National Institute of Information and Communications Technology

テラヘルツシステム応用推進協議会
平成31年3月25日

日本におけるテラヘルツ波通信の研究開発動向
Survey of Japanese R&D on Terahertz Wireless Communications

笠松　章史　（かさまつ　あきふみ）

国立研究開発法人情報通信研究機構
未来ICT研究所　兼　テラヘルツ研究センター

謝辞

本発表には以下の皆様による成果が含まれております。ご協力に感謝いたします。（敬称略）

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NECネットワーク・センサ株式会社
日本電信電話株式会社
パナソニック株式会社
富士通株式会社

本研究の一部は総務省・電波資源拡大のための研究開発「テラヘルツ波デバイス基盤技術の研究開発」の一環として実施されました。

Outline

- Introduction
- Japanese MIC 300-GHz projects and related projects
- Challenge of THz CMOS transceiver
  - 300-GHz CMOS transmitter
  - 300-GHz CMOS receiver
  - 300-GHz CMOS transceiver module
  - Advanced 300-GHz transceiver
- Conclusion

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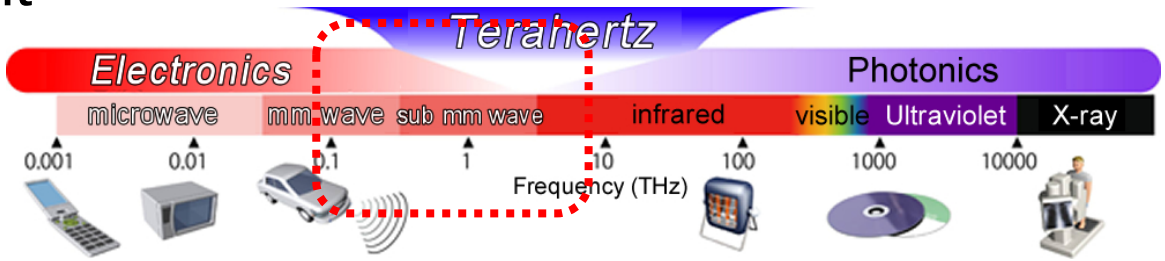
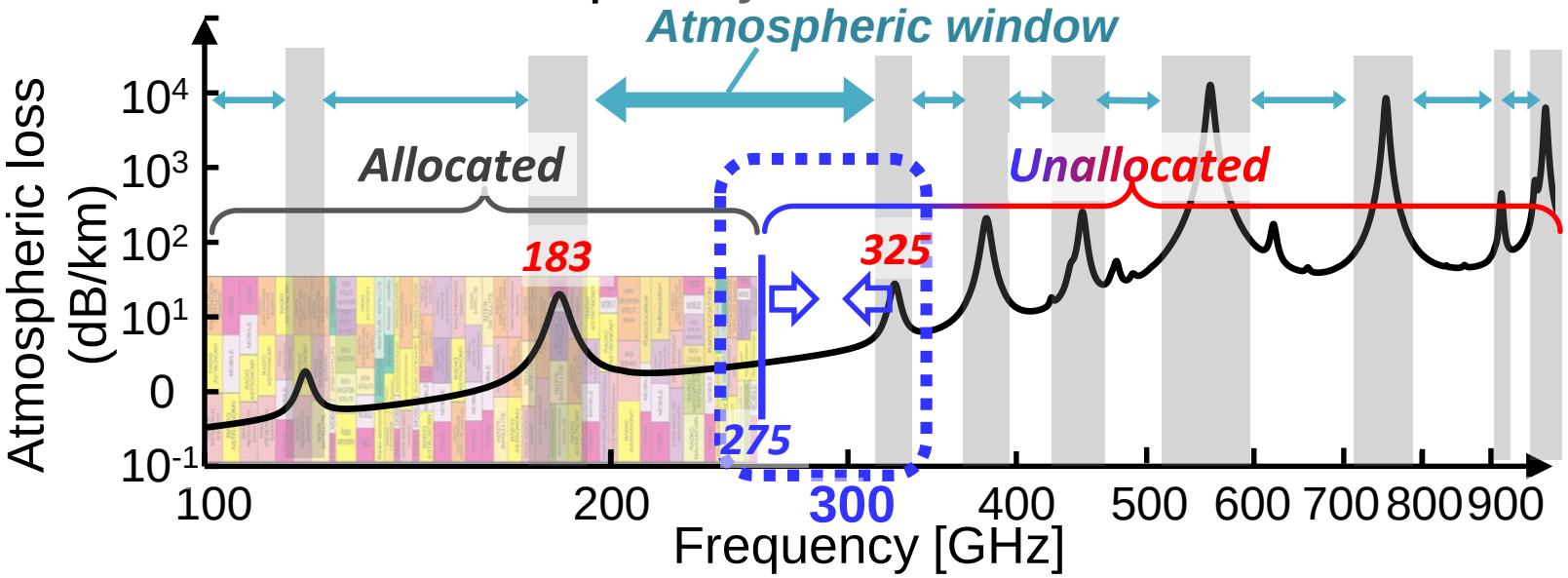
Terahertz (THz) waves

- THz waves (100 GHz to 3 THz) sit between radio waves and visible light



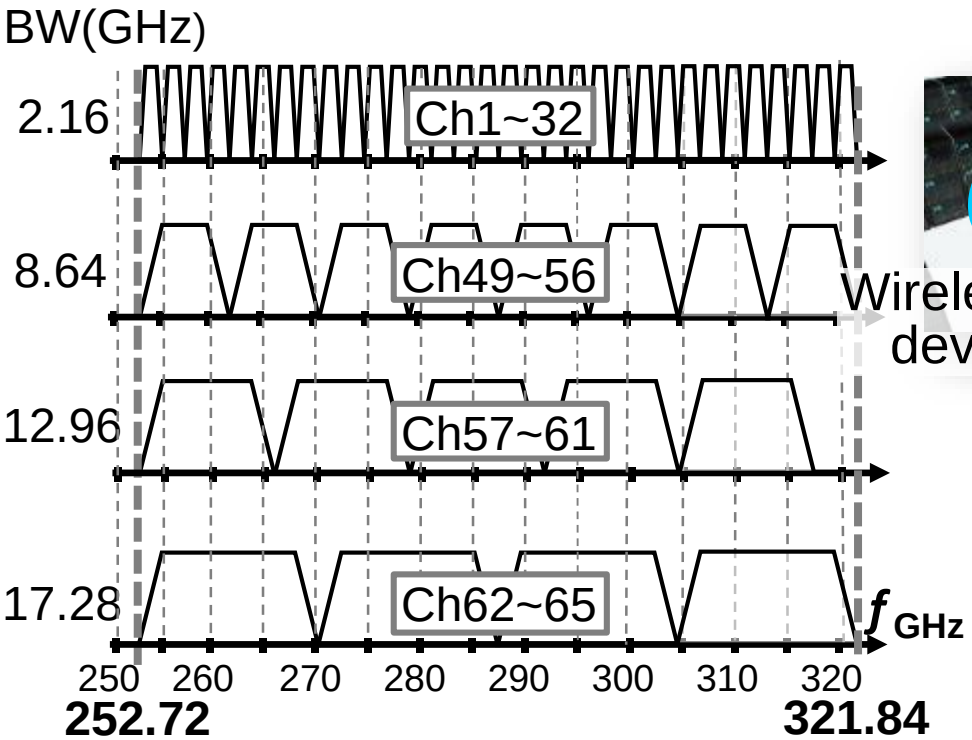
- Wide atmospheric window opens at 300-GHz band
- Vast unallocated frequency band lies above 275 GHz



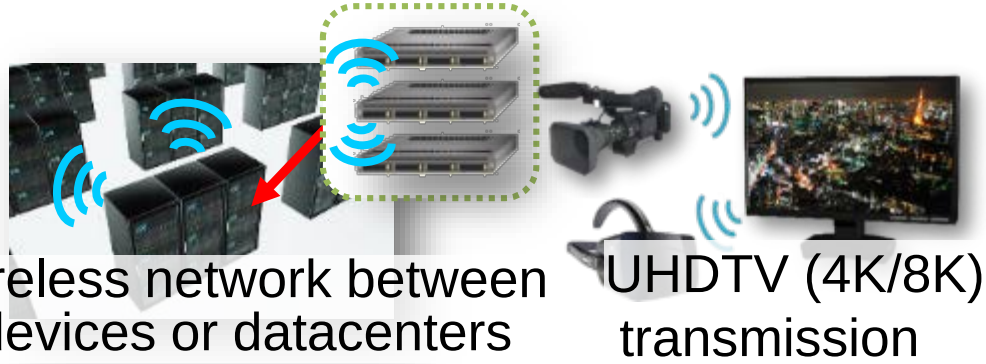
[1] https://smiles-p6.nict.go.jp/thz/en/decay_e.html
[2] https://www.ntia.doc.gov/page/2011/united-states-frequency-allocation-chart

300-GHz band in IEEE Std 802.15.3d

- 802.15.3d defined wireless physical layer using **252 – 322 GHz** for THz ultrahigh-speed wireless communications



Standardization of 300-GHz band[1]



Possible applications[2]

[1] IEEE Std. 802.15.3d-2017 (Amendment to IEEE Std 802.15.3-2016 as amended by IEEE Std 802.15.3e-2017), pp. 1–55, Oct. 2017.
[2] T. Kürner, IEEE 802.15-10-0320-02-0000-Tutorial_Igthz.

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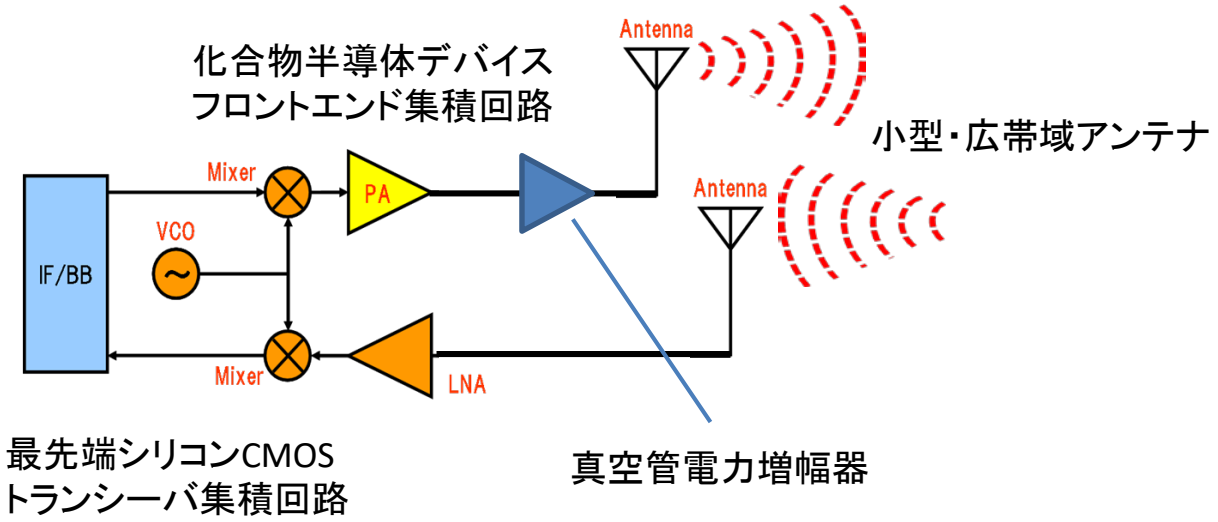
国プロ（総務省）

総務省　電波資源拡大のための研究開発	受託者	期間（年度）
超高周波搬送波による数十ギガビット無線伝送技術の研究開発 （化合物半導体デバイスとKIOSKダウンロード実証）	NTT 富士通 NICT	H23～H27 （5カ年）
テラヘルツ波デバイス基盤技術の研究開発 ～300GHz帯シリコンCMOSトランシーバ技術～	パナソニック 広島大学 NICT	H26～H30 （5カ年）
テラヘルツ波デバイス基盤技術の研究開発 ～300GHz帯増幅器技術～	NECネットワーク・センサ NICT	H26～H29 （4カ年）



キオスクダウンロードのデモ（300GHz帯、20Gbit/s、1m以内伝送）

IMS2016 Best Industry Paper Award

“Demonstration of 20-Gbps Wireless Data Transmission at 300 GHz for KIOSK Instant Data Downloading Applications with InP MMICs”

