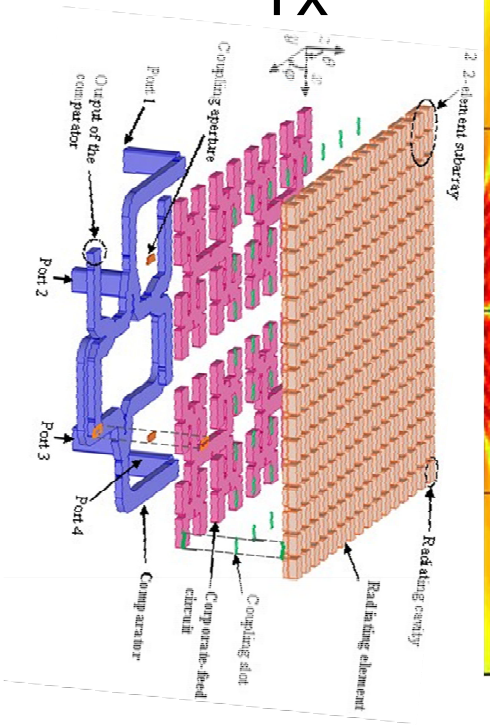
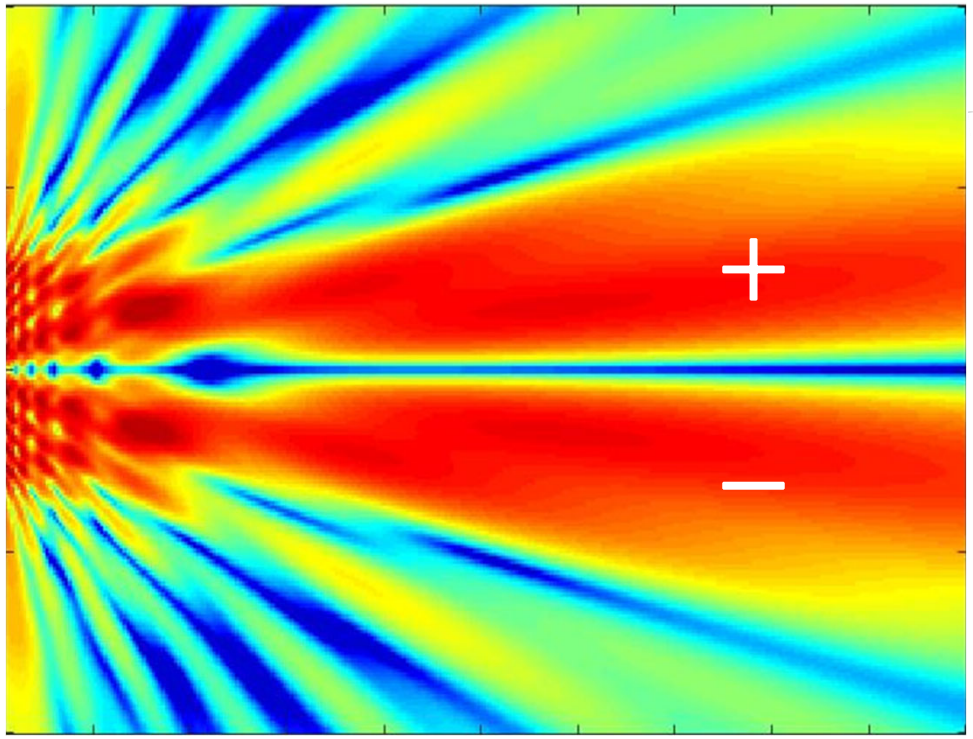
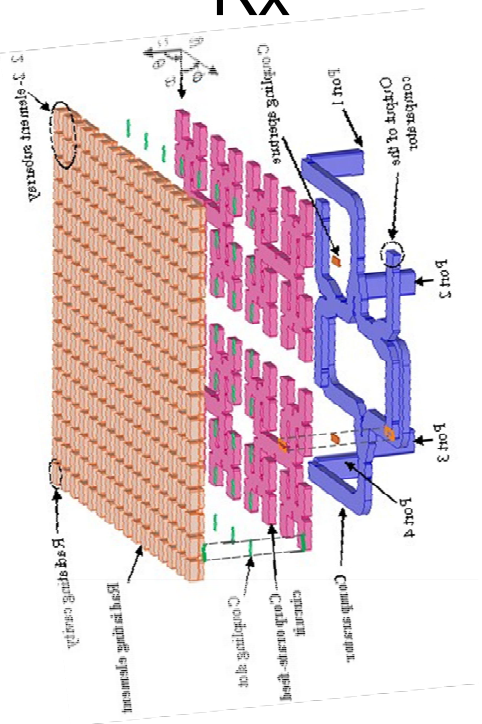
ROM Antennas
(Rectangular-coordinate Orthogonal Multiplexing)

Tx



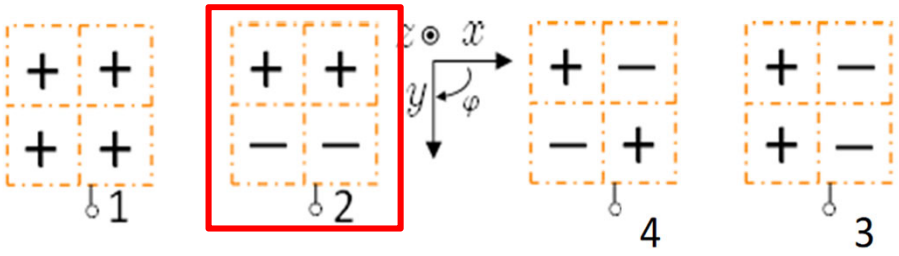


Rx



4 orthogonal mode multiplexing

WG slot array with
2D monopulse

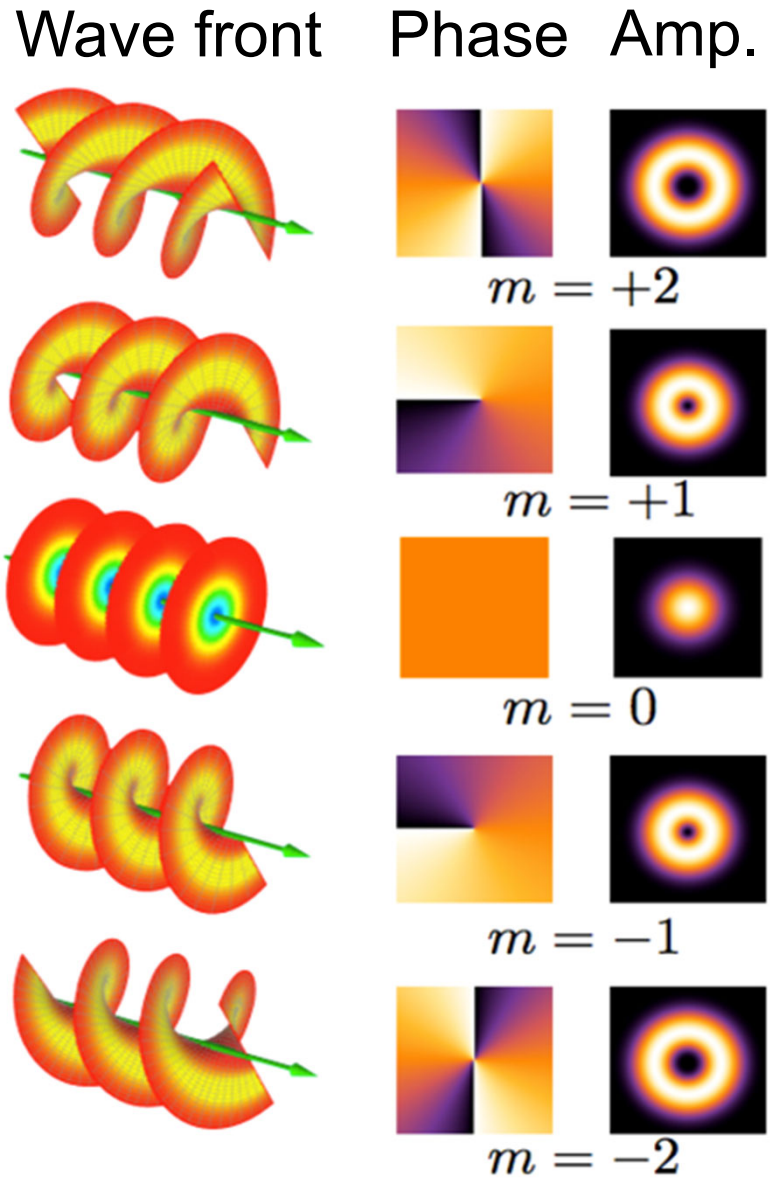


Jiro Hirokawa, Tokyo Institute of Technology, Japan

Orthogonality in wireless communication

- Code(Time) Domain: CDMA(Code Division Multiple Access)
- Frequency Domain: OFDM(Orthogonal Frequency Division Multiplexing)
- Space Domain: MIMO(Multiple-Input Multiple-Output)
  Non-Line of Sight Environment
- Space Domain: OAM(Orbital Angular Momentum)
  Line of Sight Environment
  Non-far Region

OAM transmission



G. Gibson, J. Courtial, M. J. Padgett," Free space information transfer using light beams carrying orbital angular momentum," Optics Express, Vol. 12, No. 22, pp. 5448-5456, Nov. 2004.

H. Huang, et. al. Optics Lett., Vol. 39, No. 2 pp. 197-200, Jan. 2014

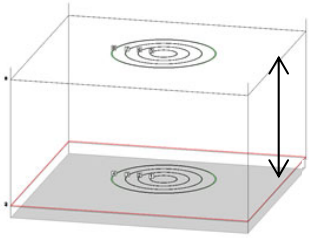
42(waves)X24(OAM modes)X100(Gbps)=100(Tbps)

S. M. Mohammadi, et. al." Orbital Angular Momentum in Radio — A System Study," IEEE Trans. Ant. Propag., Vol. 58, No. 2, pp. 565-572, 2010

OAM example

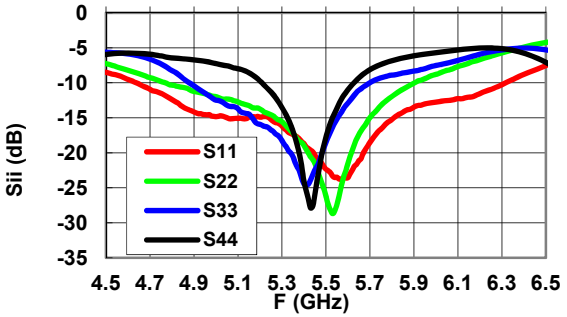
4-loop array (1λ, 2λ, 3λ, 4λ)

Matching 5.4~5.6GHz (narrow bandwidth)

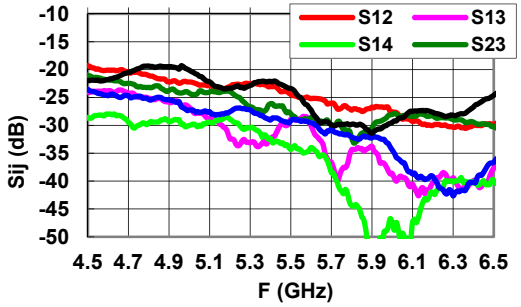


11mm

Reflection

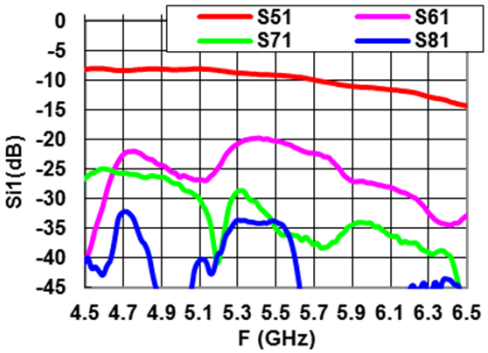


Mutual coupling

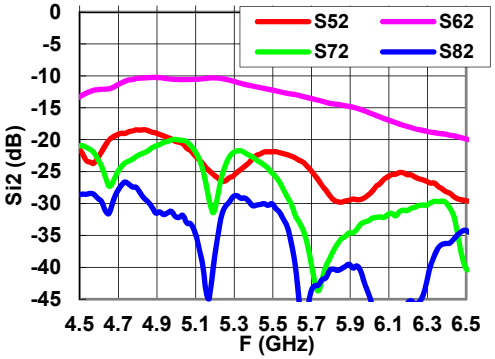


Transmission

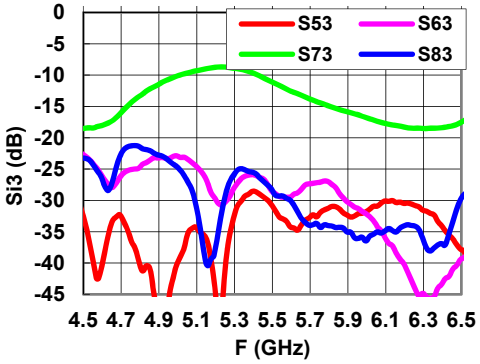
Input: loop 1



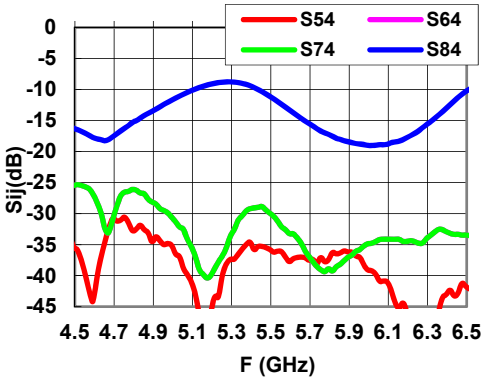
Input: loop 2



Input: loop3



Input: loop 4

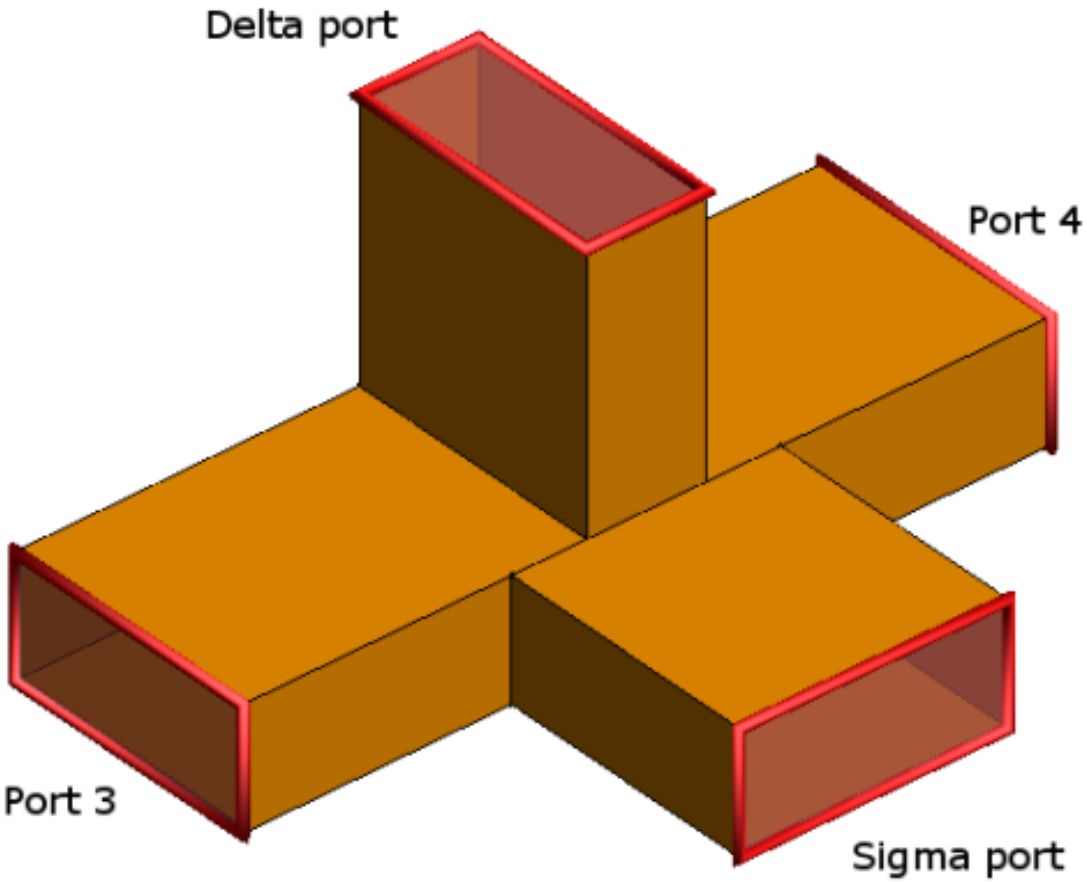


Prof. Saito et al. of Univ. of Electro-Commun.
IEICE Commun. Conf, B-1-104, 2016-9.

Features of ROM Transmission

	OAM		ROM
Band	Optics	Microwave & millimeter waves	
Fractal Bandwidth	Almost 0%	～20%	
Multiplexing	Phase variation		Polarity by structural symmetry
Frequency Dependence	No	Yes	By elements
Coordinate System	Cylindrical		Rectangular
Treatment	Different in ρ and ϕ		Same in x and y

Magic T



Structural symmetry, no frequency dependence

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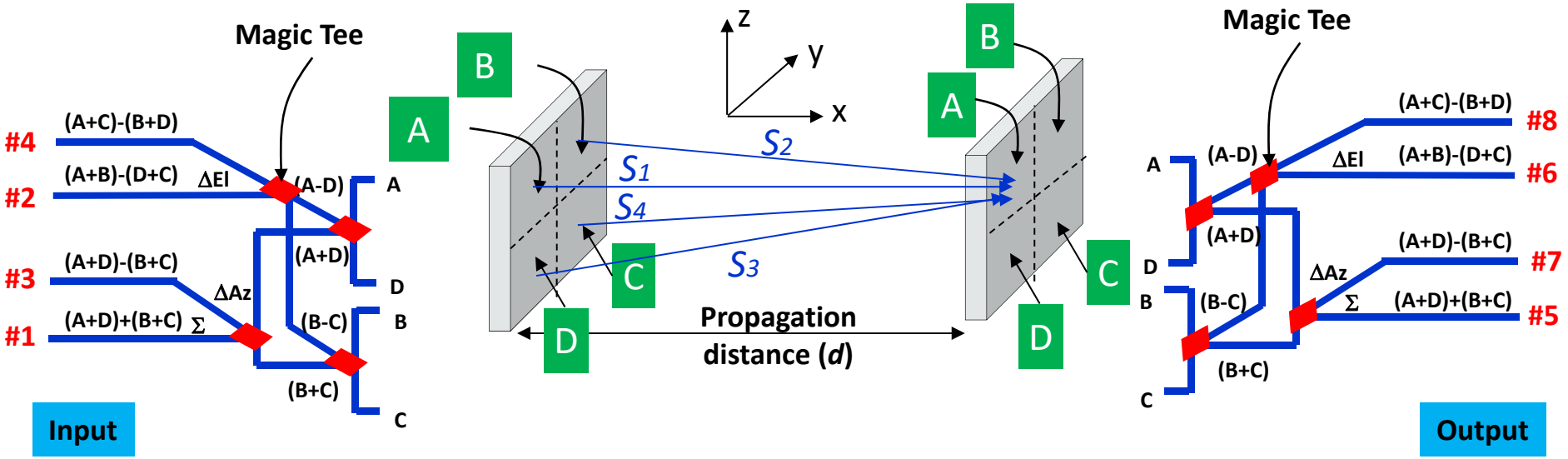
- Conclusions

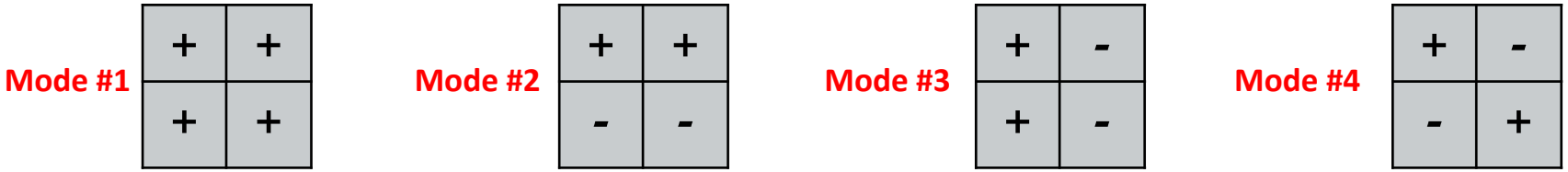
Non-far region communication system with orthogonal beams

