



6Gに向けたミリ波帯・テラヘルツ帯 フェーズドアレイ無線技術

岡田健一

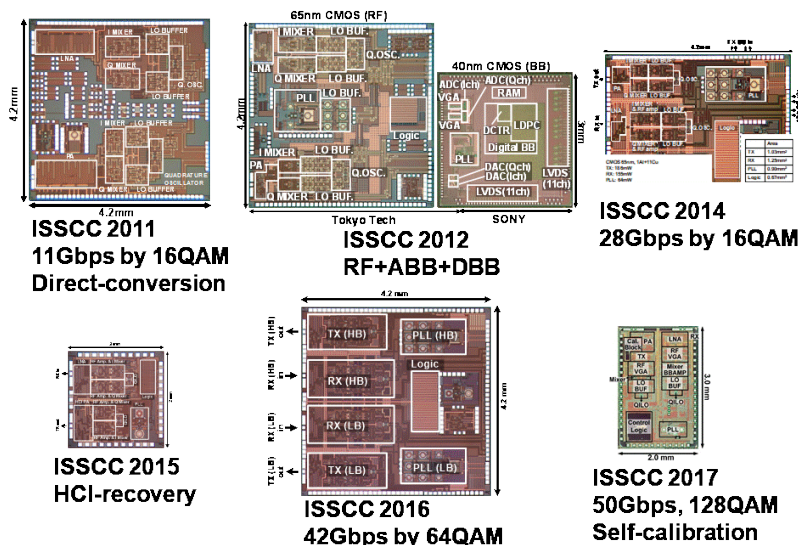
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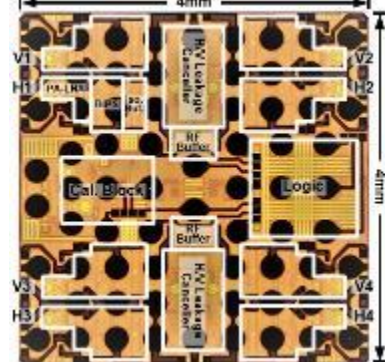
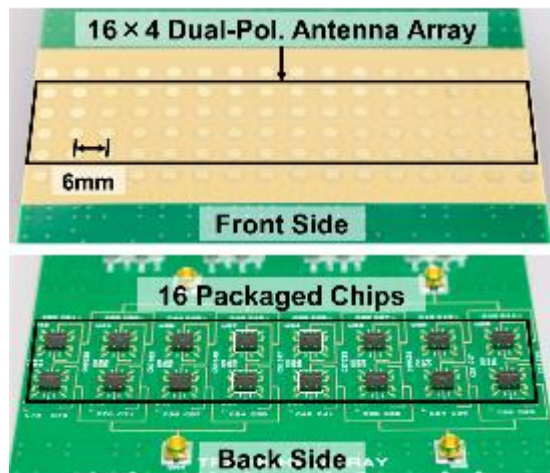


東工大における次世代無線通信技術の研究開発

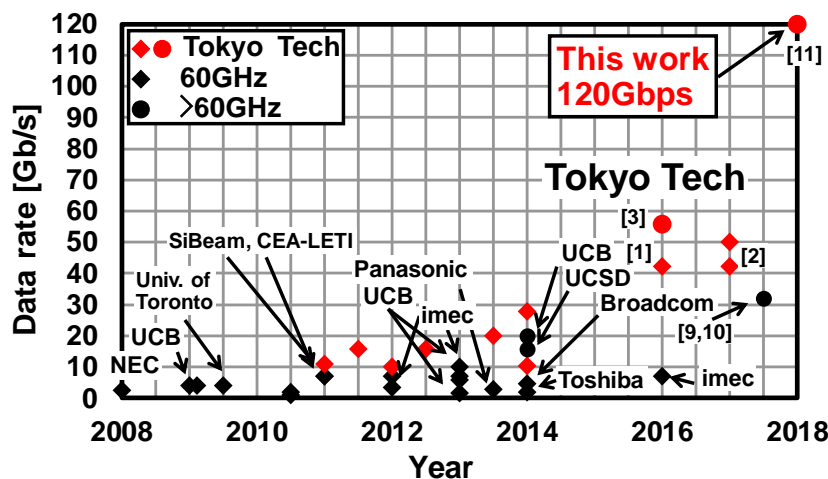
2007-2011, 2012-15 (Sony, JRC)
ミリ波無線通信用半導体チップ



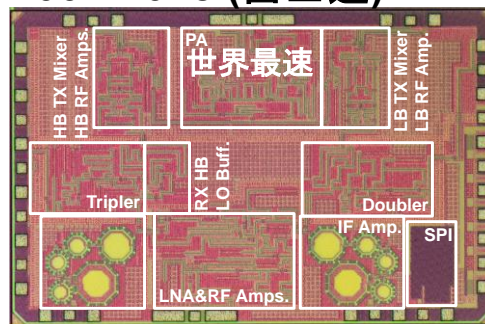
2016- (NEC)
5G基地局向けフェーズドアレイ無線機



5G用半導体チップ

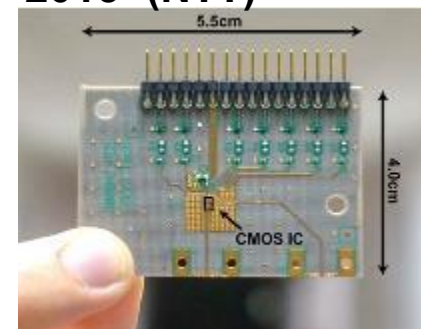


2007-2018 (富士通)



送信: 110mW, 受信: 177mW

2015- (NTT)



6G用半導体チップ
(テラヘルツ波)

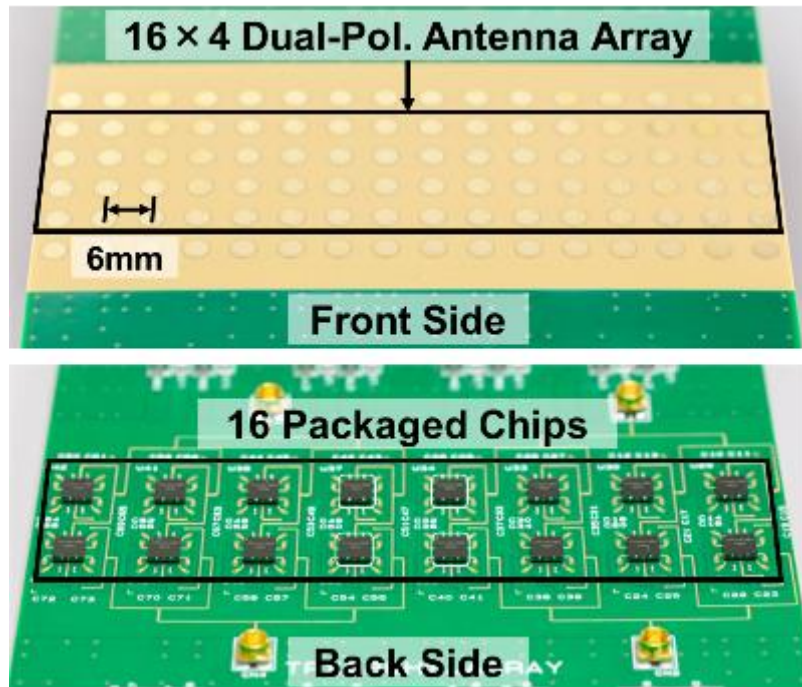
IoT: 900MHz(Sub-GHz), 2.4GHz BLE

Cellular/Wi-Fi/衛星: 20/28/39/60/100/150/300GHz

Contents

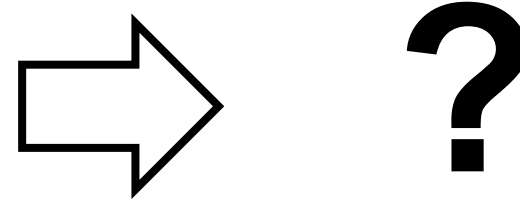
28GHz Phased Array

6G



Antenna

CMOS IC



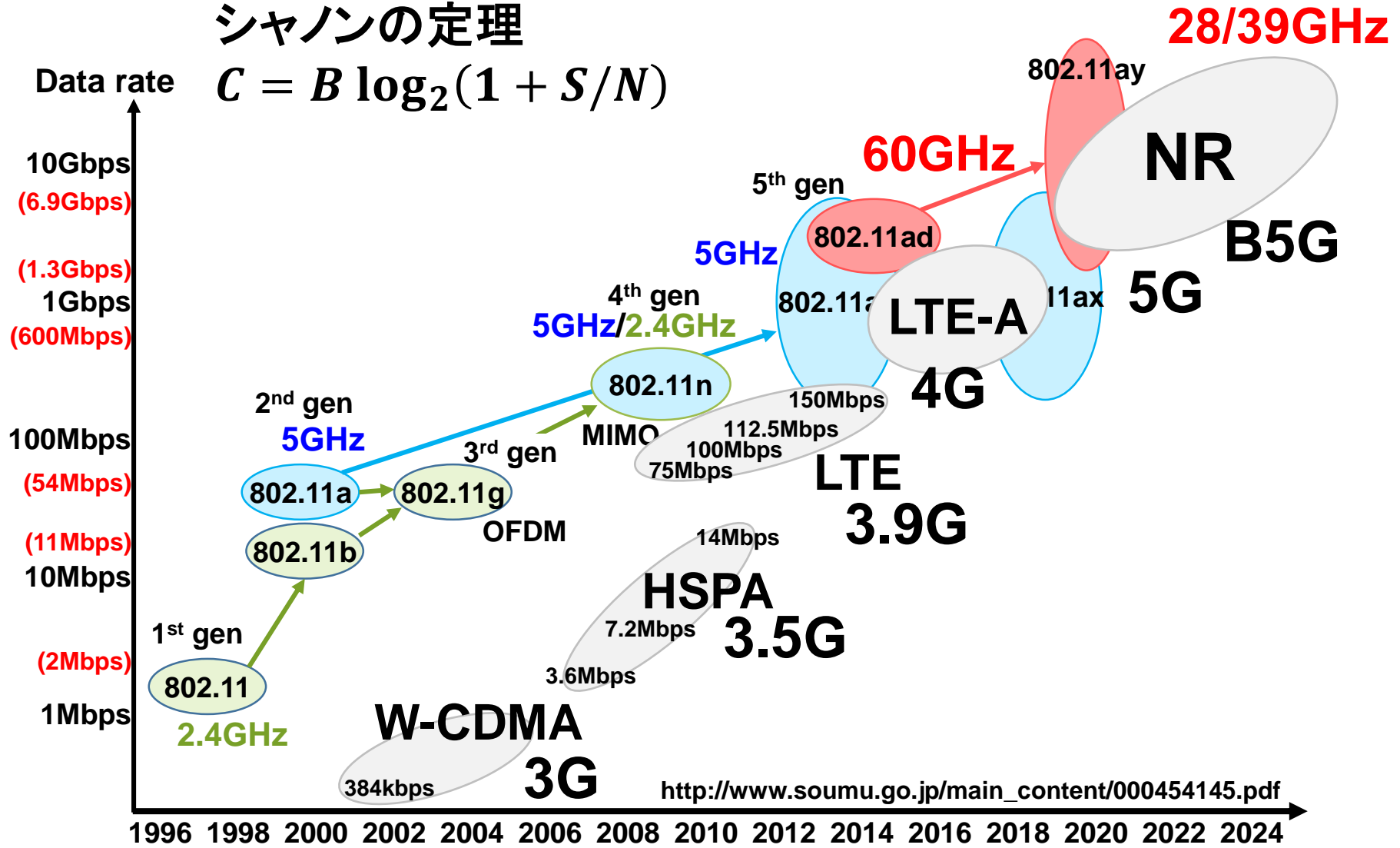
- なぜ、Phased Arrayが必要なのか？
- THzになるとミリ波と何が違うのか？
- 将来の無線通信はどうなるのか？

ミリ波帯無線通信技術の動向

Cellular & Wi-Fi Trend

シャノンの定理

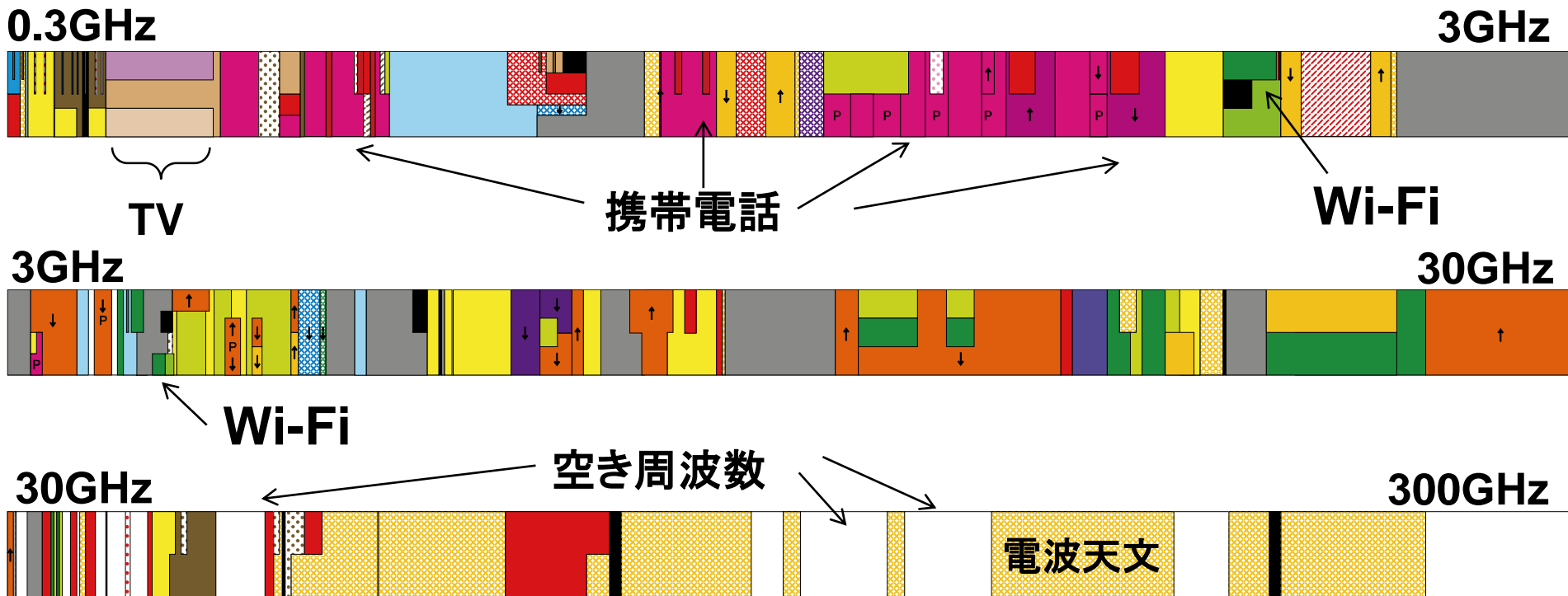
$$C = B \log_2(1 + S/N)$$



http://www.soumu.go.jp/main_content/000454145.pdf

日本国内の電波使用状況

20GHz以上の周波数は比較的空いている



年率1.4倍でトラフィックが増加

ミリ波の弱点

通信距離を長くしづらい

フリスの伝達公式

$$P_r = \left(\frac{\lambda}{4\pi d} \right)^2 G_r G_t P_t$$

P_r : 受信電力 [dBm]

P_t : 送信電力 [dBm]

G_r : 受信アンテナ利得 [dBi]

G_t : 送信アンテナ利得 [dBi]

λ : 波長 [m]

d : 送受信アンテナ間距離 [m]

※等方性アンテナ0dBiが基準

ダイポールアンテナ 2.14dBi=0dBd

$$P_r[\text{dBm}] \cong P_t[\text{dBm}] + G_r[\text{dB}] + G_t[\text{dB}] - 32.4[\text{dB}] - 20\log_{10}d[\text{km}] - 20\log_{10}f[\text{MHz}]$$

フリスの伝達公式

パッチアンテナ

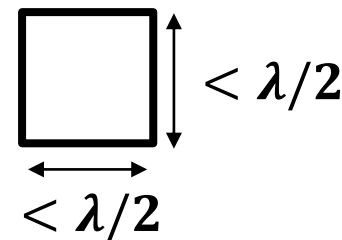


受信電力 送信電力

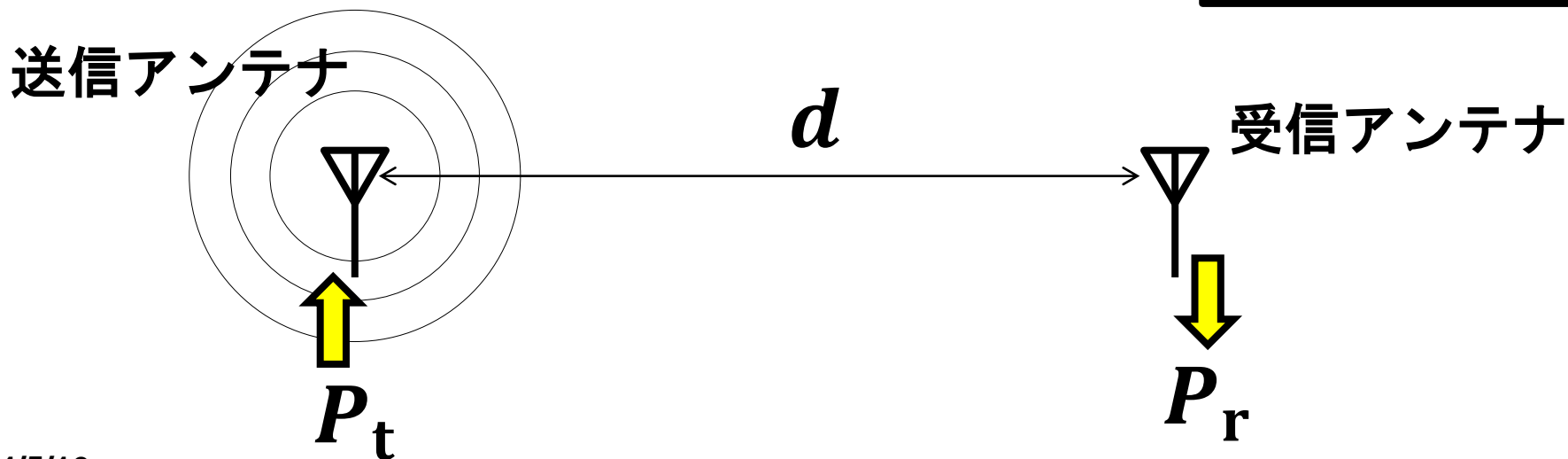
$$P_r = \left(\frac{\lambda}{4\pi d} \right)^2 P_t G_t G_r$$

送受アンテナ利得

送受アンテナ間距離



キャリア周波数 f_c
波長 λ
光速 c

$$\lambda = \frac{c}{f_c}$$


伝送距離 vs 搬送波周波数

$$C = B \log_2(1 + S/N)$$

$$N = kTB$$

$$S = P_r = P_t G_t G_r \left(\frac{c}{4\pi f_c d} \right)^2$$

$$d = \frac{c}{4\pi f_c} \sqrt{\frac{P_t G_t G_r}{kTB 2^m}}$$

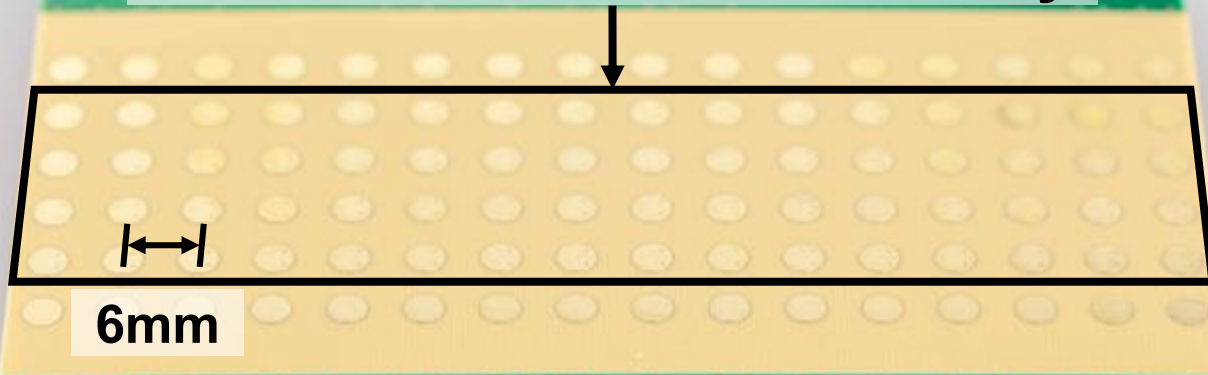
$$m = C/B$$

同じ送信電力・帯域幅・アンテナ利得において

- 2.4GHz ($\lambda=125\text{mm}$): 12m
- 28GHz ($\lambda=10.7\text{mm}$): 1m
- 300GHz ($\lambda=1\text{mm}$): 0.1m

28GHz フェーズドアレイ無線機(基地局)

