Connecting Minds. Exchanging Ideas.

The Coolest Ideas Under the Sun
SAN DIEGO 2023

WE4B-3

Student Paper Finalist

Broadband THz Switching with Extremely Low Insertion Loss and Superior Isolation

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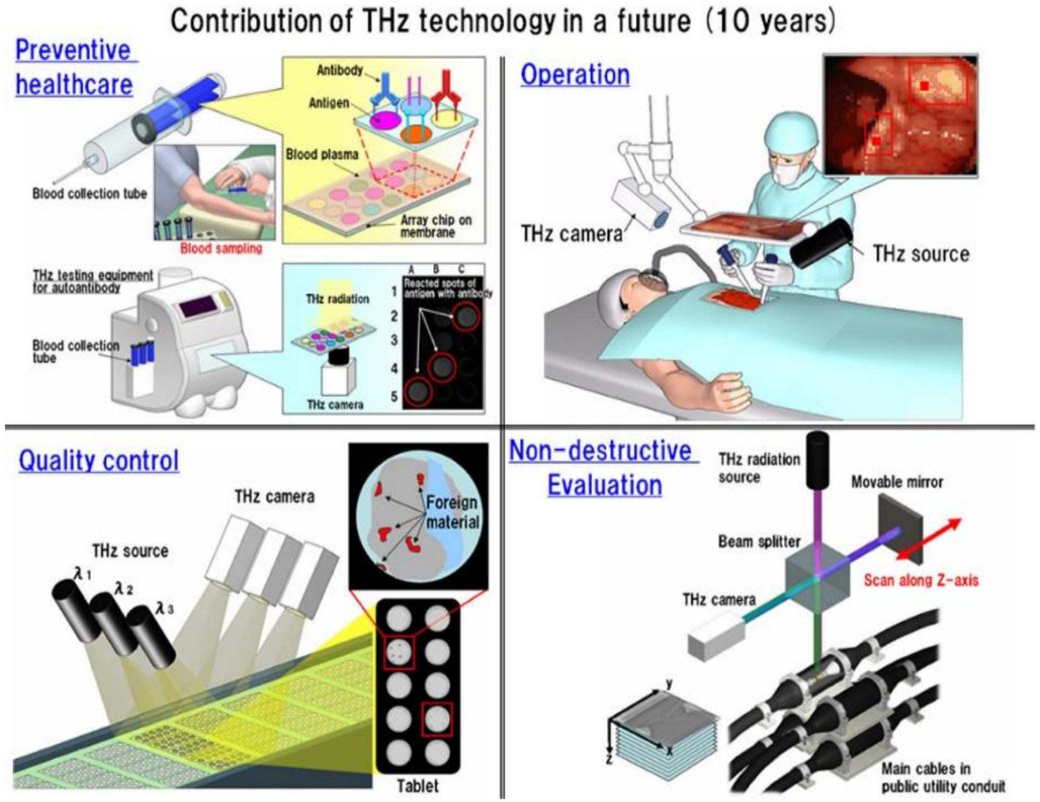
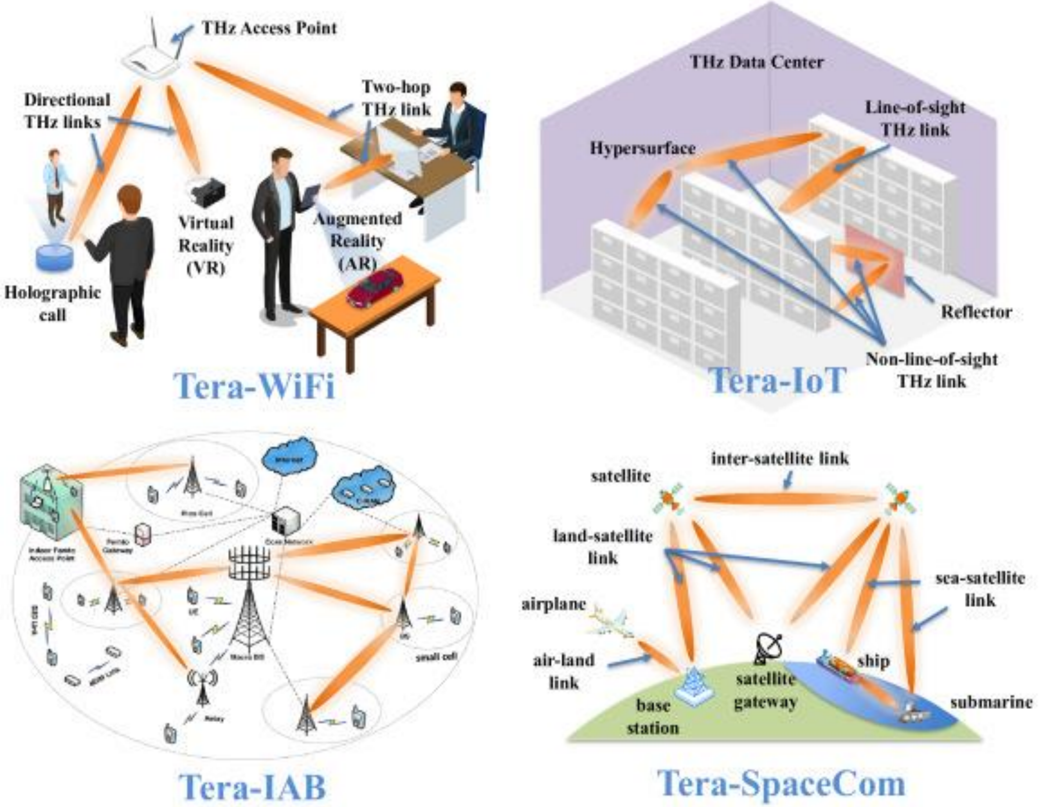
Outline

- Introduction and Motivation
  - Applications of THz wave
  - Switches for tunable/reconfigurable circuits, components and systems
  - Current switching technology
- Spatially-Resolved Photoconductivity Modulation in Semiconductors
- Switch Design, Modeling and Simulation
  - Non-contact coupling architecture design
  - Physics-based modeling and analysis
  - Full-wave simulation
- Prototype Demonstration and Performance Comparison
  - Measurement results and analysis
  - Performance comparison with state-of-art
- Future Work and Potential Applications
  - Tunable/reconfigurable bandstop filter
  - Switchable feeding network
- Conclusions

