A Terahertz FMCW Comb Radar in 65nm CMOS with 100GHz Bandwidth

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Outline

- Introduction
- Comb Radar
- Circuit Implementations
- Measurement Results
- Conclusion

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- **Introduction**
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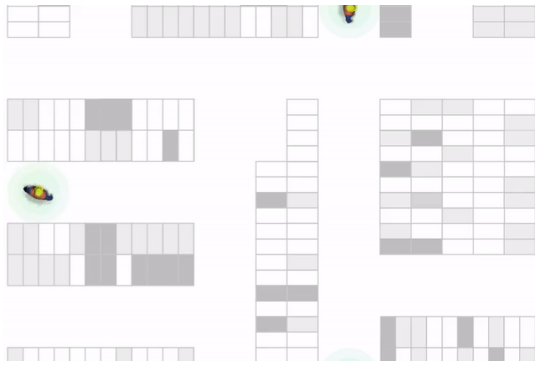
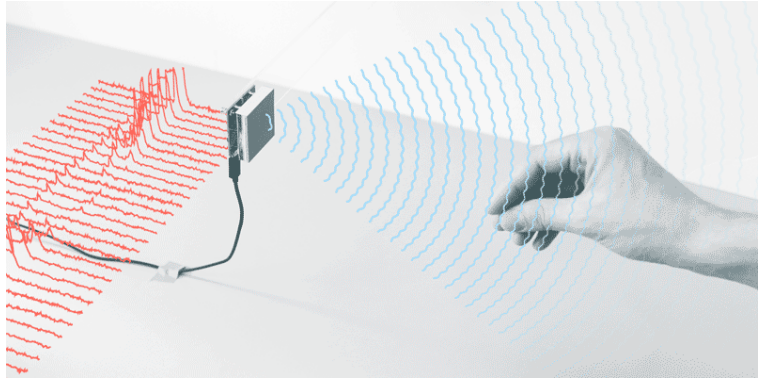
Wideband FMCW Radar Applications

- **High resolution detection**



[humatics.com]

Localization



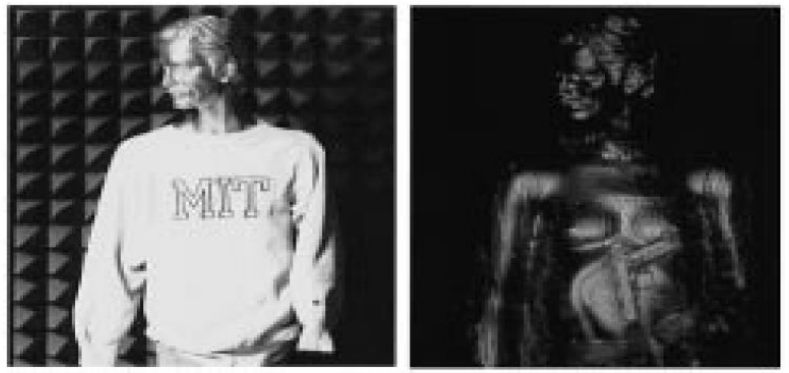
[atap.google.com/soli]

Recognition

Range Resolution

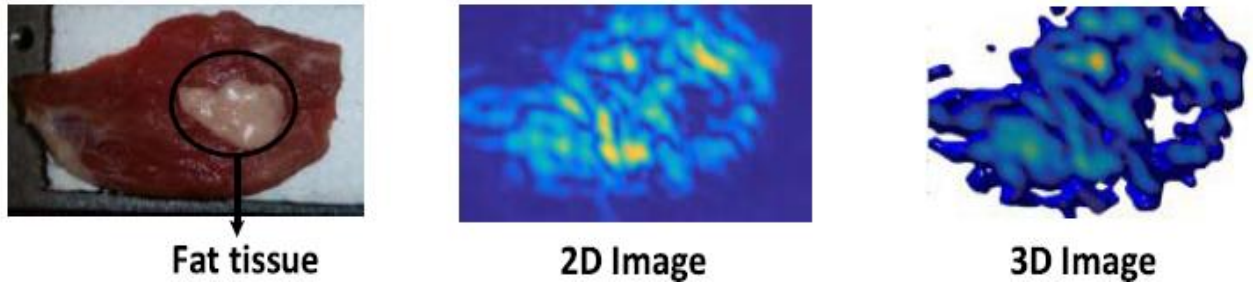
$$\Delta R = \frac{c}{2 \cdot BW}$$

- **High resolution imaging**



[Sheen, TMTT 2001]

