National Institute of Information and Communications Technology

テラヘルツシステム応用推進協議会 THz-6Gワーキンググループ
2021年3月31日

テラヘルツ帯電子デバイス技術

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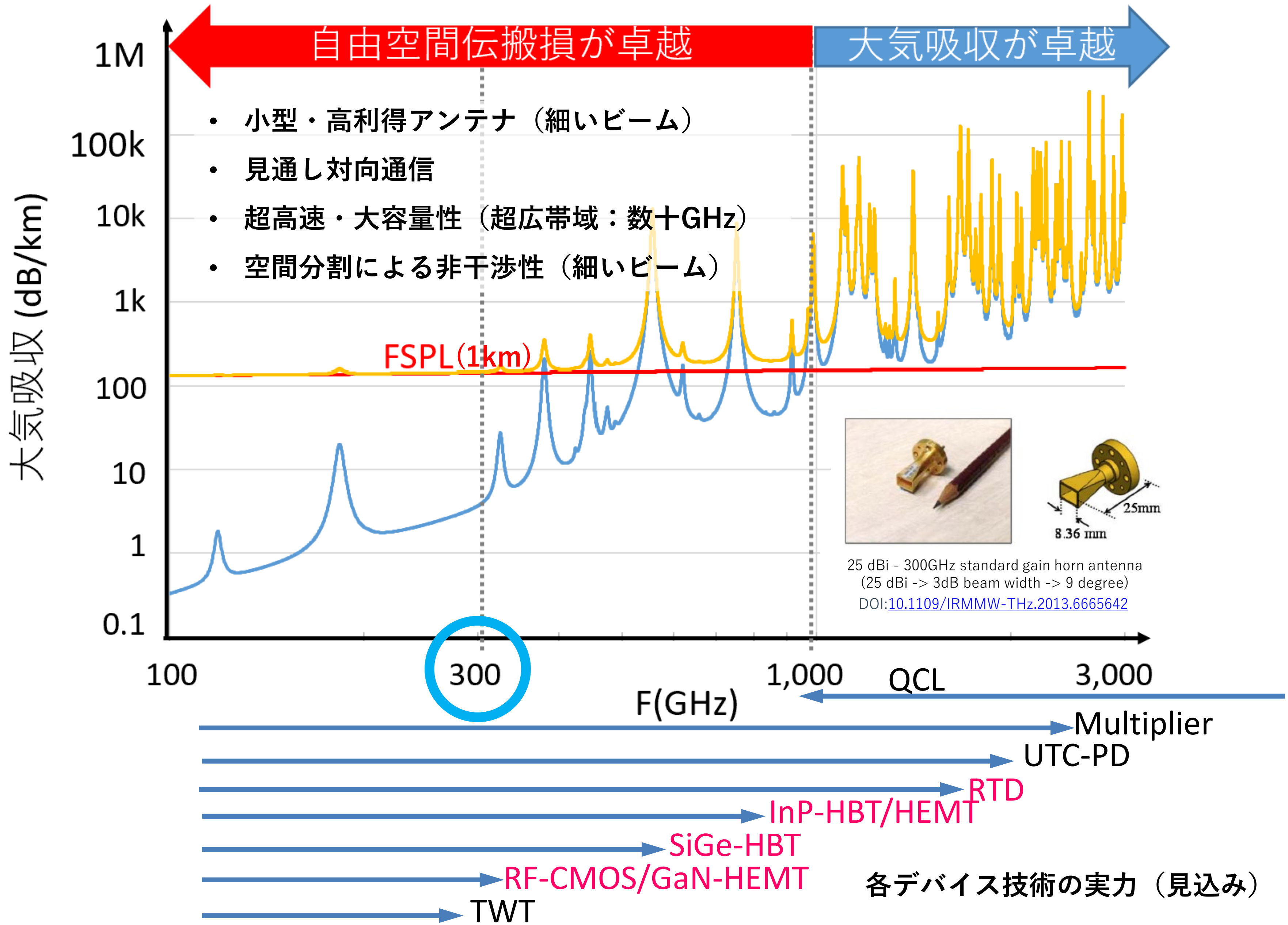
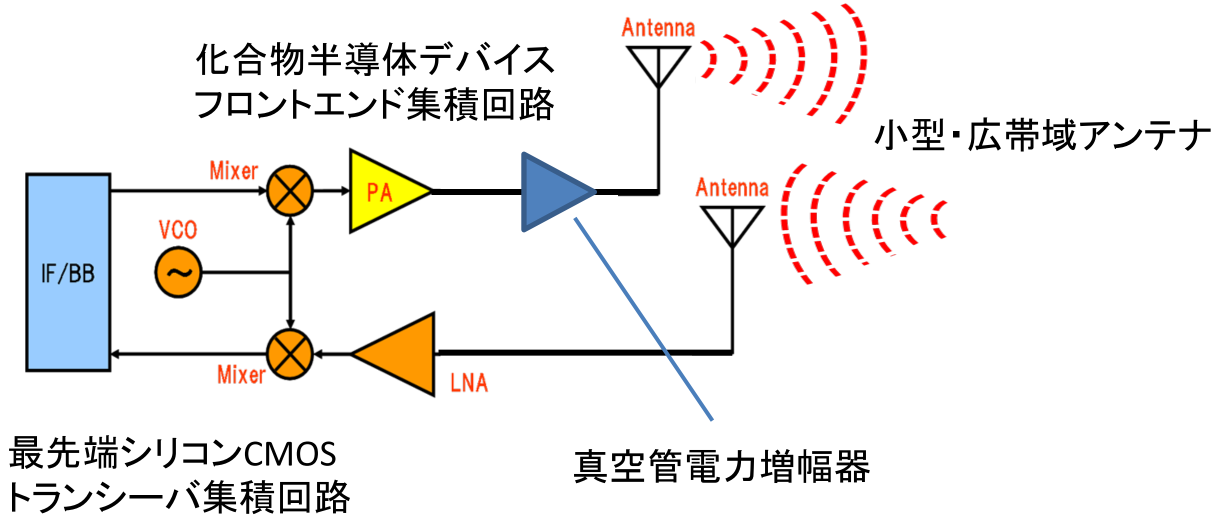
国立研究開発法人情報通信研究機構
未来ICT研究所　兼　テラヘルツ研究センター

テラヘルツ波の特徴と対応デバイス



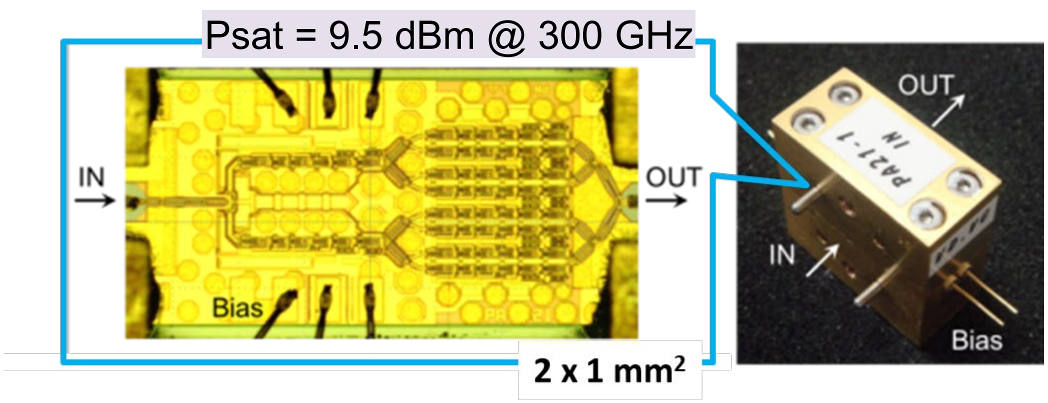
国プロ（総務省）

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）
集積電子デバイスによる大容量映像の非圧縮低電力無線伝送技術の研究開発	NICT、東京理科大 広島大、名工大 ザインエレクトロニクス	R1～R4 （4カ年）

