Wireless transmission of data and clock for CEPC

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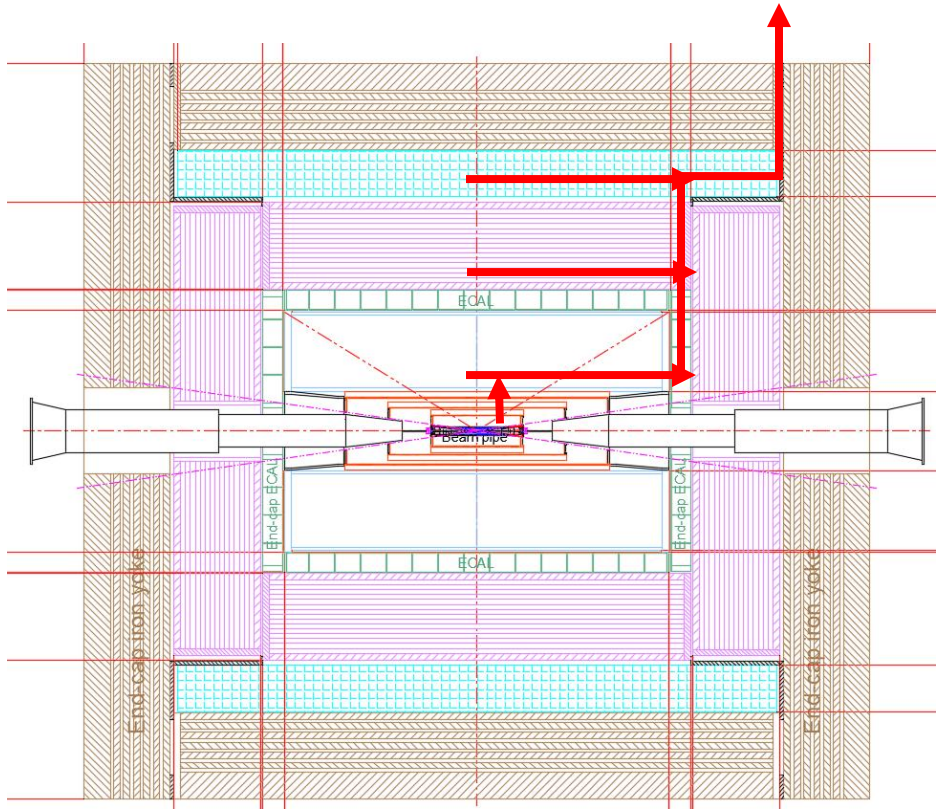
Background

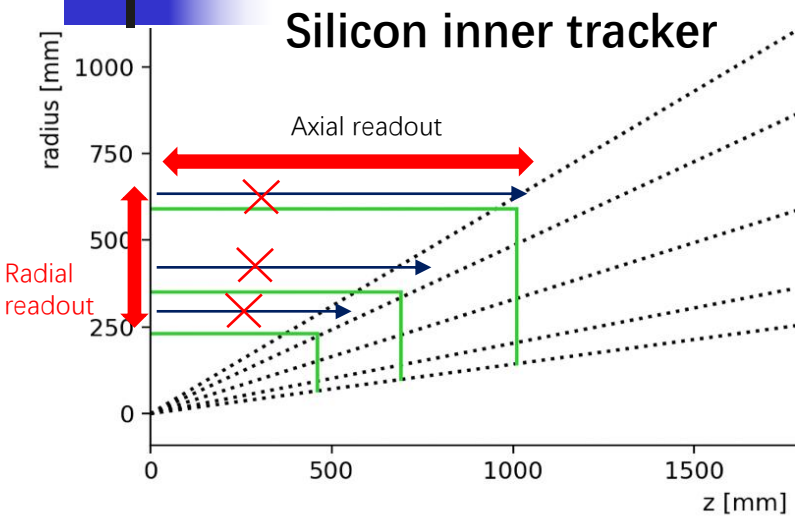
- Wireless transmission advantages include:
  - **Reducing material budget**: Minimize cables, fibers and connectors, while also reducing the dead zone.
    -> Significantly enhance the detection efficiency and resolution!!!
  - **Convenience for installation and maintenance:** Simplify the placement of the transceiver.
  - **Cost Reduction**: Removal of cables, fibers and connectors.