Applications of THz Waves

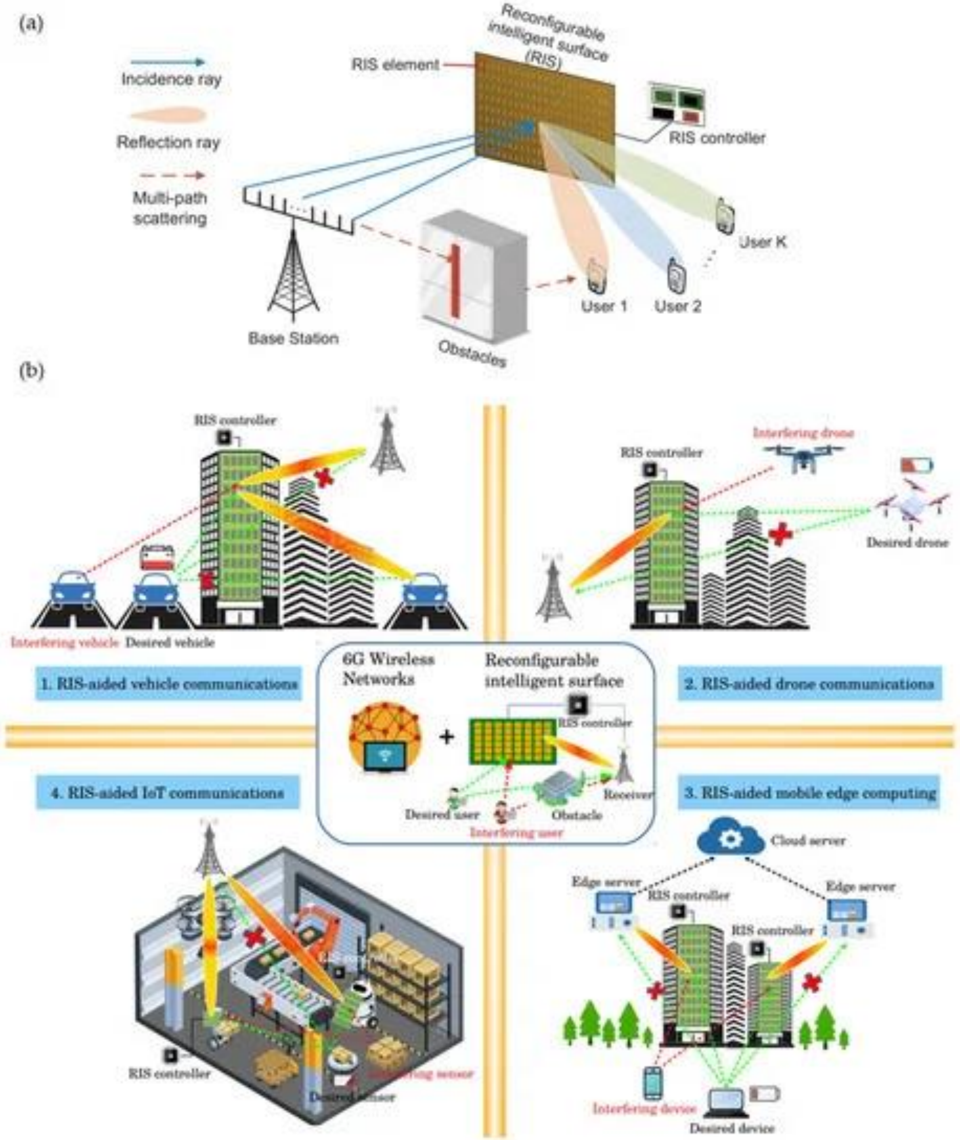




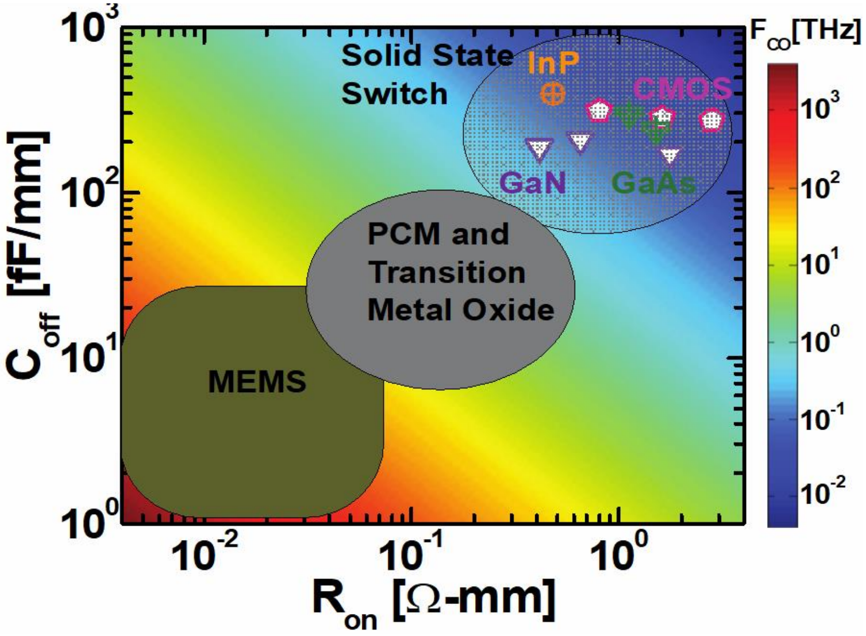
- THz sensing, imaging, spectroscopy
- THz is promising for short-range point-to-point wireless communication
- THz wireless links (6G or beyond) with potential data rate approaching 1 Tbps

THz Switches for Tunable/Reconfigurable Circuits, Components and Systems

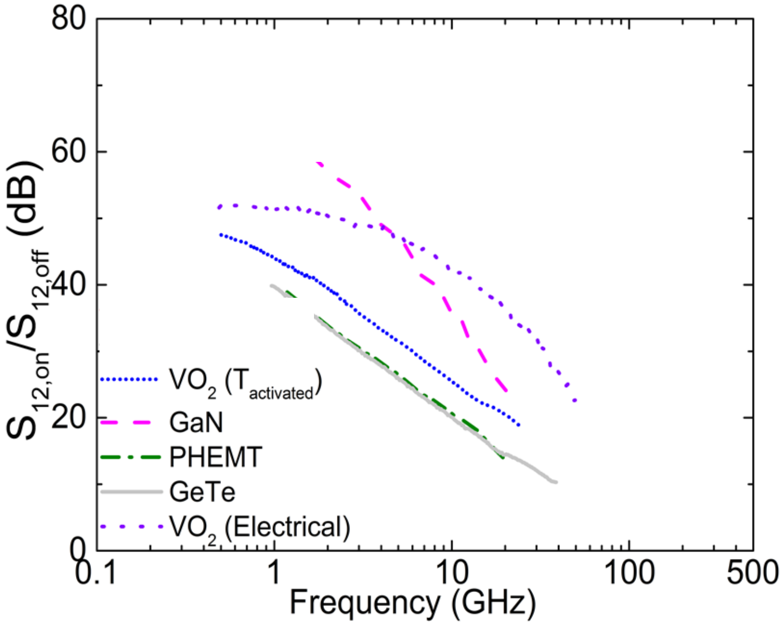
- Advanced Sensing and Imaging (e.g., spectroscopic imaging)
- Multiple-band transceiver
- Tunable filters in adaptive communication systems
- Reconfigurable frequency-selective surfaces
- Switch-based antennas/arrays (beam steering, beam forming, frequency tuning, etc.)

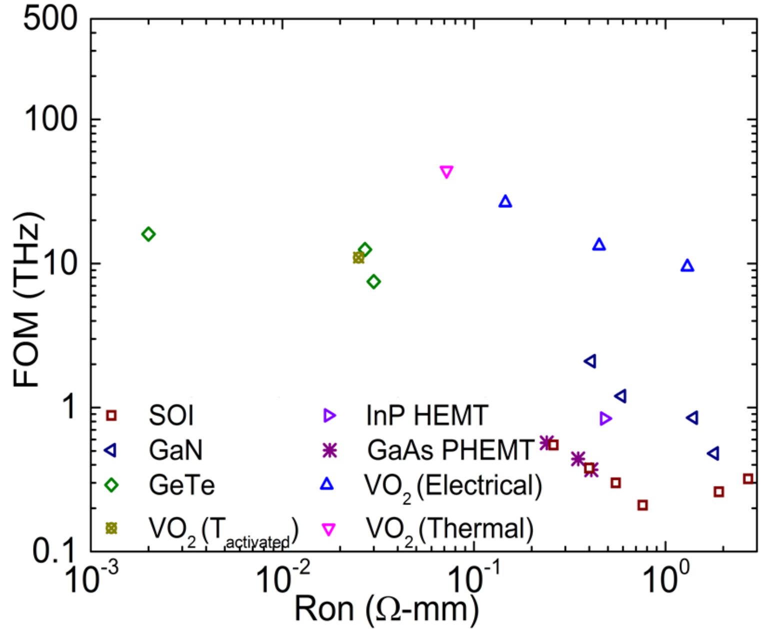


Current Switching Technology



$FOM = 1/(2\pi R_{ON} C_{OFF})$





- MEMS: fabrication complexity, low operation speed, and limited scaling
- Phase-change material: thermally driving and reliability issue
- Solid-state: low FOM and high insertion loss
- A Novel Technology for High Performance THz switching are required

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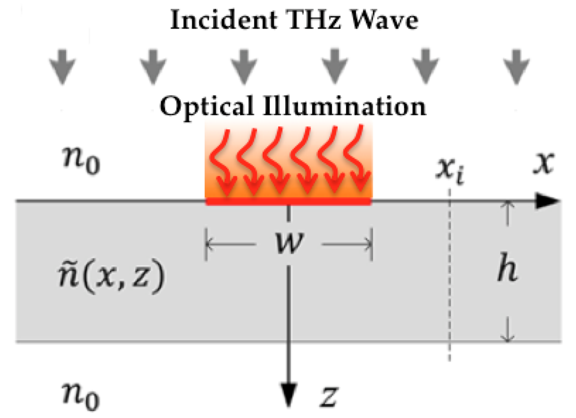
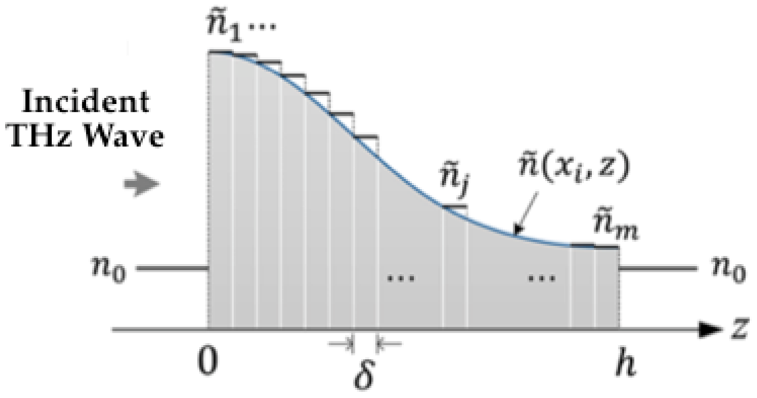
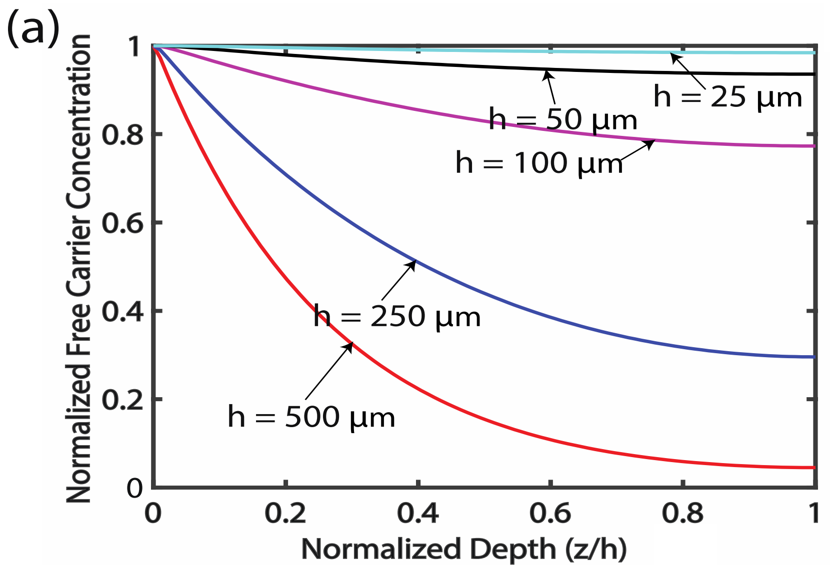
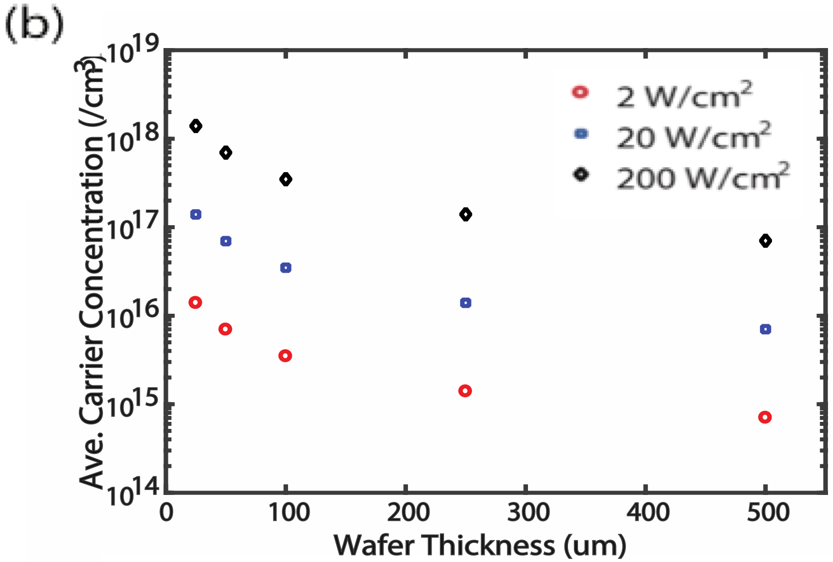
Theory and Modeling: Optically-Controlled Photoconductivity Modulation for THz Waves