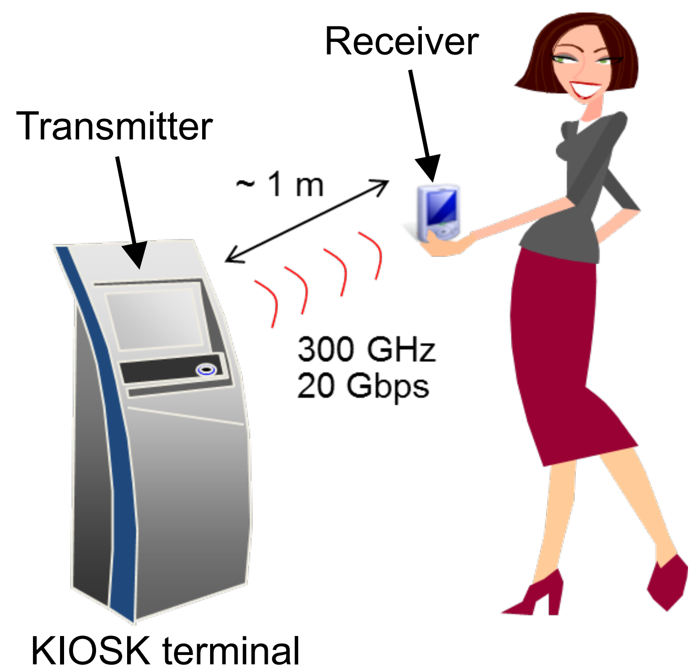


総務省
電波資源拡大のための研究開発（FY2011～）

課題名	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）



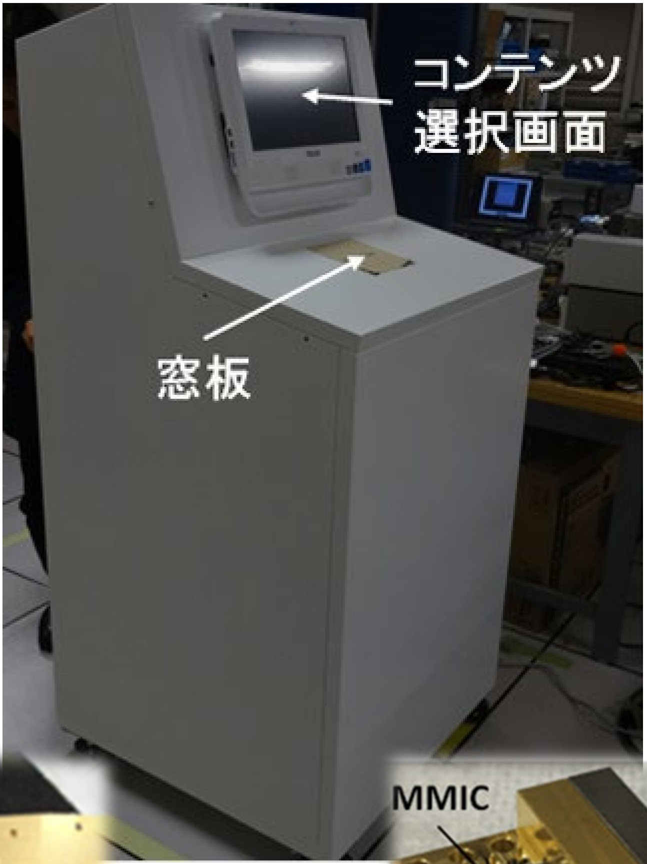
InGaAs系PA-MMIC chip (left) and PA module (right)



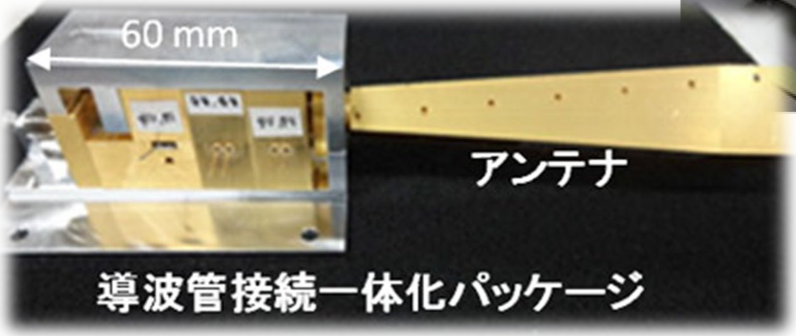
http://www.tele.soumu.go.jp/resource/j/fees/purpose/pdf/H27_RD05.pdf

化合物半導体ICによる送受信モジュール(NTT、富士通、NICT)

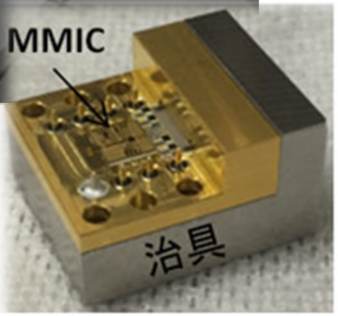
300GHz帯無線技術を
使ったキオスクダウンロード
（2016年5月26日ニュースリリース）