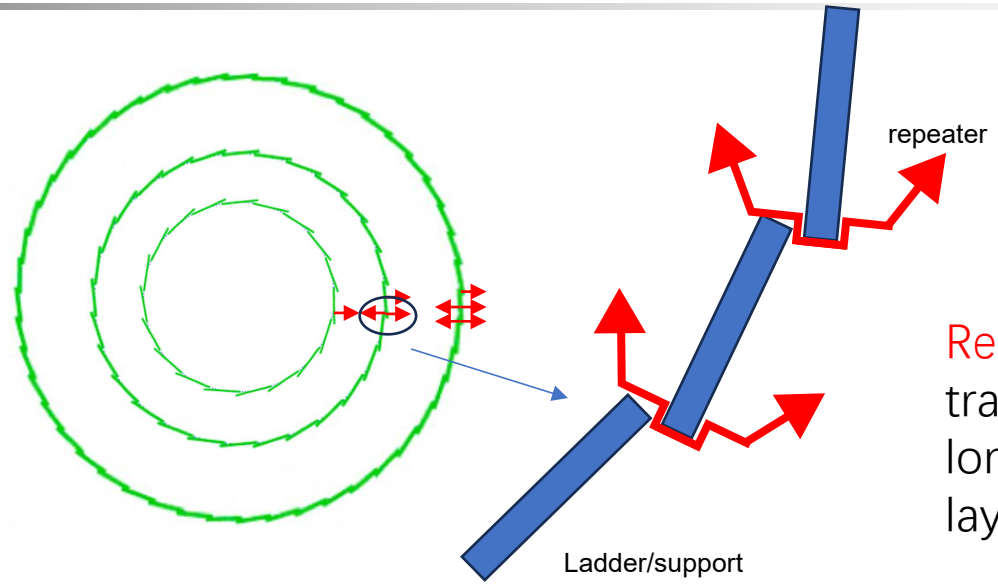
- Application ideas for CEPC detector
  - **Radial data readout between barrel layers:** Provides a new data exchange pathway compared to traditional data readout methods.
  - **Axial data readout from barrel to endcap**: Serve as an alternative to optical fibers, minimizing space and material usage.
  - **Data readout in the endcap:** Concentrates the data at the edge of endcap to simpify the complexities of cables routing



CEPC Detector Geometry

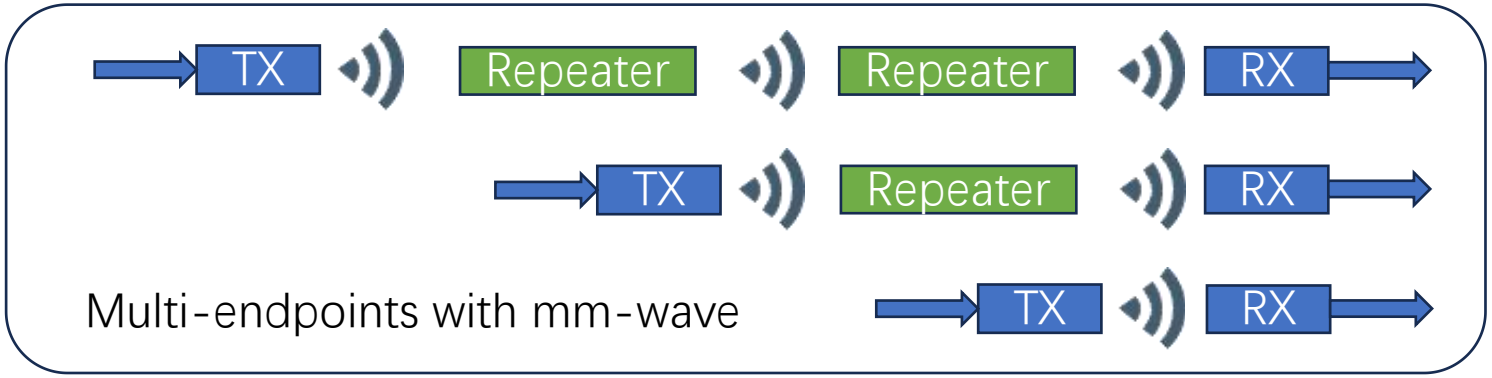
Radial data readout



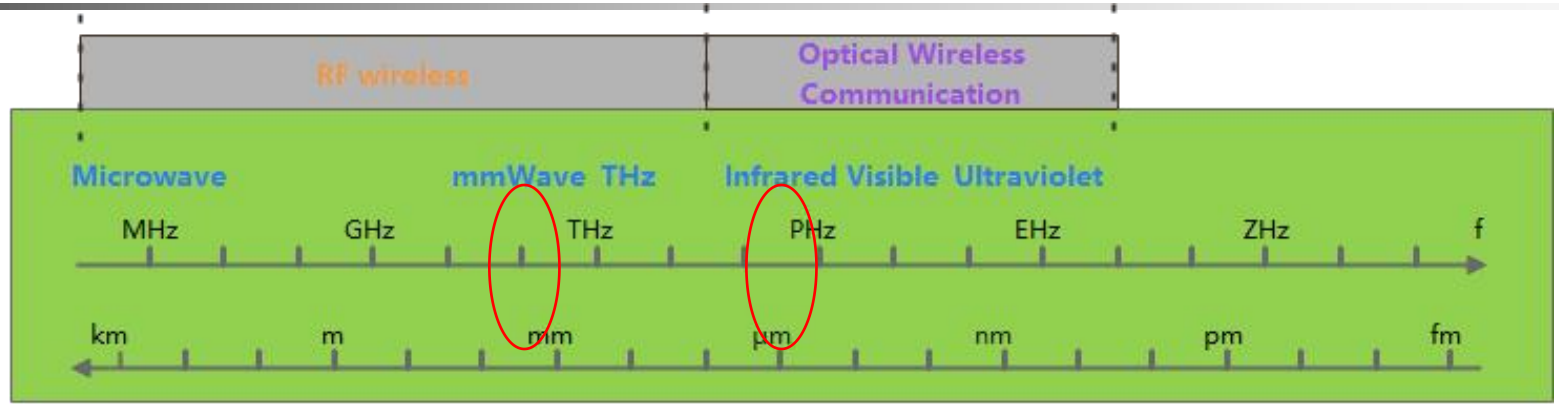


Repeaters: Amplify and re-transmit RF signals over long distances or through layers.