超高周波搬送波による数十ギガビット無線伝送技術の研究開発

目的

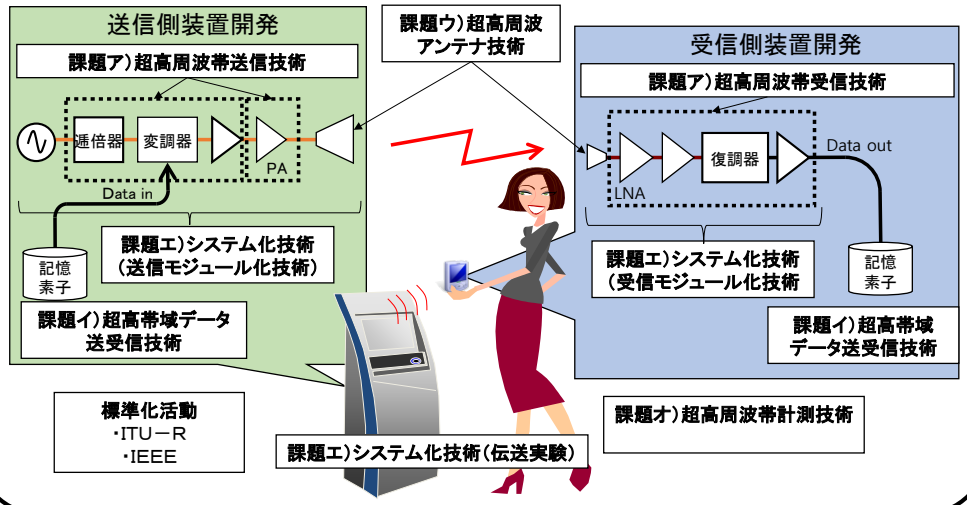
275～370GHzの超高周波搬送波を用いて、1m程度の距離を20～40Gbpsで伝送する無線通信システムを実現するための基盤技術を平成27年度までに確立し、平成32年度までに技術基準策定を目指す。

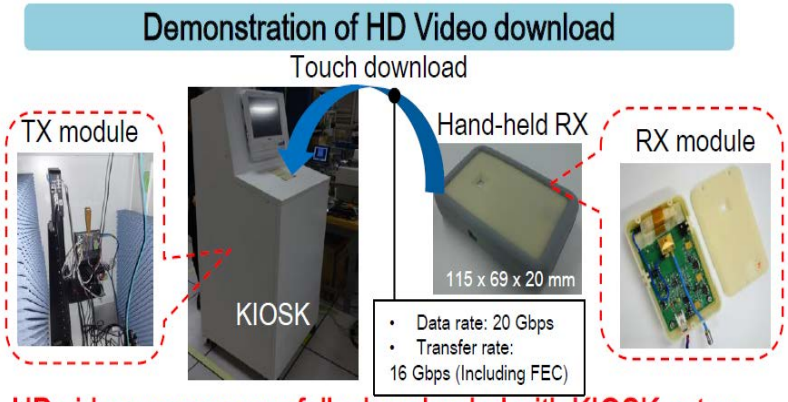
KeyTechnology

化合物半導体(InP)、振幅変調、立体アンテナ

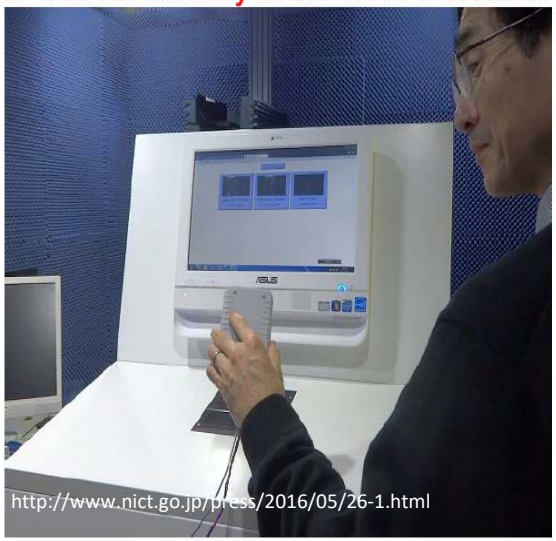
実施期間　平成23～27年度　（5カ年）

実施機関　総務省電波利用料：NTT、FUJITSU、NICT

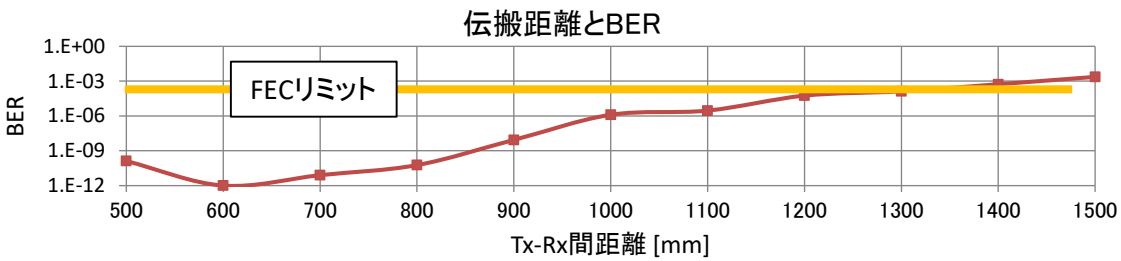


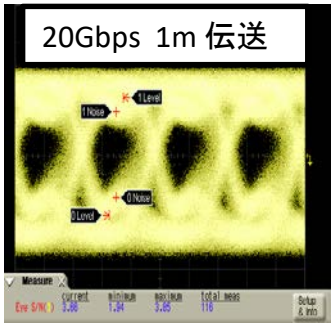


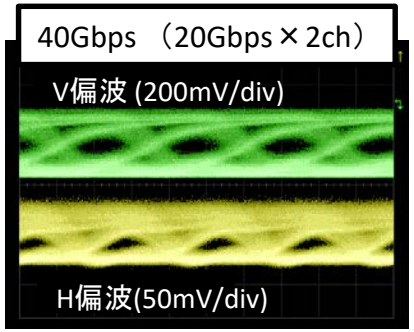
HD video was successfully downloaded with KIOSK setup



キオスクダウンロードのデモ（300GHz帯、20Gbit/s、1m以内伝送）







20Gbps、1m伝送ならびに、40Gbps伝送結果

FEC on RS(255,223)	実データ転送平均速度[Gbps]
2.9GB	10.3～12.6
3.8GB	12.1～13.3
17.9GB	12.1～13.8

キオスクダウンロード実験と結果

Advanced Result (NTT, IMS2018, 16QAM, 100Gbit/s)

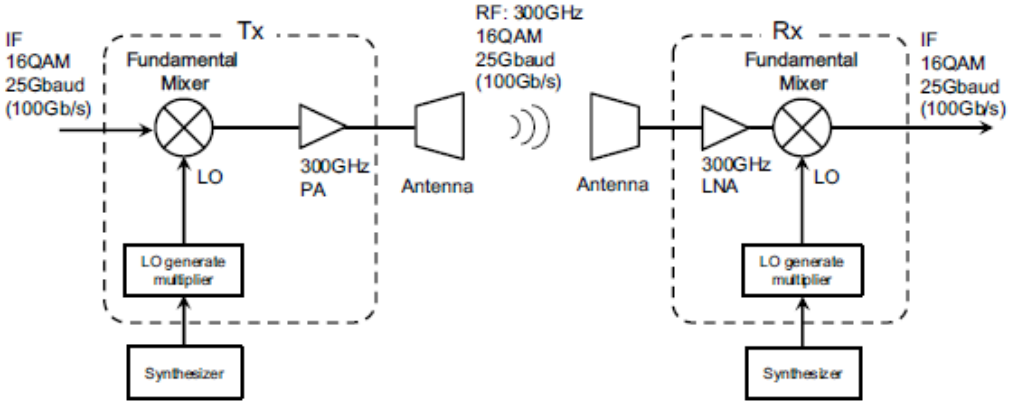


Fig. 1. Conceptual schematic of the proposed 300-GHz TRx.

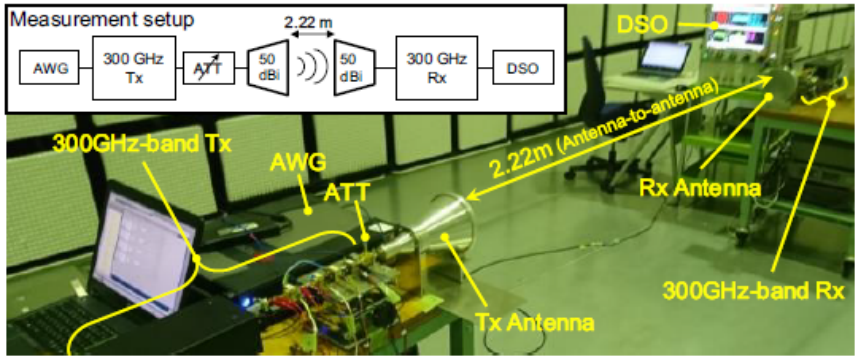


Fig. 10. Measurement setup for wireless transmission demonstration.

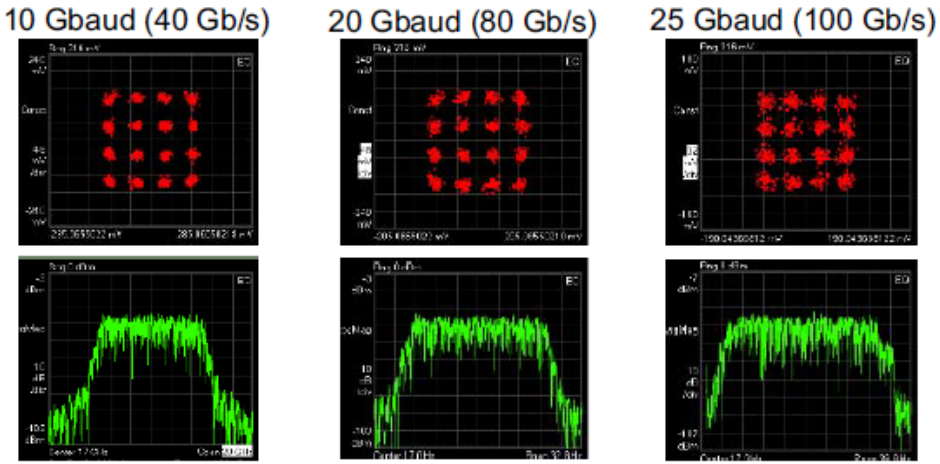


Fig. 9. Measured constellations and spectrums of 300-GHz TRx.

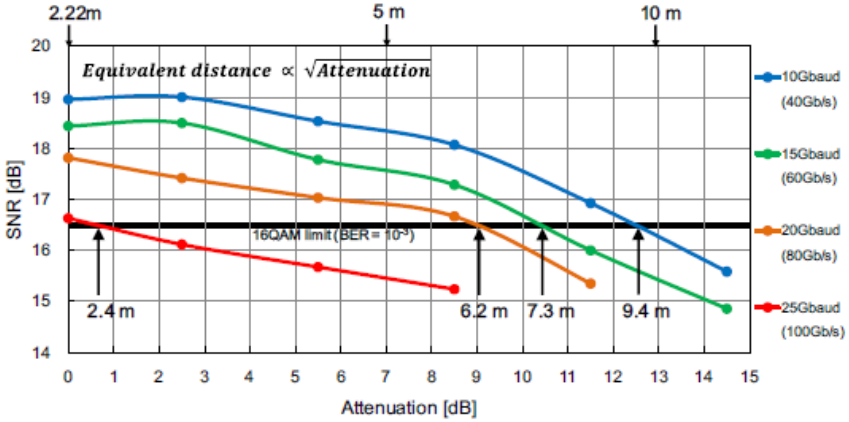
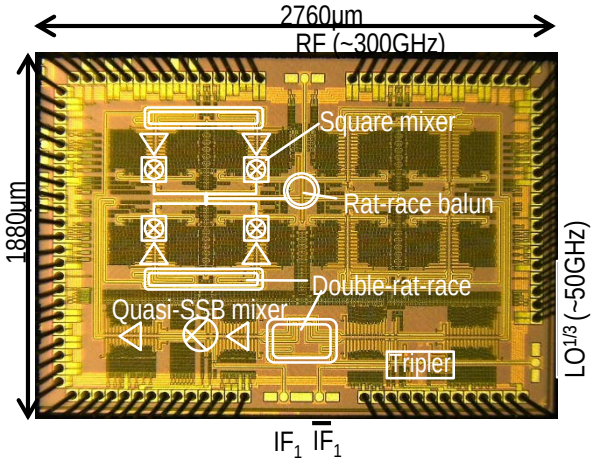


Fig. 11. Results of wireless transmission using 300-GHz TRx.

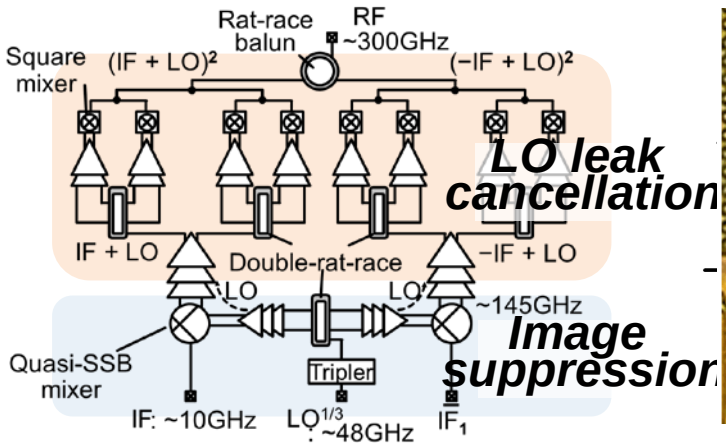
H. Hamada, et al., IMS2018, pp. 1480-1483, June 2018.

