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Advanced Technologies for Beyond 5G

-- 60GHz- & 300GHz-Band Millimeter-wave/THz-wave Circuits and Antennas For High-Speed Wireless Communications --

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Outline of This Talk

- **Brief Background of 5G**
- **mmW/THz-wave for 5G and Beyond**
  60GHz- and 300GHz-Band as two examples
- **Some Key Technologies (Using mmW/THz)**
  1. **Measurement**
  2. **Devices, Circuits and Antennas**
  3. **High-speed Wireless Systems**

mmW or mm-Wave: Millimeter-wave

mmW/THz-wave for 5G and Beyond

- **More Frequency Resource (Bandwidth)**

  5G and Beyond, require much more frequency (bandwidth) to achieve high data rate.

→ **Millimeter-wave (mmW) & THz-wave**

  They have bandwidth available. Ex. 9GHz at 60GHz-band, 50GHz at 300GHz-band.

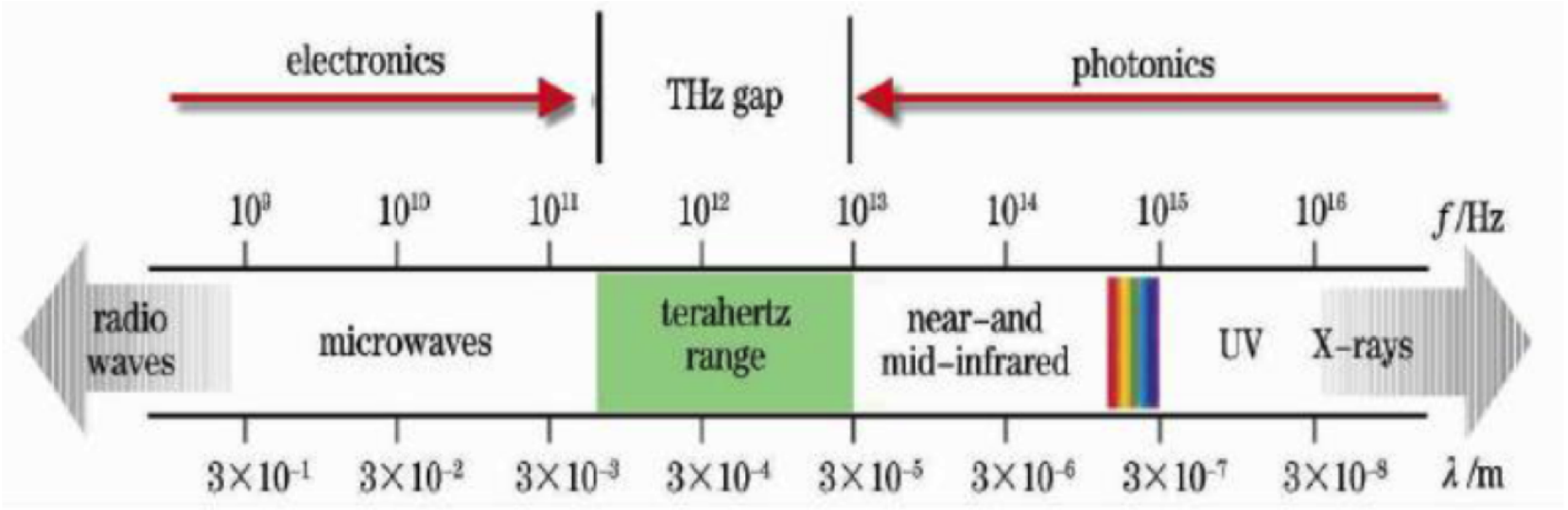
- **Compactness for Antenna/Massive MIMO**

→ **Millimeter-wave & THz-wave**

  They have short wavelength. Ex. 5mm at 60GHz-band, 1mm at 300GHz-band.

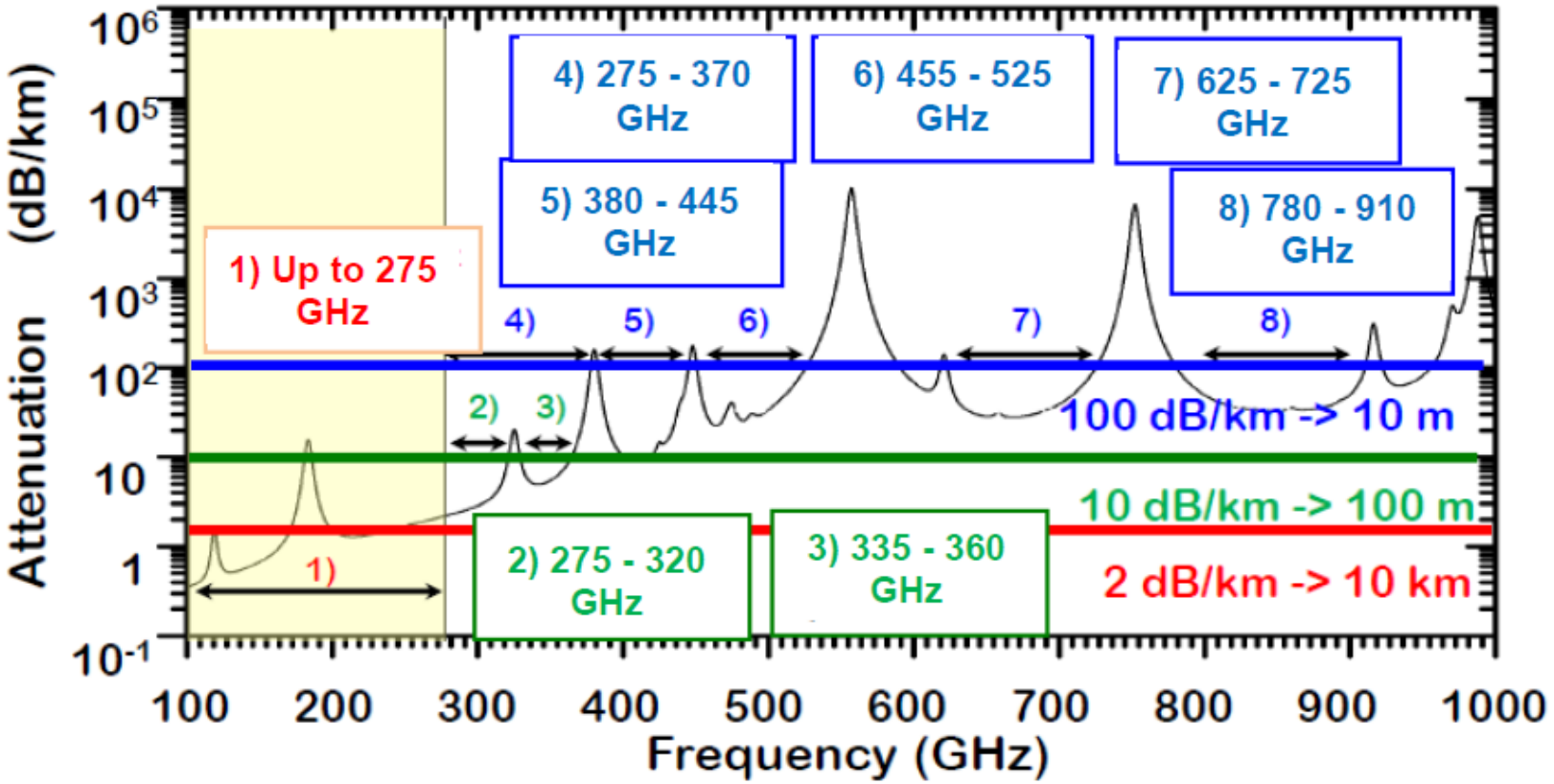
Millimeter-wave/THz Spectrum

- **Millimeter-wave/THz-wave, Freq. & Wavelength**
- **Millimeter-wave: 30 GHz ~ 300 GHz**
  (Wavelength: 10 mm ~ 1mm)
- **THz-wave: 300 GHz ~ 3 THz**
  (Wavelength: 1 mm ~ 0.1mm)