Security Imaging

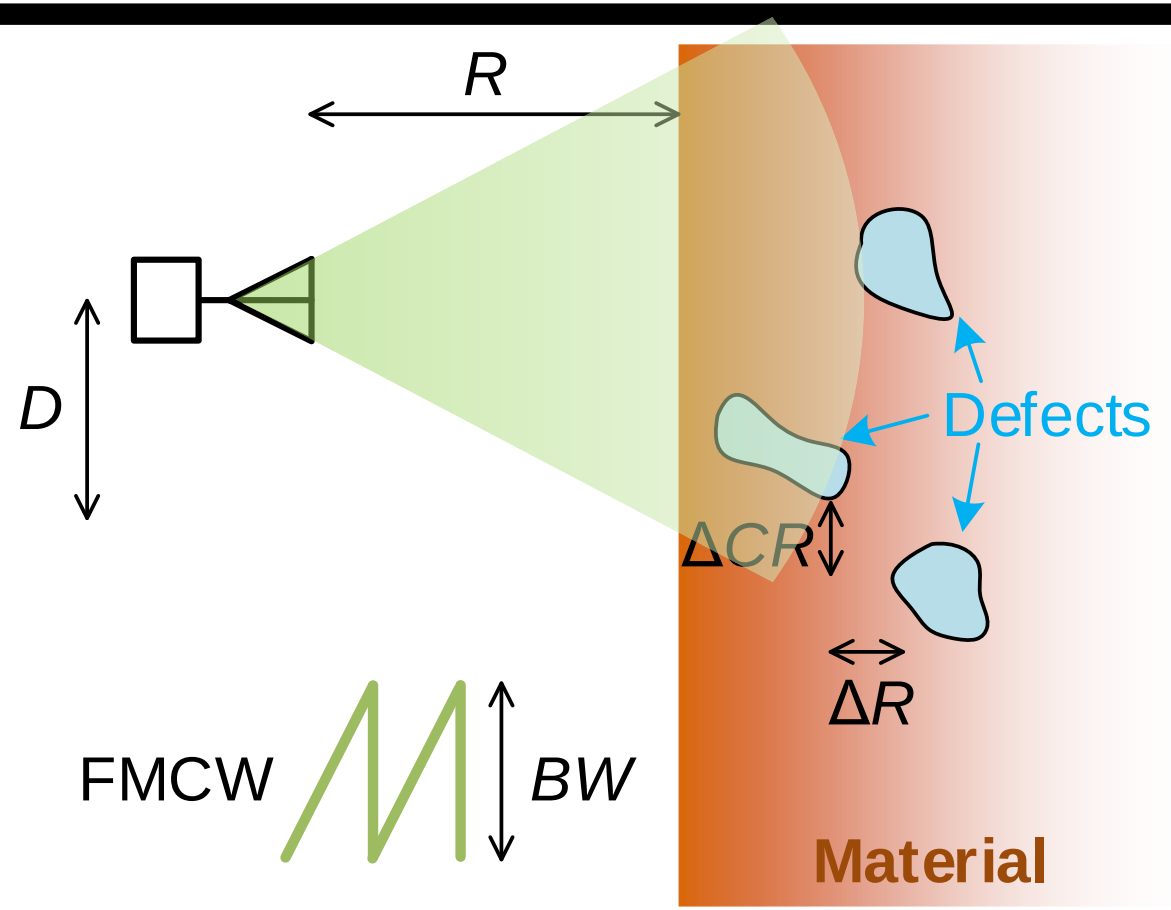


[Mostajeran, TMTT 2019]

Non-Ionizing/Destructive Imaging

Wideband THz FMCW Radar Example

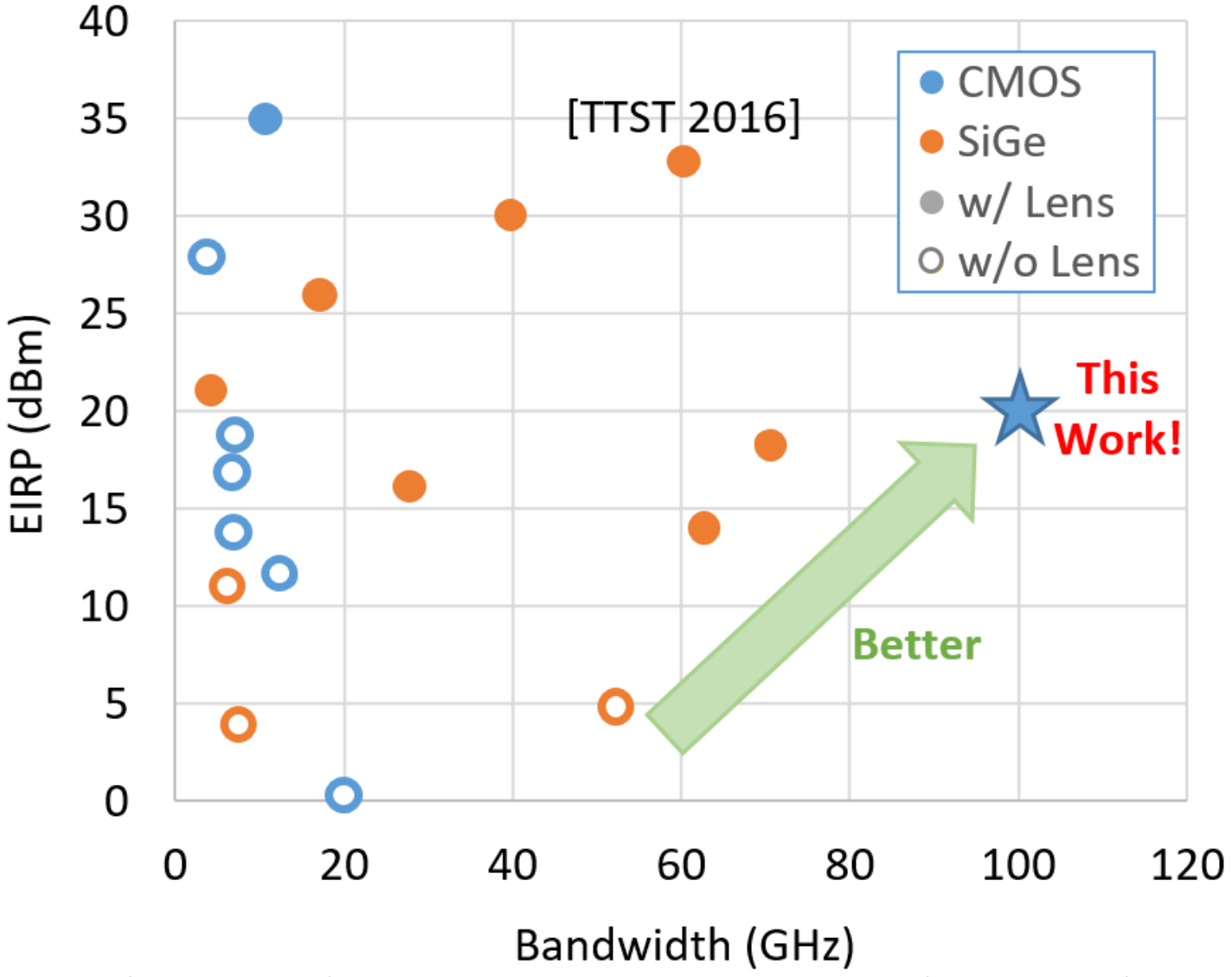
- SAR 3D imaging
- Cross-range resolution ΔCR
  - Relies on synthetic aperture D
  - Mm resolution is readily available (e.g. R=3D, ΔCR=1.5mm)
- Range resolution ΔR
  - Relies on bandwidth BW only
  - Mm resolution: wideband (e.g. BW=100GHz, ΔR=1.5mm,)