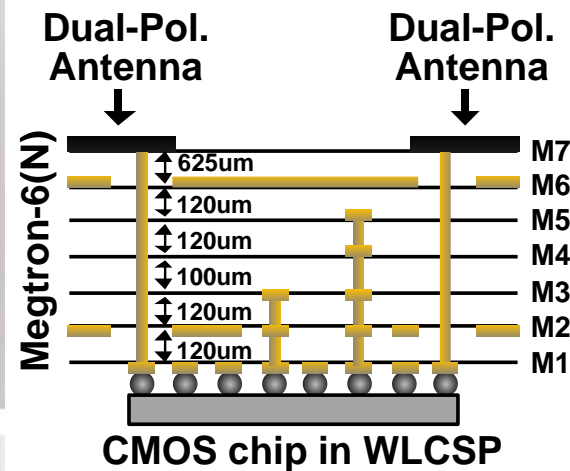
16 × 4 Dual-Pol. Antenna Array



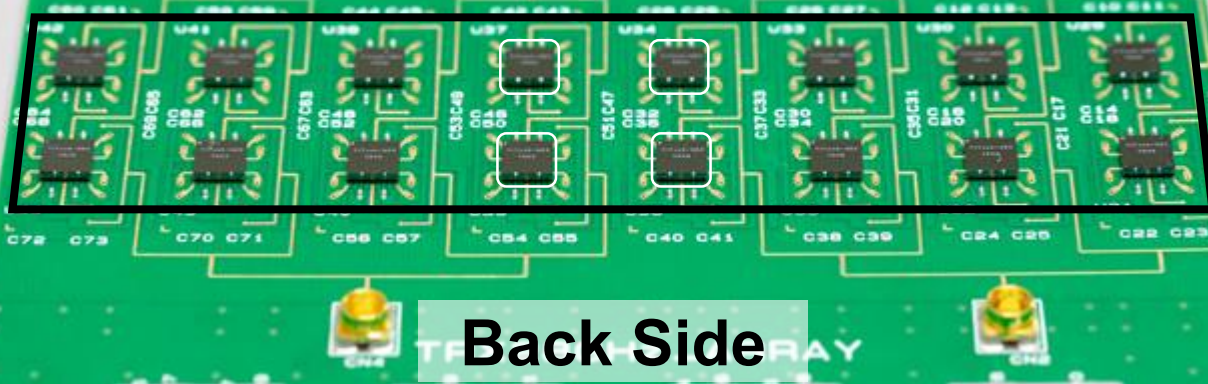
6mm

Front Side

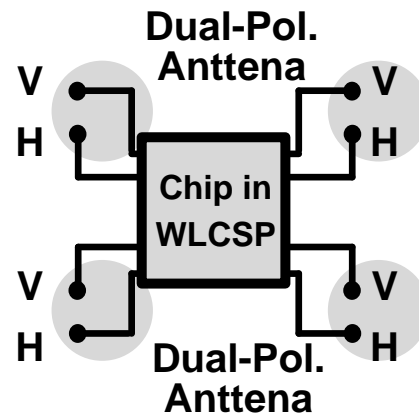
PCB Structure



16 Packaged Chips

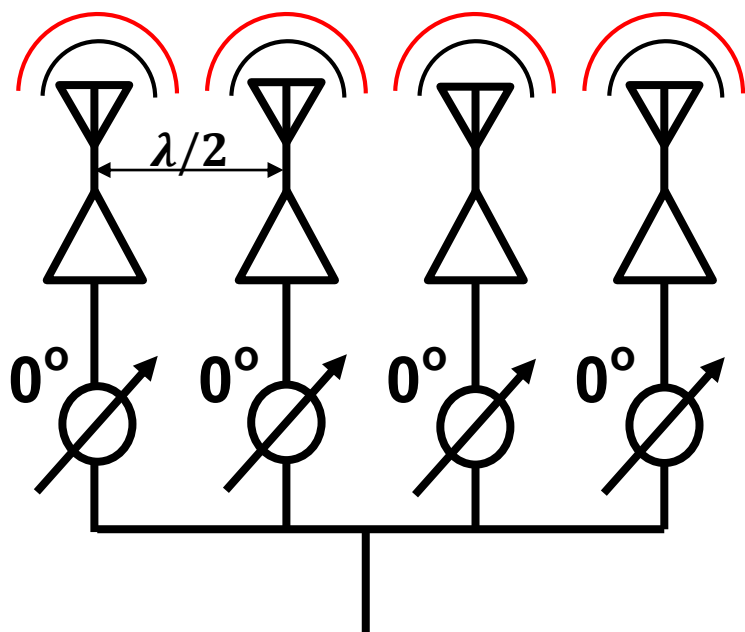
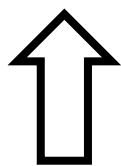


Back Side

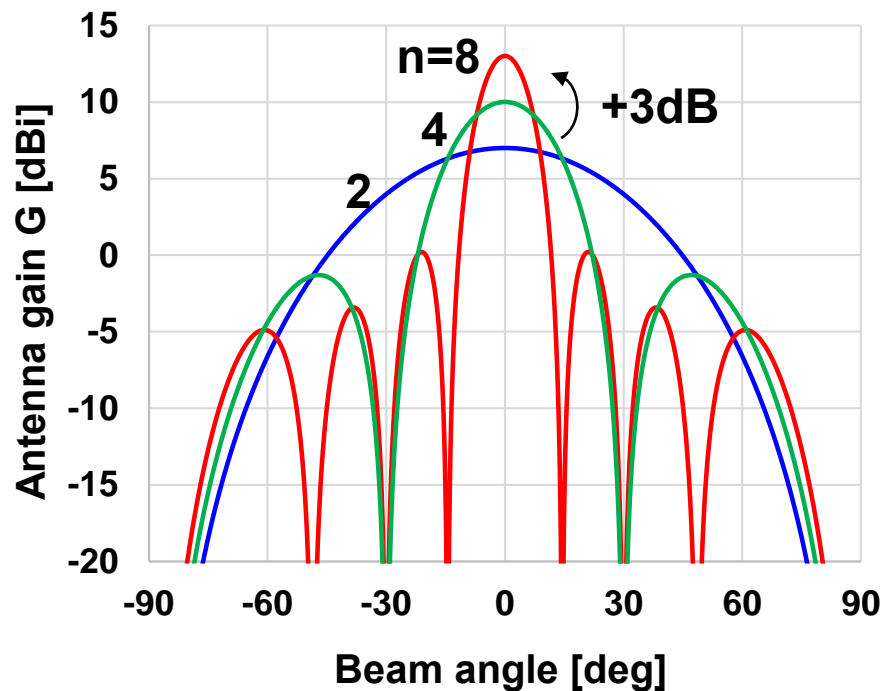


64-element phased array

フェーズドアレイアンテナ



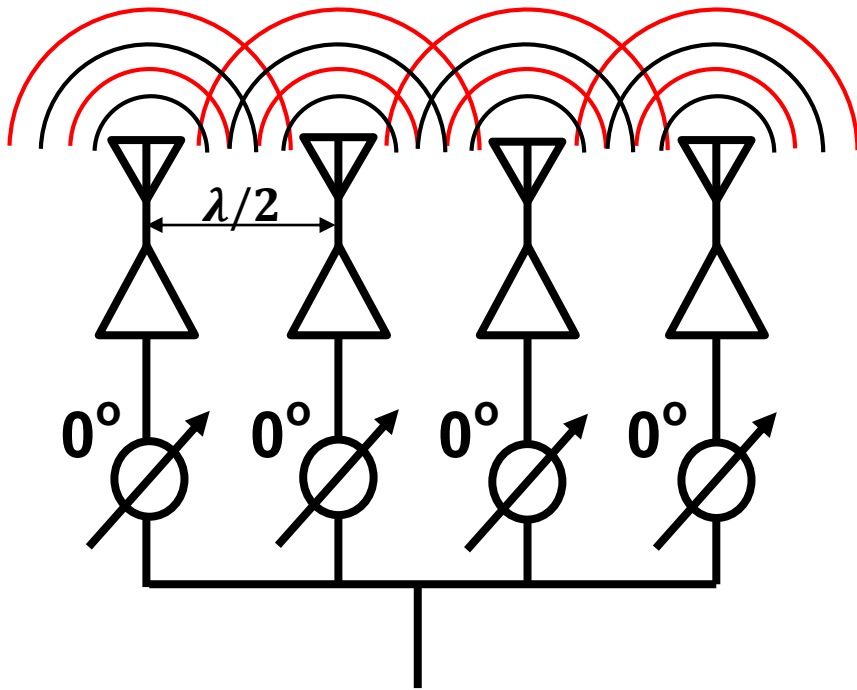
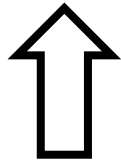
パッチアンテナ利得4dBi
($n=256$ で+24dB)



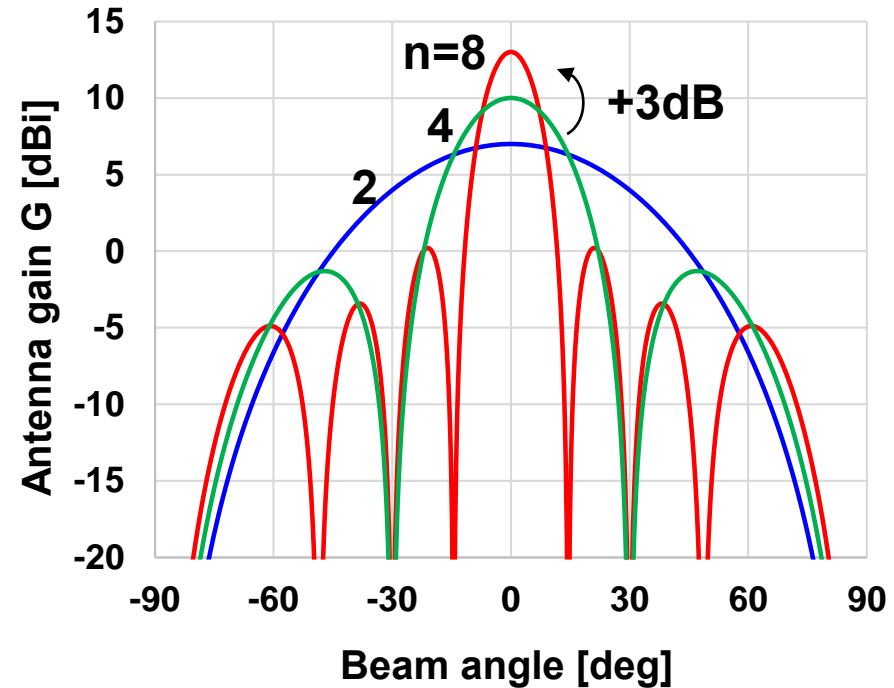
PA output: $P_t \Rightarrow n P_t$
Antenna gain: $G_t \Rightarrow n G_t$

n : #antenna

フェーズドアレイアンテナ



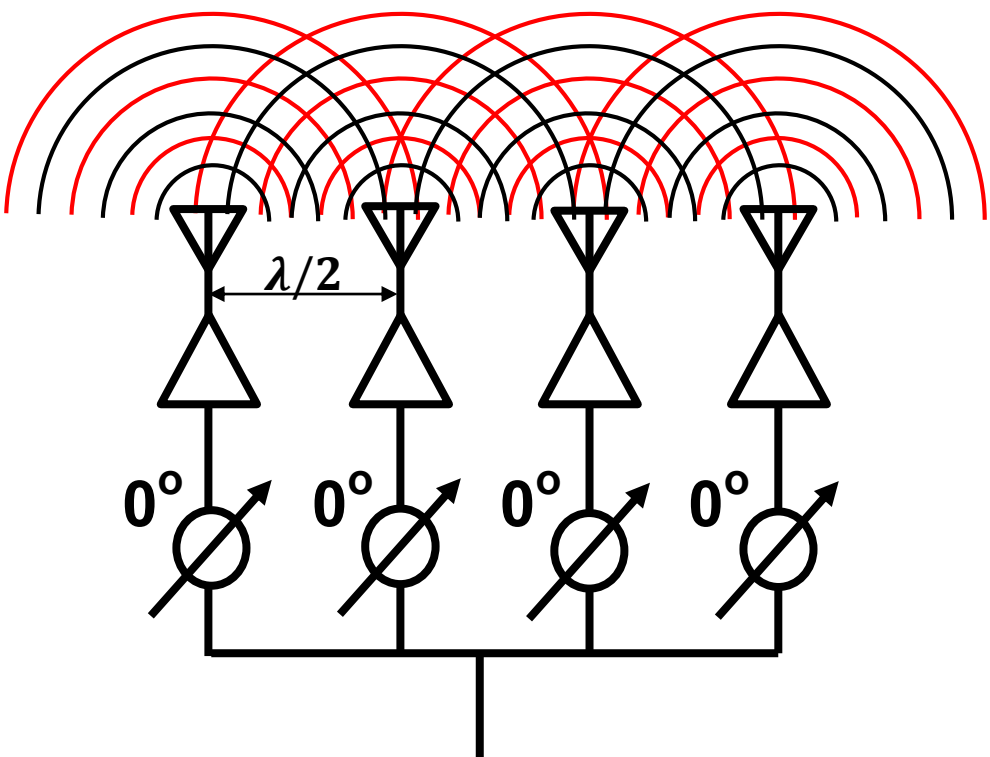
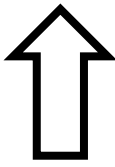
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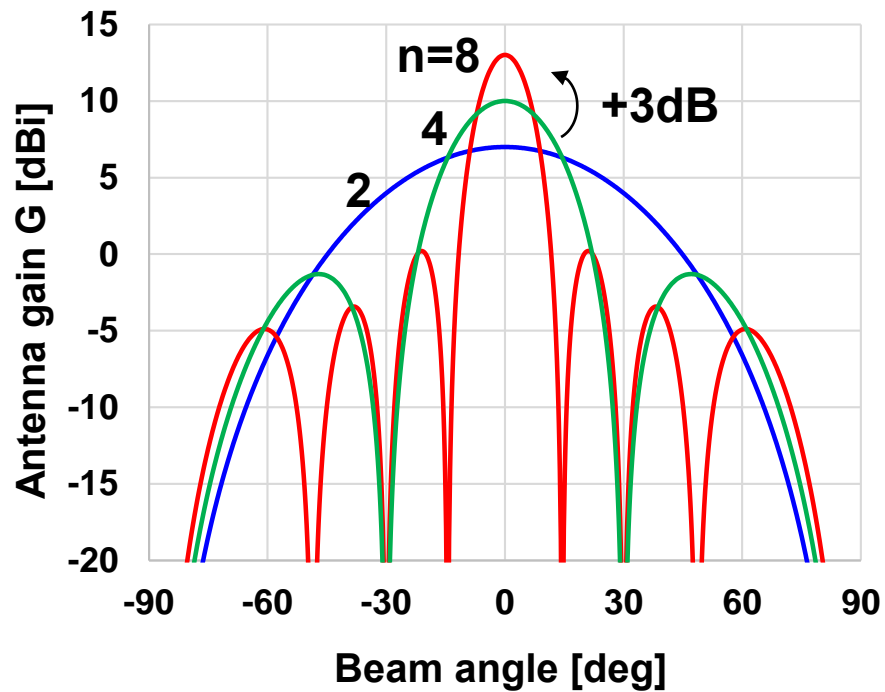
PA output: $P_t \Rightarrow n P_t$
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フェーズドアレイアンテナ



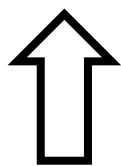
パッチアンテナ利得4dBi
(n=256で+24dB)



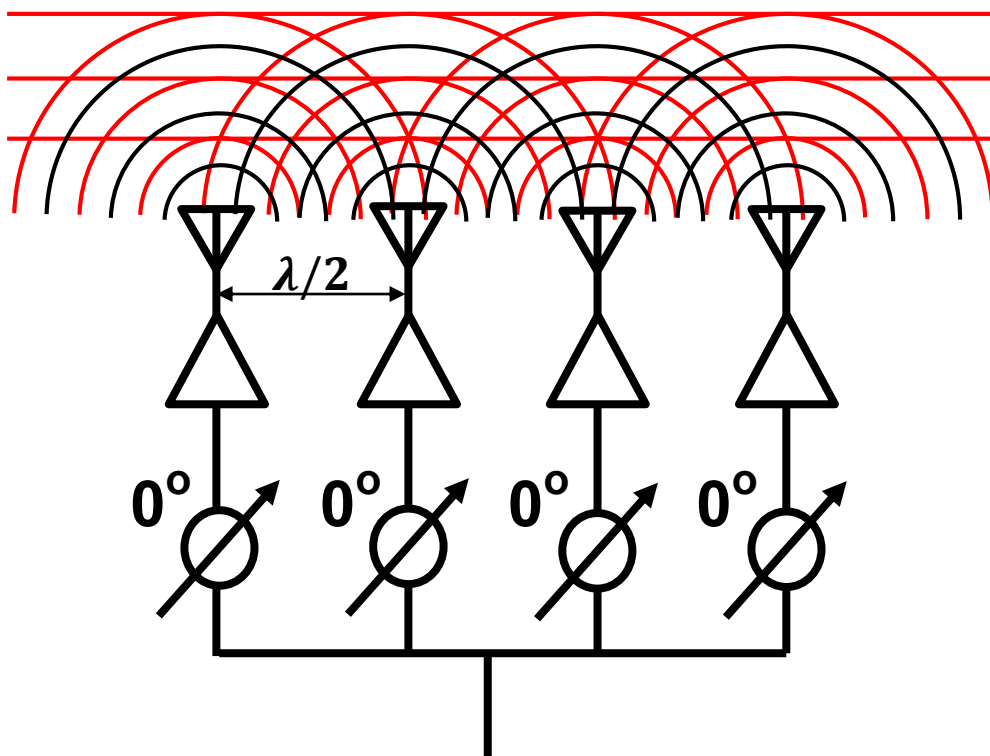
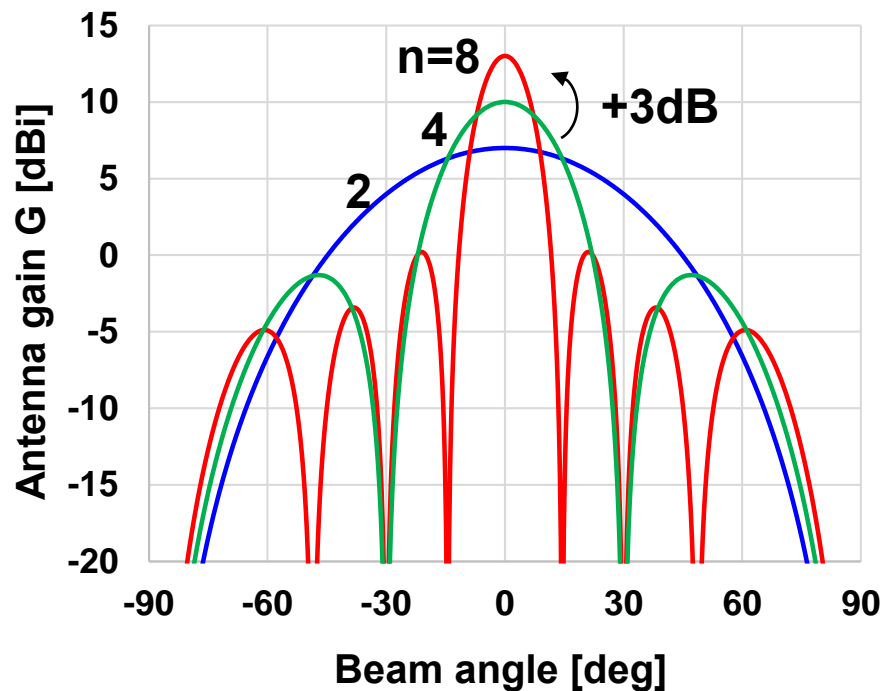
PA output: $P_t \Rightarrow n P_t$
Antenna gain: $G_t \Rightarrow n G_t$

n : #antenna

フェーズドアレイアンテナ



パッチアンテナ利得4dBi
($n=256$ で+24dB)

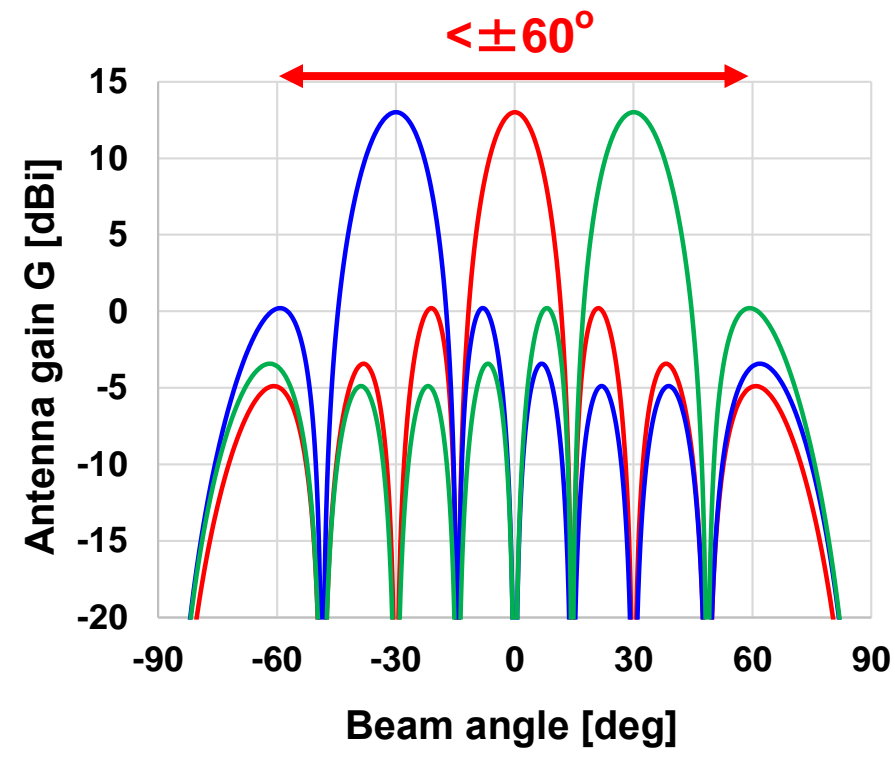
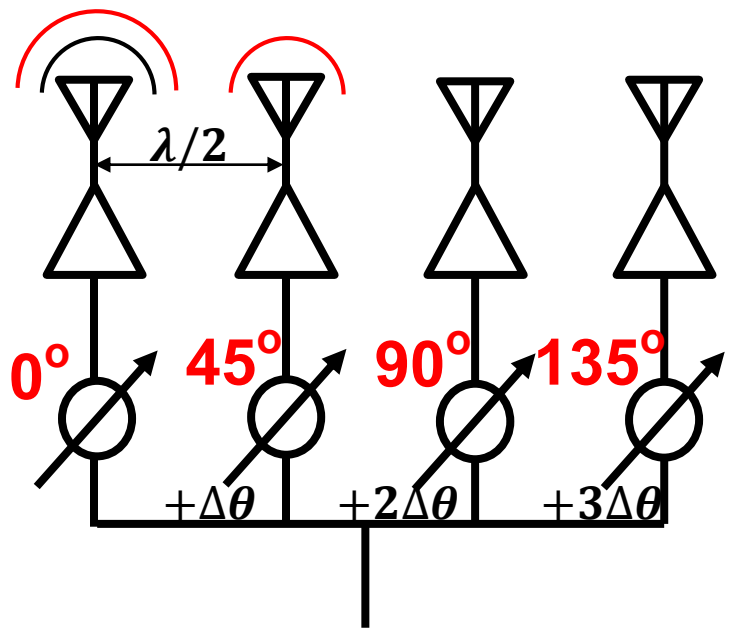
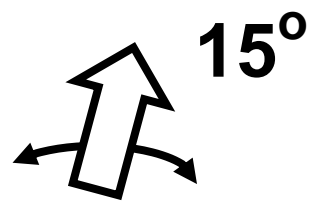