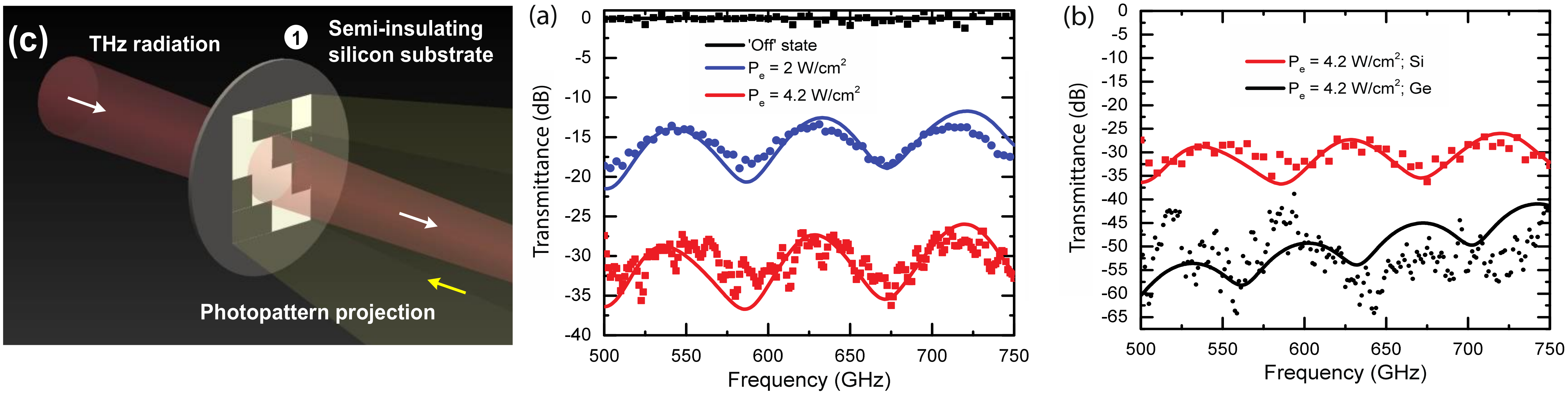
- Free carriers generated (photon energy > bandgap)
- Photoconductivity can be controlled
- THz transmission can be spatially modulated

- **Physics-based model:**

$$D_n \frac{d^2 n}{dz^2} + \frac{\alpha P(1-R)}{\hbar\omega} e^{-\alpha z} - \frac{n}{\tau_{eff}} = 0$$

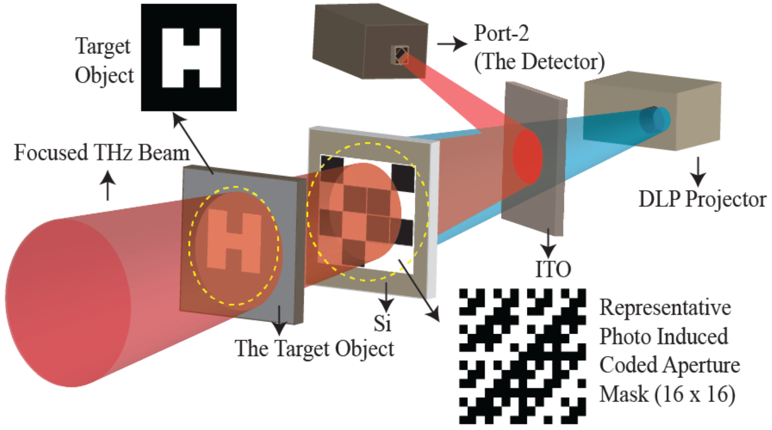
$$D_n \left.\frac{dn}{dz}\right|_{z=0} = D_n \left.\frac{dn}{dz}\right|_{z=H} = 0$$

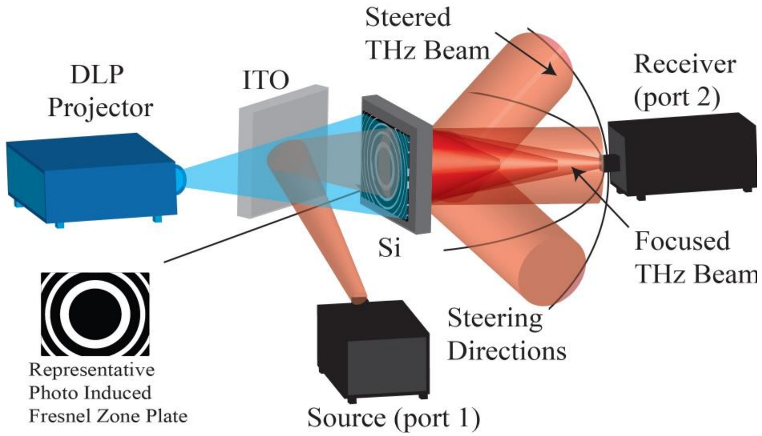
Theory and Modeling: Experiment Verification

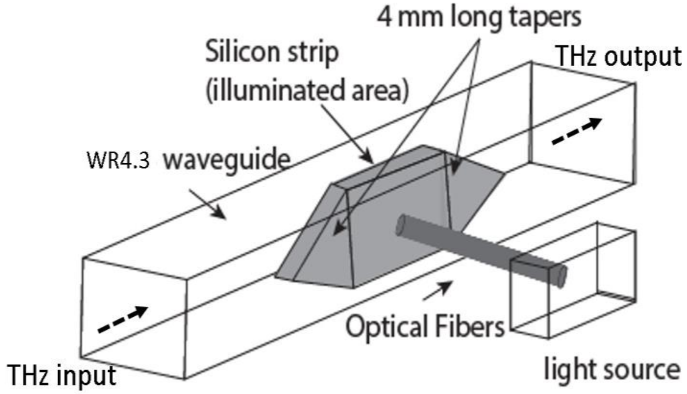


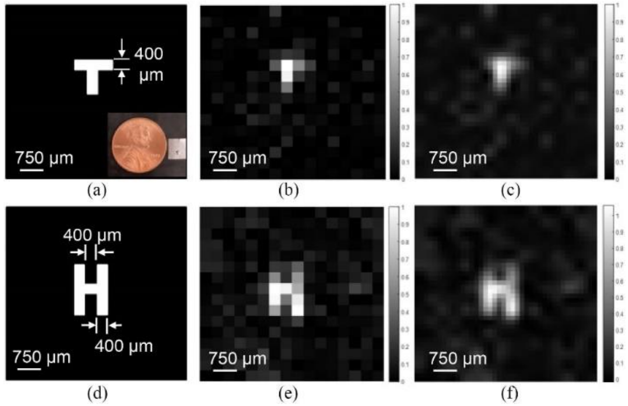
- Photo patterns projected on Si and Ge wafers
- Photoconductivity is modulated by changing the light intensity
- Higher light intensity leads to higher modulation depth
- Ge offers a higher modulation depth than Si