シリコン集積回路トランシーバ（300GHz帯）

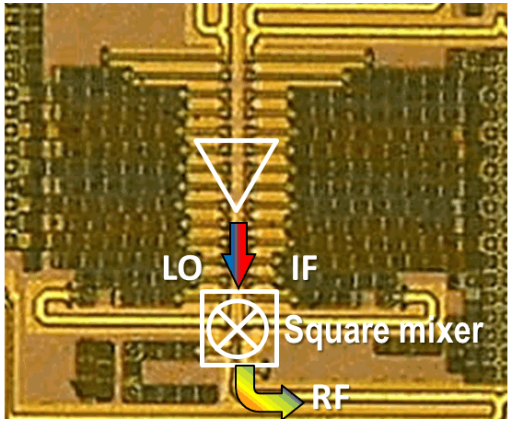
■シリコンCMOSによる300GHz帯無線送信機　K. Takano, et al., ISSCC2017, pp.308-309 (2017).



300GHz Si CMOS送信機 チップ写真
Chip micrograph of 300GHz Si CMOS transmitter

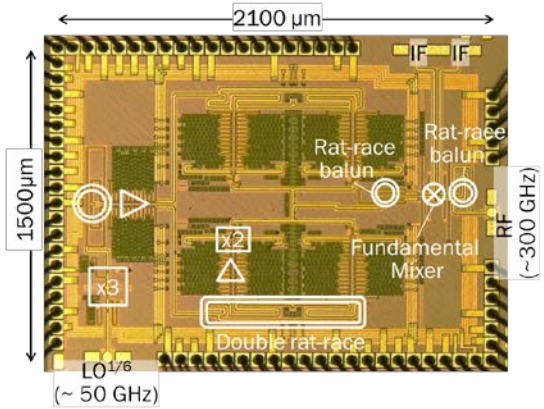


300GHz Si CMOS送信機 回路図
Block diagram of 300GHz Si CMOS transmitter

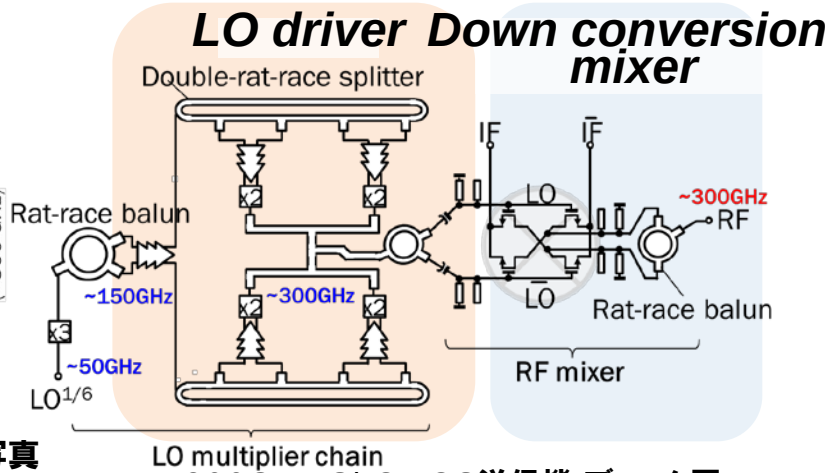


2逓倍器ミキサー
Square Mixer

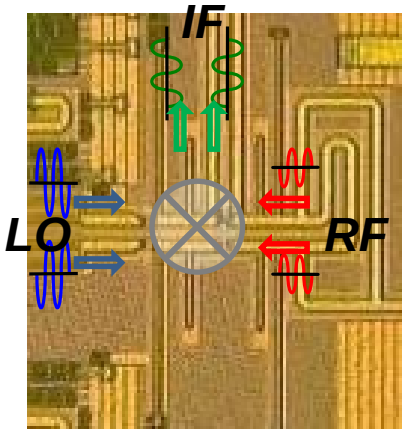
■シリコンCMOSによる300GHz帯無線受信機　S. Hara, et al., IMS2017, pp.1-4 (2017).



300GHz Si CMOS受信機 チップ写真
Chip micrograph of 300GHz Si CMOS reviever



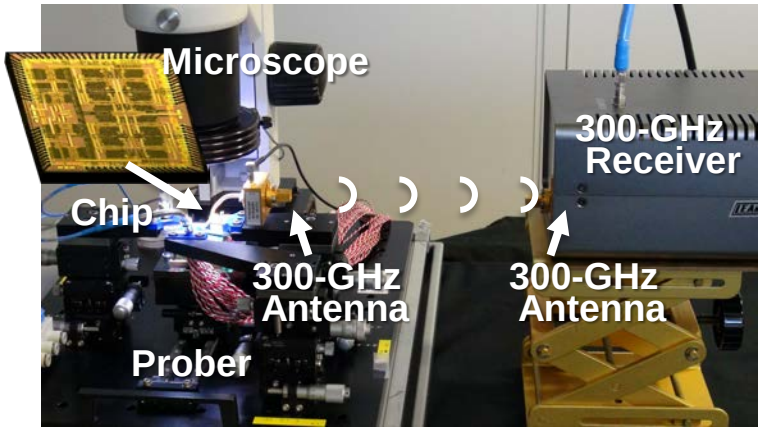
300GHz Si CMOS送信機 ブロック図
Block diagram of 300GHz Si CMOS receiver



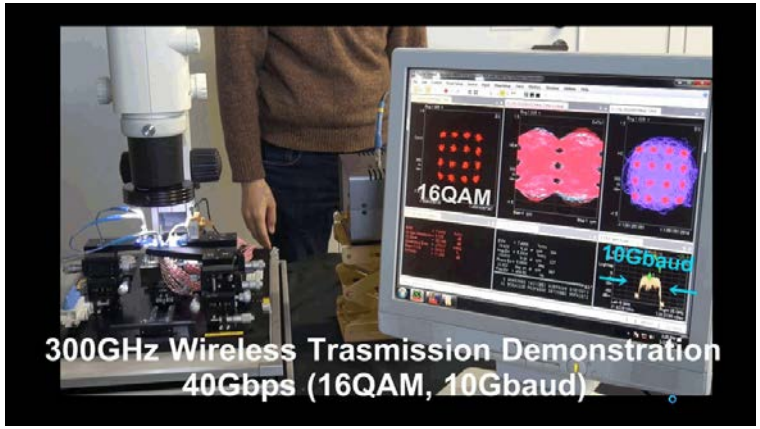
広帯域ミキサー
Square Mixer

シリコン集積回路トランシーバ（300GHz帯）

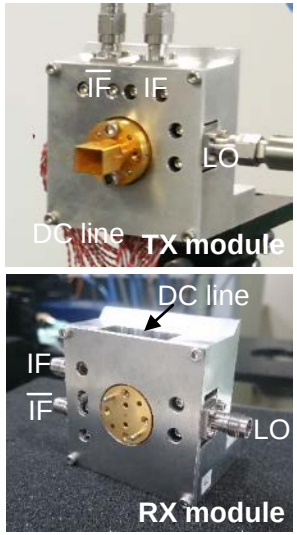
■Si CMOSプロセス（40nm）の動作限界を超える300GHzで、
1ch 105Gb/sの伝送速度を実現



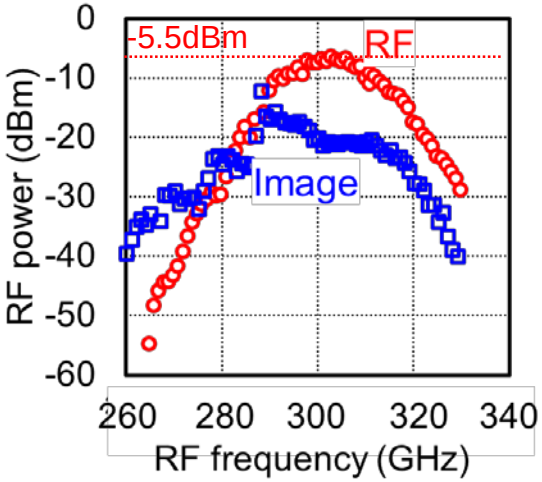
300-GHz Si CMOS送信機 無線実験のセットアップ
Setup of wireless transmission of 300-GHz Si CMOS transmitter



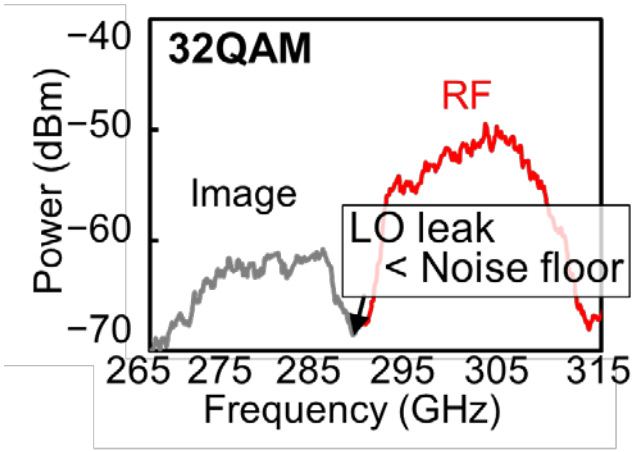
無線実験風景
Wireless transmission of 300GHz Si CMOS transmitter



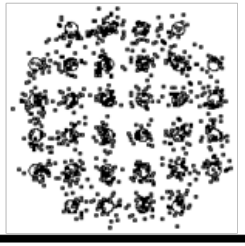
送受信機モジュール
300GHz Si CMOS transmitter and receiver modules



出力特性
Output power of 300GHz Si CMOS transmitter



出力スペクトル
Output power spectra of 32-QAM

Modulation	32QAM
Constellation (Equalized)	
EVM	8.9%
Data rate	105Gb/s

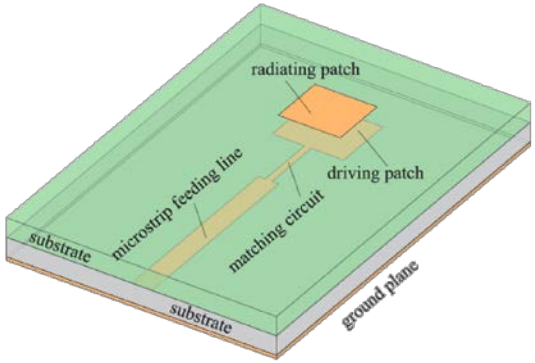
コンスタレーション
Constellations of 32-QAM

T. Takano, et al., ISSCC2017, pp.308-309 (2017).

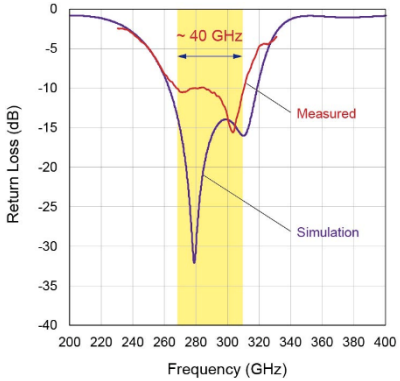
■300GHz帯 近距離無線通信用の小型・広帯域アンテナ技術の確立

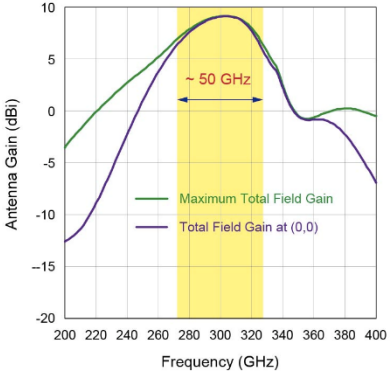
Development of small wideband antenna technology for terahertz wireless communication

インピーダンス帯域20GHz以上（実測）
アンテナ利得7dBi以上、利得帯域30GHz以上（シミュレーション）

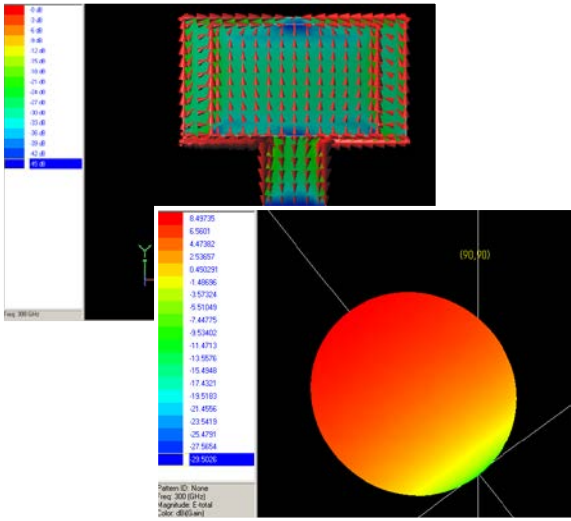


スタックパッチを持つマイクロストリップパッチアンテナ
Microstrip patch antenna with stacked patches





アンテナの反射特性と利得特性
Reflection and gain characteristics of microstrip patch antenna with stacked patches