- Radial readout with mm-wave
  - 12- 24 cm transmission distance
- Axial readout to endcap
  - Only at the outermost layer or dedicated aggregation layer.



Research focus

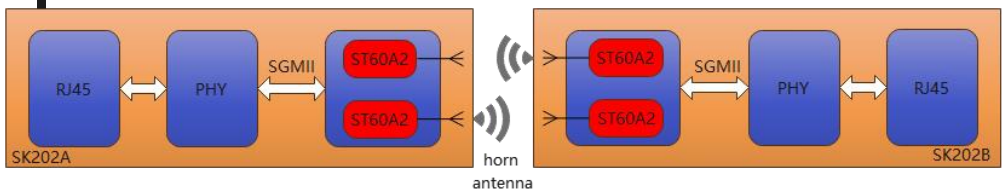


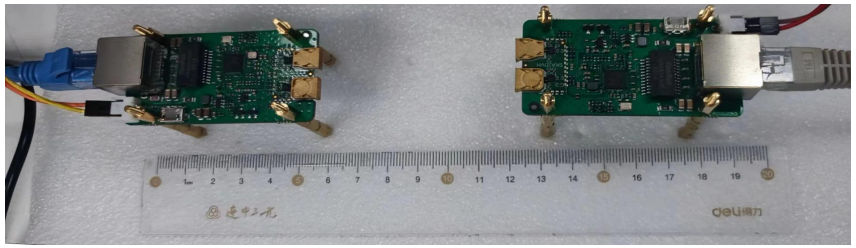
Electromagnetic Spectrum

- **Millimeter Wave (60GHz)**
  - High bandwidth, low power consumption
  - Antenna size miniaturization, can even be integrated into chips
  - Low interference between channels, minimal interference with detectors
  - Medium level of technological maturity

- **Optical Wireless Communication (OWC) / Free Space Optical (FSO)**
  - Extremely high transmission bandwidth
  - High technological maturity
  - Stringent alignment requirements

MM-wave commercial module





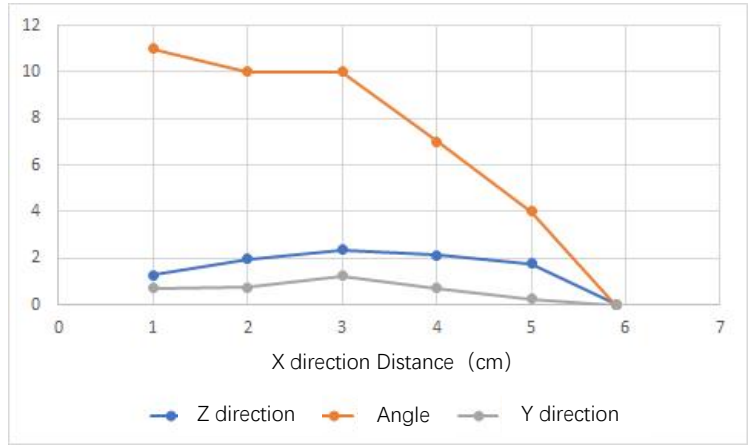
Distance (cm)	Bandwidth (Mbps)	Packet loss rate
1	914	0.031%
3	917	0.061%
5	915	0.05%
6	913	0.13%
>6	No link	No link

Test result at different distances of TX/RX

Material	Thickness	Penetration Ability
Paper	2mm	√
Plastic ruler	2mm	√
FR4 PCB	1.6mm	×
Flex	0.2mm	×

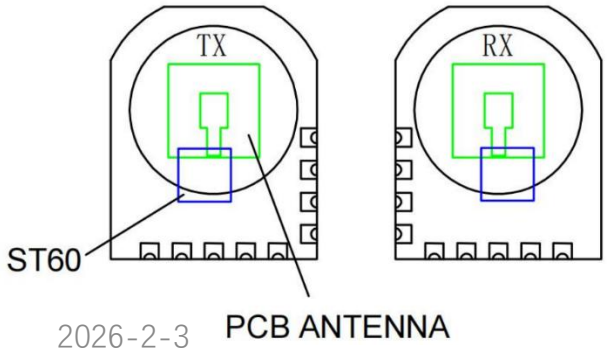
Penetration Test with 3 cm distance

- Test with evaluation boards – SK202 (short-range module)
  - Based on the commercial 60GHz RF chip, **ST60A2G0** transceiver from STMicroelectronics.
  - The transmission speed can exceed 900Mbps when the distance is less than **6 cm**.
  - The 60GHz mm-wave signals can easy penetrate materials such as paper, plastic; but **cannot** pass through FR4 PCBs or Flex cables due to the copper's shielding.
  - Compared to optical communication, mm-wave requires less precise alignment.
  - Power comsuption: Approximately **0.5W** (TX+RX)