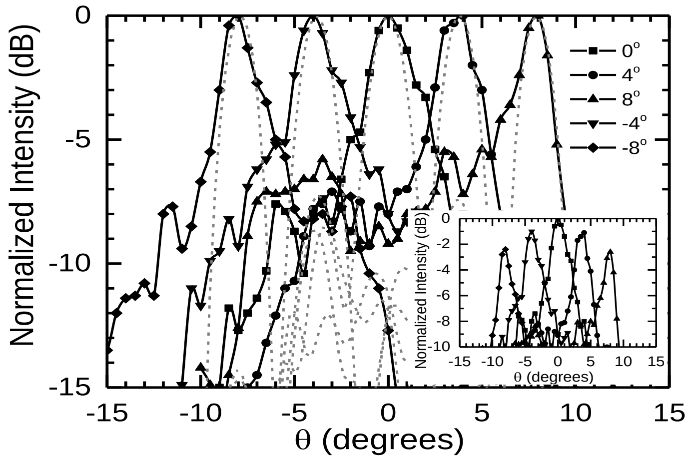
Application Demonstration

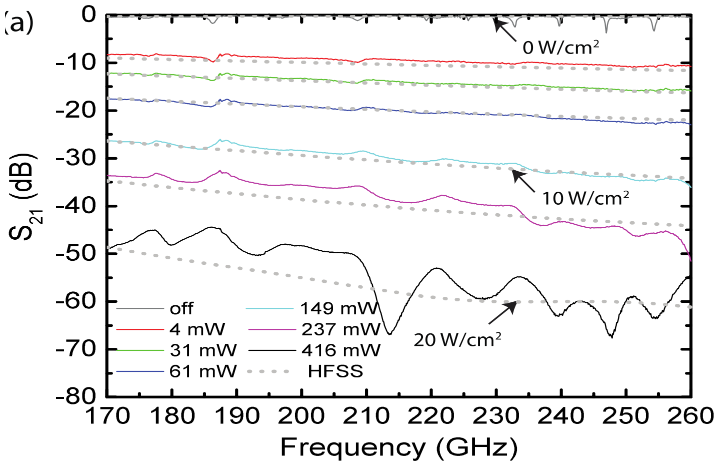












- ❖ Coded aperture imaging
- ❖ Beaming steering
- ❖ Waveguide attenuator

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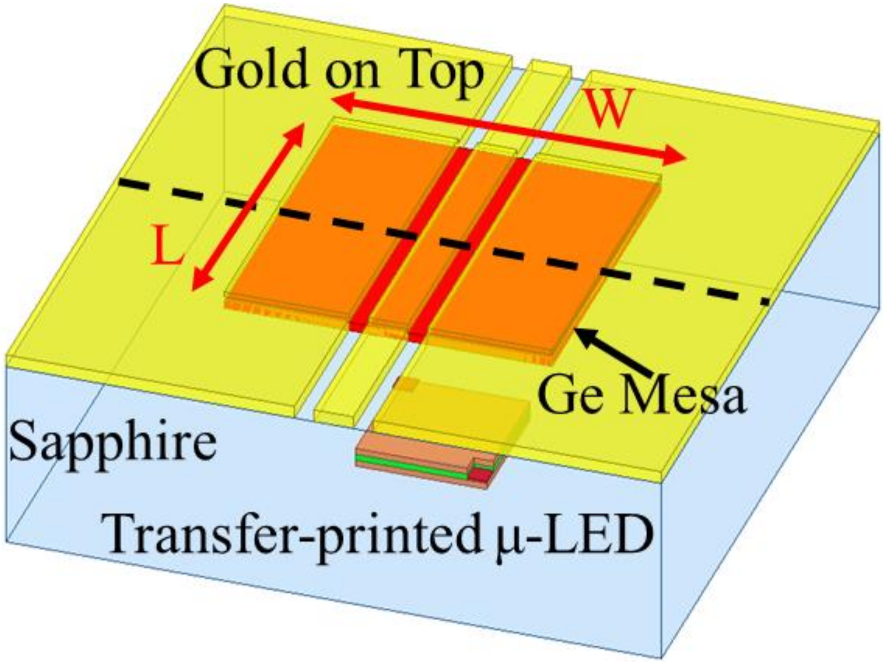
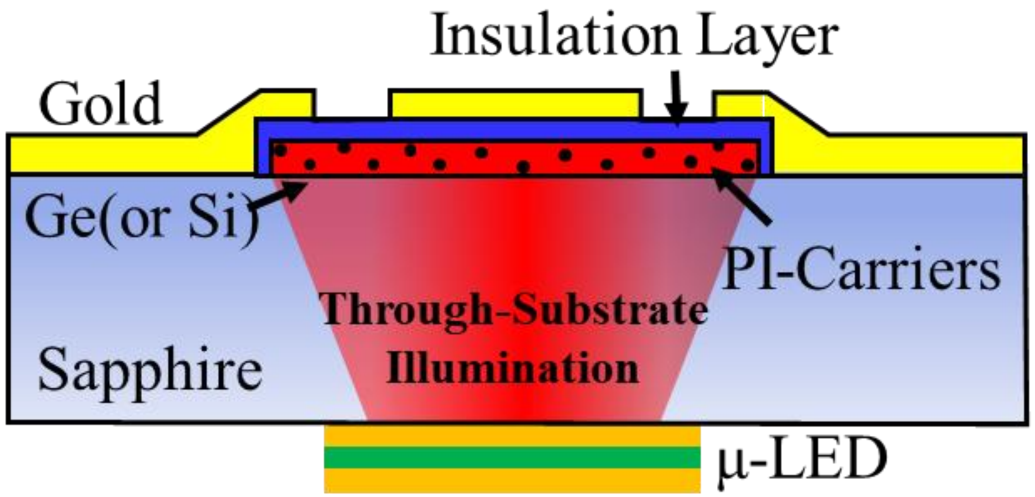
Switch Design and Configuration Using Unconventional Device Architecture

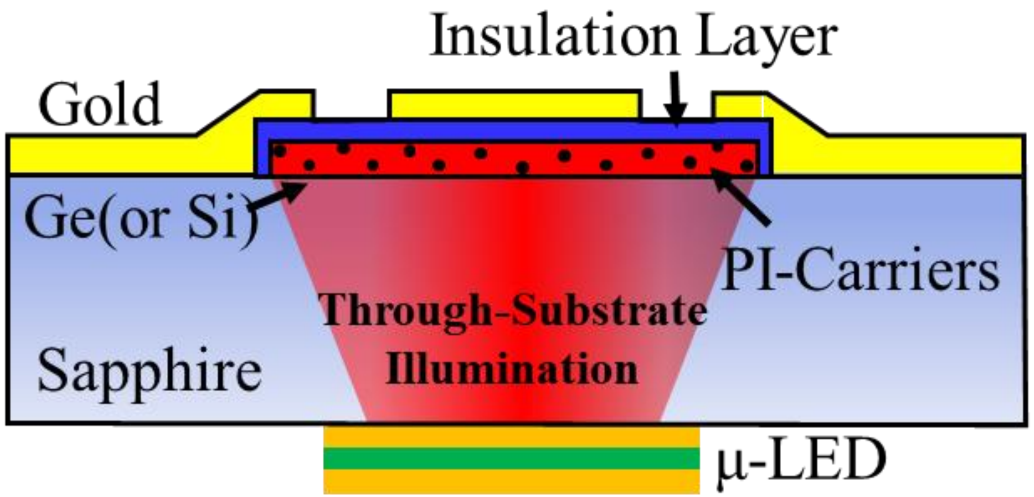




- CPW with shunt configuration for potential low IL and high isolation
- Insulation layer to form non-contact configuration
- Capacitive coupling for reducing contact resistance
- Transparent sapphire is used for through-substrate illumination
- Potential integration of micro-LED for operation

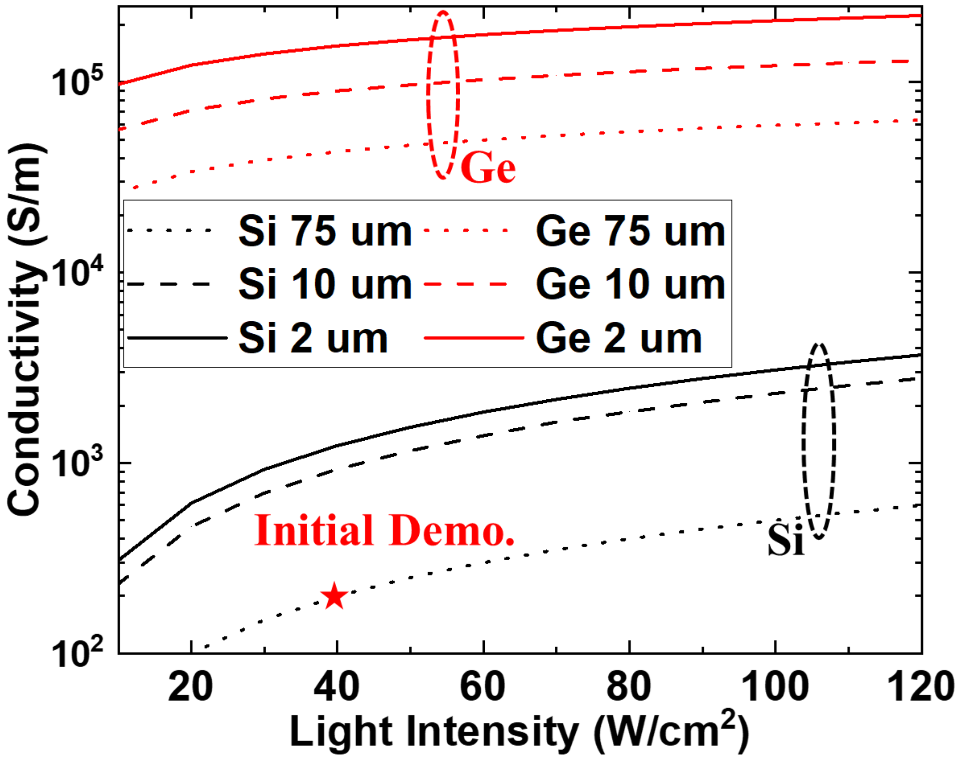
Advantages for Non-contact Switch Configuration