アンテナの電流分布と3D放射パターン
Current distribution and radiation pattern of microstrip patch antenna with stacked patches

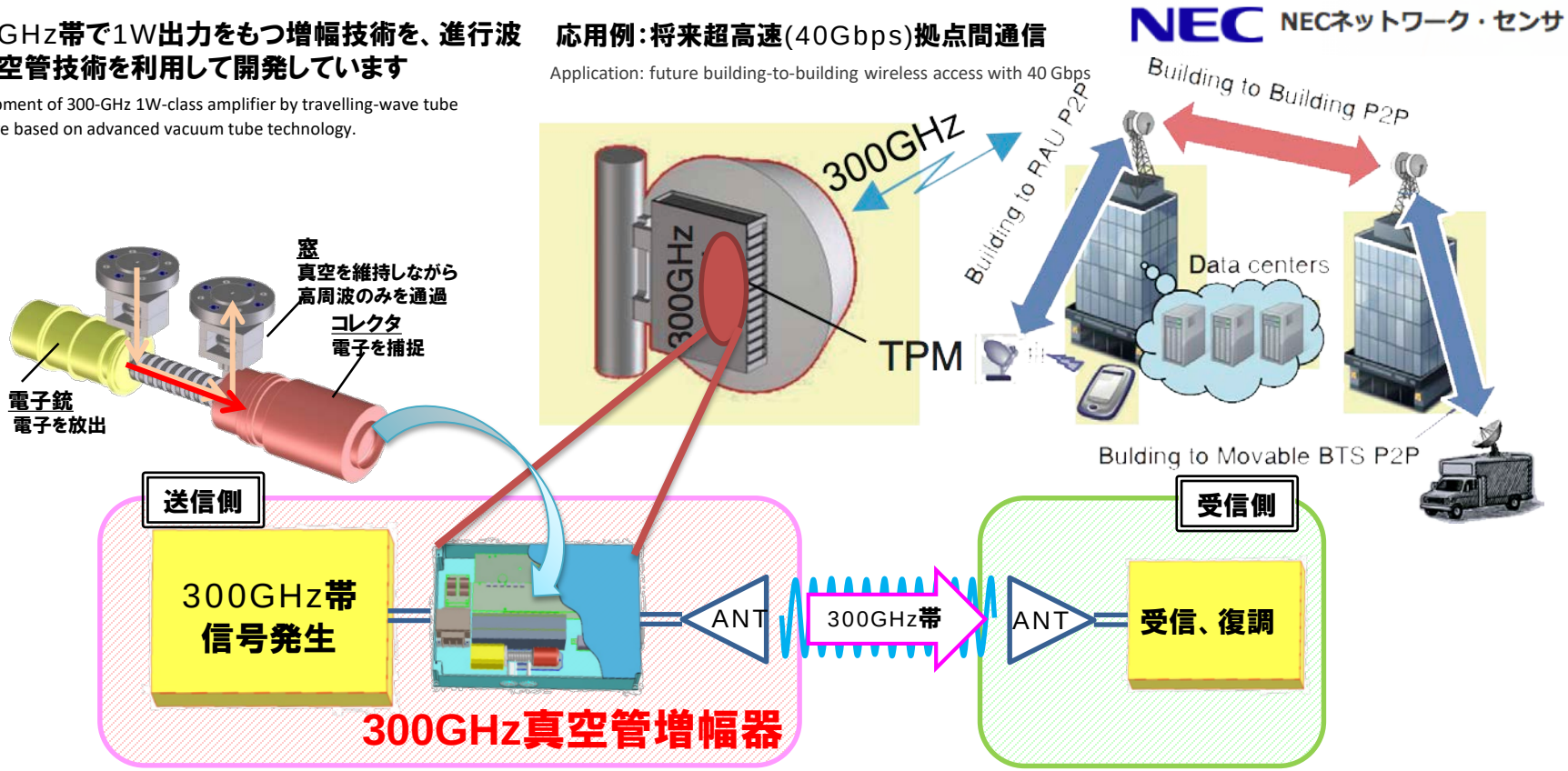
真空管技術によるテラヘルツ帯増幅技術

■ 300GHz帯で1W出力をもつ増幅技術を、進行波型真空管技術を利用して開発しています

Development of 300-GHz 1W-class amplifier by travelling-wave tube structure based on advanced vacuum tube technology.

応用例：将来超高速(40Gbps)拠点間通信

Application: future building-to-building wireless access with 40 Gbps



最先端光技術を活用したテラヘルツ帯信号発生・伝送技術

■ **光技術によるテラヘルツ帯IQミキサによるテラヘルツ帯多値信号発生**

Multi-level signal generation in terahertz bands by photonics-based IQ mixer and optical frequency comb source

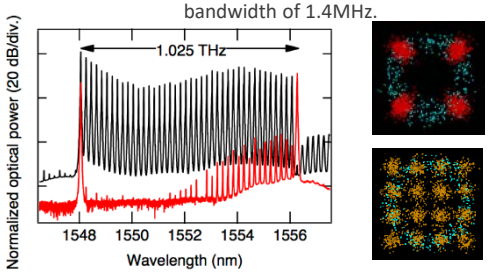
N. Sekine, doc.: IEEE 802.15-13-0653-00-0thz (2013).

■ **超広帯域光周波数コム発生技術、光変調技術を援用した1THz帯多値信号伝送の原理検証実験に成功**

Combination of ultra-broadband optical frequency comb generator and optical modulation technique realizes multi-level signal transmission at 1 THz.

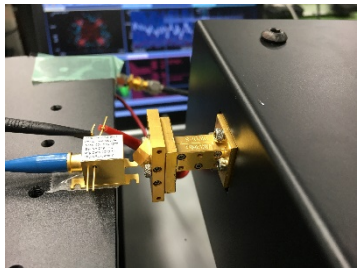
1THz幅光周波数コム信号の光スペクトルと1.4MHz幅QPSK、16QAM信号の復調コンスタレーション

Optical spectrum of 1-THz-bandwidth optical frequency comb and demodulated constellation maps for QPSK and 16QAM with a signal bandwidth of 1.4MHz.



4mm空間伝送実験の様子

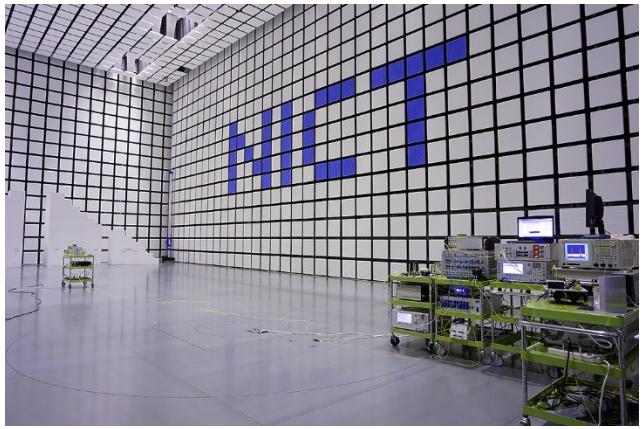
Photo of 4mm transmission over the air



A. Kanno et al., IEEE MWP2016. WM2.3, Nov. 2016.

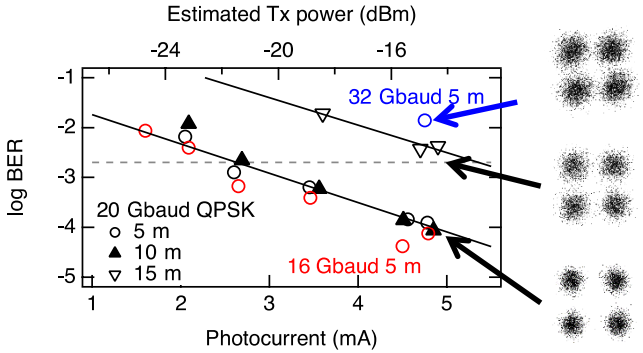
電波暗室内での300GHz QPSK伝送実験の様子

Photo of 300-GHz QPSK transmission in NICT's large-scale anechoic chamber



300GHz QPSK伝送時のビット誤り率計測例

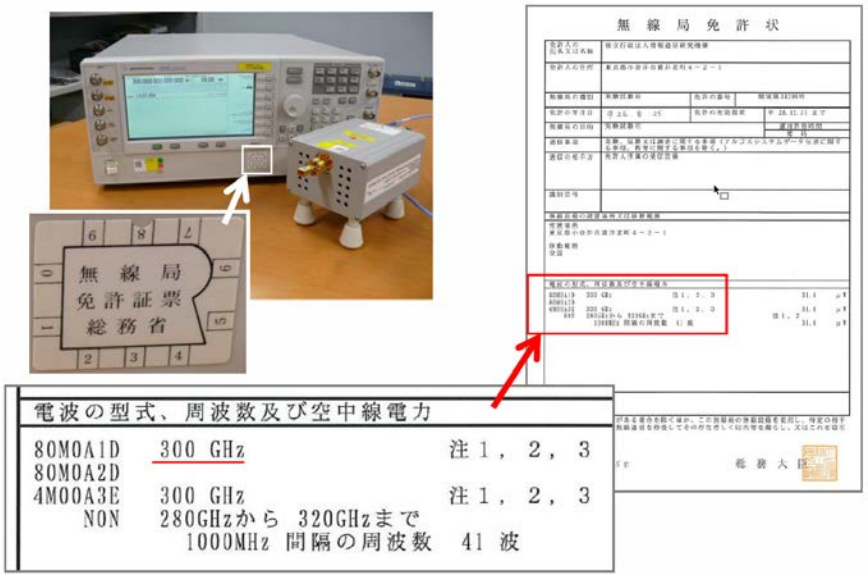
Observed BER of 300GHz QPSK transmission



300GHz伝搬の実験と特性検討

■300 GHzでの屋内伝搬測定の結果から，パスロスモデルを検討

A Consideration of Indoor Path Loss Model in 300 GHz Band

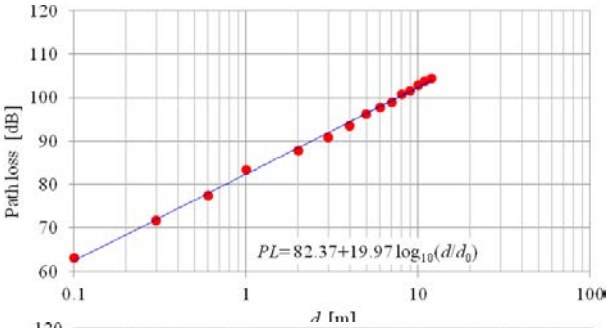


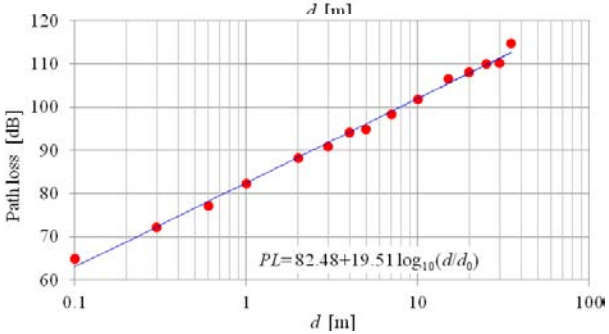
300GHz実験局免許

License of a 300-GHz experimental transmitter

オフィス環境

廊下環境





屋内伝搬実験とパスロスモデル

Measurement of indoor propagation characteristics and pass loss models

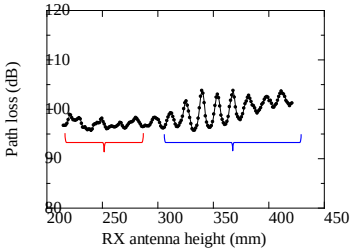
300GHz伝搬の実験と特性検討

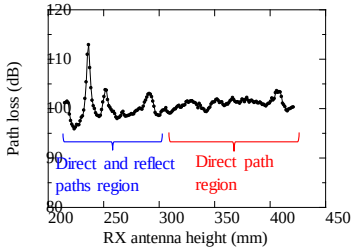
■データセンタ環境のパスロスモデル、建物侵入損失を検討

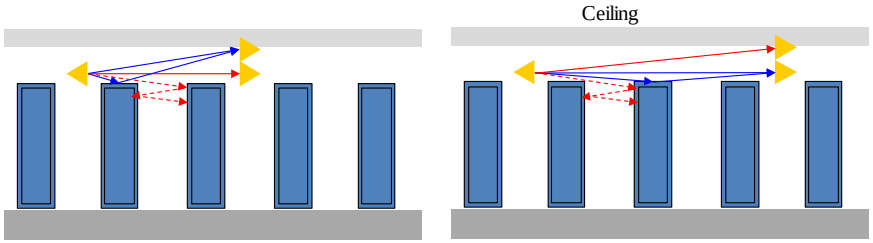
Consideration of Path Loss Model at Data Center and Building Entry Loss in 300 GHz Band

