

Wideband Terahertz FMCW Radar

宽带太赫兹FMCW雷达

Xiang Yi (易翔)^{1,2}, Cheng Wang², Muting Lu²,

Jinchen Wang², Jesus Grajal^{2,3}, and Ruonan Han²

^{1,2}South China University of Technology (华南理工大学), Guangzhou, China

²Massachusetts Institute of Technology (麻省理工学院), Cambridge, MA, USA

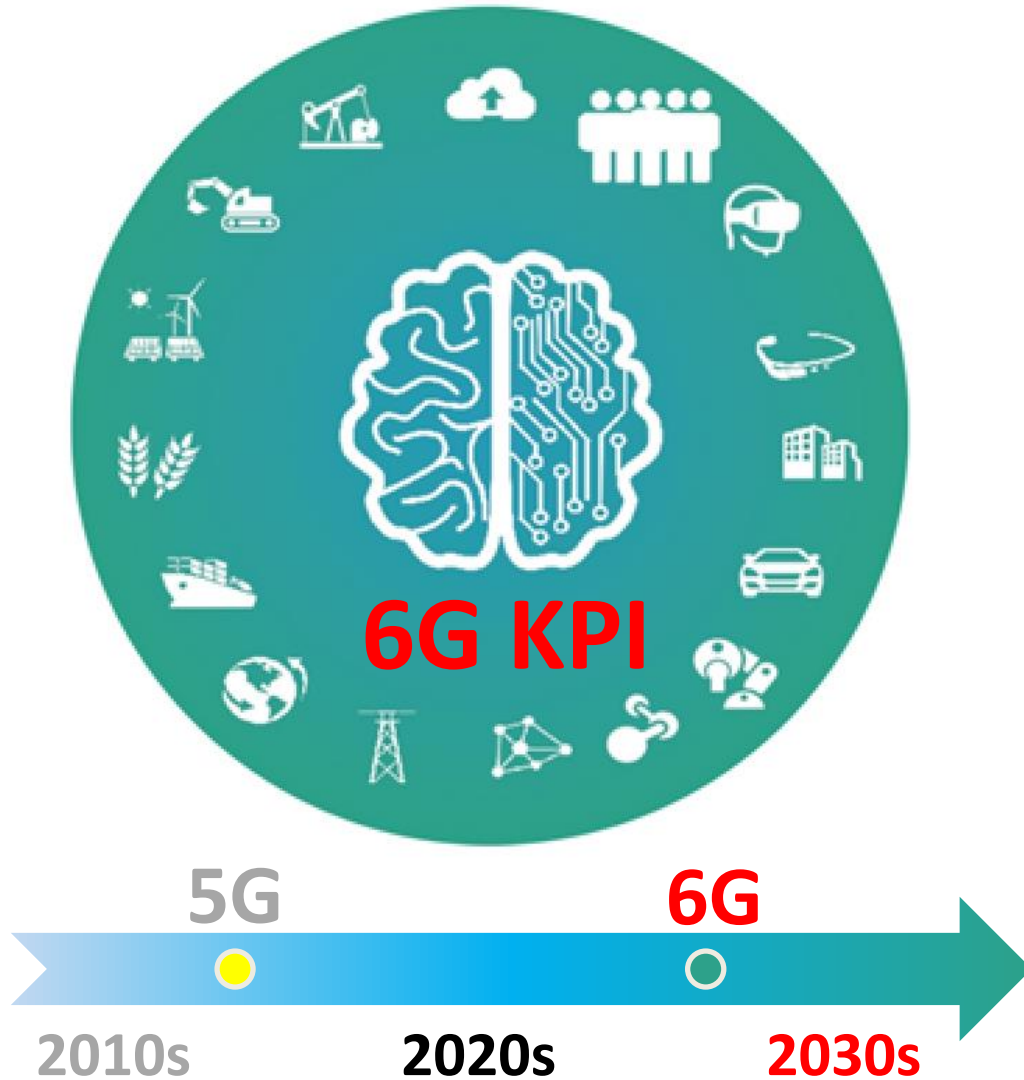
³Universidad Politécnica de Madrid (马德里理工大学), Madrid, Spain



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Outline

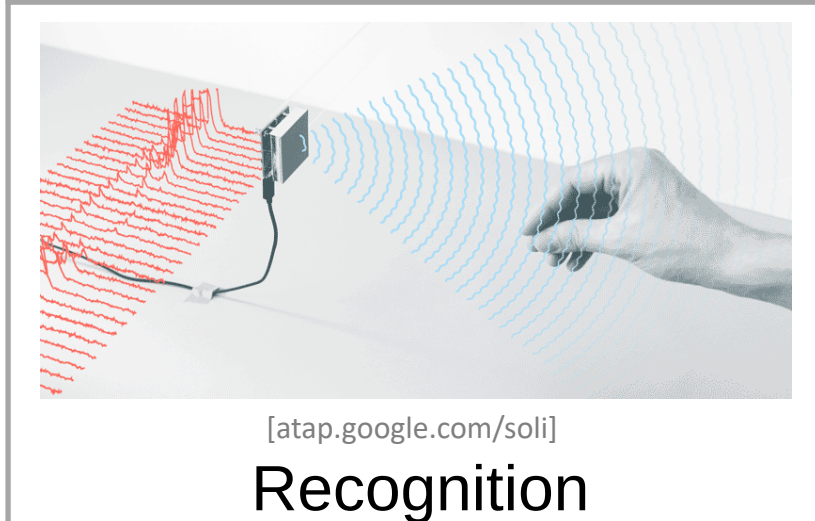
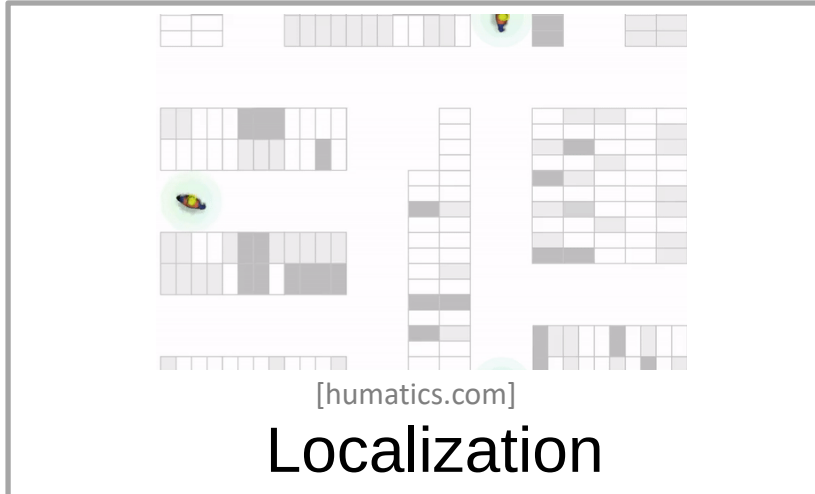
- **Introduction**
- **THz FMCW Comb Radar**
- **Circuit Implementations**
- **Measurement Results**
- **Conclusion**



- Frequency: towards **THz**
- Joint **Radar**-Communication
- Localization accuracy: 1cm
- Sensing/Imaging **resolution:**
1-3mm

Wideband FMCW Radar Applications

- High resolution detection



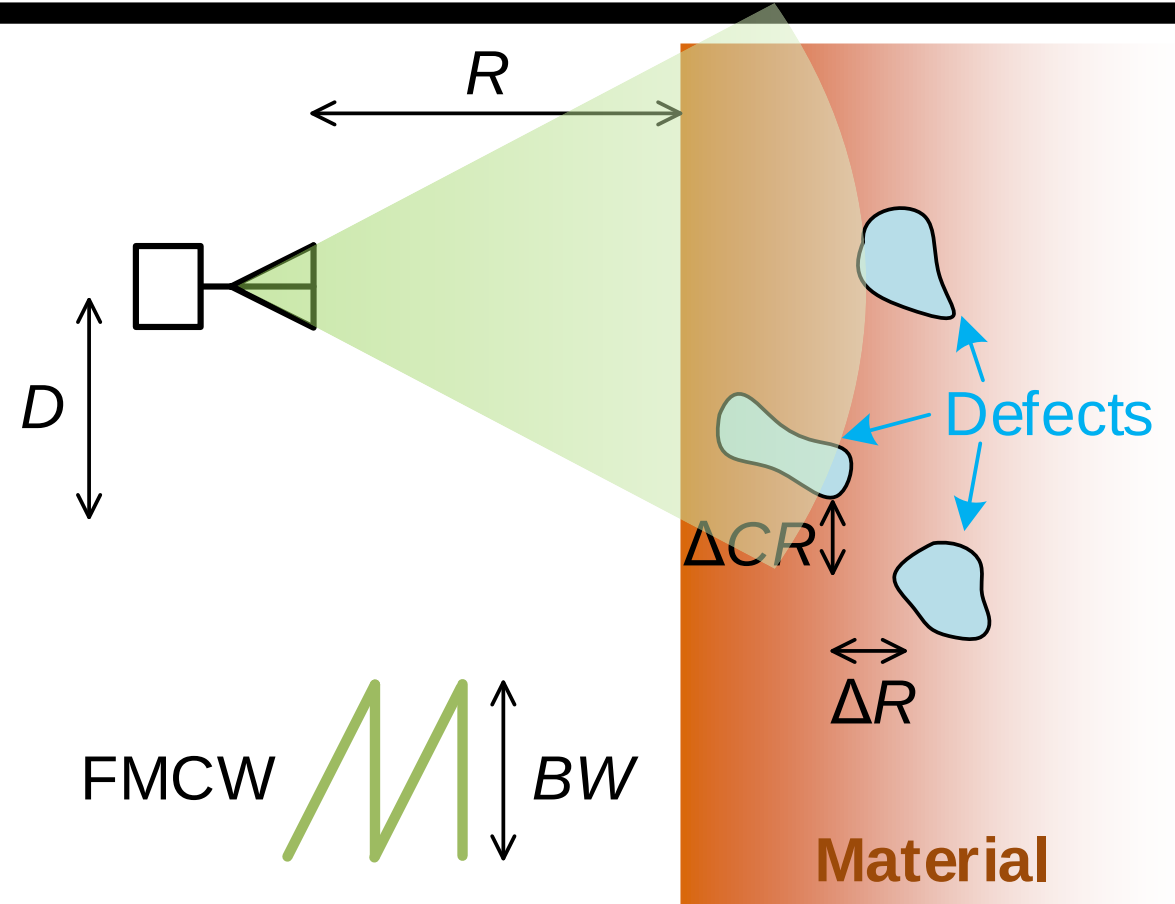
- High resolution imaging


$$\Delta R = \frac{c}{2 \cdot BW}$$



Wideband THz FMCW Radar Example

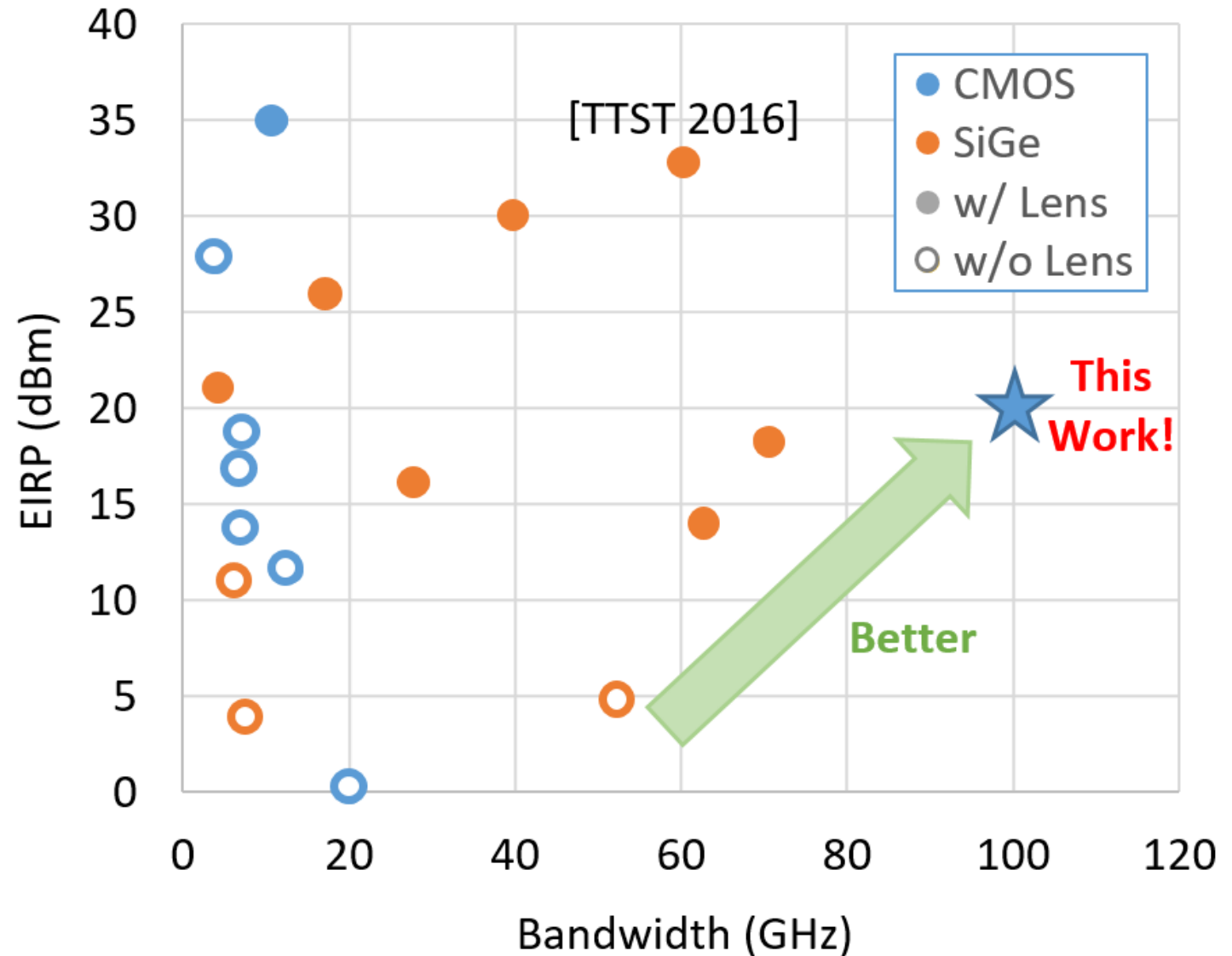
- SAR 3D imaging
- Cross-range resolution ΔCR
 - Relies on synthetic aperture D
 - Mm resolution is readily available (e.g. $R=3D$, $\Delta CR=1.5\text{mm}$)
- Range resolution ΔR
 - Relies on bandwidth BW only
 - Mm resolution: wideband (e.g. $BW=100\text{GHz}$, $\Delta R=1.5\text{mm}$,)



300GHz Radar Imaging for Non-Destructive Detection of Material Defects

Integrated Wideband Radar Survey

- CMOS radar is desired
 - Low cost
 - Integration with analog and digital circuits
- Bandwidth of CMOS radars is limited
- Wideband THz FMCW radar issues
 - Performance fluctuation
 - Chirp signal generation

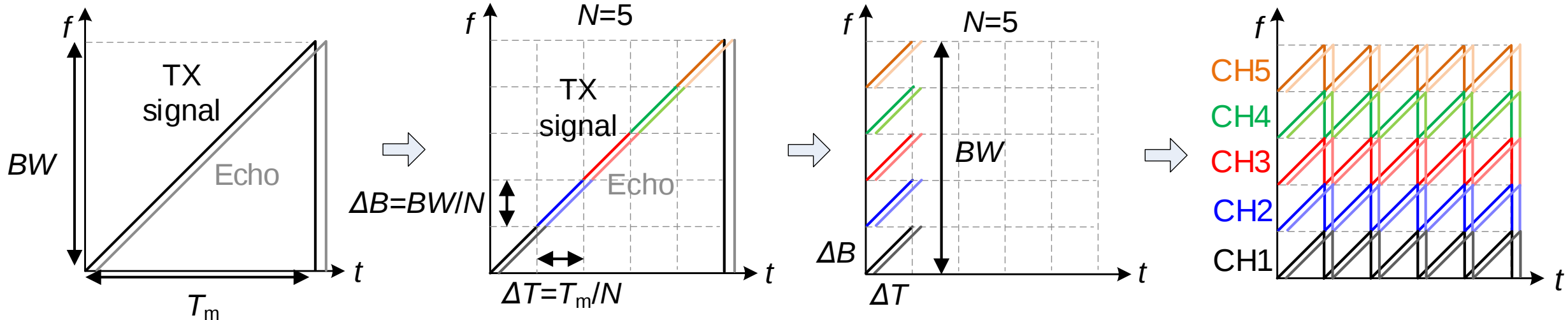
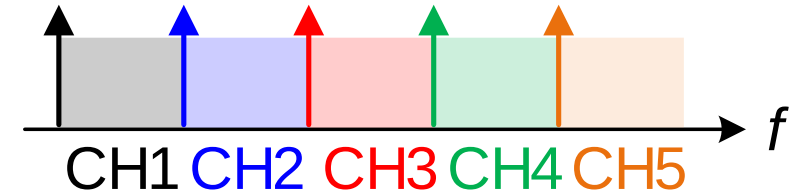