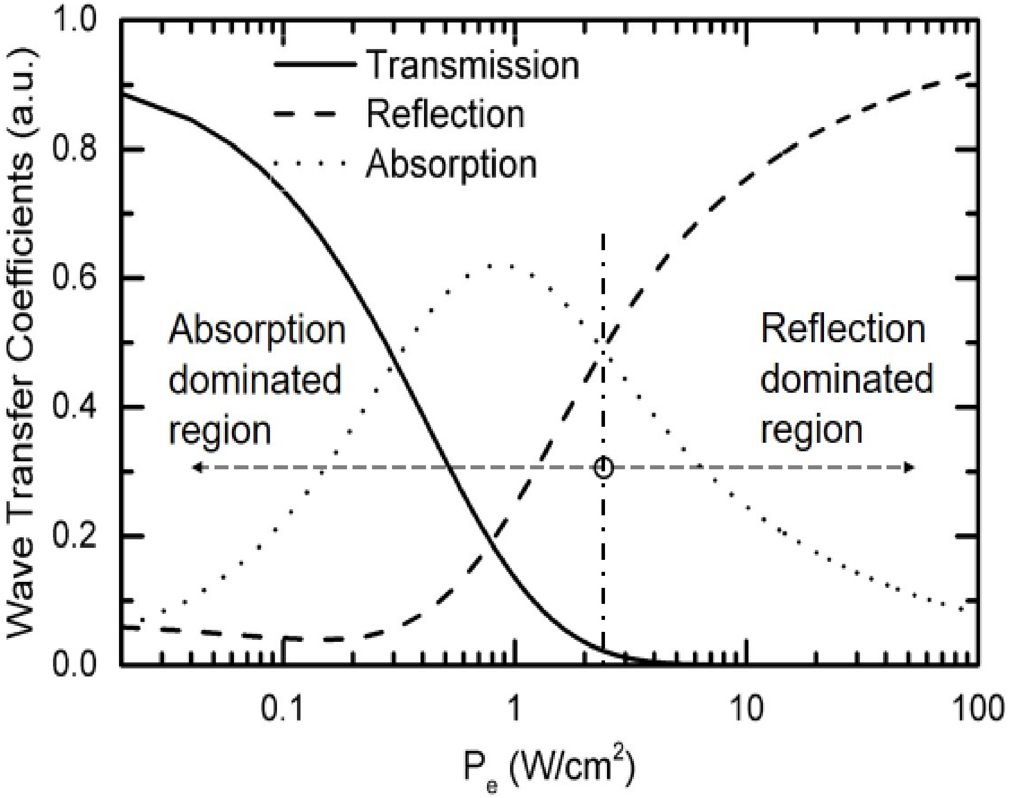
- Photo-induced free carriers generated in the semiconductors
- Avoids electron diffusion at the metal-semiconductor interface
- Reduces rapid surface recombination
- Capacitively coupling avoids contact resistance
- High carrier concentration can be maintained
- Enhanced achievable photoconductivity
- Maximizes switching performance at THz



Non-contact architecture

Physics-Based Modeling and Analysis

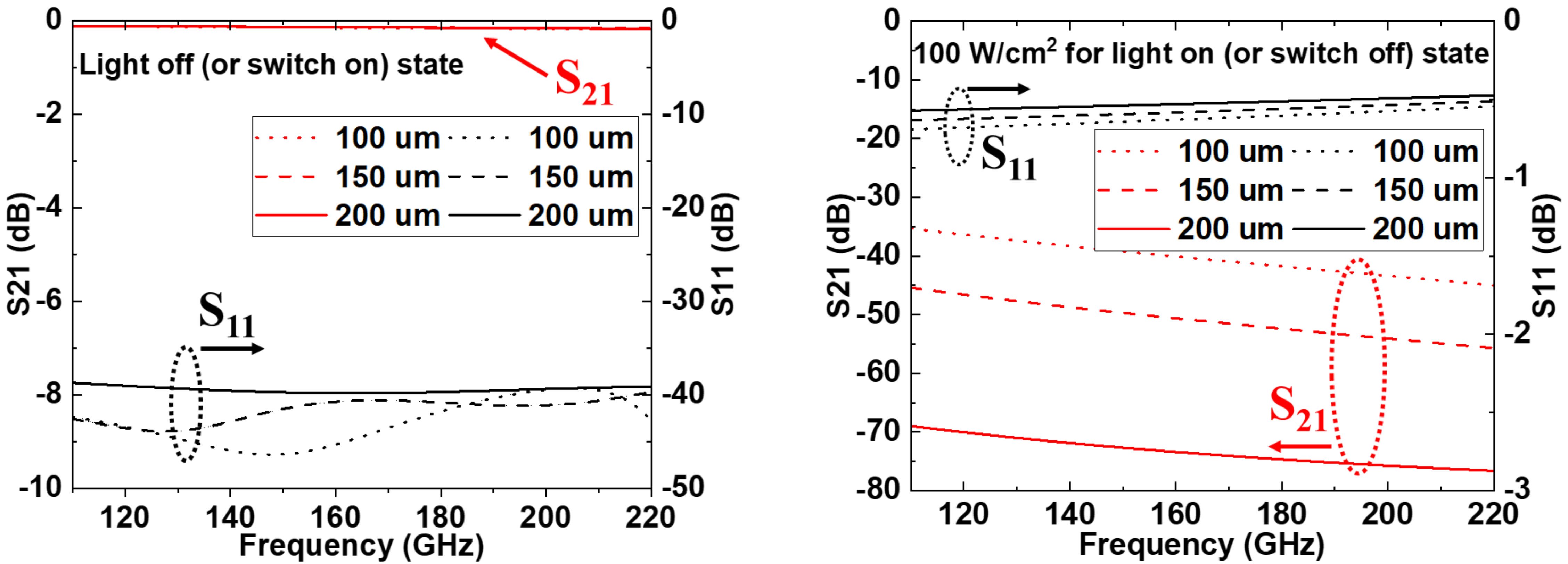




- 0.5 μs and 1 ms carrier lifetime for Si and Ge, respectively
- Auger recombination leads to saturation

- Semiconductor first becomes a lossy dielectric with increasing light intensity

Full-Wave Simulation



- On-state insertion loss <0.2 dB
- Off-state isolation > 70 dB (L=200 µm)
- Light intensity of 100 W/cm^2

IMS
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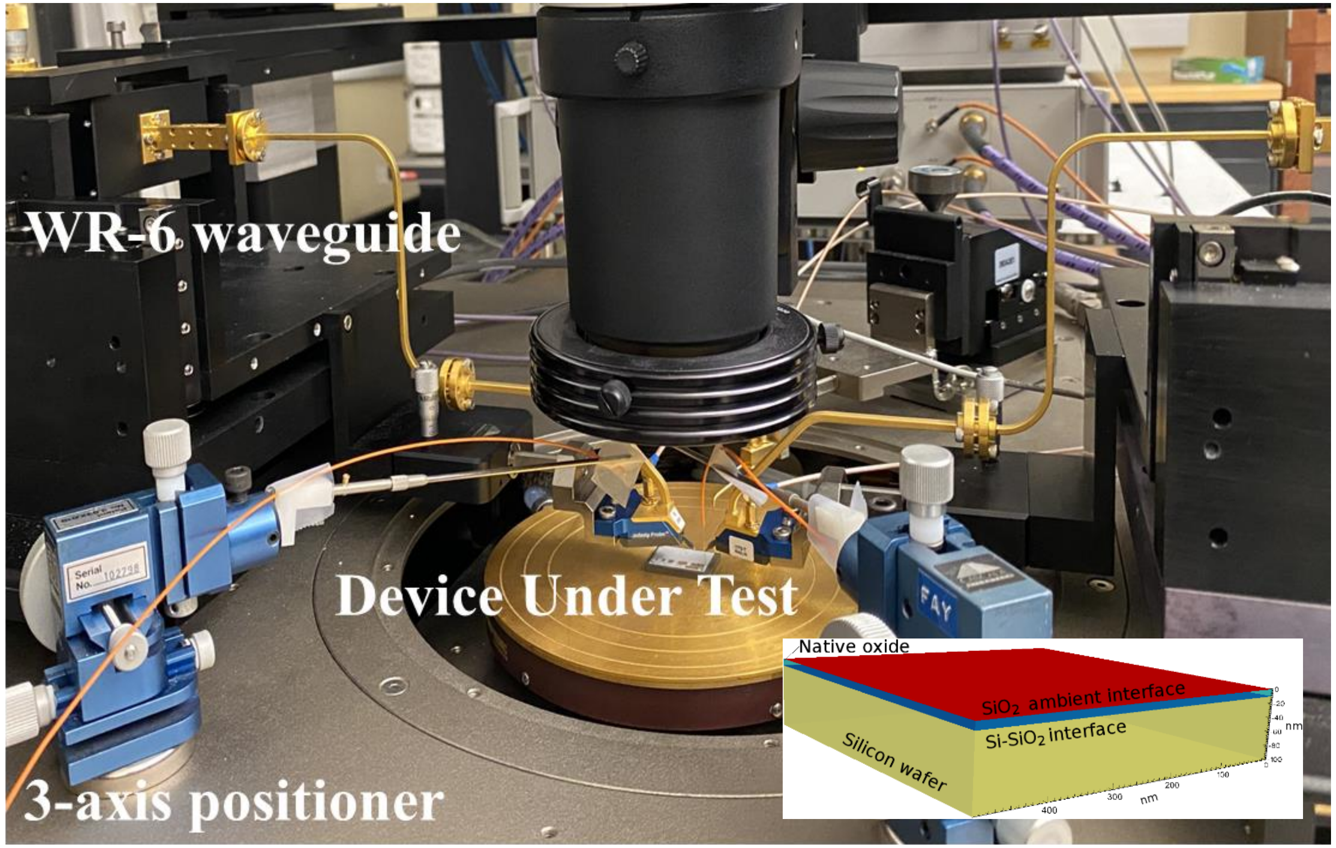
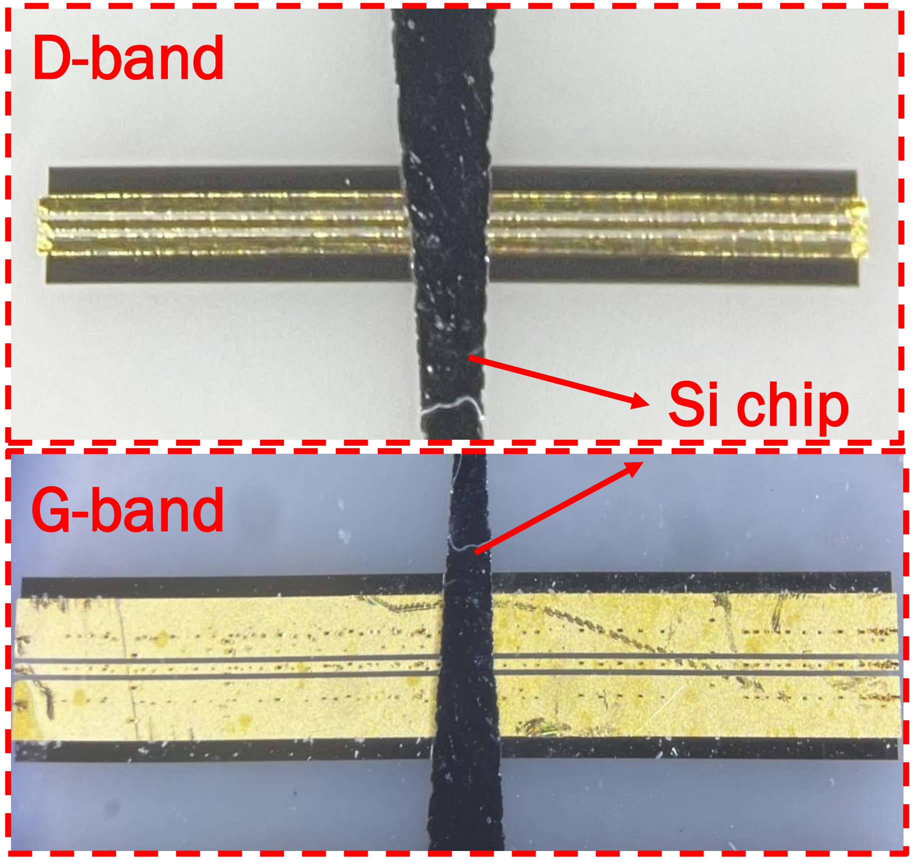
Prototype Demonstration