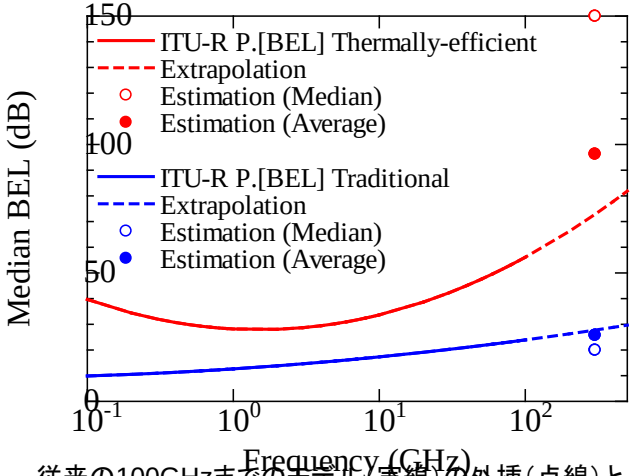
様々な実環境での測定（左）と
各種建材の透過特性測定（右）

- 正規反射点にサーバがある場合とない場合で比較
- 直接波とサーバ筐体からの反射波で2波干渉することが明確化









従来の100GHzまでのモデル（実線）の外挿（点線）と
300GHzの実測を基にした推定値

データセンタ環境のパスロスモデル検討

Consideration of pass loss model in the data center

建物侵入損失の検討

Consideration of building entry loss

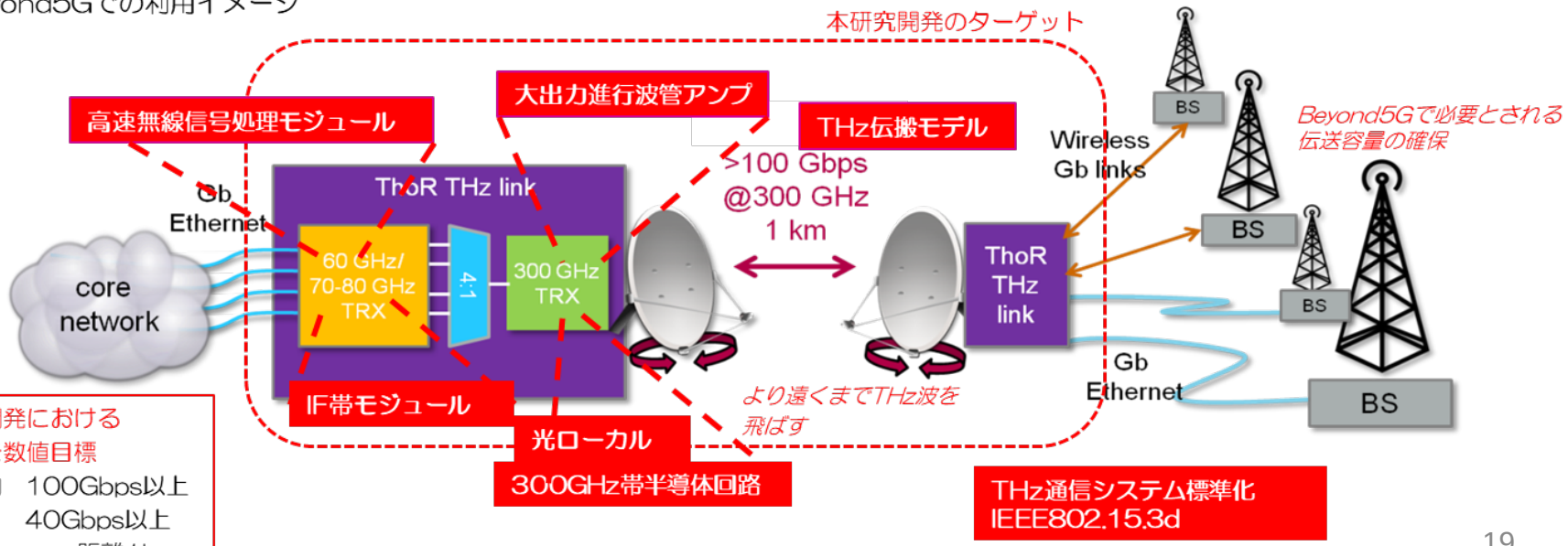
Beyond 5Gモバイルシステムに向けての研究開発

■大容量アプリケーション向けテラヘルツエンドトゥーエンド無線システムの開発
NICTからの日欧連携委託研究（平成30～32年）

早稲田大学／千葉工業大学／岐阜大学
日本電気株式会社／高速近接無線技術研究組合

ブラウンシュヴァイク工科大学（ドイツ）／ドイツテレコム（ドイツ）
フラウンホーファー応用固体物理研究所（ドイツ）
Siklu Communications（イスラエル）
リール第一大学／マイクロエレクトロニクス・ナノテクノロジ電子研究所（フランス）
シュツットガルト大学（ドイツ）／VIVID Components（イギリス）

Beyond5Gでの利用イメージ



本研究開発における
伝送デモ数値目標
実験室内　100Gbps以上
実環境　40Gbps以上
距離1km

Outline

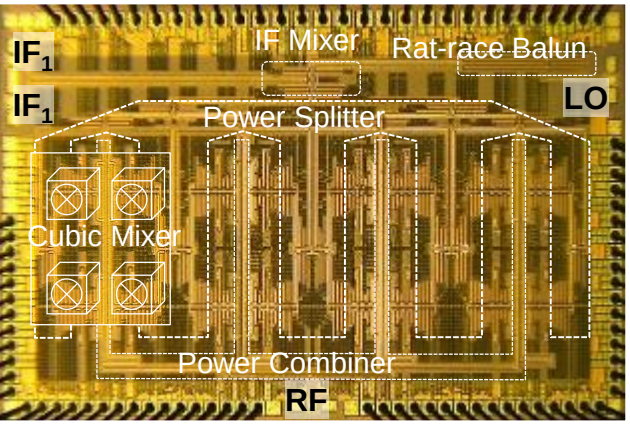
- Introduction
- Japanese MIC 300-GHz projects and related projects
- Challenge of THz CMOS transceiver
  - 300-GHz CMOS transmitter
  - 300-GHz CMOS receiver
  - 300-GHz CMOS transceiver module
  - Advanced 300-GHz transceiver
- Conclusion

Challenge of 300-GHz CMOS transceiver

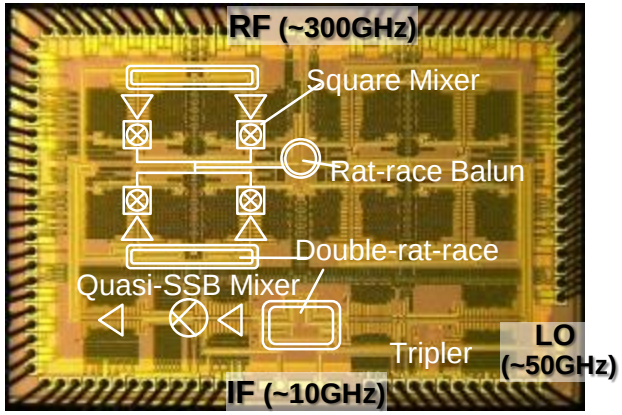
Si CMOS THz front-end will allow seamless integration with ***base-band CMOS*** circuitry

- PA- and LNA-less architecture because of f_{max} < 300 GHz
- Capable of supporting QAM

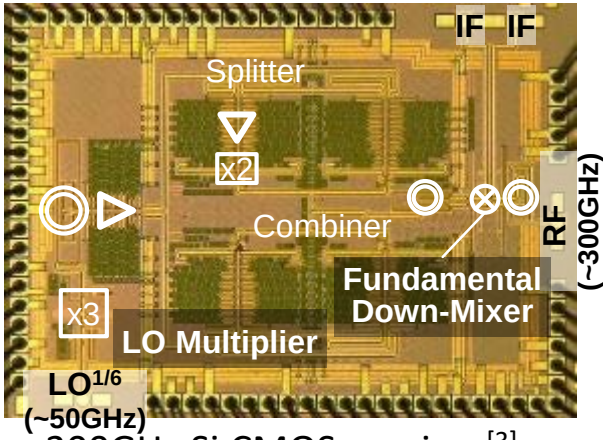
Developed 300-GHz transceivers in 40-nm Si CMOS process with f_{max} ≃ 280 GHz with Hiroshima Univ., Panasonic, NICT.



300GHz Si CMOS transmitter[1]



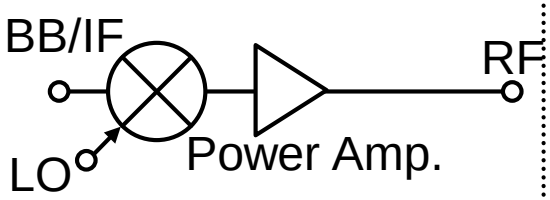
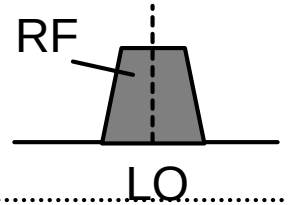
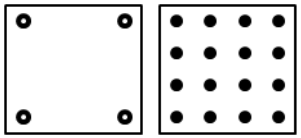
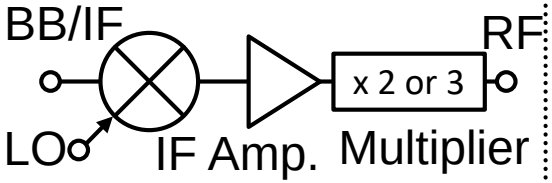
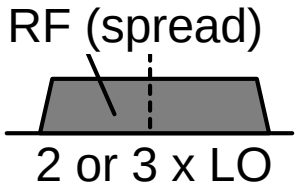
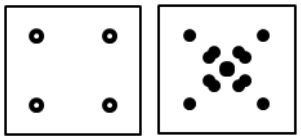
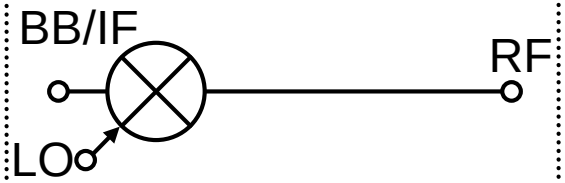
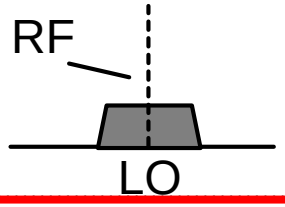
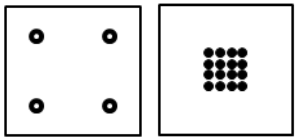
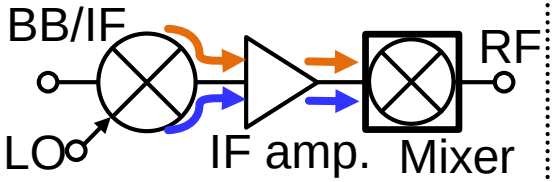
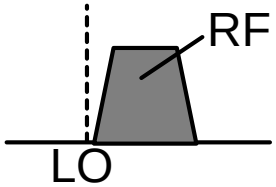
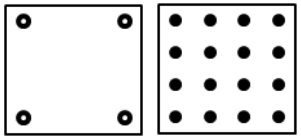
300GHz Si CMOS transmitter[2]



300GHz Si CMOS receiver[3]

[1] K. Katayama, et al.,ISSCC2016, pp. 342–343, Feb. 2016. [2] K. Takano, et al., ISSCC2017, pp. 308–309, Feb. 2017.
[3] S. Hara, et al., IMS2017, pp. 1-4, June 2017.