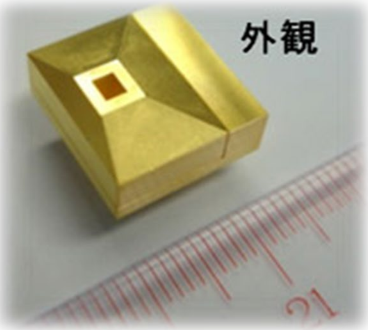


送信機
モジュール

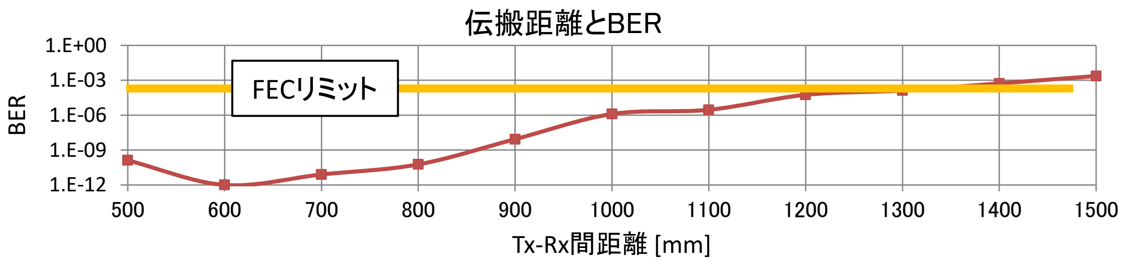


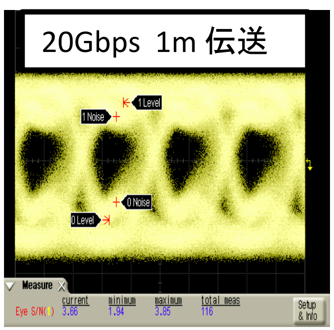
受信機
モジュール

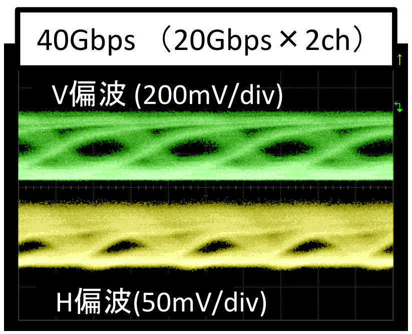




キオスクダウンロードのデモ(300GHz帯、20Gbit/s、1m以内伝送)







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)

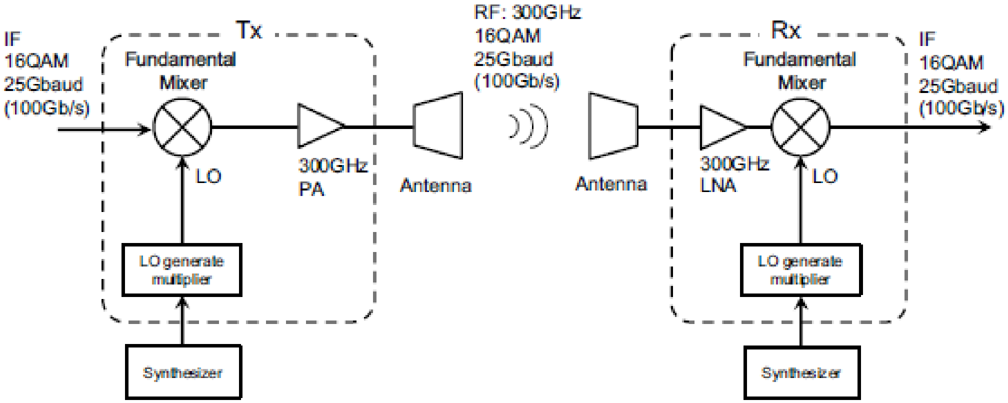


Fig. 1. Conceptual schematic of the proposed 300-GHz TRx.

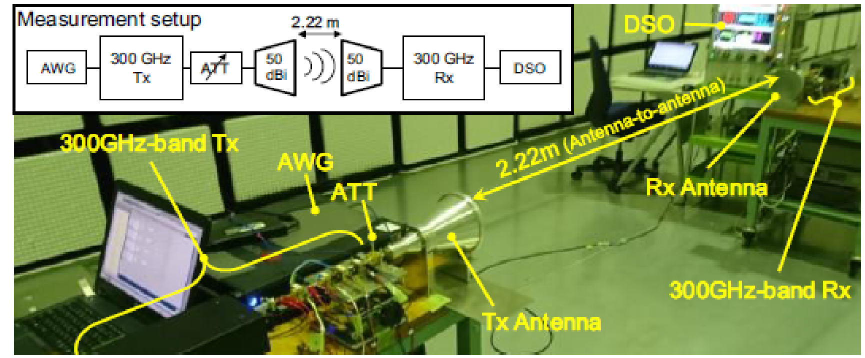


Fig. 10. Measurement setup for wireless transmission demonstration.

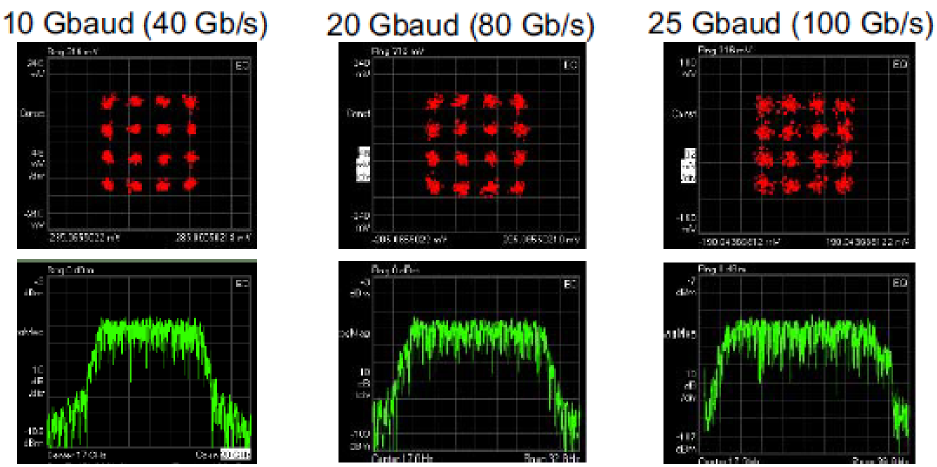


Fig. 9. Measured constellations and spectrums of 300-GHz TRx.

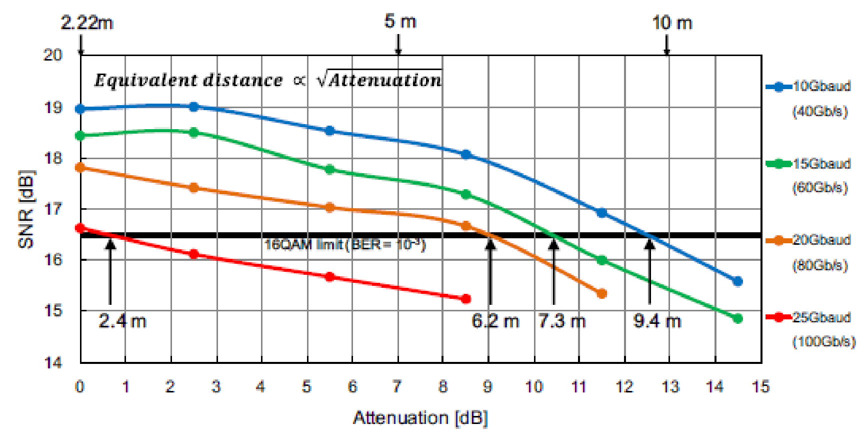


Fig. 11. Results of wireless transmission using 300-GHz TRx.