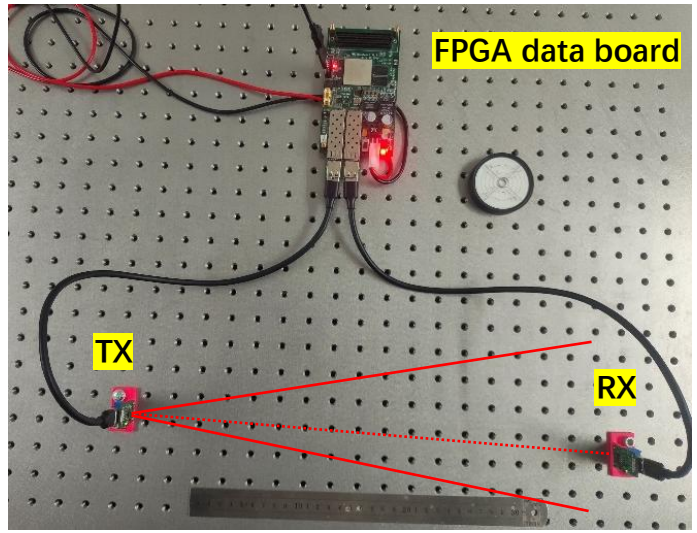
Alignment test

Long-range mm-wave module development



ST60A2 + PA + patch Antenna

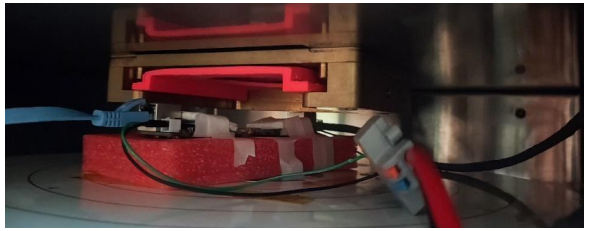
- Long-range mm-wave transceiver module
  - Based on ST60A2 with amplifier
  - Utilizing PCB antenna minimizes size and material costs
  - Features stamp-hole interface and simplified peripheral circuit
  - Dimensions: 14mm x 9mm
- Bandwidth test
  - The transmission distance has reached **67.5cm @ 1.25Gbps**
  - The maximum line speed has reached **6.6Gbps @ 22.5cm**

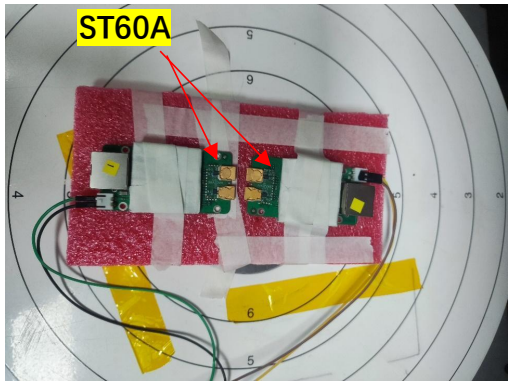


Line rate (Gbps)	Transmit Distance (cm)
1.25	**67.5**
4	50
5	45
6.6	22.5

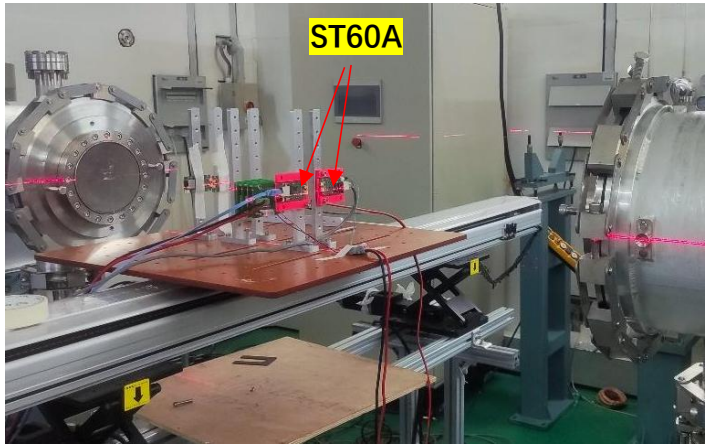
Transmission distance under different line rate