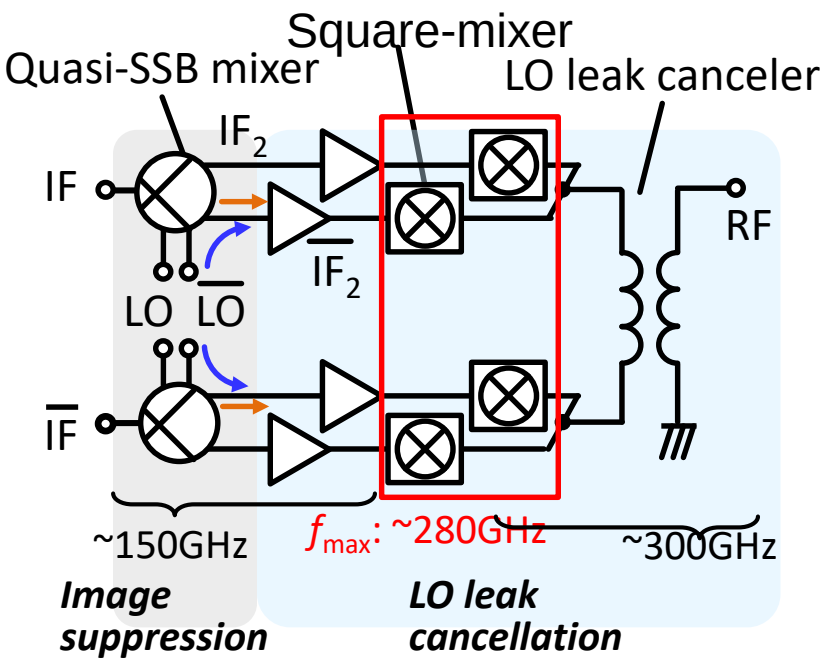
THz transmitter architectures

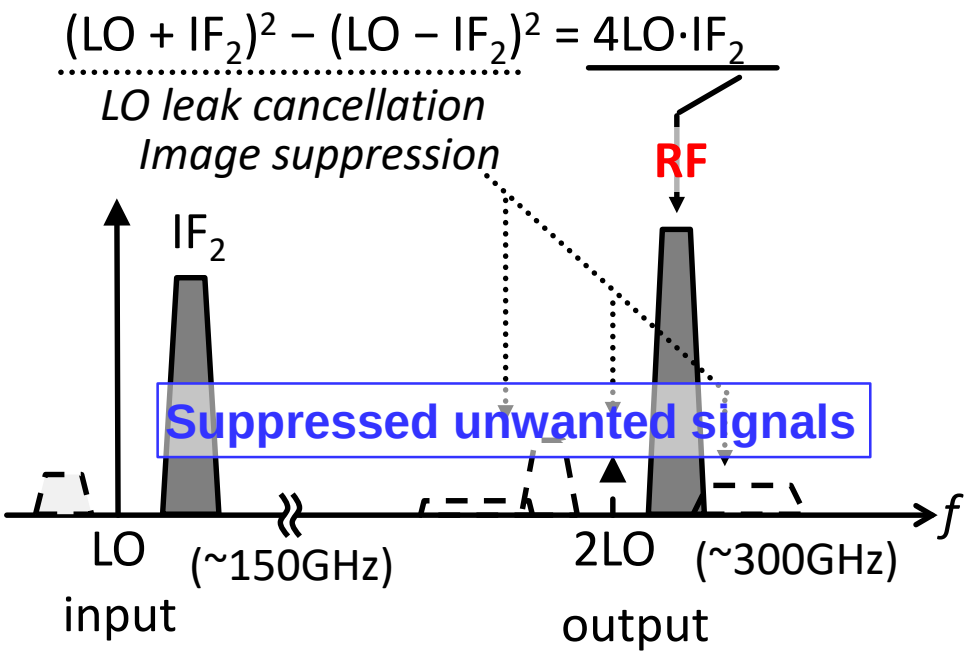
Architecture	Block diagram	Spectrum	QPSK 16QAM	Characteristics
PA-last high f_{max}				High output power QAM-capable
Multiplier-last low f_{max}				Low output power QAM incapable
Mixer-last low f_{max}				Low output power QAM-capable Complex layout
Square-mixer-last low f_{max}				High output power QAM-capable Uncomplex layout

[1] K. Katayama, et al.,ISSCC2016, pp. 342–343, Feb. 2016. [2] K. Takano, et al., ISSCC2017, pp. 308–309, Feb. 2017.

Key technology for CMOS transmitter

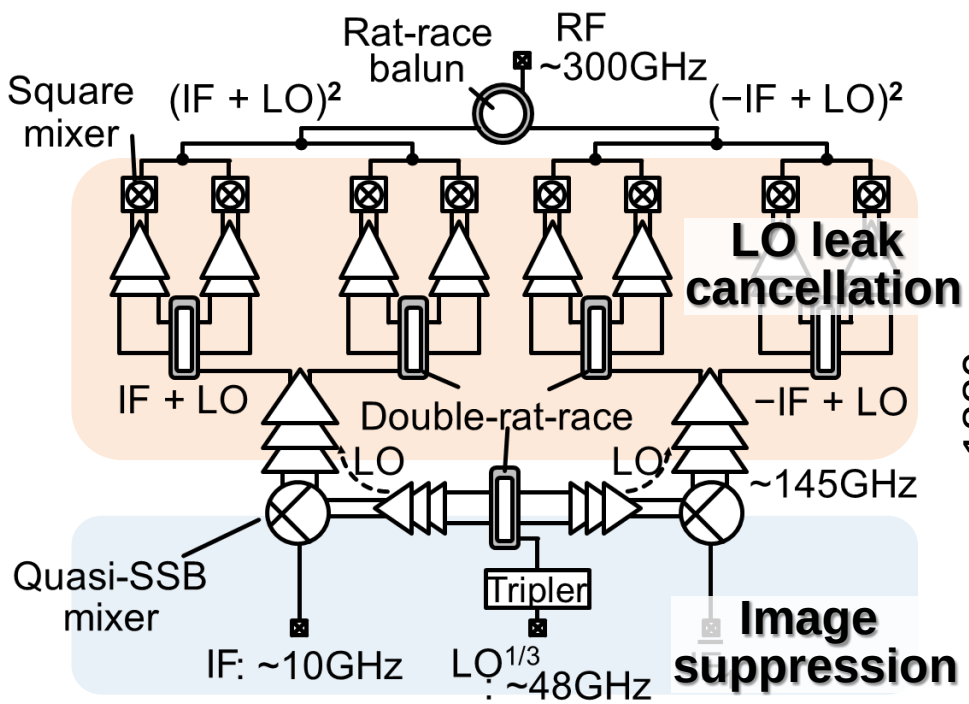
- Square mixer—Doubler-based mixer
  - IF_2 and LO are applied to the gate of an FET doubler
  - IF_2 is linearly upconverted by the cross term, $IF_2 \cdot LO$
  - Relatively high output power and good linearity
- Image suppression and LO leak cancellation performed

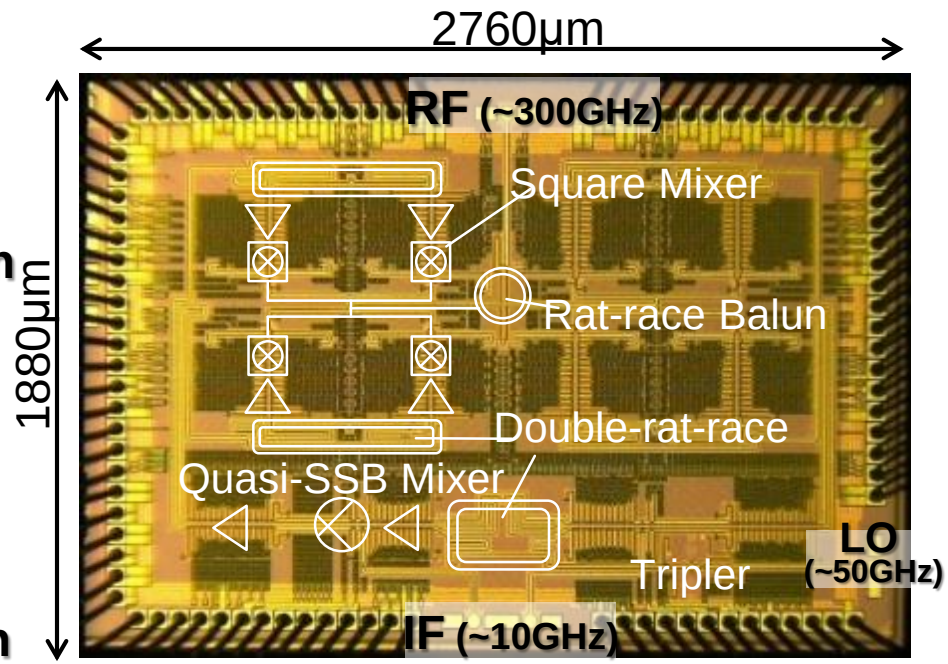




K. Takano, et al., ISSCC2017, pp. 308–309, Feb. 2017.

300-GHz CMOS transmitter

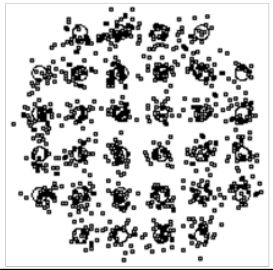


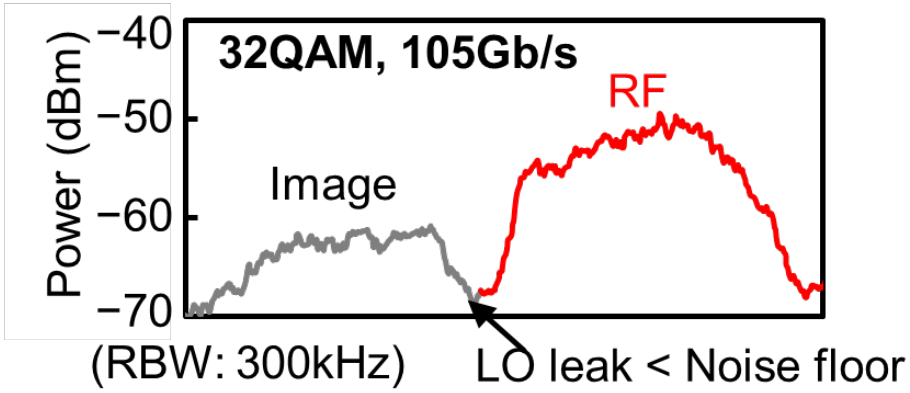


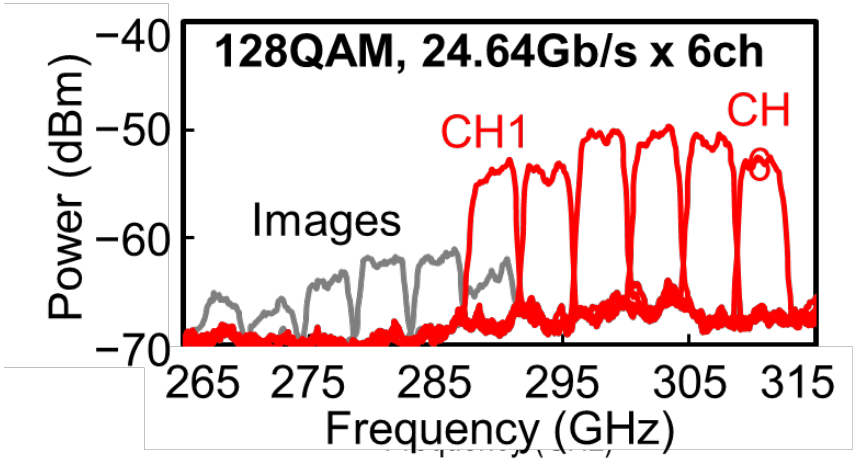
Pout: –5.5 dBm
RF Freq.: 302 GHz
3dB BW: 16 GHz

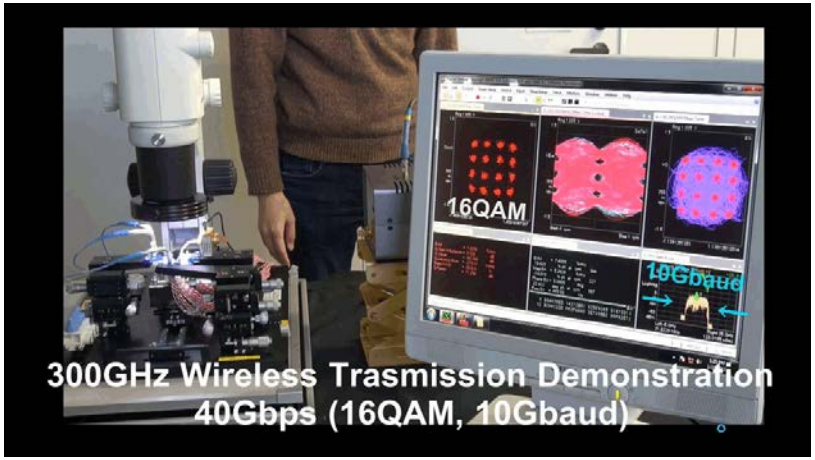
K. Takano, et al., ISSCC2017, pp. 308–309, Feb. 2017.