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

Integrated Radar Survey

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



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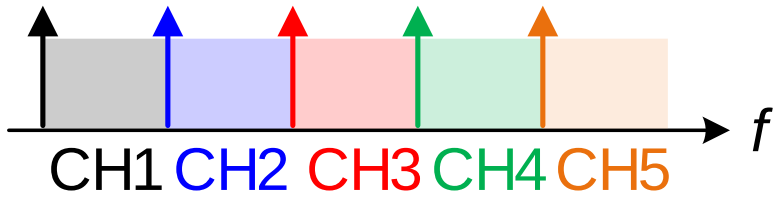
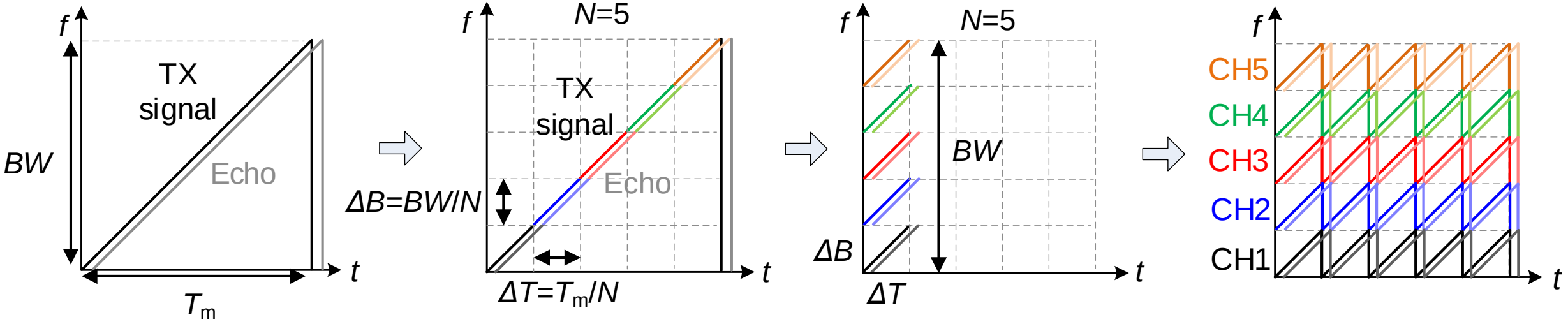
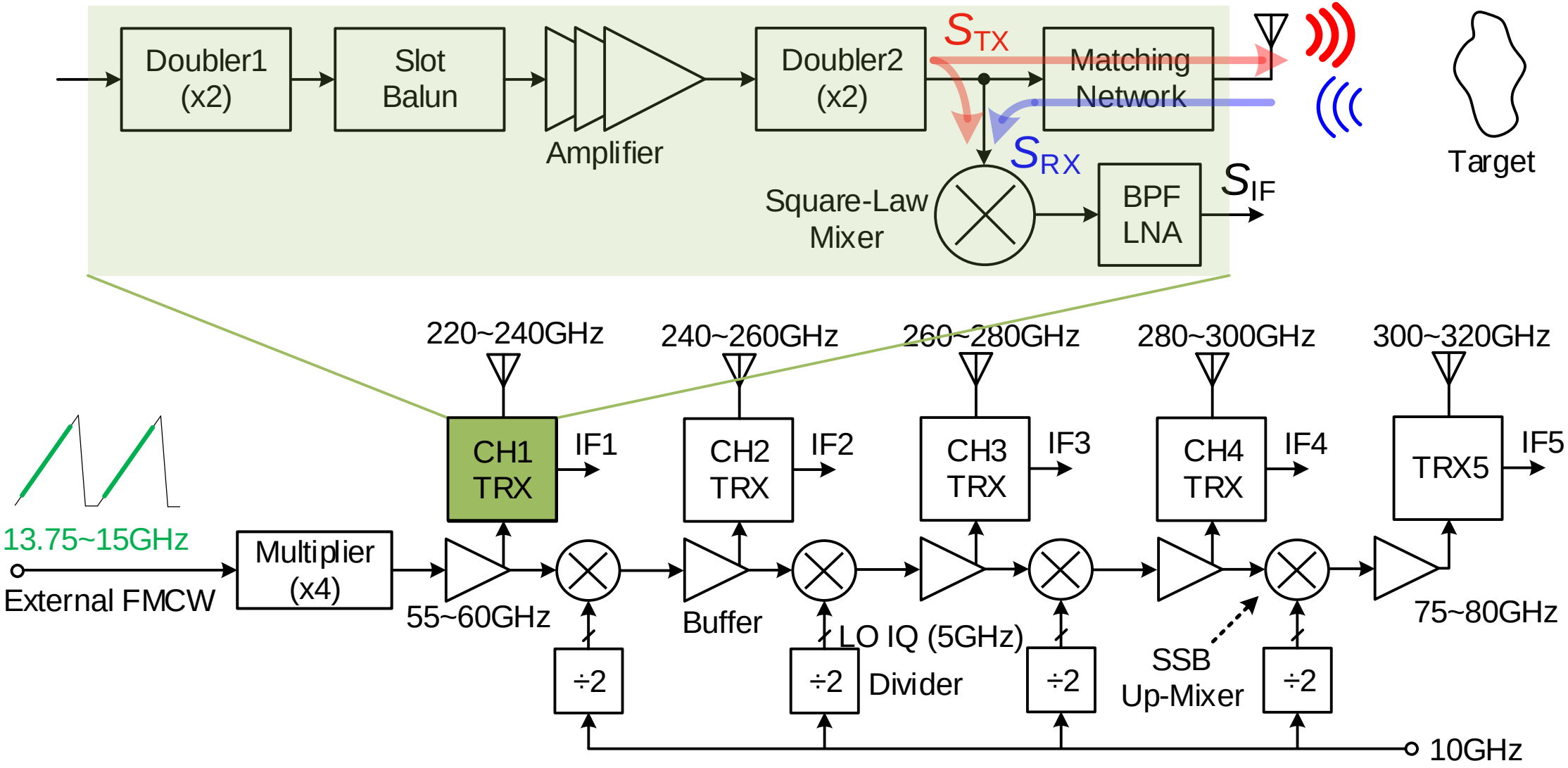
Comb Radar Concept

