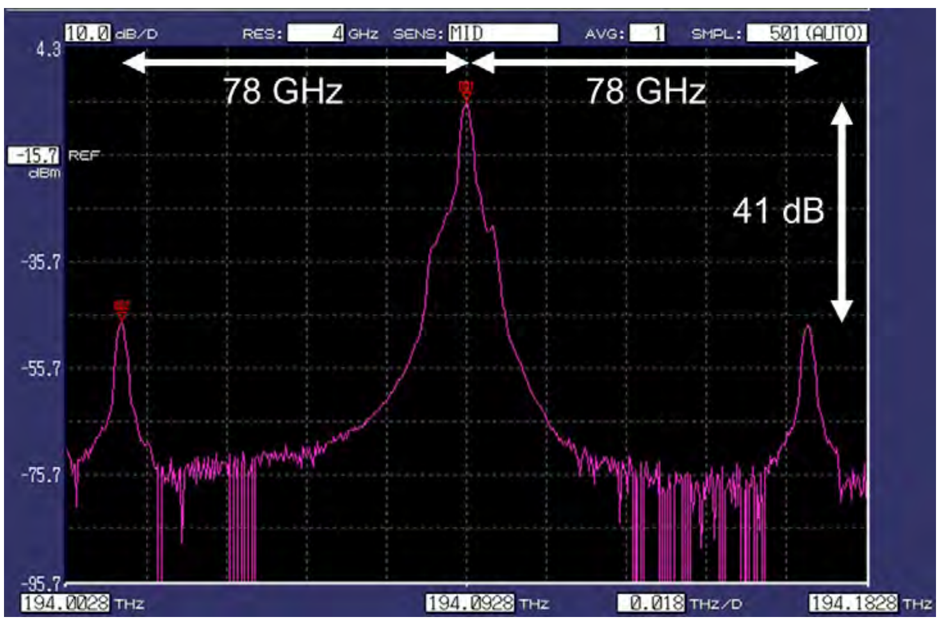


Experiment for W-band signal conversion

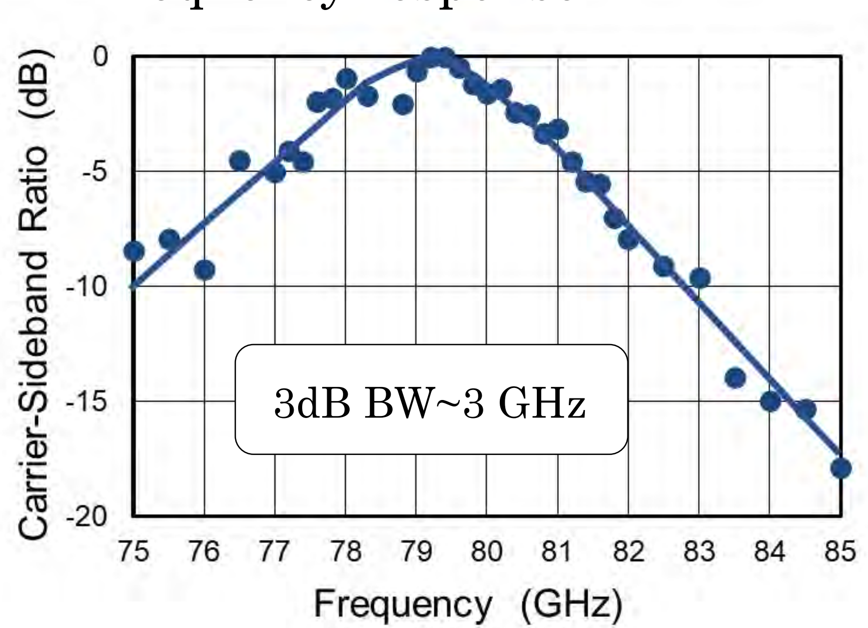
- Experimental set-up



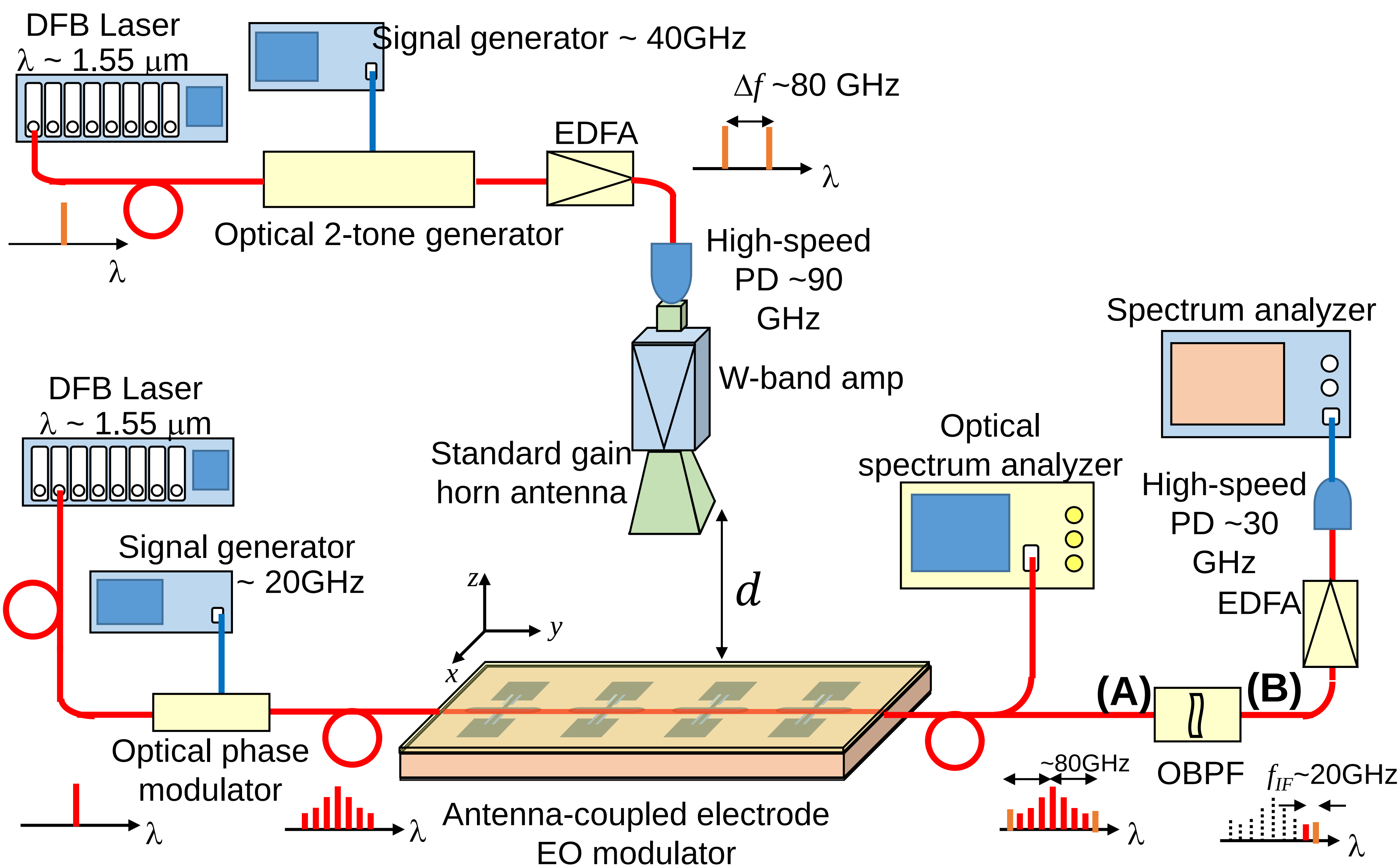