Millimeter-wave/THz-wave Spectrum

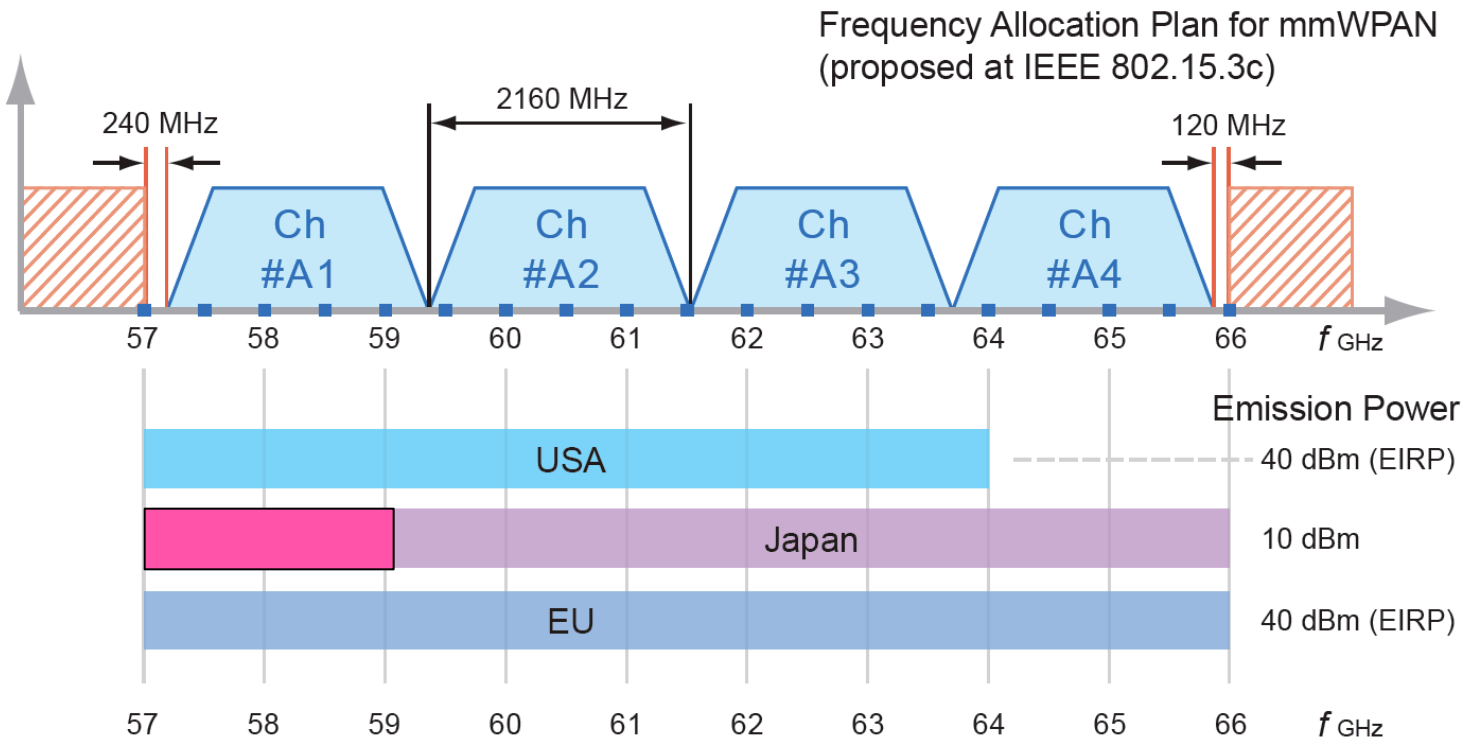
Available contiguous bandwidth in the frequency range from 100 GHz to 1000 GHz



THz communication has unique advantages which most microwave and laser communication don't have.

Unlicensed-60GHz-Band for IEEE 802.15.3c/11ad

- mmWPAN: Millimeter-wave Wireless Personal Network



- IEEE Standard Working Group for mmWPAN: 802.15.3c
  http://www.ieee802.org/15/pub/TG3c.html

300GHz-Band Frequency Allocation

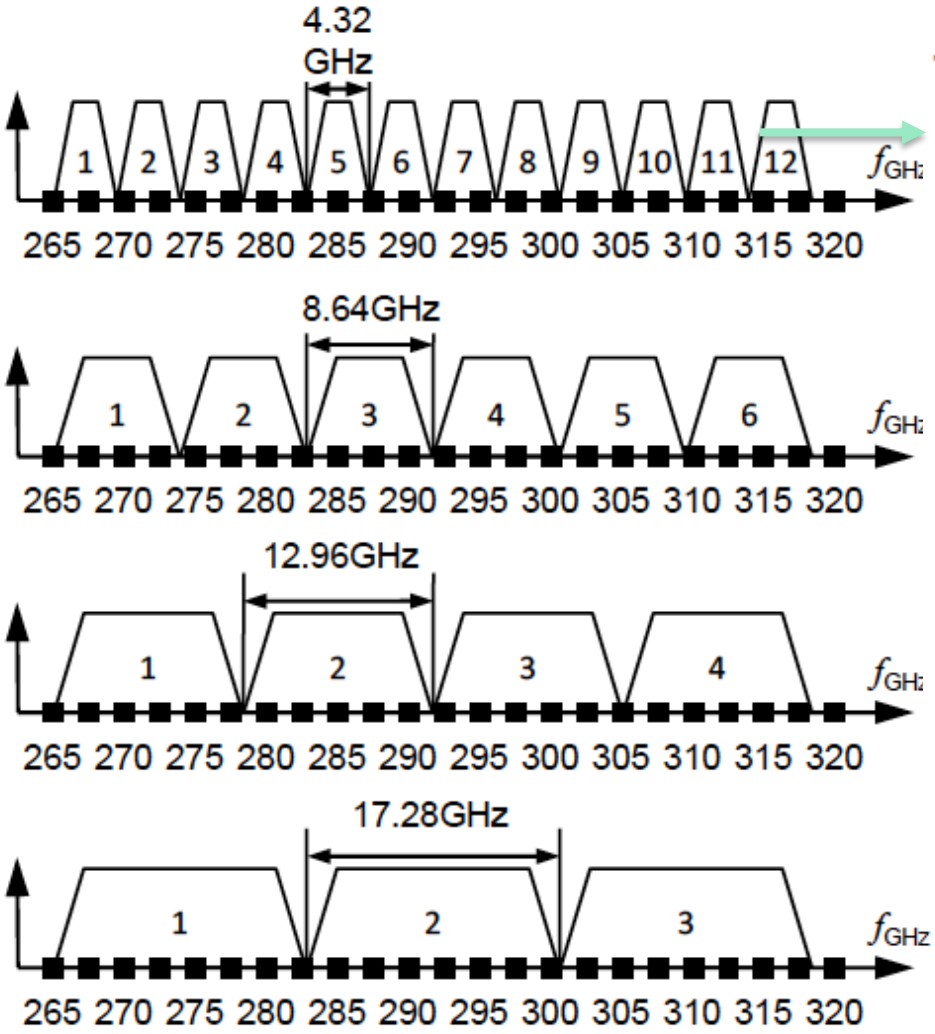


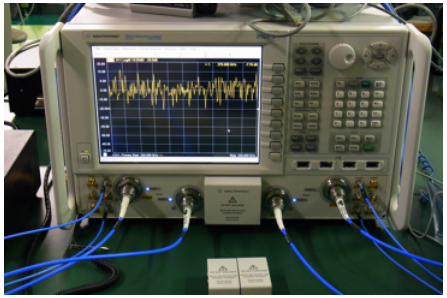
TABLE I. CHANNEL ALLOCATION TABLE FOR 4.32GHZ BANDWIDTH

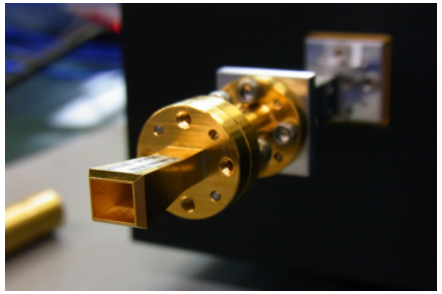
Channel Number	Low Freq. (GHz)	Center Freq. (GHz)	High Freq. (GHz)
1	265.68	267.84	270.00
2	270.00	272.16	274.32
3	274.32	276.48	278.64
4	278.64	280.80	282.96
5	282.96	285.12	287.28
6	287.28	289.44	291.60
7	291.60	293.76	295.92
8	295.92	298.08	300.24
9	300.24	302.40	304.56
10	304.56	306.72	308.88
11	308.88	311.04	313.20
12	313.20	315.36	317.52