PA output: $P_t \Rightarrow n P_t$
Antenna gain: $G_t \Rightarrow n G_t$

n : #antenna

フェーズドアレイアンテナ

振り幅は最大 $\pm 60^\circ$

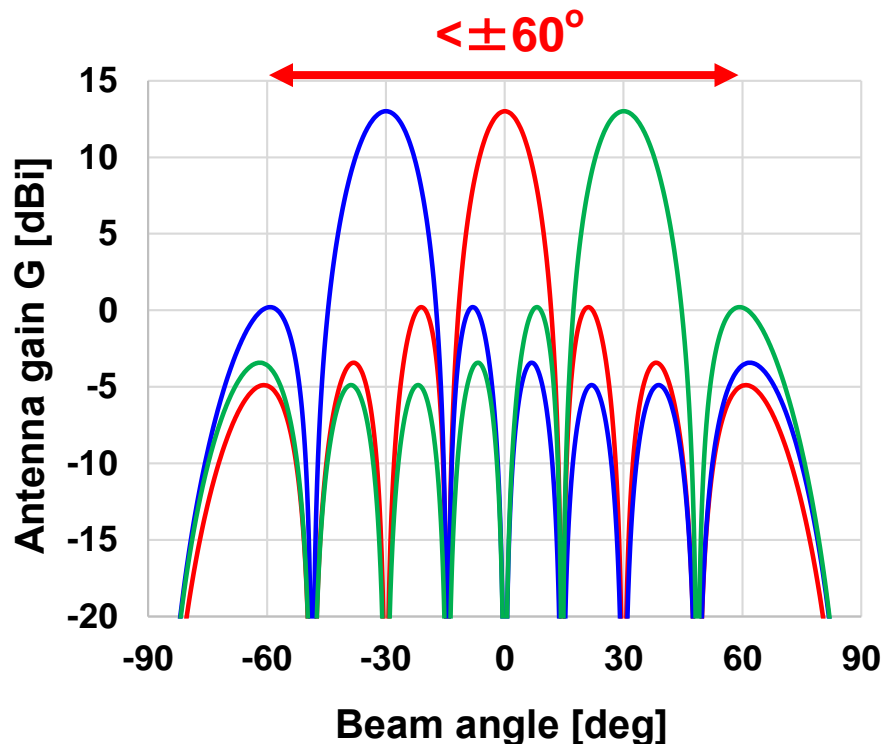
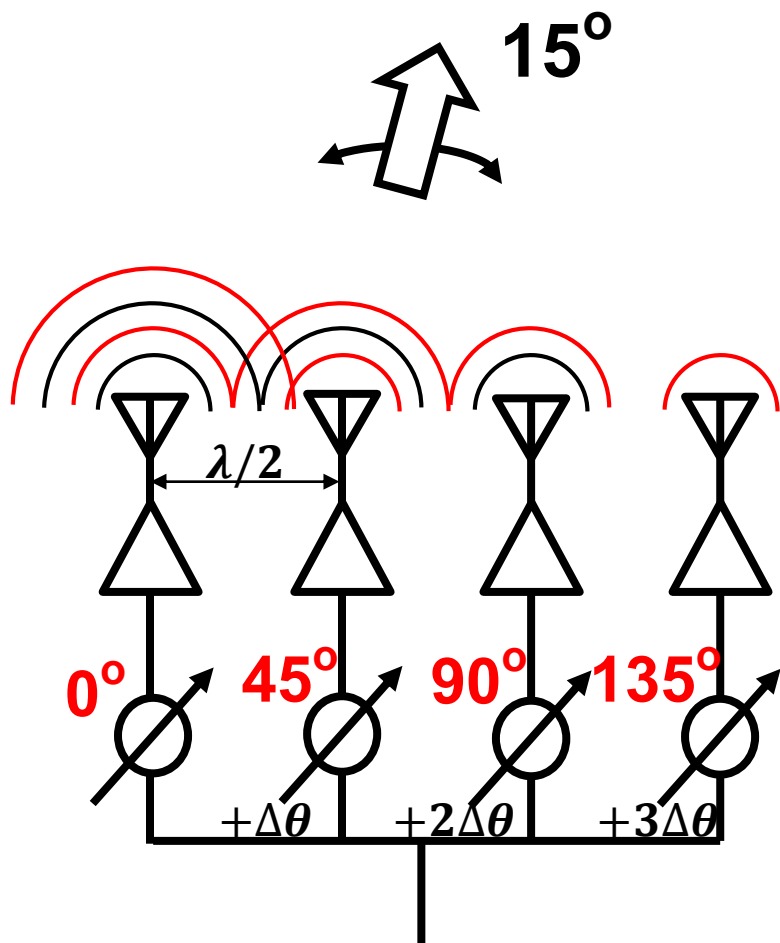


PA output: $P_t \Rightarrow n P_t$
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フェーズドアレイアンテナ

振り幅は最大 $\pm 60^\circ$

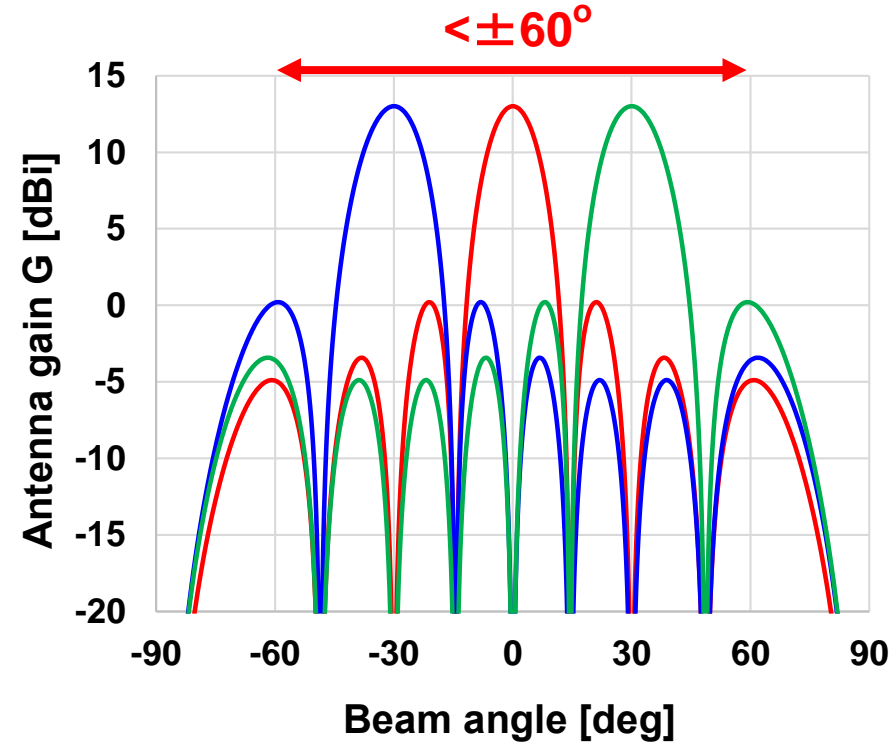
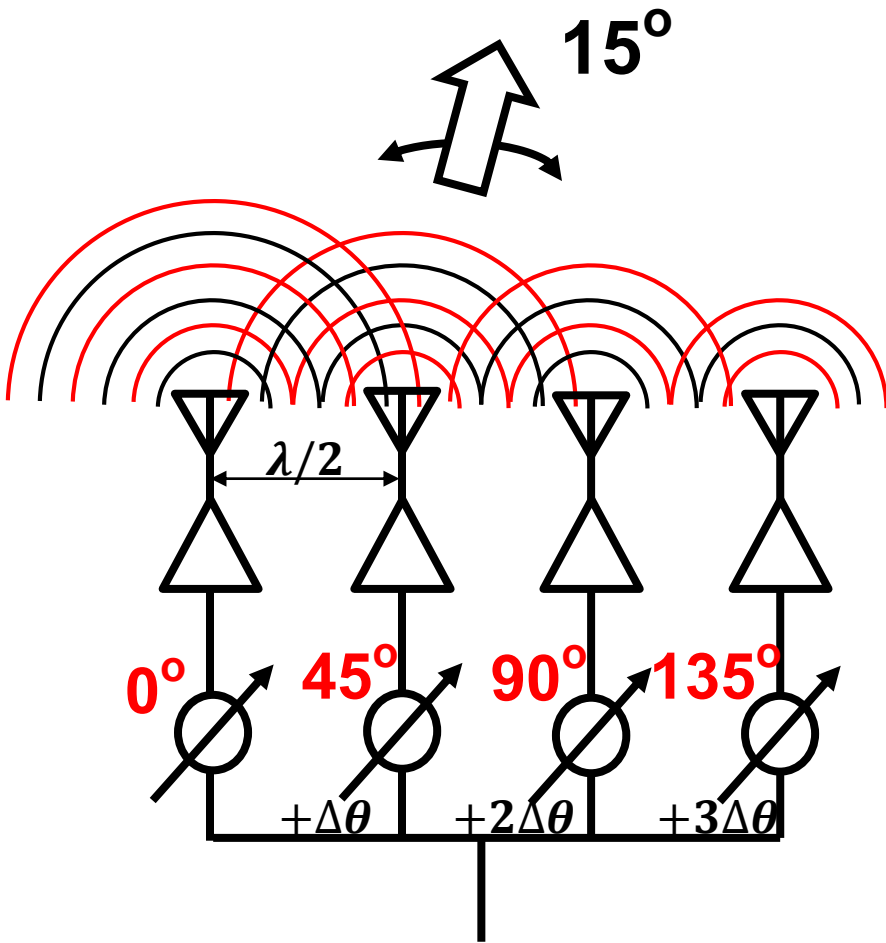


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フェーズドアレイアンテナ

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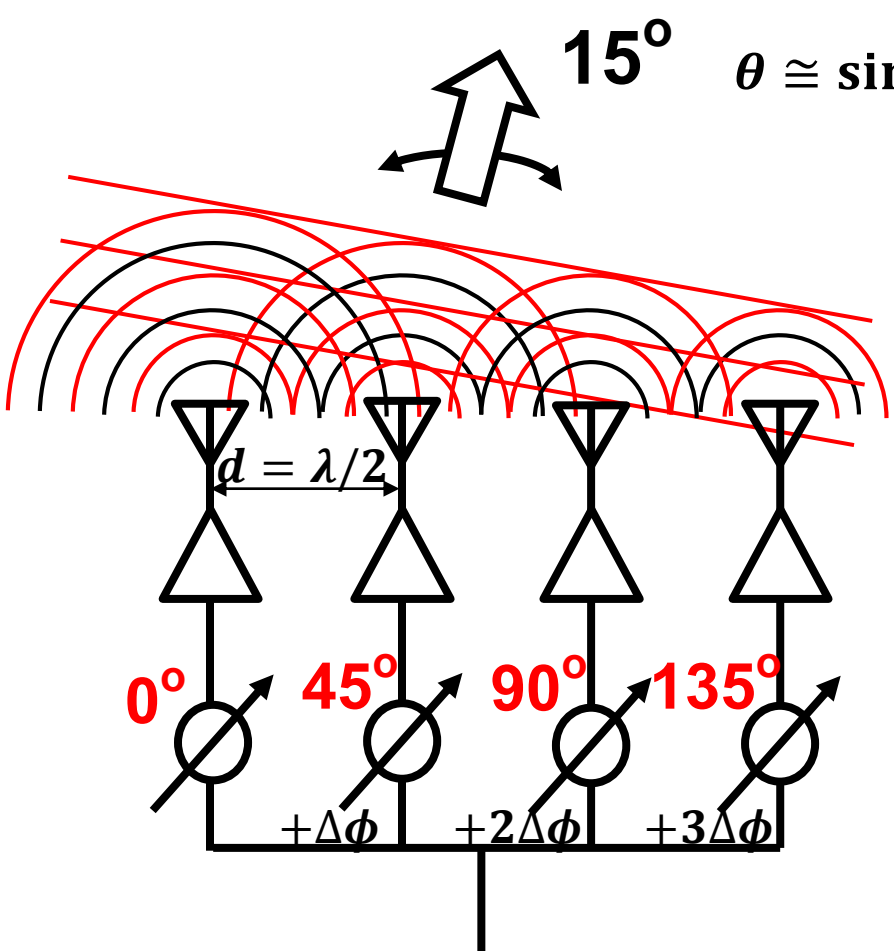


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Antenna gain: $G_t \Rightarrow n G_t$

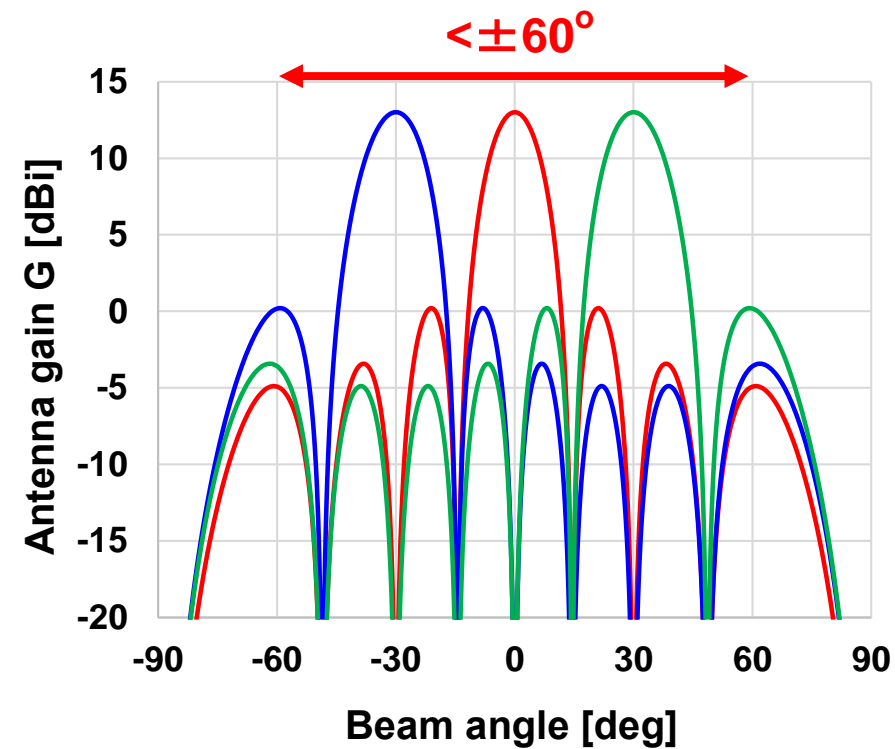
n : #antenna

フェーズドアレイアンテナ

振り幅は最大±60°



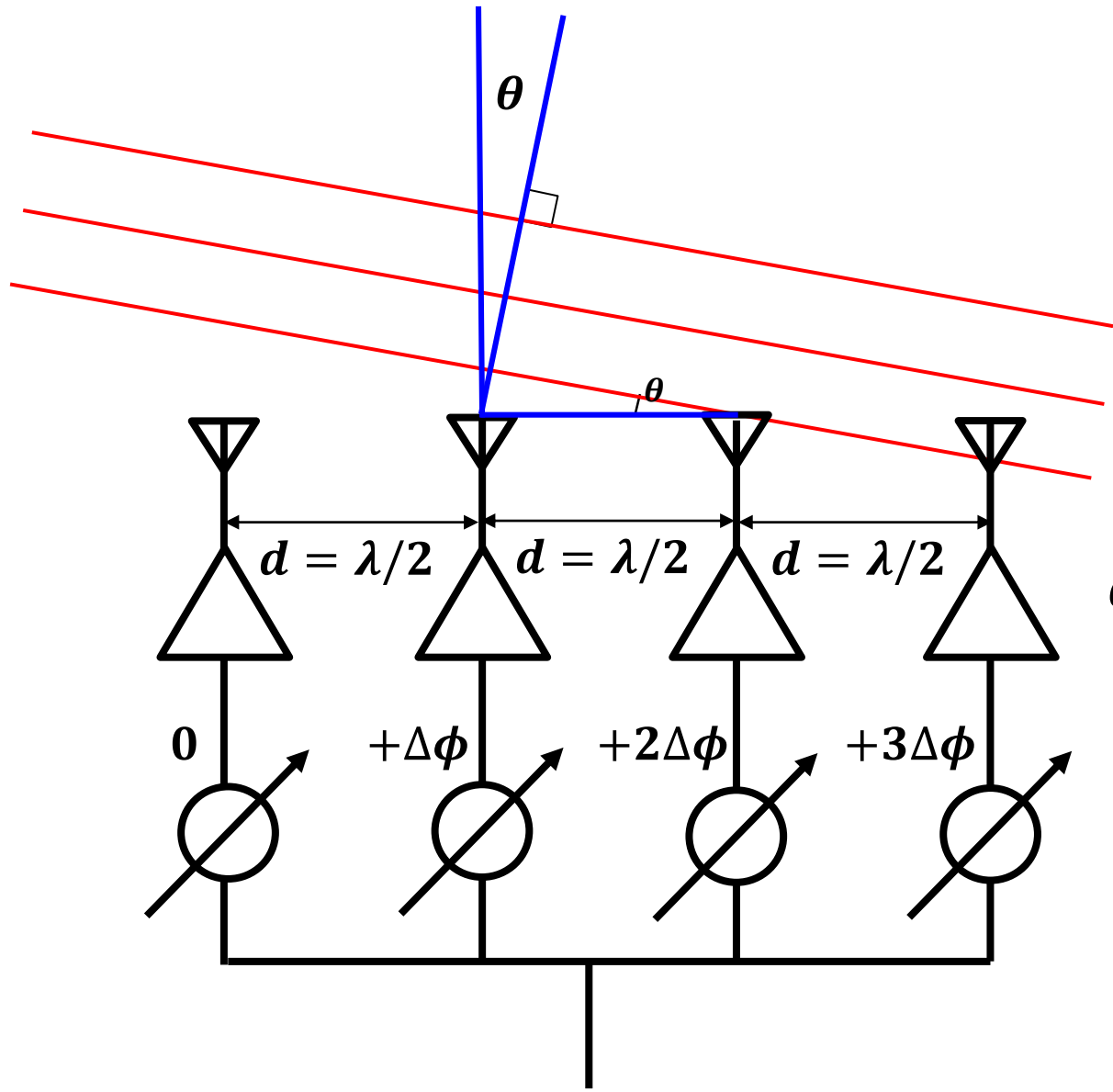
$$\theta \cong \sin^{-1} \frac{\Delta\phi}{\pi}$$



PA output: $P_t \Rightarrow n P_t$
 Antenna gain: $G_t \Rightarrow n G_t$

n : #antenna

フェーズドアレイアンテナ



$$d \sin \theta \cong \lambda \frac{\Delta\phi}{2\pi}$$

$$\theta = \sin^{-1} \left(\frac{\lambda \Delta\phi}{d 2\pi} \right)$$

$d = \frac{\lambda}{2}$ のとき

$$\theta = \sin^{-1} \left(\frac{\Delta\phi}{\pi} \right) \cong \frac{\Delta\phi}{\pi}$$

Phased array

送信アンテナ n_{TX} 本、受信アンテナ n_{RX} 本

$$\begin{aligned}
 P_t &\Rightarrow n_{TX} P_t \\
 G_t &\Rightarrow n_{TX} G_t \\
 G_r &\Rightarrow n_{RX} G_r
 \end{aligned}
 \quad
 d = \frac{c}{4\pi f_c} \sqrt{\frac{(n_{TX} P_t) (n_{TX} G_t) (n_{RX} G_r)}{kTB2^m}}$$

28GHz LOS (NLOSなら約1/10)

- $n = 1: d = 1\text{m}$
- $n = 4: d = 8\text{m}$
- $n = 16: d = 64\text{m}$
- $n = 64: d = 512\text{m}$
- $n = 256: d = 4,096\text{m}$
- $n = 10000: d = 1000\text{km}$ (60cm x 60cm array)

LOS: Line of Sight
 NLOS: Non Line of Sight

利点1: 通信距離が伸ばせる
 利点2: 通信の向きを変えられる

最高伝送速度

(参考) 1CCあたりの理論的な最高伝送速度

✓ 1コンポーネントキャリア(CC)あたりの理論的な最高伝送速度は、次式により算出

$$\text{Data rate [bps]} = N_{\text{MIMO}} \times N_{\text{Mod}} \times f \times R_{\text{max}} \times (N_{\text{RB}} \times 12 / T_{\text{symbol}}) \times (1 - R_{\text{OH}}) \times R_{\text{DL/UL}}$$

- N_{MIMO} : 最大MIMOレイヤ数
- N_{MOD} : 変調シンボルあたりのビット数
- f : UEのベースバンド処理におけるピークレートを算出するためのスケーリングファクター
- R_{MAX} : 最大符号化率
- N_{RB} : 1CCあたりのリソースブロック数
- T_{symbol} : 1 OFDMシンボルあたりの時間長[sec]
- R_{OH} : 無線フレームあたりのオーバーヘッド率 (参照信号や制御チャネルなど)
- $R_{\text{DL/UL}}$: TDDのUL/DLの割当て比率

(算出例:DLの場合)

※3GPPで詳細検討中。今後変更される可能性有

$$10.1 \text{ [Gbps]} = 8 \times 6 \times 1 \times (948/1024) \times (264 \times 12 / (8.93 \times 10^{-6})) \times (1 - 0.2) \times (4 / 5) \times 10^{-9}$$

- $N_{\text{MIMO}} = 8$ ※1 DL:最大8レイヤ (SU-MIMO) ,12レイヤ (MU-MIMO) 、UL:最大4レイヤ (SU-MIMO) ,12レイヤ (MU-MIMO)
- $N_{\text{MOD}} = 6$ ※2 QPSK : 2ビット、16QAM : 4ビット、64QAM : 6ビット、256QAM : 8ビット
- $f = 1$ ※3 システム帯域の最高伝送速度の計算の際は1、UEのベースバンド処理能力に応じて0.75も選択可能
- $R_{\text{MAX}} = 948/1024$ ※4 データチャネル : LDPC符号 (最大符号化率948/1024) 、制御チャネル : Polar符号
- $N_{\text{RB}} = 264$ ※5 下表。264は、ミリ波・サブキャリア間隔120kHz・400MHz幅の場合
- $T_{\text{symbol}} = 8.93 \times 10^{-6}$ ※6 スライド[5G NR(New Radio)フレーム構成]参照。サブキャリア間隔120kHzの場合、8.93μsec (= 8.93×10⁻⁶ sec)
- $R_{\text{OH}} = 0.2$ ※7 復調用参照信号や制御チャネル、ミリ波では位相雑音低減用の信号等。一般的にSub-6は0.14、ミリ波は0.2
- $R_{\text{DL/UL}} = 4/5$ ※8 TDDのDL/ULの割当て比率。4/5は、DL:UL=4:1とした場合のDLの割合。