Proposed system



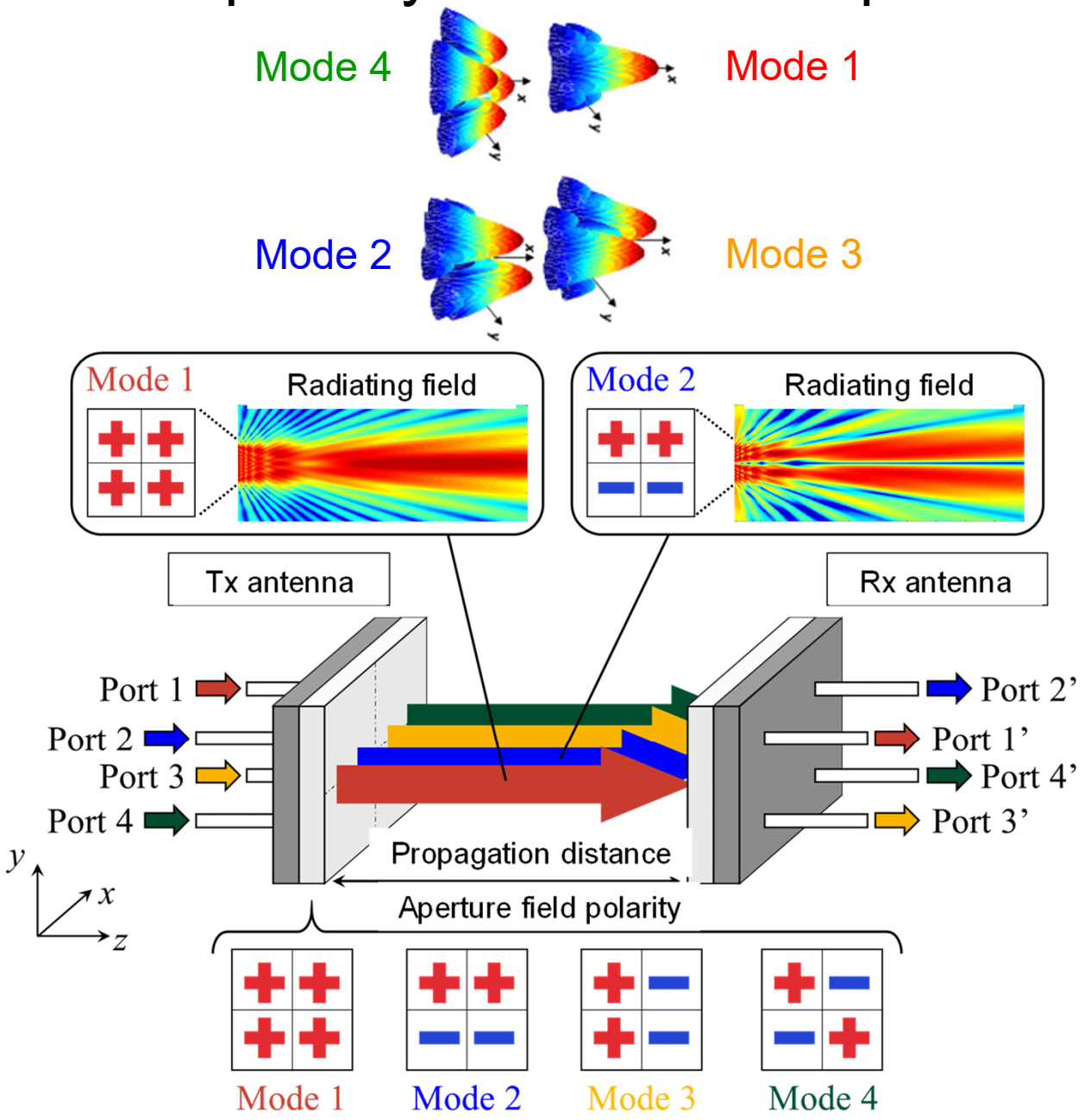
- 2-stage magic T
- Increase of the number of the stages → increase of the number of modes

Aperture field distribution



K. Tekkouk, J. Hirokawa, and M. Ando, IEEE Trans. Antennas Propagat., vol. 66, no. 3, pp. 1507-1515, Mar. 2018.

Aperture field polarity and beam shape



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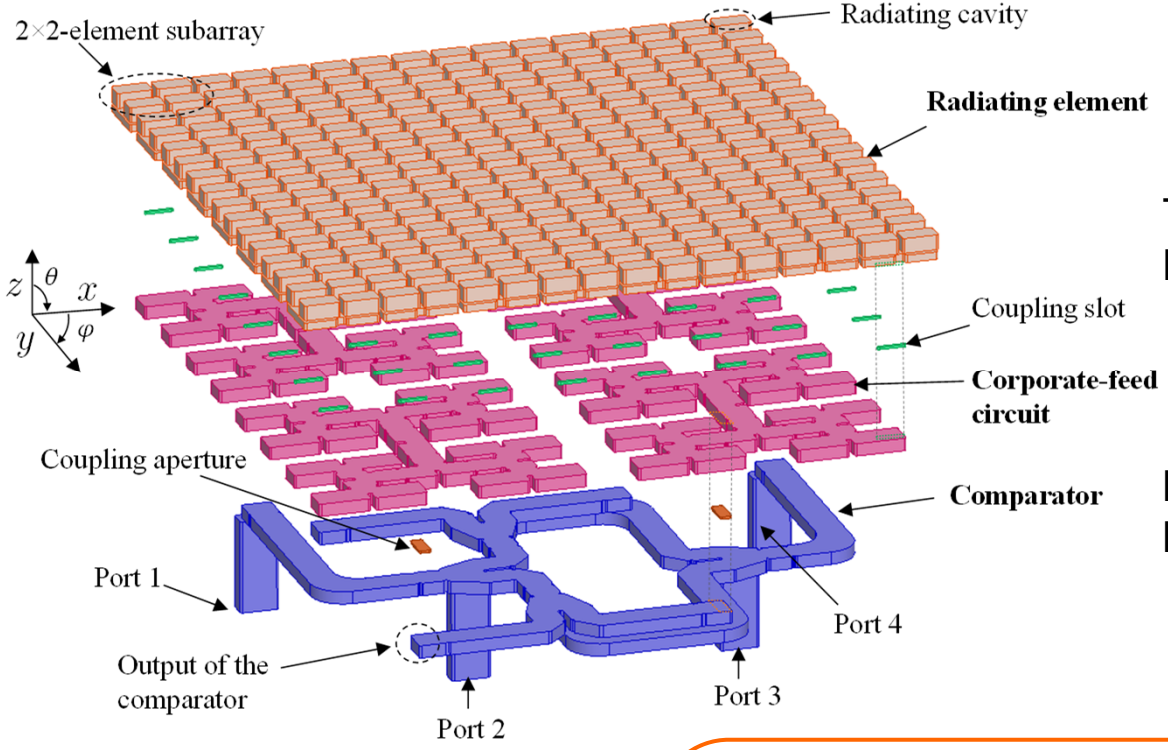
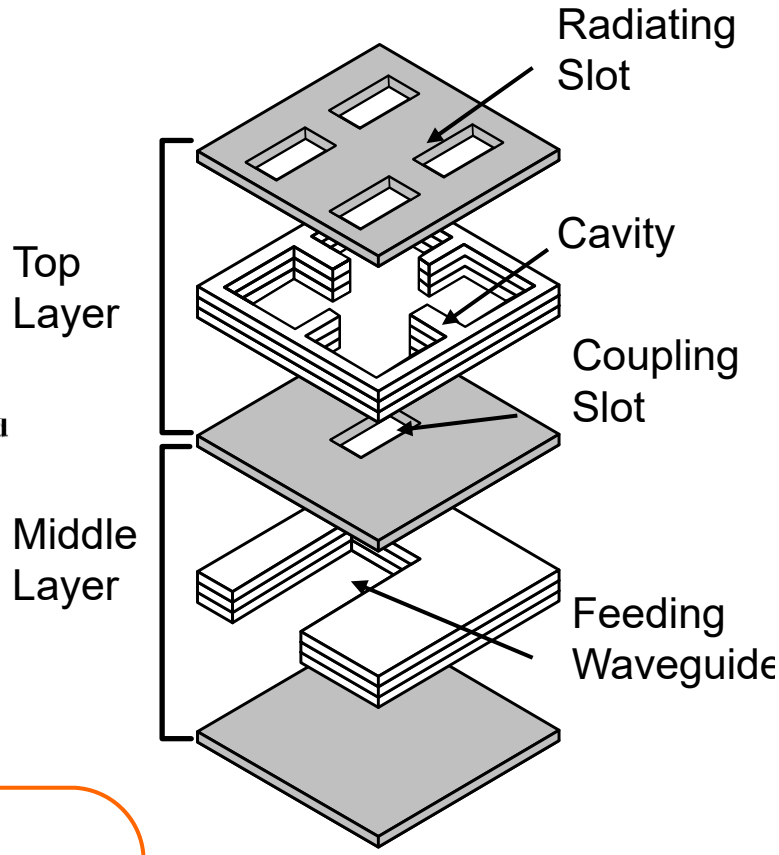
Monopulse corporate feed slotted WG array

Monopulse Corporate Feed Slotted Waveguide Array



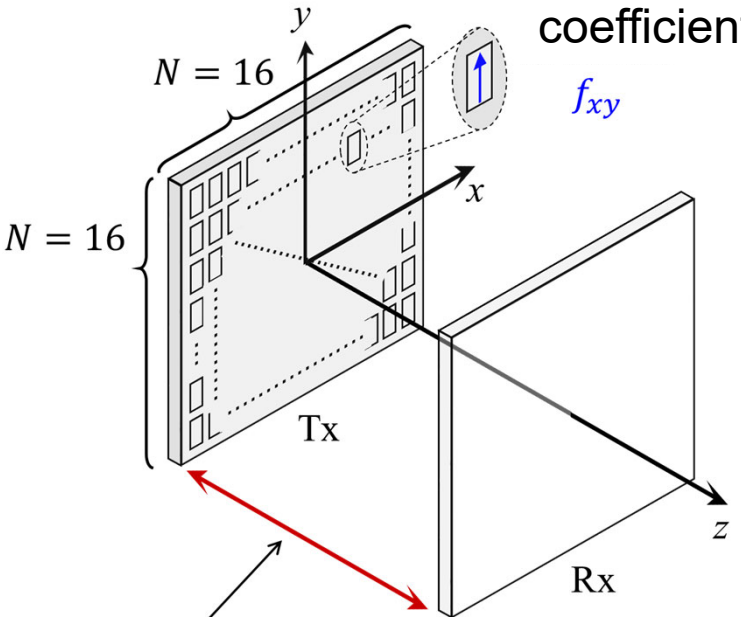


f_0 = 78.5 GHz
Array Size: 16×16
Ant. Thickness: 5.8 mm
Etching Patterns: 10
Plates used: 29 copper plates
Feeding: Full-corporate
Fabrication: Diffusion bonding

Coupling coefficient

- Coupling between radiating field of Tx antenna and aperture field of Rx antenna

$$T_{rt}(f_{xy}, z) = \frac{\iint_{Sr} \boldsymbol{E}_r(f_{xy}, z) \cdot \boldsymbol{E}_t\,(f_{xy}, z)^* dS}{\iint_{Sr} |\boldsymbol{E}_r(f_{xy}, z)| dS \iint_{St} |\boldsymbol{E}_t(f_{xy}, 0)| dS}$$

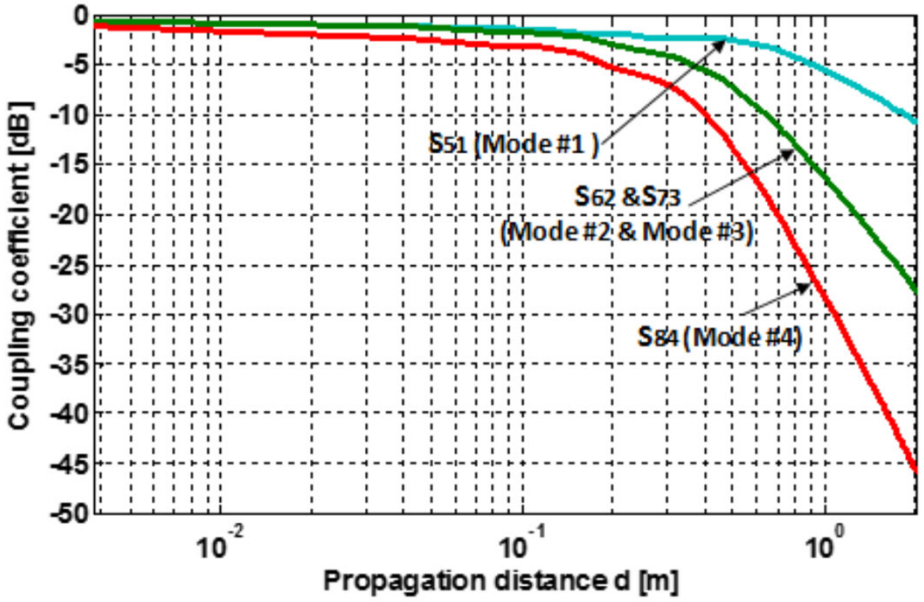


Far-field approximation

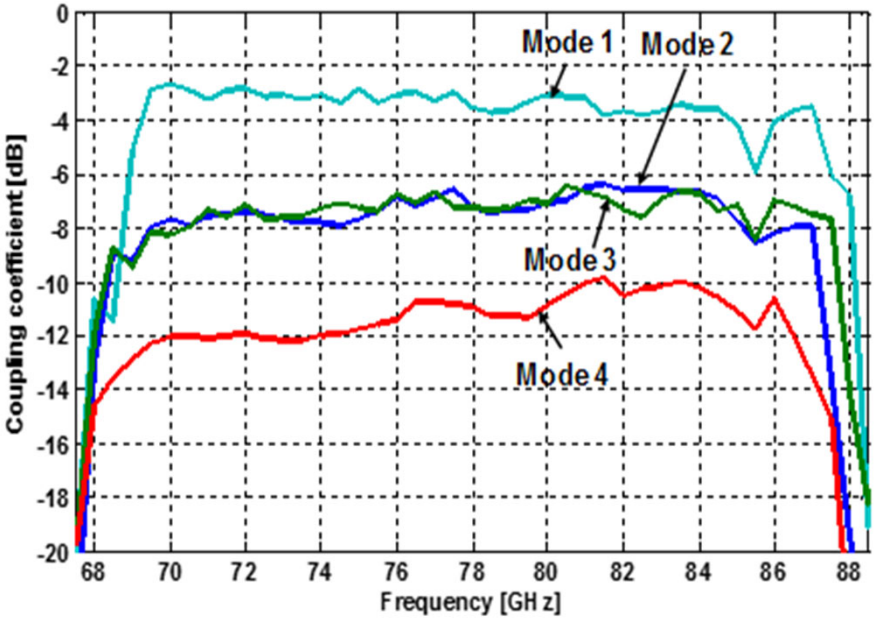
$E_t(f_{xy}, 0)$	:	aperture field of Tx antenna
$E_t(f_{xy}, z)$	:	radiating field of Tx antenna
$E_r(f_{xy}, z)$	:	aperture field of Rx antenna

Simulated results

Distance dependence (78.5GHz)

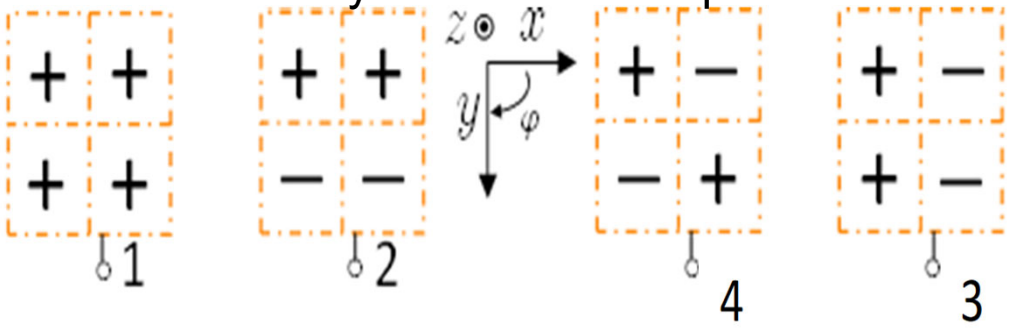


Frequency dependence (41cm)

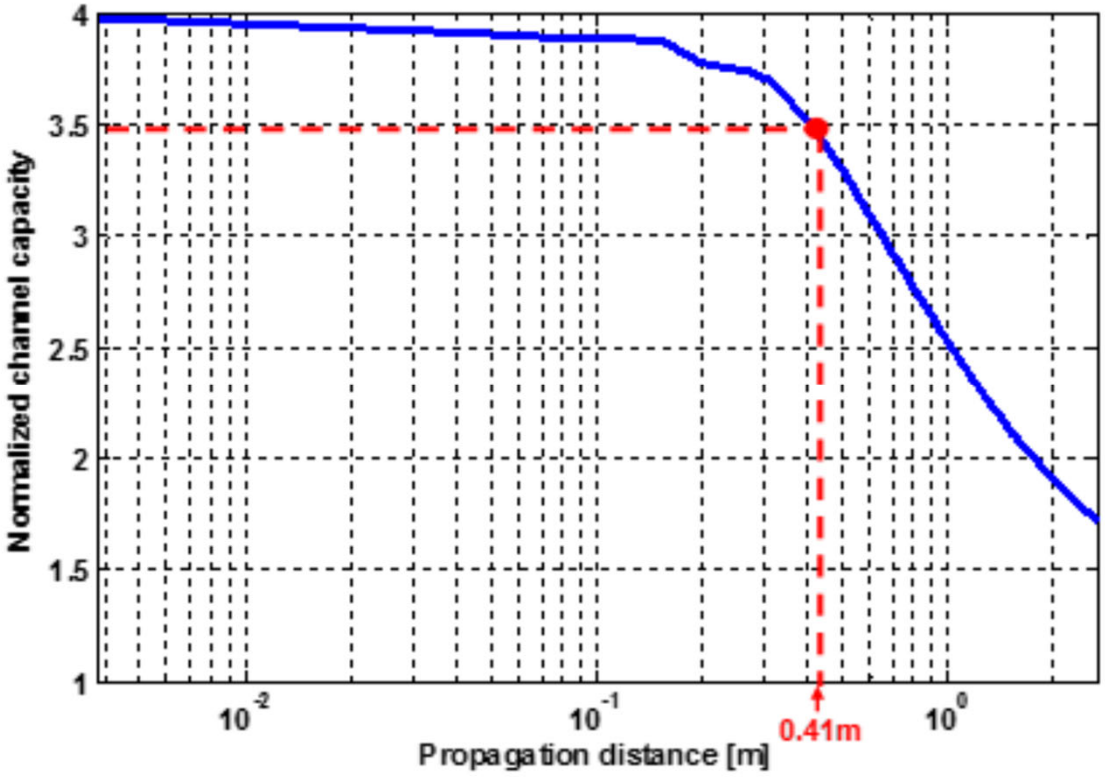


Array size: 50.88mm (13.32 λ) square, Uniform excitation

Beams: 1 pencil boresite | 2 separated in y-dir. | 4 separated oblique | 2separated in x-dir.