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

総務省
電波資源拡大のための研究開発（FY2014～）

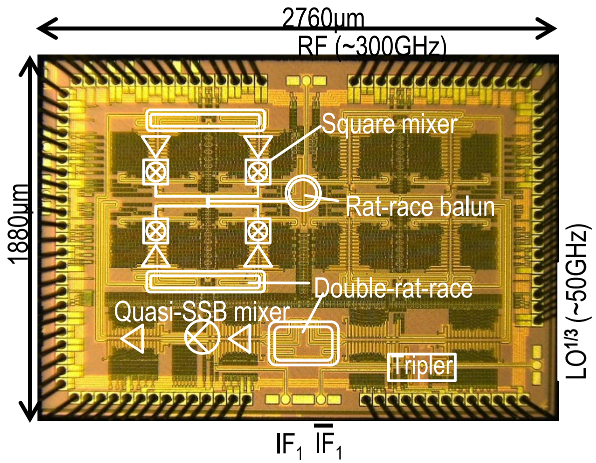
課題名	受託者	期間（年度）
テラヘルツ波デバイス基盤技術の研究開発 -300GHz帯シリコン半導体CMOSトランシーバ技術- （Si-CMOSデバイスとIntra-Device実証）	広島大学 パナソニック NICT	H26～30 （5カ年）

Intra-device Model

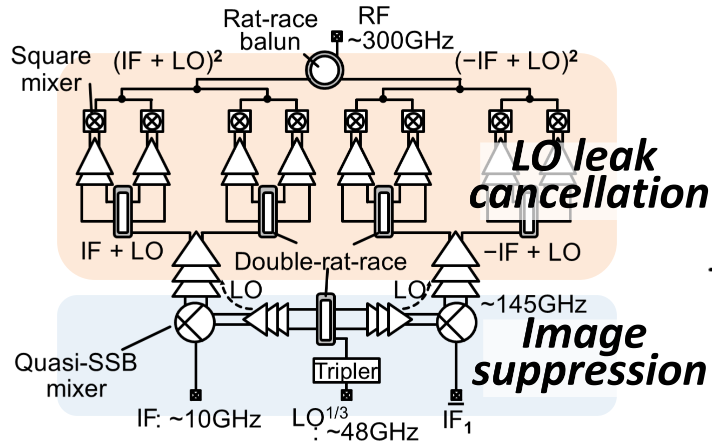
Issues:
High speed devices and ICs(Si-CMOS),
Base band, packaging, antenna,
100 Gbps data Transmission experiment within 10 cm

シリコン集積回路トランシーバ（300GHz帯）

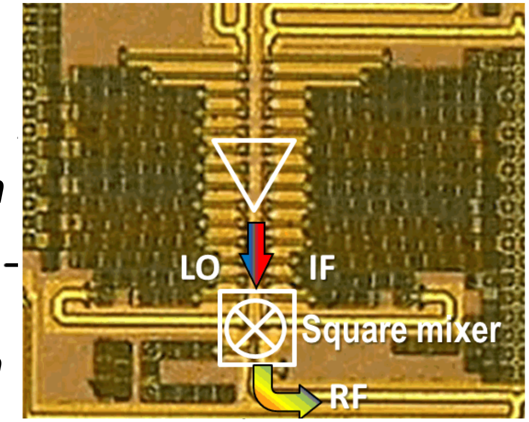
■シリコンCMOSによる300GHz帯無線送信機 K. Takano, et al., ISSCC2017, pp.308-309 (2017).



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

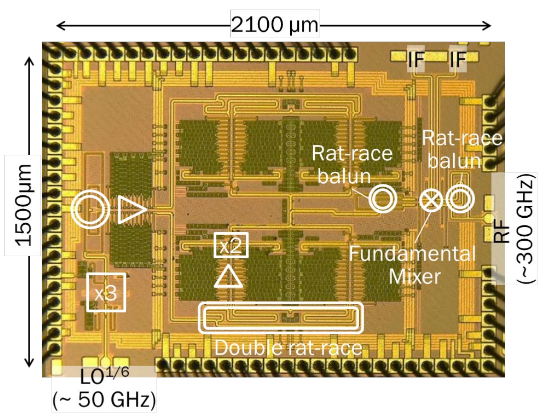


300GHz Si CMOS送信機 回路図
Block diagram of 300GHz Si CMOS transmitter

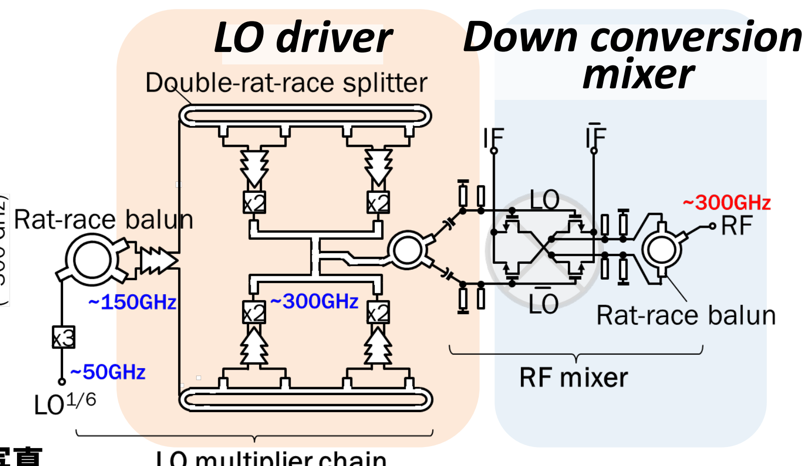


2逓倍器ミキサー
Square Mixer

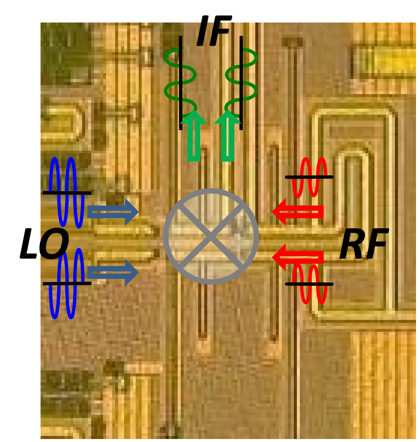
■シリコンCMOSによる300GHz帯無線受信機 S. Hara, et al., IMS2017, pp.1-4 (2017).



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



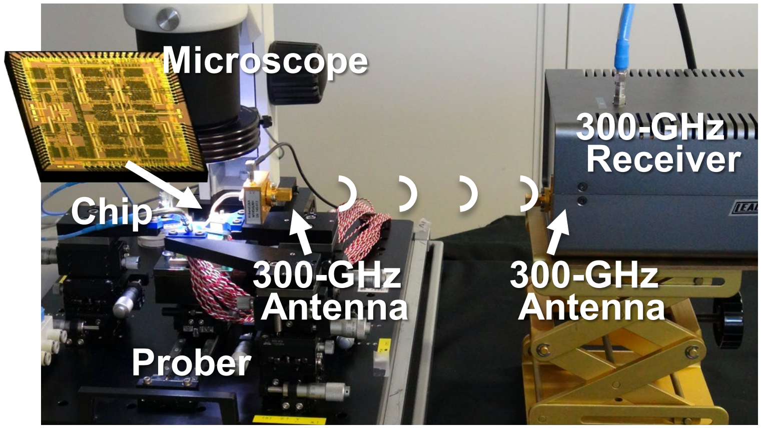
300GHz Si CMOS送信機 ブロック図
Block diagram of 300GHz Si CMOS receiver