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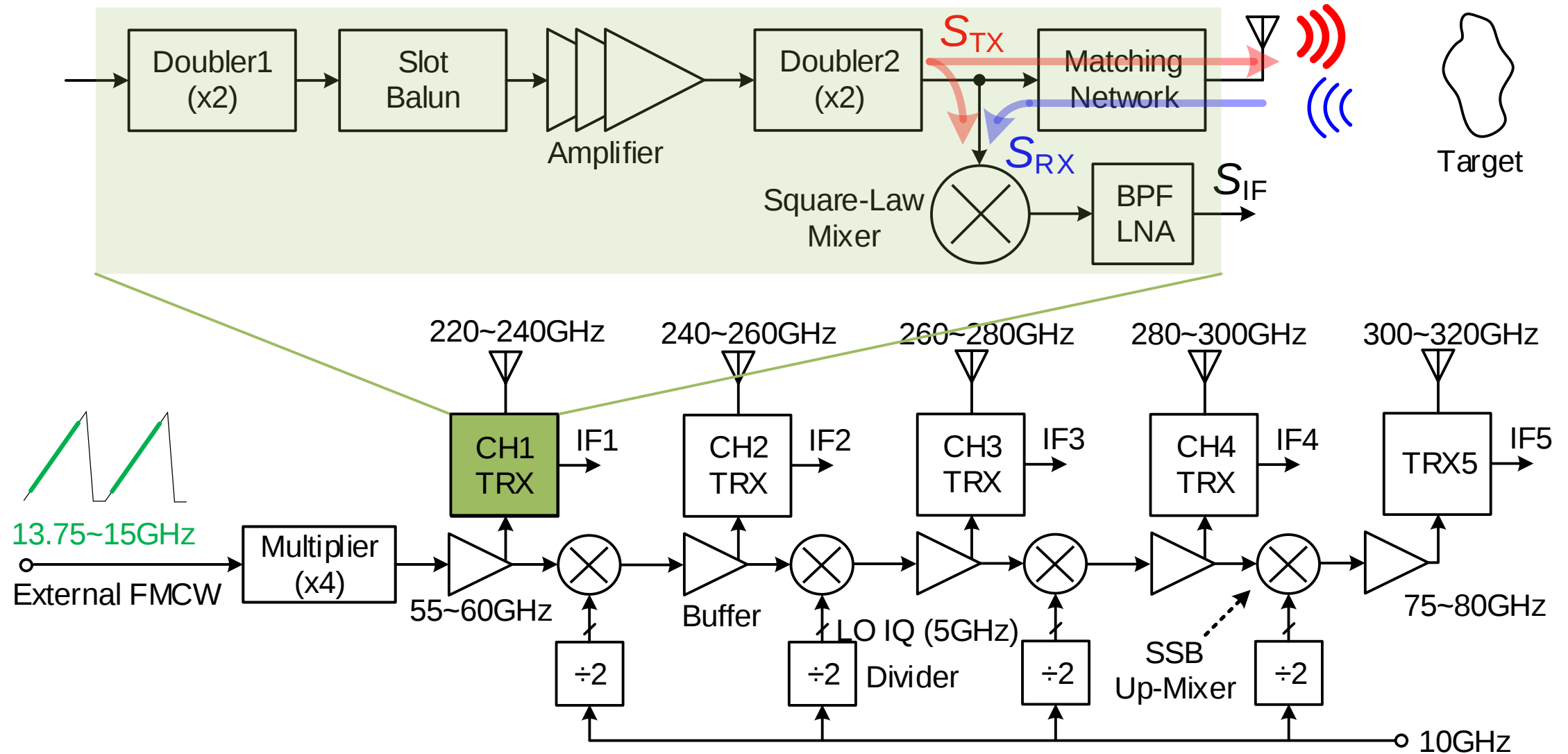
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FMCW Comb Radar Concept

- Divide a single wideband channel into N narrowband channels
- Make these N channels operate simultaneously
- Multi-tone operation looks like a comb



THz FMCW Comb Radar System Diagram



Phase of IF Signals

- For Channel N, the TX signal is

$$S_{TX,N}(t) = \cos \left[\left(2\pi f_{c,N} + \frac{\pi \Delta B}{\Delta T} t \right) t + \underline{\varphi_N} \right]$$

Initial RF phase

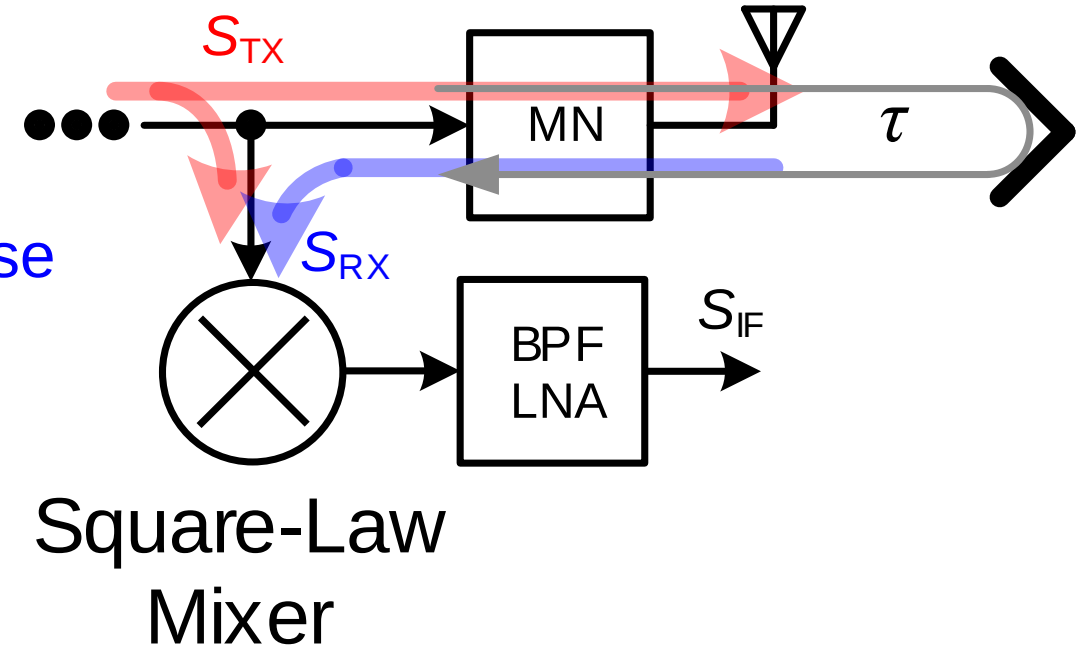
- The echo signal ($\tau \ll \Delta T$) is

$$S_{RX,N}(t) = \cos \left[\left(2\pi f_{c,N} + \frac{\pi \Delta B}{\Delta T} (t - \tau) \right) (t - \tau) + \varphi_N \right]$$

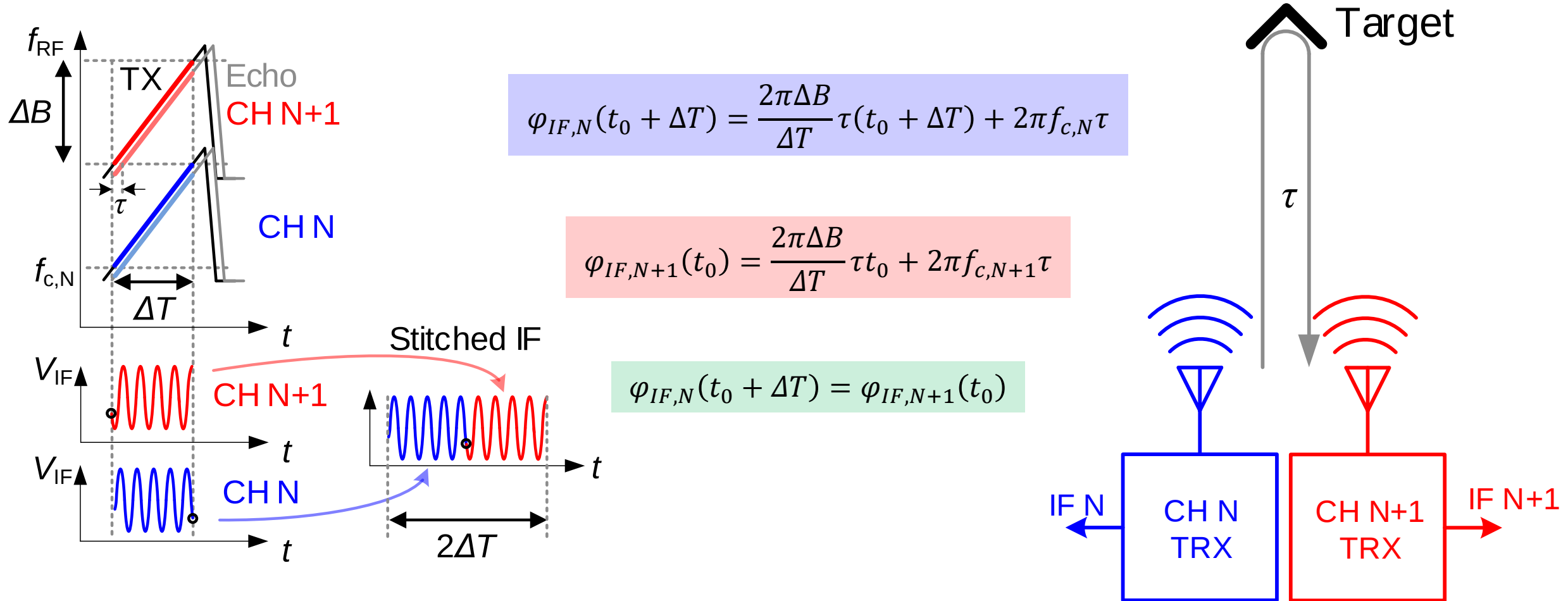
- The band-pass-filtered IF signal is

$$S_{IF,N}(t) = \cos \left(\underline{\frac{2\pi \Delta B}{\Delta T} \tau t + 2\pi f_{c,N} \tau} \right) = \varphi_{IF,N}(t)$$

- The phase of IF signal $\varphi_{IF,N}$ has no initial RF phase φ_N



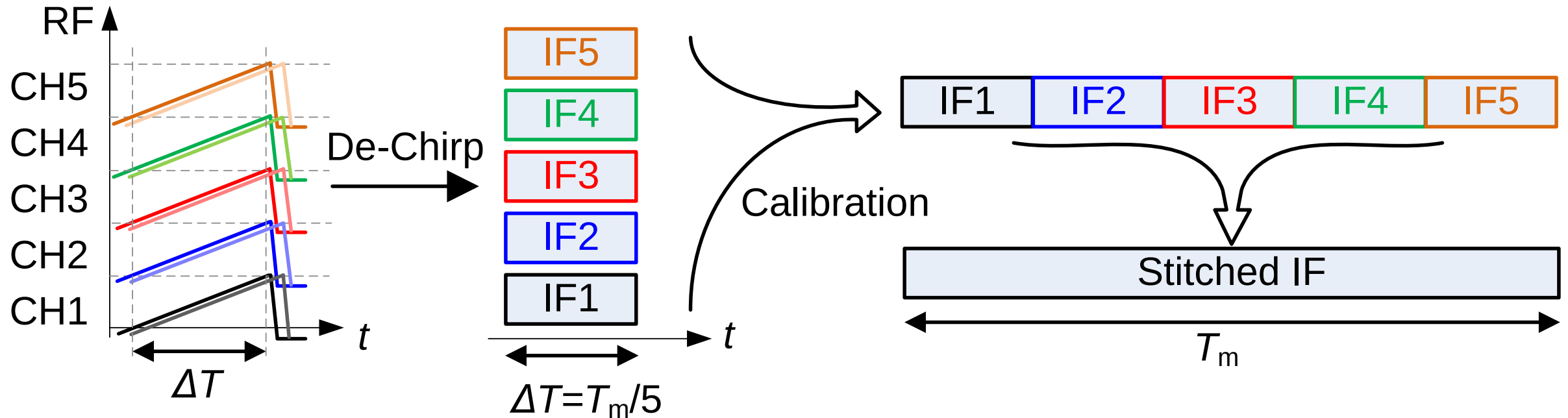
Phase of IF Signals



- The phases of adjacent IF signals are continuous despite of their initial phases

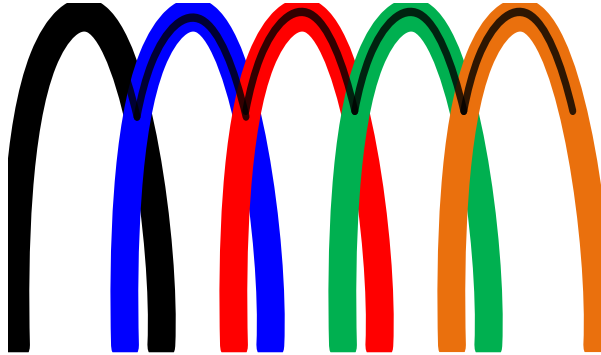
Stitching Process

- IF signals are directly stitched in time domain after calibrations



Compared with Single Channel Radar

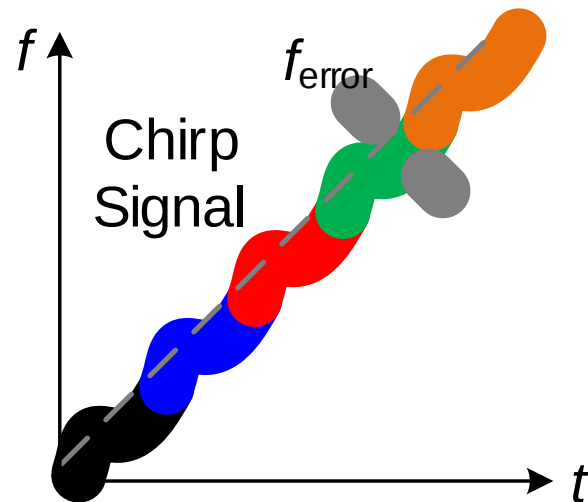
- Flatter frequency responses



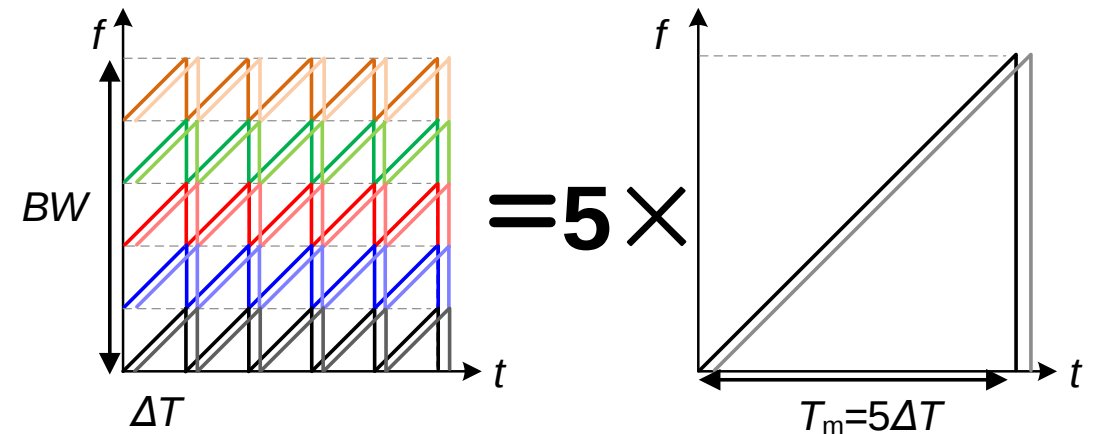
- Finer velocity resolution

$$\Delta v = \frac{\lambda}{2NT_{frame}}$$

- More linear chirp signal



- SNR is improved

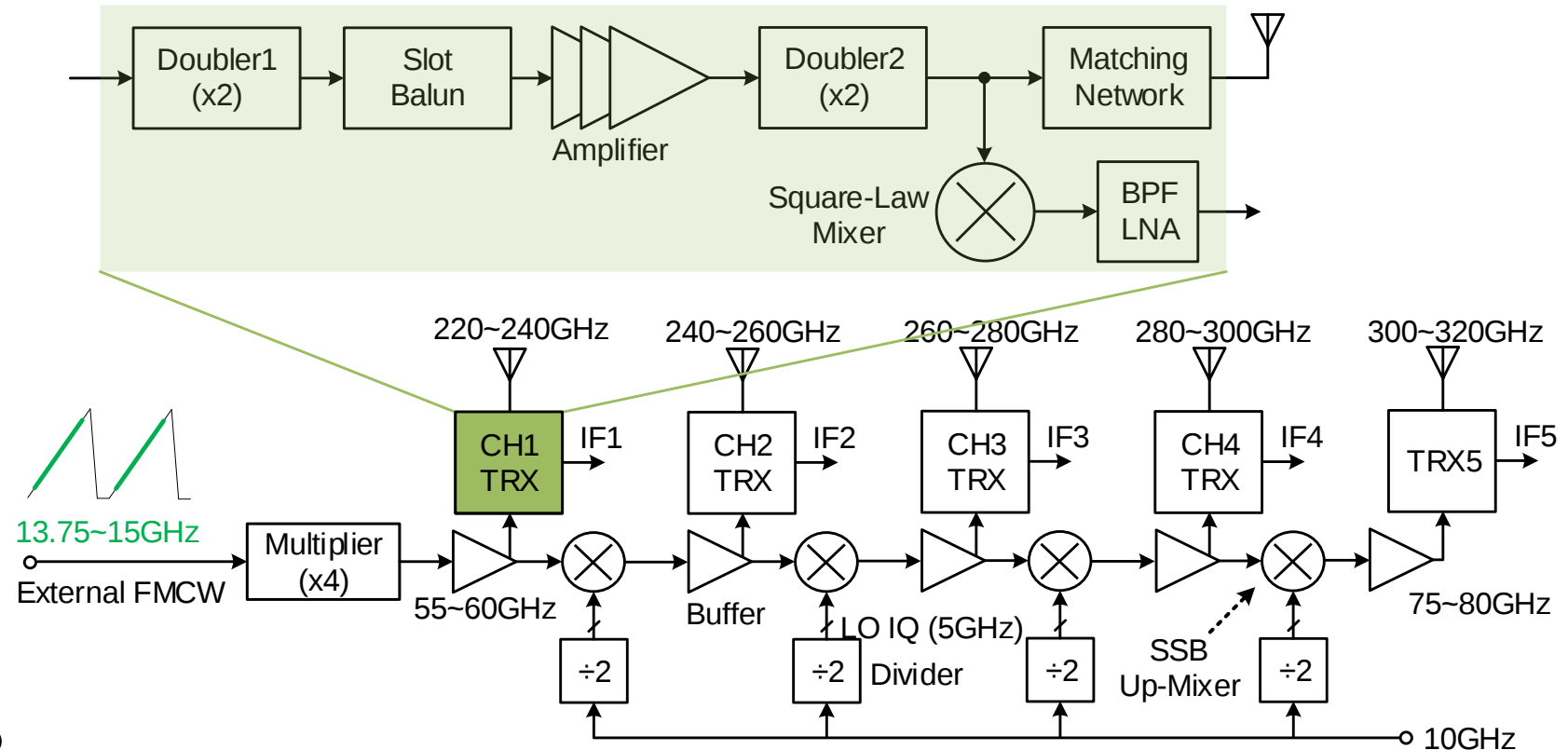


Outline

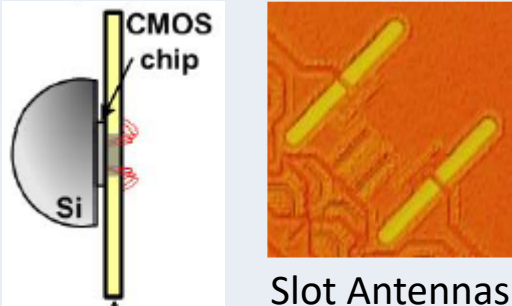
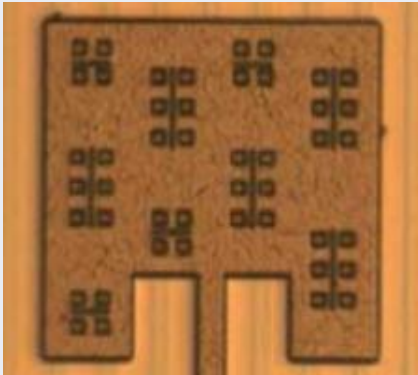
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THz FMCW Comb Radar System Diagram