Capacity gain (simulated)



$$\text{Normalized } C_{ROM} = \frac{B \log_2 \left\{ \det \left(\mathbf{I} + \mathbf{H}^{\dagger} \frac{P_t}{N} \mathbf{H} \right) \right\}}{B \log_2 \left(1 + \frac{P_t}{N} |T_{11\,uni.}|^2 \right)}$$

Each of 4 subarrays is fed an equal power.
SNR=30dB

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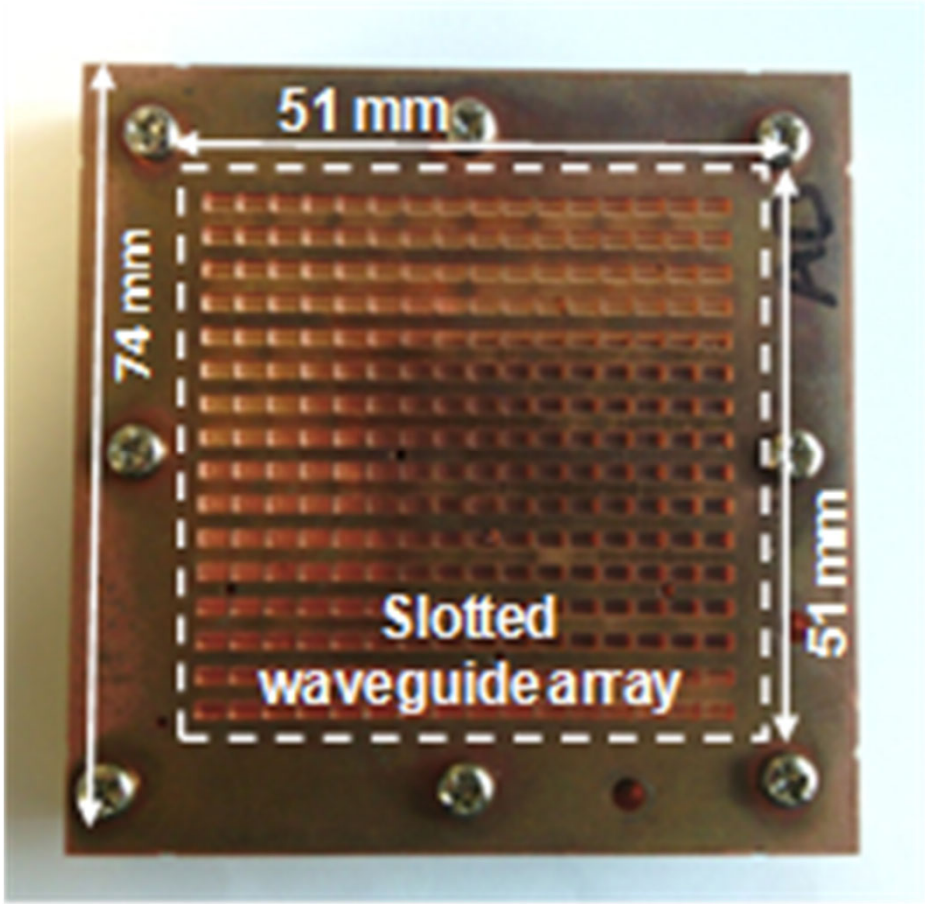
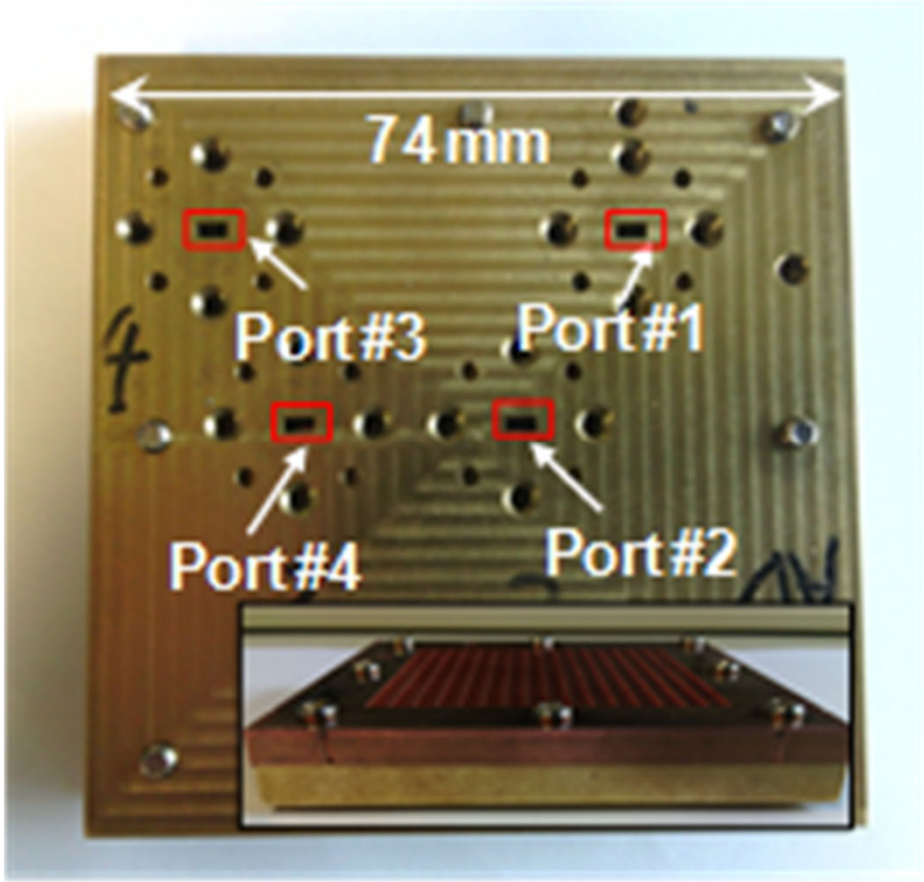
Antenna pictures

Top view

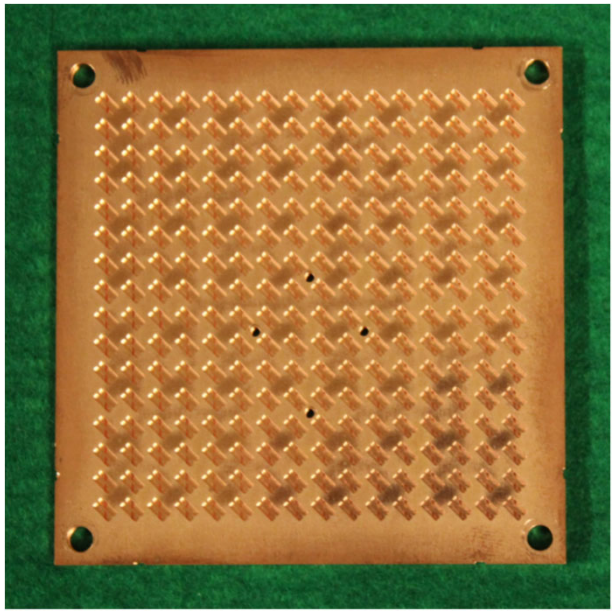


Bottom view

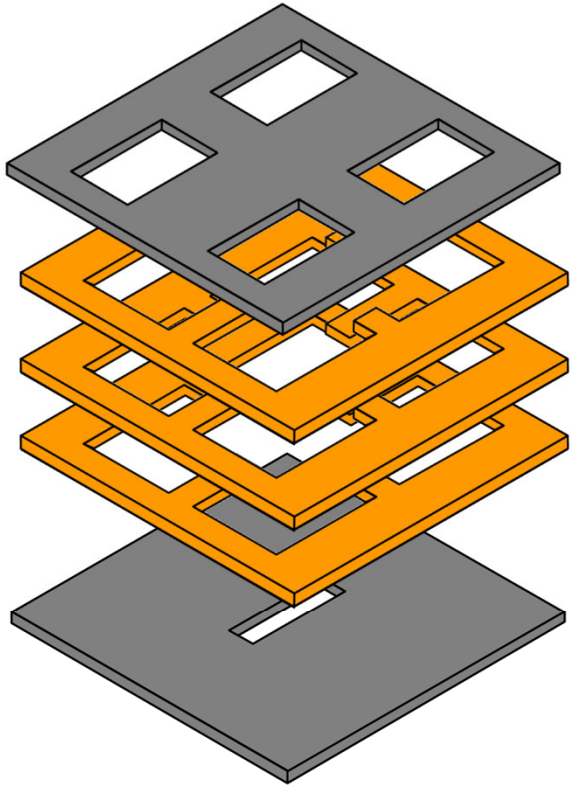


Side view

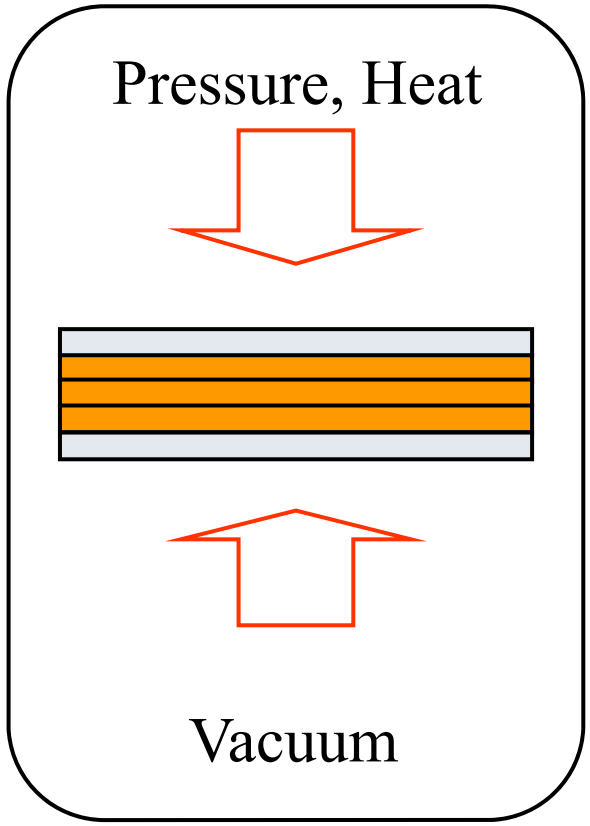
Diffusion bonding of laminated thin metal plates



1.Etching thin metal plates



2.Diffusion bonding



- Hollow waveguide: low loss, corporate feed: wide bandwidth
- Etching: high precision ($20\mu m$), diffusion bonding: electric contact
- Easy to make multi-layers

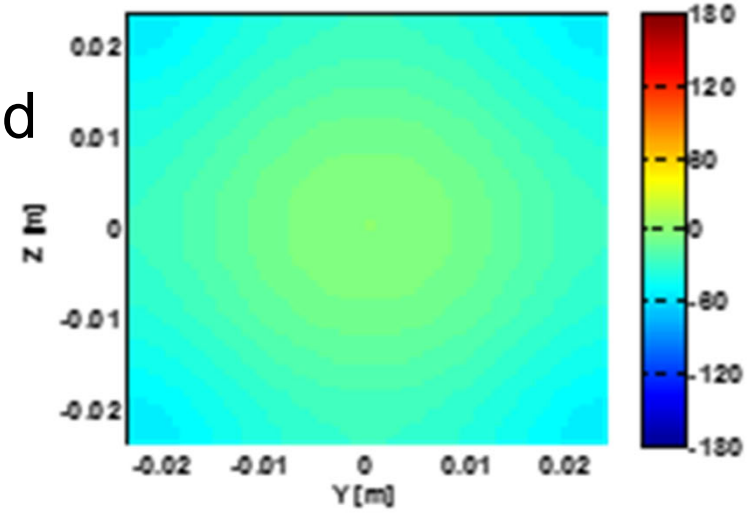
Radiating field at z=41cm at 78.5GHz (Mode 1)

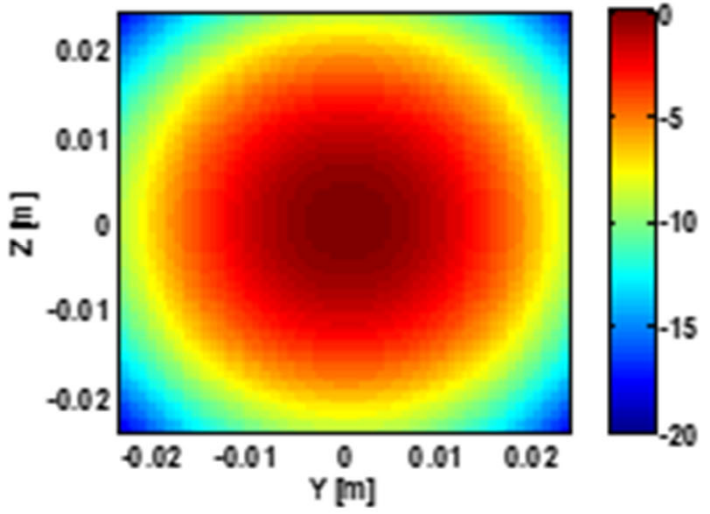
Tokyo Tech

Phase (deg)

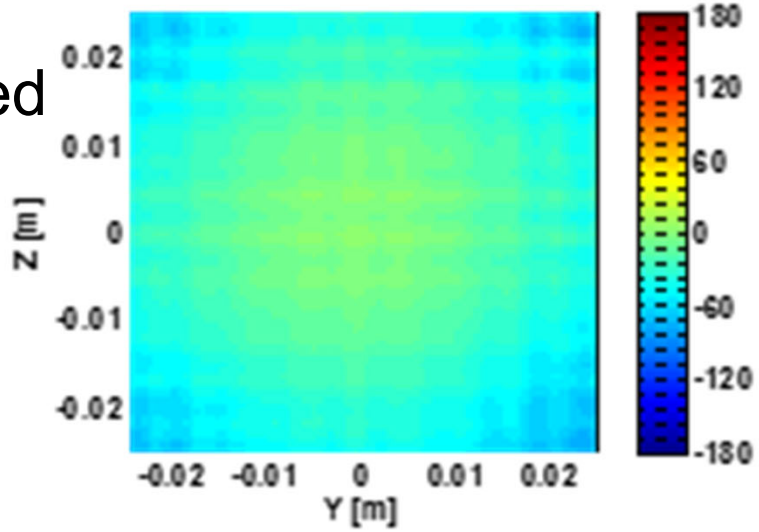
Amplitude (dB)

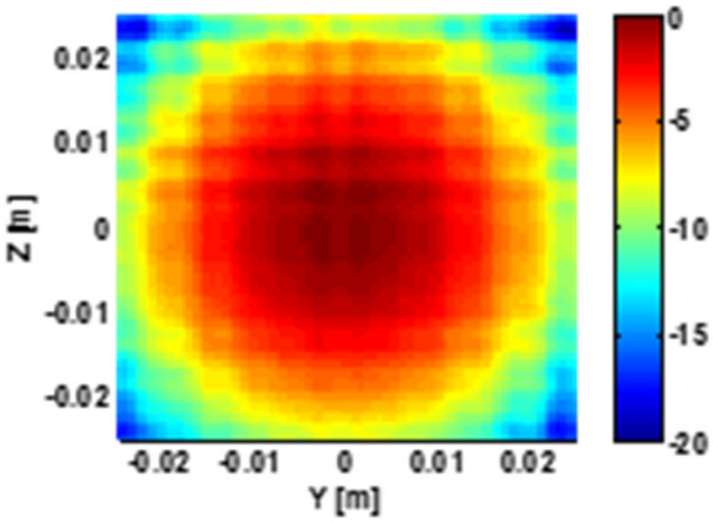
Simulated





Measured





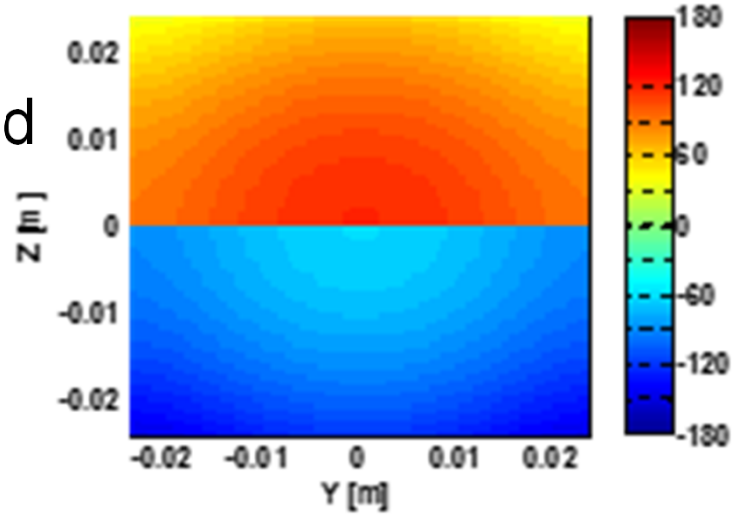
Radiating field at z=41cm at 78.5GHz (Mode 2)

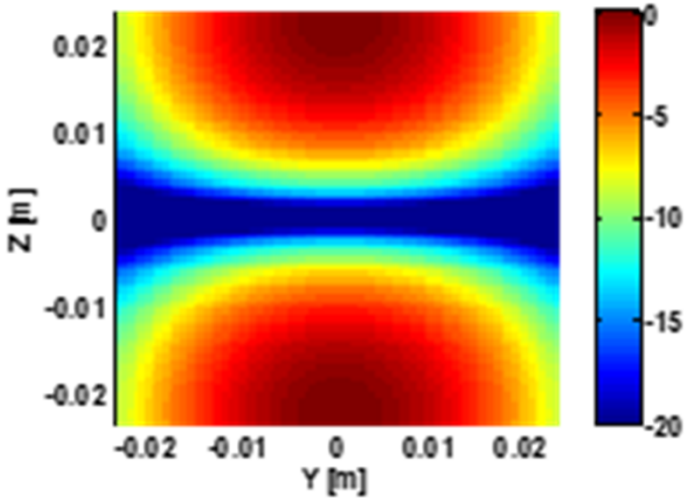
Tokyo Tech

Phase (deg)

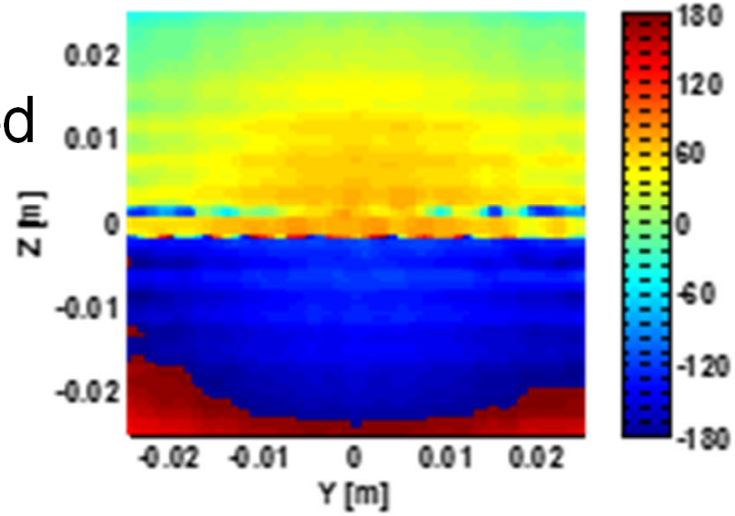
Amplitude (dB)

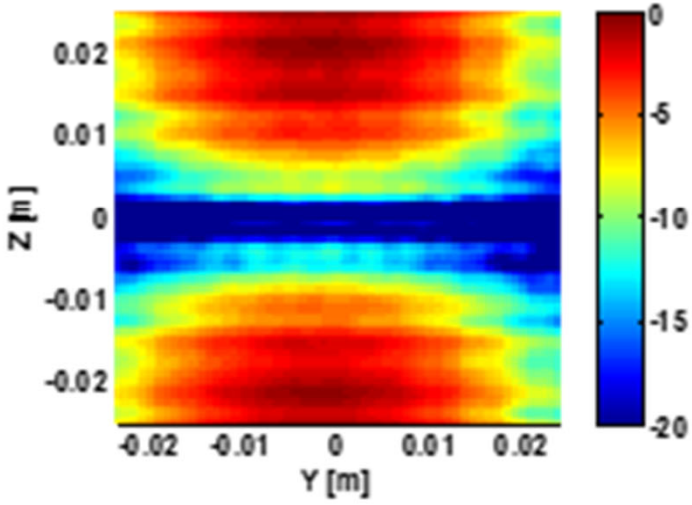
Simulated





Measured



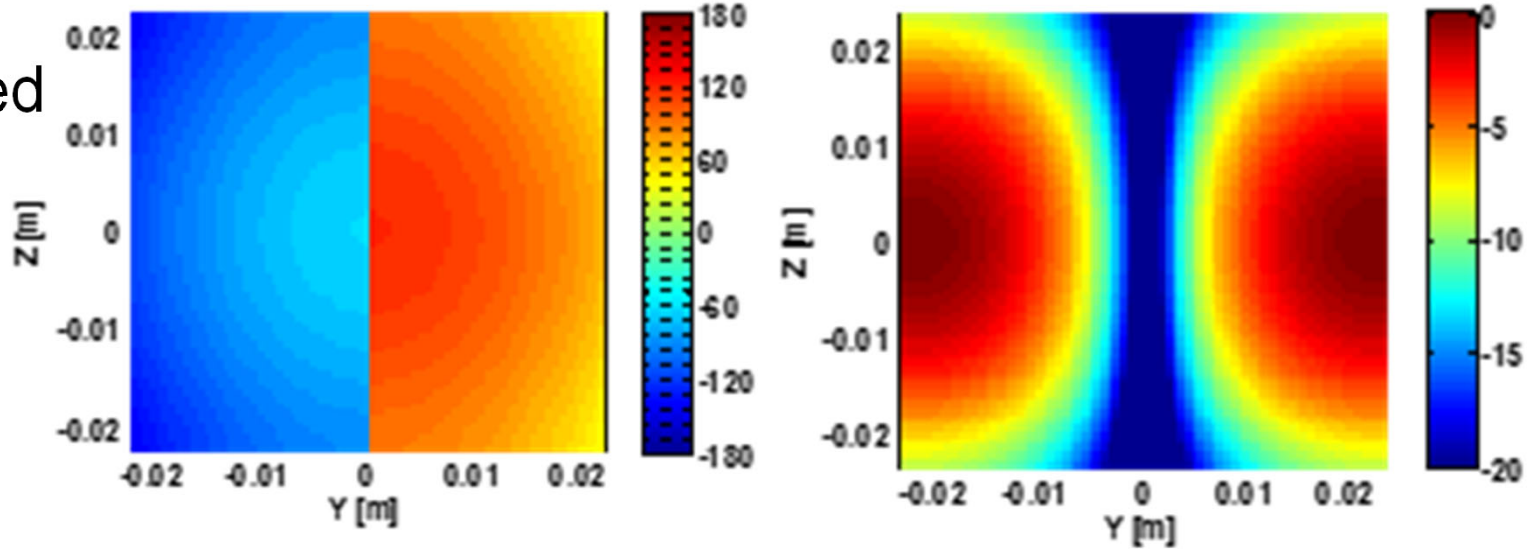


Radiating field at z=41cm at 78.5GHz (Mode 3)