表 : 3GPP 1CC (コンポーネントキャリア) 幅あたりのリソースブロック (RB) 数

サブキャリア間隔 [kHz]	1CC (コンポーネントキャリア) 幅 [MHz]あたりのリソースブロック (RB) 数													
	10	15	20	30	40	50	60	70	80	90	100	200	400	
Sub-6	15	52	79	106	160	216	270	-	-	-	-	-	-	-
	30	24	38	51	78	106	133	162	189	217	245	273	-	-
	60	11	18	24	38	51	65	79	93	107	121	135	-	-
28GHz帯	60	-	-	-	-	66	-	-	-	-	132	264	-	-
	120	-	-	-	-	32	-	-	-	-	66	132	264	-

伝送速度の計算

SISO, 64QAM, NR準拠PHY/MAC overhead込み

$$(1 * 6 * 1 * (948/1024) * (264 * 12 / (8.93e-6)) * (1 - 0.2) * (4 / 5) * 1e-9) \\ = \mathbf{1.2612Gbps}$$

2xMIMO, 64QAM, NR準拠PHY/MAC overhead込み

$$(2 * 6 * 1 * (948/1024) * (264 * 12 / (8.93e-6)) * (1 - 0.2) * (4 / 5) * 1e-9) \\ = \mathbf{2.5223Gbps}$$

2xMIMO, 256QAM, NR準拠PHY/MAC overhead込み

$$(2 * 6 * 1 * (948/1024) * (264 * 12 / (8.93e-6)) * (1 - 0.2) * (4 / 5) * 1e-9) \\ = \mathbf{3.3631Gbps}$$

伝送速度と距離の関係 @28GHz

DL(64QAM): 256(BS)-to-4(UE)

Carrier Freq.	28GHz	Distance	500m
Channel BW.	400MHz	FSPL	115dB
kTB	-88dBm	Req. SNR	26dB (64-QAM)
TX		RX	
TX Array Size	256	RX Array Size	4
TX Array Gain $G_{TXArray}$	24dB	RX Array Gain $G_{RXArray}$	6dB
Antenna Gain-Imp. Loss G_{Ant}	4dB	Antenna Gain-Imp. Loss G_{Ant}	4dB
PA Pout P_{outPA}	5dBm+24dB	NF	8dB
TX EIRP	57dBm ($P_{outPA} + G_{TXArray} + G_{Ant}$)	Pwr. After FSPL P_{Rev}	-58dBm (EIRP-FSPL)
Received TX-to-RX SNR	32dB ($P_{Rev} + G_{RXArray} + G_{Ant} - NF - kTB$)		

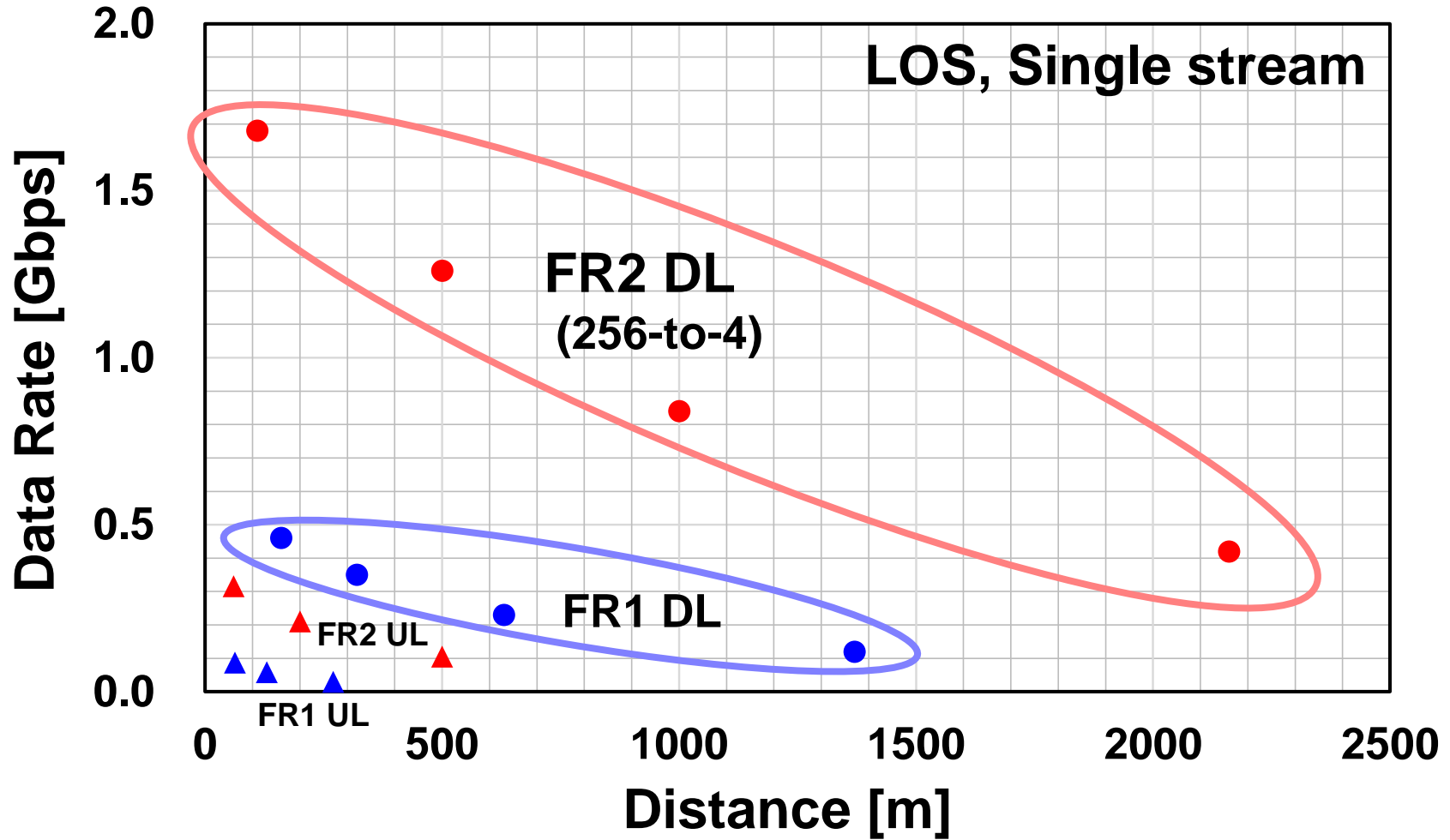
$$d \propto n_{TX} \sqrt{n_{RX}}$$

Downlink(基地局⇒端末)
QPSK 0.42Gbps @ 2160m
16QAM 0.84Gbps @ 1000m
64QAM 1.26Gbps @ 500m
256QAM 1.68Gbps @ 110m

Uplink(端末⇒基地局)
QPSK 0.105Gbps @ 500m
16QAM 0.210Gbps @ 200m
64QAM 0.315Gbps @ 60m

BS: Backoff 6dB(QPSK, 16QAM, 64QAM), 13dB(256QAM)
 UE: Backoff 0dB(QPSK), 2dB(16QAM), 6dB(64QAM)

UL/DL Data Rate vs Distance



テラヘルツ通信技術の意義

6Gへ向けて

THz (>100GHz)

Extreme high data rate (>100Gb/s)

Extreme low latency (~1ms)

NTN(非地上)

Extreme coverage extension

6G
Requirements

Extreme high reliability

Extreme low energy and cost

Extreme massive connectivity & sensing

低消費電力
低コスト

Theoretical Data Rate Limit

$$C = B \log_2(1 + S/N)$$

$$N = kT B$$

$$S = P_r = P_t G_t G_r \left(\frac{c}{4\pi f_c d} \right)^2$$

$$B = \alpha f_c$$

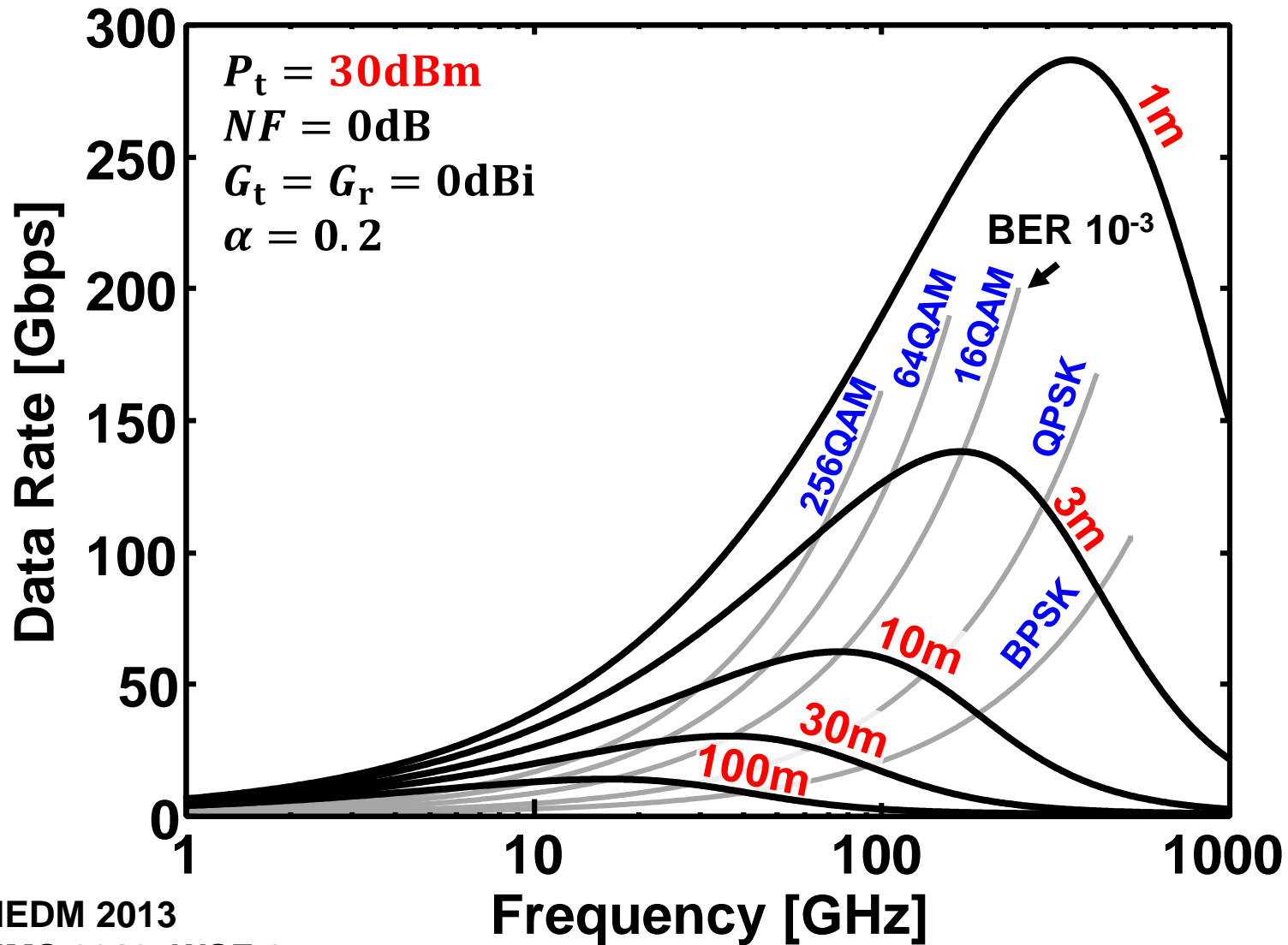
- C**: channel capacity
- B**: bandwidth
- S**: signal power
- N**: noise power
- P_t**: transmitting power
- P_r**: receiving power
- G_t G_r**: antenna gains
- f_c**: carrier frequency
- c**: light of speed
- d**: distance btw Tx and Rx

new assumption

$$C_{\text{peak}} = C_0 \alpha^{\frac{2}{3}} \left(\frac{P_t G_t G_r}{d^2} \right)^{\frac{1}{3}}$$

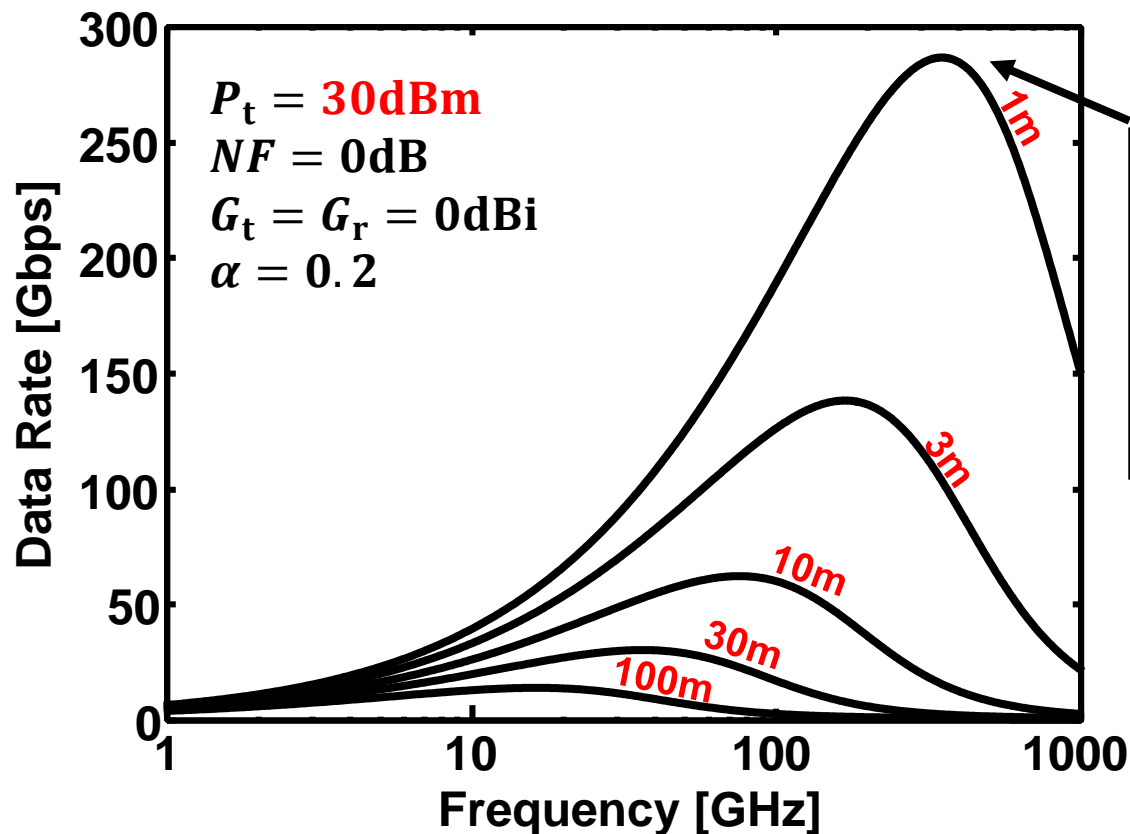
$$C_0 = 822 \text{ Gb/s}$$

Theoretical Data Rate Limit



K. Okada, IEDM 2013
 K. Okada, IMS 2019, WSF-2
 K. Okada, BCICTS 2019

Theoretical Data Rate Limit



280Gbps @ 350GHz
1m, 30dBm
= 0.1m, 10dBm
= 6.4m, 10dBm, 16 array
= 100m, 10dBm, 100 array

K. Okada, IEDM 2013
K. Okada, IMS 2019, WSF-2
K. Okada, BCICTS 2019

Capacity with **Multiple Antennas**

$$C = B \log_2 \left\{ \det \left(I + \frac{\gamma_0}{n} H^H H \right) \right\} \quad \gamma_0 = SNR$$

① **SISO**

$$C = B \log_2(1 + \gamma_0)$$

② **MIMO (spatial correlation=1)** e.g. $H = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$

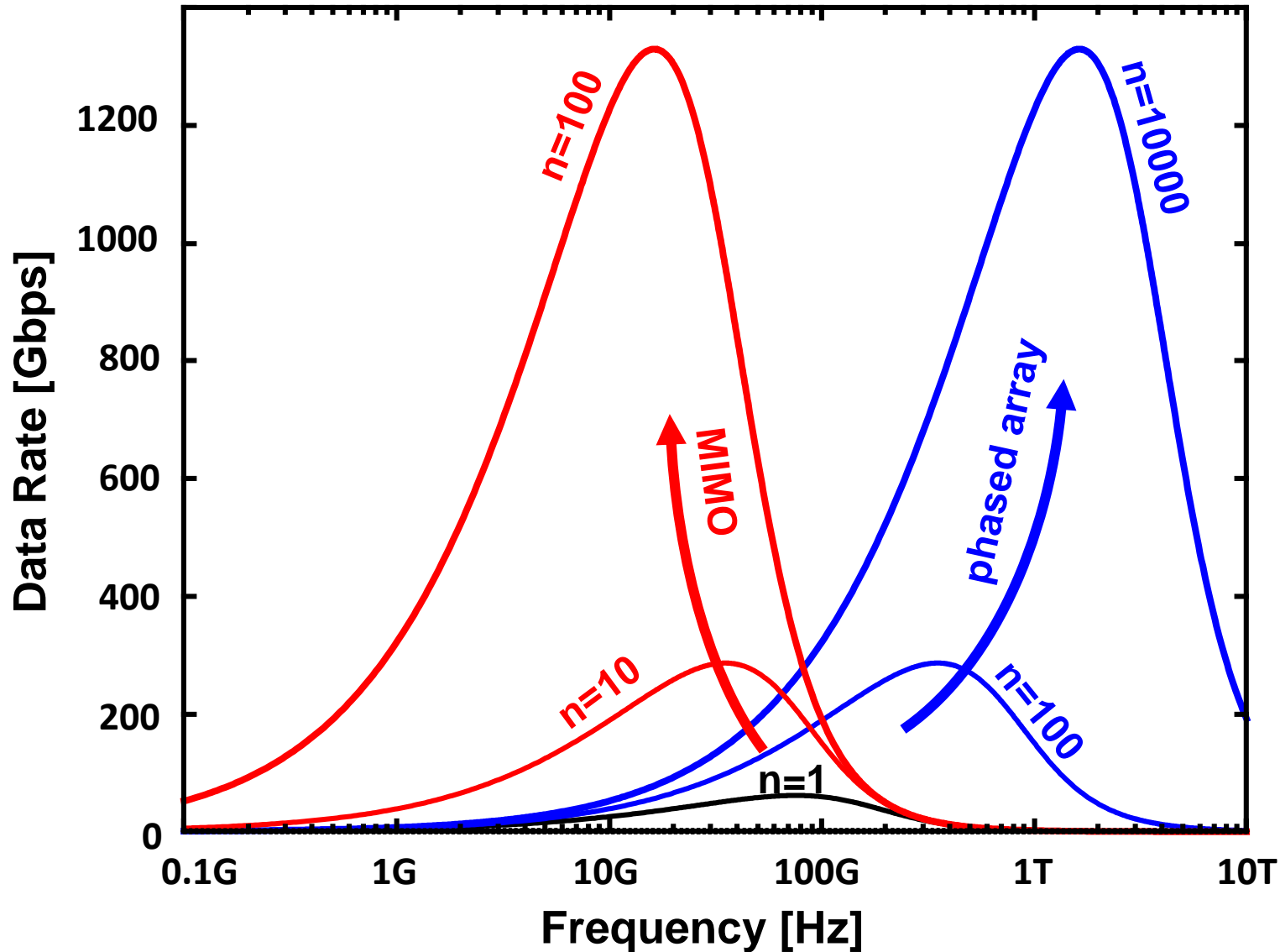
$$C = B \log_2(1 + n \gamma_0) \quad \text{*equivalent to phased array}$$

③ **MIMO (spatial correlation=0)** e.g. $H = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

$$C = B n \log_2(1 + \gamma_0/n)$$

E. Telatar, "Capacity of Multi-antenna Gaussian Channels," European transactions on telecommunications, vol. 10, no. 6, pp. 585-595, Nov. 1999.