Radiation tolerance

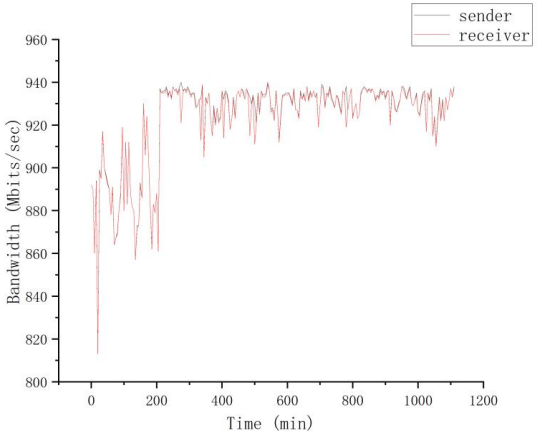




X-ray (20 kV, 40 mA)
Dose rate： 21.2krad/min
Duration： **5.5 hours (7 Mrad)**



CSNS neutron beam



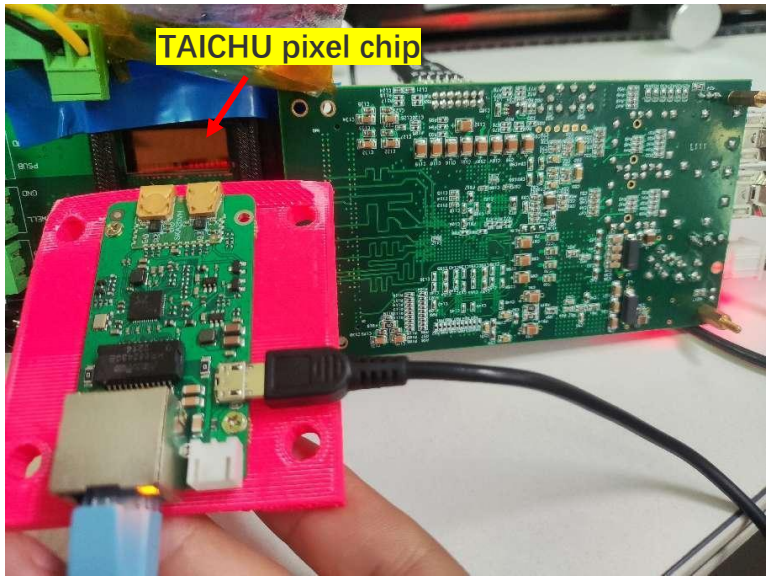
Bandwidth during irradiation

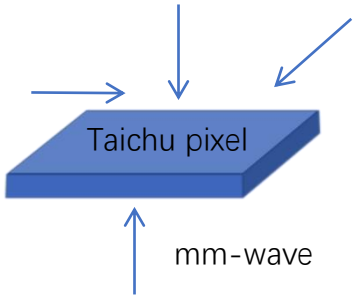
Beam intensity:: $1.65*10^7 n_{eq}/cm^2$
Absorption coefficient: 0.95
Duration: **21 hours (1.2 X 10^{12} n_{eq}/cm)**

- Total dose test
  - Target value: Total dose 5 Mrad (Si).
  - Real-time monitoring during the irradiation process, wireless communication all normal.

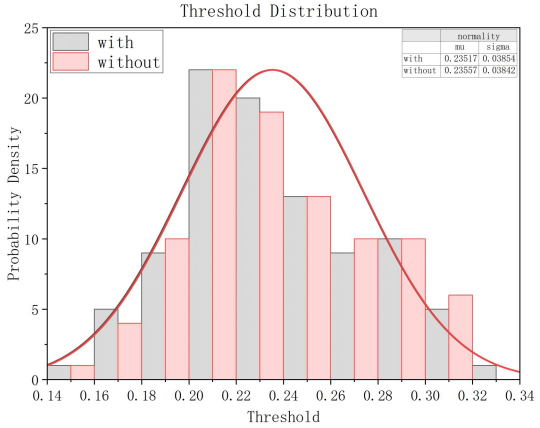
- NIEL test
  - Target value： 0.97 X 10^{12} n_{eq}/cm （1MeV Equivalent Neutron）
  - The real-time test bandwidth during irradiation process, with transmission rate basically unaffected.