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





Comb Radar System Diagram



Phase of IF Signals

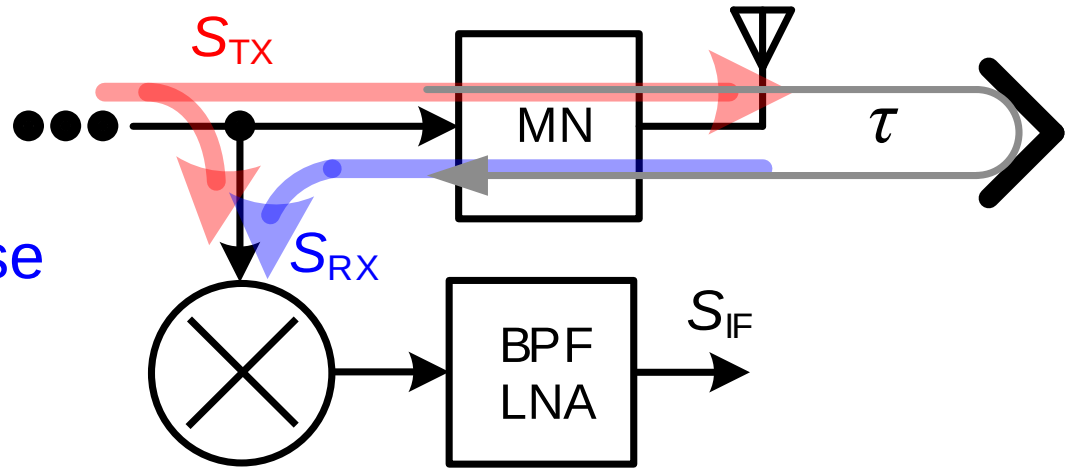
- For Channel N, the TX signal is

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

Initial RF phase

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

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



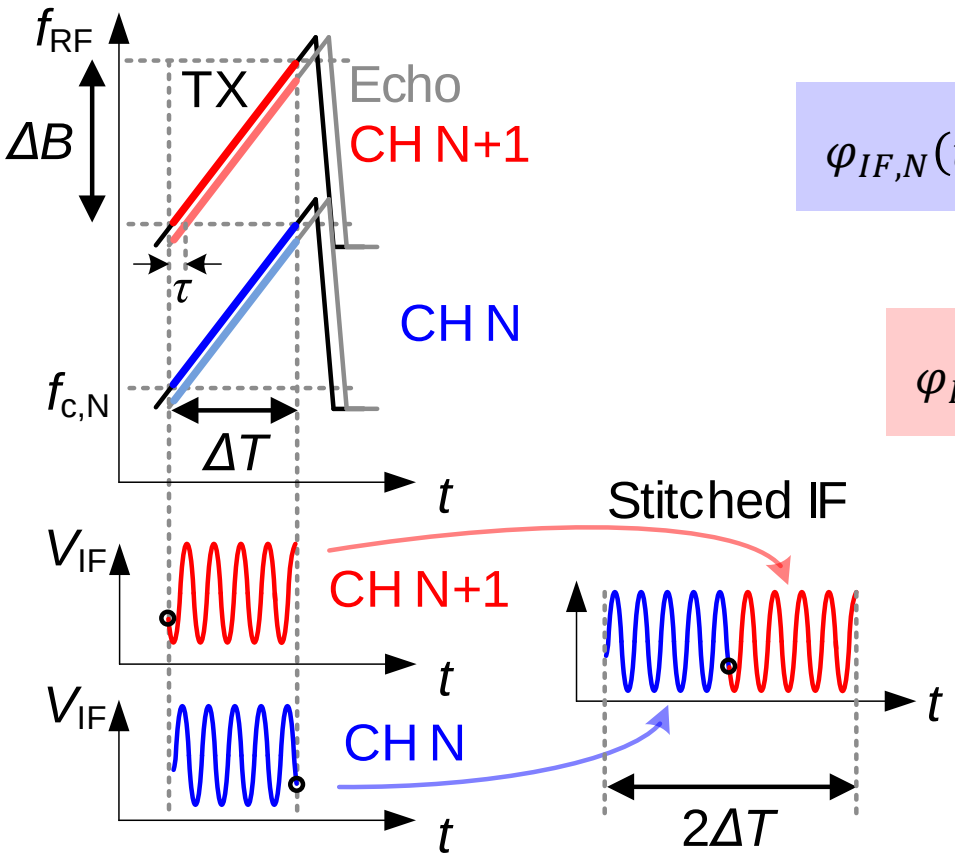
Square-Law Mixer

- The band-pass-filtered IF signal is