Theoretical Limit of Data Rate



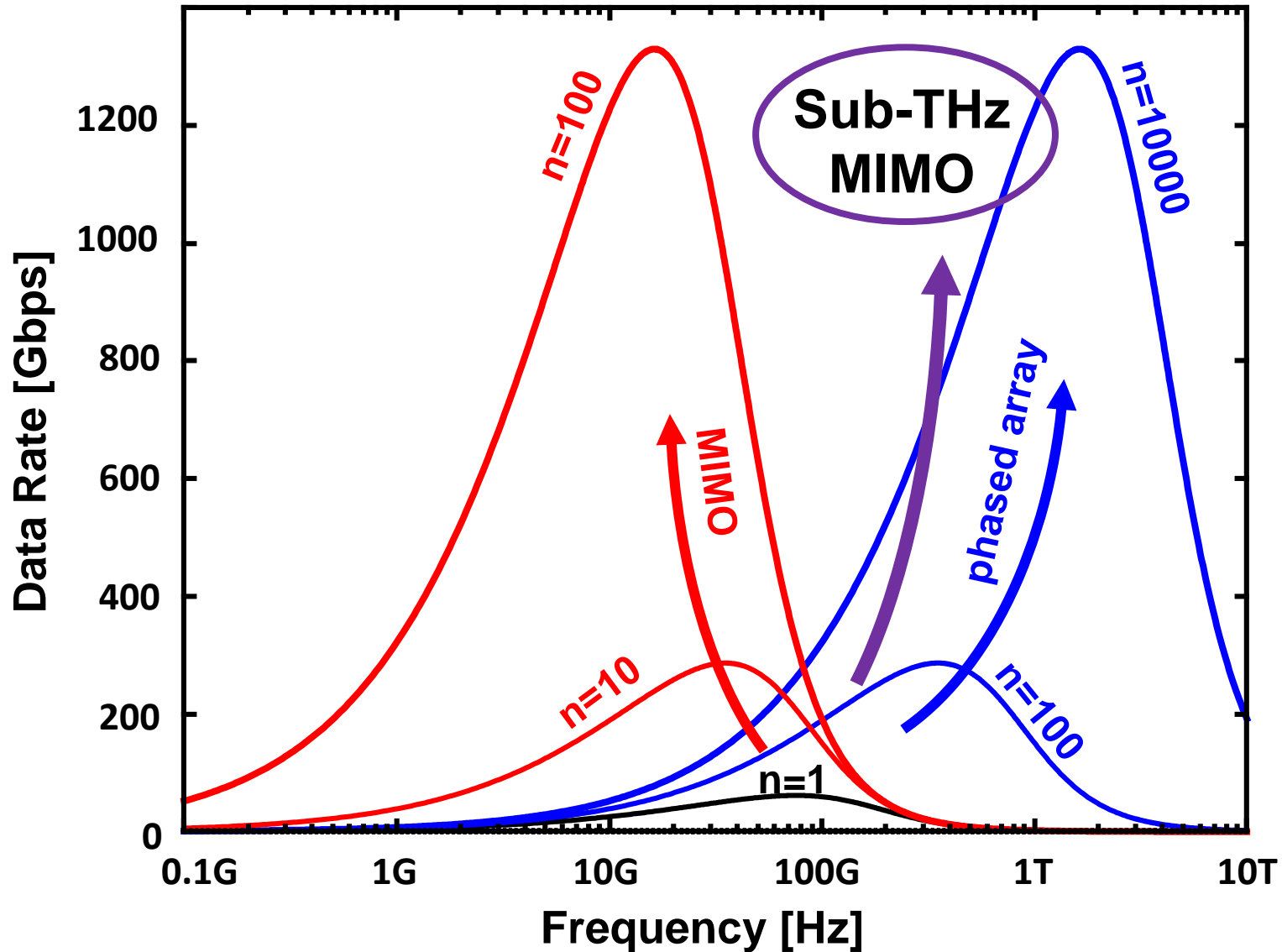
(1) Spatial multiplexing

- Analog beamforming with MIMO

(2) Higher frequency & wider BW

- more EIRP with phased array
- more output power by non-CMOS technology

Theoretical Limit of Data Rate



(1) Spatial multiplexing

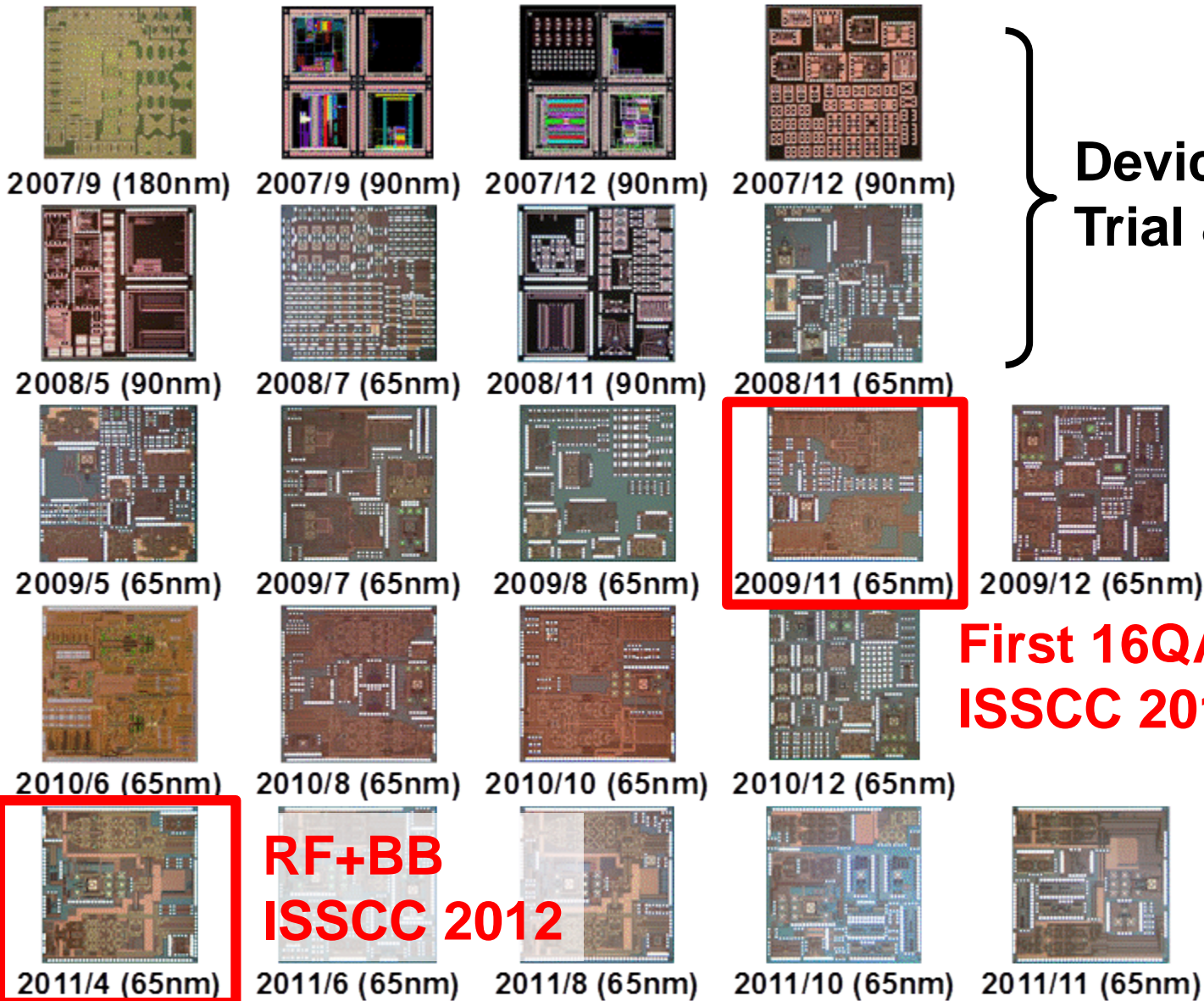
- Analog beamforming with MIMO

(2) Higher frequency & wider BW

- more EIRP with phased array
- more output power by non-CMOS technology

テラヘルツCMOS無線機

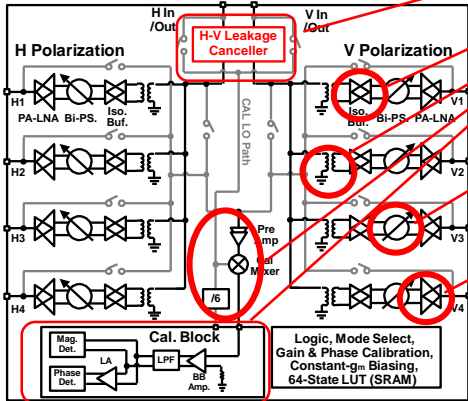
Development History of 60GHz



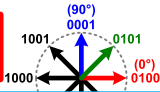
**RF+BB
ISSCC 2012**



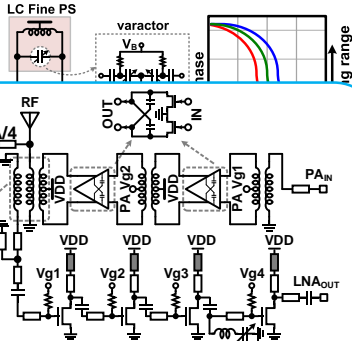
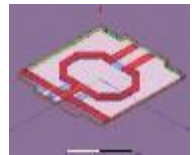
アーキテクチャ設計



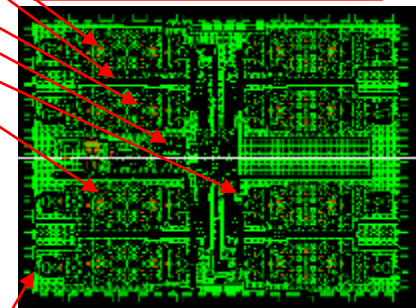
移相器設計



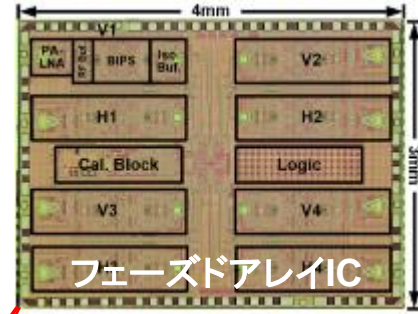
電力増幅器設計



レイアウト統合設計

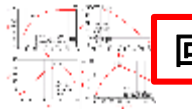


統合0.5か月、製造2か月



フェーズドアレイIC

回路設計検証



レイアウト設計検証

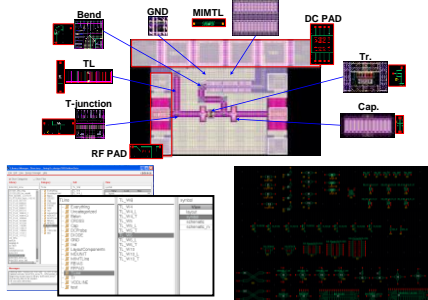


回路考案、回路設計2か月x(1-2人)

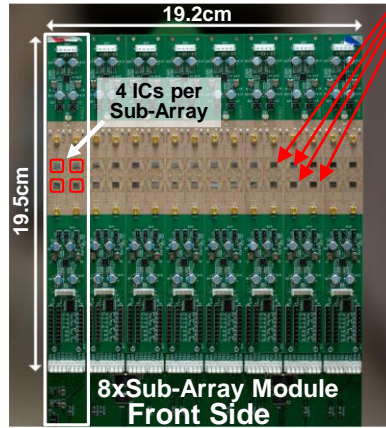
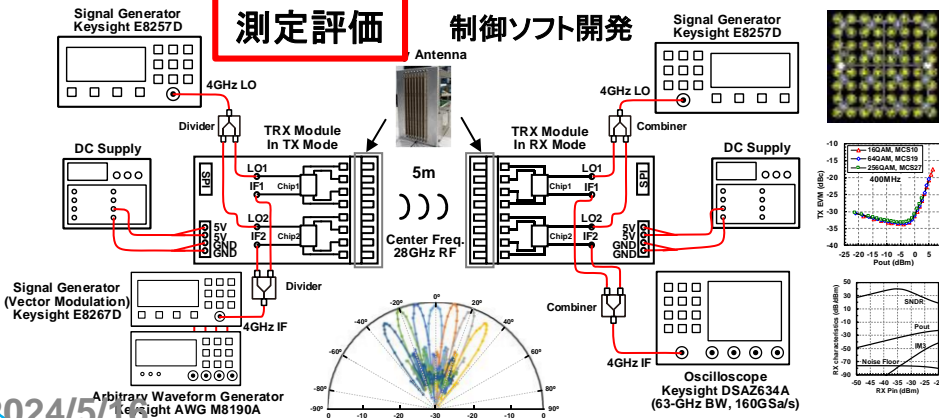
電磁界解析1か月、レイアウト設計1か月x(1-2人)、レイアウト後回路特性検証2か月、レイアウト修正

アーキテクチャ設計から測定評価まで半年に圧縮して推進

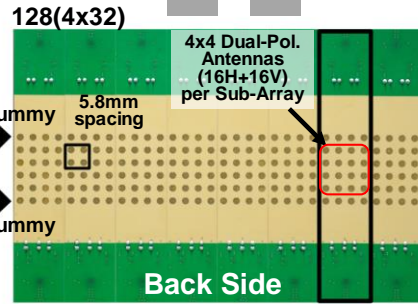
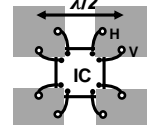
設計環境構築



測定評価

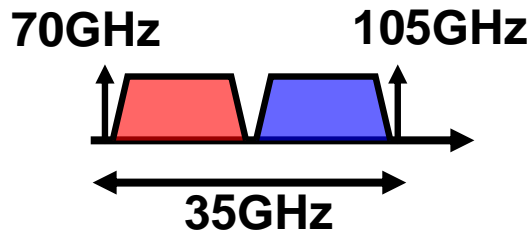


プリント基板・パッケージ設計



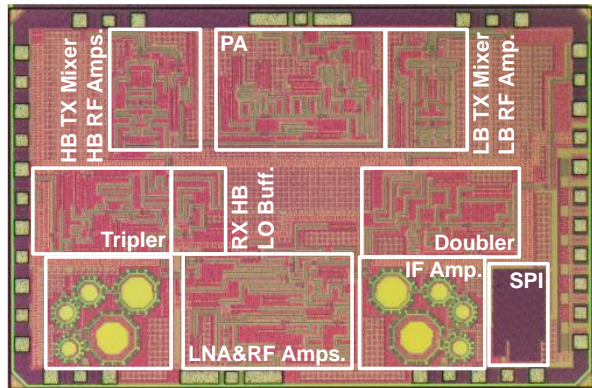
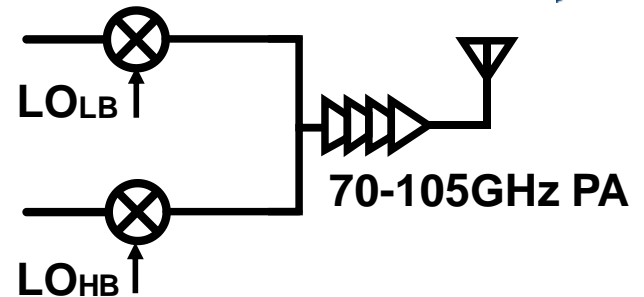
アンテナ設計

120Gbps 100GHz帶CMOS無線機

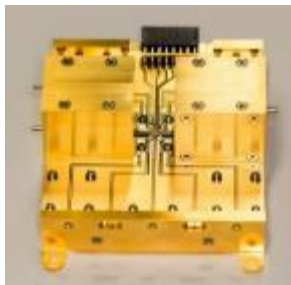


Low Band (LB): 0.3-20GHz

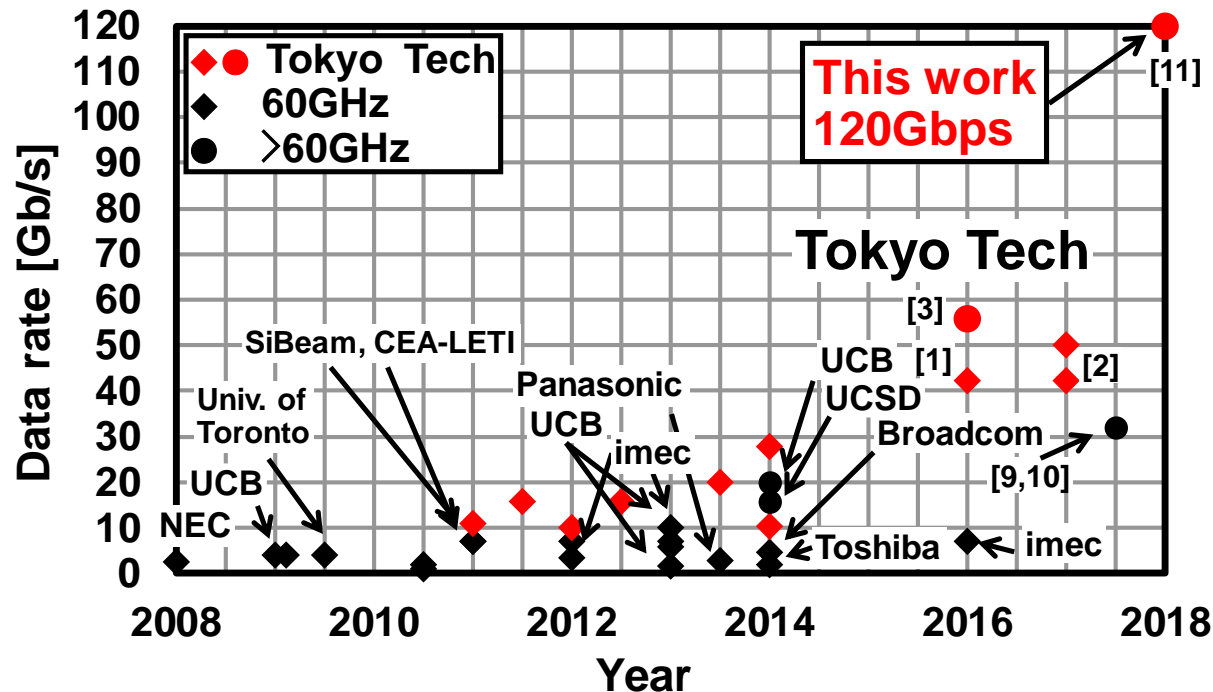
High Band (HB): 0.3-20GHz



65nm CMOS, 2mm x 3mm
TX: 110mW, RX: 177mW



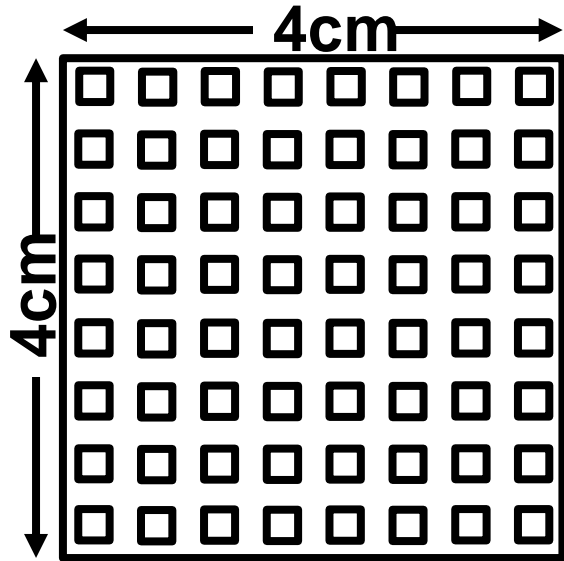
waveguide module



16QAM, 23dBi horn **120Gb/s @ 0.2m**
 (with 56dBi antenna 120Gb/s @ 400m is possible)

同面積での比較

5G phased-array (~30GHz)



5mm pitch

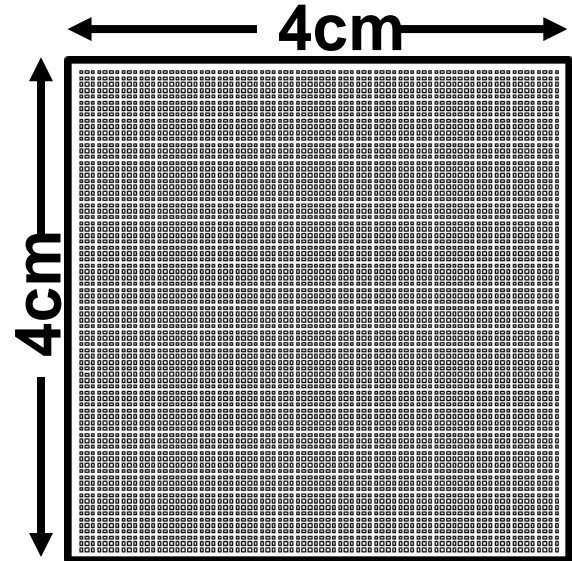
64 elements

for 100m distance:

Required $P_t = 10\text{dBm}$

$P_{DC} = 6400\text{mW}$ (10% efficiency)

300GHz phased-array



0.5mm pitch

6400 elements

for 100m distance:

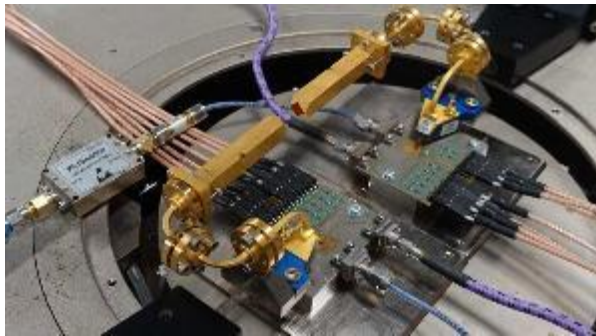
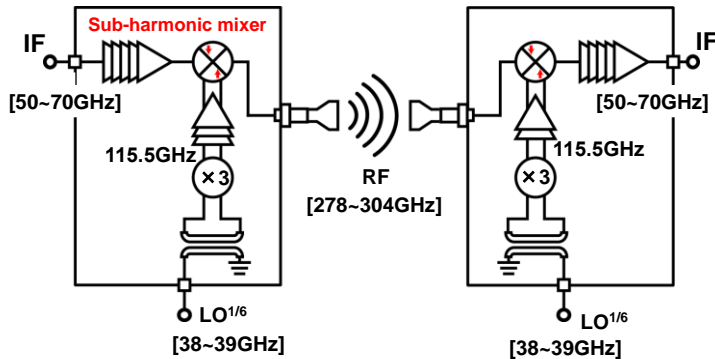
Required $P_t = -30\text{dBm}$

$P_{DC} = 64\text{mW}$ (10% efficiency)