Measured constellation, spectra, and wireless demonstration

Modulation	32QAM
Constellation (Equalized)	
EVM	8.9%
Data rate	105Gb/s



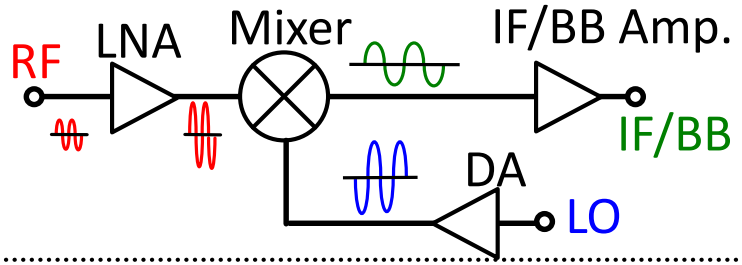
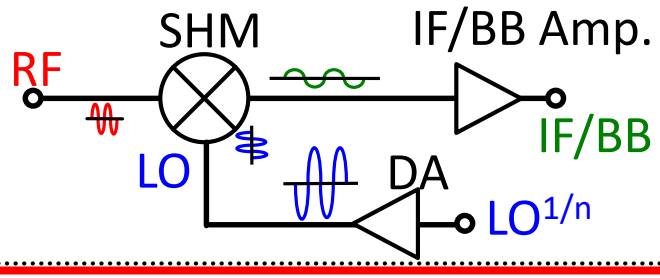
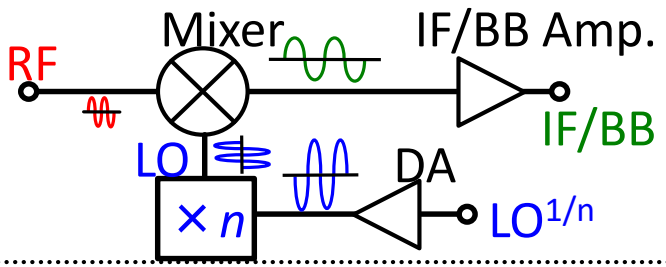




Achieved a data rate of 105 Gbit/s with 32QAM

K. Takano, et al., ISSCC2017, pp. 308–309, Feb. 2017.

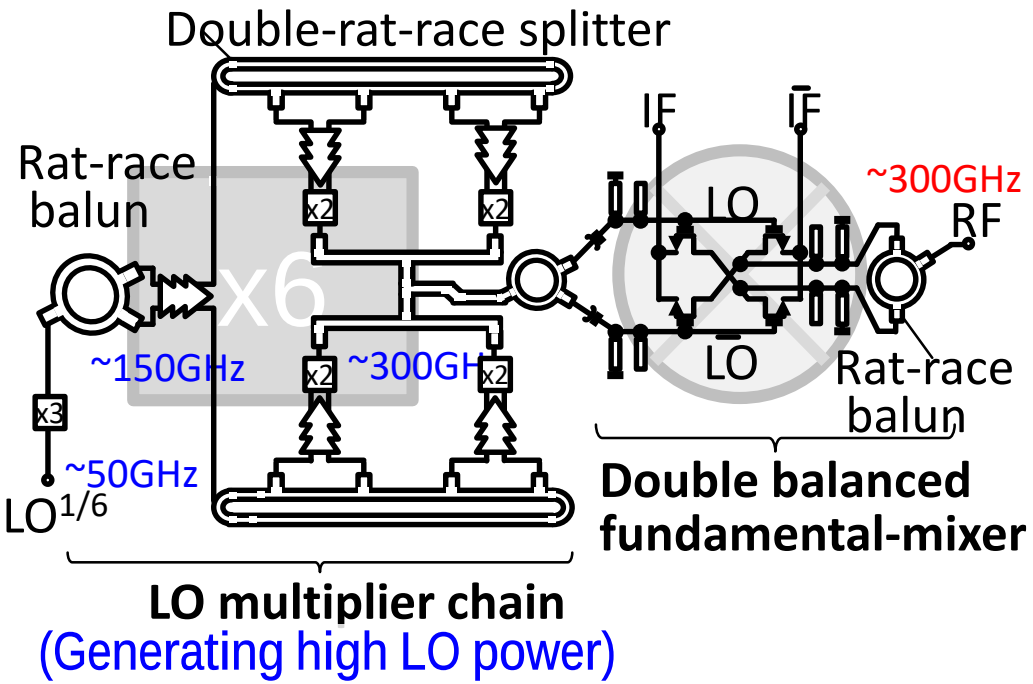
THz receiver architectures

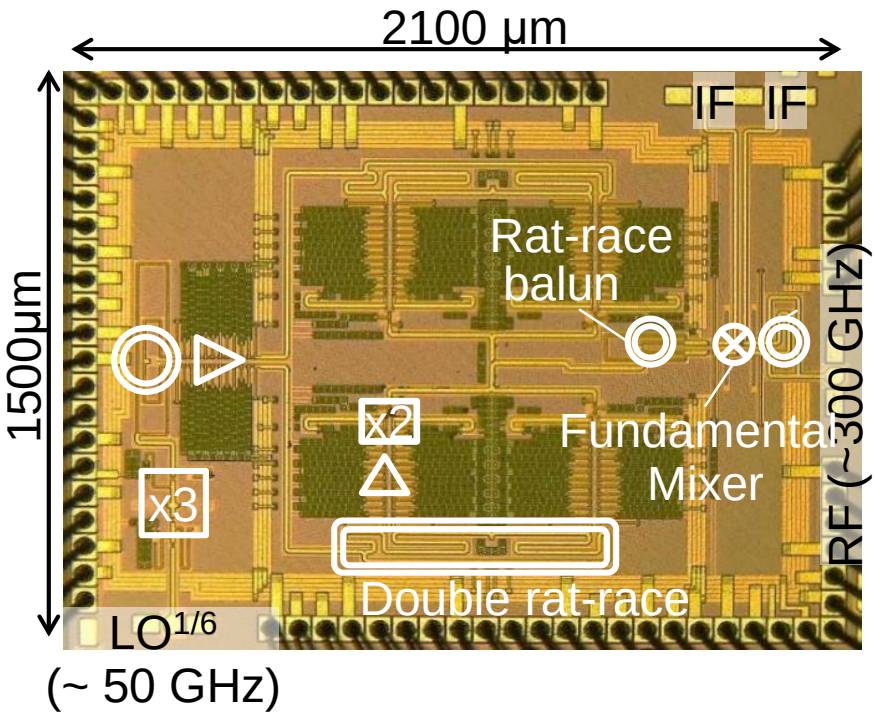
Architecture	Block diagram	Characteristics
LNA-first high f_{max}		High conversion gain Low noise
Sub-harmonic - mixer-first low f_{max}		Lower conversion gain → **Higher NF**
Fundamental -mixer-first low f_{max}		Using × n multiplier Higher conversion gain → **Lower NF** (However, higher LO power is needed.)

VS

S. Hara, et al., IMS2017, pp. 1-4, June 2017.

300-GHz CMOS receiver

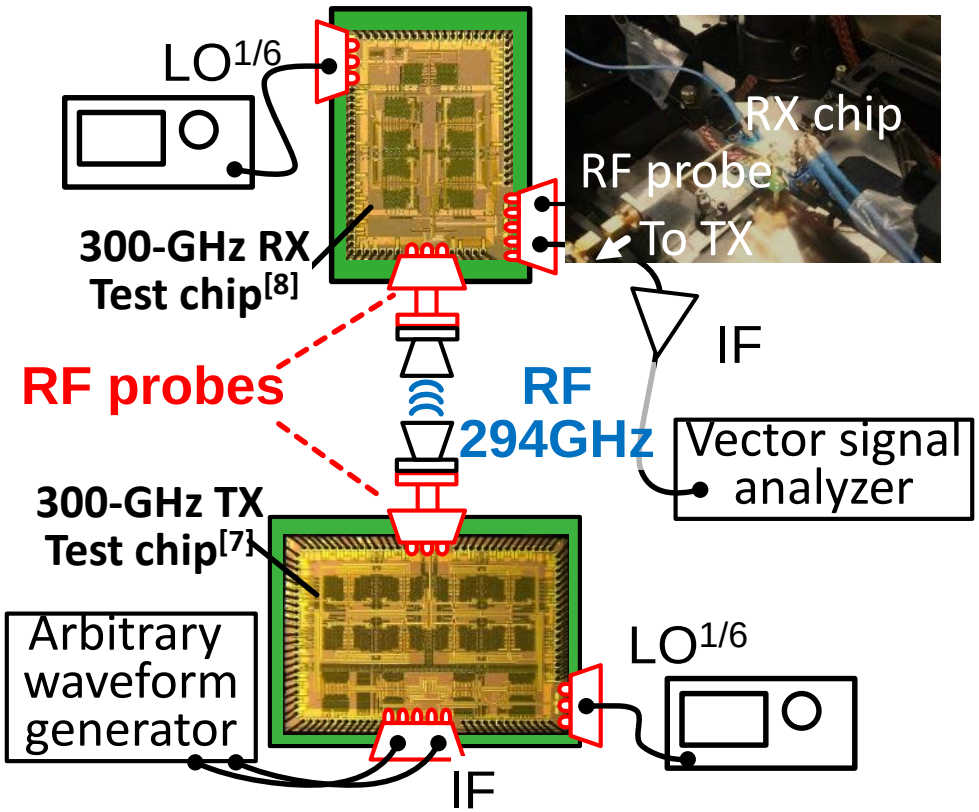


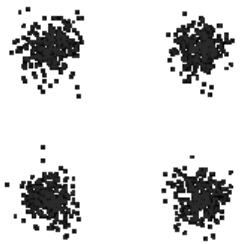
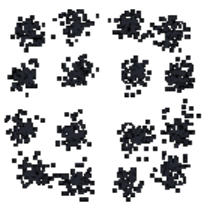


Peak CG : –19.5 dB
Noise figure: 27 dB
3-dB BW: 26.5 GHz

S. Hara, et al., IMS2017, pp. 1-4, June 2017.

Wireless link between 300-GHz CMOS TX and RX chips

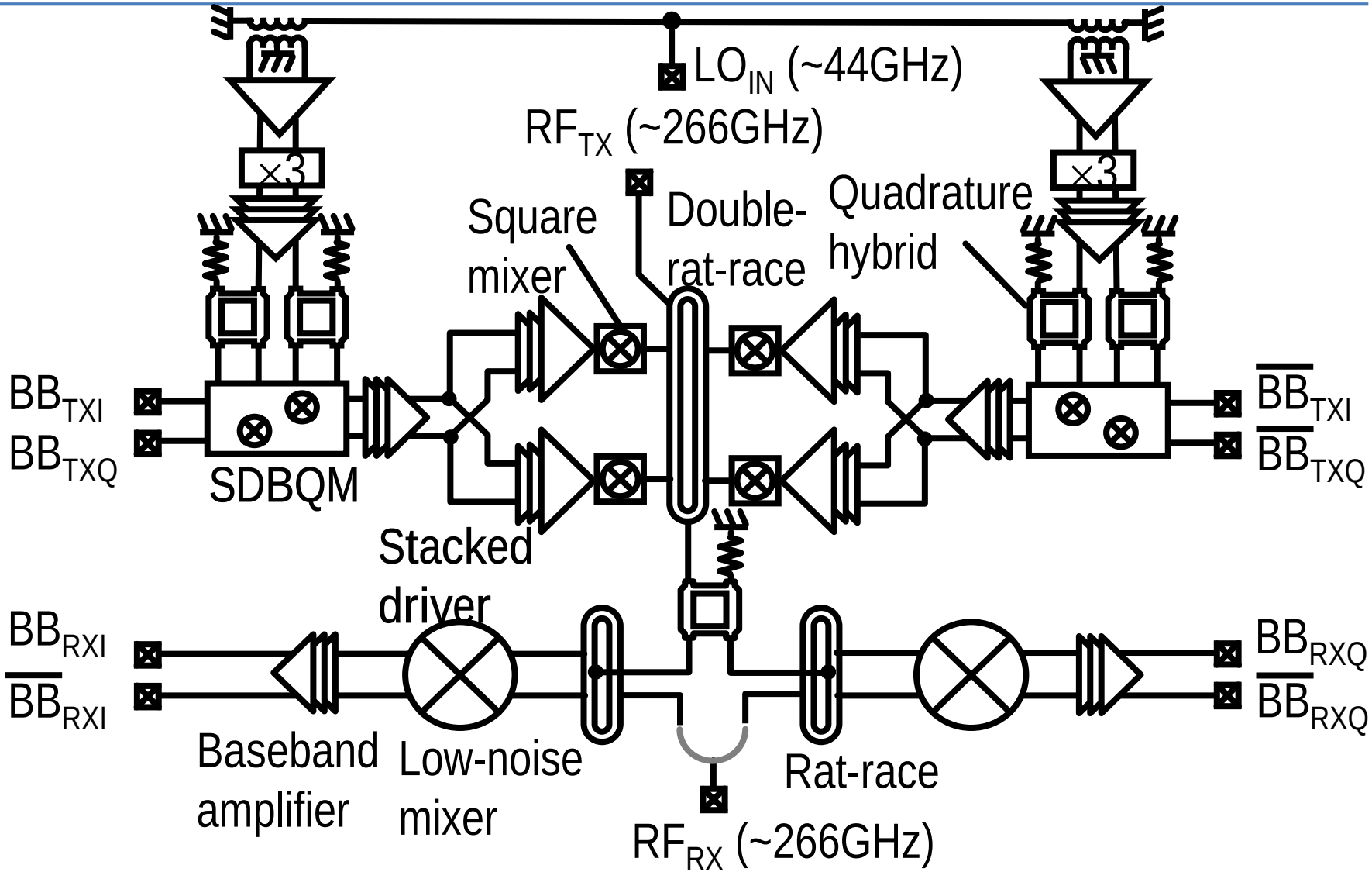


	QPSK	16QAM
Constellation (Equalized)		
EVM	19.0%rms	12.2%rms
BER	7.1×10^{-8}	9.3×10^{-5}
Sym. rate	14 Gbaud	8 Gbaud
Data rate	28 Gbit/s	32 Gbit/s