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

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

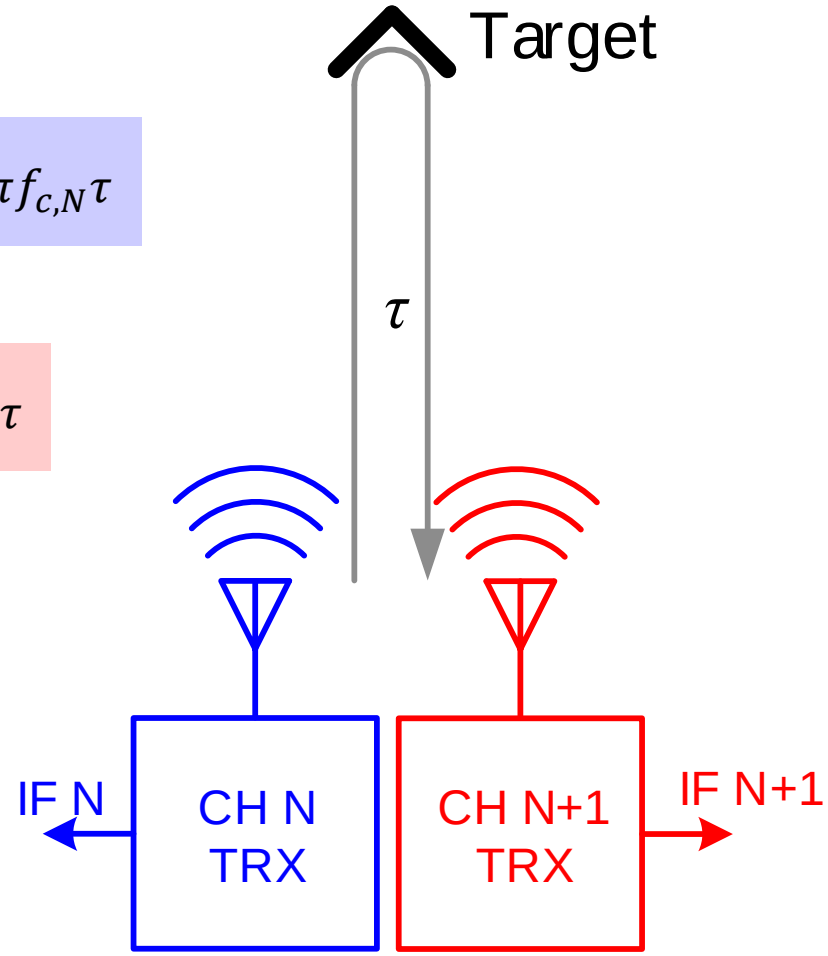
Phase of IF Signals



$$\varphi_{IF,N}(t_0 + \Delta T) = \frac{2\pi\Delta B}{\Delta T}\tau(t_0 + \Delta T) + 2\pi f_{c,N}\tau$$

$$\varphi_{IF,N+1}(t_0) = \frac{2\pi\Delta B}{\Delta T}\tau t_0 + 2\pi f_{c,N+1}\tau$$

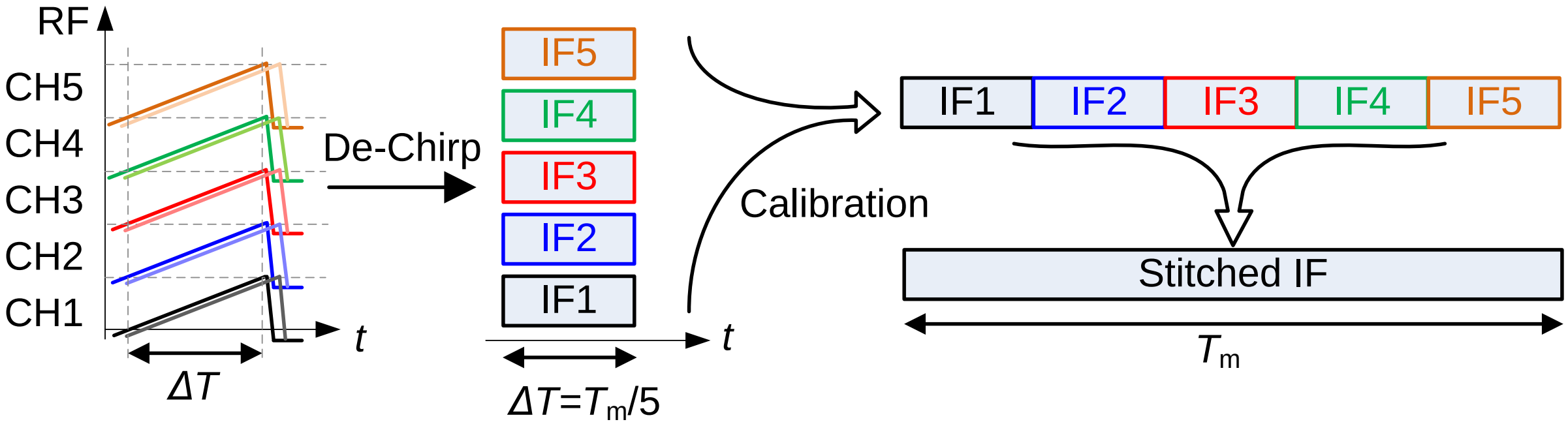
$$\varphi_{IF,N}(t_0 + \Delta T) = \varphi_{IF,N+1}(t_0)$$