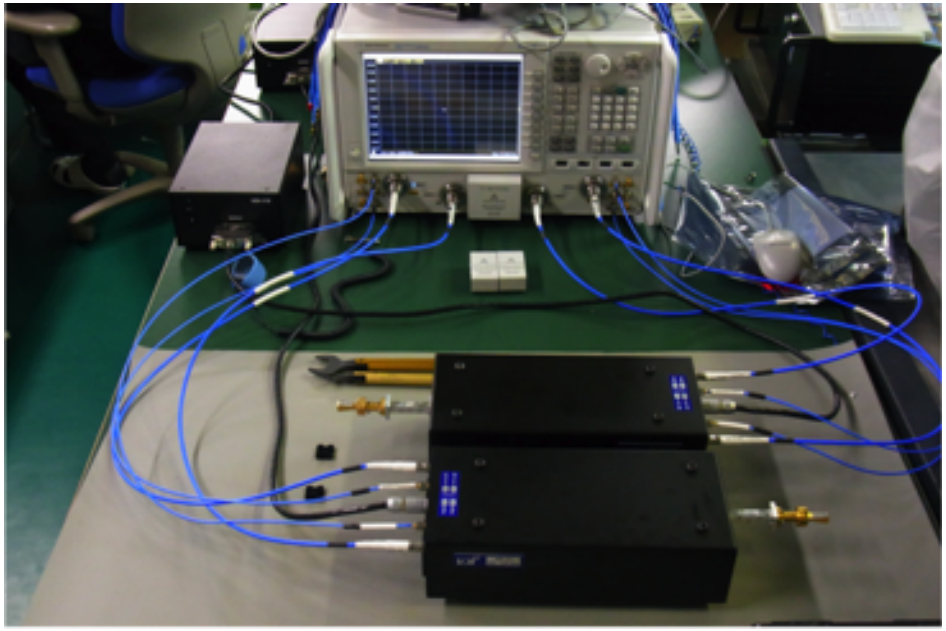
Fujishima, Channel Allocation of 300GHz Band for Fiber-Optic-Speed Wireless Communication, AP-RASC2016.

Some Facilities for mmW/THz R&D

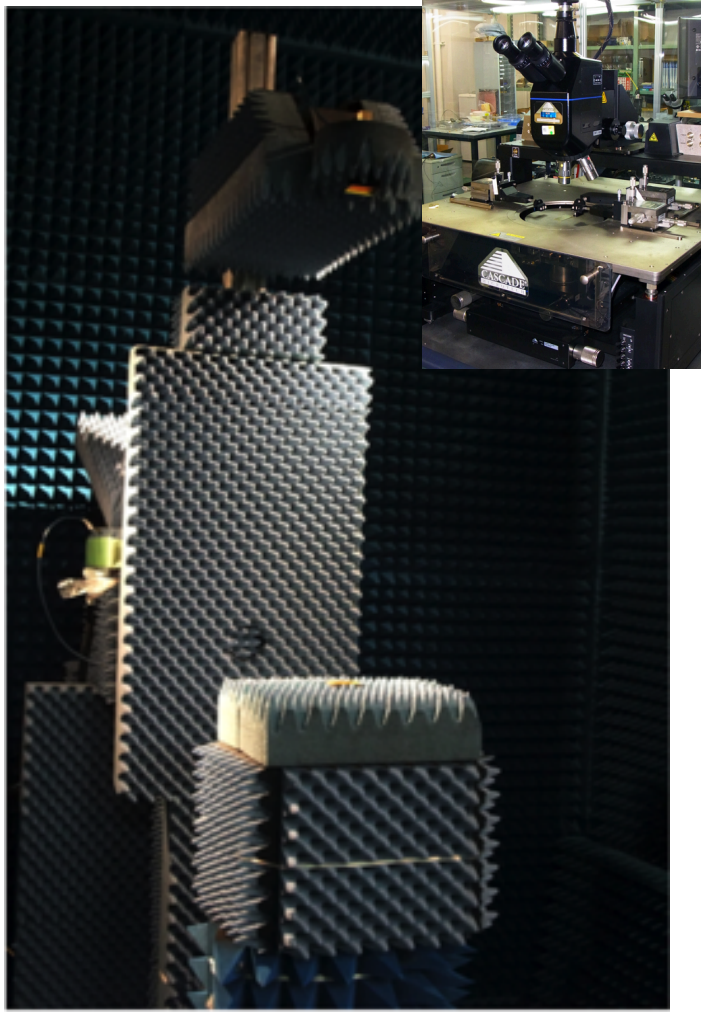
- For mmW/THz-wave devices and Antenna
- 70GHz-4-Port VNA & 300GHz－Expander