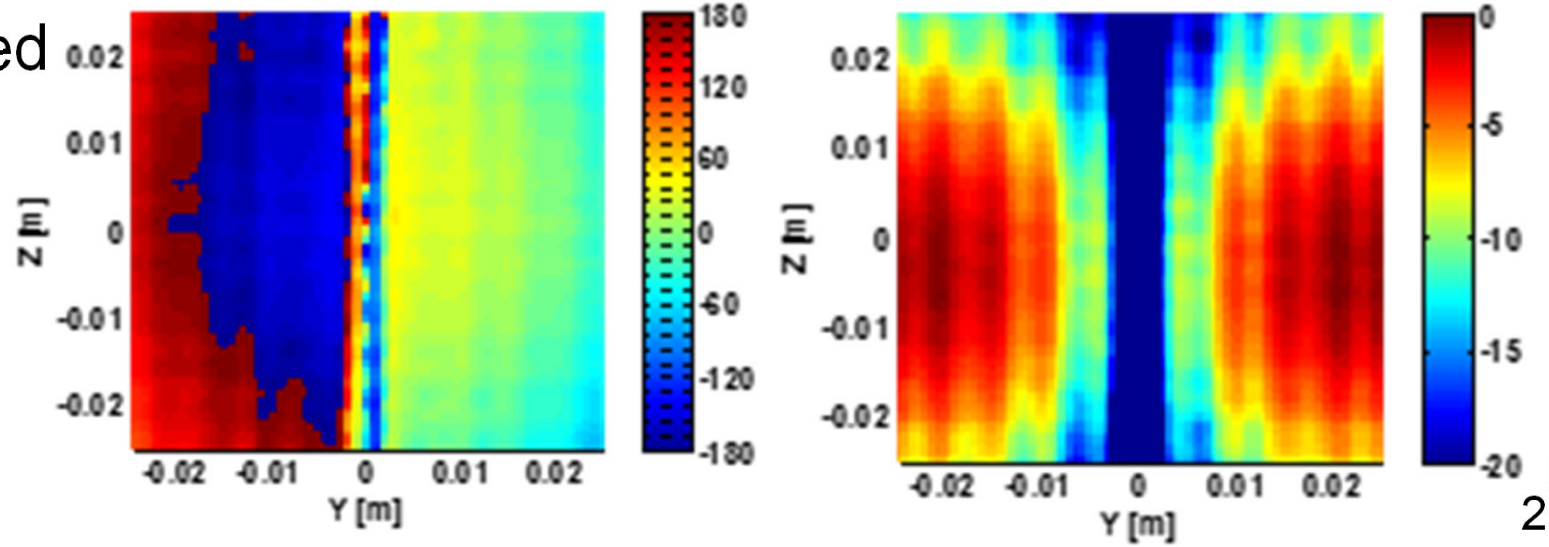
Tokyo Tech

Phase (deg) Amplitude (dB)

Simulated



Measured



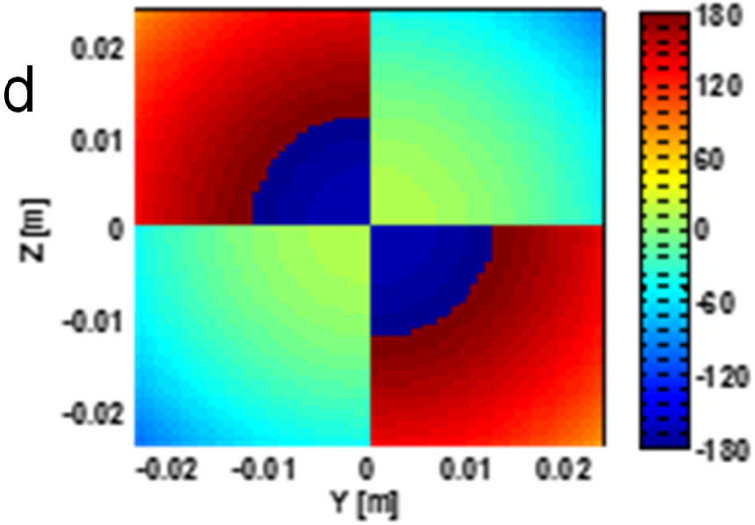
Radiating field at z=41cm at 78.5GHz (Mode 4)

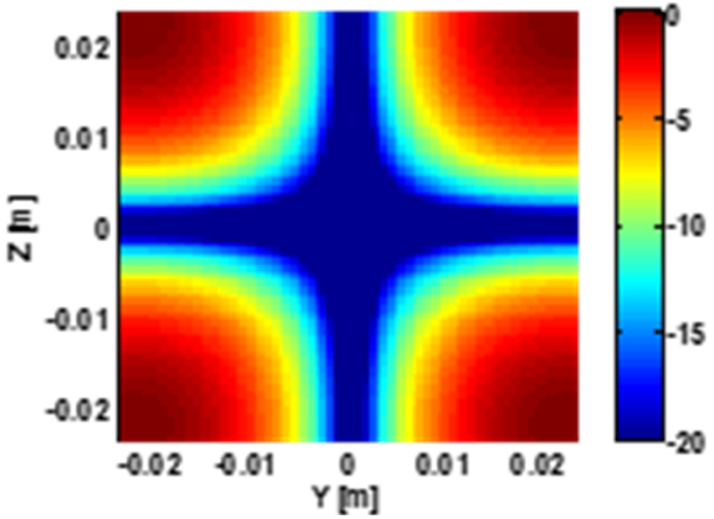
Tokyo Tech

Phase (deg)

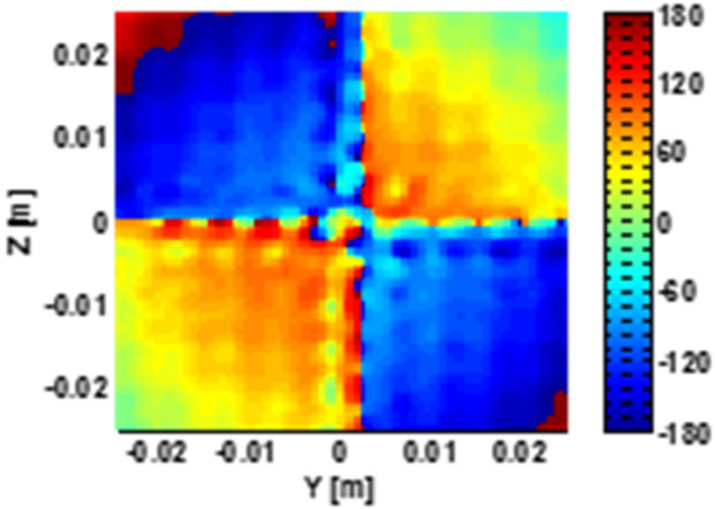
Amplitude (dB)

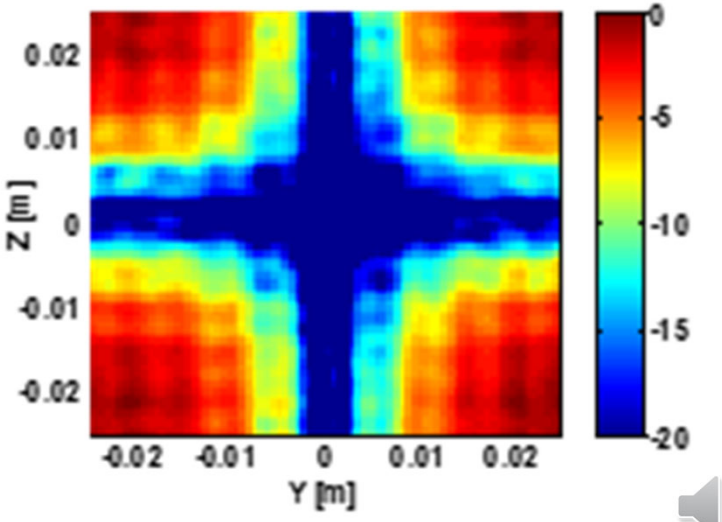
Simulated



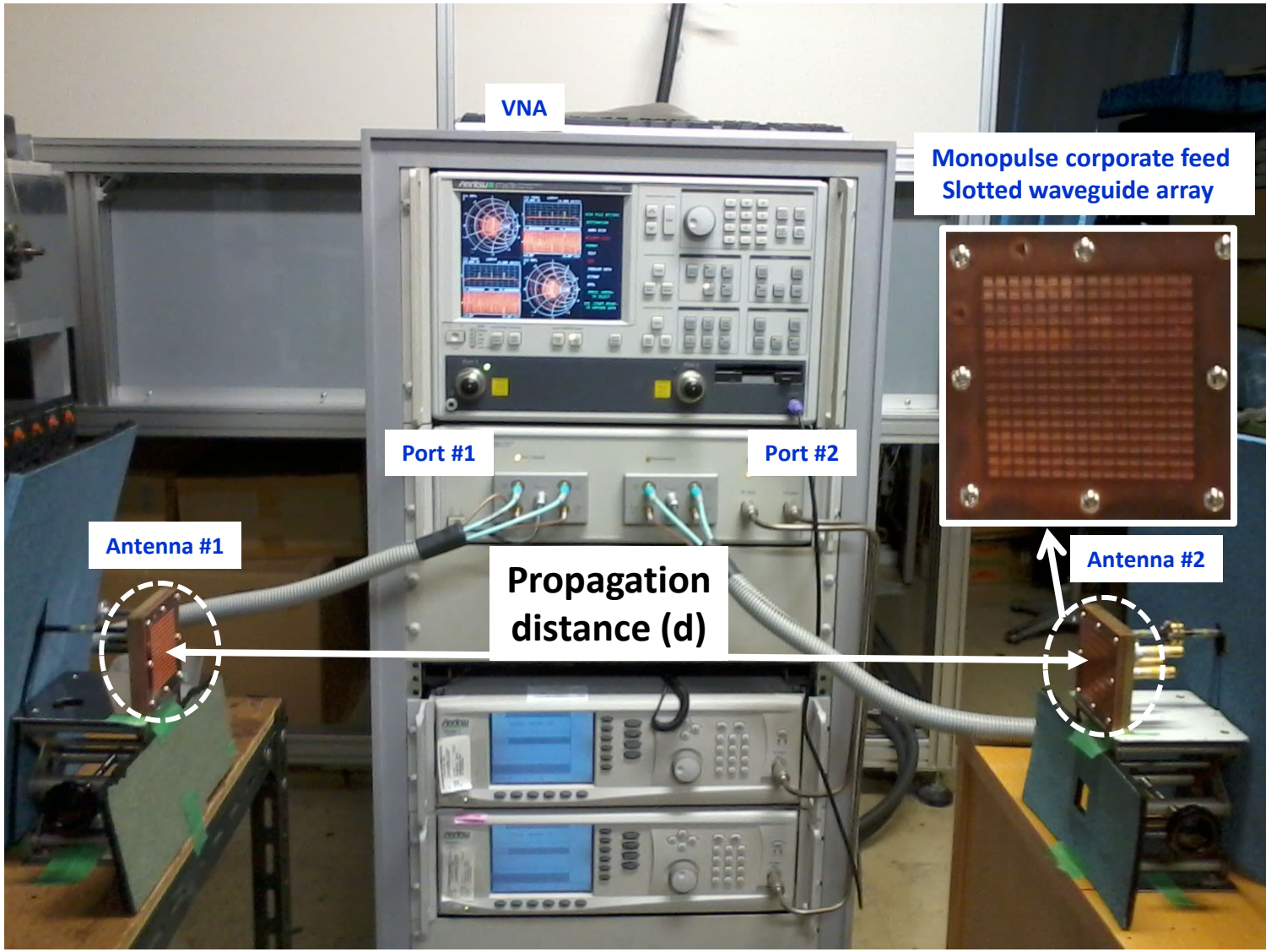


Measured





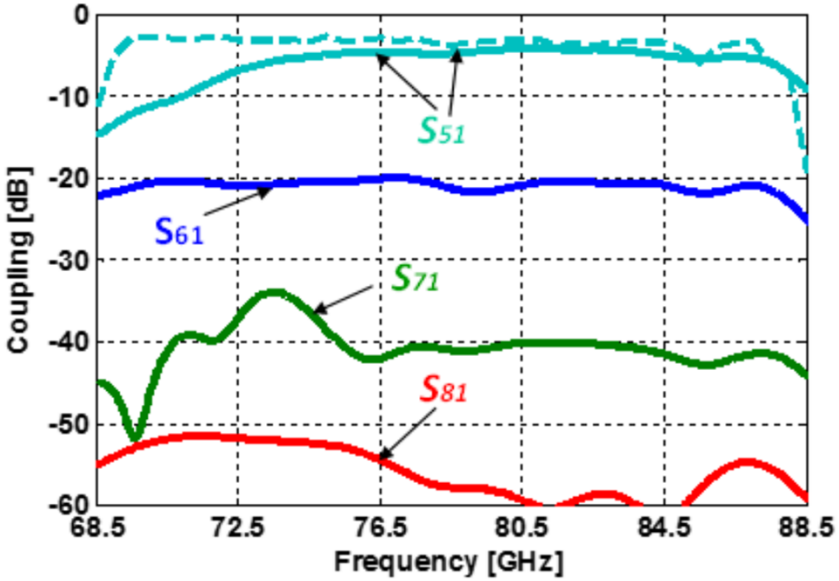
Measurement setup



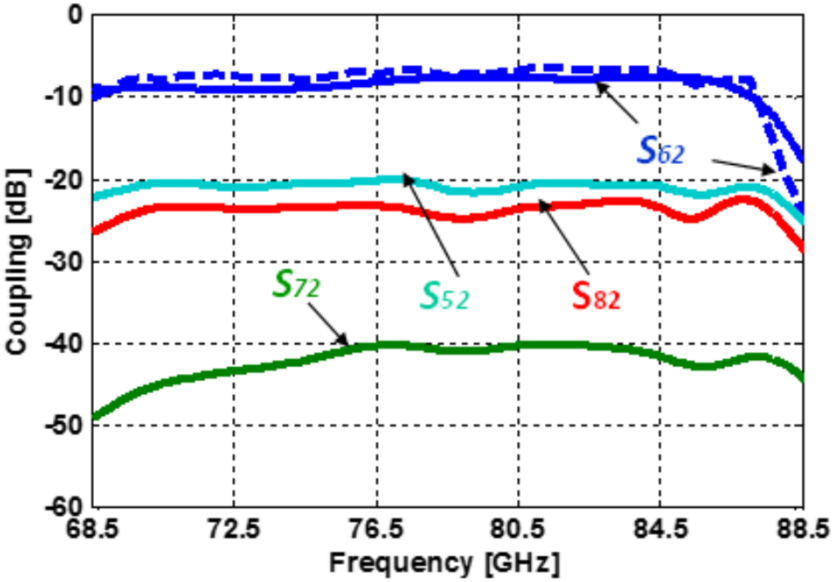
Measured coupling

(Dashed: sim.)

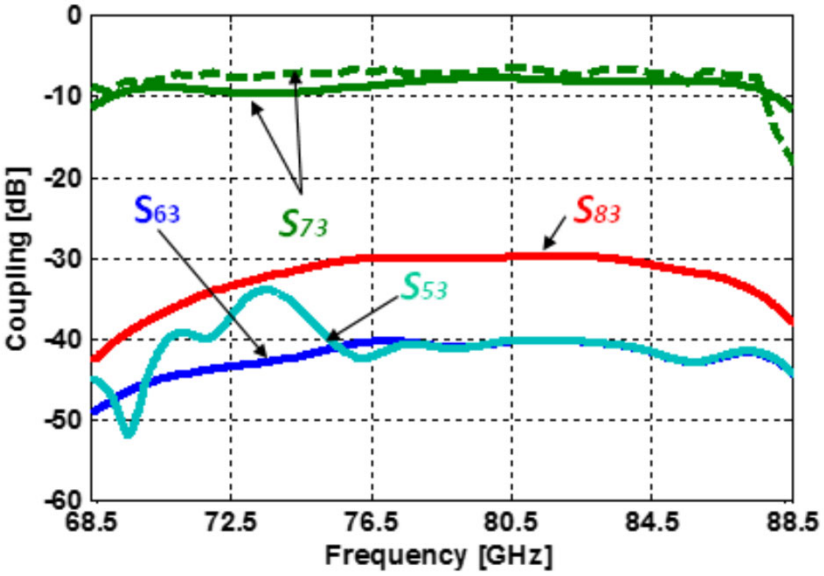
Mode #1



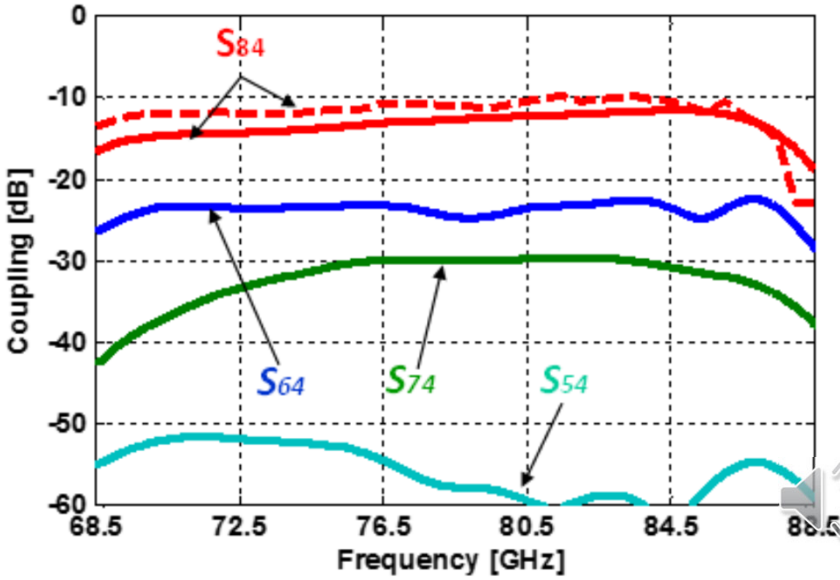
Mode #2



Mode #3

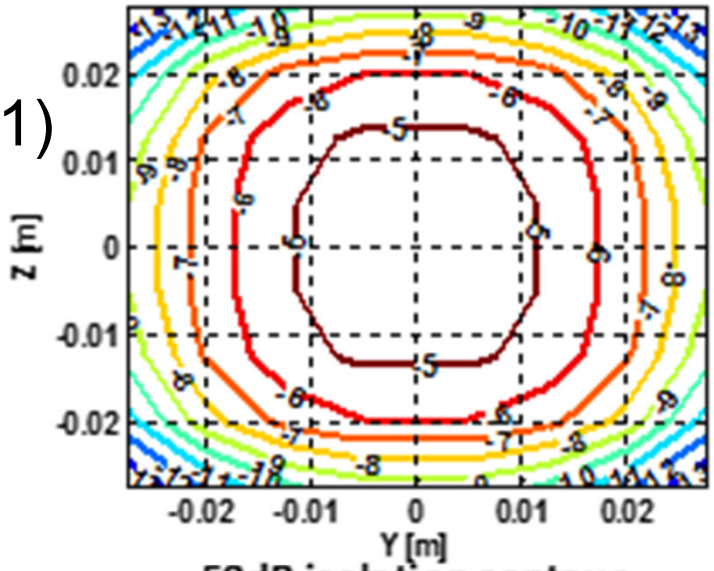


Mode #4

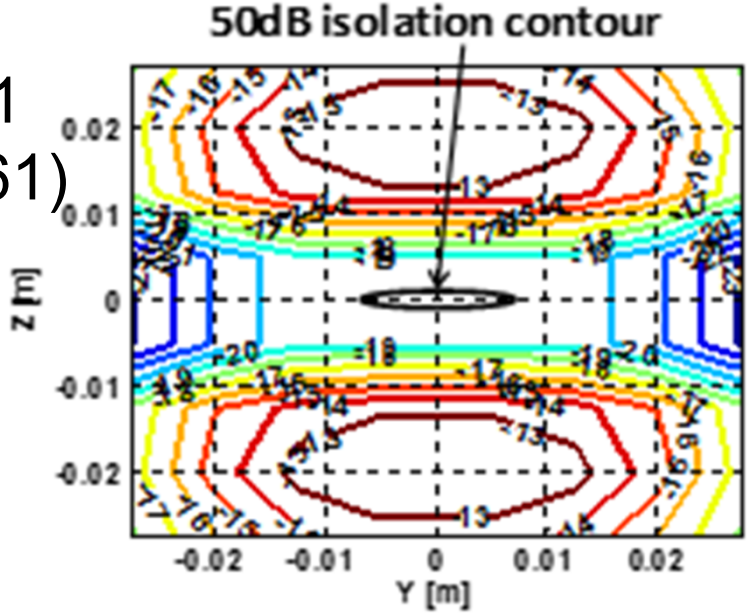


Effect of misalignment (simulated)