- Total bandwidth:
 $5 \times 20\text{GHz} = 100\text{GHz}$
- Scalable bandwidth extension
- Single antenna solution for each transceiver: 5 antennas, coupling?

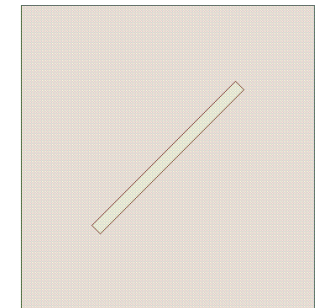
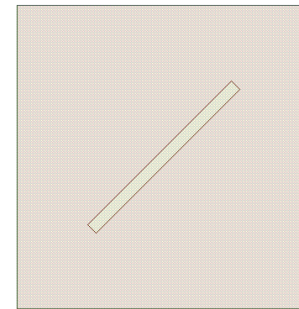
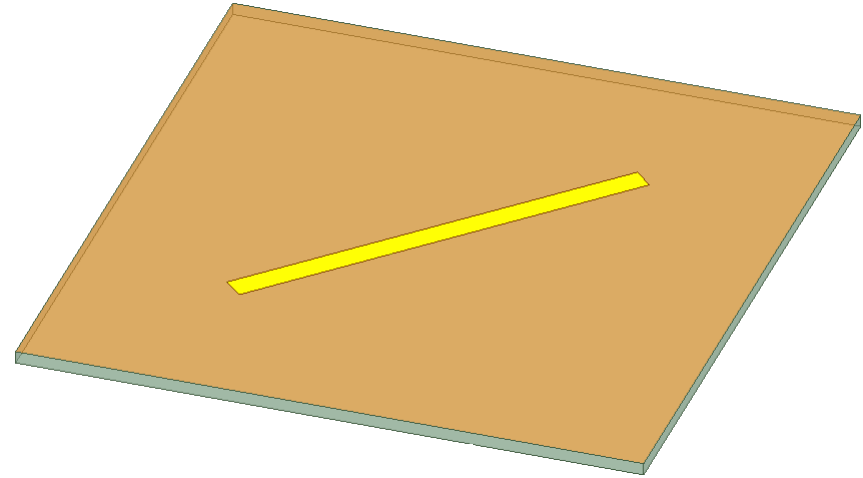
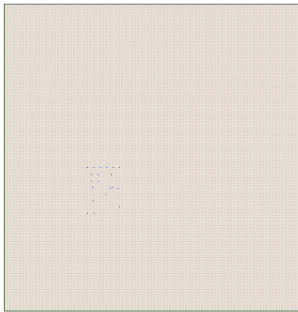
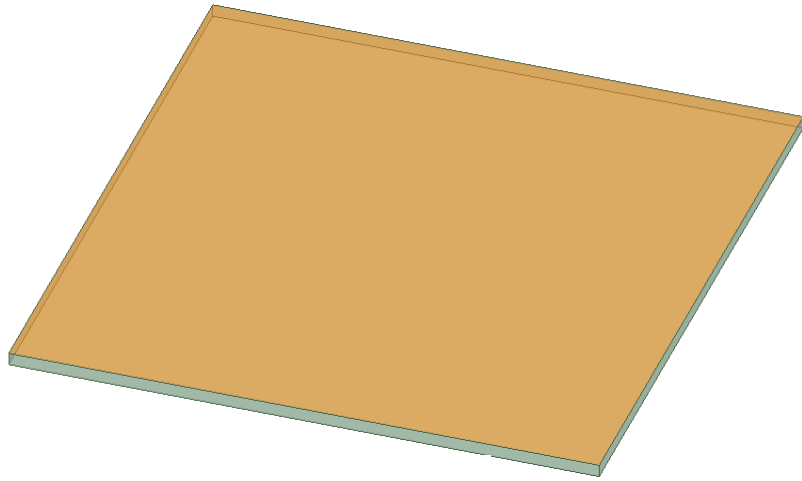


On-Chip Antenna Background

	Slot Antenna	Patch Antenna	Substrate Integrated Waveguide (SIW)
Expensive Silicon Lens	Need 😞	No Need 😊	No Need 😊
Bandwidth	Wide 😊	Narrow 😞	Narrow 😞 ?
Inter-Antenna Coupling	Medium 😊	Large 😞	Small 😊
Example	 Slot Antennas [R. Han, ISSCC 2012]	 [R. Han, JSSC 2013]	 [S. Hu, JSSC 2012]

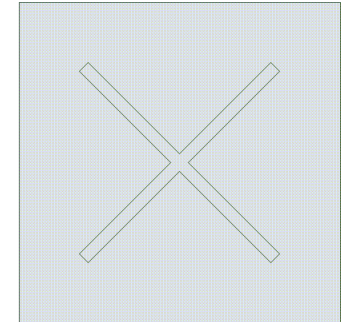
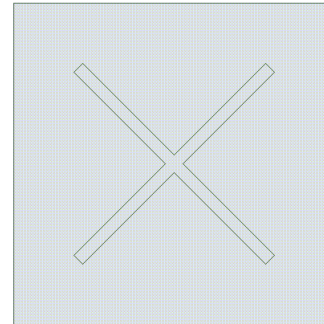
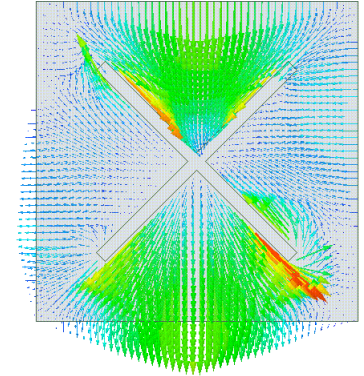
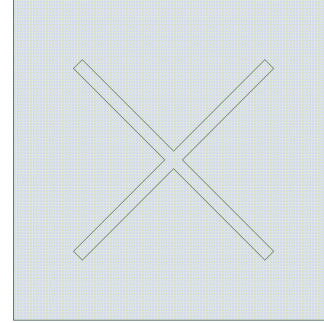
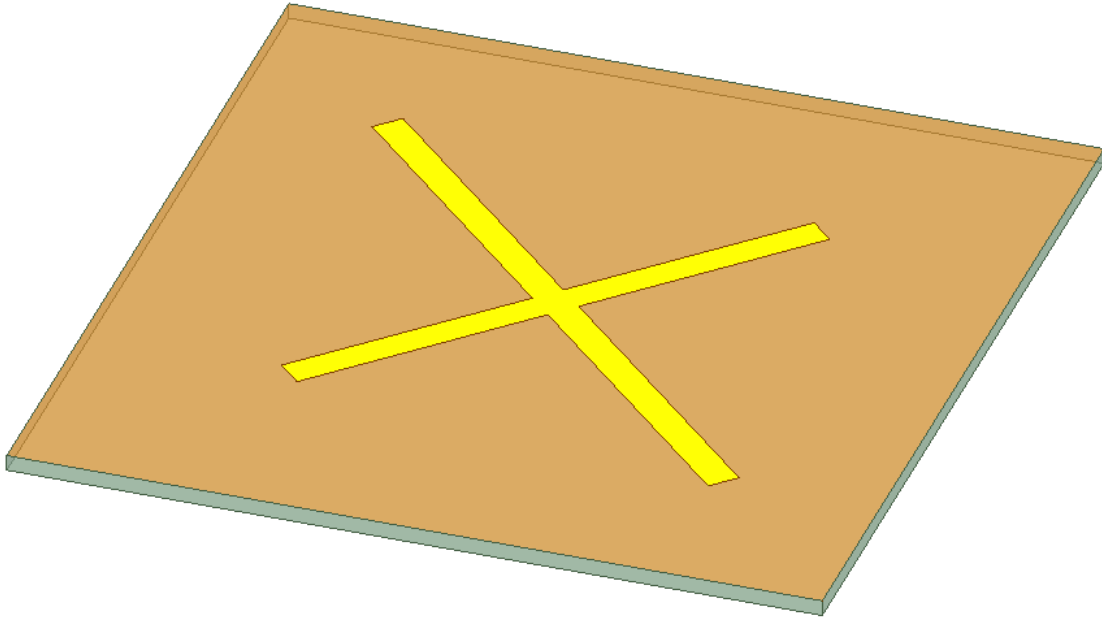
SIW Cavity and Slot

- Eigenmode simulation



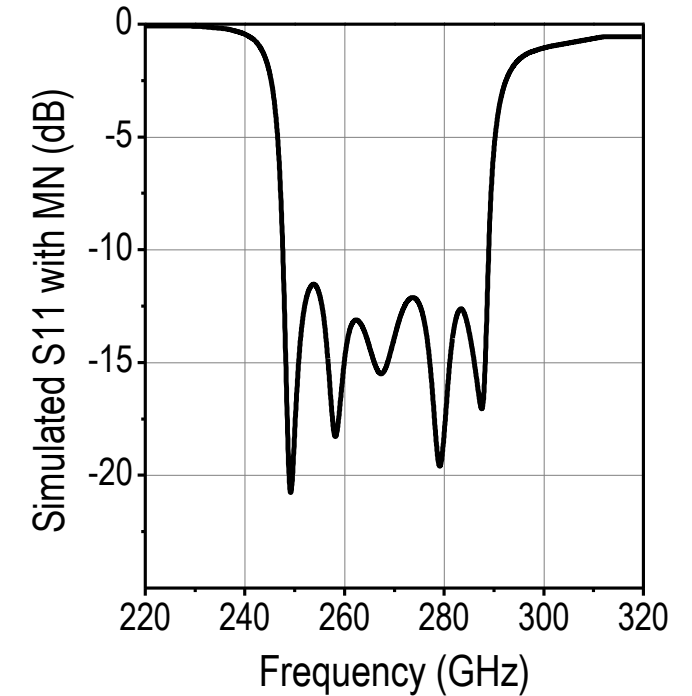
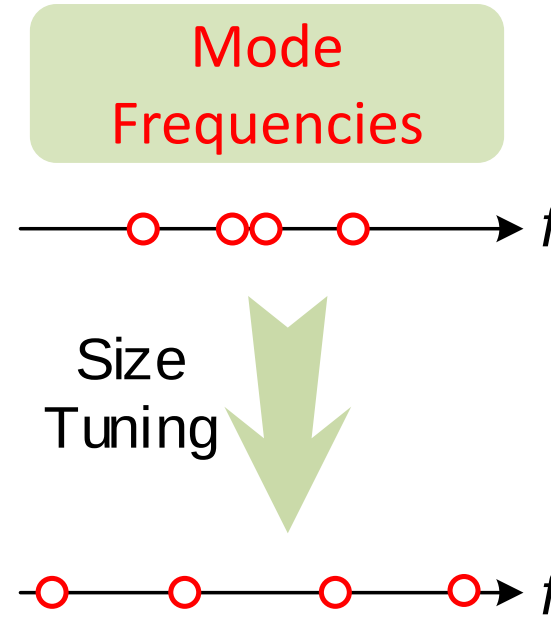
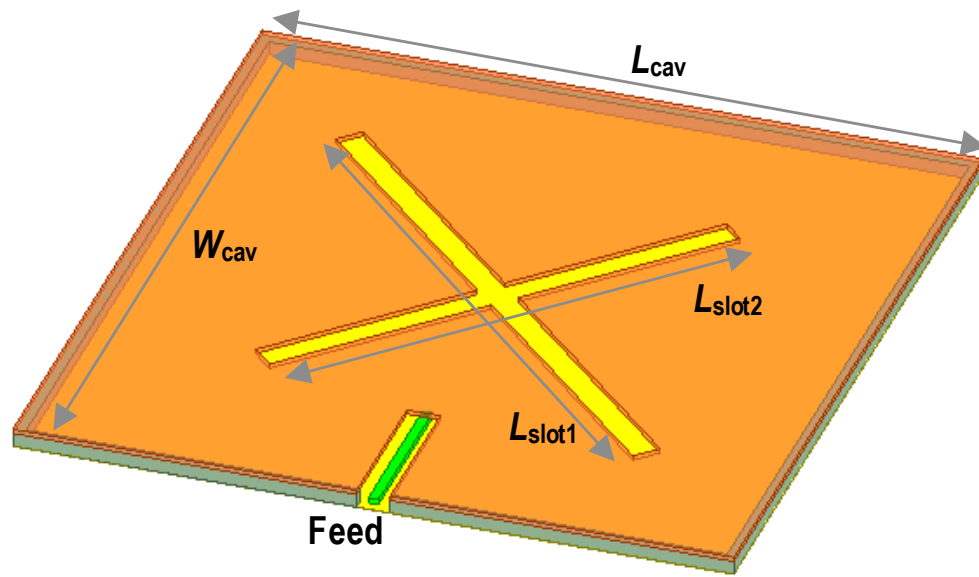
SIW Cavity with Orthogonal Slots