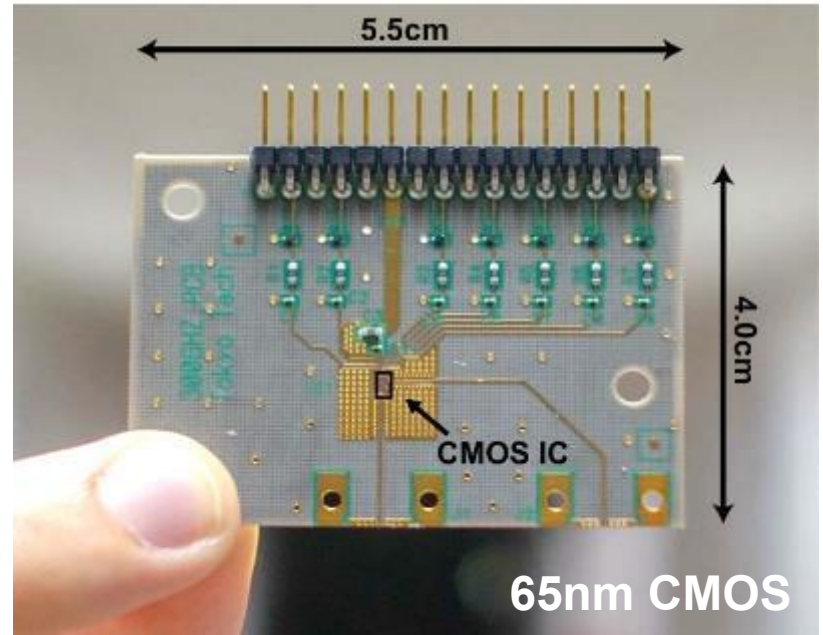
同じ送信電力なら100倍距離が延びる

300GHz-Band CMOS TRX

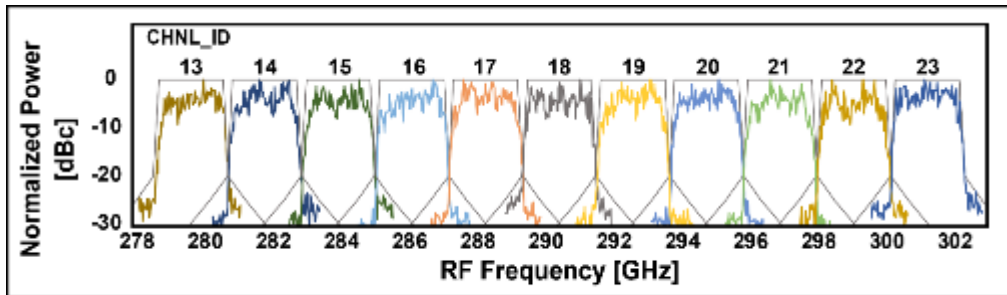
mixer-first, mixer-last



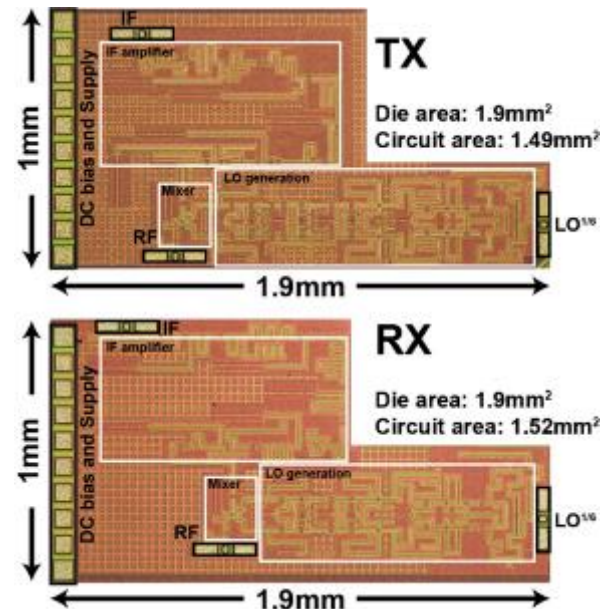
TX: 270mW
RX: 140mW
TX-RX: 34Gbps



IEEE802.15.3d Standard compatibility

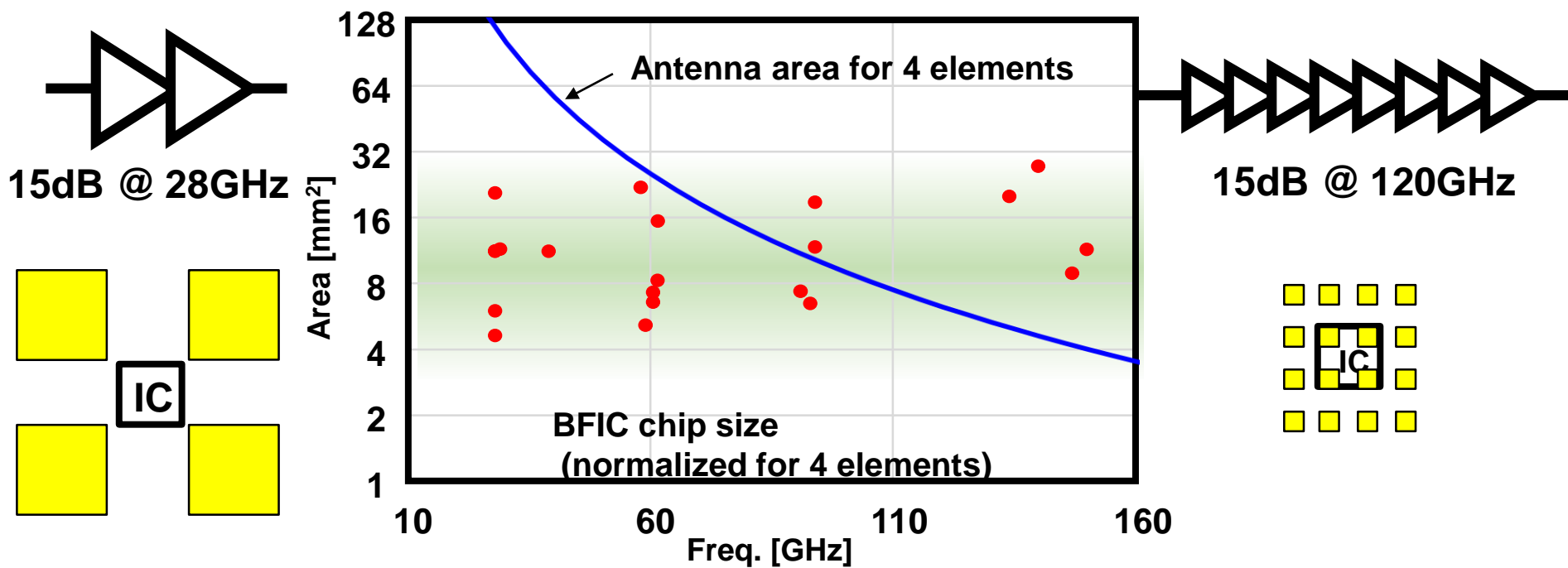


*CHNL_ID is the channel ID as defined by IEEE802.15.3d standard [1] (e.g. for ch.20, CHNL_ID=20).
 **Roll-off factor of all the measurements is 0.25 as specified by the standard.

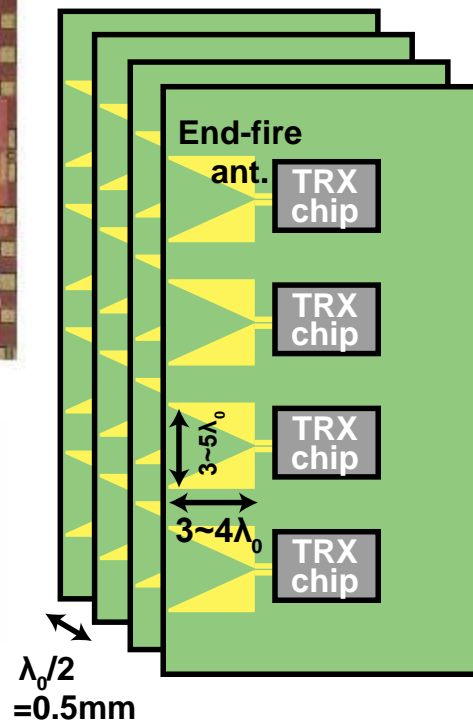
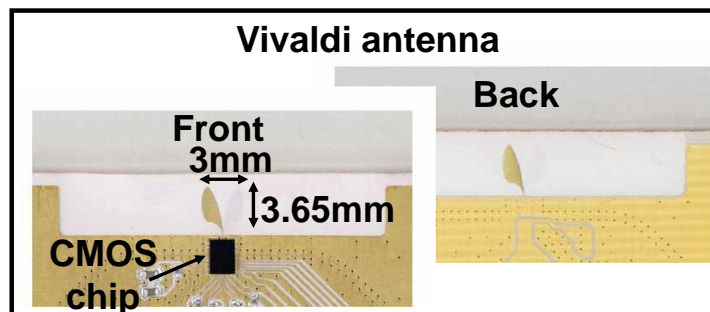
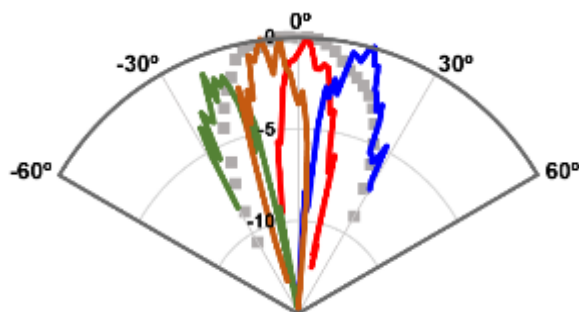
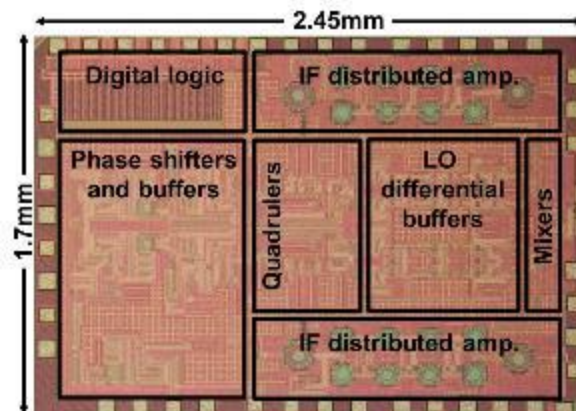
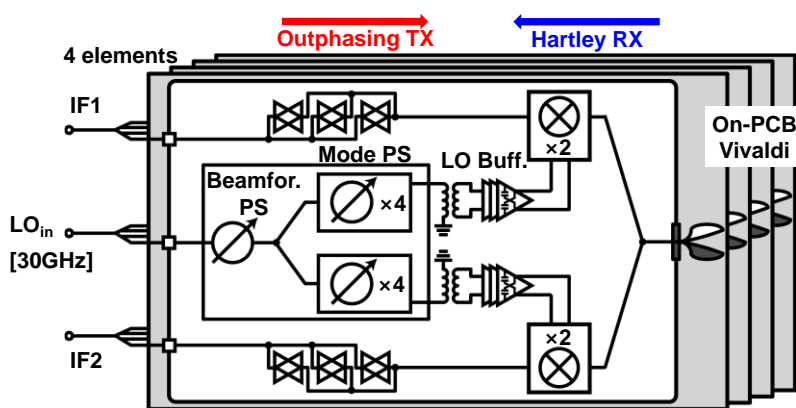
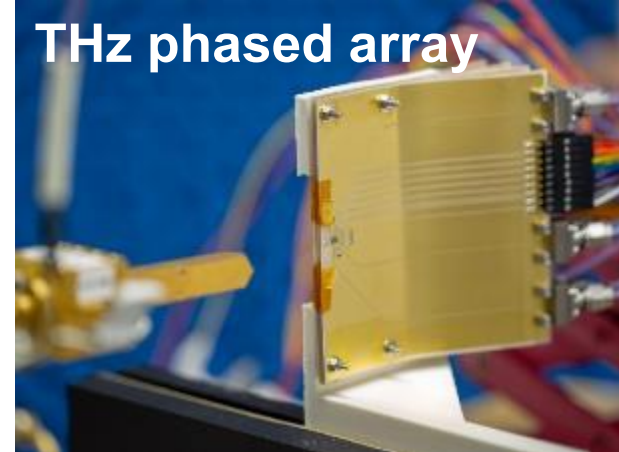
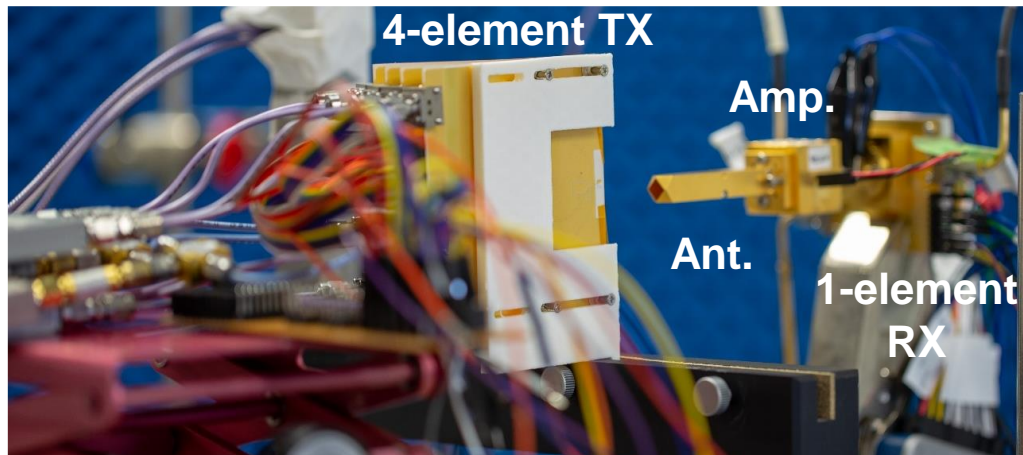


Chip Size over Frequency

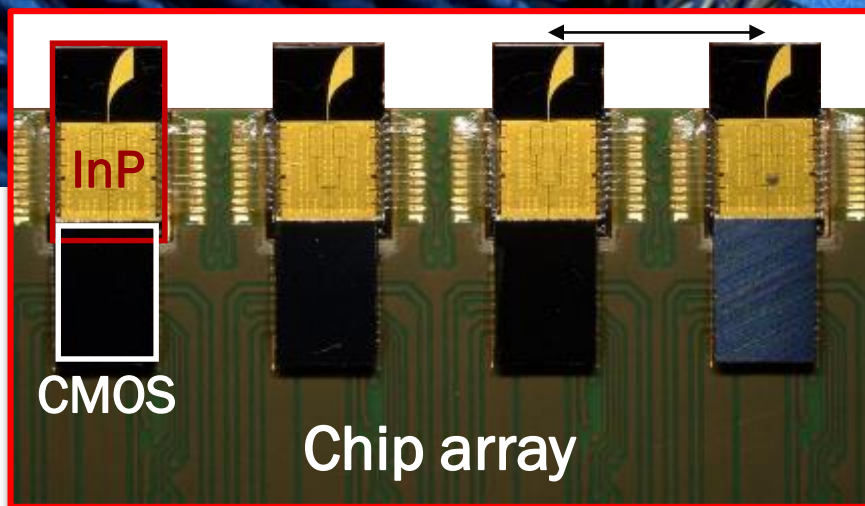
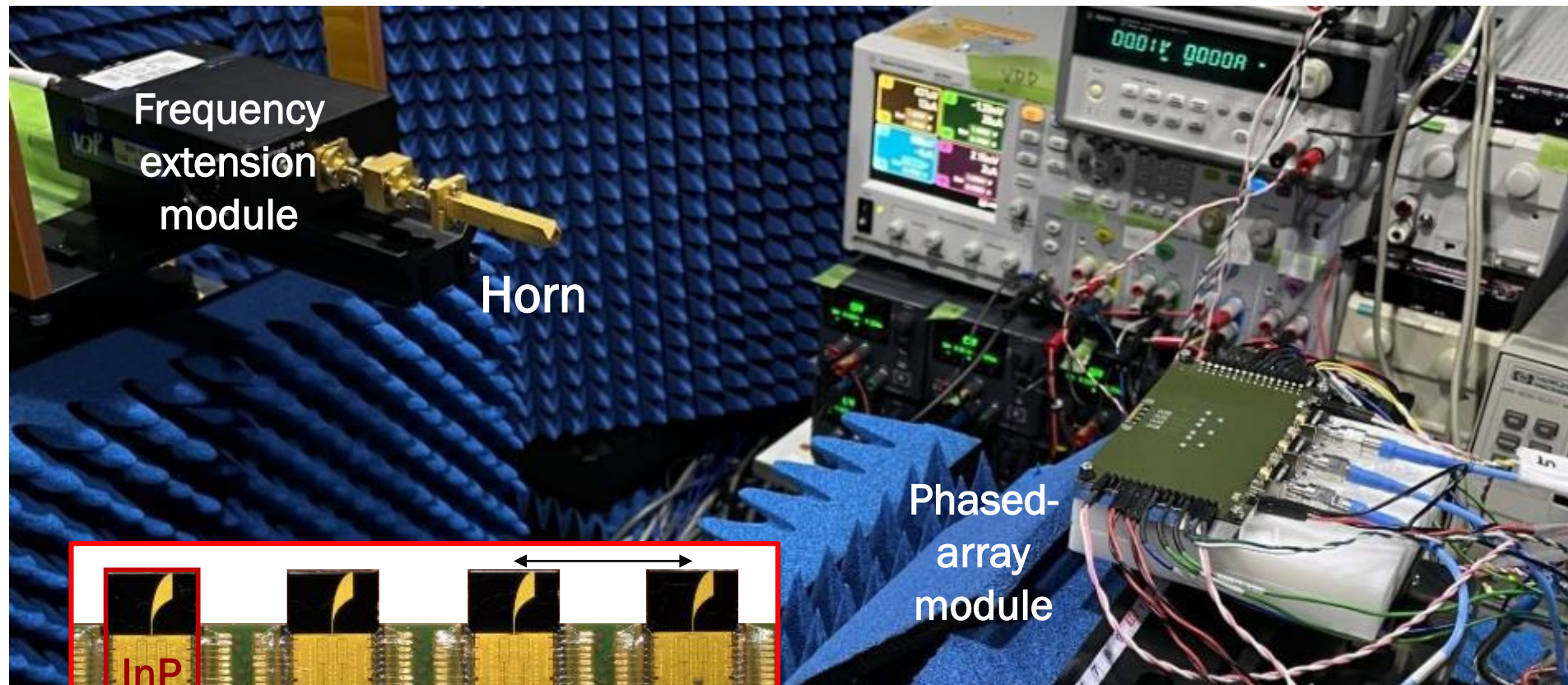
Chip size is not scaled, and the 2D array implementation is difficult for >80GHz



300GHz-band CMOS Phased-Array TRX



InP+CMOS Hybrid Phased Array

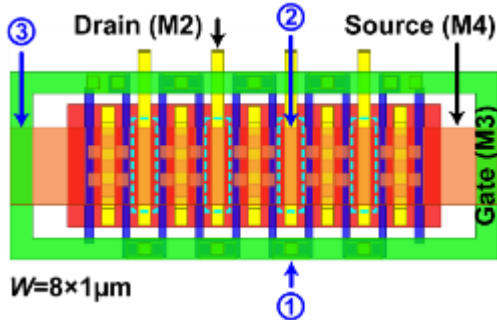


I. Abdo, et al., IMS 2023

Collaboration with NTT

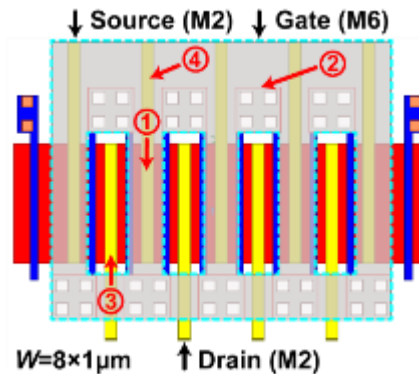
Transistor Layout Optimization

conventional

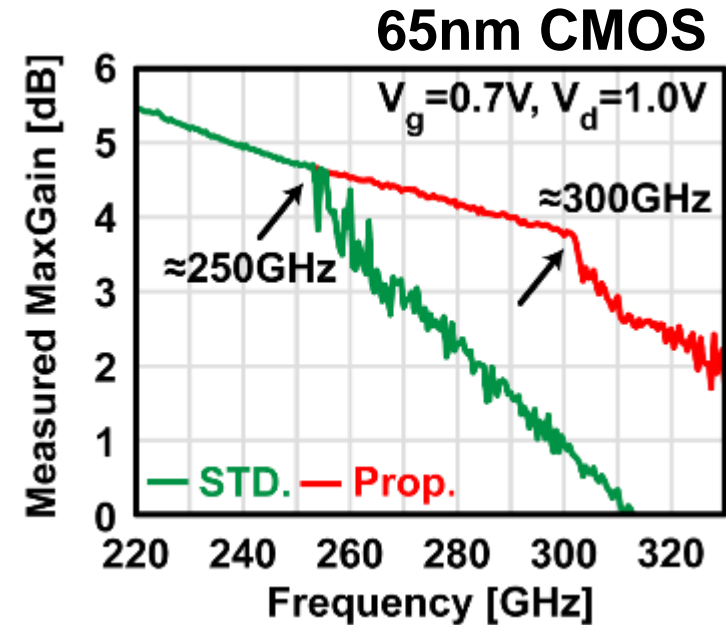


① 😞	only 2 vias to connect gate with PO → large Gate resistance
② 😞	large Drain-Source (M2-M4) overlap area → large C _{ds} capacitance
③ 😞	Gate-Source (M3-M4) overlap → large C _{gs} capacitance

proposed



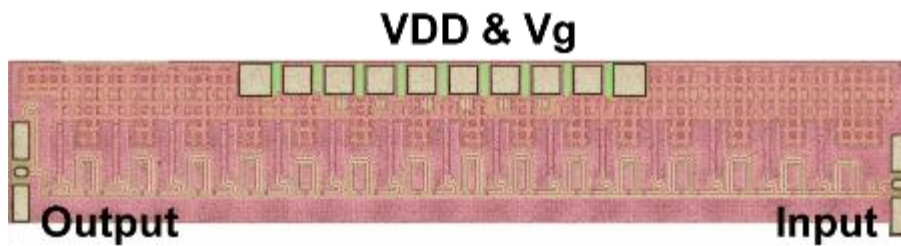
① 😊	additional drain path in M6 → Gate resistance ↓
② 😊	increase vias from 2 to 4 to connect Gate and PO → Gate resistance ↓
③ 😊	hollow rectangles in M6 to avoid Gate-Drain overlap → C _{gd} capacitance ↓
④ 😊	less Gate-Source (M6-M2) overlap → C _{gs} capacitance ↓