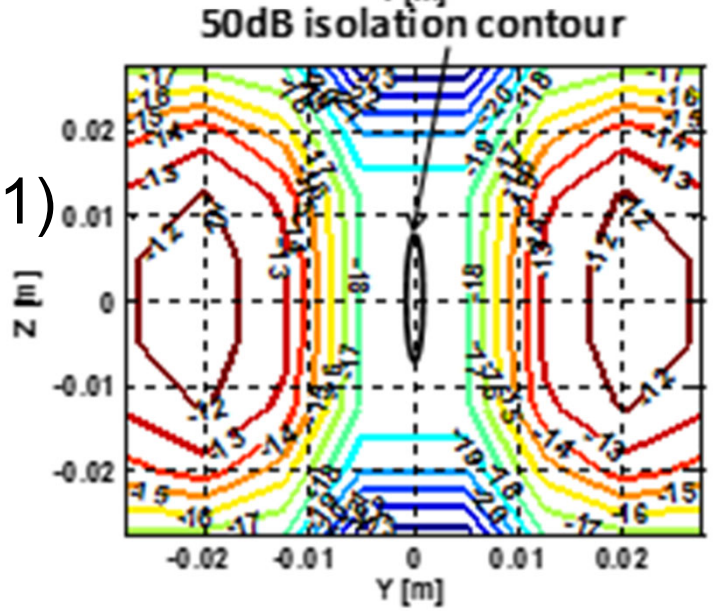
T11
(S51)



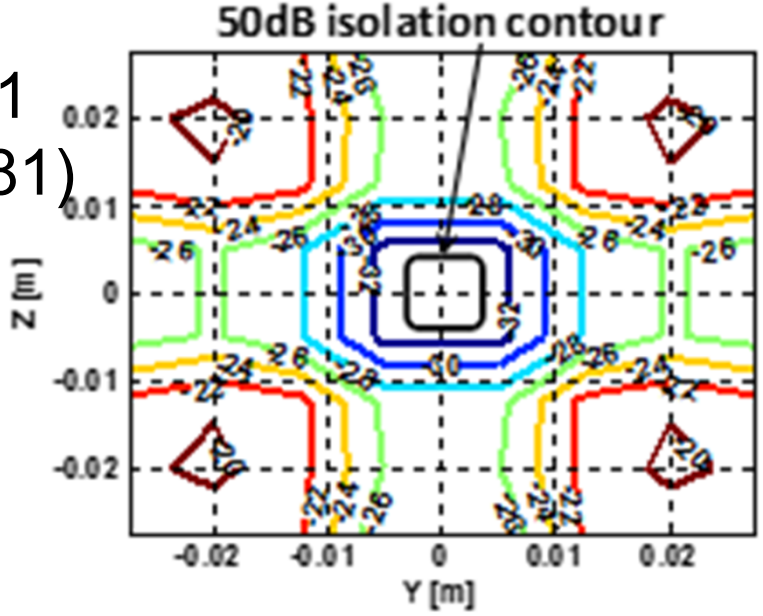
T21
(S61)



T31
(S71)



T41
(S81)



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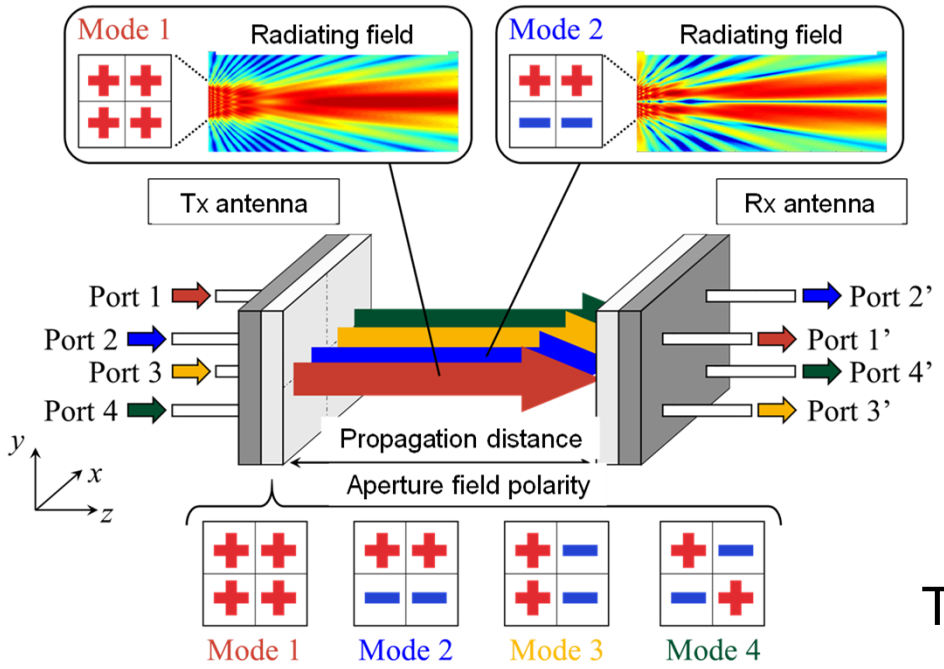
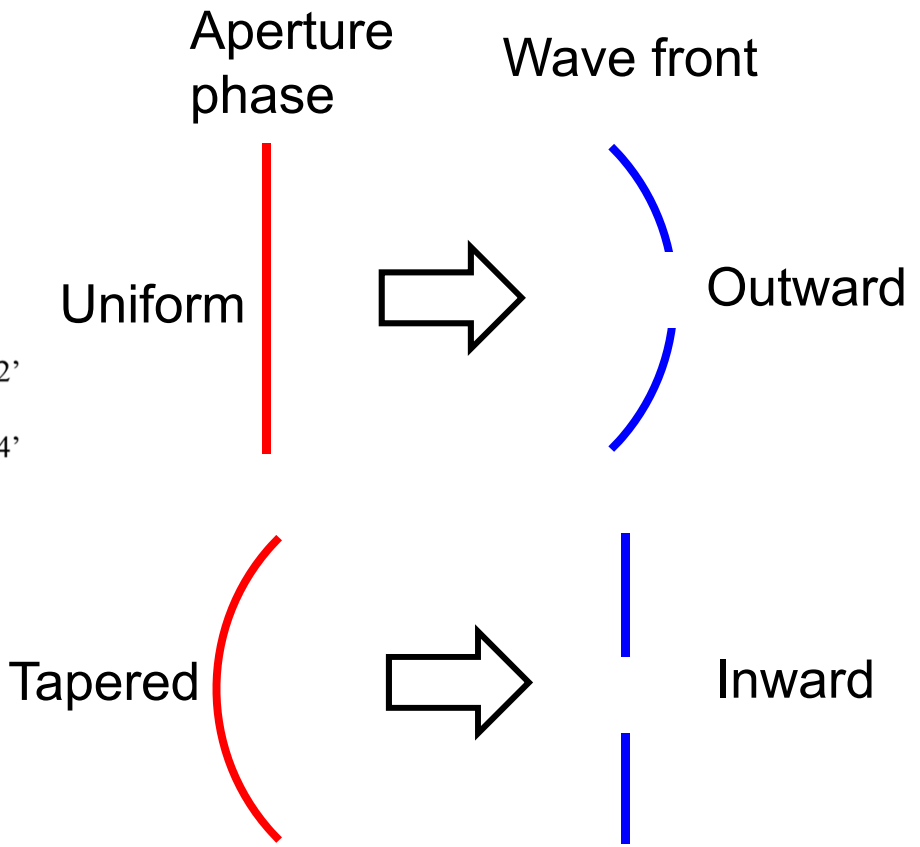
Control of propagation distance



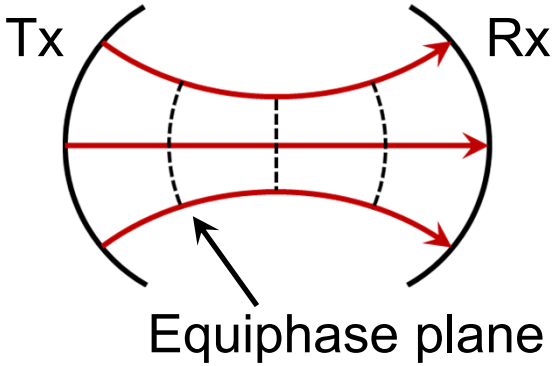


- Null in the boresite → large beam separation for long distance
- Phase taper in aperture → beam direction inward
  → long propagation distance

Design of aperture field distribution

- Amplitude & Phase taper

(EM field on Rx plane by Tx ant.)
= (Aperture distribution of Rx ant.)



- Mathematical optimization

✓ Analysis parameters

Frequency	61.5 GHz
Antenna size	16x16-elements (13.3λ x 13.3λ)
Distance	0.4m (82λ)
Number of modes	4

✓ Design parameters

- Amplitude taper : 10 parameters
  - (one eighth + α) elements
  - Pair excitation : 36 ⇒ 10 parameters
- Phase taper : 1 parameter
  - Shape : Parabola (Rotationally sym.)
  - $phase$

$$f(r) = phase \times r^2$$

✓ Objective function

$$\max.\left\{\prod_{i=1}^{4} T_{ii}(z_0)\right\}$$

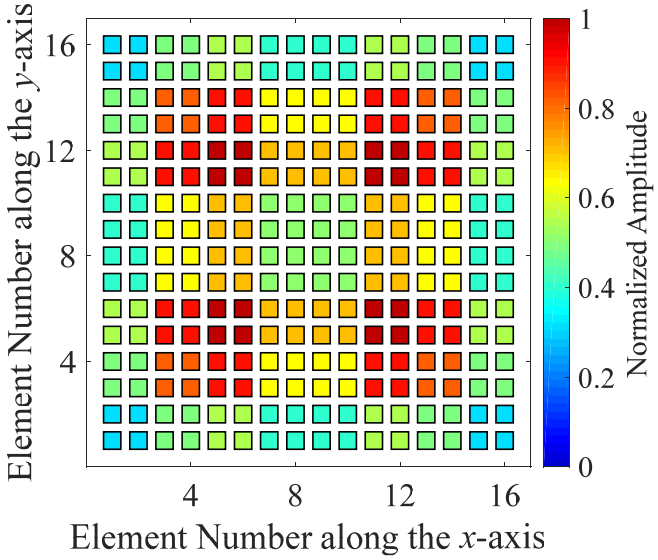
$$C = \sum_{i=1}^{4} B\log_2\left(1+\frac{P_t}{N}|T_{ii}|^2\right) \cong B\log_2\left(\frac{P_t}{N}|T_{ii}|^2\right) \text{ (if } |T_{ii}|^2 \gg 0\text{: in non} - \text{far region)}$$

$$\propto \sum_{i=1}^{4}\log_2(|T_{ii}|) \Rightarrow \prod_{i=1}^{4}|T_{ii}|$$

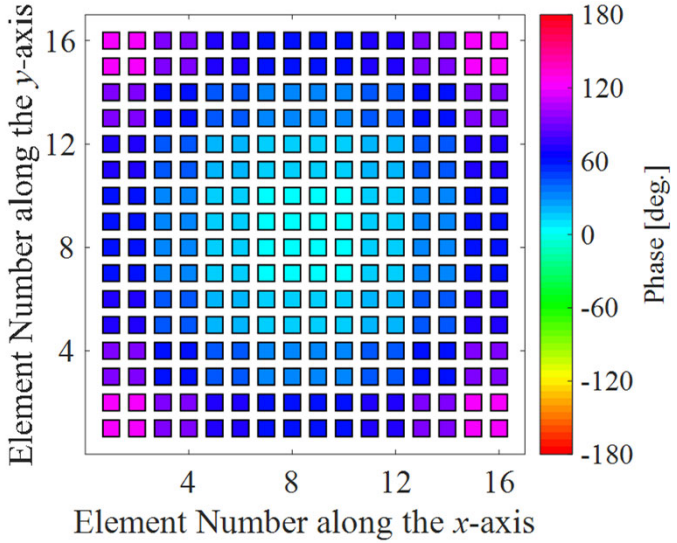
T_{nm}: transmission between Mode m (Tx) and Mode n (Rx)

Optimization result (0.4m)

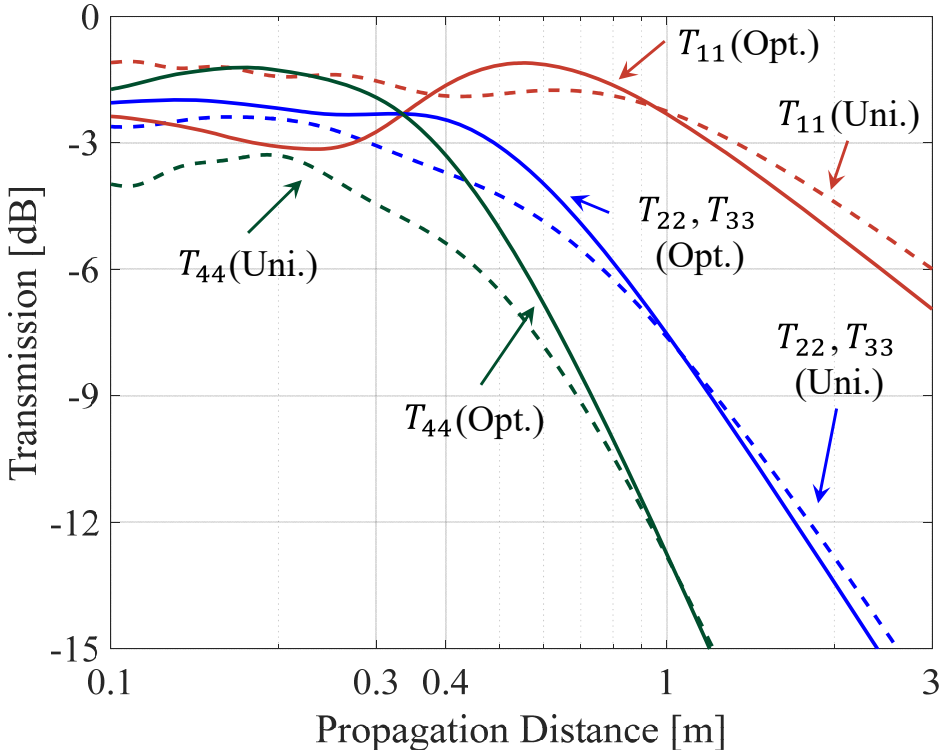
Amplitude



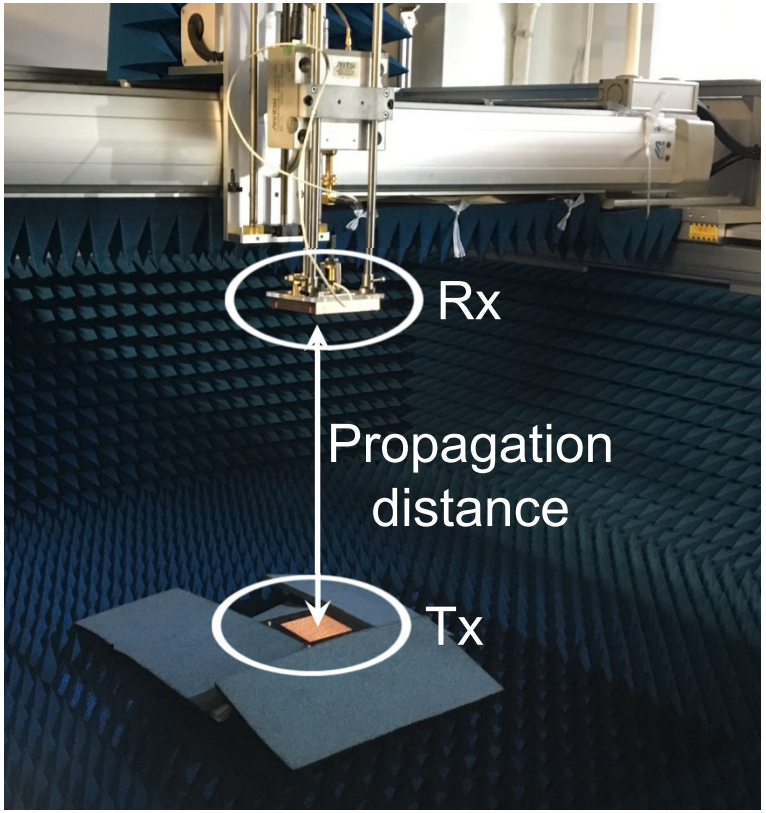
Phase



Transmission



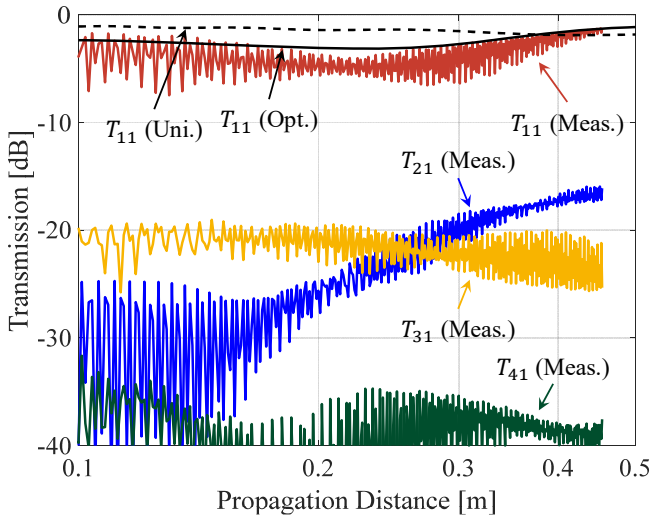
Measurement



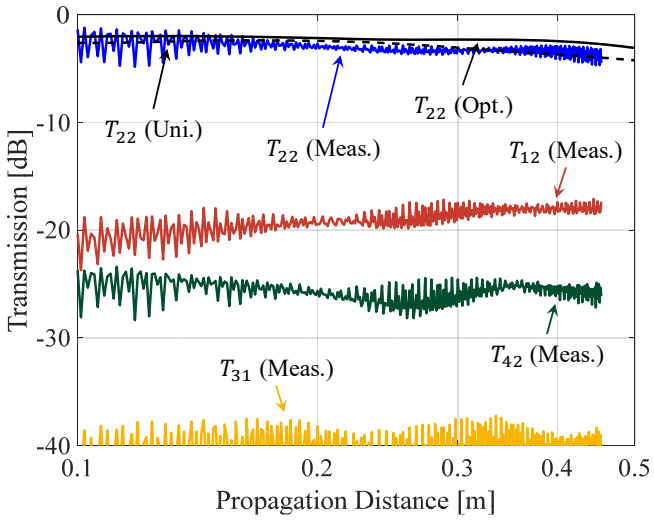
Frequency	61.5 GHz
Propagation distance	55-454 mm
z step	1 mm (400 points)
Tx ant.	fixed

Transmission(61.5GHz)