- Four modes



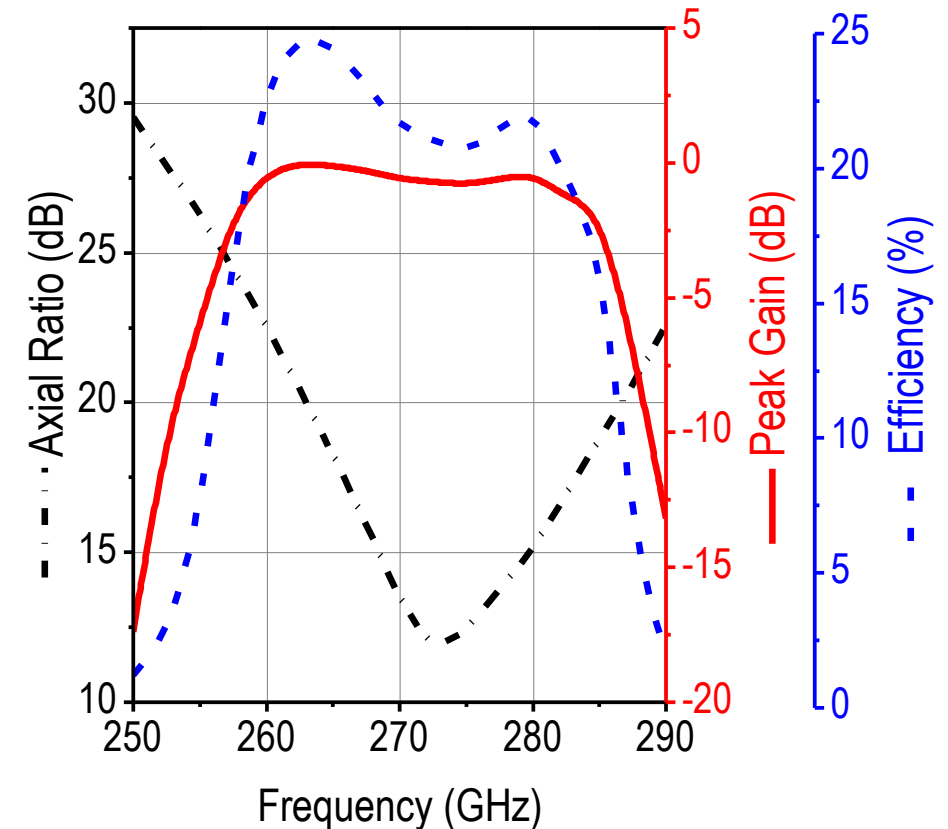
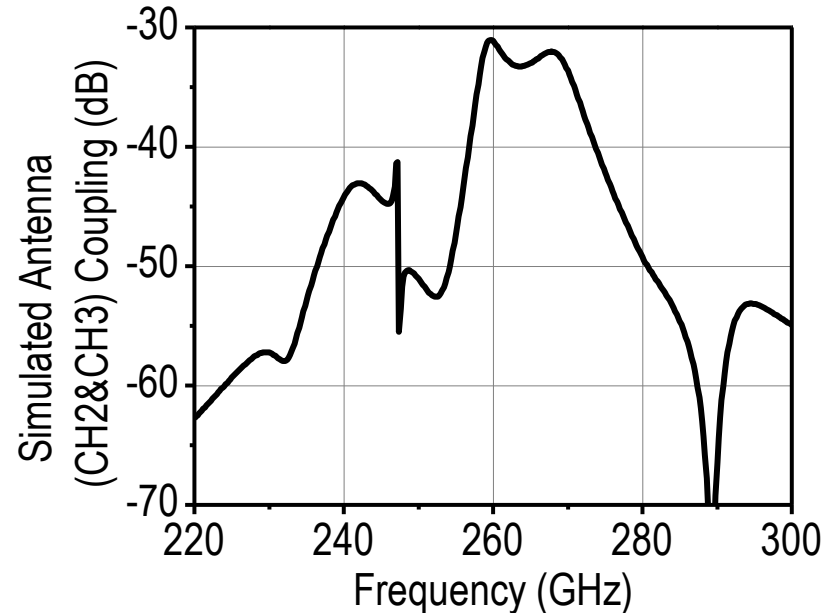
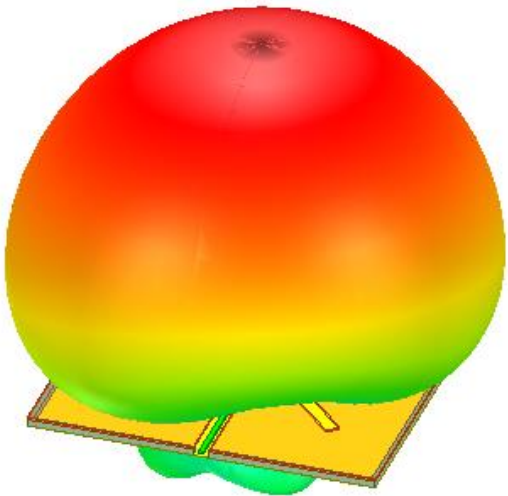
SIW Orthogonal Slot Antenna

- Multiple resonant modes due to orthogonal slots in SIW cavity
- Tune size parameters to arrange mode frequencies

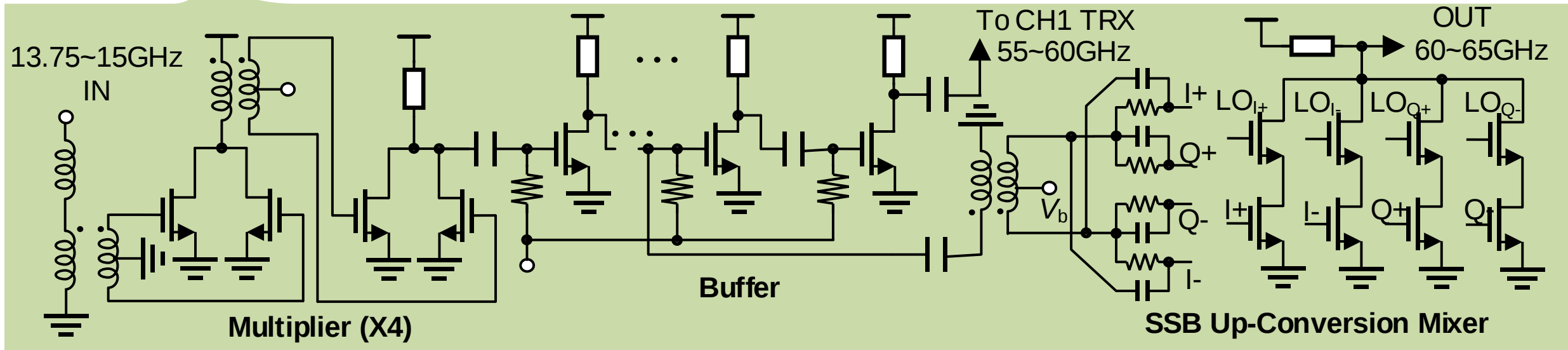
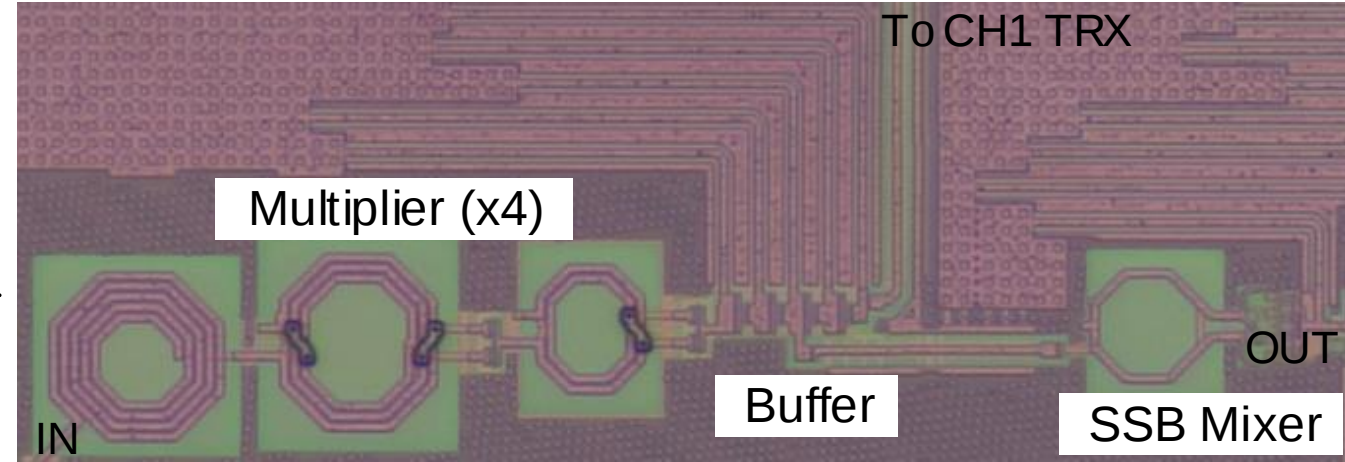
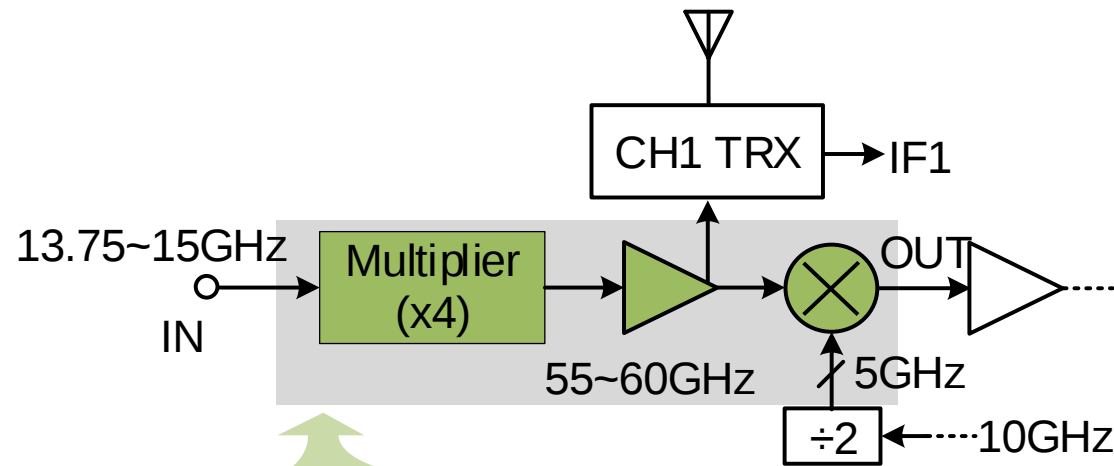


SIW Orthogonal Slot Antenna

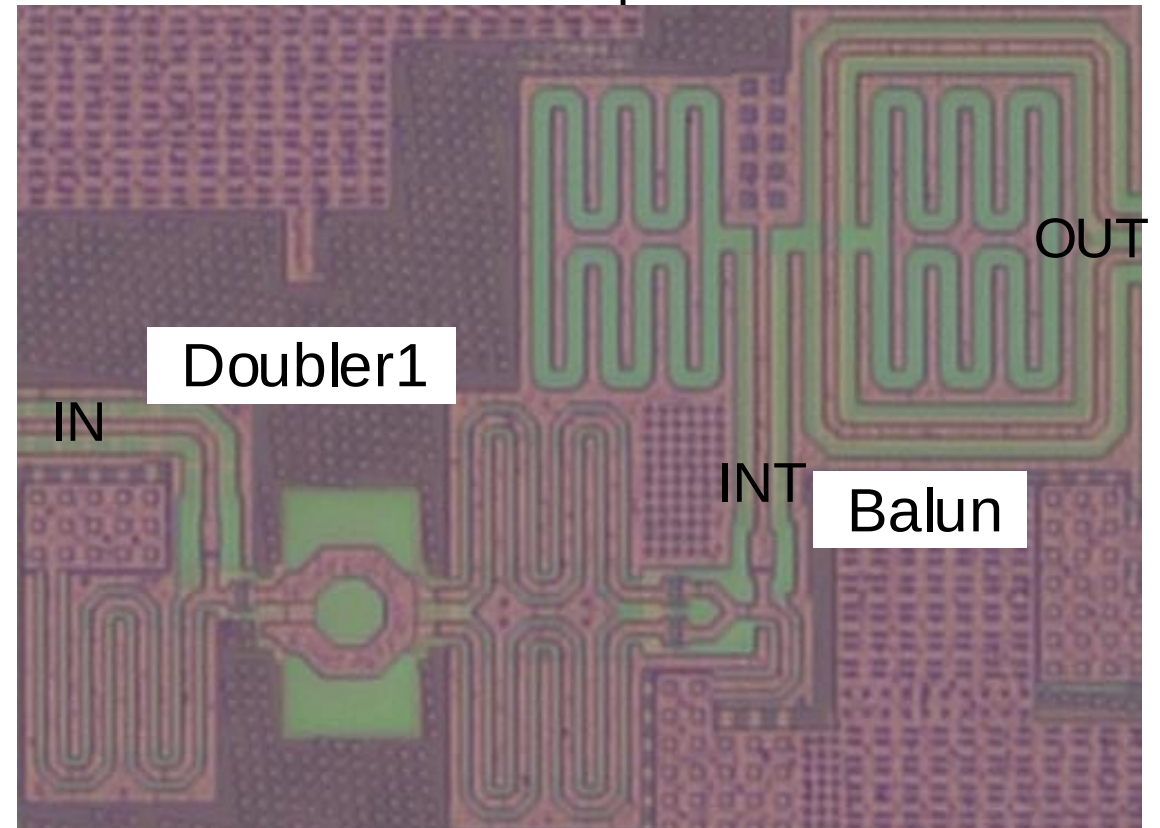
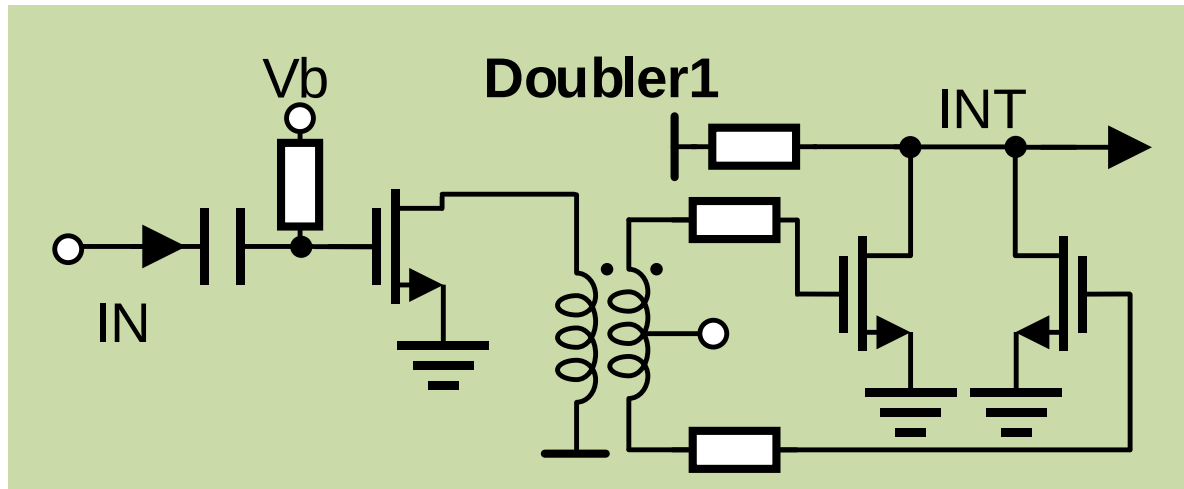
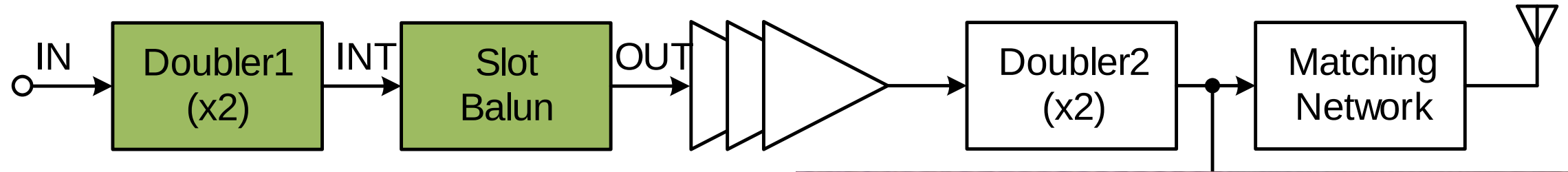
- Wide bandwidth ($\sim 40\text{GHz}$, 14.8%)
- 0dBi peak gain
- Linear polarization (axial ratio $> 11.6\text{dB}$)
- Low coupling ($< -31\text{dB}$)
- 20.5% efficiency



Input Multiplier, Buffer, and SSB Mixer

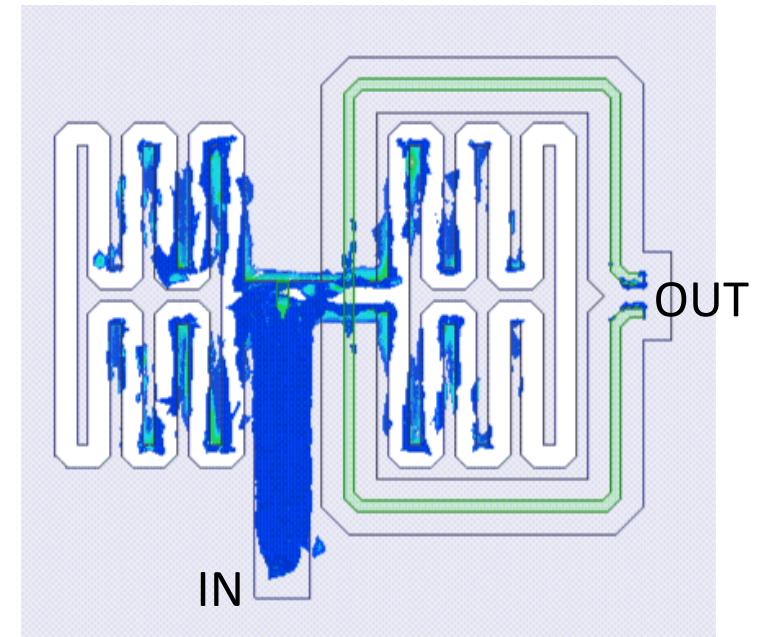
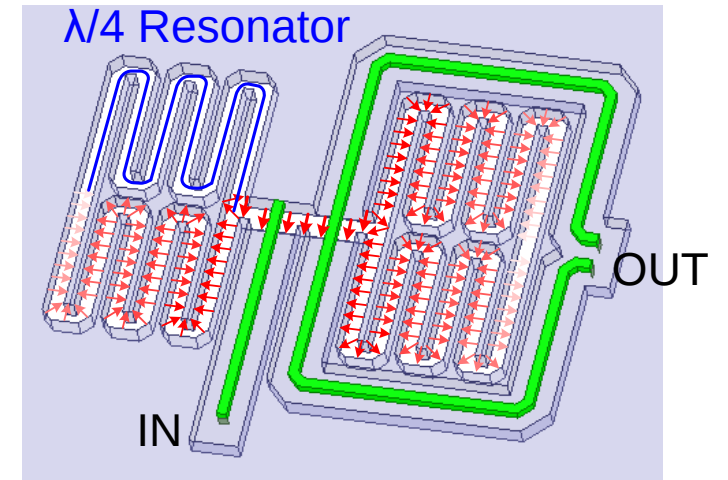
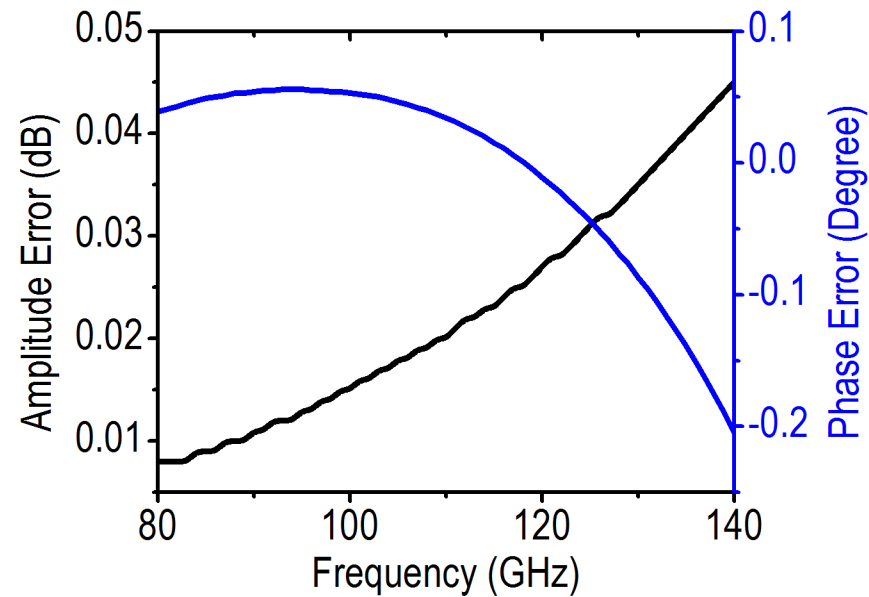
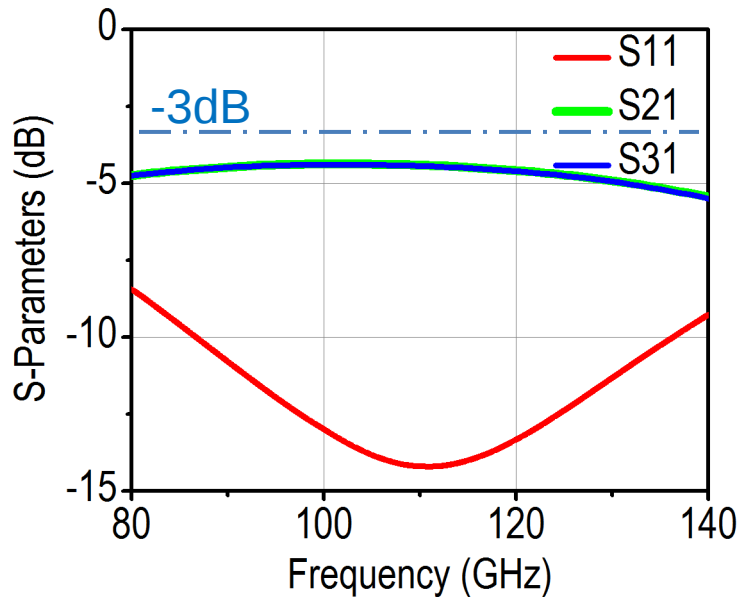