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

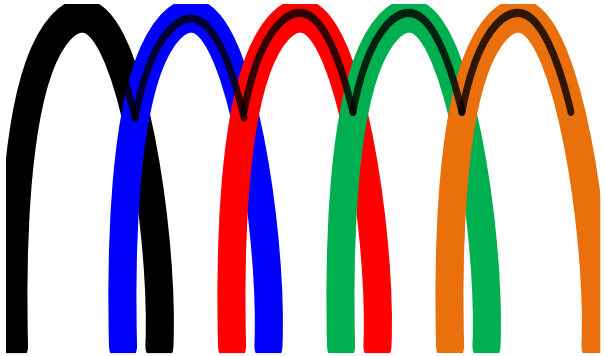
Stitching Process

- IF signals are directly stitched in time domain after calibrations



Compared with Single Channel Radar

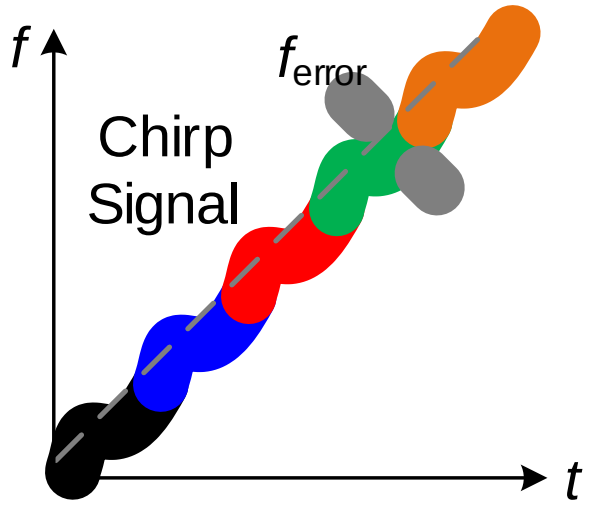
- Flatter frequency responses



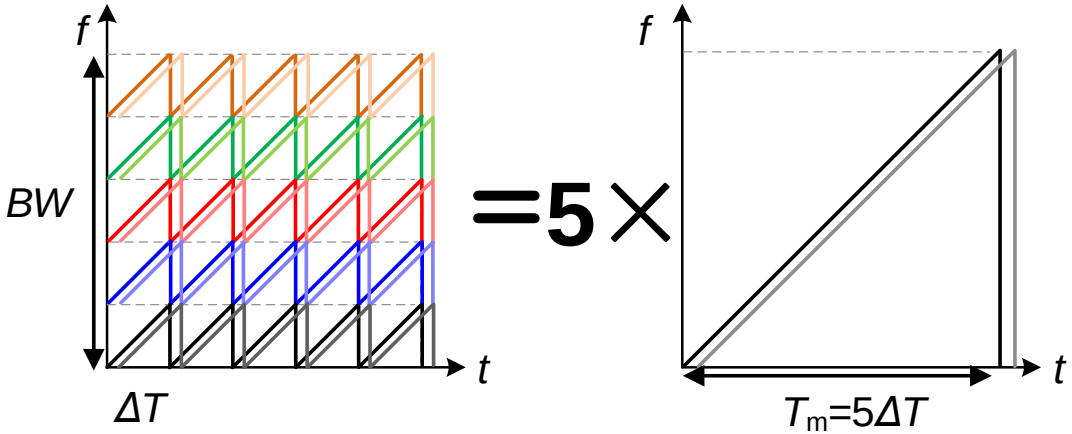
- Finer velocity resolution

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

- More linear chirp signal



- *SNR* is improved



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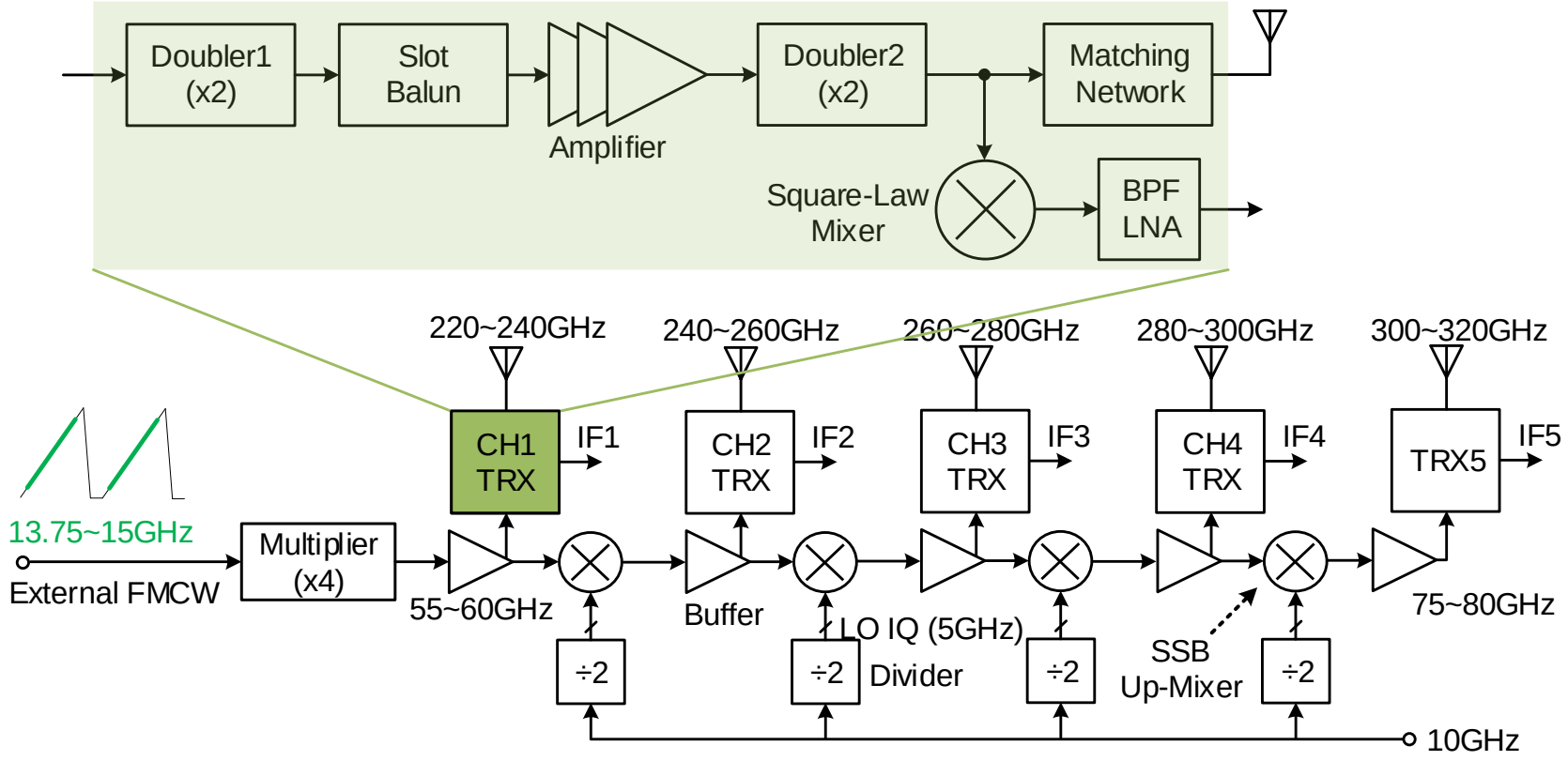
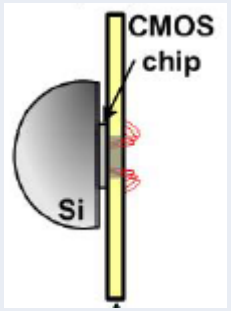
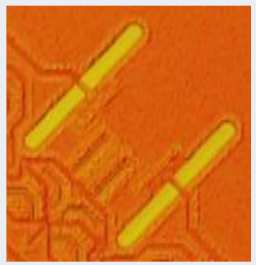
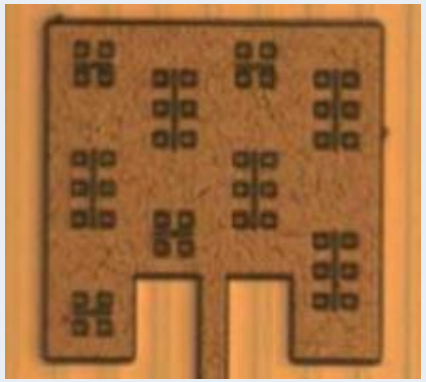
Comb Radar System Diagram