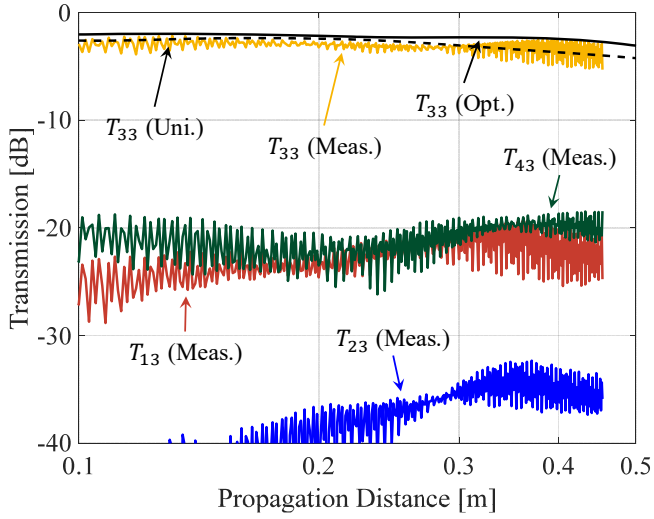
✓ Tx Mode 1



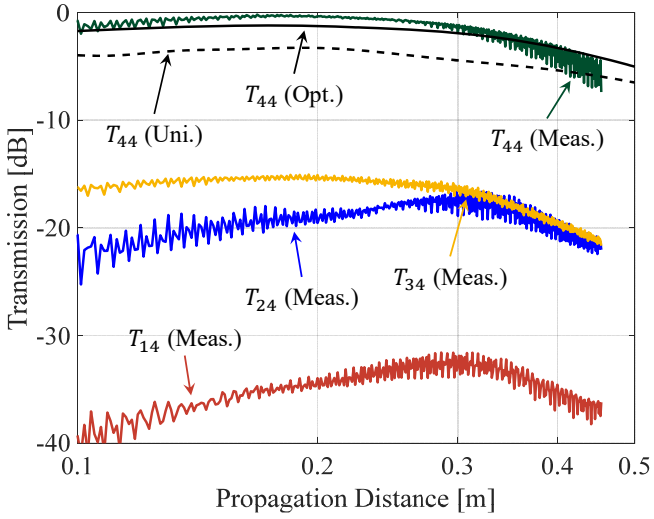
✓ Tx Mode 2



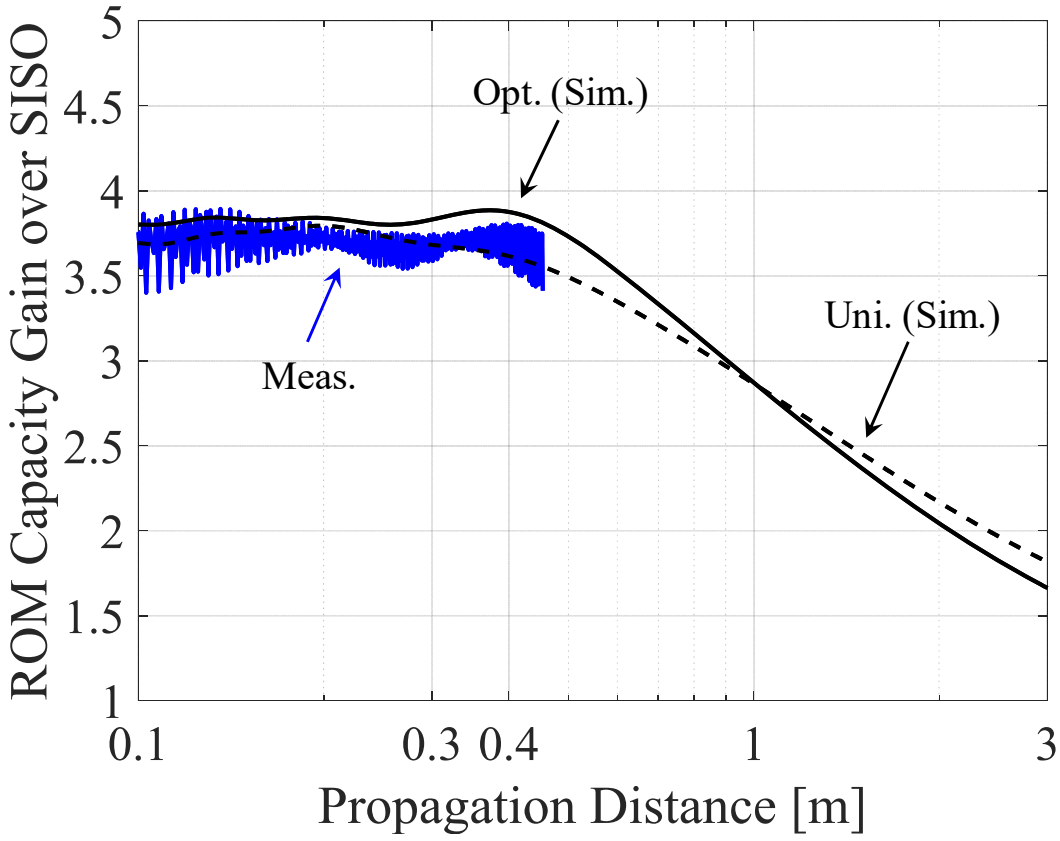
✓ Tx Mode 3



✓ Tx Mode 4



Capacity Gain



S/N=30dB

$$\text{Normalized } C_{ROM} = \frac{B \log_2 \left\{ \det \left(\mathbf{I} + \mathbf{H}^{\dagger} \frac{P_t}{N} \mathbf{H} \right) \right\}}{B \log_2 \left(1 + \frac{P_t}{N} |T_{11\,uni.}|^2 \right)}$$

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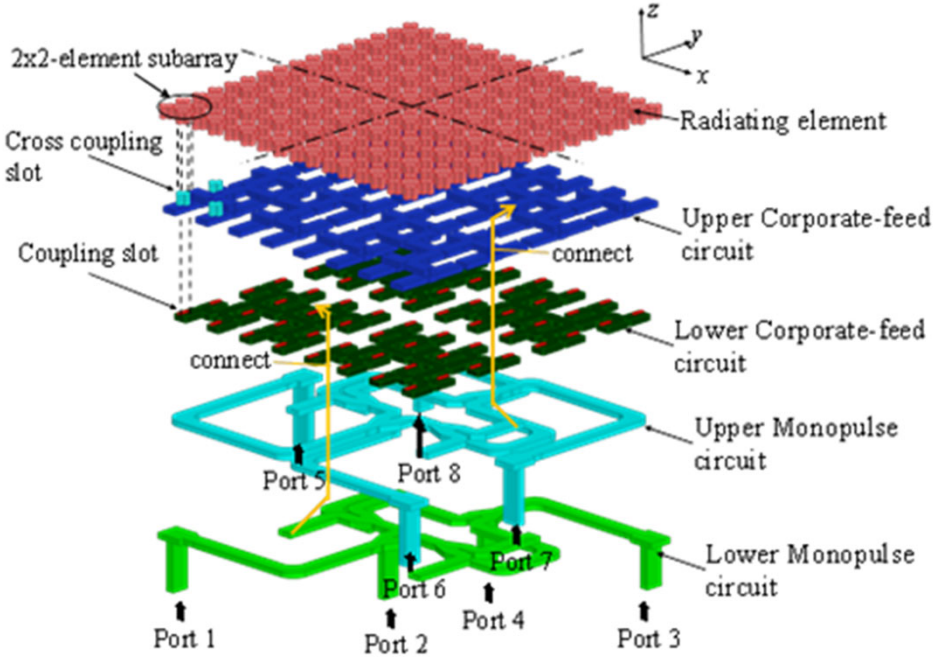
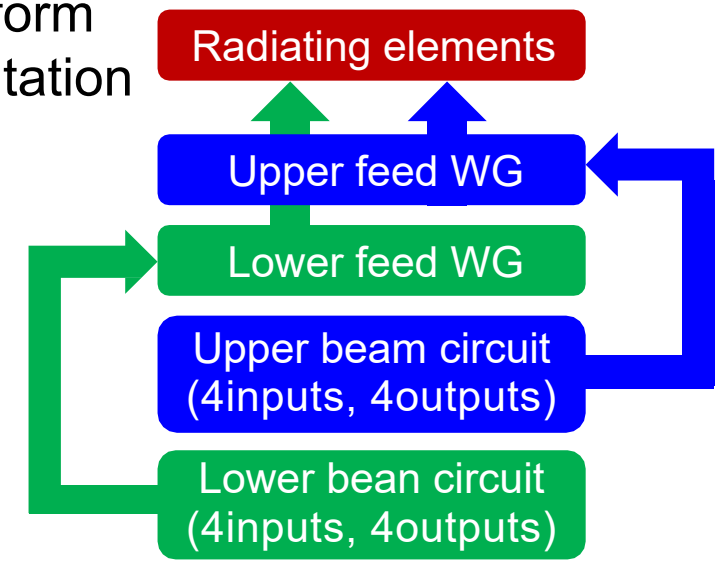
Dual polarization use: 8 modes



Uniform excitation

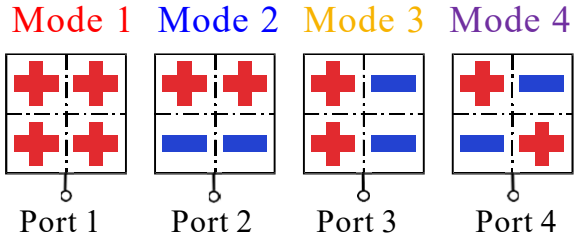


Top layers

Dual-polarized corporate-feed WG slot array

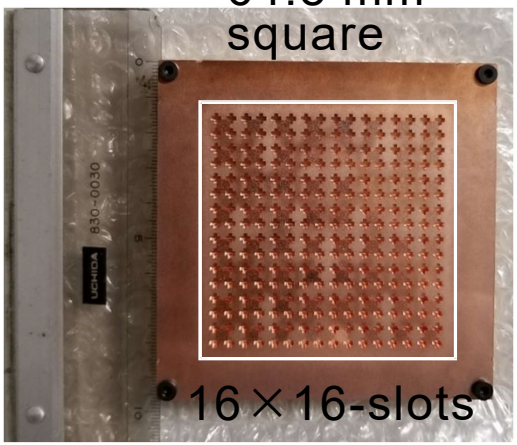
Bottom layers

2-D monopulse circuits

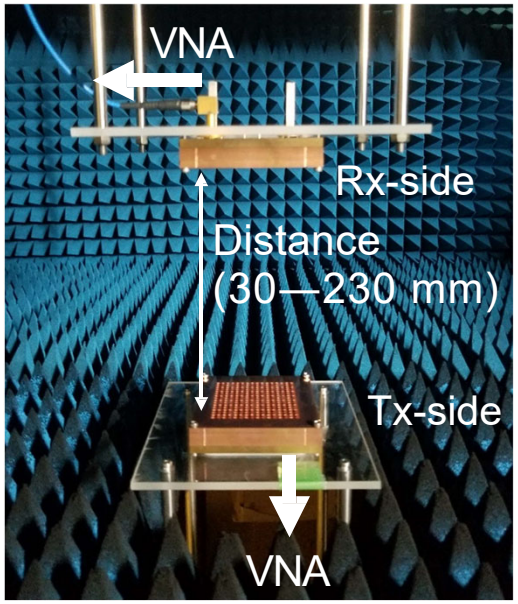


Frequency	57—66 GHz
	WG slot array
Number of elements	16×16 （Four 8x8-element subarrays）
Size	64.8mm square （0.83λ0×16）
Polarization	Linear, dual pol.
Fabrication	Diffusion bonding of thin metal plates

Measured reflections & isolations

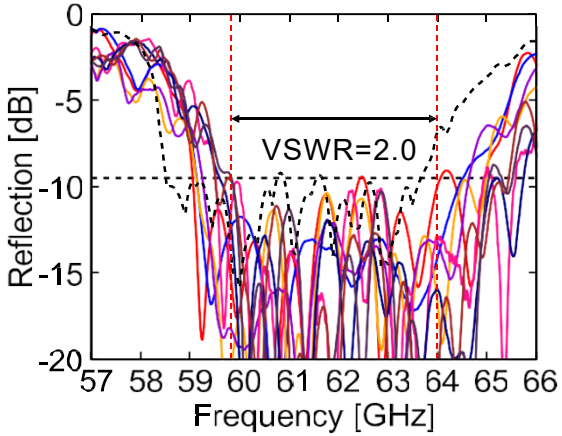


Fabricated antenna



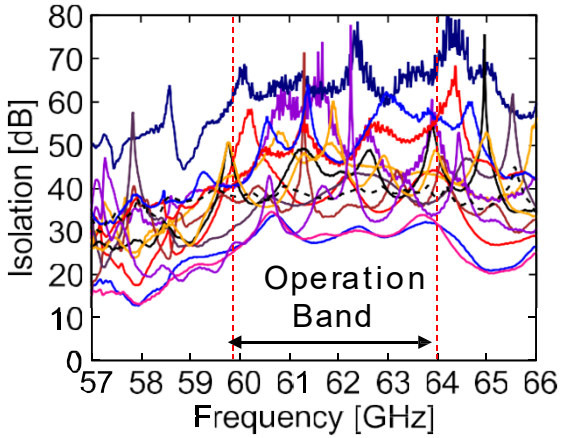
Setup

Reflections



Bandwidth (VSWR≦2.0): 4.2 GHz (59.8-64.0 GHz)

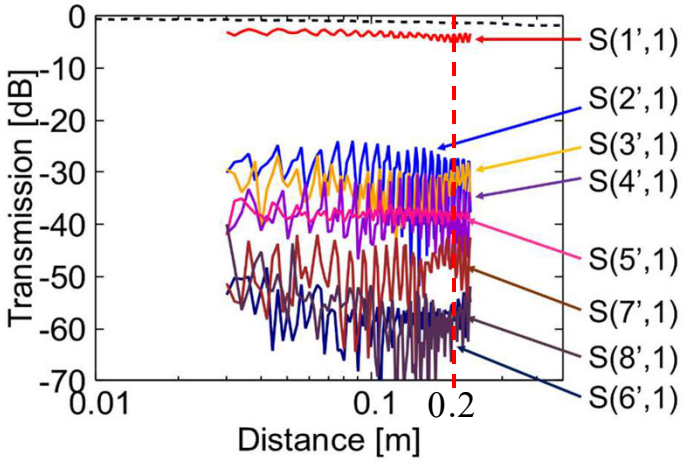
Isolations

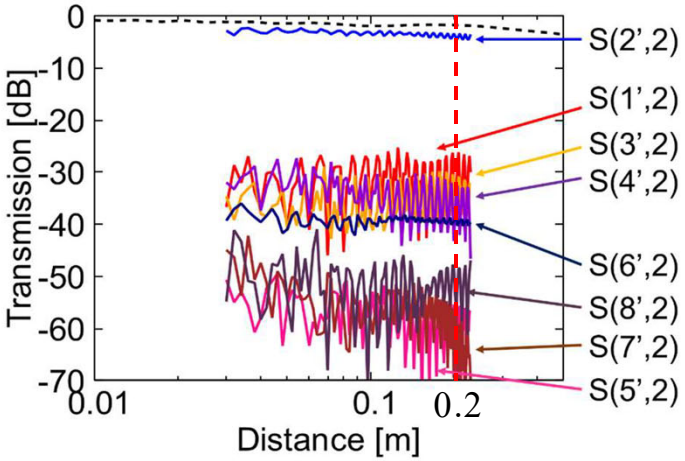


More than 22 dB

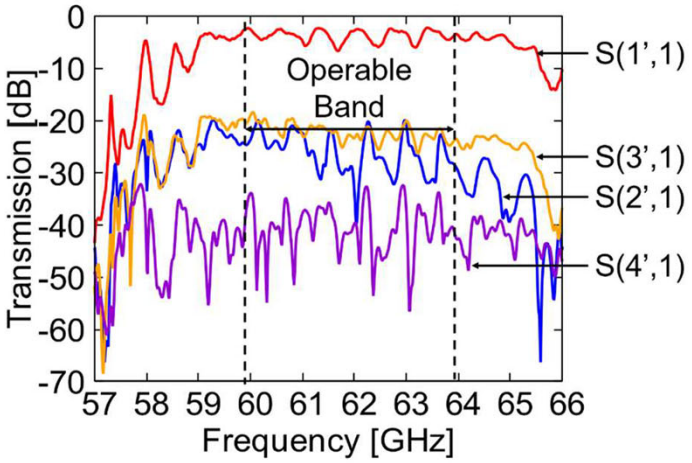
Measured transmissions(1/2)

Distance dependence at 61.5GHz

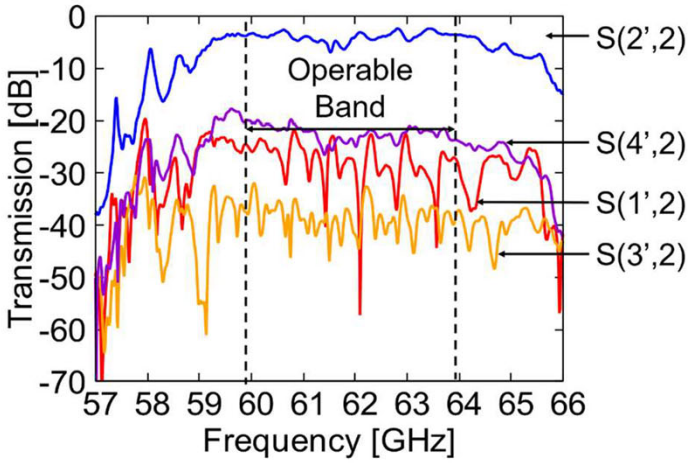




Frequency dependence at z=200mm



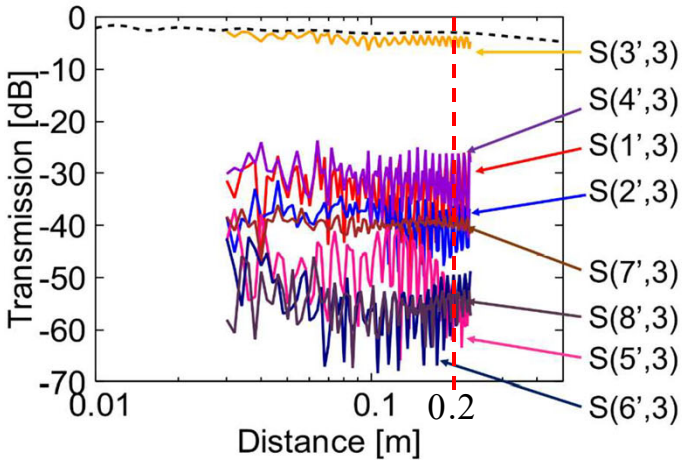
Tx mode: Mode 1

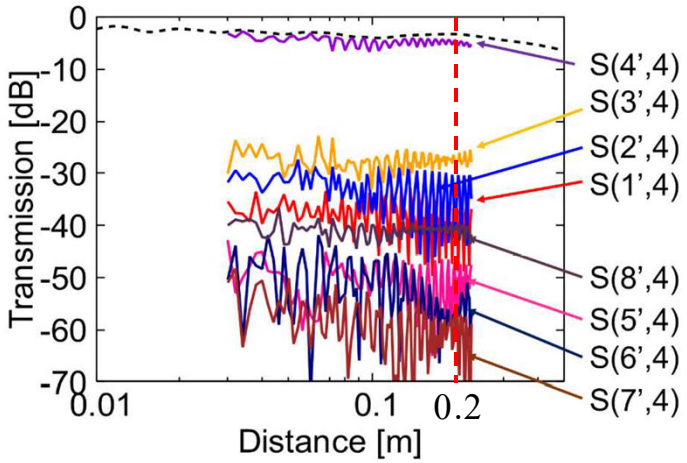


Tx mode: Mode 2

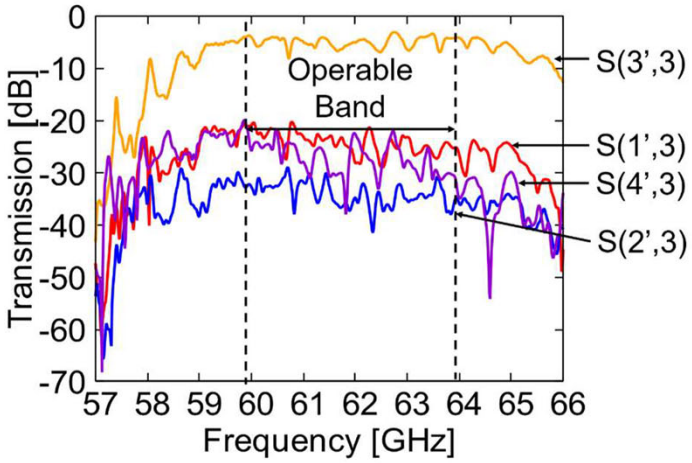
Measured transmissions(2/2)