Doubler1 and Folded Slot Balun

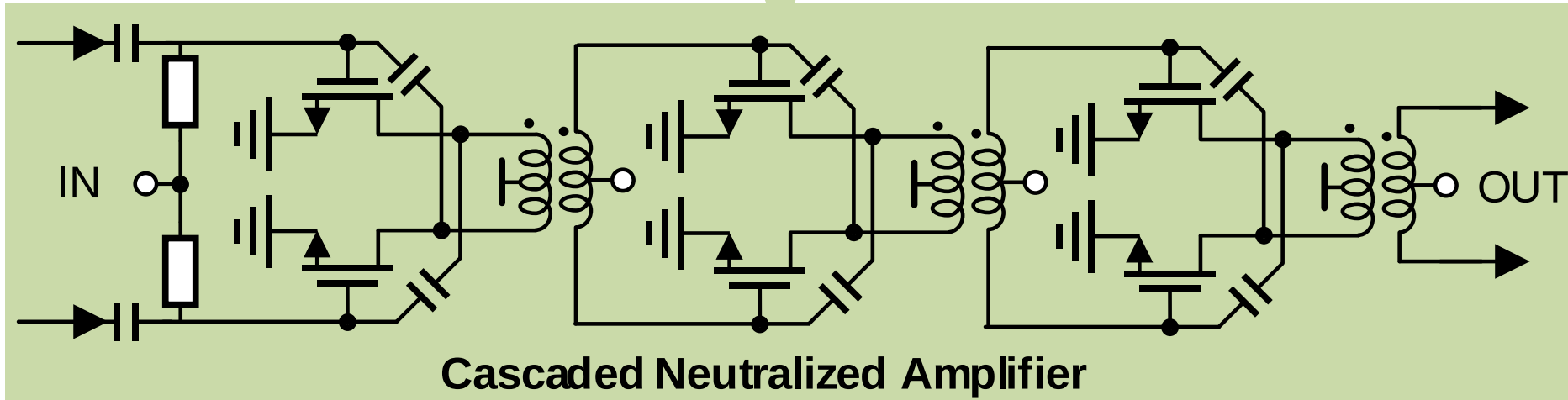
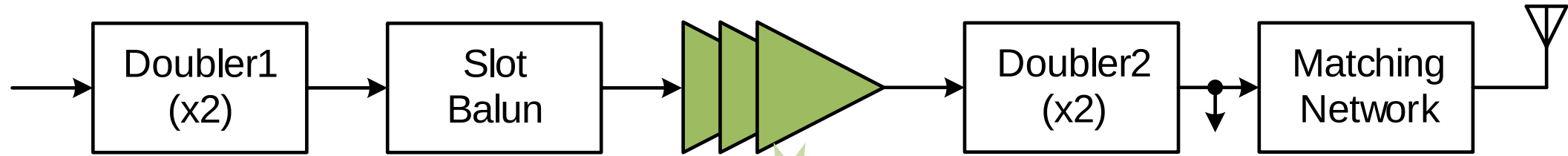


Folded Slot Balun

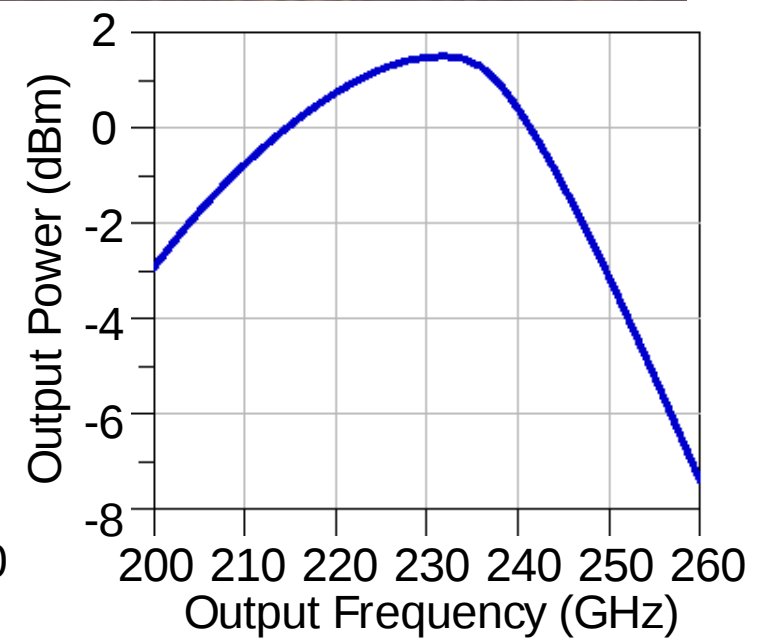
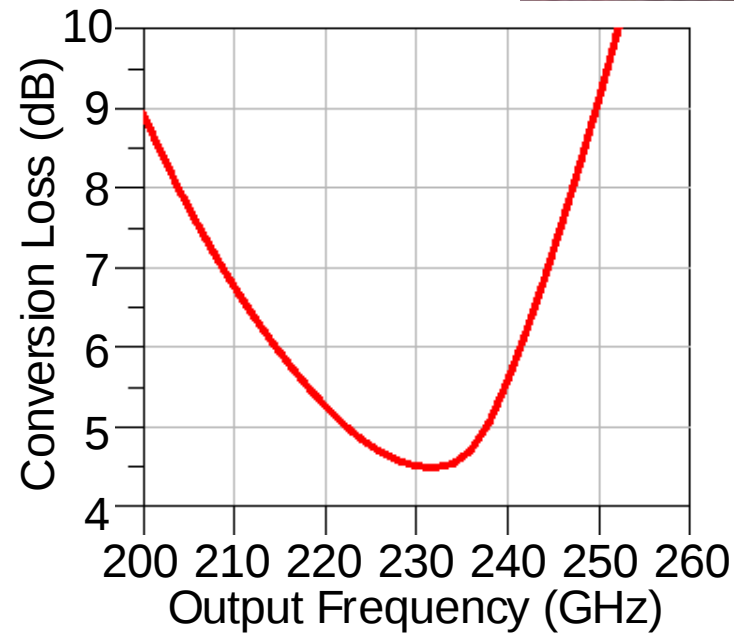
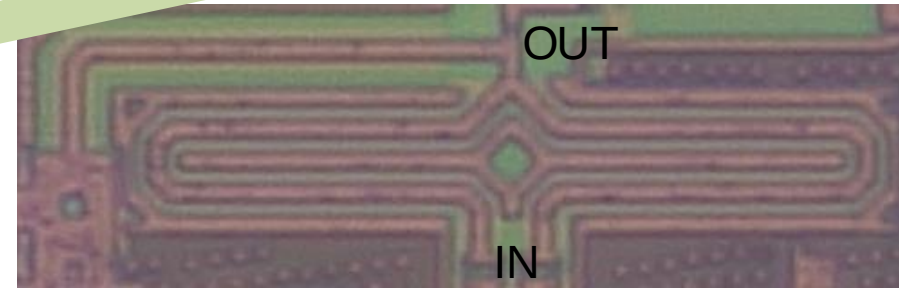
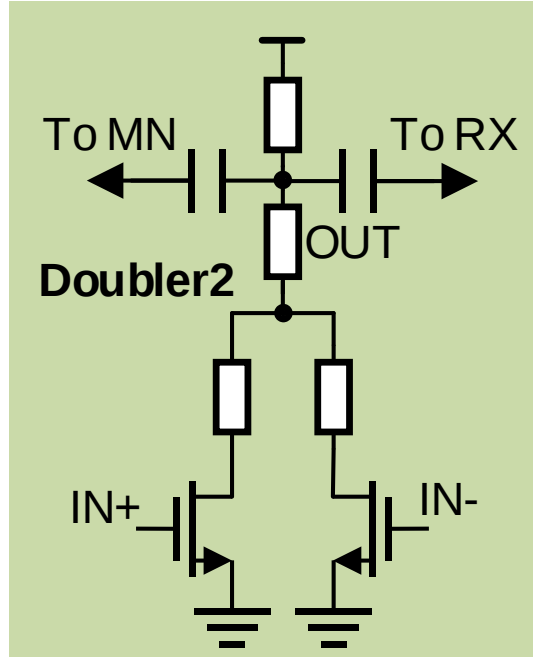
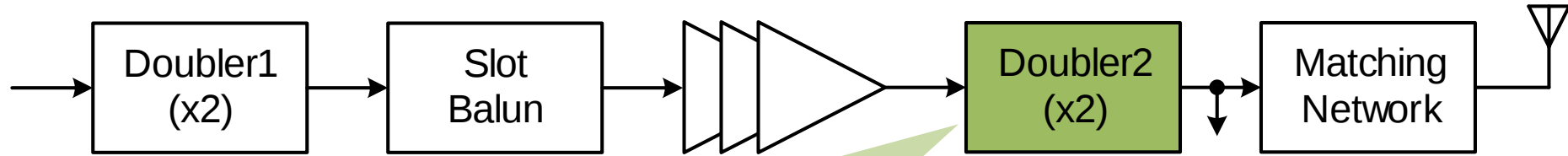
- Nearly perfect differential output
 - 50GHz (45%) bandwidth
 - 1.3dB insertion loss
 - 0.05dB/0.5° amplitude/phase errors



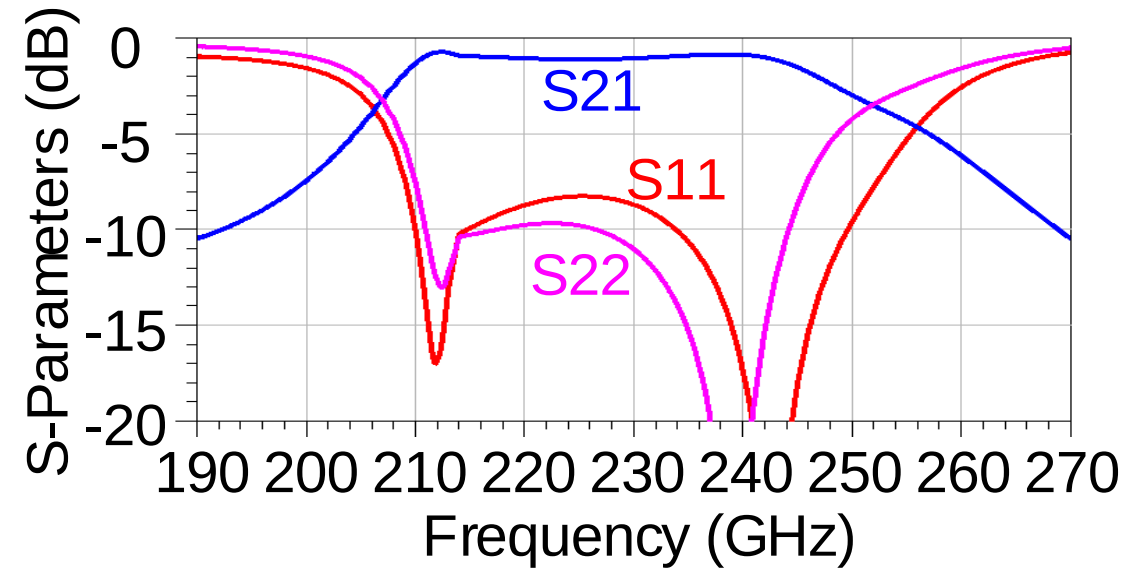
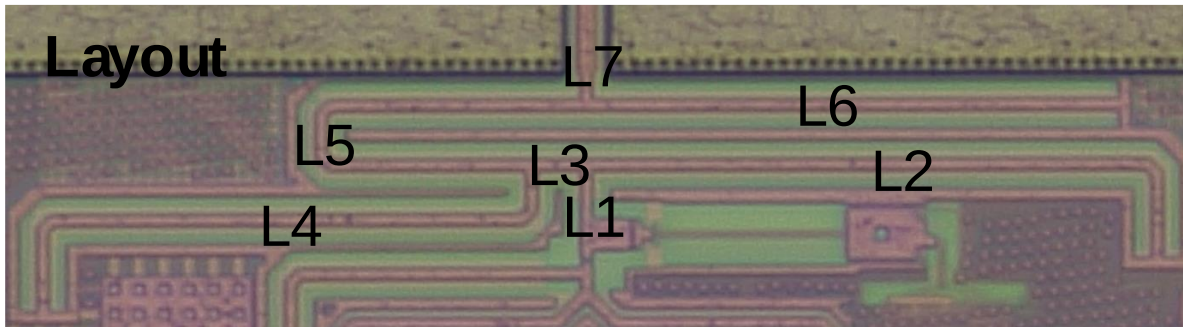
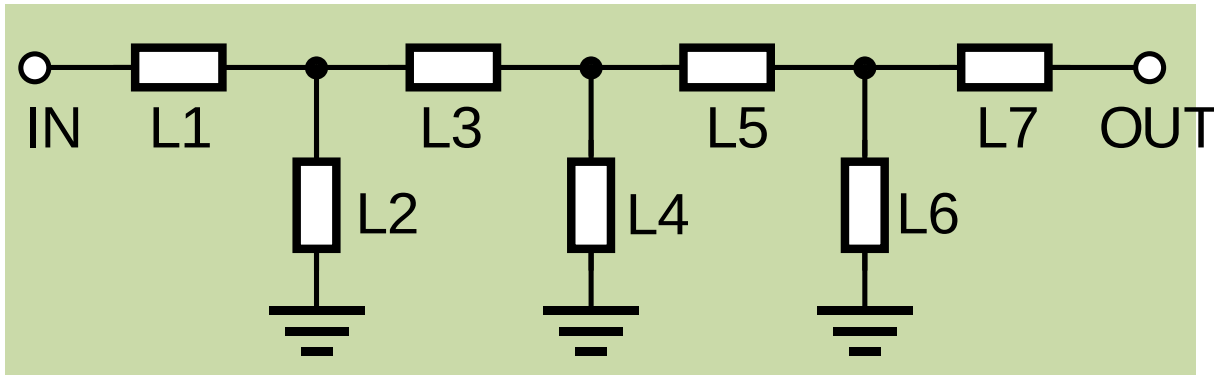
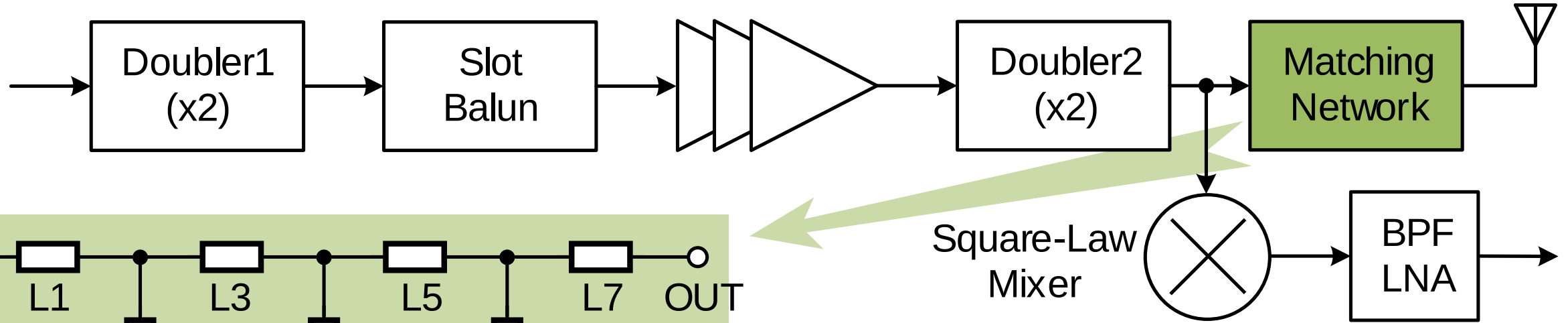
Cascaded Neutralized Amplifier