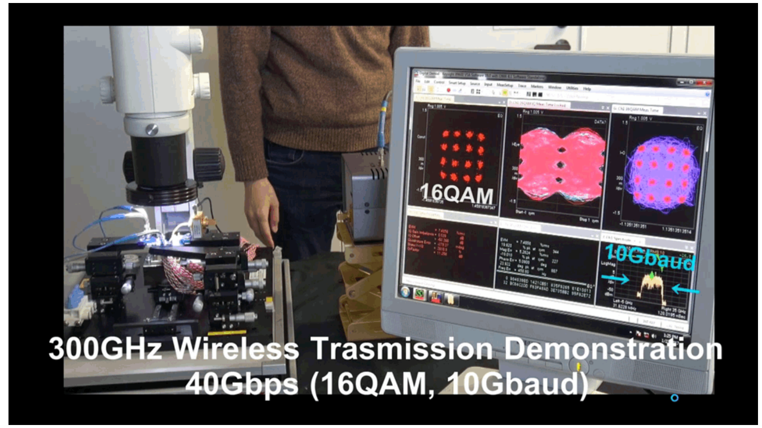
広帯域ミキサー
Square Mixer

シリコン集積回路トランシーバ(300GHz帯)

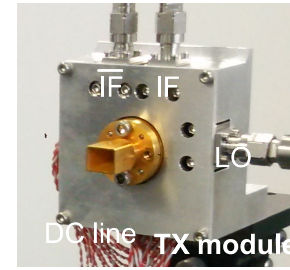
■Si CMOSプロセス(40nm)の動作限界を超える300GHzで、
1ch 105Gb/sの伝送速度を実現

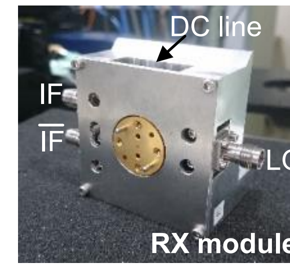


300-GHz Si CMOS送信機 無線実験のセットアップ
Setup of wireless transmission of 300-GHz Si CMOS transmitter

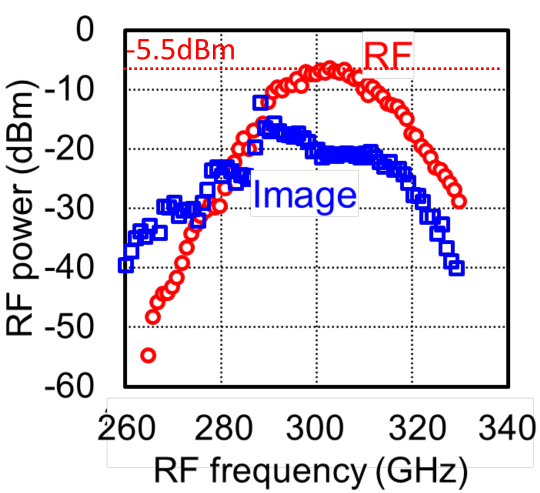


無線実験風景
Wireless transmission of 300GHz Si CMOS transmitter

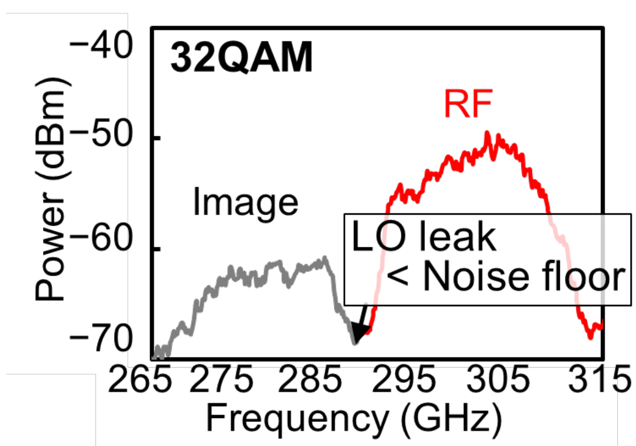




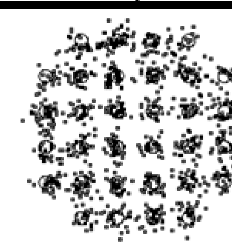
送受信機モジュール
300GHz Si CMOS transmitter and receiver modules



出力特性
Output power of 300GHz Si CMOS transmitter



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

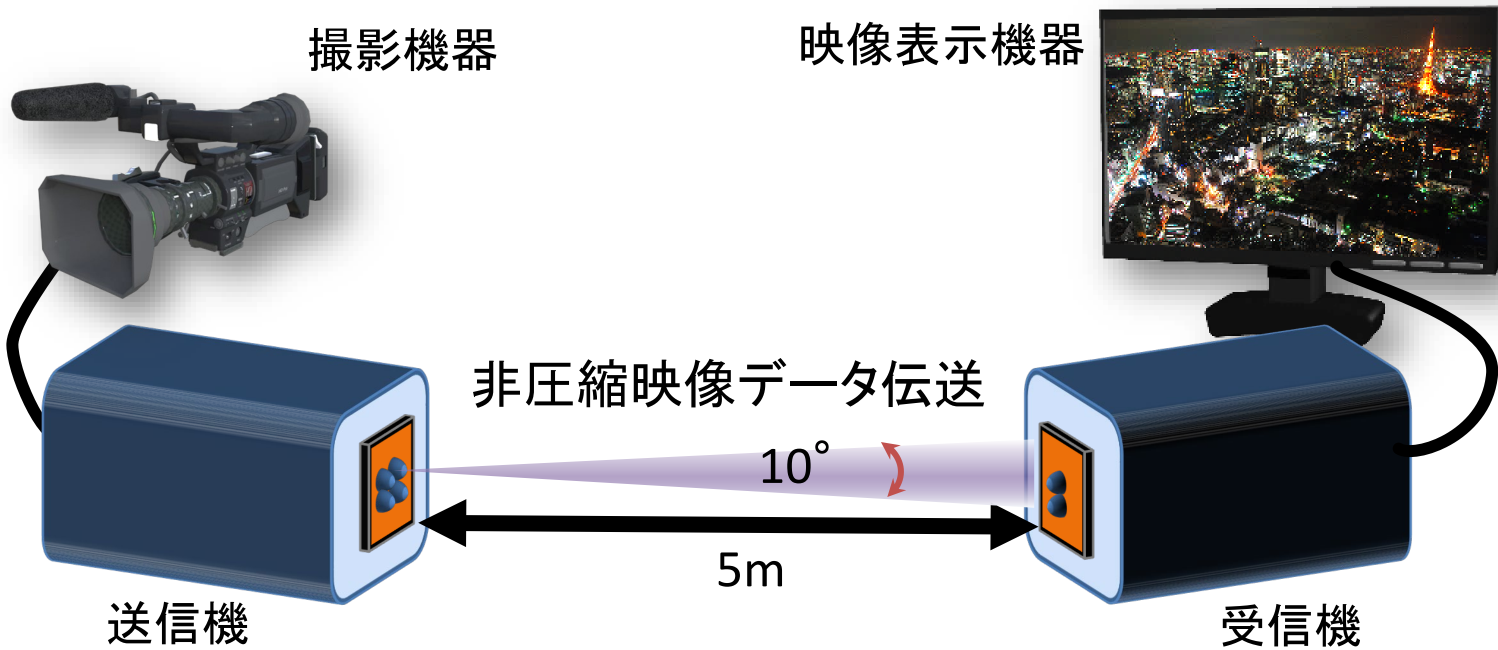
Modulation	32QAM
Constellation (Equalized)	
EVM	8.9%
Data rate	105Gb/s