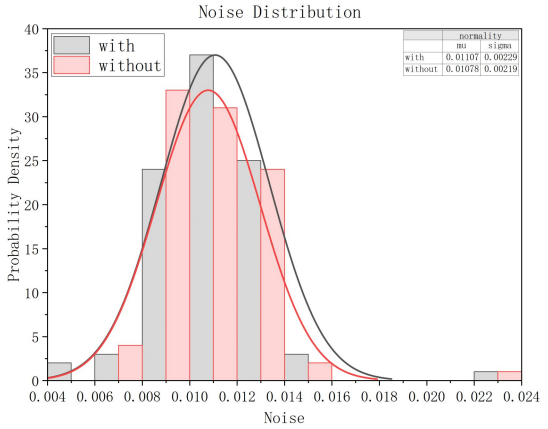
Interference with detectors



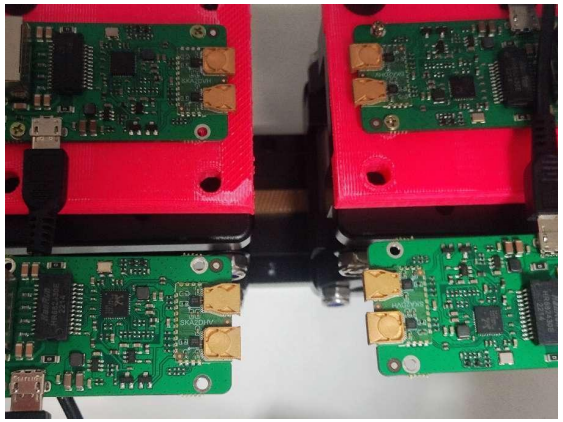


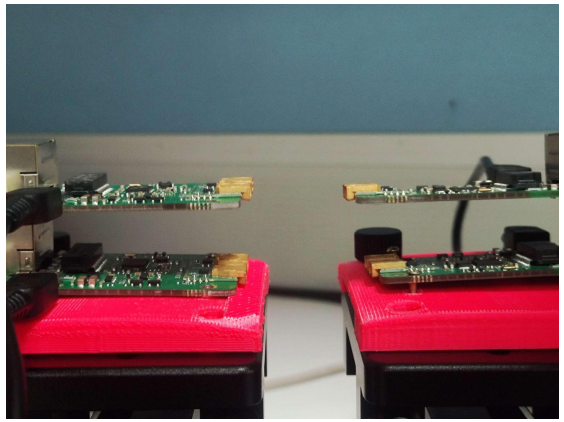
- Test with the vertex pixel prototype chip TAICHU3
  - Test two types of modules (short-range and long-range modules).
  - Approach Taichu3 from various directions and distances.
  - Assess the impact on chip threshold and noise levels.
- The test outcomes demonstrate that the influence of 60GHz millimeter waves on the detector signal is minimal.
- Furthermore, the detector signal poses little to no interference with the transmission of millimeter wave signals.

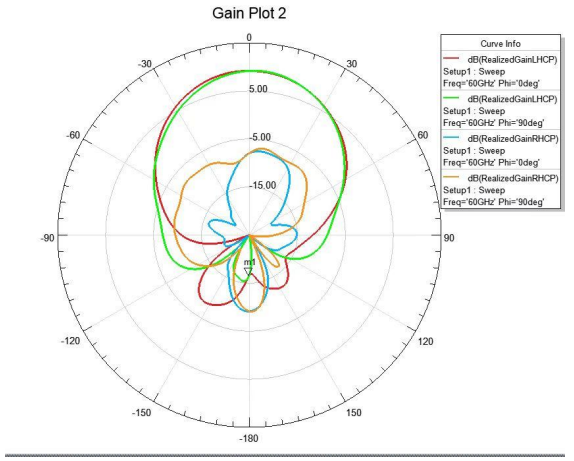


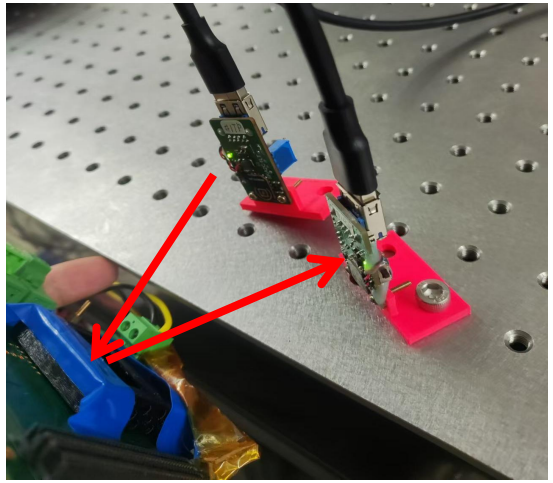


Crosstalk with each other









- For short-range modules with horn antennas, a minimum distance of **3 cm** will not affect transmission, enabling high-density placement.

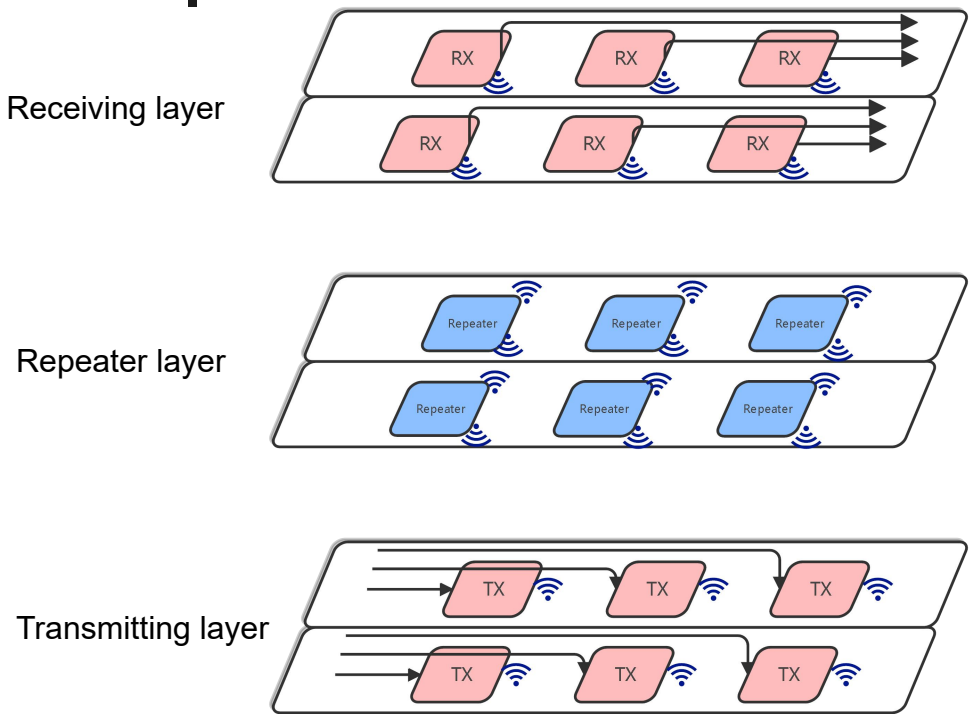
- For long-range modules, the spacing needs to be increased to **15 cm**. Meanwhile, the antenna features a half-power radiation angle of around **90 degrees**.
- It is observed that reflected signals can also affect the interval at specific angles. A balance must be considered by both transmission distance and crosstalk.