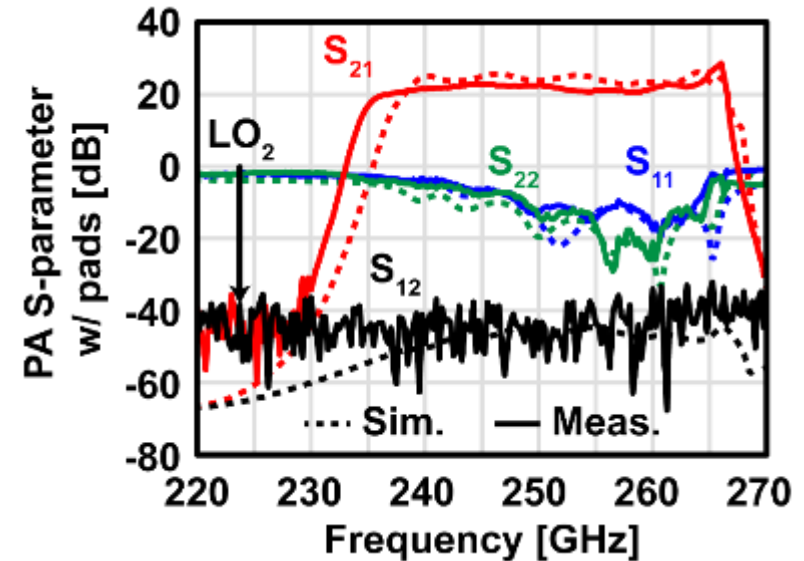
f_{max}: 310GHz ⇒ 350GHz

300GHz-band PA by 65nm CMOS

■ A stand-alone PA TEG

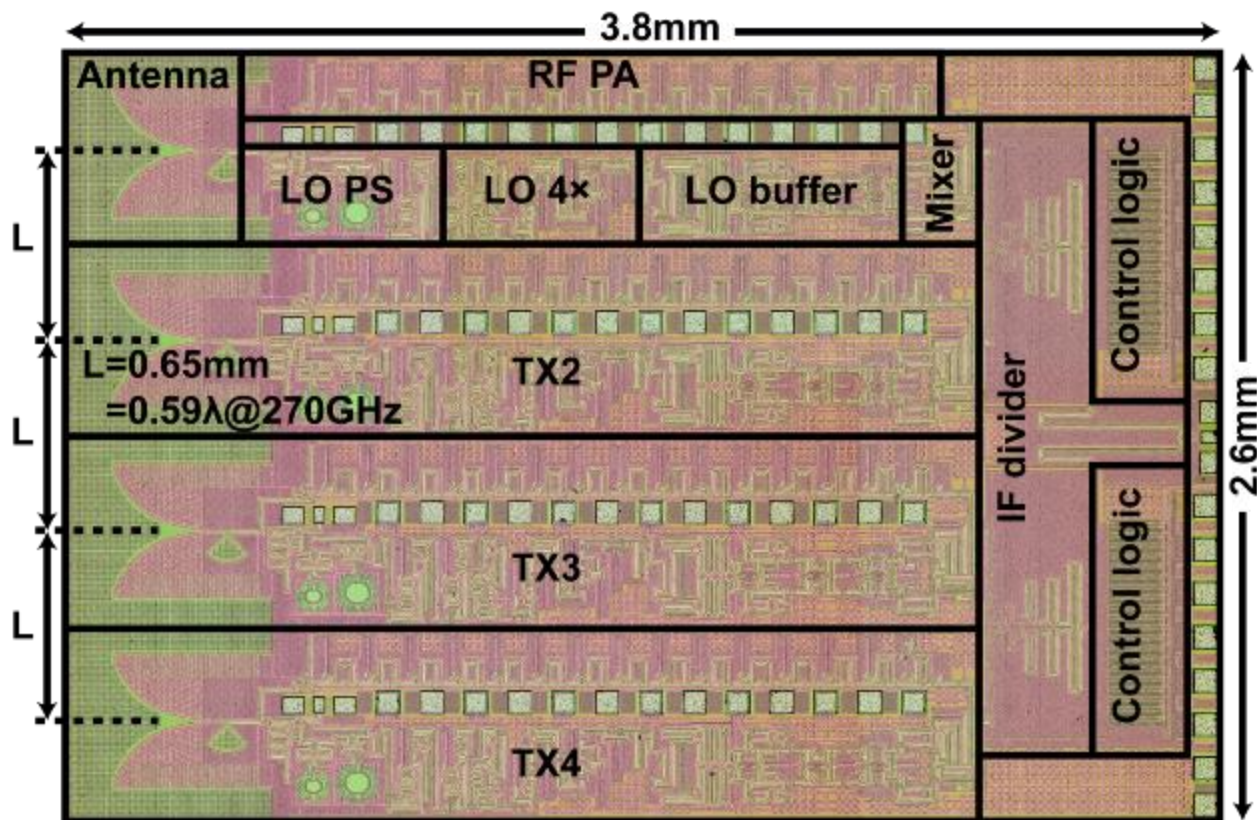


$$P_{dc} = 38.8 \text{ mW} (VDD = 1 \text{ V})$$



- Each PA stage was optimized with different transmission line lengths to boost different operation frequencies.
- The PA gain is higher than 20 dB from 237 to 267 GHz with a sharp cut-off frequency window to suppress out-of-band undesired signals.

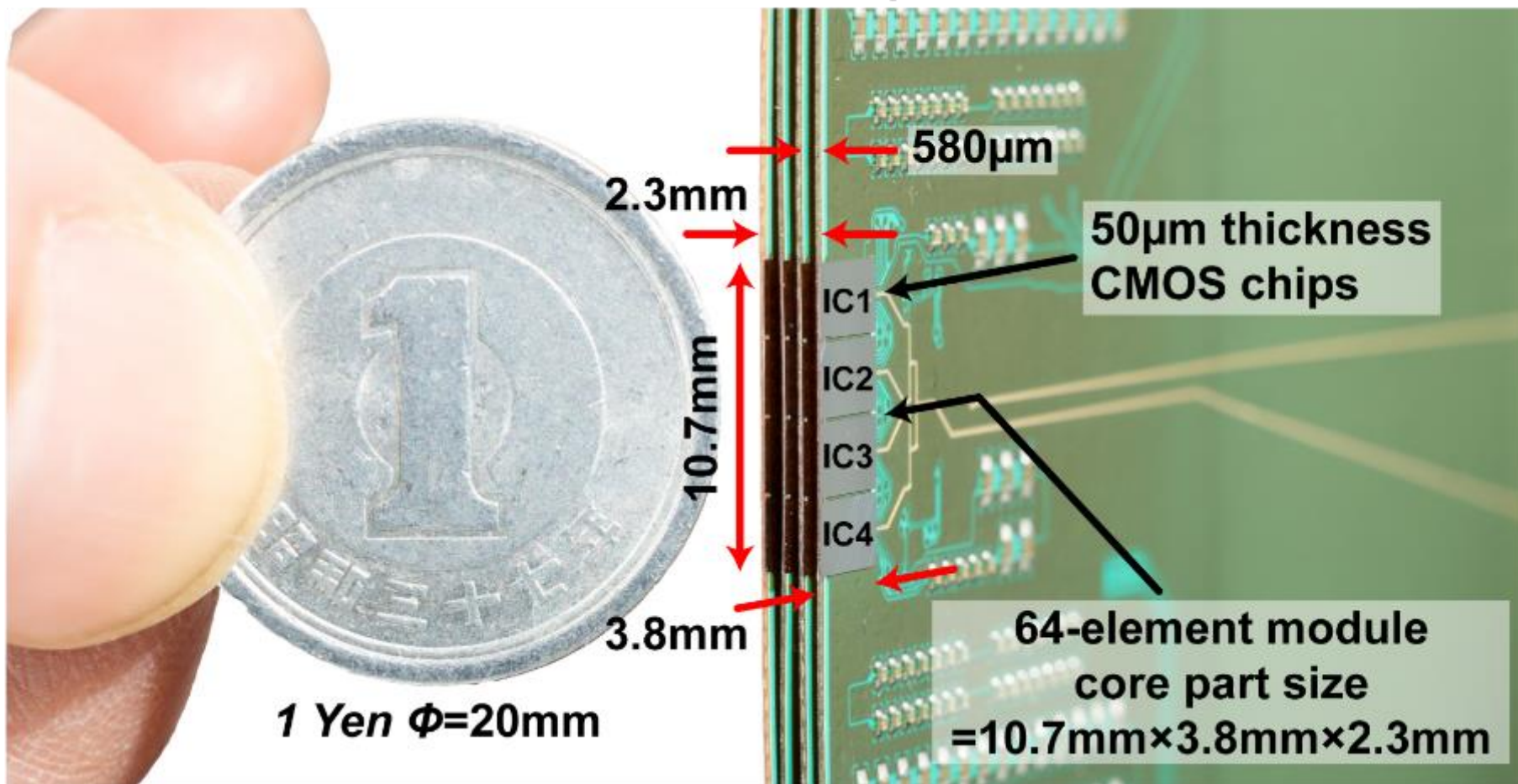
4-element 300GHz-band PA-Last Phased Array



1-element	Area(mm ²)	P _{dc} (mW)
RF PA	0.48	38
LO buffer	0.31	66
LO 4x	0.23	41
LO PS	0.24	64
Mixer	0.08	-
IF divider	0.84	-
Antenna	0.34	-

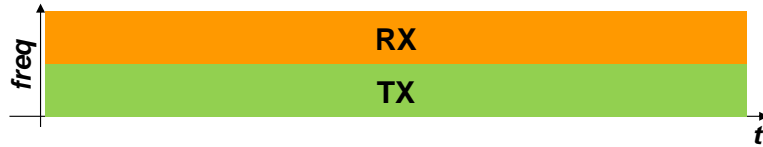
4-element 300GHz-band PA-Last Phased Array

64-element module size vs Japanese coin 1 Yen



88-136GHz Full-Duplex Phased Array

Frequency Division Duplex (FDD)

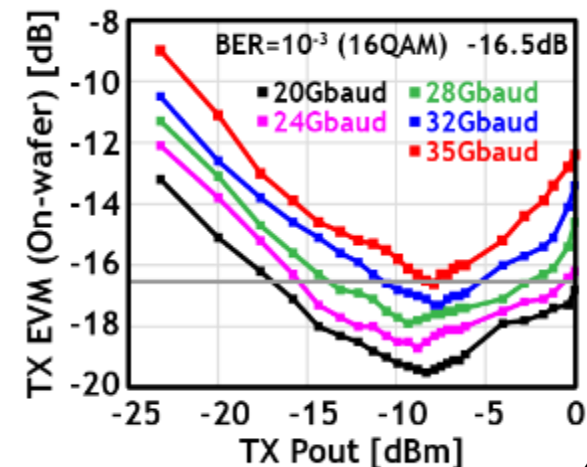
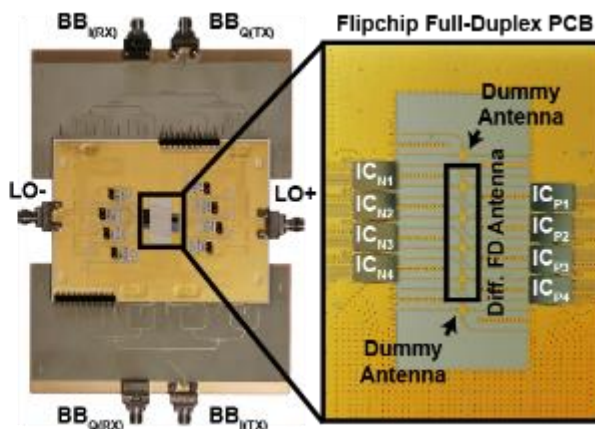
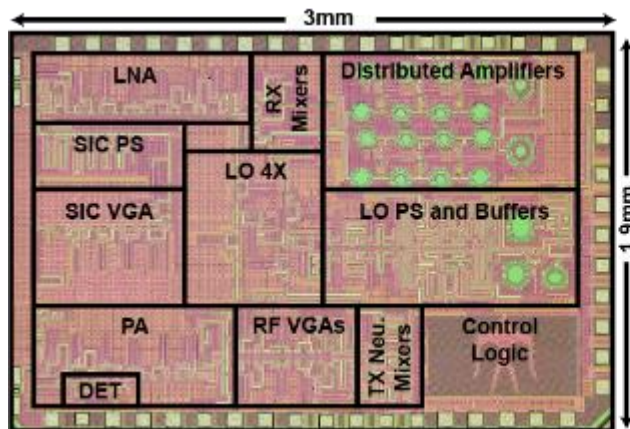
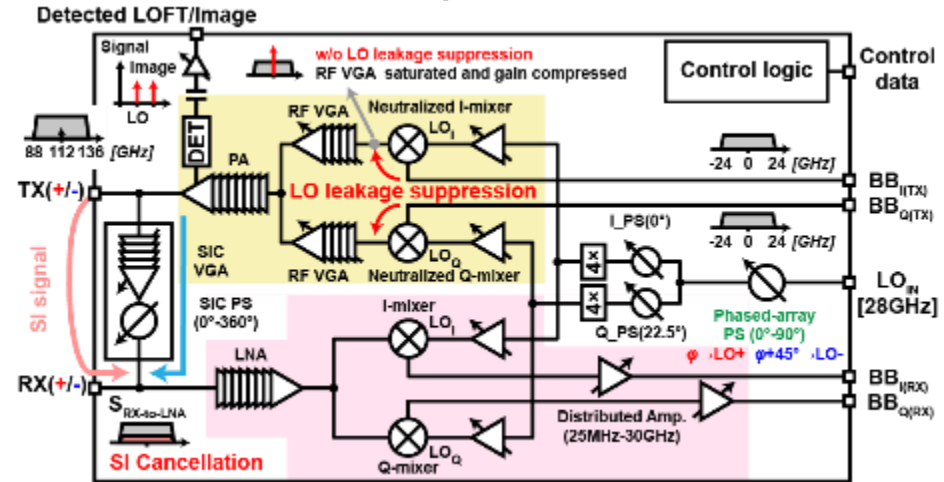


TX: 140Gb/s
OTA: 112Gb/s
FD: 6Gb/s

Time Division Duplex (TDD)



Full Duplex (FD)



C. Wang, et al., JSSC 2024

6Gへ向けて

THz (>100GHz)

Extreme high data rate (>100Gb/s)

Extreme low latency (~1ms)

NTN(非地上)

Extreme coverage extension

6G
Requirements

Extreme high reliability

Extreme low energy and cost

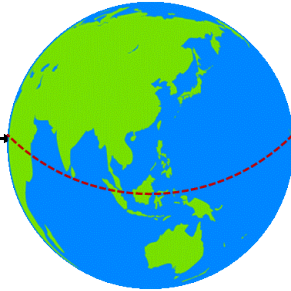
Extreme massive connectivity & sensing

低消費電力
低コスト

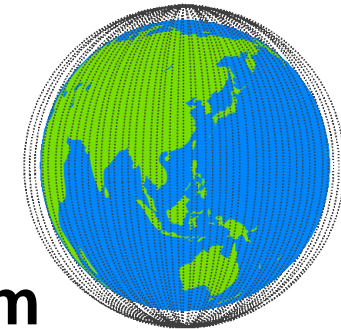
NTN: from GEO to LEO

GEO(静止軌道)

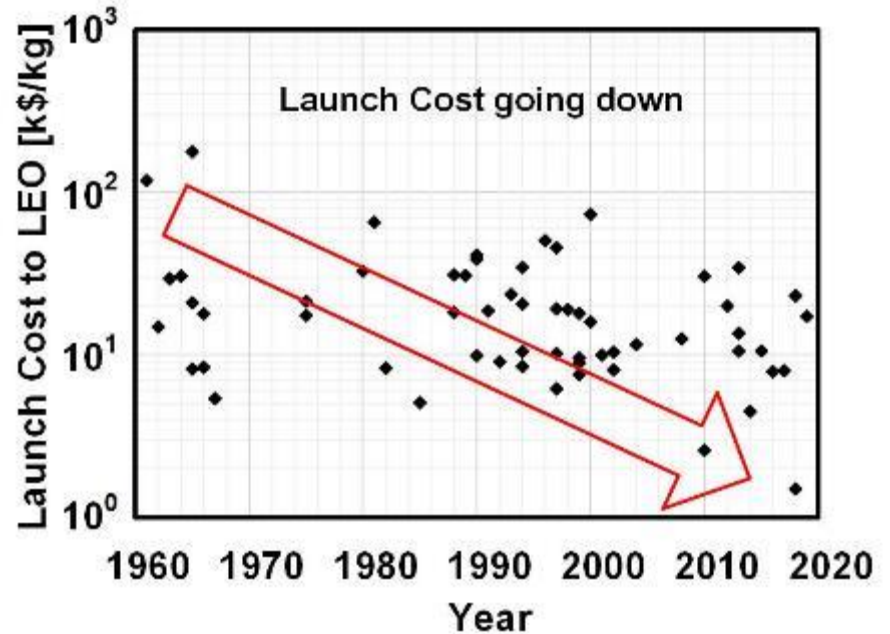
36,000km



500km



LEO(低軌道)



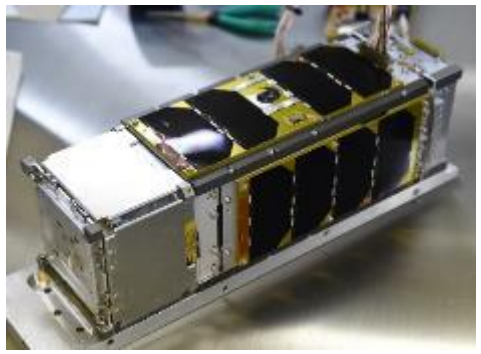
- Shorter latency
- Higher data rate
- Lower launch cost

NTN: from GEO to LEO

	GEO (Geostationary Orbit) 静止軌道衛星	LEO (Low Earth Orbit) 低軌道衛星
Orbit altitude	36,000km	500-1500km
Latency	120ms	2-5ms
Free-space path loss	212dB @ 28GHz	175-187dB @ 28GHz
Antenna	Fixed beam	Active phased array (± 60degree)
Sat deployment	2-3 satellites	Constellation by hundreds/thousands of satellites
Lifetime	15- years	5-10 years
Satellite Size	Several tons	-300kg e.g. Starlink 260kg CubeSat(1U) 1.33kg

東工大 OrigamiSat Projects

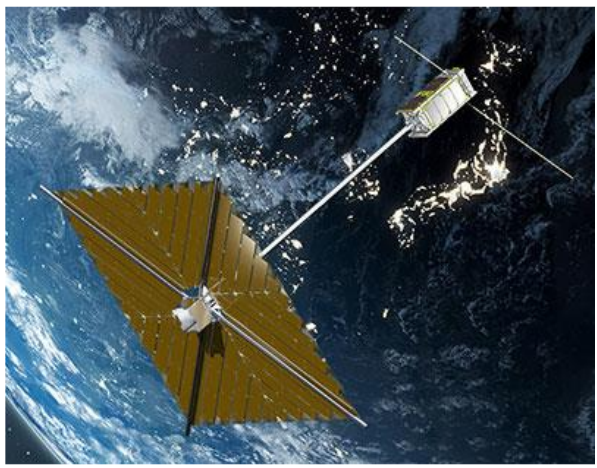
OrigamiSat-1



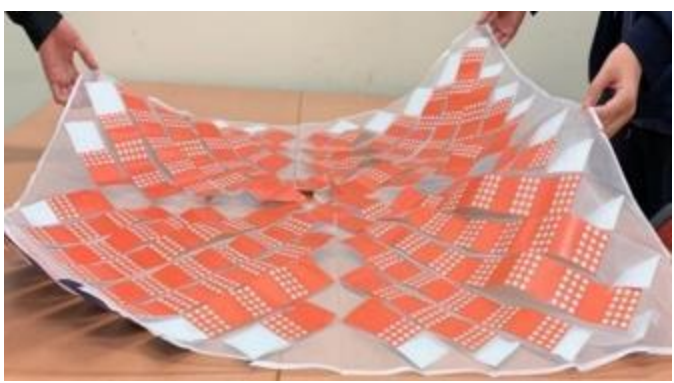
- 代表:東工大機械系 坂本啓教授
- 折り紙に着想を得た展開型アンテナ技術
- JAXA革新的衛星技術実証プログラム

HELIOS

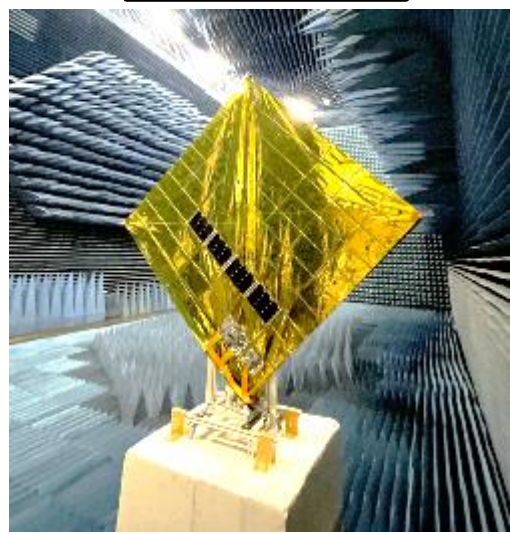
OrigamiSat-2



deployable membrane



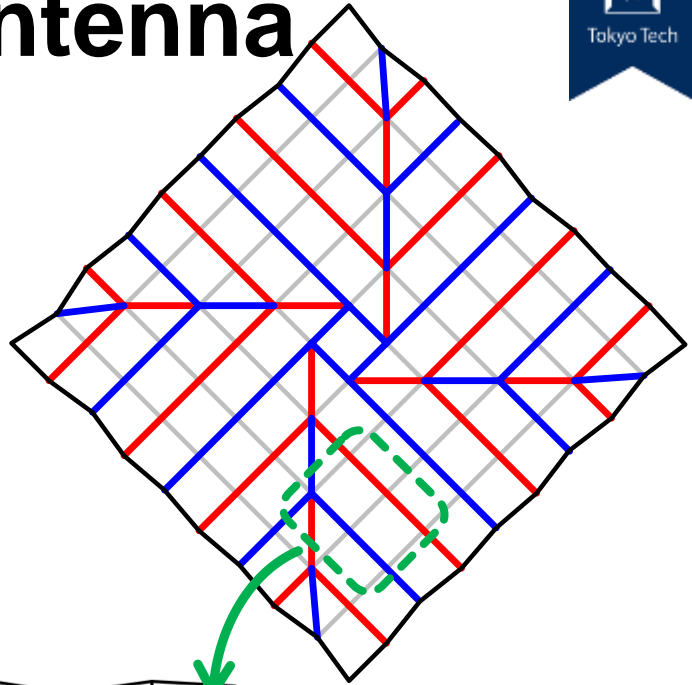
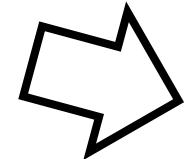
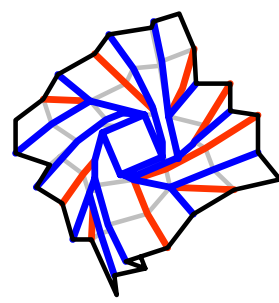
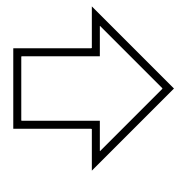
fabric-based reflect array



active phased array

MTT-Sat Challenge winner
<https://mtt.org/mtt-sat-challenge/>

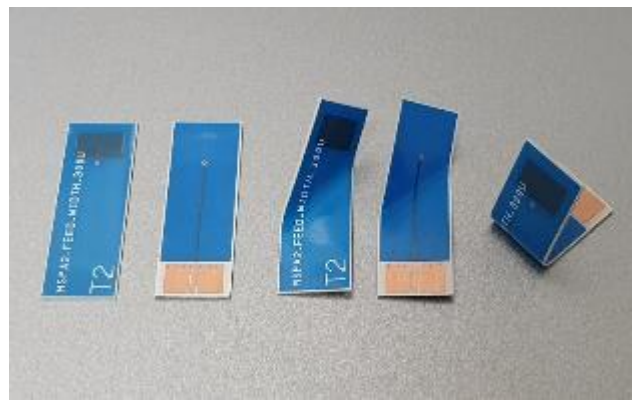
Origami Phased Array Antenna



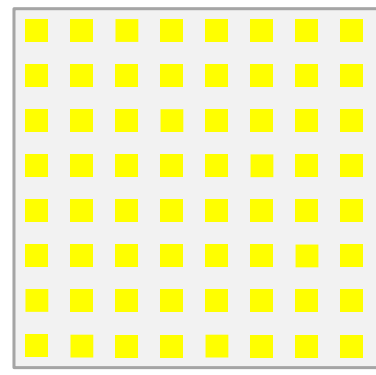
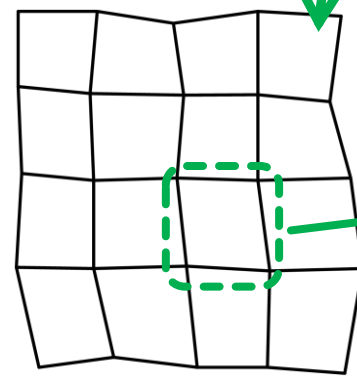
1:81 stow rate