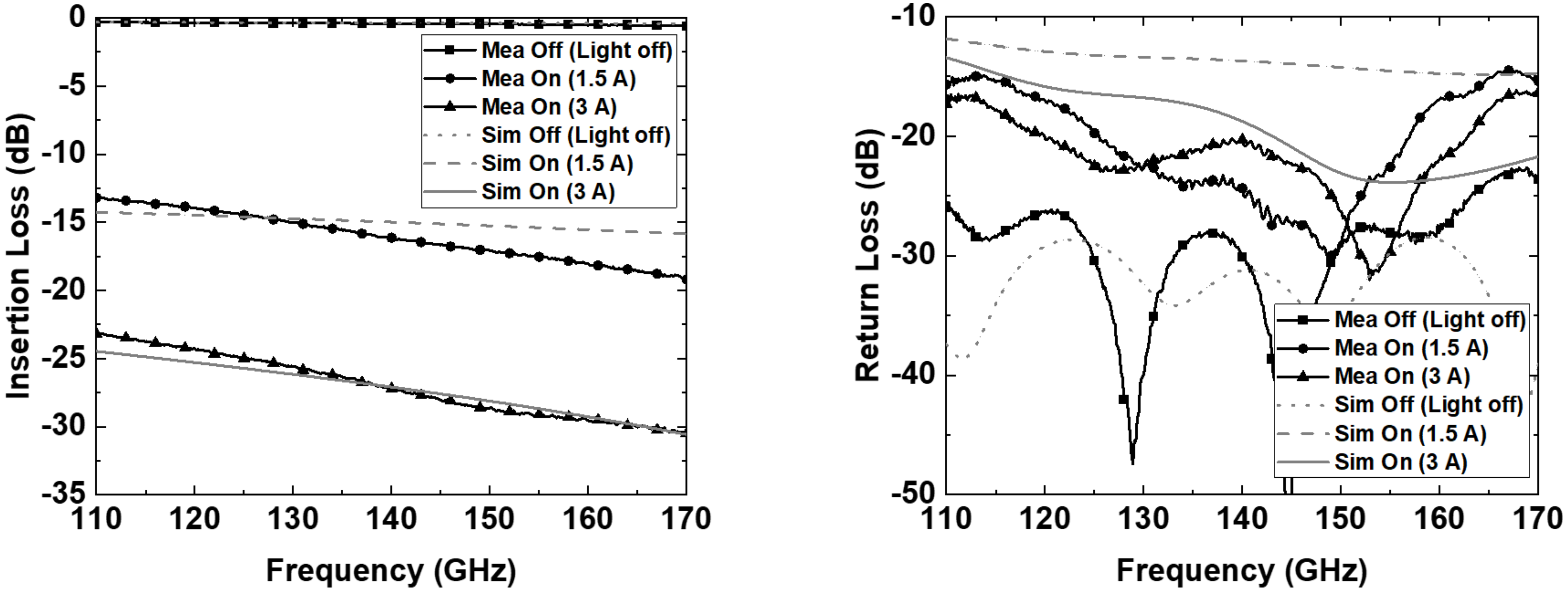




- On-wafer measurement
- Two extenders were used
- With native oxide serving as the insulation

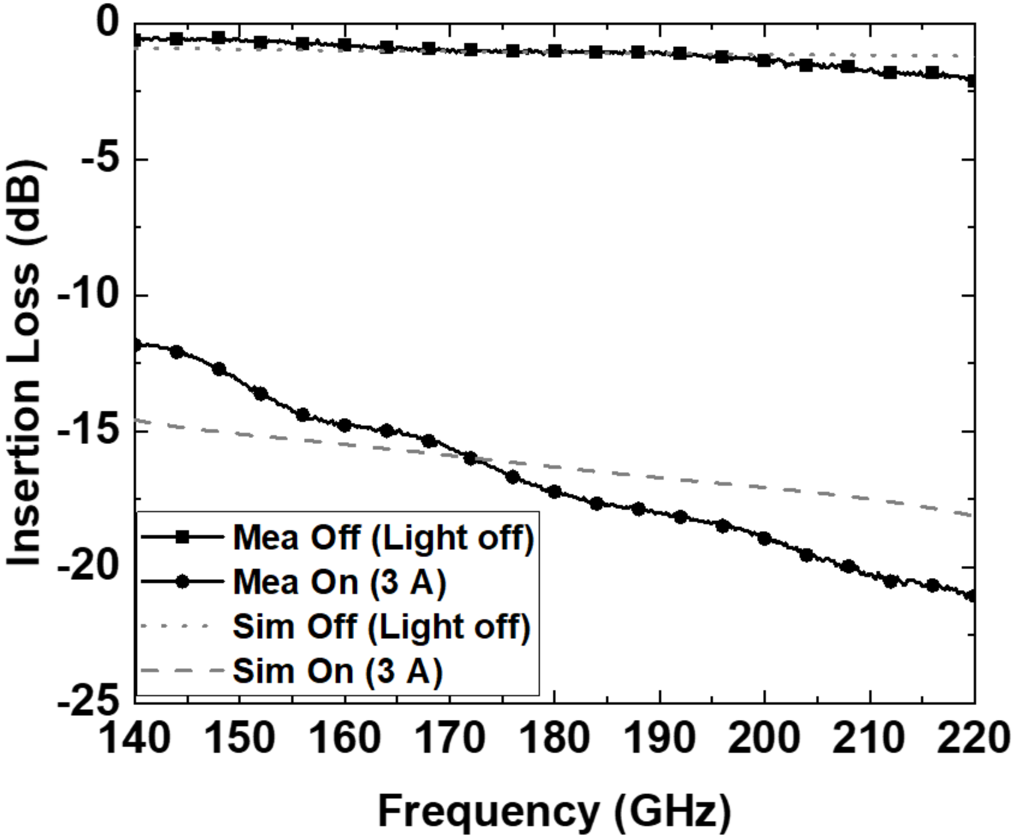
- Silicon chip of ~73 μm was used
- Estimated Si area of 5 mm^2
- Insulator: Si native oxide (~2 nm)