- Optical spectrum



- Frequency response

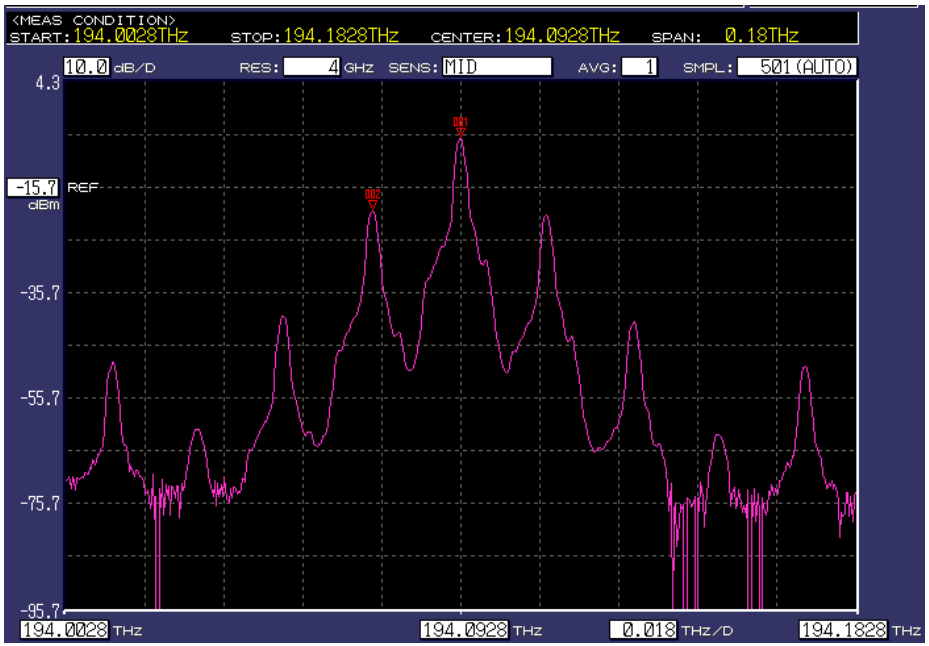


W-band signal IF Conversion using photonic technique

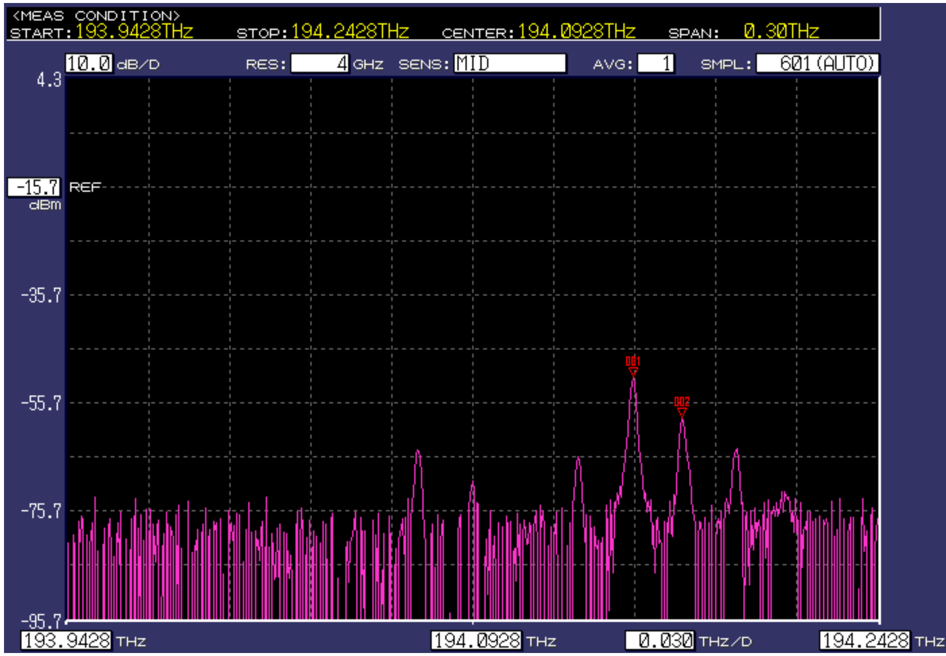


W-band signal IF Conversion using photonic technique

- Measured optical spectrum at (A) (Just before OBPF)



- Measured optical spectrum at (B) (After OBPF)