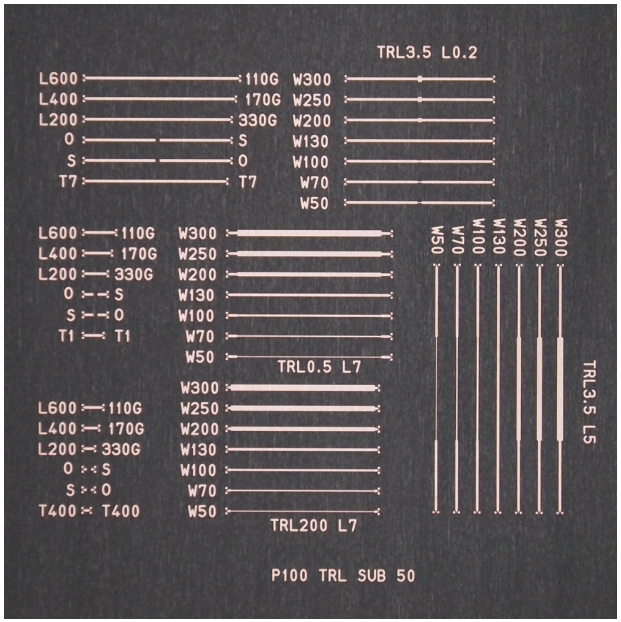




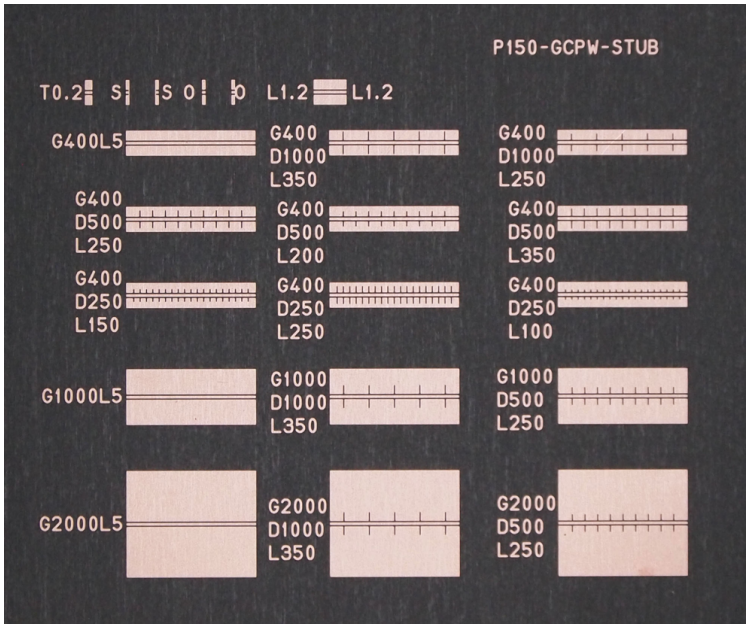
- Anechoic Chamber



Fabricated Transmission Lines on LCP



Microstrip Lines



Coplanar Waveguides

Jing Gao, Akifumi Kasamatsu, Fumihide Kojima, and Keren Li, "Performance of Transmission Line on Liquid Crystal Polymer (LCP) from 220GHz to 330GHz," 8th UK, Europe, China Workshop on Millimeter Waves and THz Technologies (UCMMT 2015), National Museum of Wales, Cardiff, UK, Sept. 14-16, 2015.

Keren Li, and Jing Gao, "Measurement of Transmission Line Characteristics Using Linear Resonator Technique in Millimeter-wave/Terahertz-wave regions," Session MO1B, Millimeter Wave & THz Components, 2015 Asia-Pacific Microwave Conference (APMC2015), Nanjing. P. R. China, December 6-9, 2015.

Summary of Line Performance @ 300 GHz-Band

Width (MSL) (micrometer)	ε_{reff}	Total Loss (dB/mm)	Characteristic Impedance (Ω)
43.8	2.41	0.83	86
63.6	2.47	0.85	73
93.6	2.53	0.83	60
124.2	**2.58**	**0.87**	**52**
144.2	**2.61**	**0.86**	**48**
193.6	2.67	0.88	39

LCP: Liquid Crystal Polymer,
Er = 2.95, tand = 0.0022@10GHz from data sheet
MSL: Microstrip Line

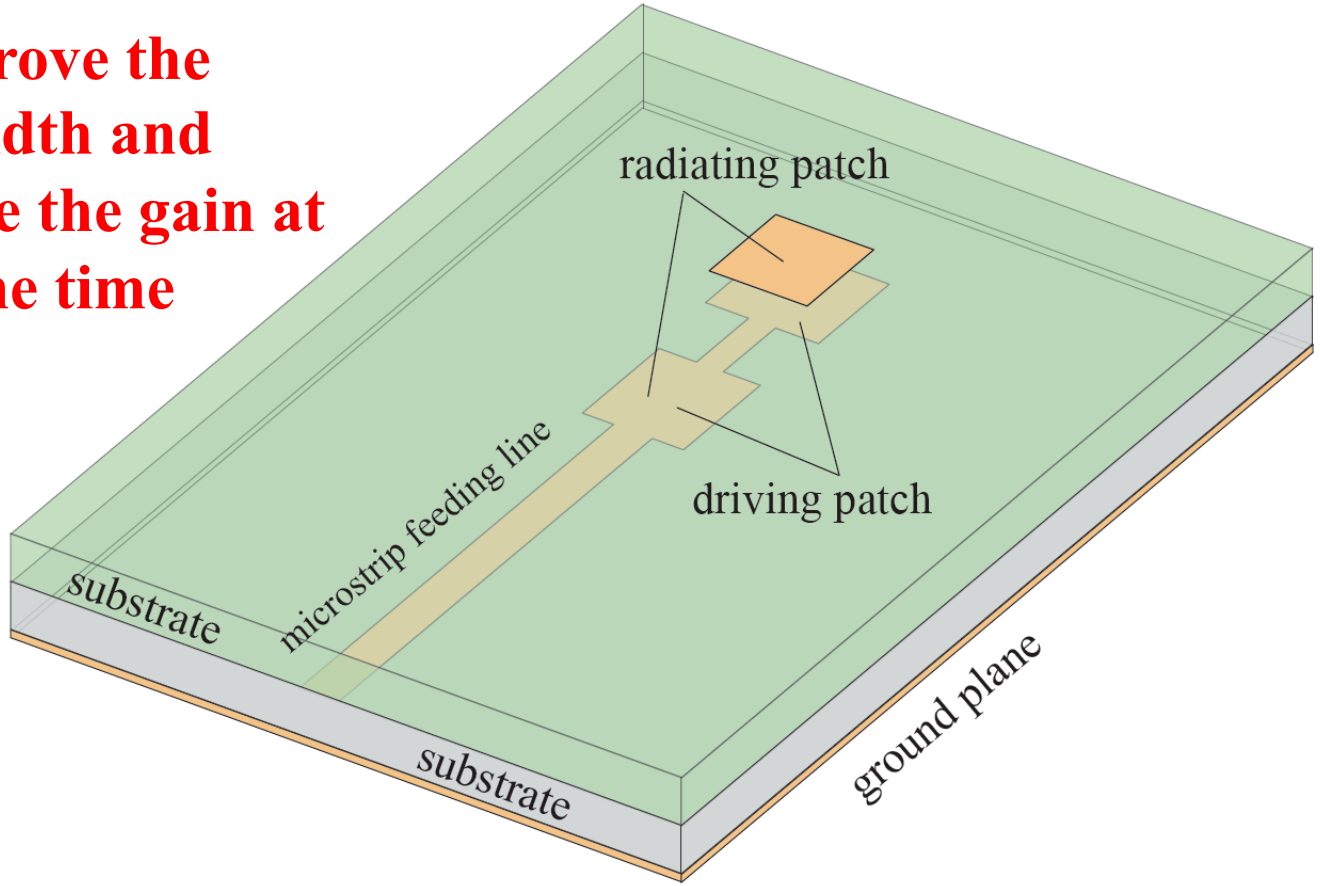
Total loss : < 0.16 dB/mm @ 70 GHz
< 0.90 dB/mm @ 300 GHz

Wideband Antennas for mm-Wave/ THz-wave

1. Wideband Planar Antennas
2. Beamforming/Steering Antenna

New Stacked Microstrip Patch Antenna

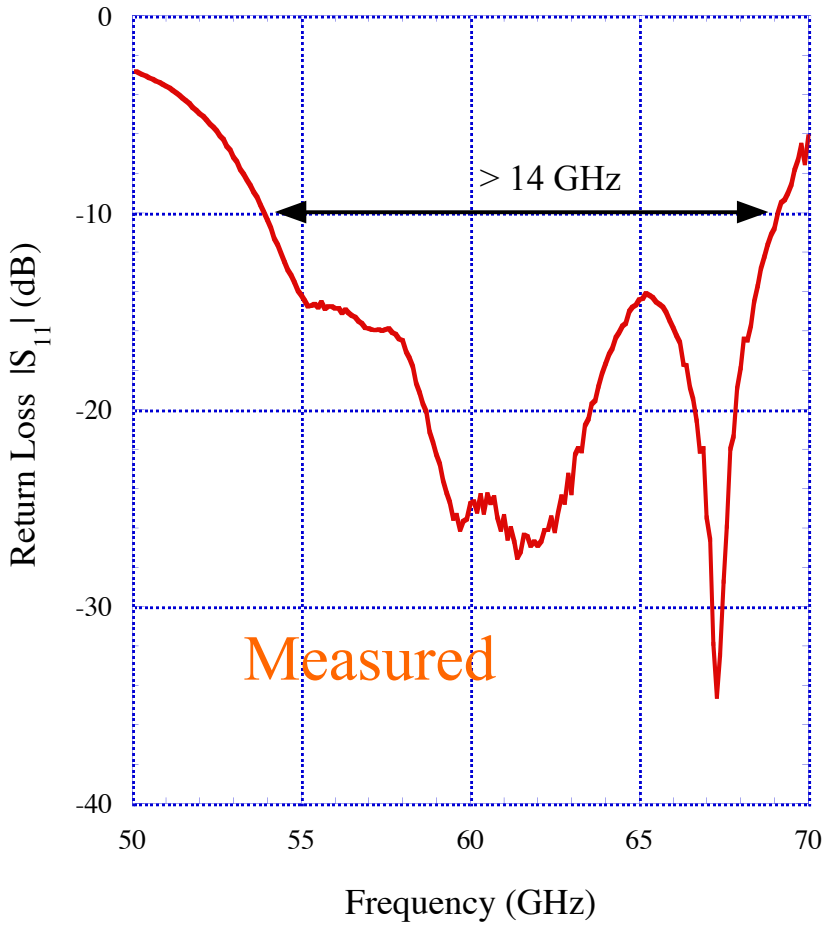
- **To improve the bandwidth and increase the gain at the same time**