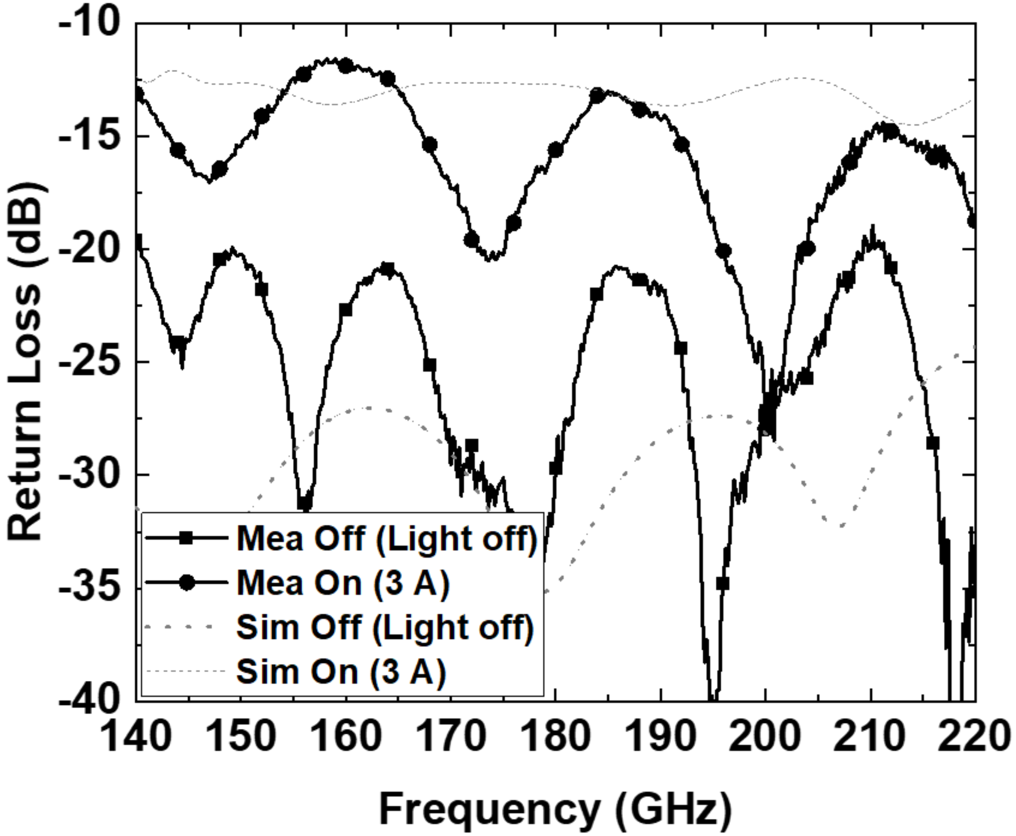
Results and Analysis: D-Band



- On-state insertion loss < 0.4 dB
- Off-state isolation increases with increasing of driving current
- Isolation of 32 dB has been achieved at 170 GHz
- S_{11} remains low level due to power absorption of semiconductor

Results and Analysis : G-Band





- On-state insertion loss (IL) < 1 dB (This can be improved with matching design)
- Off-state isolation(I_{so}) is ~22 dB at 220 GHz
- Low-reflection property caused by lossy dielectric

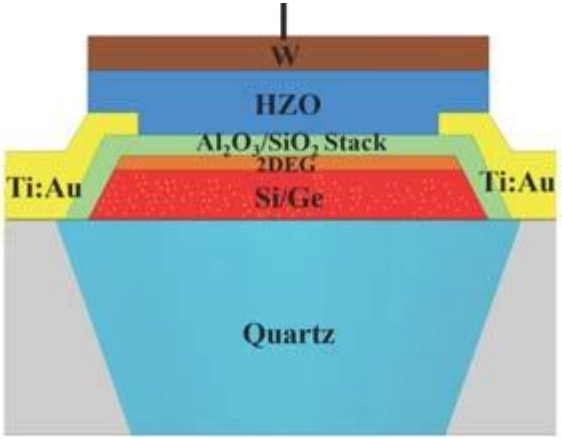
Performance Comparison

	Technology	Frequency(GHz)	Insertion loss/Isolation (dB)	Size(mm^2)
This work (Initial demo.)	Optical	@170 @220	0.4/32 2/22	~0.04
This work (With optimization)	Optical	110-220	0.2/70	0.04
MWCL, 2021 [1]	CMOS	@170	~3/~35	0.163
IMS, 2017 [2]	CMOS	@170	2.4/~30	0.145
MWCL, 2016 [3]	MEMS	@170	~1.9/20	N.A

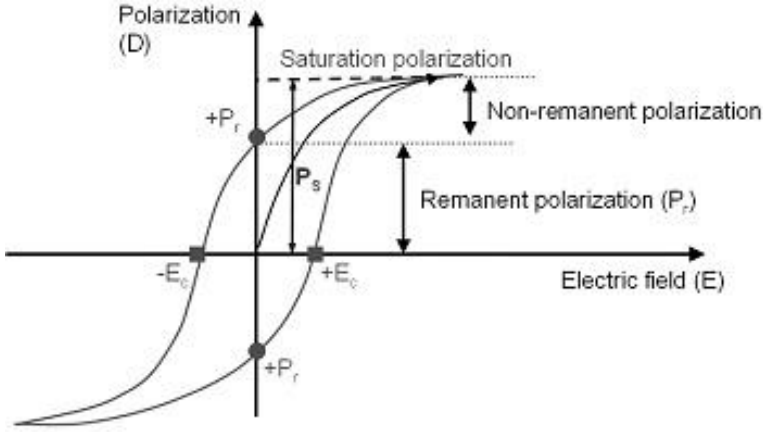
[1] L. Wu, H. Y. Hsu and S. P. Voinigescu IEEE MWCL
[2] Y. Wang et al.,2017 IMS
[3] S. Tolunay Wipf, A. Göritz, M. Wietstruck, C. Wipf, B. Tillack and M. Kaynak, *IEEE MWCL*

Discussion

- Fully integrated THz switches with μ-LEDs can be realized for smaller size and higher performance
- Lower on-state insertion loss (e.g., < 0.2 dB) is expected with further impedance matching
- Off-state isolation of 70 dB can be achievable by using Ge
- The operation frequency can be scaled up to 500-750 GHz based on previous experiment results
- The power consumption could be significantly reduced by integrating FE (Ferroelectric) latching for non-volatile switching