Distance dependence at 61.5GHz

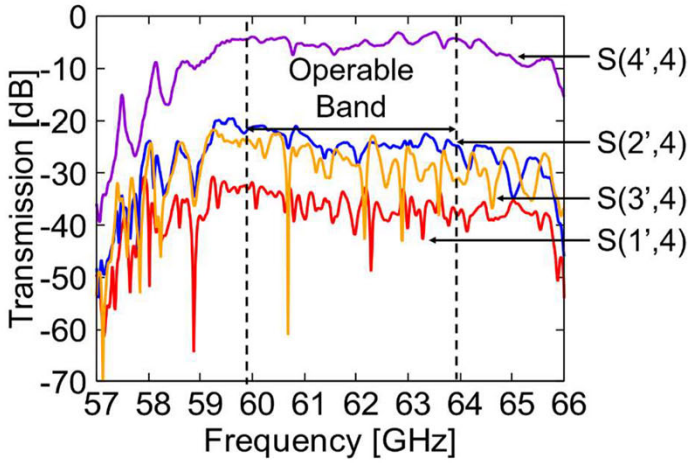




Frequency dependence at z=200mm

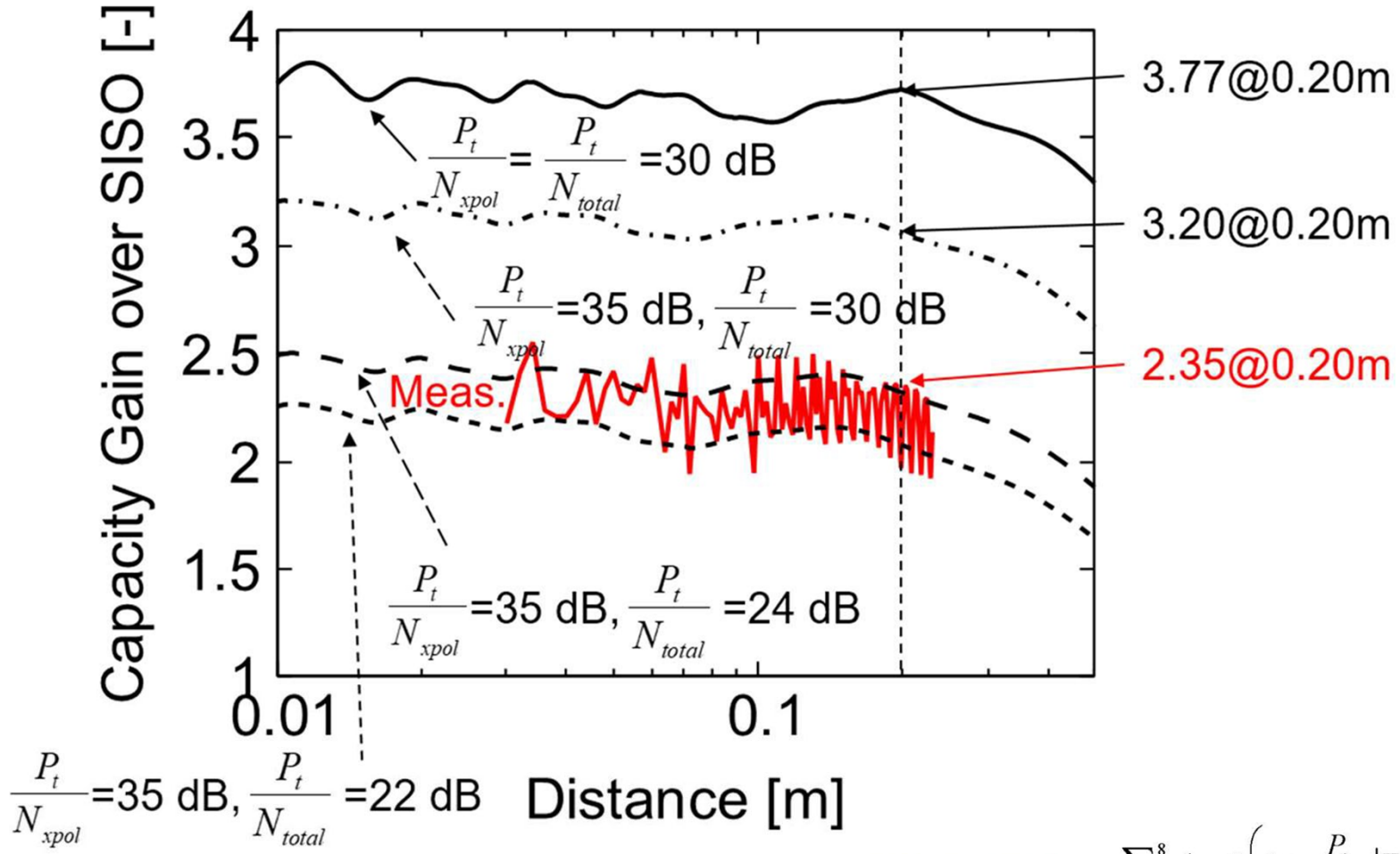


Tx mode: Mode 3



Tx mode: Mode 4

Capacity gain



$$G_{ROM}(z) = \frac{\sum_{i=1}^{8} \log 2\left(1 + \frac{P_t}{N_{total}}|T_{ii}|^2\right)}{\log 2\left(1 + \frac{P_t}{N_{xpol}}|T_{11}|^2\right) + \log 2\left(1 + \frac{P_t}{N_{xpol}}|T_{55}|^2\right)}$$

SNR: 30 dB

Measured XPD: 35 dB

Interference (isolation): -22～-24 dB

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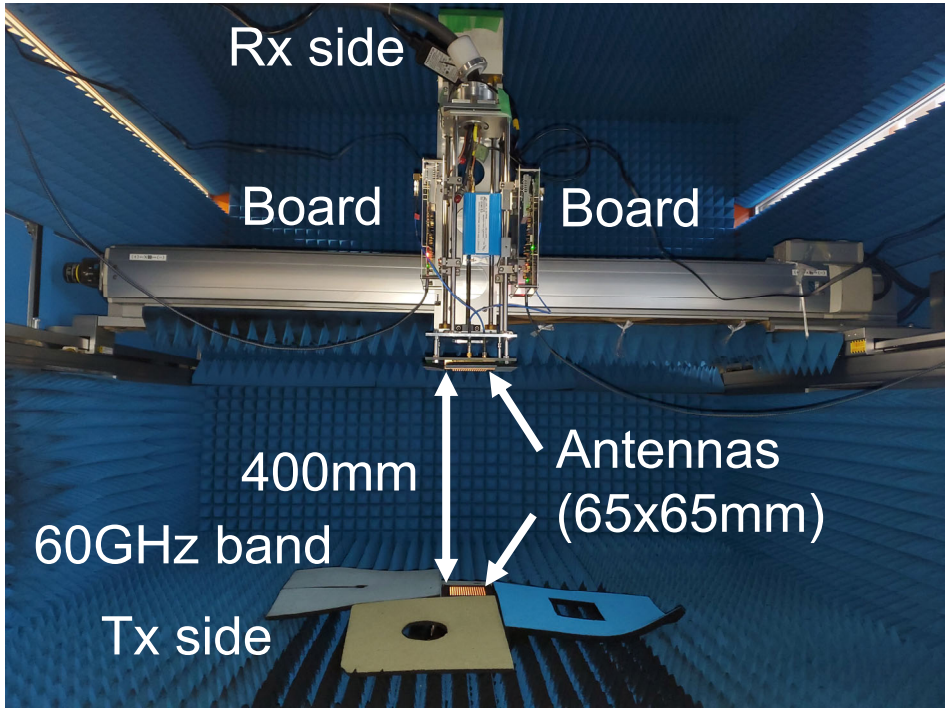
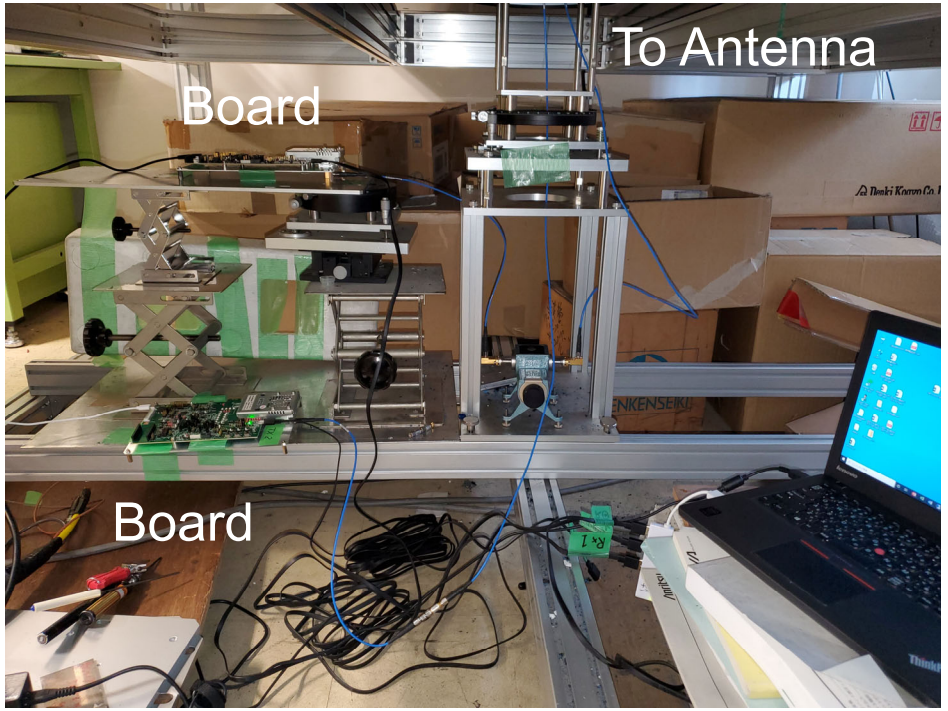
Two-multiplexing QPSK transmission (Radio)

Overall view



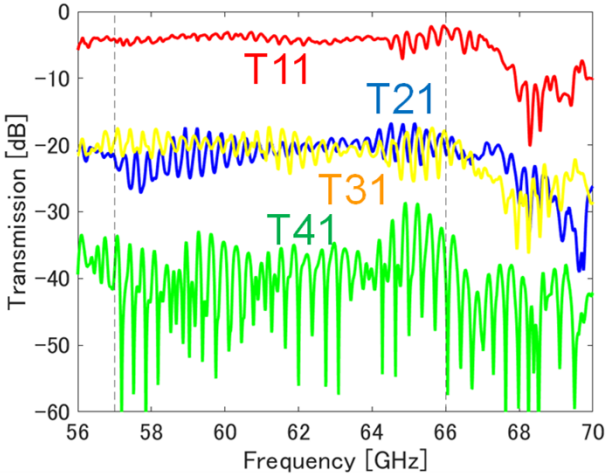
Tx side



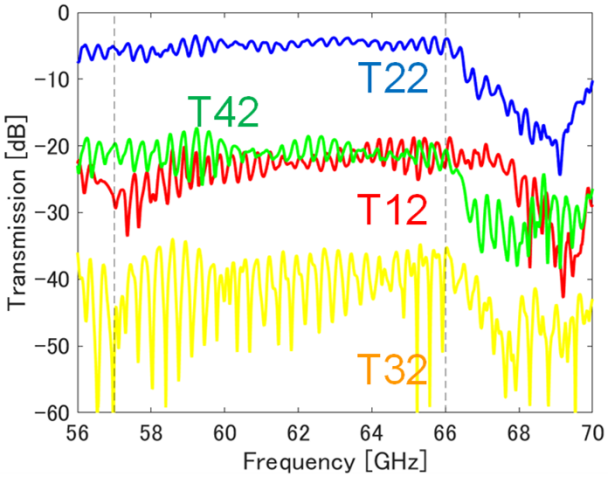
- Antenna…design freq.61.5GHz, 16x16 elements(65x65mm), excitation… 4-mode channel capacity sum maximum（distance: 400mm, infinitesimal dipole approximation）
- Module…Transmission power –5.6dBm(at WR15 port), maximum rate 3.2Gbps(QPSK) per channel(2.16GHz BW)
- Collaborated with Niigata University, Japan Radio, and HRCP Research and Development Partnership

Frequency dependence of transmission(CW)