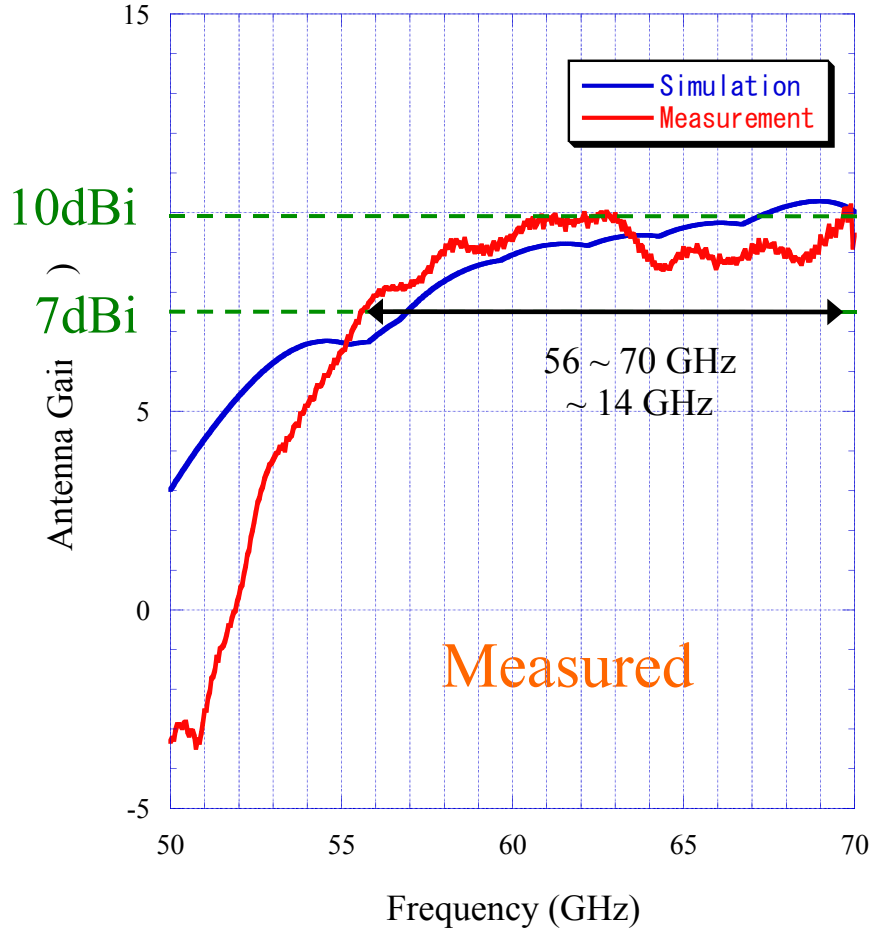
- Two-layer-substrate stacked microstrip patch antenna with a series-feeding/radiating/driving circuits on first layer

Antenna Performance at 60GHz-Band

Return Loss (dB)

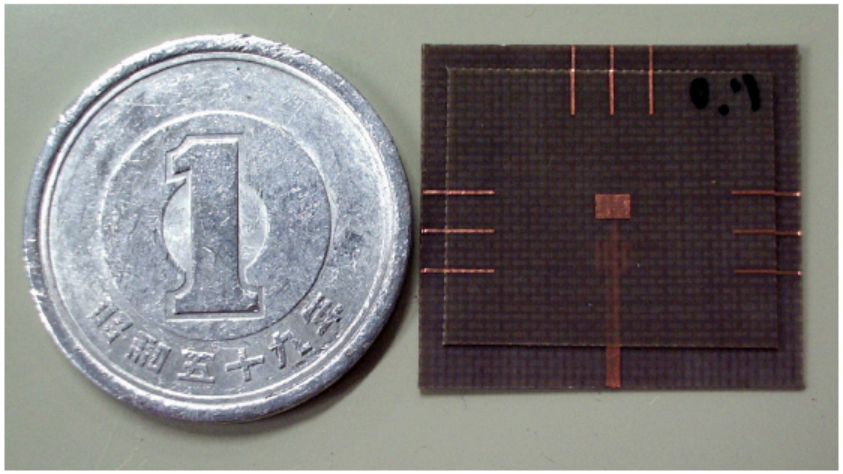


Antenna Gain (dBi)



Wideband Planar Antenna

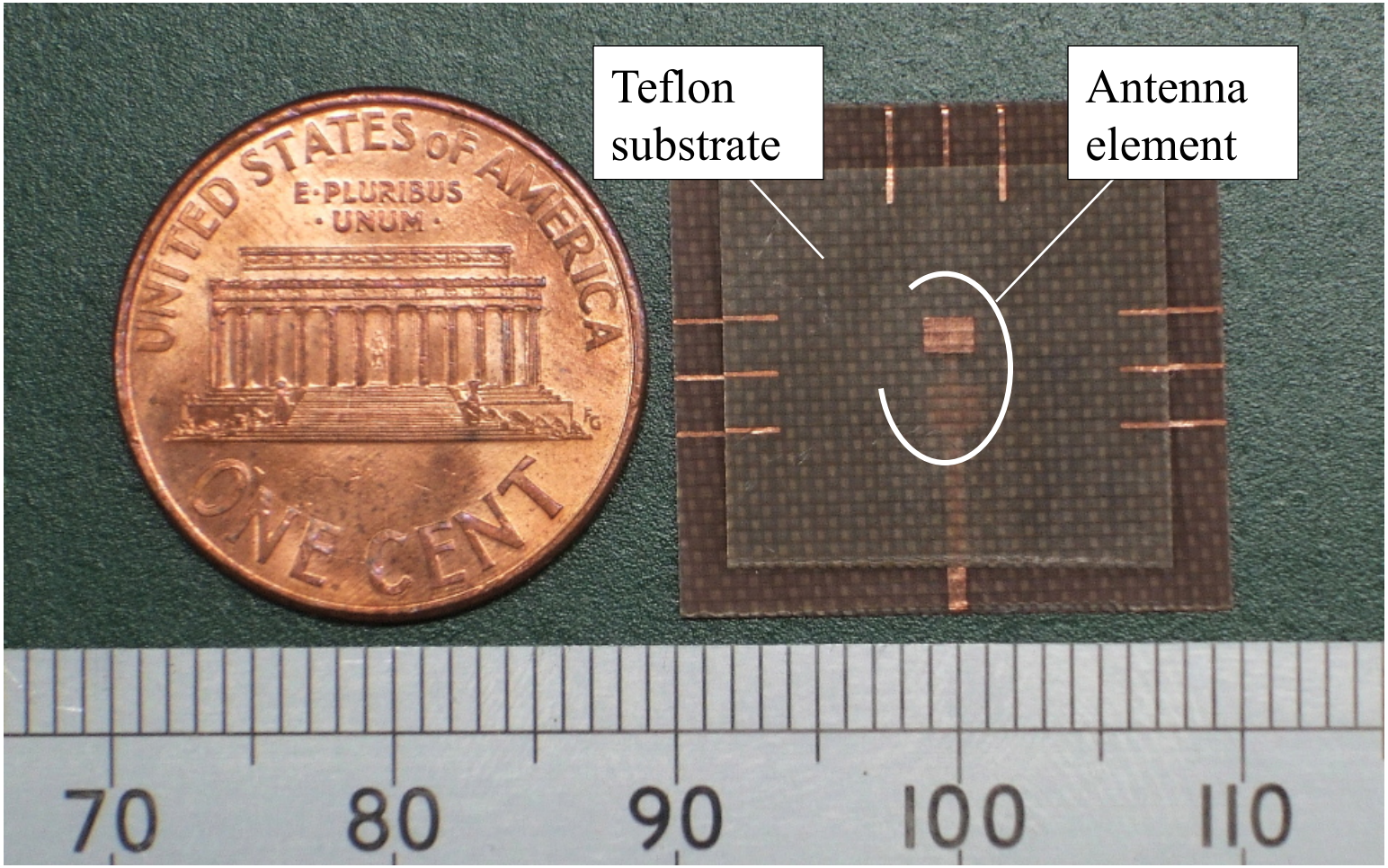
- **A wideband antenna for LOS application like Kiosk File Downloading Model proposed at IEEE 802.15.3c**