- Total bandwidth: 5×20GHz=100GHz
- Scalable bandwidth extension
- Single antenna solution for each transceiver: 5 antennas, coupling?

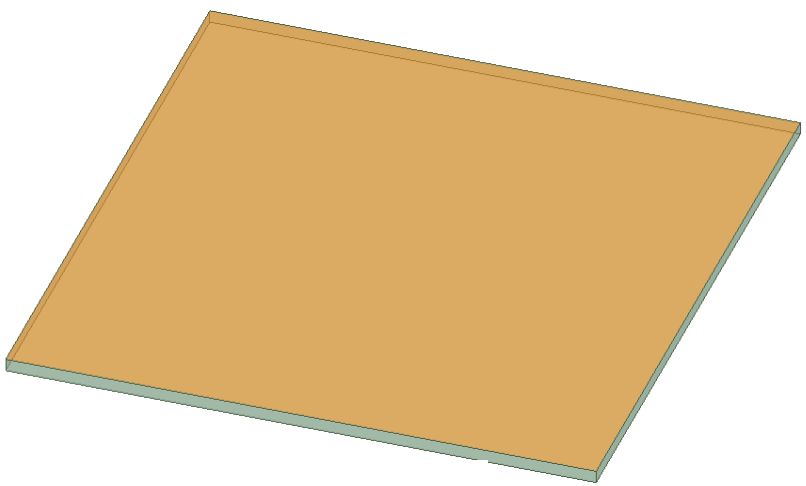


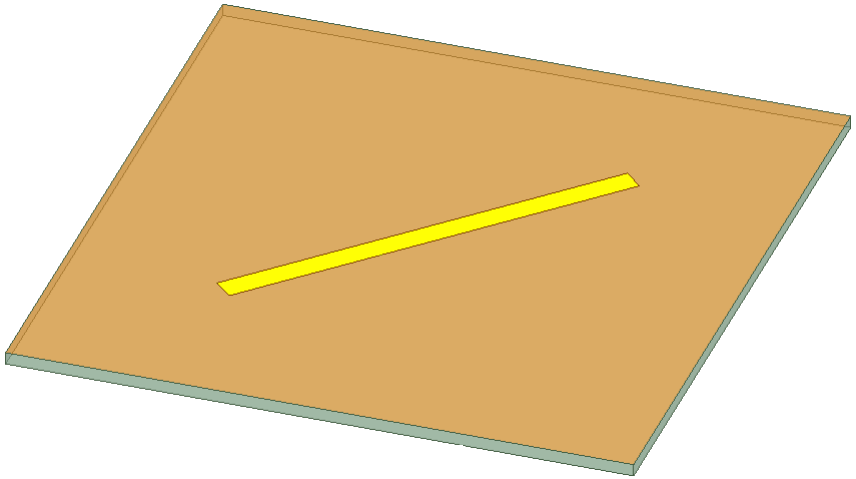
On-Chip Antenna Background

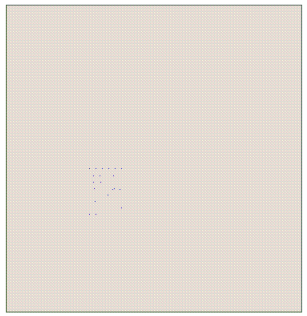
	Slot Antenna	Patch Antenna	Substrate Integrated Waveguide (SIW)
Expensive Silicon Lens	Need ☹	No Need ☺	No Need ☺
Bandwidth	Wide ☺	Narrow ☹	Narrow ☹ ?
Inter-Antenna Coupling	Medium ☺	Large ☹	Small ☺
Example	  Slot Antennas [R. Han, ISSCC 2012]	 [R. Han, JSSC 2013]	 [S. Hu, JSSC 2012]