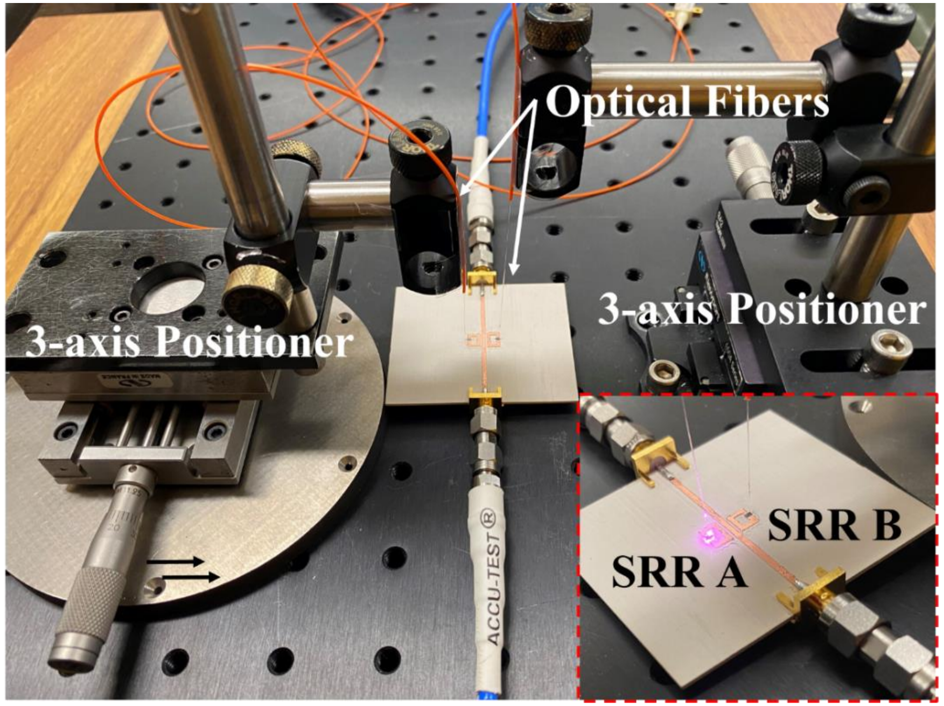


FE-Assisted Non-volatile switching

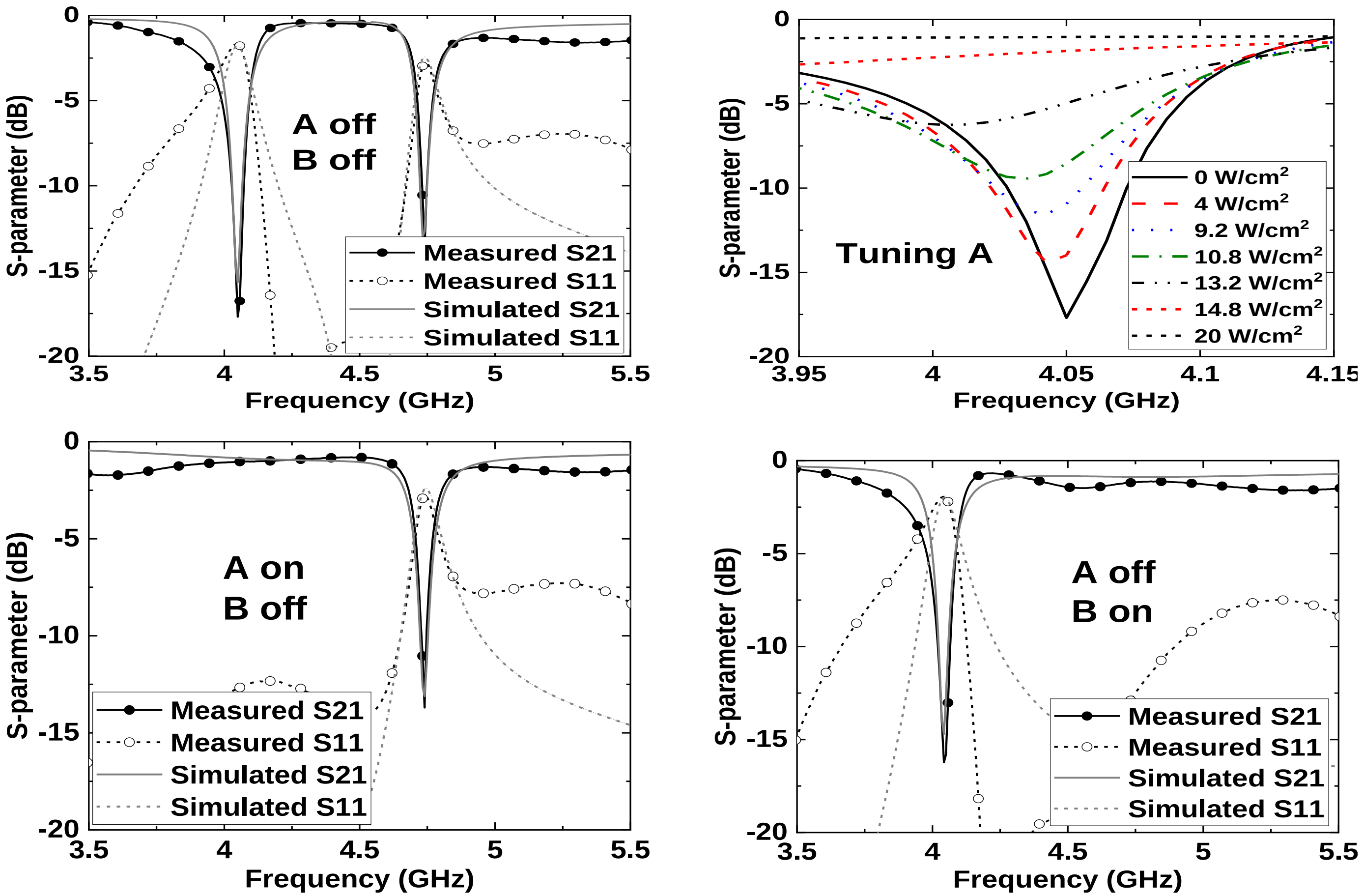


Hysteresis effect in FE material (e.g., HZO)

Potential Applications: Tunable/Reconfigurable THz Filters



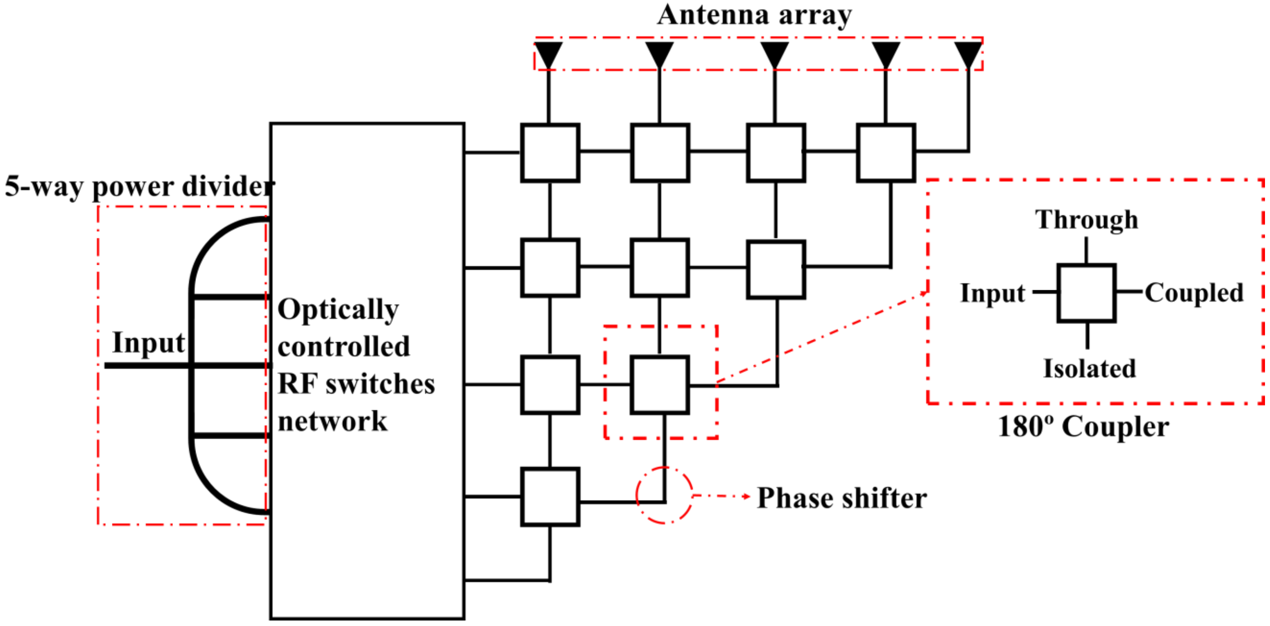
Initial prototype at microwave frequency showing high performance and strong versatility



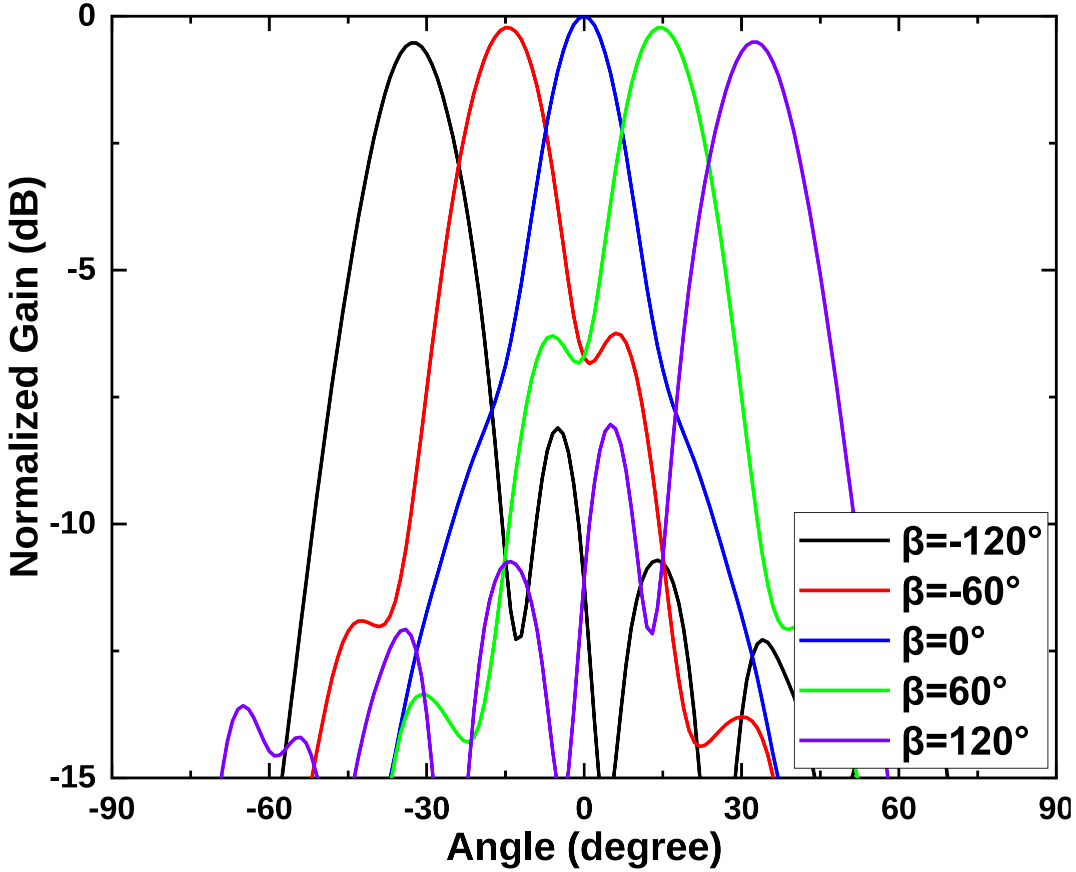
- Strong tunability and reconfigurability
- Multiple functionality
- Scalable to THz frequencies

Potential Applications: THz Beam Steering

❖ Switch-based feeding network for THz phased arrays



- Phased array fed by matrix network
- Reconfigurable Input excitation controlled by switches
- Beam steering and forming can be achieved



Simulation results for switch-based beam steering

Conclusions

The novel THz switch features:

- Extremely low insertion loss (0.4 dB at 170 GHz, 0.2 dB is potentially achievable with matching design)
- Superior isolation (32 dB at 170 GHz, and 70 dB is expected with Ge)
- Compact size (~0.04 mm^2)
- Broadband operation (from 110 GHz to 220 GHz)
- Scalability (the operation frequency can be scaled up to 500 GHz and 1 THz)
- Potential for advanced THz circuits (e.g., tunable bandstop filters and switch-based networks)