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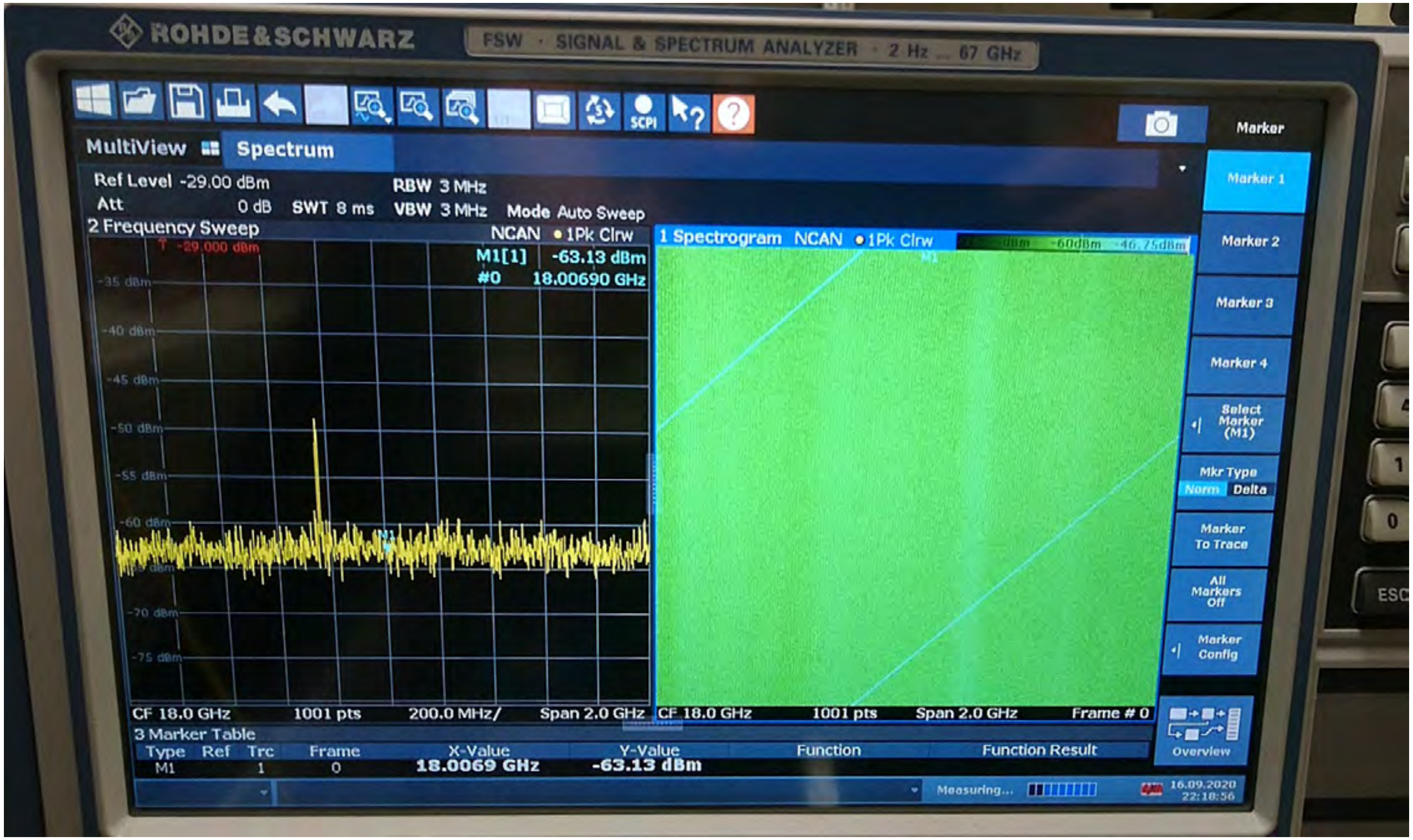
W-band FMCW signal conversion experiment



Conclusions

◆Antenna-coupled electrode EOM for 5G/Beyond 5G/6G

- ✓Critical coupling between antenna & electrode
  - ✓Field enhancement factor > 8,000
  - ✓Negligible re-emission of fields
- ✓Experimental demonstration
  - ✓Bandwidth ~ 2 GHz
  - ✓Data transfer ASK ~2.5 Gb/s ⇒ > 10 Gb/s with QAM
- ✓Precise antenna measurement systems
  - ✓Commercially available (From 2021 summer)
- ✓Wireless signal convolution
  - ✓Correlation of wireless data signal
- ✓W-band operation
  - ✓Photonic IF conversion

◆Future Works

- ✓5G systems /Beyond 5G mobile tranceiver
- ✓Antenna precise measurement
- ✓W-band wireless comm./radar system

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