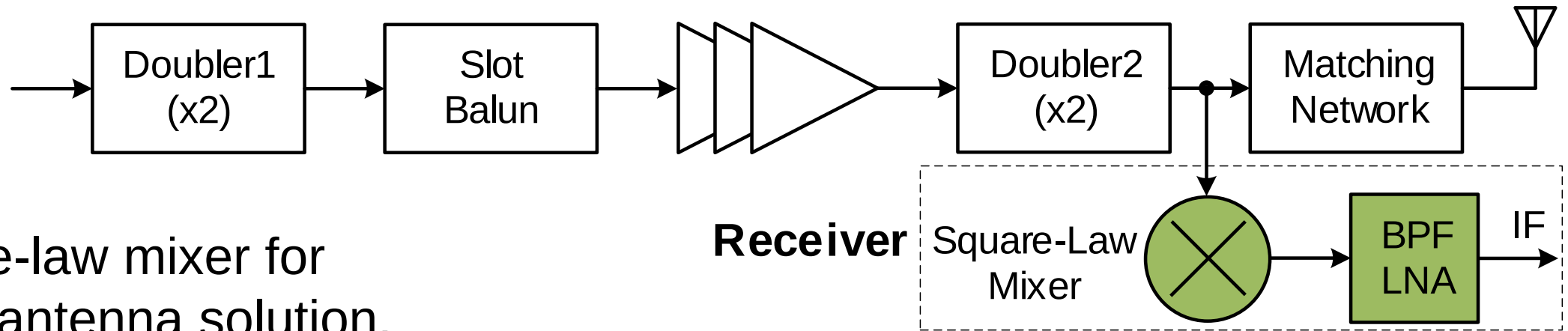
Doubler2



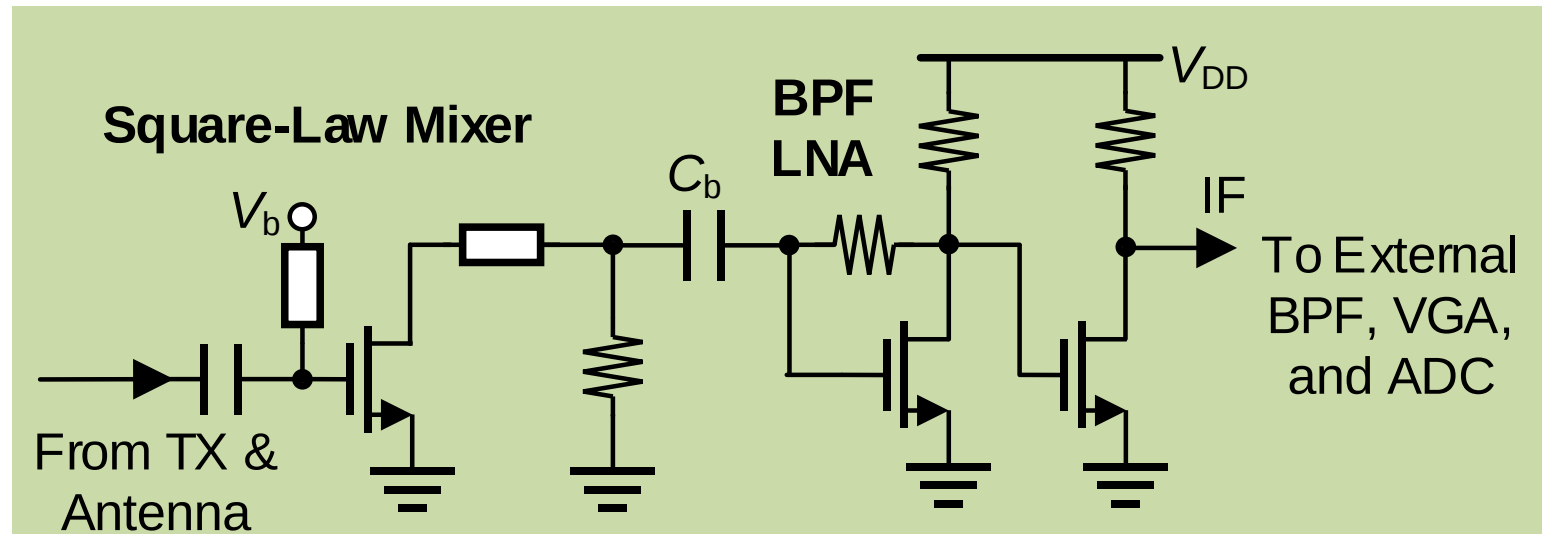
Multi-Stub Matching Network



Receiver



- Square-law mixer for single antenna solution, passive circuit for smaller flicker noise
- Self-biased LNA with high-pass input to suppress unwanted low frequency components

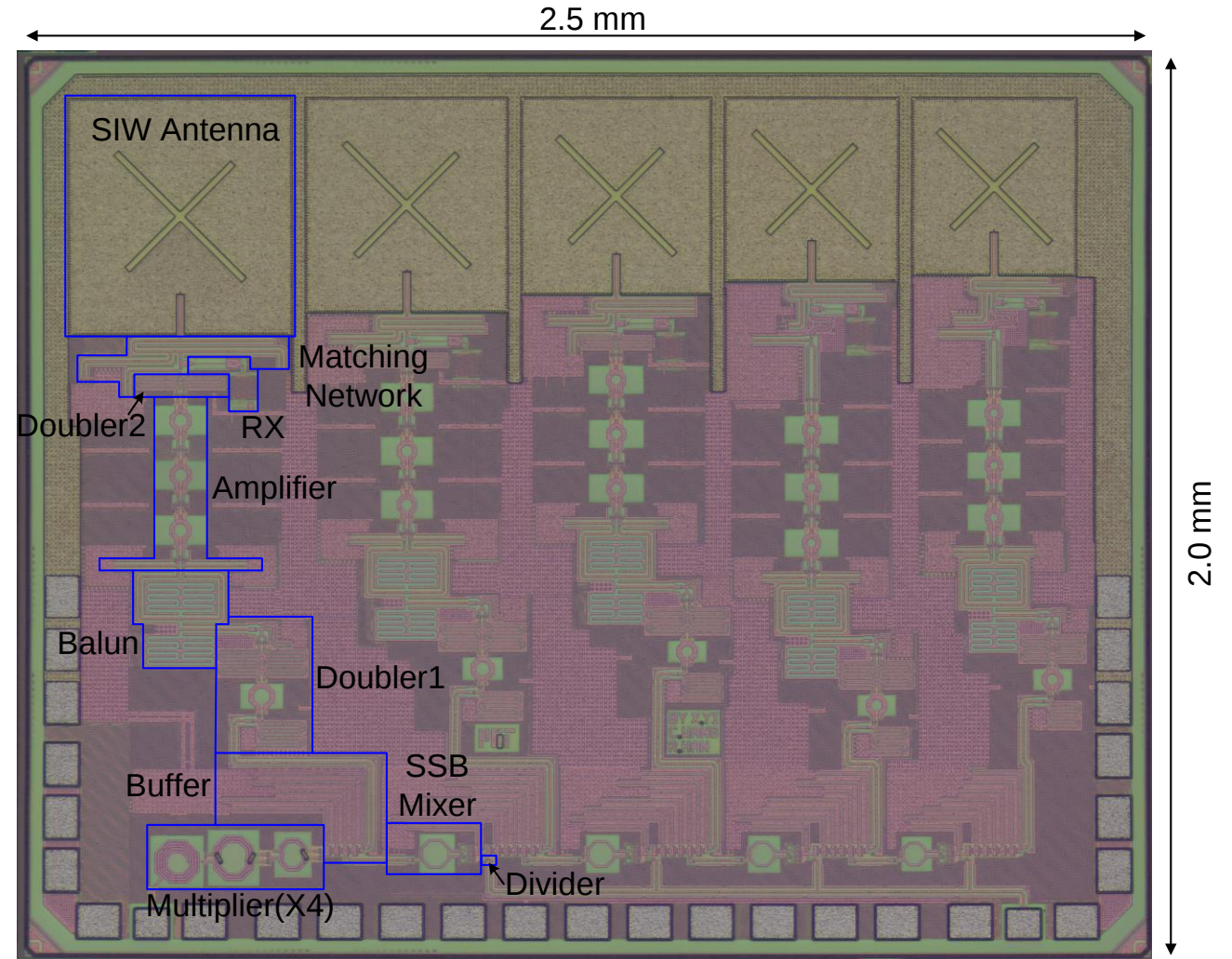
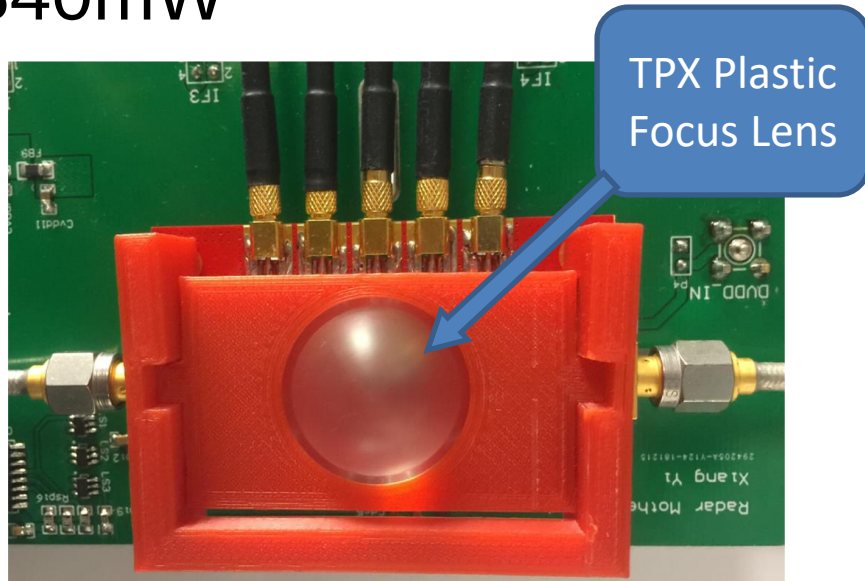


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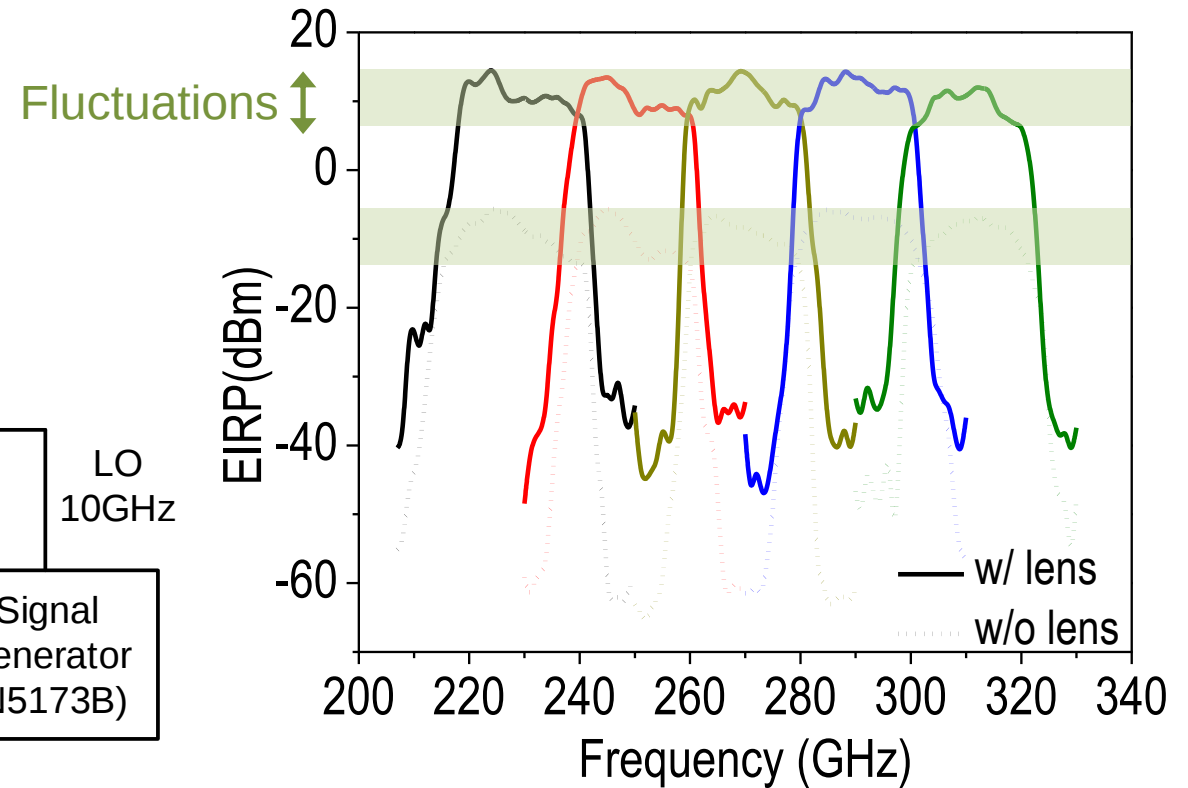
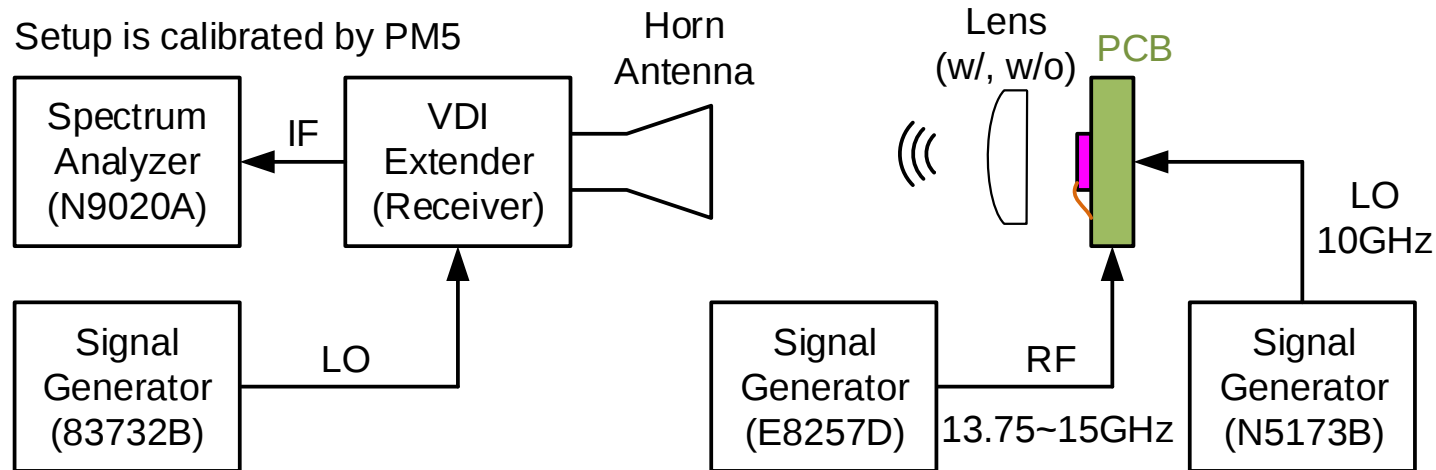
Chip and PCB Photograph

- TSMC 65nm bulk CMOS technology
- Area: 2.5mm by 2.0mm
- Total power consumption: 840mW