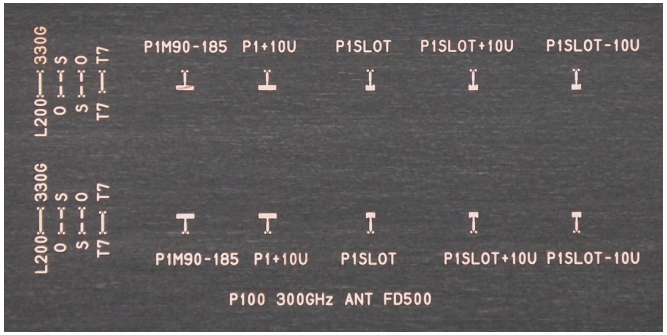
- **Main Features:**
  Wideband Operation
  BW > 14GHz
- **Relative high gain**
  ~ 9dBi
- **Stable radiation patterns over all 60GHz-band**

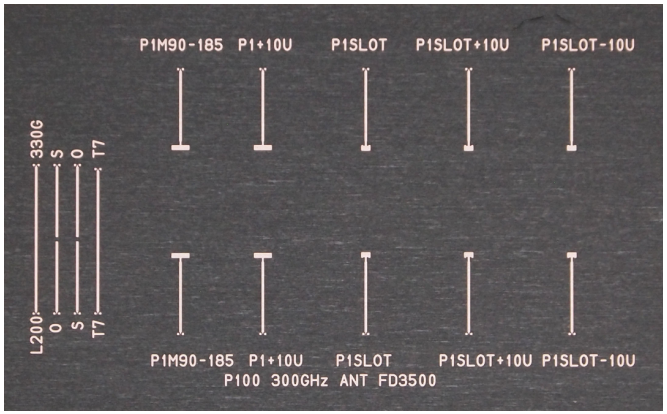
Summary of Antenna Performances	
Antenna Bandwidth	55 - 69 GHz
Antenna gain	> 9 dBi (57 - 69 GHz)
Polarization	Linear
Radiation Parts Size (mm)	4.5 (L) x 2.5 (W) x 0.5 (H)

Photo of Developed Antenna

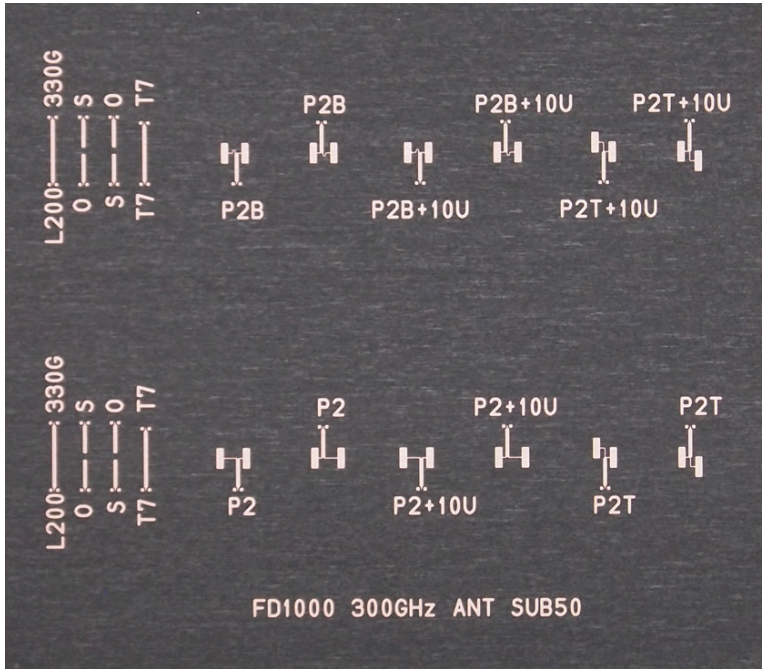


Planar Antennas on LCP (300GHz-Band)