コンスタレーション
Constellations of 32-QAM

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

総務省
電波資源拡大のための研究開発（FY2019～）

課題名	受託者	期間（年度）
集積電子デバイスによる大容量映像の非圧縮低電力無線伝送技術の研究開発 （**Si-CMOSデバイス**と**非圧縮映像伝送実証**）	NICT、東京理科大 広島大、名工大 ｻﾞｲﾝｴﾚｸﾄﾛﾆｸｽ	R1～R4 （5ヵ年）



<u>到達目標</u>　8K映像の非圧縮50 Gbit/s程度の無線伝送実証実験
遅延時間0.5 ms未満、伝送距離5 m以上、誤り率10-4以下、
角度10度程度のビーム制御、トランシーバ単体の消費電力15 W以下

- ■65nm CMOS
- ■Bi-directional architecture
- ■Stacked antenna array

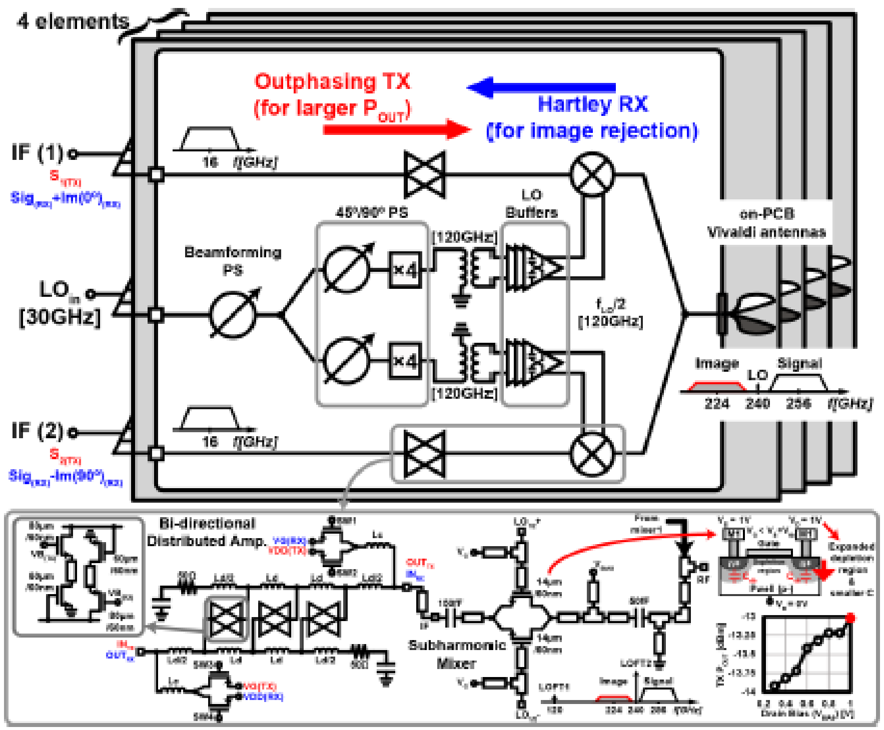
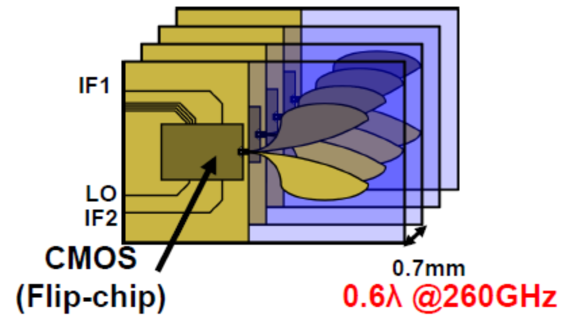
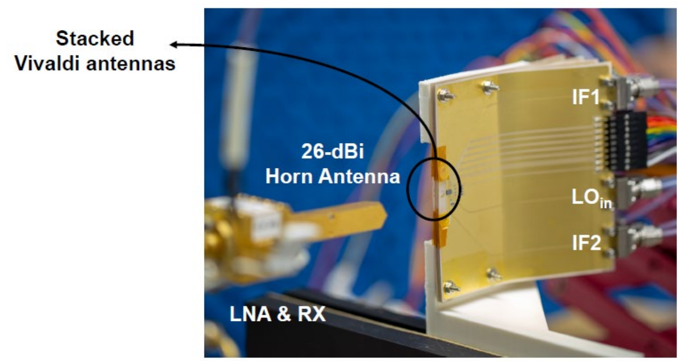
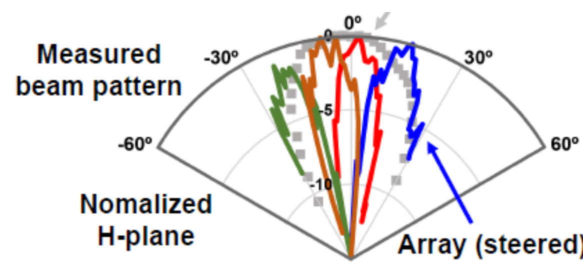


Figure 22.2.2: Block diagram of 300GHz-band CMOS bi-directional phased-array TRX system.

End-fire antennas stacked vertically







I. Abdo, et al., ISSCC2021, 22.2, Feb. 2021.

436-467GHz Lens Integrated Source（UC Davis)

- ■65nm CMOS
- ■Lens-integrated reconfigurable Source
- ■Coupling capacitor mesh

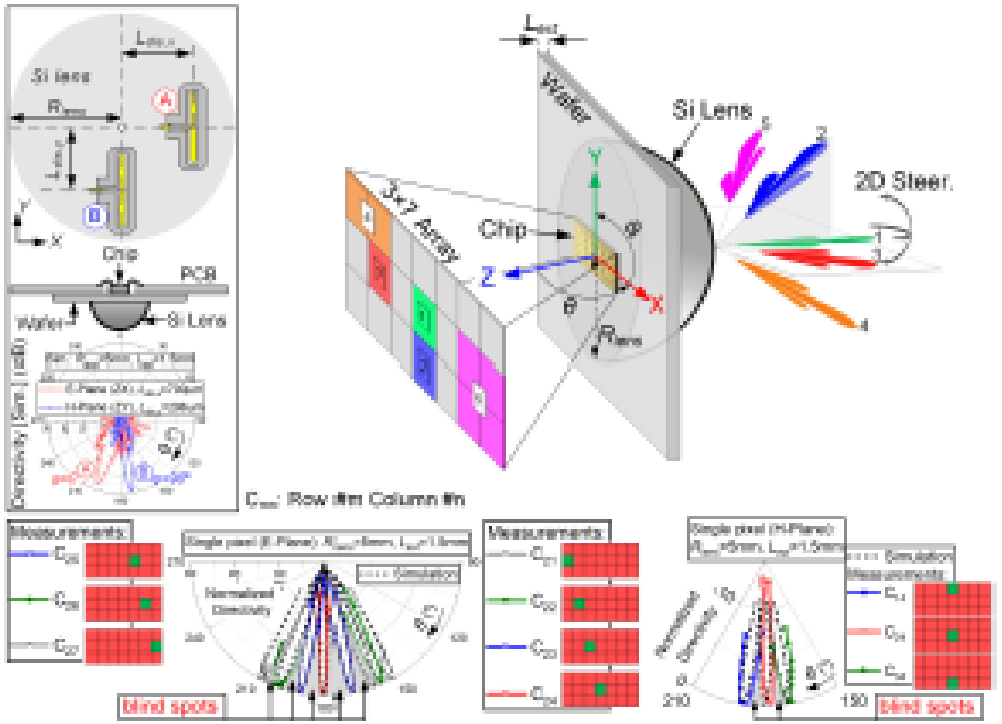


Figure 23.2.1: Activation of various sections of the reconfigurable array steers the beam in different directions (top right) due to displacement from the lens center (top left). Mere single-pixel activation creates blind spots for imaging/sensing between beams (bottom).