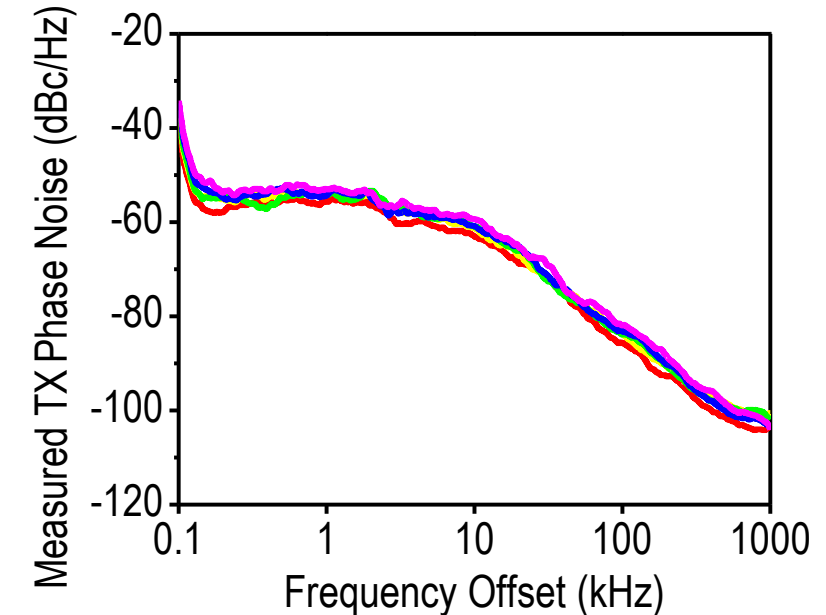
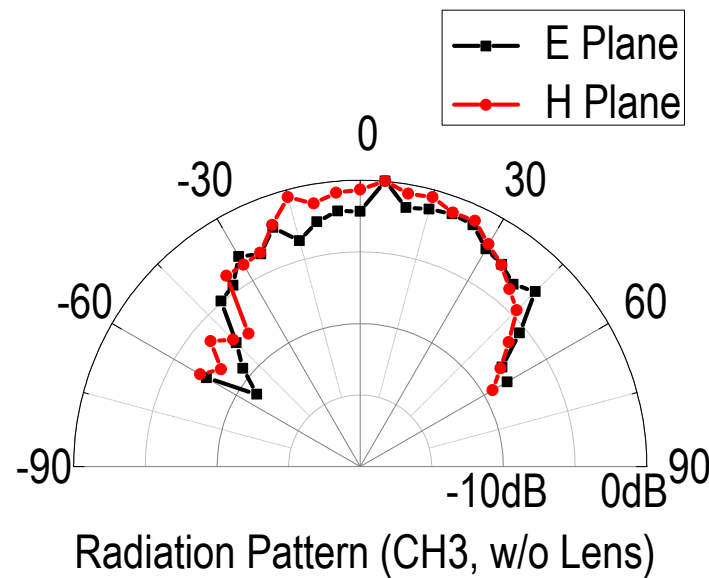
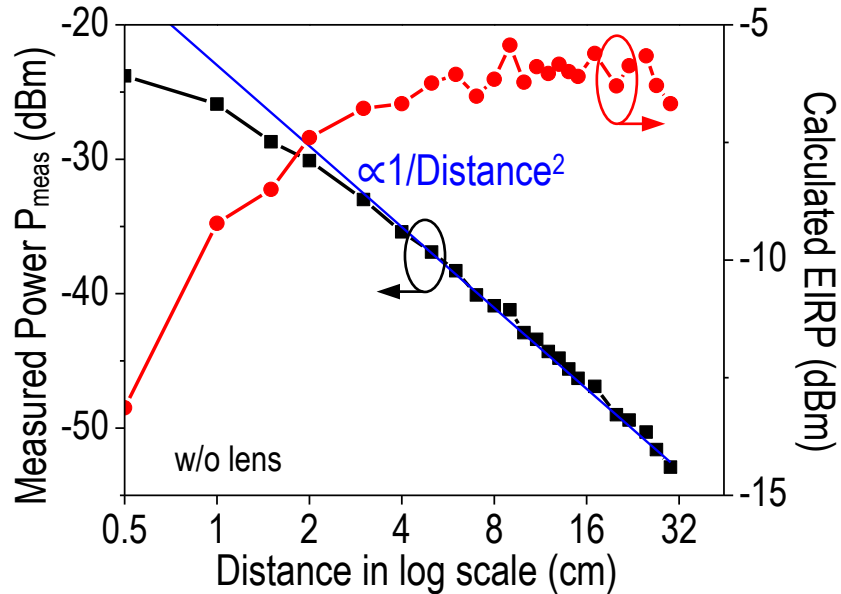
Transmitter Mode Measurement

- Total EIRP without lens: 0.6dBm
- Total EIRP with lens: 20dBm
- Fluctuations: within 8.8dB



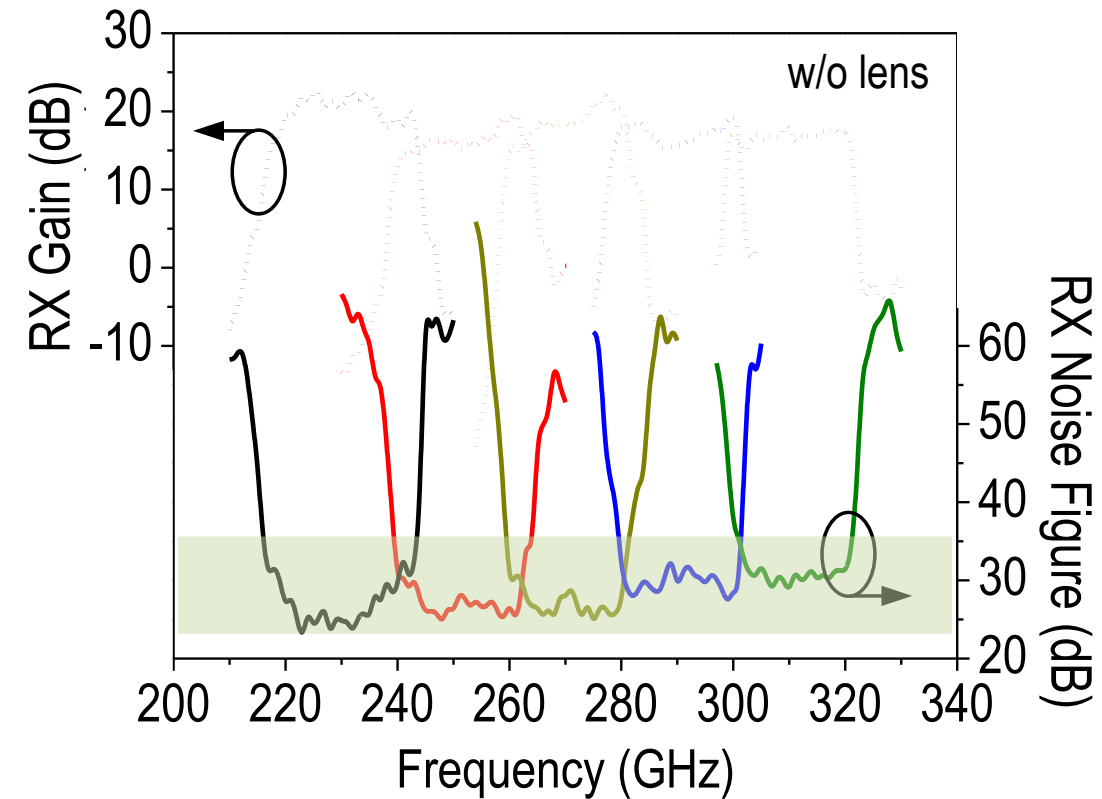
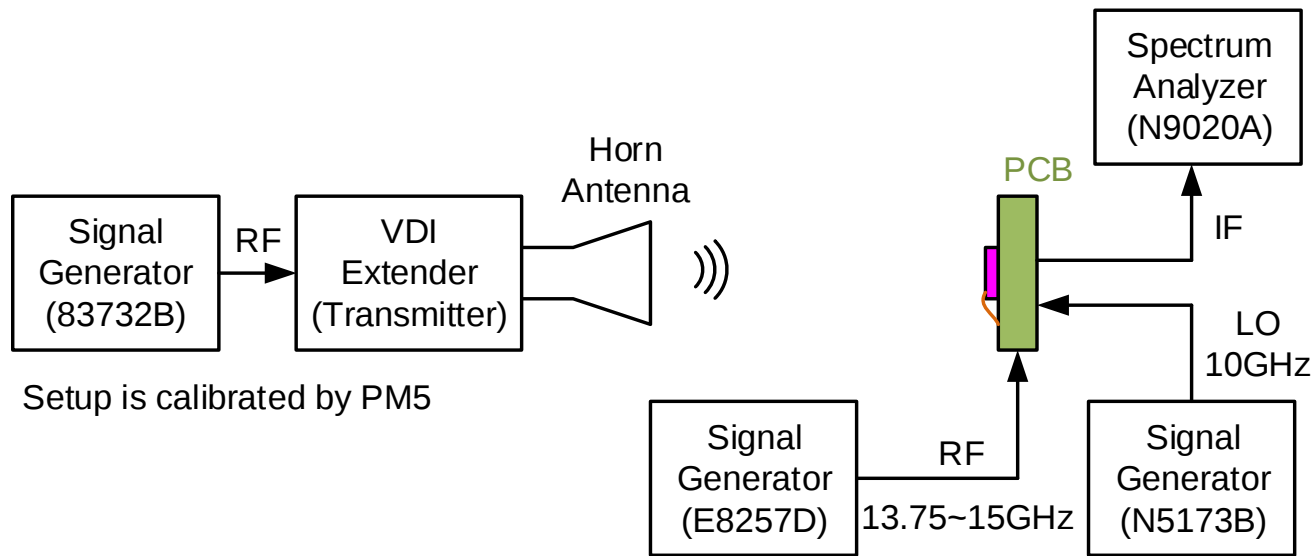
Transmitter Mode Measurement

- Friis equation is met at far-field
- Antenna radiation pattern 3dB beamwidth: 90°
- Phase noise: better than -100dBc/Hz @1MHz

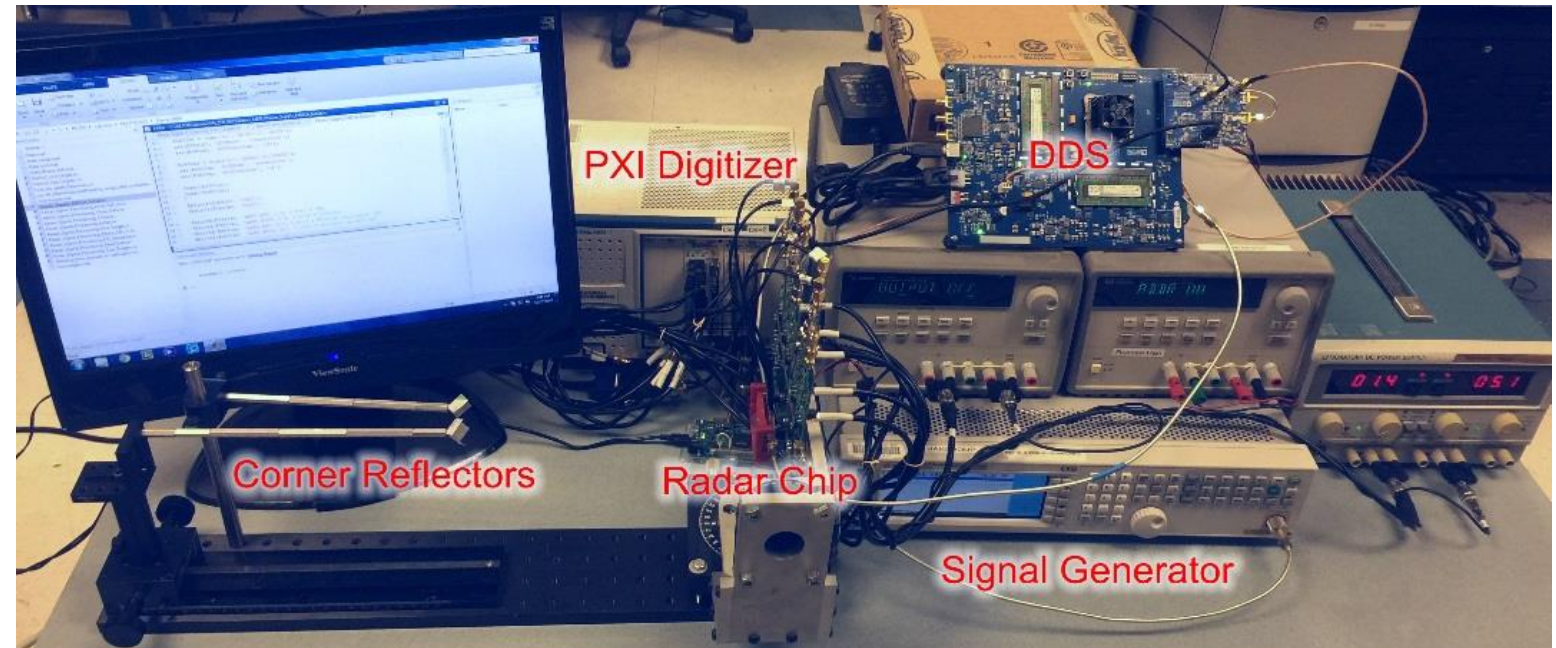
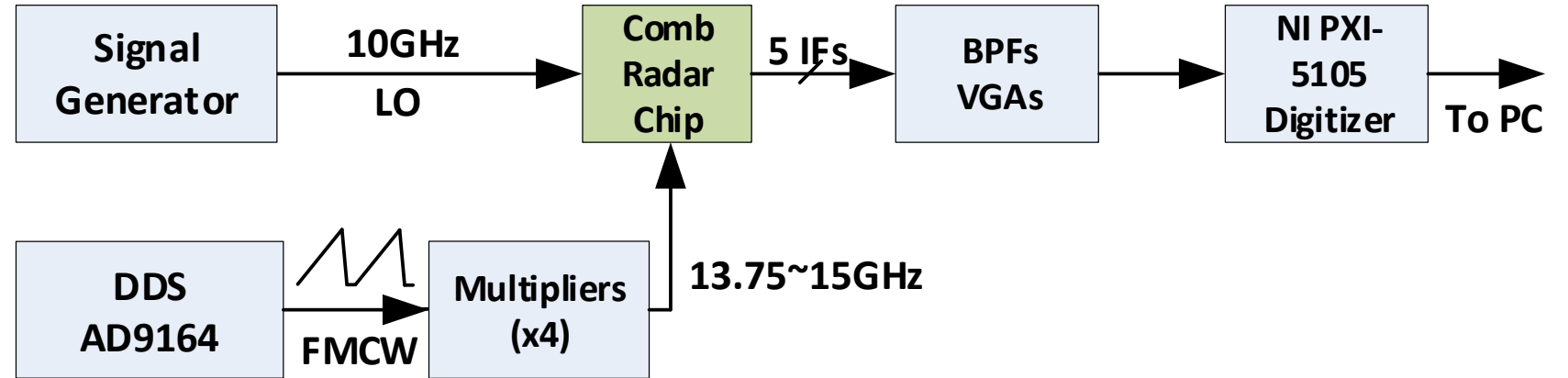
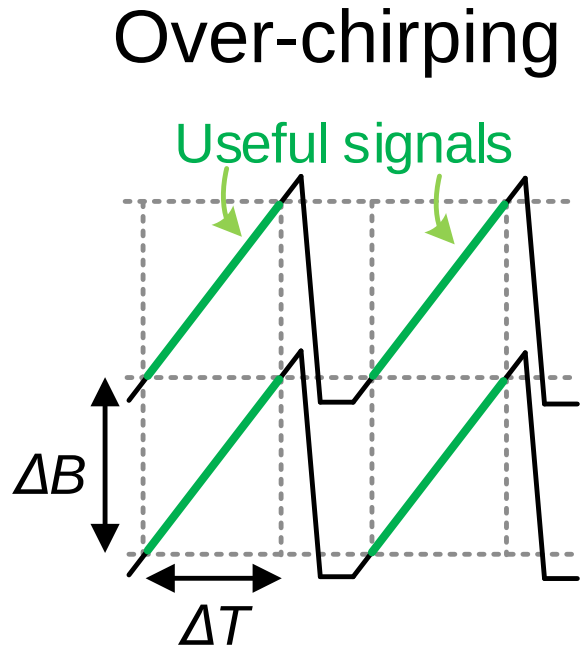


Receiver Mode Measurement

- Minimum SSB NF including antenna loss: 22.8dB
- Fluctuation of NF: 14.6dB
- Receiver gain: 22.2dB