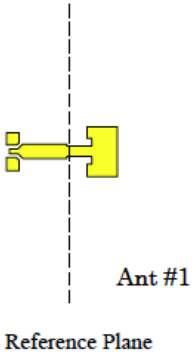
Microstrip Patch Antennas

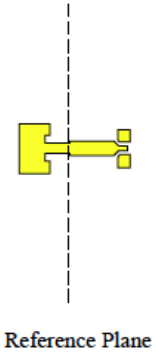


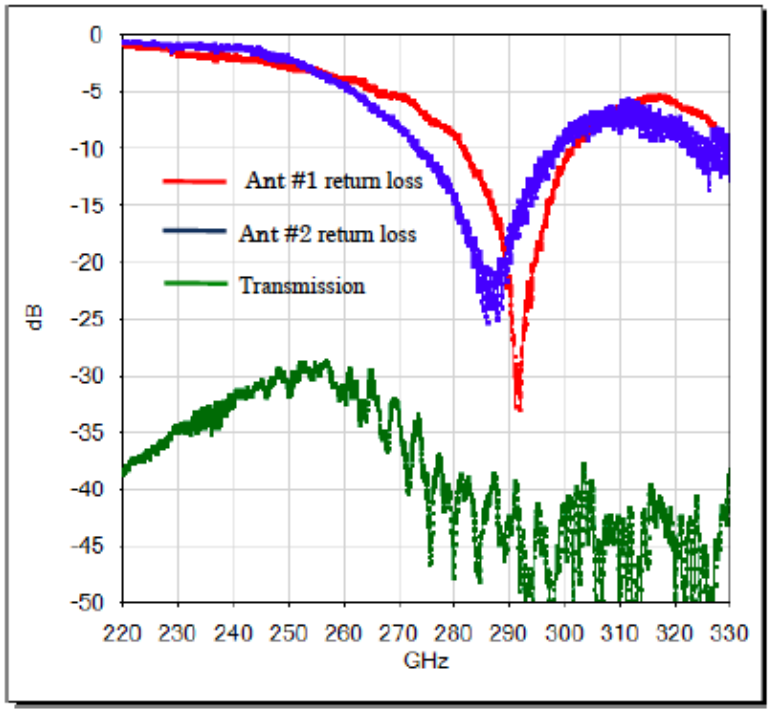
Array Antennas

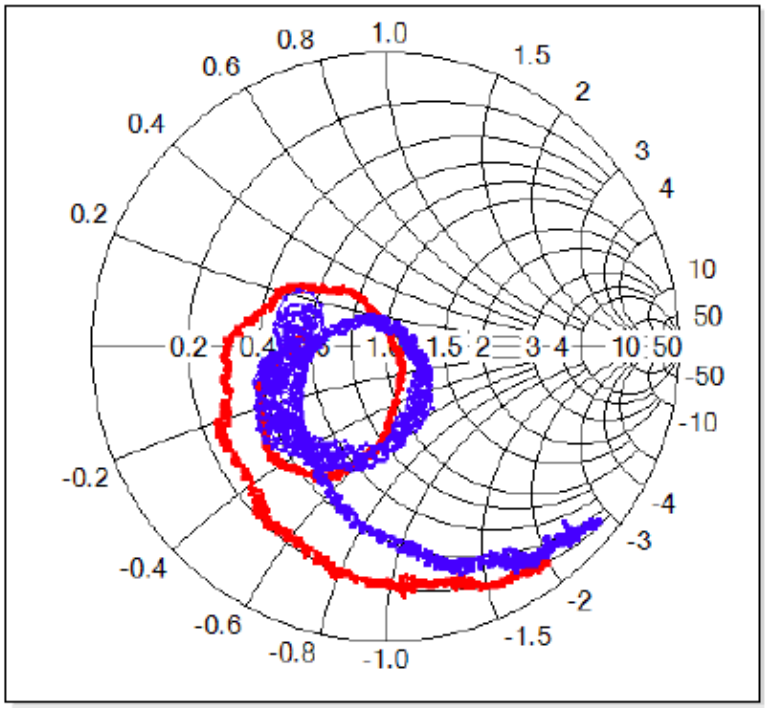
Size of a Single Antenna:
< 0.5 mm x 1 mm

300GHz-Band Antennas (Transmission)