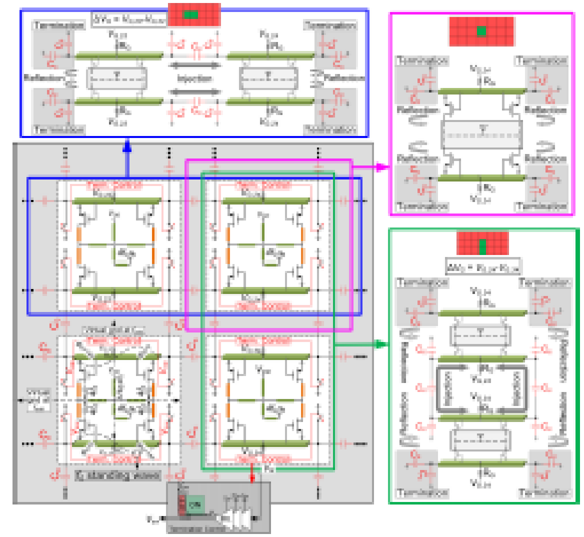


Figure 23.2.2: The structure of the implemented array with the coupling capacitor mesh and the circuit operation when a single pixel, 1×2, or 2×1 section is activated.

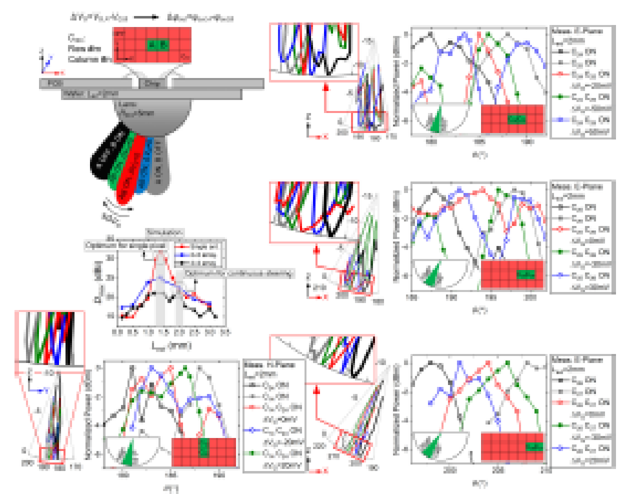


Figure 23.2.4: Measured beam patterns for fine and coarse beam steering showing the coverage of the blind spots between discrete steering steps by creating a variable phase shift between two activated adjacent cells.

H. Jalili, et al., ISSCC2021, 23.2, Feb. 2021.

T-MUSIC Selects Performers to Develop Integrated Mixed-Mode RF Electronics in Onshore Foundries

Nine research teams selected to develop advanced RF mixed-mode electronics critical to emerging defense applications in communications, radar, and electronic warfare

OUTREACH@DARPA.MIL
2/4/2020

Today's defense electronics systems rely on radio frequency (RF) mixed-mode electronics – those that integrate RF, analog, and digital circuits onto a single chip – to interface RF signals with digital processors. This technology supports critical communications, radar, and electronic warfare (EW) capabilities, as well as being widely used to support commercial telecommunications. The Department of Defense (DoD) has capability demands that far exceed the requirements of the commercial world in terms of speed, fidelity, capacity, and precision. Current commercial RF mixed-mode systems on a chip (SoCs) are implemented on digital complementary metal oxide semiconductor (CMOS) platforms, a technology that has been used for decades to construct integrated circuits, highly integrated transceivers, microprocessors, and beyond. Despite continued advancement and scaling along the trajectory of Moore's Law for high integration density, these CMOS platforms are unable to support operations at higher frequencies with larger signal bandwidths and higher resolutions, essentially limiting their use in next-generation mixed-mode interfaces needed for emerging defense RF applications.

To advance RF mixed-mode interfaces beyond current limitations, DARPA established the Technologies for Mixed-mode Ultra Scaled Integrated Circuits (T-MUSIC) program. T-MUSIC was first announced in January 2019 as a part of the second phase of DARPA's Electronics Resurgence Initiative (ERI). One area of research under ERI Phase II focuses on the integration of photonics and RF components directly into advanced circuits and semiconductor manufacturing processes, enabling unique and differentiated domestic manufacturing capabilities. As such, T-MUSIC will explore the integration of mixed-mode electronics into advanced onshore semiconductor manufacturing processes. The goal is to develop highly integrated RF electronics with an unprecedented combination of wide spectral coverage, high resolution, large dynamic range, and high information processing bandwidth. Further, the program will work to establish a domestic ecosystem that can facilitate enduring DoD access to high-performance RF mixed-mode SoCs.

"T-MUSIC's goal is to develop next-generation terahertz (THz) mixed-mode devices that integrate digital processing and intelligence on the same chip through an advanced CMOS fabrication platform," said DARPA program manager, Dr. Y.K. Chen who leads the T-MUSIC program. "These technologies will provide DoD systems with differentiating capabilities in advanced RF sensors, high capacity wireless and wireline communications, and beyond."

The T-MUSIC program has selected nine research teams from academic institutions, as well as commercial companies, to take on the program's research objectives. In particular, five research teams will work to develop and implement advanced broadband RF mixed-mode circuit designs. These designs will essentially form "building blocks" that can be used by DoD-relevant applications. The building blocks will also establish the foundation of a mixed-mode IP library for the DoD user community. The research teams selected for this area of research include:

- BAE Systems
- Raytheon
- University of California, Los Angeles
- University of California, San Diego
- University of Utah

T-MUSICの目標は、先進的なCMOSファブリケーションプラットフォームを通じて、デジタル処理とインテリジェンスを同一チップ上に統合した次世代テラヘルツ（THz）ミックスドモードデバイスを開発することです。

The five circuit design teams will closely collaborate with two foundry partners selected to support the development of advanced mixed-mode technologies in U.S. onshore CMOS foundries. The foundry partners include Global Foundries and TowerJazz.

Finally, a third group of researchers will explore foundational breakthroughs in ultra-broadband transistors, pushing well beyond current near-term advances in foundry technology. Research teams from the University of California, Los Angeles and University of California, Berkeley will explore new types of RF mixed-mode transistors capable of demonstrating transistor-switching speed up to 1 THz in a scalable CMOS platform.