Achieved a wireless data rate of 32 Gbit/s with 16QAM

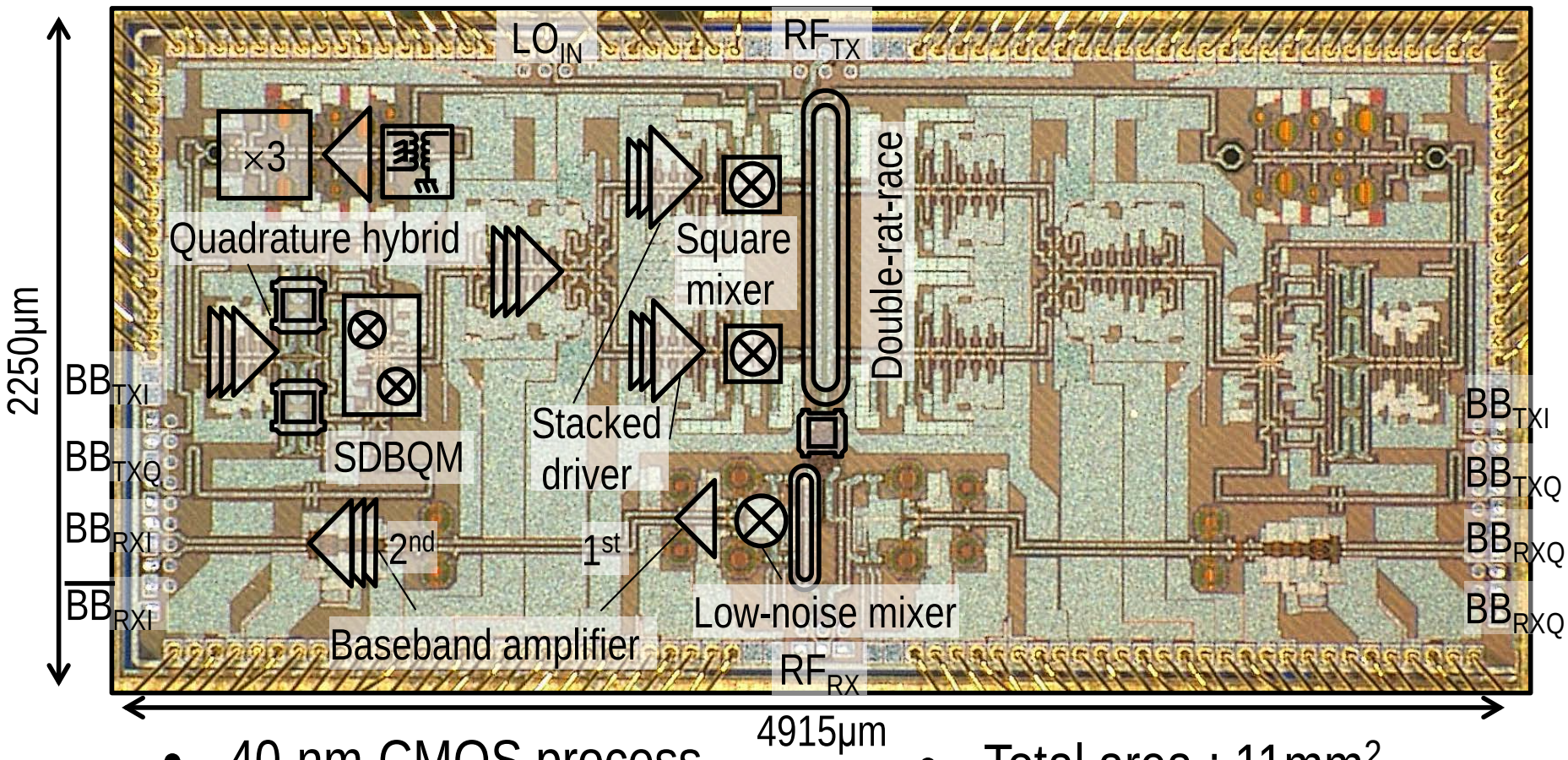
[1] K. Takano, et al., ISSCC2017, pp.308-309, Feb. 2017. [2] S. Hara, et al., IMS2017, pp. 1-4, June 2017.

Schematic of the 300-GHz transceiver



S. Lee, et al., ISSCC2019, 9.5, Feb. 2019.

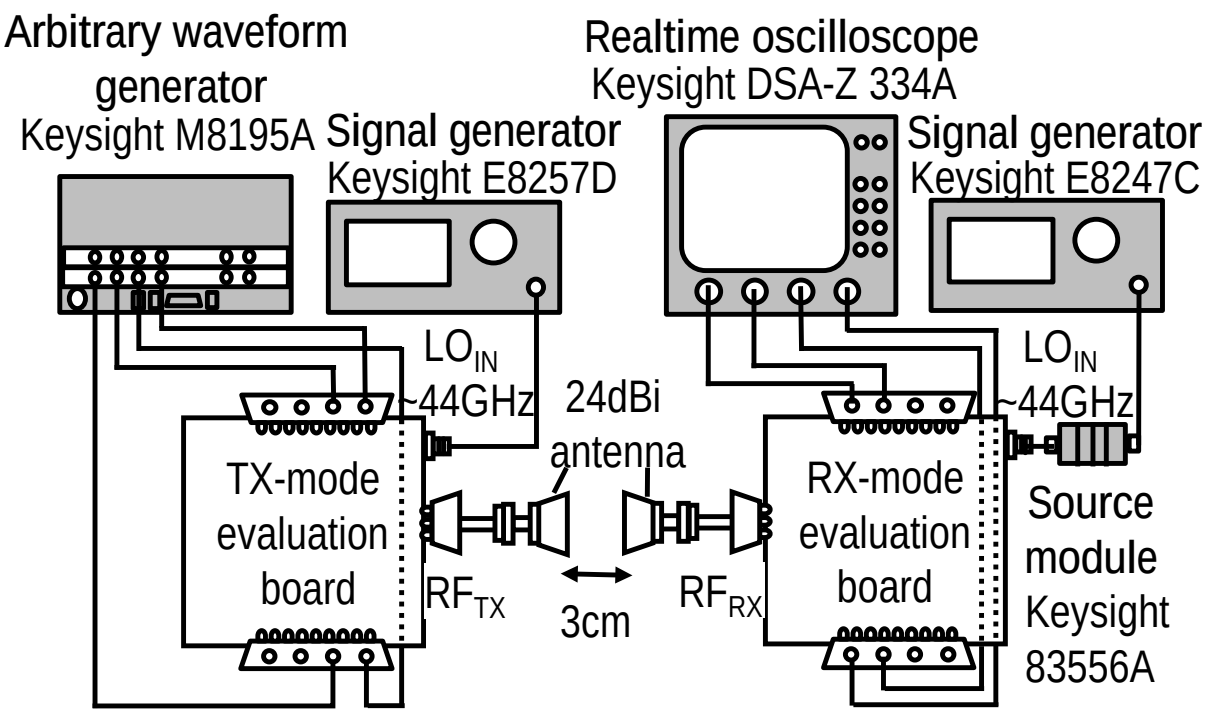
Chip micrograph

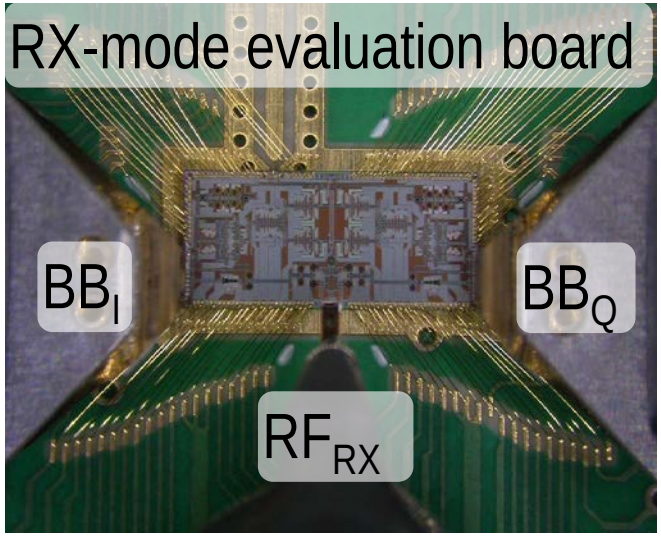


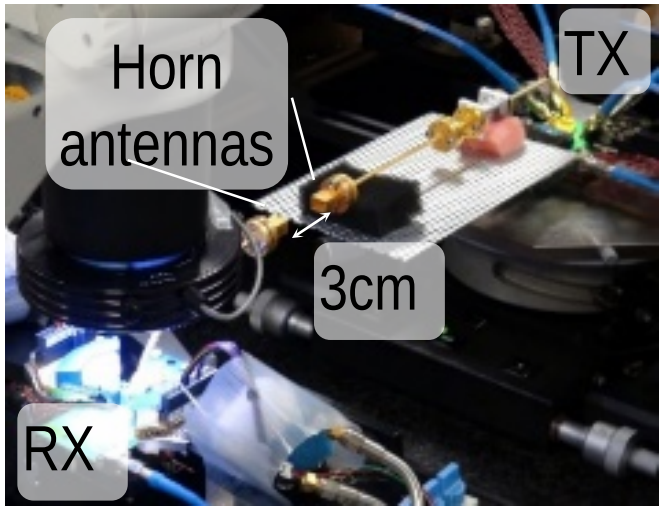
- 40-nm CMOS process
- Total area : 11mm^2

S. Lee, et al., ISSCC2019, 9.5, Feb. 2019.

Wireless measurement setup



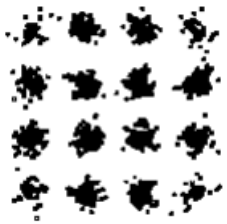
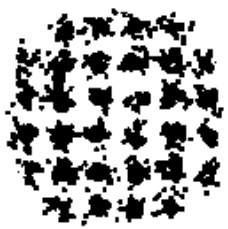




S. Lee, et al., ISSCC2019, 9.5, Feb. 2019.

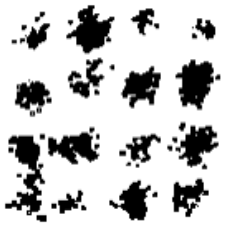
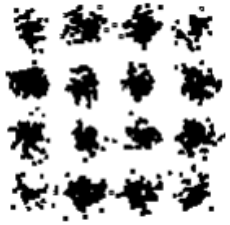
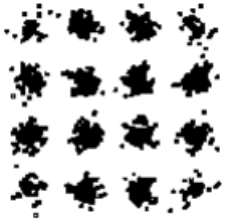
Measured wireless performance

TX alone

Center freq.	265.68GHz	
Modulation	16QAM	32QAM
Constellation (Equalized)		
EVM (%rms)	9.1%rms	7.4%rms
Symbol rate	28Gbaud	28Gbaud
Data rate	112Gb/s	140Gb/s

TX wireless performance using VDI down converter

TX → RX

	Ch.49	Ch.50	Ch.66
Center freq.	257.04GHz	265.68GHz	265.68GHz
Modulation	16QAM	16QAM	16QAM
Constellation (Equalized)			
EVM (%rms)	10.9%rms	11.3%rms	12%rms
Symbol rate	7.04Gbaud	7.04Gbaud	20Gbaud
Data rate	28.16Gb/s	28.16Gb/s	80Gb/s

BW→ Ch.49, 50 : 8.64GHz, Ch.66 : 25.92GHz

S. Lee, et al., ISSCC2019, 9.5, Feb. 2019.

Conclusion

- **InP-HEMT**
  - **KIOSK download demonstration, 20 Gbps**
  - **Over 2m, 100 Gbps**

- **300-GHz Traveling Wave Tube Amplifire**
  - **Under development**

- **300-GHz CMOS**
  - **TRX in 40nm CMOS (f_{max} < 300GHz)**
  - **TX/RX modules using CMOS-chip-to-WG transition in a multilayer glass epoxy PCB**

- **The other R&Ds for terahertz wireless on going in Japan**