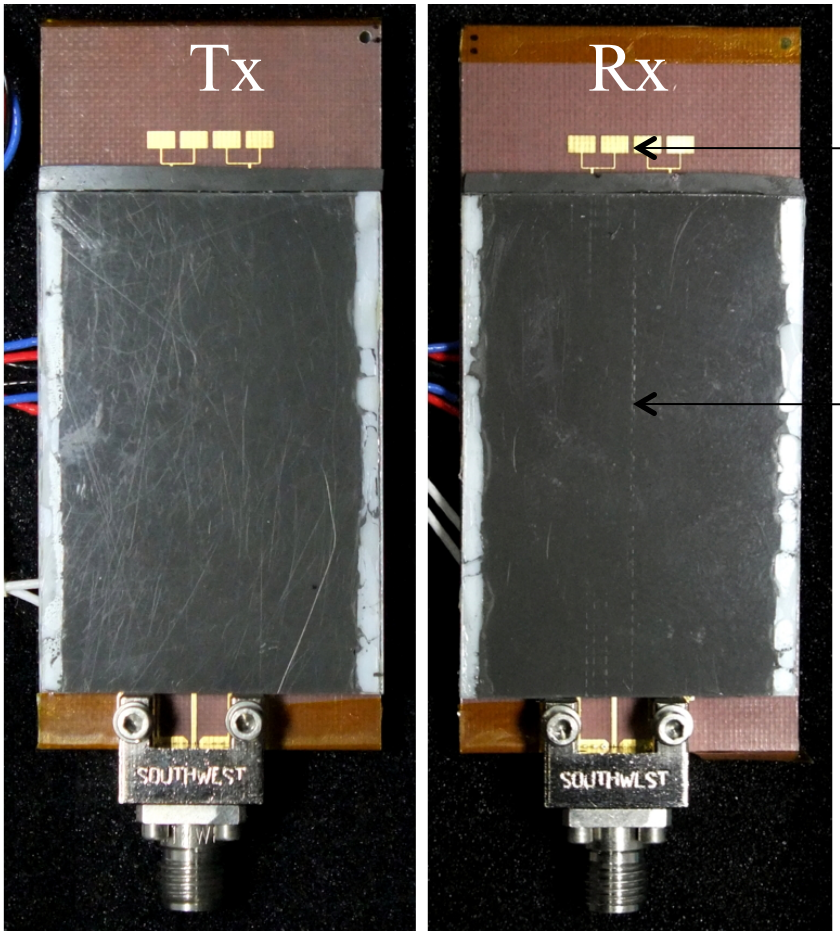






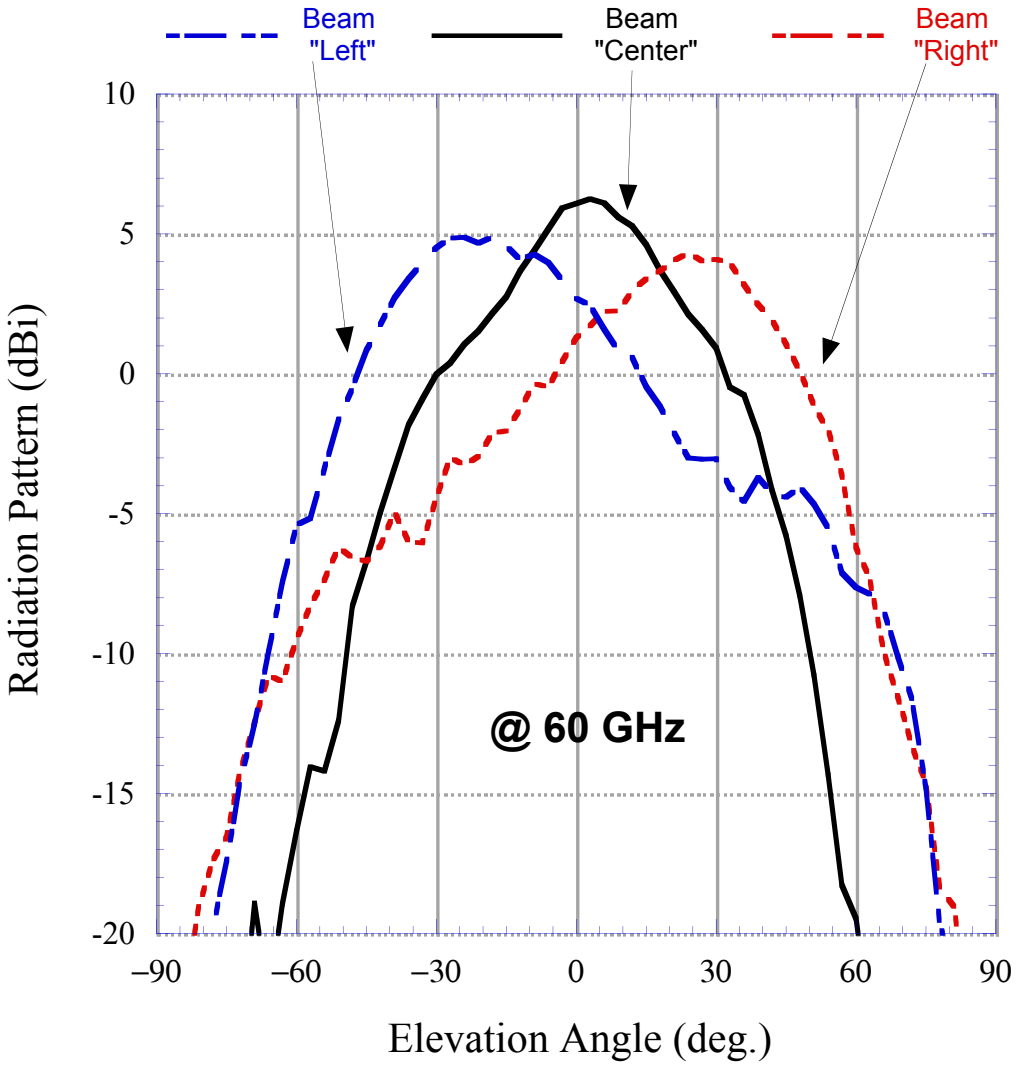
60GHz Beamforming Antenna Modules

- Tx/Rx Antenna Modules

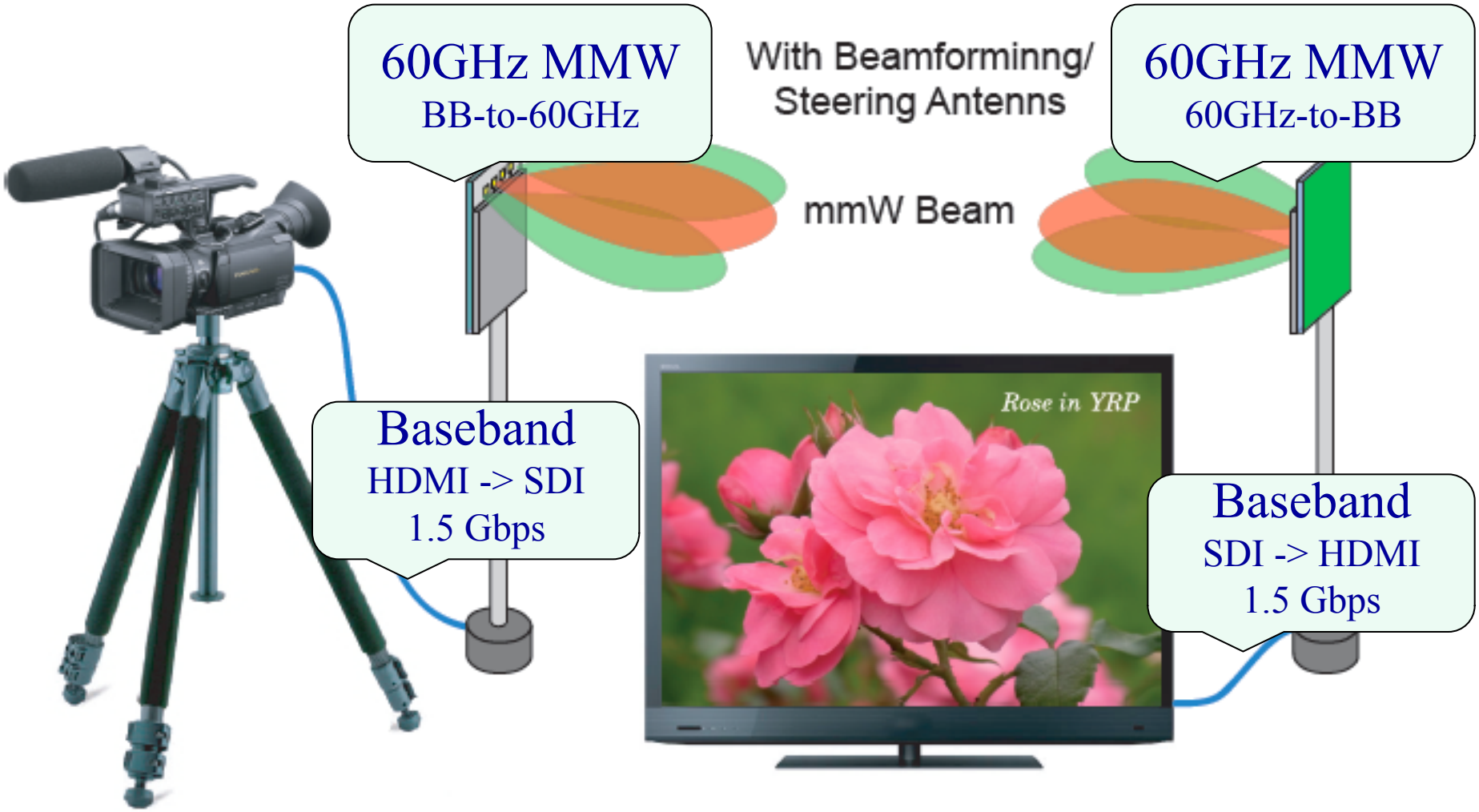


- The Module includes
  - Array Antenna and Beamforming Circuits
  - Amplifier (PA&LNA)
  - Switch
  - Mixer (I/Q Modulator)
  - IF Circuits

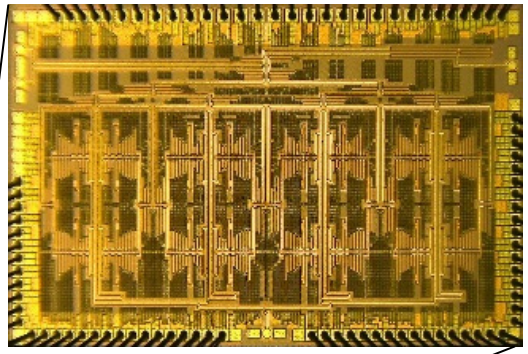
60GHz Beamforming Antenna, Pattern

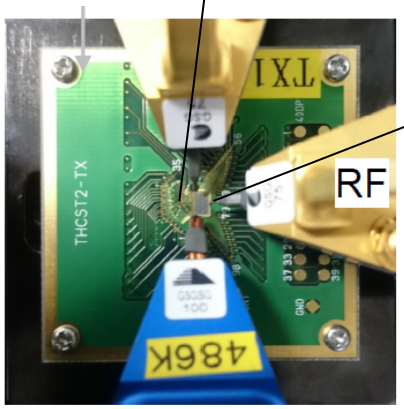


Full-HD Wireless Transmission System

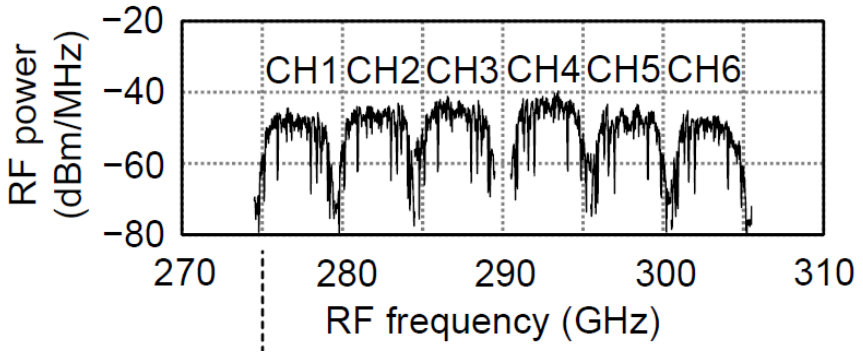


300GHz-Band CMOS Transceiver





300GHz-Band CMOS Transceiver



Total Rate:
> 100 Gbps

Channel	CH1	CH2	CH3
Constellation (Equalized)			
EVM	8.9%rms	4.8%rms	7.0%rms
Data-rate	17.5Gb/s	17.5Gb/s	17.5Gb/s
Channel	CH4	CH5	CH6
Constellation (Equalized)			
EVM	7.1%rms	6.4%rms	5.9%rms
Data rate	17.5Gb/s	17.5Gb/s	17.5Gb/s

2016 IEEE Solid-State Circuits Conference (ISSCC 2016), Jan. 31 – Feb. 4, Univ. of Pennsylvanian, USA.

Conclusion

- **Millimeter-wave & THz-wave are keys for 5G and beyond. Their large bandwidth and short wavelength are important and very attractive.**

⇨ **Great progress has been carried out in recent years, including devices, circuits, antennas, modules, and systems**

- **Many challenges remained for real applications, including technical issues and cost issues**

⇨ **Need much more R&D in the field.**

Special Thanks

謝辞 ・ Special Thanks

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Thank you for your kind attention!

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