Mass production

MMW transmission module

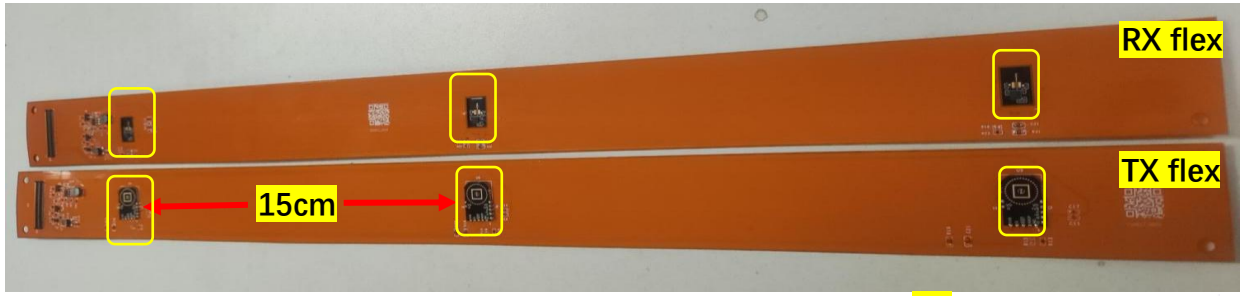
- The assembly process required carefully handling for the bare-die amplifier wire bonding and module soldering.
- Manufactured 200 pairs for subsequent testing and research.

mm-wave demonstrator



mmWave demonstrator schematic

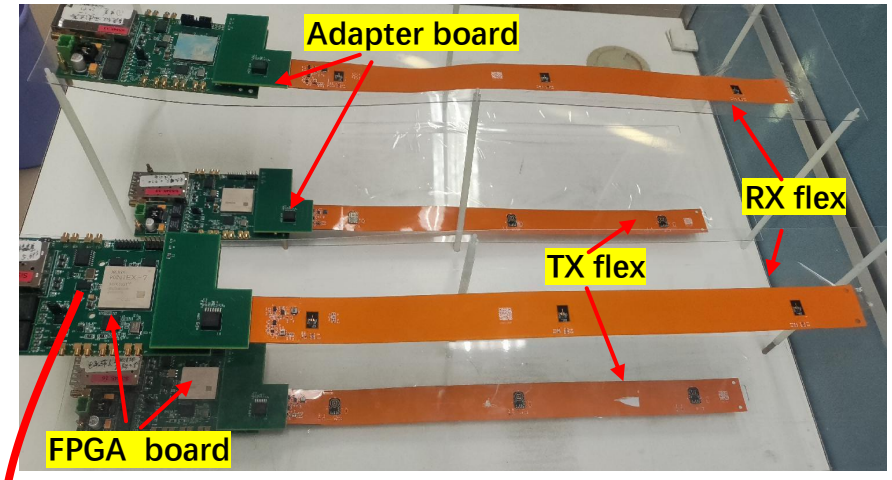
- Two flex PCBs per layer.
- Each flex PCB accommodates 3-channel transceiver modules.

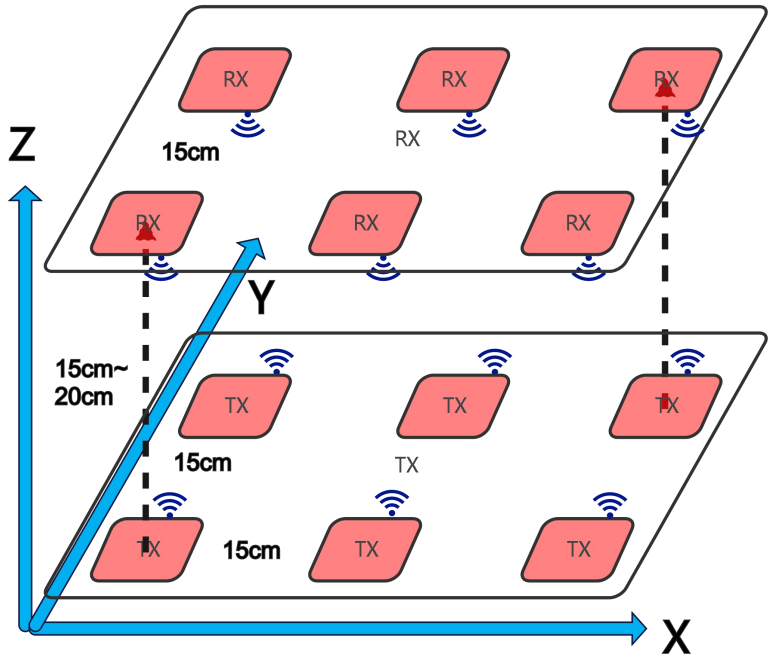


Repeater structure: RX is at the bottom layer of PCB, TX is at the top layer of PCB