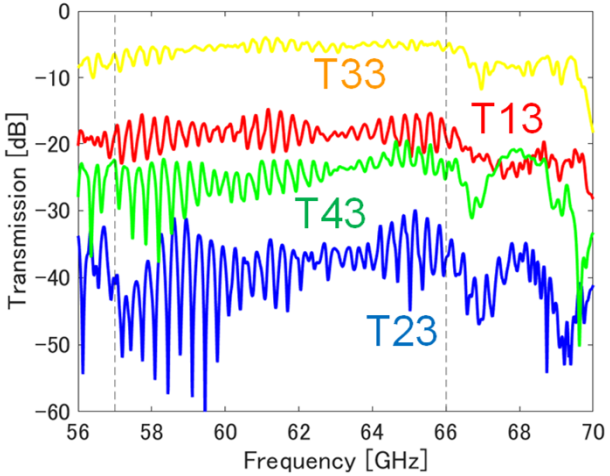
✓ Tx Mode 1



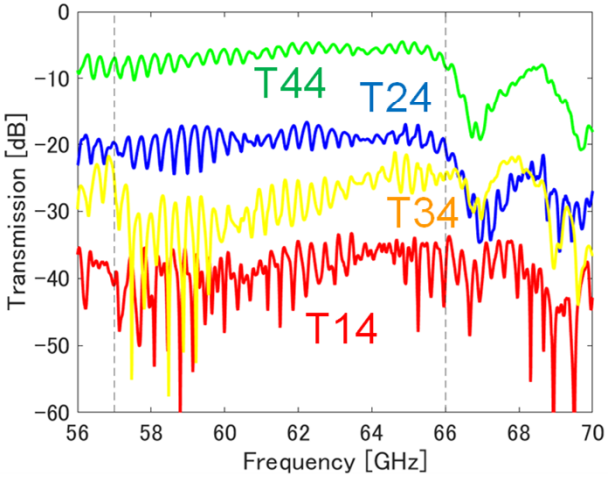
✓ Tx Mode 2



✓ Tx Mode 3



✓ Tx Mode 4

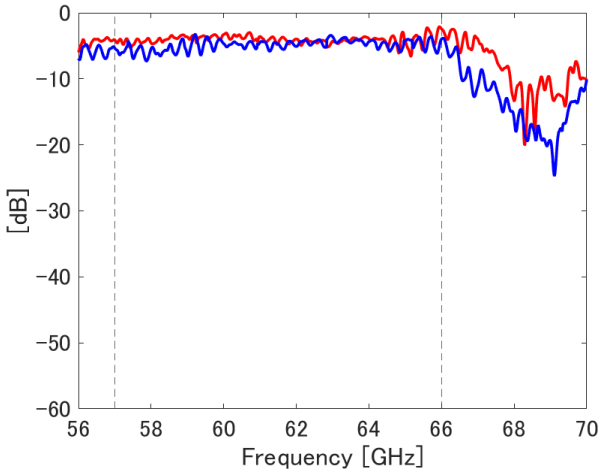


Beam shape

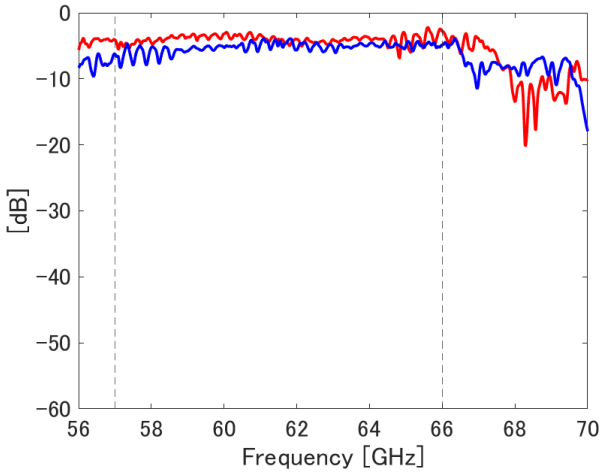
Frequency dependence of eigenvalues

Tokyo Tech

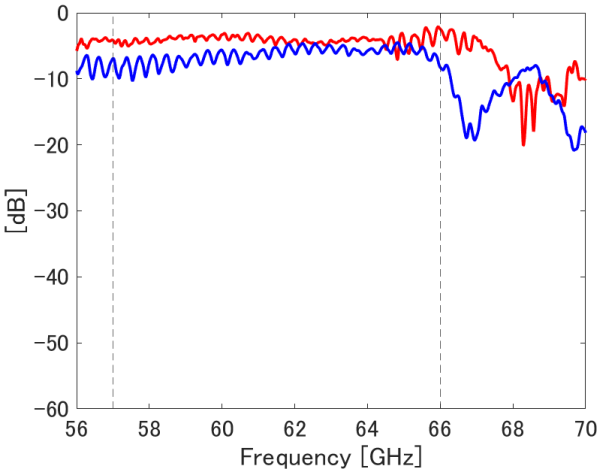
Mode1 & Mode2



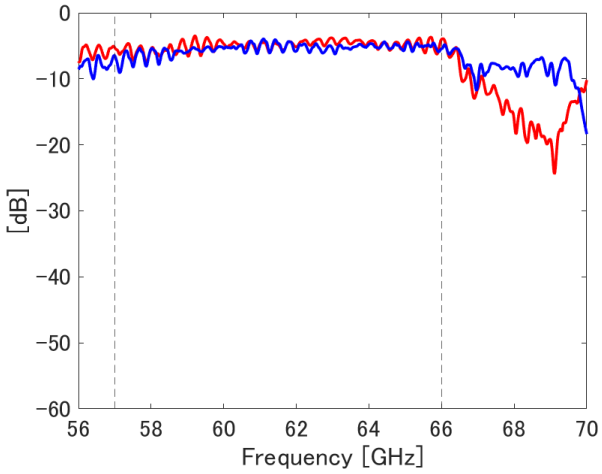
Mode1 & Mode3



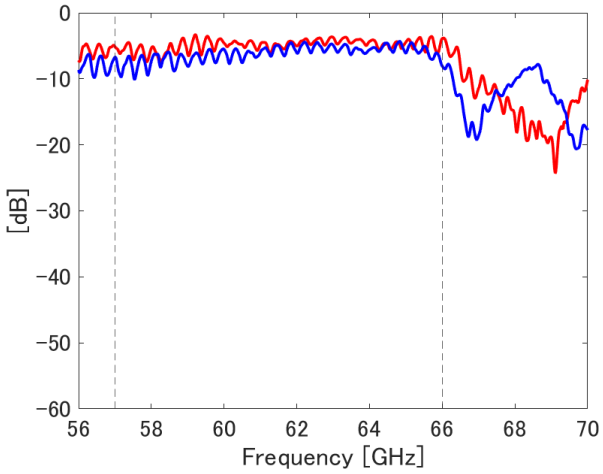
Mode1 & Mode4



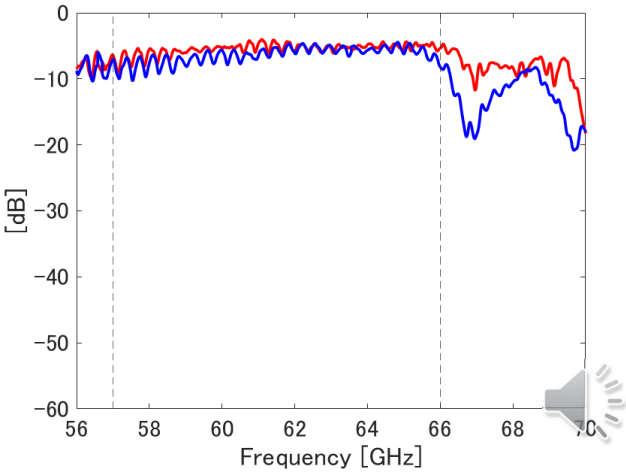
Mode2 & Mode3



Mode2 & Mode4

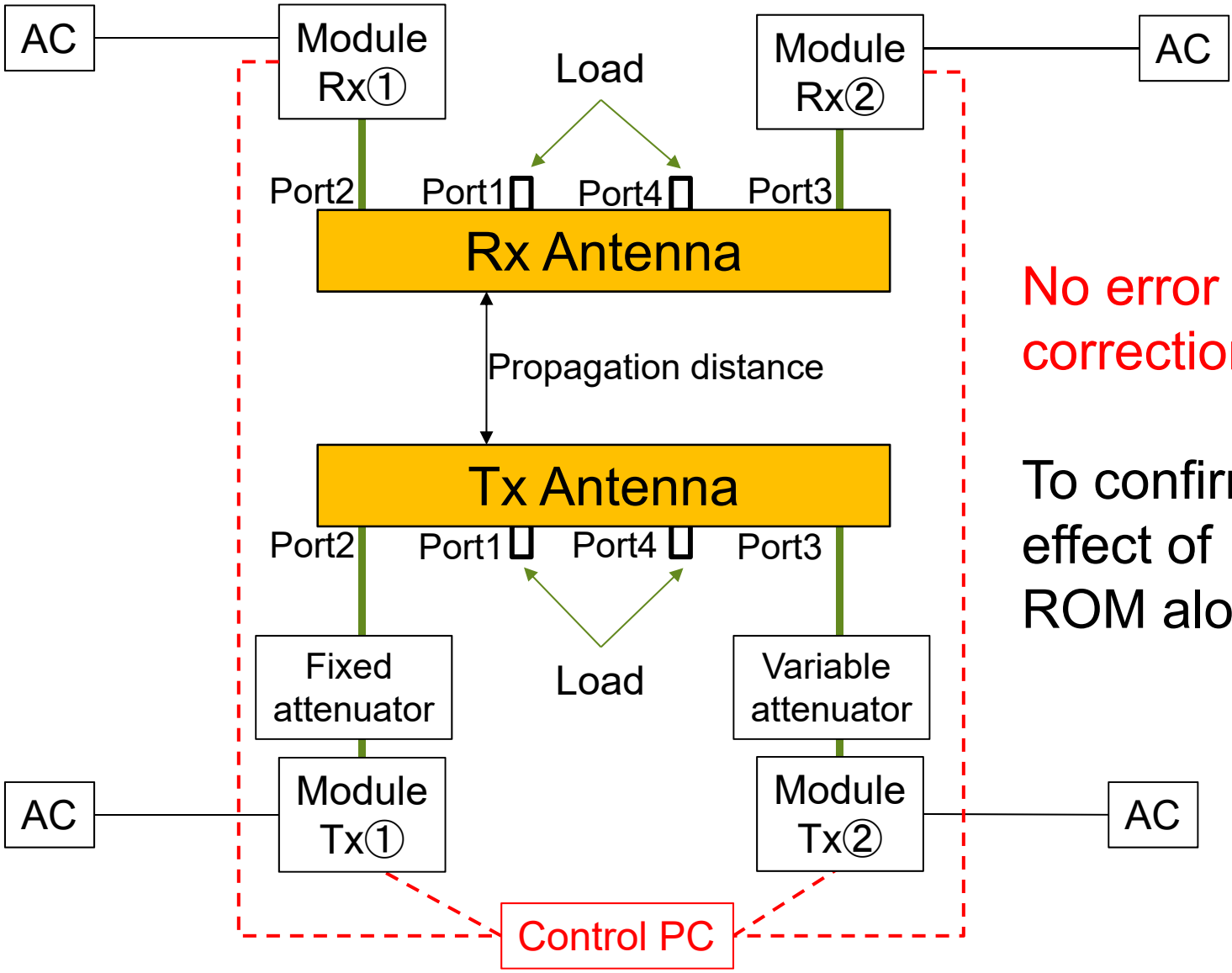


Mode3 & Mode4



Two-multiplexing

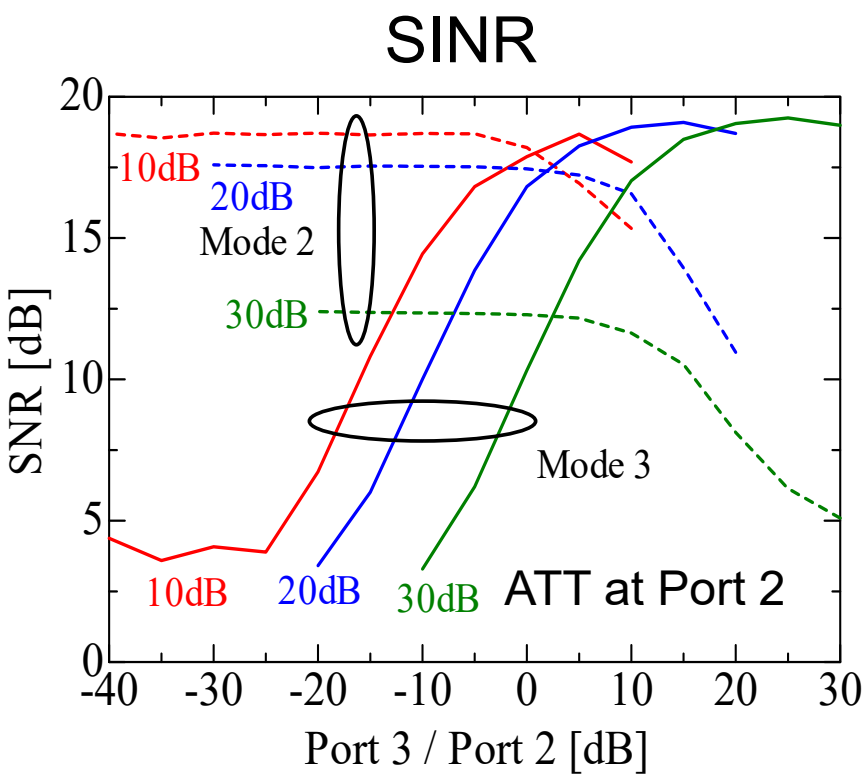
Ex. Use of Modes 2 and 3

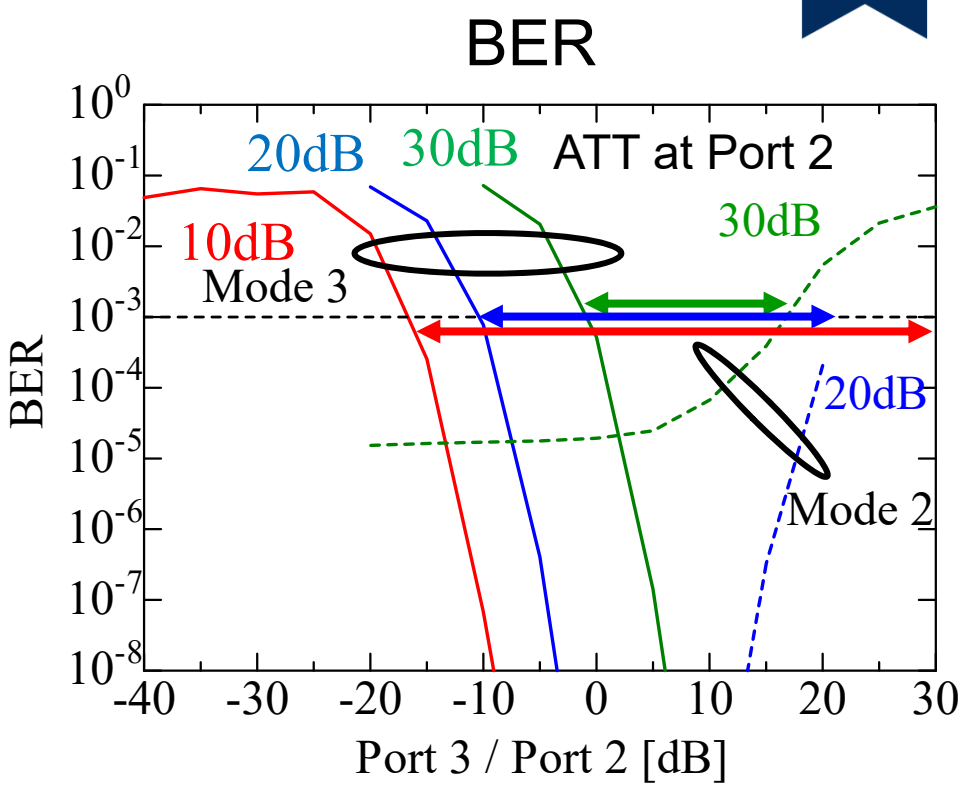


No error correction

To confirm effect of ROM alone

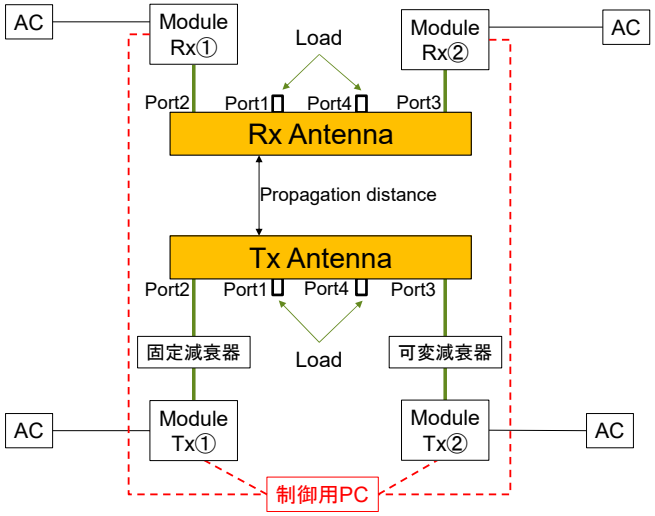
SINR, BER for two-port input power ratio





- Transmission power: port 2: fixed, port 3: variable
- 1 channel (CH2) transmission

  BER<10^{-3}…SNR>9.8dB



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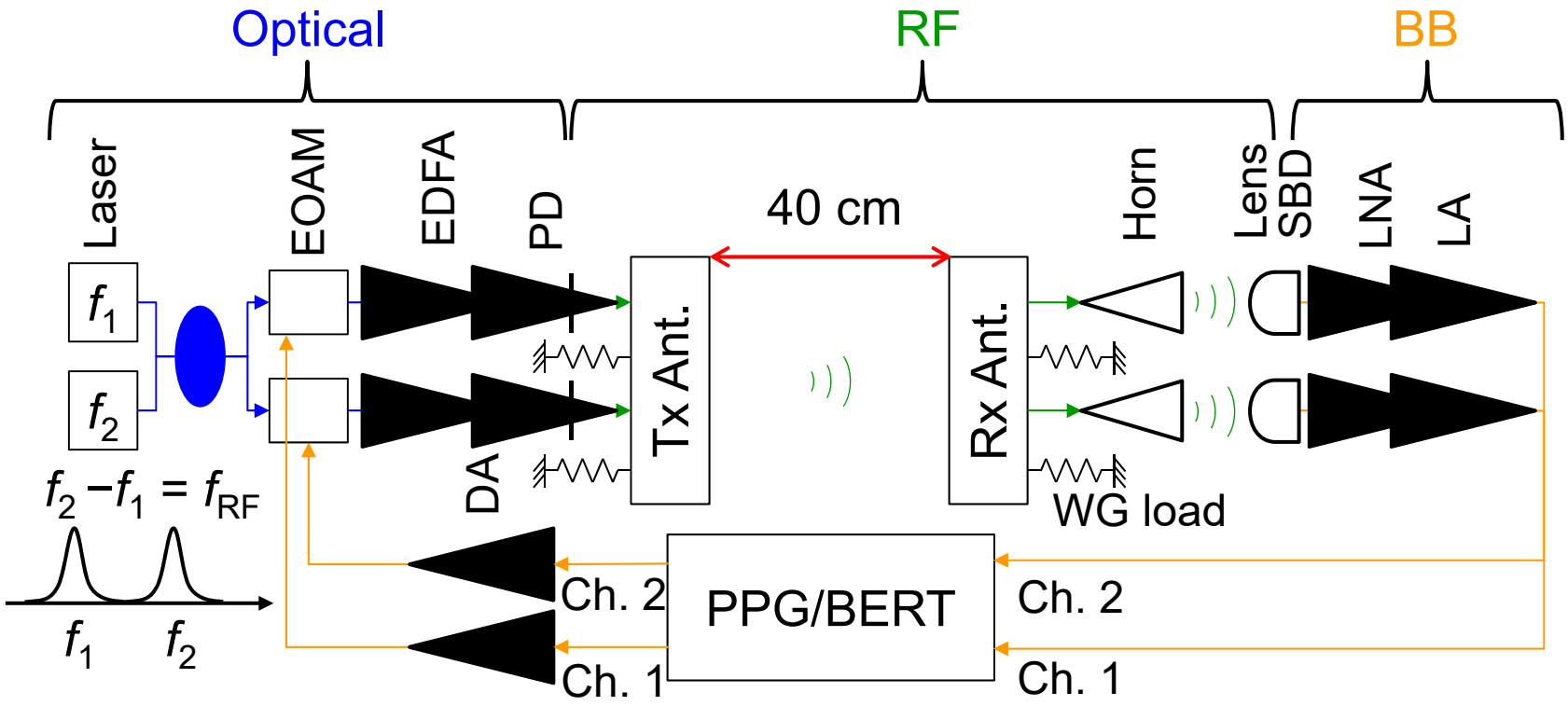
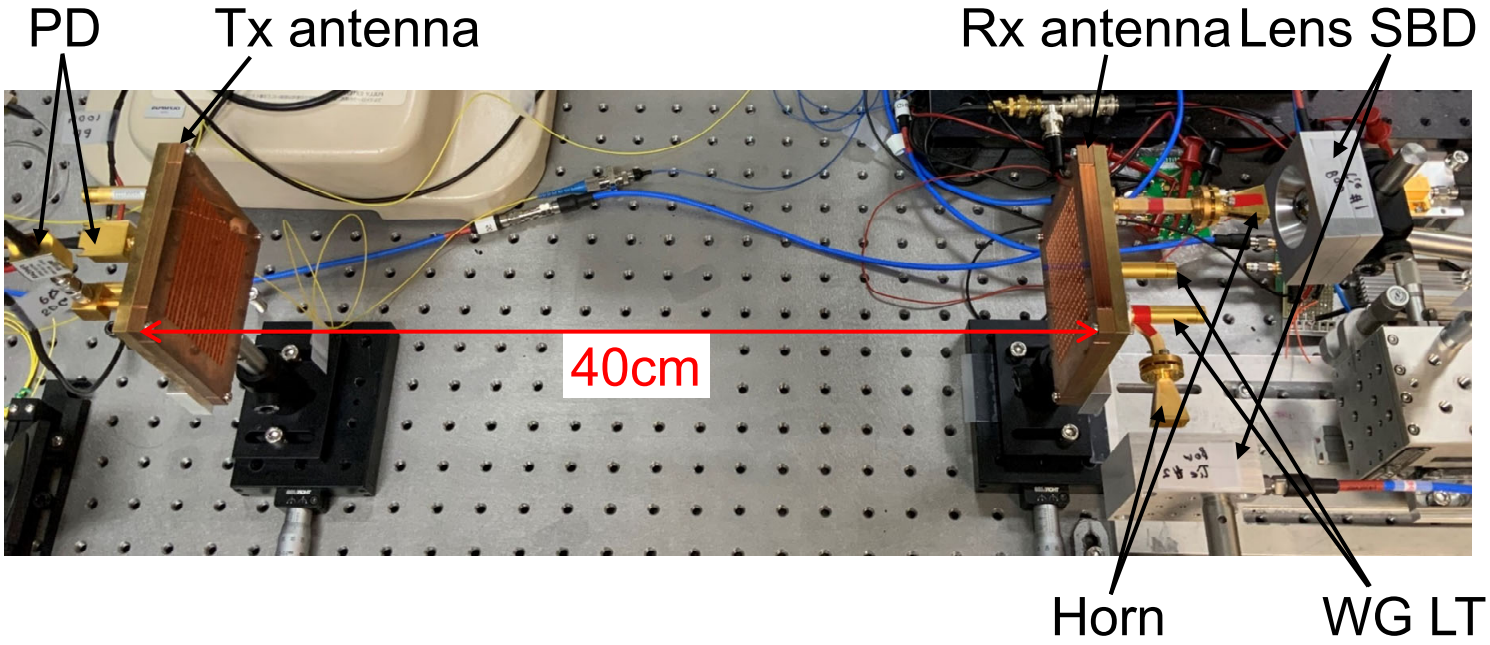
Two-multiplexing OOK transmission (RoF)



- Optical: C band, RF frequency: f_{RF} = 61.5 GHz
- PD maximum operating frequency (#1: 100GHz, #2: 50GHz)
- Modulation: OOK

T. Tomura, et al, *J. Lightw. Technol.*, Dec. 2021, doi:10.1109/JLT.2021.3093445, open access.

Photo of the measurement system

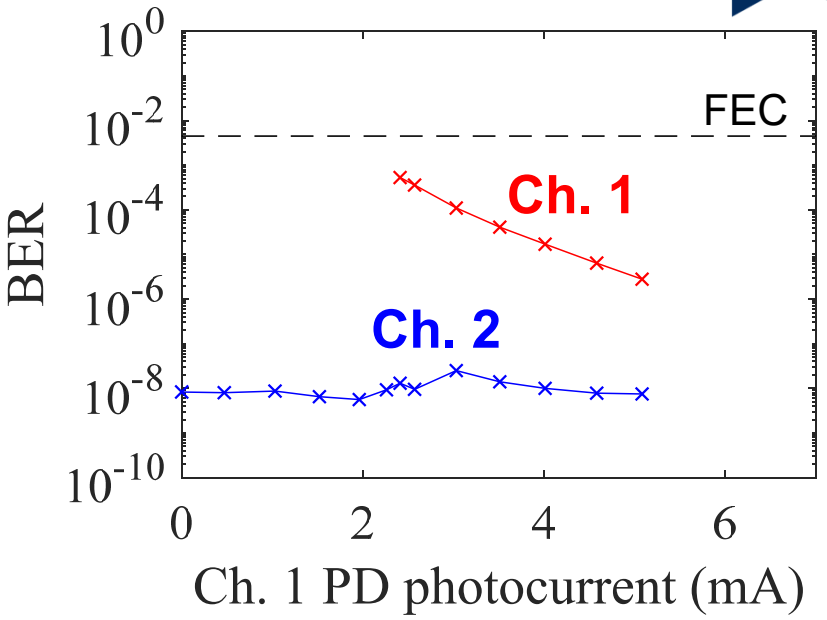


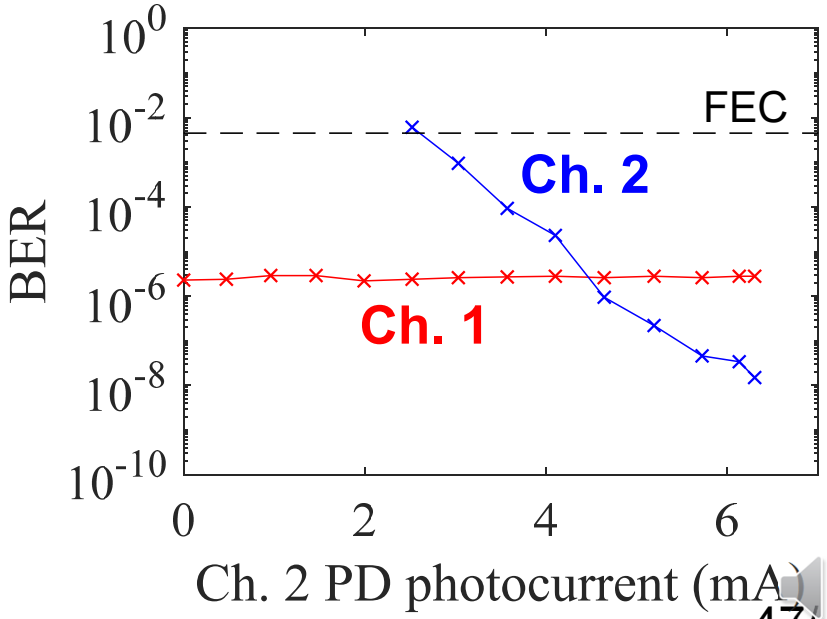
- Covered by absorbers in testing

Result using modes 4 and 1

Channel	1	2
PD	100 GHz	50 GHz
Data rate	4.3 Gbps	3.1 Gbps
ROM mode	4	1

- Increase photo current of one channel
  - BER of the channel is improved
  - BER of the other channel is almost unchanged
- High isolation between modes 4 and 1





Conclusion

Rectangular Coordinate Orthogonal Multiplexing Antenna System for Non-Far Region Communication

- Antenna＋beam switching circuit→no signal processing for multiplexing

- Rectangular-coordinate Orthogonality Multiplexing (ROM)
  - Structural symmetry with no frequency dependence
    same treatment for the x and y directions
  - Corporate feed WG slot array + monopulse
  - Optimized excitation for a given distance in non-far region
  - Dual polarization use to double capacity
  - Two-multiplexing transmission (Radio, RoF)