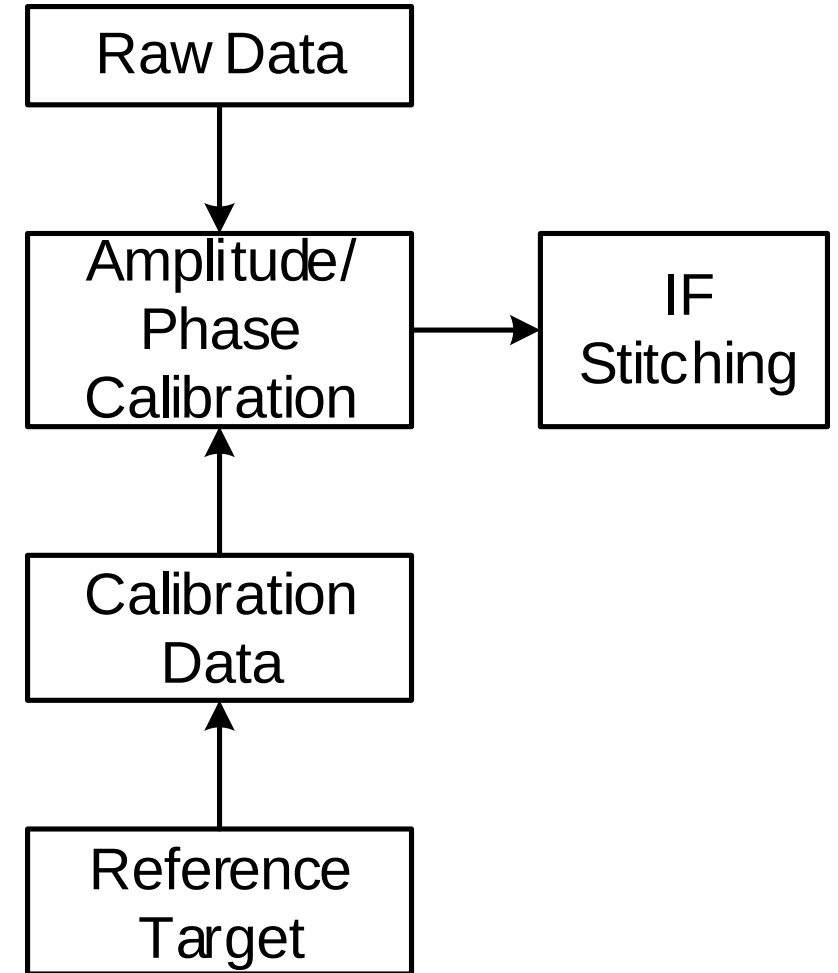


THz FMCW Radar Measurement Setup



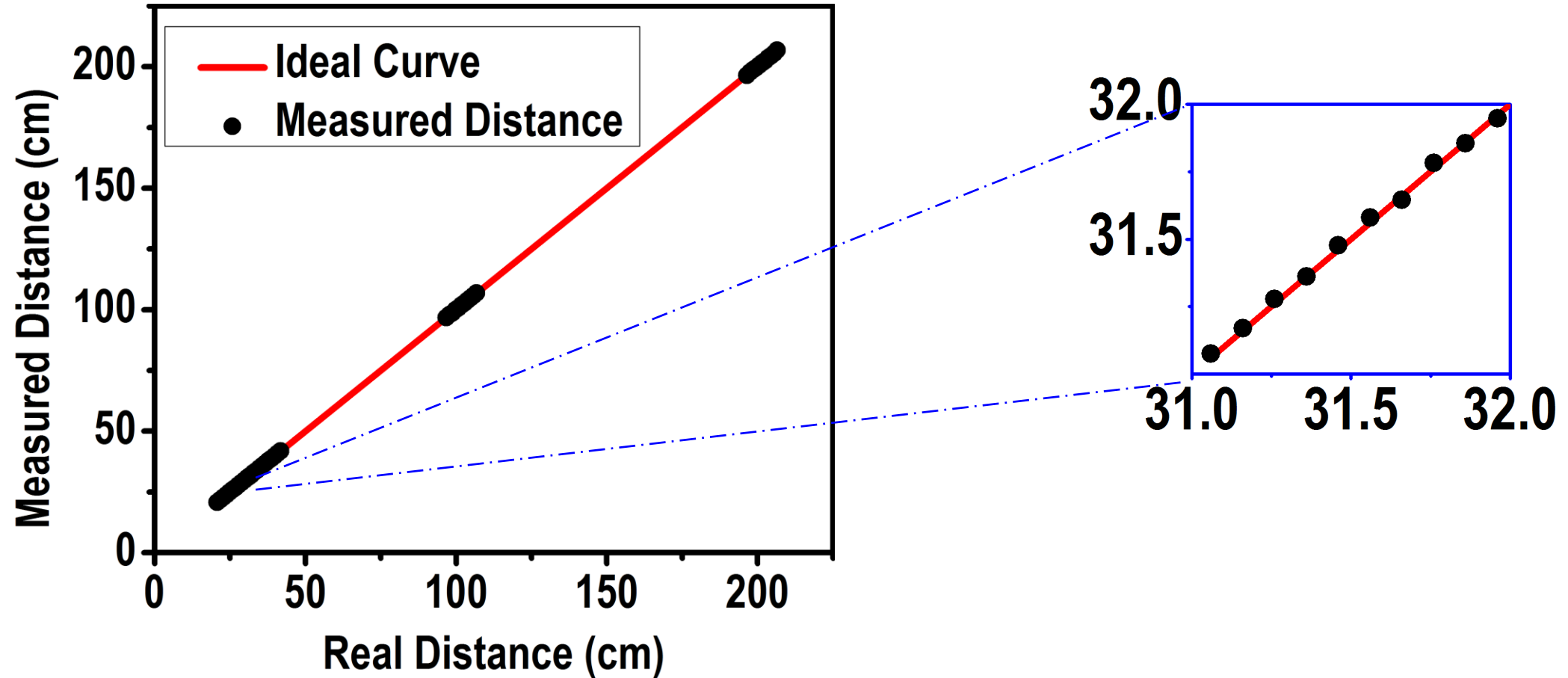
Radar Signal Calibration

- Amplitude mismatch
 - Gain mismatch among channels
- Phase mismatch
 - Matching network delay mismatch: fixed
 - Antenna off-axis: range should be large ($>20\text{cm}$)
- Calibration method [J. Grajal, TMTT 2015]
 - Reference: one single-point like target
 - One-time calibration



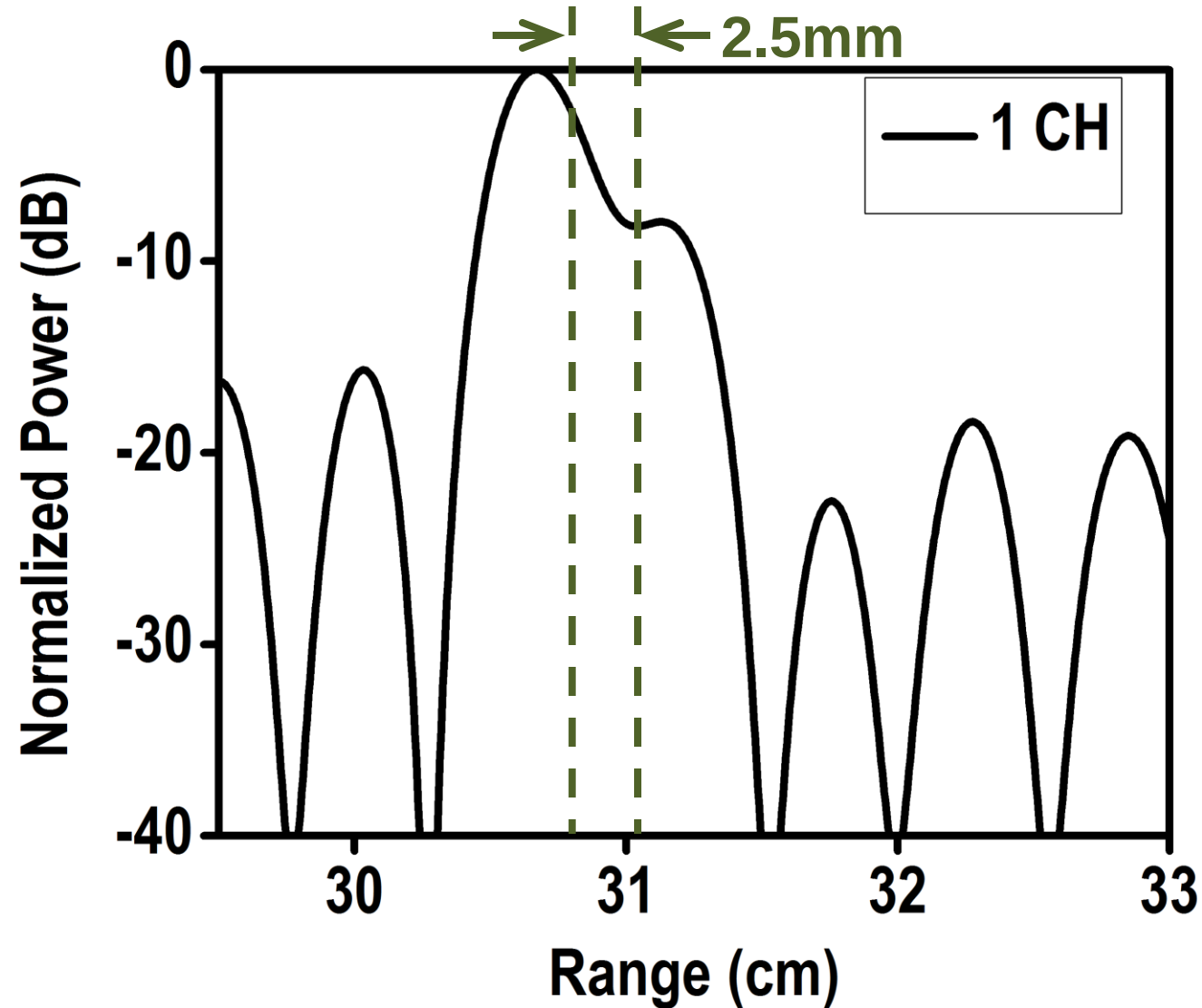
Range Accuracy Measurement

- Measured distance matches real distance



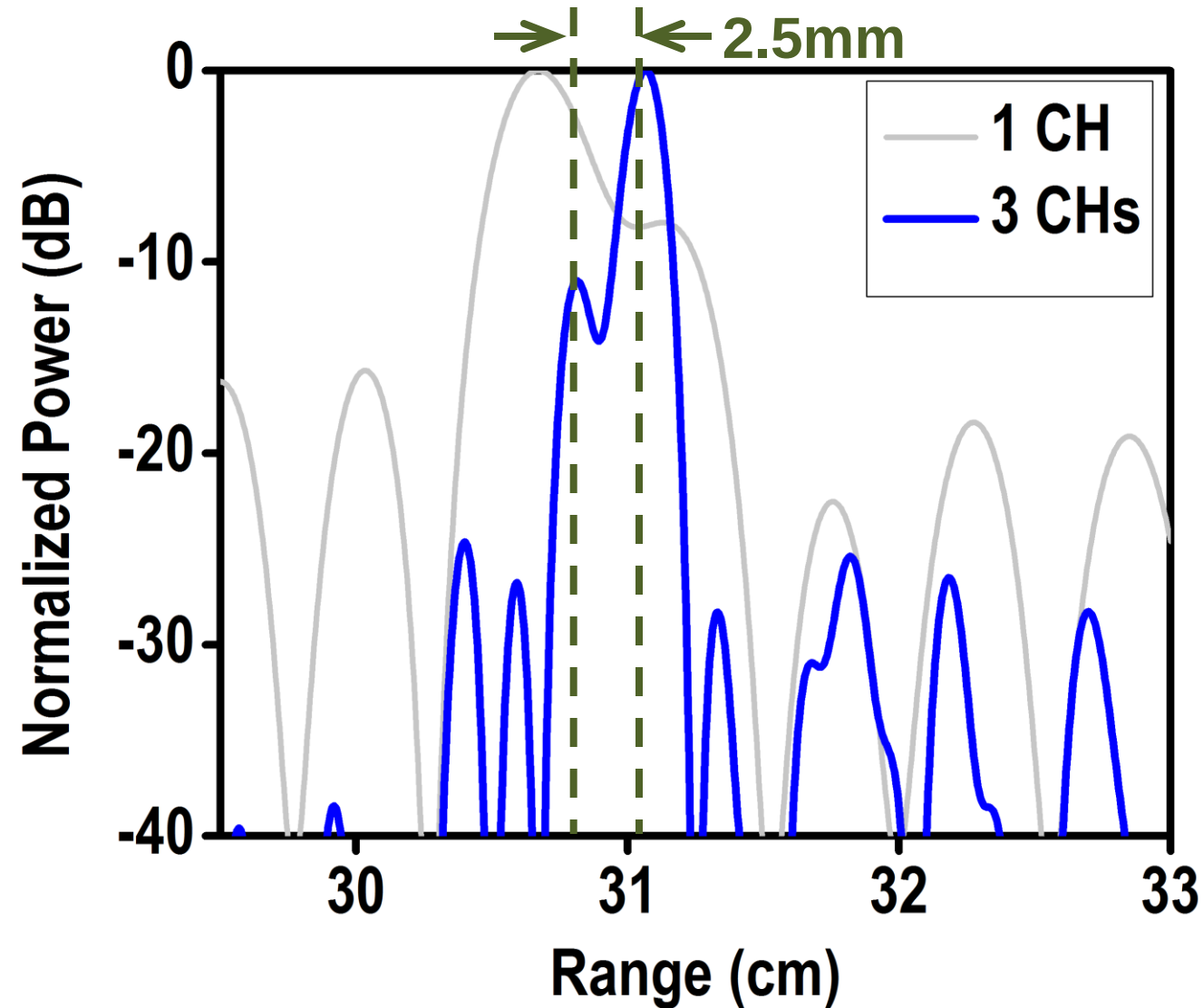
Range Resolution Measurement

- Two targets with 2.5mm distance
- Hamming window
- One channel
- 20GHz



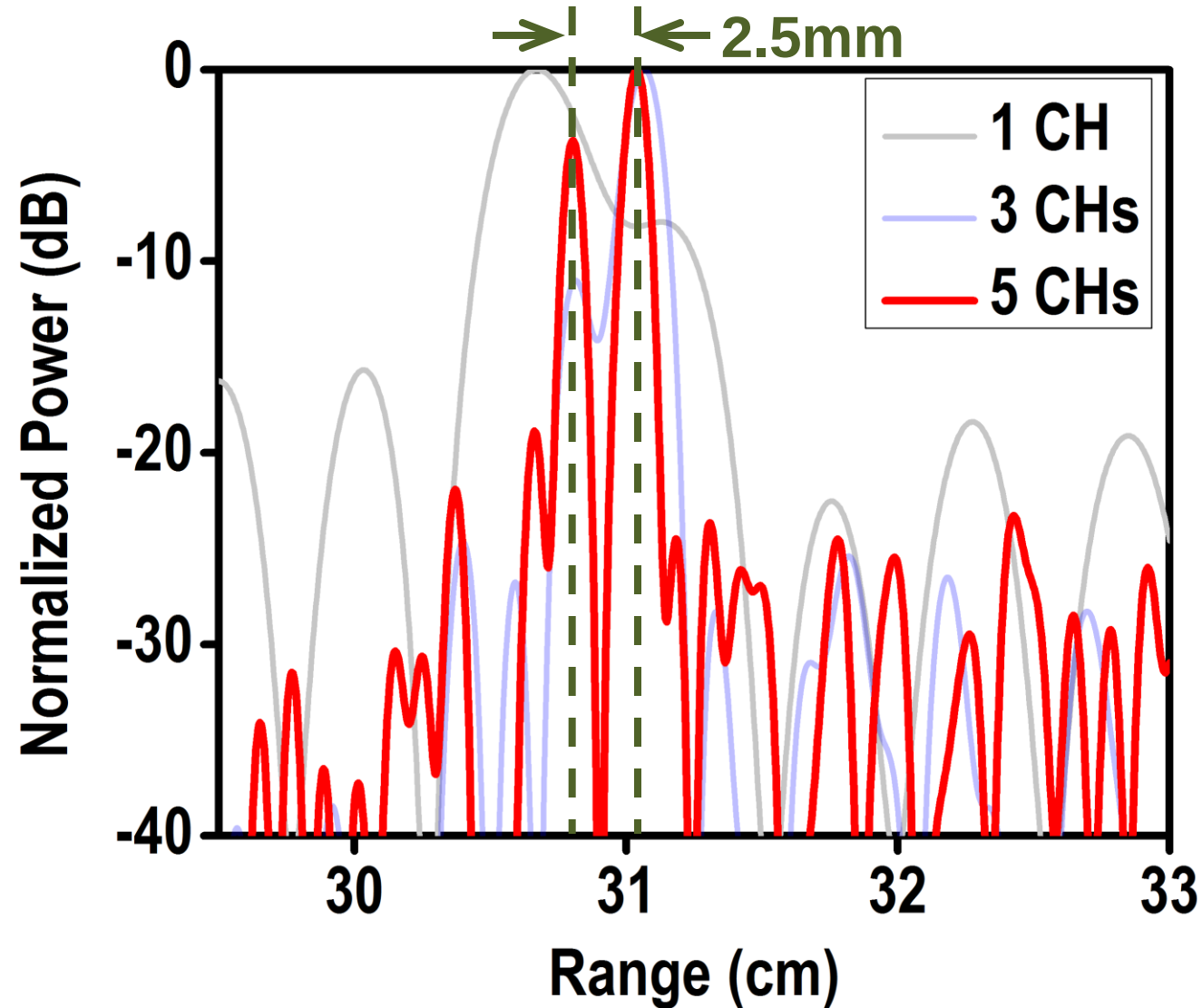
Range Resolution Measurement

- Three channels
- 60GHz



Range Resolution Measurement

- Five channels
- 100GHz



Comparison Table

References	This Work	JSSC 2014 [1]	Trans. THz 2016 [2]	Trans. THz 2018 [3]	T-MTT 2019 [4]	ISSCC 2019 [5]
Technology	65nm CMOS	65nm CMOS	130nm SiGe	130nm SiGe	55nm SiGe	28nm CMOS
Frequency (GHz)	220~320	157.9~164.9	210~270	305~375	189.9~252.3	138~151
Bandwidth (GHz)	100	7	60	70	62.4	13
Resolution (mm)	1.5	21	2.5	2.1	2.4	11.5
Output EIRP (dBm)	0.6, 20 ^(a)	18.8	32.8 ^(b)	6, 18.4 ^(a)	14 ^(b)	11.5
Minimum Noise Figure (dB)	22.2 ^(c)	22.5	21	19.7	NA	4(EINF) ^(d)
Power/NF Fluctuation (dB)	8.8/14.6	3/NA	20/29	10.5/28.6	7.7/NA	1.5/4
Chip Size (mm ²)	5.0	20	3.2	2.85	0.51	6.5
DC Power (mW)	840	2200	1800	1700	87	500

(a) With TPX focus lens; (b) with silicon lens; (c) includes antenna and baseband; (d) effective isotropic NF which includes the antenna directivity.

[This work: Yi, etc., ISSCC2020, JSSC2021]

Outline

- Introduction
- THz FMCW Comb Radar
- Circuit Implementations
- Measurement Results
- **Conclusion**

Conclusion

- **FMCW comb radar for wideband THz applications**
 - Flatter frequency responses
 - More linear chirp signal
 - Finer velocity resolution
 - Improved SNR
 - Scalable bandwidth extension
- **A THz FMCW comb radar with 100GHz bandwidth was demonstrated in 65nm bulk CMOS technology**

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