- All the hardware design have been completed
  - TX/RX flex, adapter boards, repeater,and FPGA board.
- Multi-channel test with 6 pairs of transceiver module have been completed.

mm-wave demonstrator



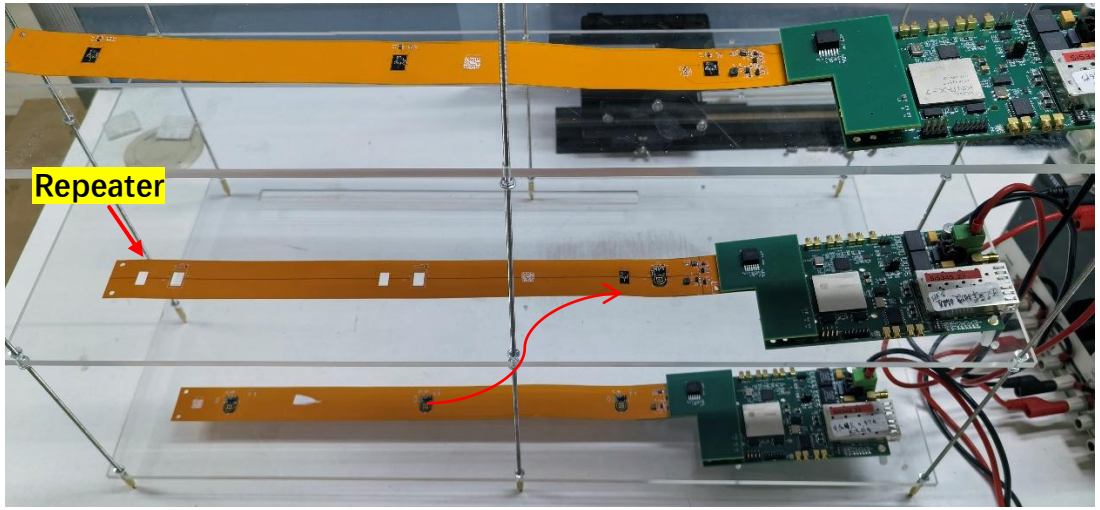


Name	TX	RX	Status	Bits	Errors	BER	BERT Reset	TX Pattern	RX Pattern	TX Pre-Cursor	TX Post-Cursor	TX Diff Swing
Ungrouped Links (0)												
Link Group 0 (3)							Reset	PRBS 7-bit	PRBS 7-bit	1.67 dB (00111)	0.68 dB (00011)	1018 mV (1100)
Link 5	Quad_116/MGT_X0Y5/TX (xc7k325t_0)	Quad_116/MGT_X0Y5/RX (xc7k325t_0)	3.125 Gbps	1.005E13	0E0	9.955E-14	Reset	PRBS 7-bit	PRBS 7-bit	1.67 dB (00111)	0.68 dB (00011)	1018 mV (1100)
Link 6	Quad_116/MGT_X0Y6/TX (xc7k325t_0)	Quad_116/MGT_X0Y6/RX (xc7k325t_0)	3.125 Gbps	1.005E13	0E0	9.955E-14	Reset	PRBS 7-bit	PRBS 7-bit	1.67 dB (00111)	0.68 dB (00011)	1018 mV (1100)
Link 7	Quad_116/MGT_X0Y7/TX (xc7k325t_0)	Quad_116/MGT_X0Y7/RX (xc7k325t_0)	3.125 Gbps	1.005E13	0E0	9.955E-14	Reset	PRBS 7-bit	PRBS 7-bit	1.67 dB (00111)	0.68 dB (00011)	1018 mV (1100)

The IBERT test on 3 pairs of modules within one FPGA (1 hour running): NO error bit

- A stable and crosstalk-free transmission can be achieved.
  - 3D arrangment, **2X3** one direction transmission pairs
  - Line rate: **3.125 Gbps**
  - Reducing the transmit power and increasing the receive power to avoid crosstalk.
  - Spatial constraints: **15 cm** in the XY plane directions and within a range of **15–20 cm** in the transmission direction (Z direction),
  - Power comsuption: 1.5W / pairs

mm-wave demonstrator



15 cm is a highly critical distance, which causes interference within repeaters. Practical tests show that a larger spacing is required to ensure the normal operation of the repeater layer.

- With the demonstrator, we preliminarily identified the difficulties in controlling crosstalk of mm-wave transmission.
- For actual detectors, customized adaptable power of modules and specific matching of different modules should be employed based on transmission distance demands to mitigate internal signal reflection and interference.

Thanks!