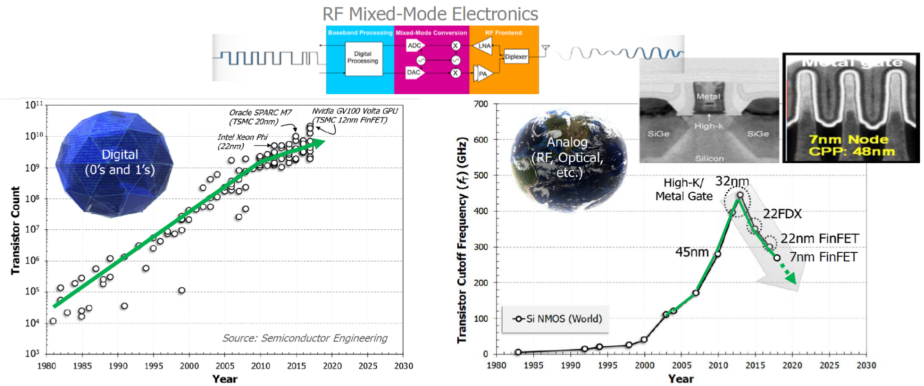
T-MUSIC Selects Performers to Develop Integrated Mixed-Mode RF Electronics in Onshore Foundries (darpa.mil)
https://www.darpa.mil/attachments/T-MUSIC_Proposers%20Day_Presentations_Combined.pdf

https://www.darpa.mil/attachments/T-MUSIC_Proposers%20Day_Presentations_Combined.pdf

Performance Wall of Today's CMOS

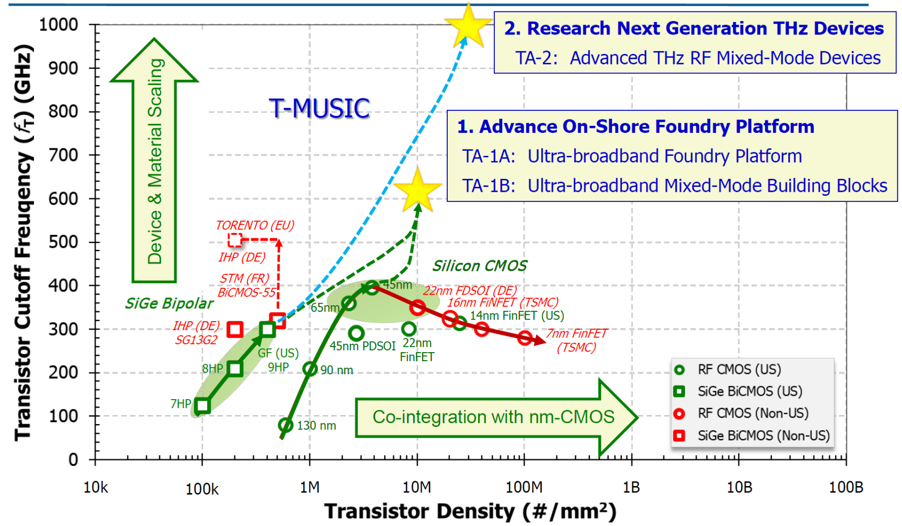
Problem:

Scaling digital CMOS does not support the growth of analog information.



Moore's Law has multiplied digital CMOS with high density and low power
… but hits the performance wall to increase fidelity, sensitivity and bandwidth for next generation mixed-mode electronics.

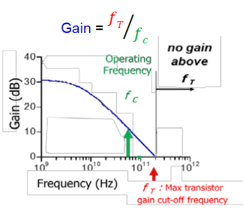
Invigorate On-Shore Foundry Capability



T-MUSIC leverages Moore's Law to scale on-shore mixed-mode semiconductors to THz while integrating advanced digital CMOS.

Remove Analog Performance Bottlenecks

Broadband RF Frontend



- RF frontends require transistors 10x faster than the operating frequency
- High DC to RF efficiency

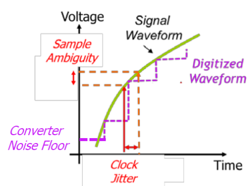
State of the Art

f_T = 300 GHz

T-MUSIC 2 X

f_T = 600 GHz

High Resolution Converters



- Fast matched transistors to digitize fast signals
- Low transistor noise enables high resolution and precision

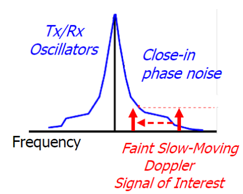
State of the Art

- Resolution: 32 levels (5 effective bits) over 20 GHz @ 64 GSps

T-MUSIC 10 X

- Resolution: 256 levels (8 effective bits) over 50GHz @ 100 GSps

Precision Oscillators



- Fast transistors enable high frequency sensing
- Low close-in and broadband noises to capture faint signal

State of the Art

Phase Noise @ 30GHz
< -97 dBc/Hz @ 1MHz offset

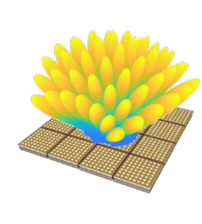
T-MUSIC 100 X

Phase Noise @ 30GHz
< -120 dBc/Hz @ 1MHz offset

T-MUSIC will develop key mixed-mode IP blocks in foundries for HF to 100+GHz operating frequency span with 10x bandwidth, 10x finer resolution and 100x lower oscillator noises.

T-MUSIC Will Multiply DoD Capabilities In Sensing, EW And Communications

Broadband RF Frontend



Millimeter wave digital arrays

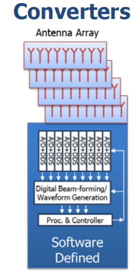
T-MUSIC Transistors

2X Faster, 2x Higher Gain

System Impacts

- >2X wider span: HF to 100+GHz
- >2X energy efficient

High Resolution Converters



Direct-sample digital arrays

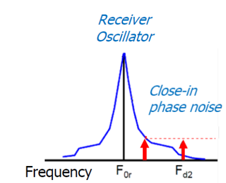
T-MUSIC Converters

10X Lower Uncorrelated Noises

System Impacts

- 10X higher resolution
- 10X fewer number of elements

Precision Oscillators



Moving target detection

T-MUSIC Oscillators

100X Lower Phase Noise

System Impacts

- 10X slower moving Doppler targets
- 10X energy efficiency

T-MUSIC will develop key mixed-mode IP blocks in foundries for HF to 100 GHz operating frequency span with 10x bandwidth, 10x finer resolution and 100x lower oscillator noises.

まとめ

・総務省プロジェクト
化合物半導体（InP系HEMT） キオスクダウンロード
シリコンCMOS 非圧縮映像伝送への応用
進行波管増幅器

・ISSCC2021発表 ピックアップ
・DARPA T-MUSICプロジェクトの紹介

・今後の技術の要点
アンテナシステム技術の確立
多素子アンテナ、MIMO
ビームステアリング
多素子アンテナへの信号配線技術

実用システムを意識したトランシーバ技術の開発
PAN無線通信、Beyond 5Gモバイル通信システム