折り紙技術による展開型アンテナ

LCPによる曲がるアンテナ



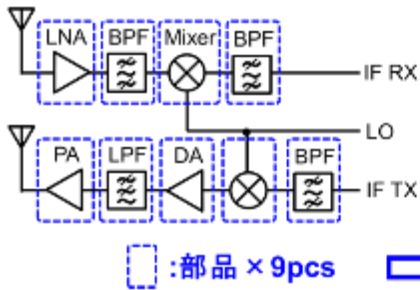
D. You, et al, APMC 2020



Phased array

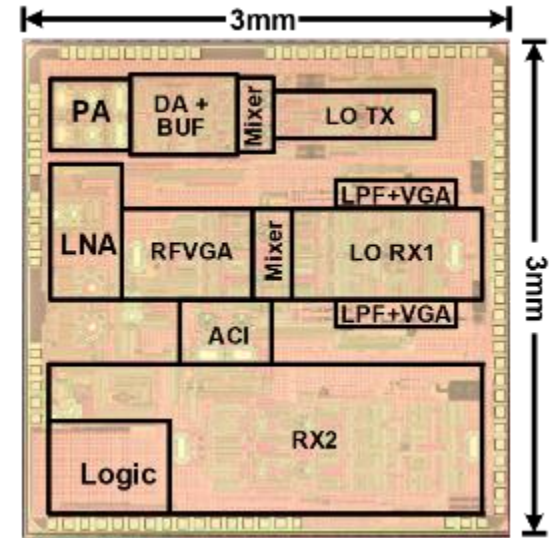
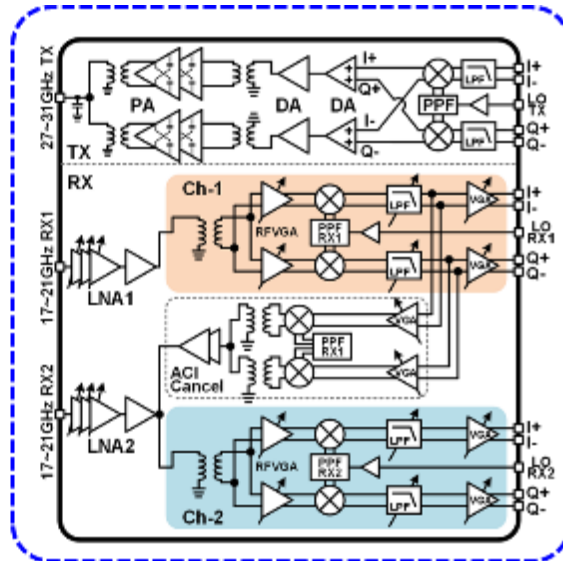
D. You, et al, IMS 2021

Ka-band Earth Station (26-40GHz)



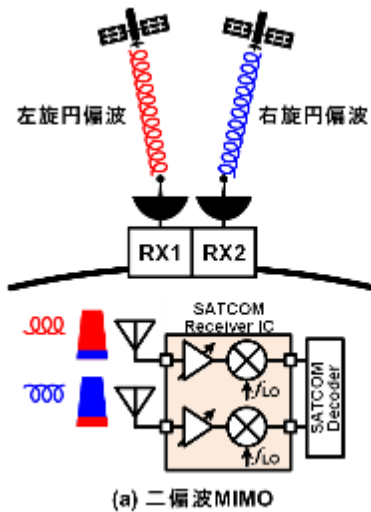
PA: Power Amplifier
 DA: Driver Amplifier
 PPF: Poly-Phase Filter
 LPF: Low Pass Filter
 BPF: Band Pass Filter
 LO: Local Oscillator
 LNA: Low Noise Amplifier
 RFVGA: RF Variable Gain Amplifier
 ACI: Adjacent Channel Interfere

一つのIC
 に集積化

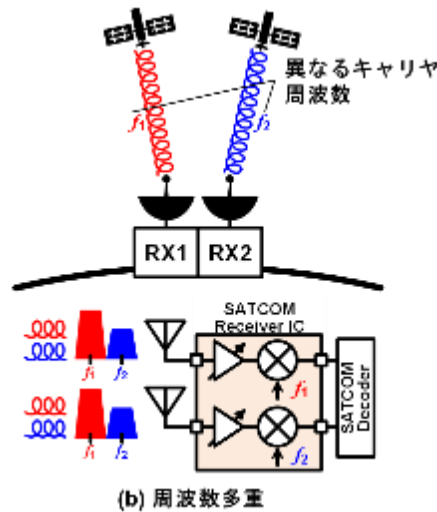


一般的な衛星通信用無線機

開発した無線IC



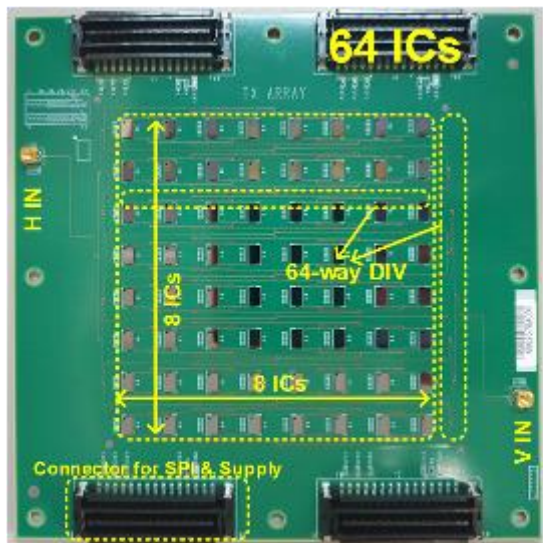
(a) 二偏波MIMO



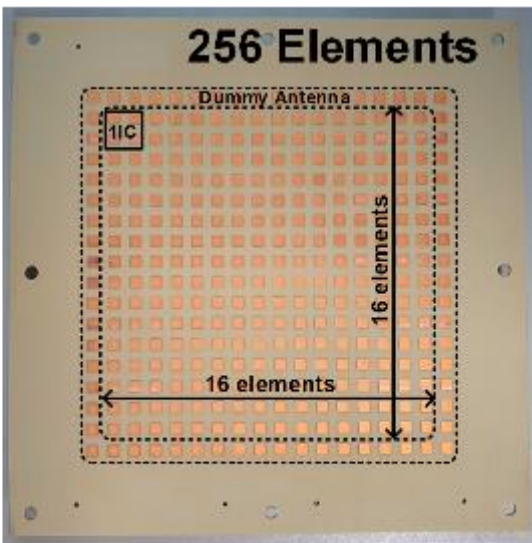
(b) 周波数多重



64dBm-EIRP 26.6W Ka-band Satcom TX



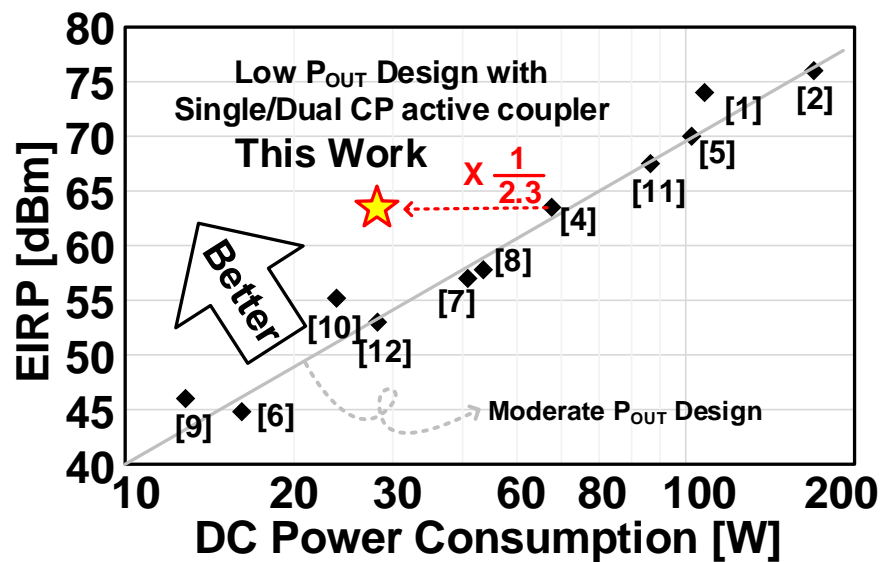
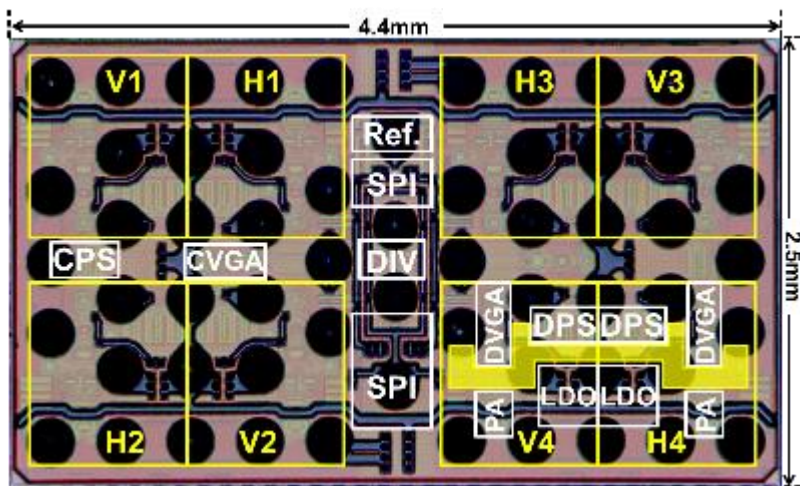
IC side



Antenna side

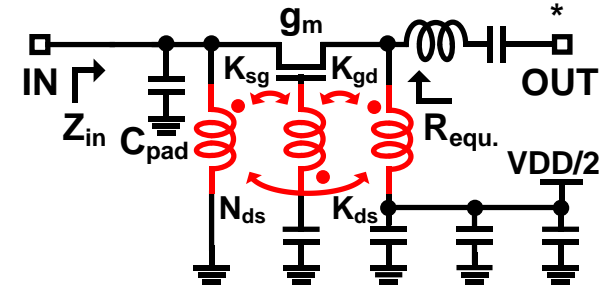
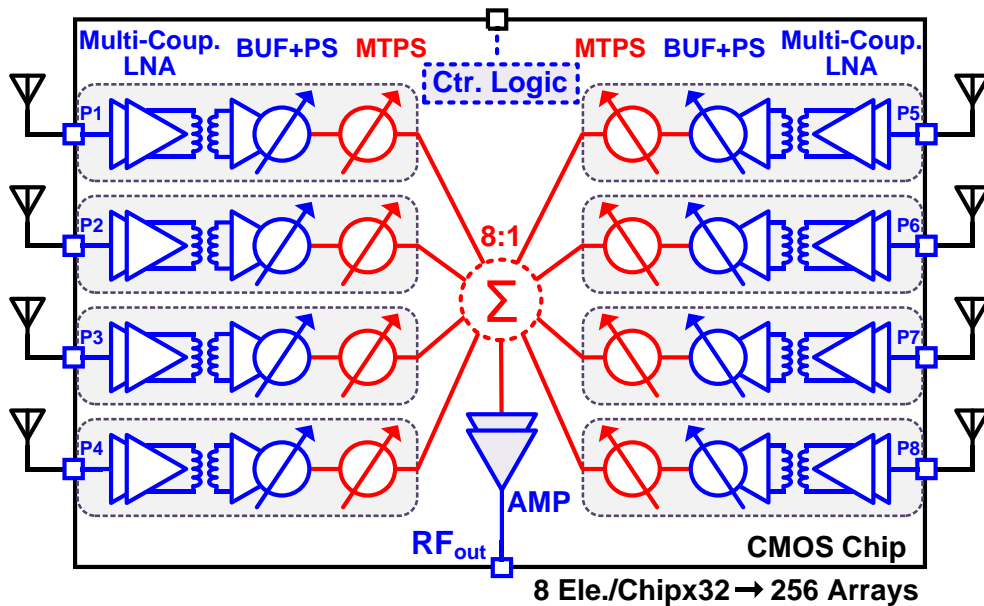
Modulation	256APSK	
Polarization	LHCP	RHCP
Constellation		
Spectrum		
ACPR [dB]	37	33
EVM [dB]	-27.1	-26.8

25.5-27.2GHz, 250Mbaud each

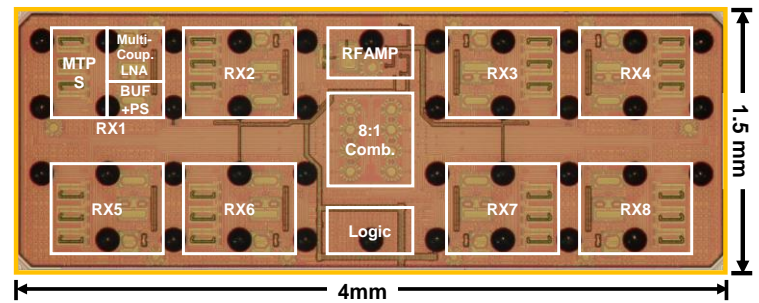


3.4mW/element Satcom RX

26.7-30.4GHz

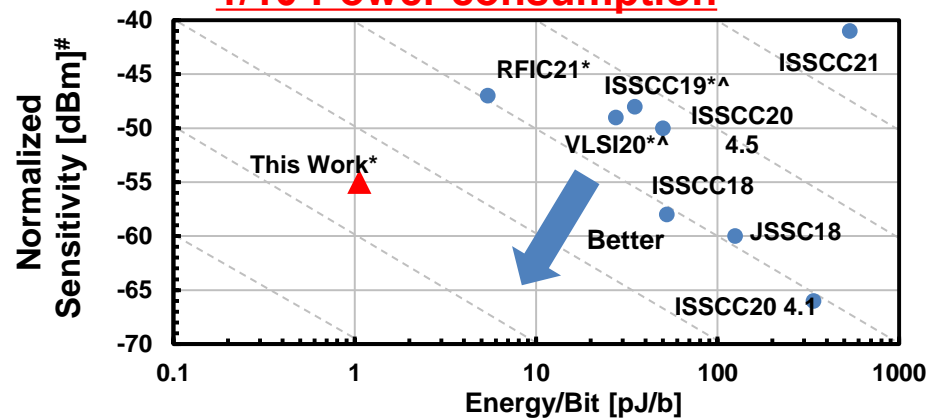


Multi-Coupling Common-Gate LNA



8-element Phased-Array RX

1/10 Power consumption

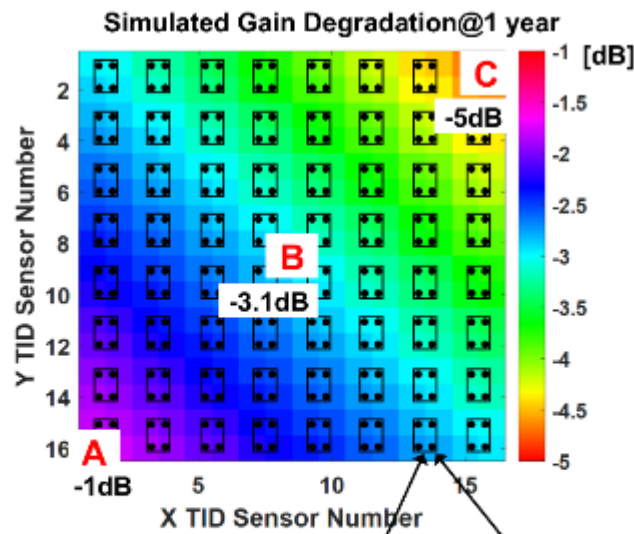
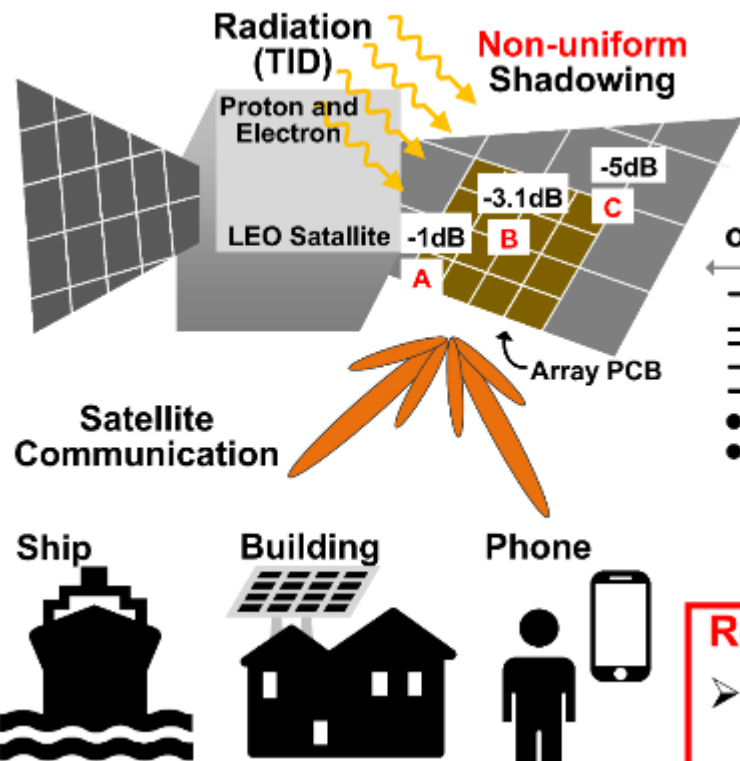


Note: #: normalized to 256APSK, BW_c=1.6GHz, *: single element, ^: calculated from SNDR

Modulation	16 APSK	16 APSK	256 APSK	256 APSK
Symbol Rate	0.8 GBaud	1.6 GBaud	0.8 GBaud	1.6 GBaud
Constellation *				
Data Rate	3.2 Gb/s	6.4 Gb/s	6.4 Gb/s	12.8 Gb/s
RX EVM (RMS)	-36.4dB	-33.1dB	-35.7dB	-33.2dB

*Measured by 8x8 Sub-Array Module

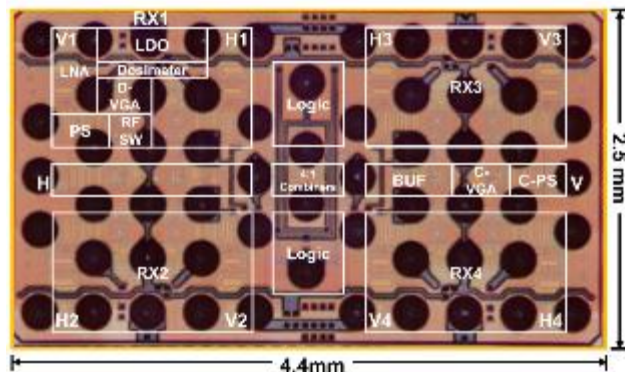
2.95mW/element Satcom RX with Radhard



Requirement 1:
 ➤ Tolerant for the Non-Uniform Radiation

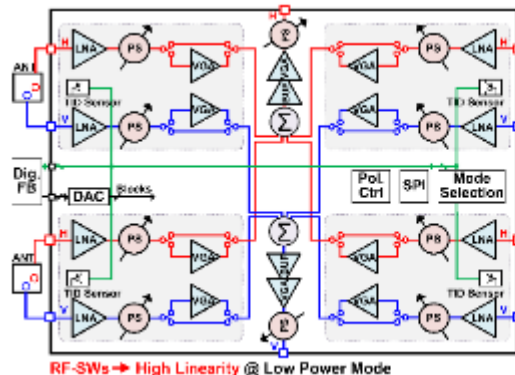
Phased-Array Chips
 TID Sensors @Same Chips

Standard 65nm CMOS in WLCSP



2.95mW per element

Block	Area (mm ²)	P _{DC} (mW)
LNA	0.14	2.95
PS	0.06	0
RFSW	0.04	0
D-VGA	0.08	2.65*
Comb.	0.06	0
BUF	0.08	2.7
C-VGA	0.08	3.2
C-PS	0.04	0



- 27.5-30 GHz
- RF Phase-Shifting
- 4H+4V Elements
- 65nm CMOS
- On-Chip TID Sensors
- Low Power LNA
- Low Power VGA

まとめ・今後の課題

6Gへ向けたテラヘルツフェーズドアレイモジュール実現のための超高密度・低消費電力IC技術の確立

- フェーズドアレイの使いこなし(高精度ビーム制御)
- 高エネルギー効率(**高電力効率IC**設計)
- 低コストIC・低コストテスト技術
- 高密度化(**高密度IC**, 高密度モジュール)
- 高周波実装技術・高周波材料技術
 - 低コスト
 - 低損失、協調設計、熱設計、高信頼(量産実績)



Tokyo Tech

Thank You