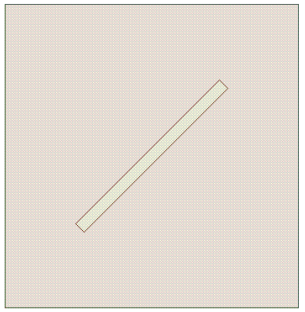
SIW Cavity and Slot

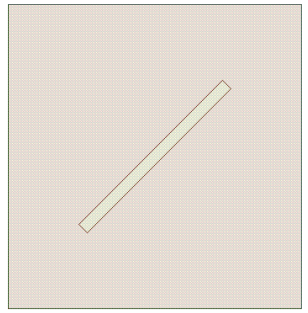
- Eigenmode simulation





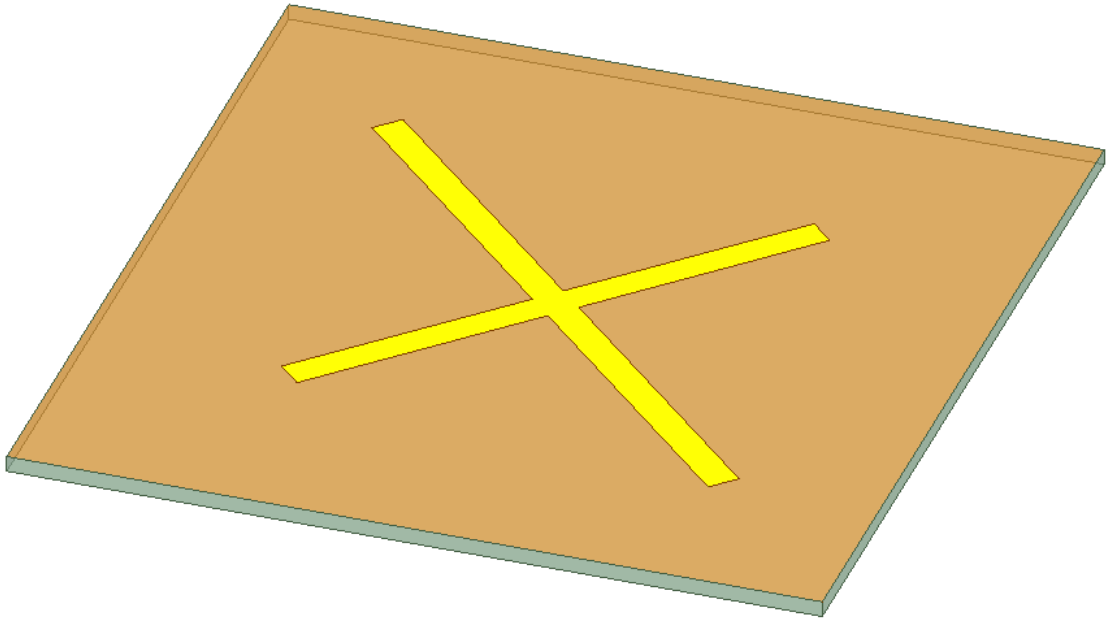


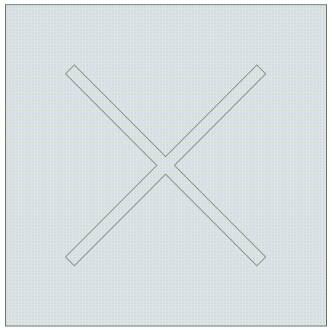


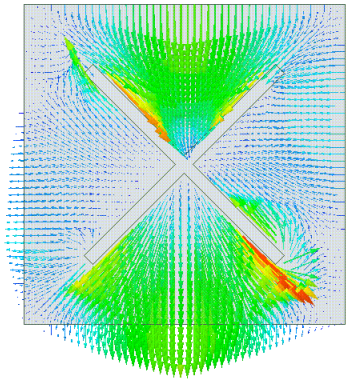


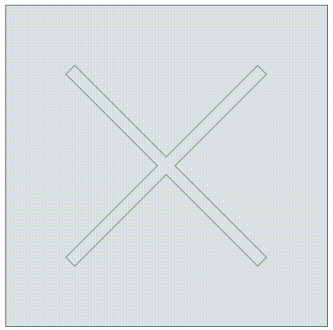
SIW Cavity with Orthogonal Slots

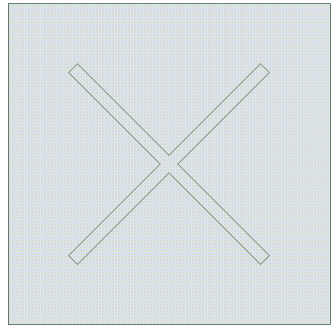
- Four modes





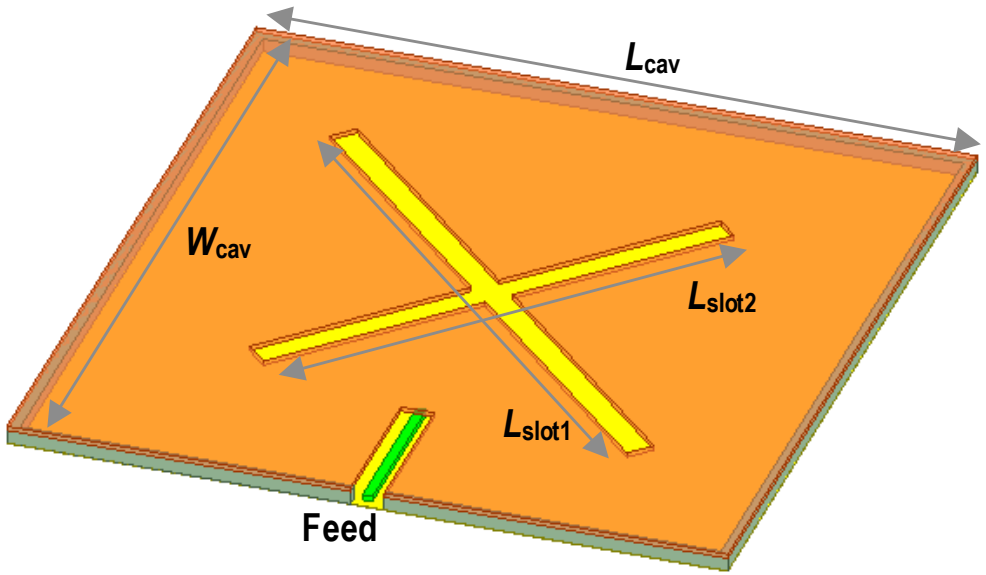


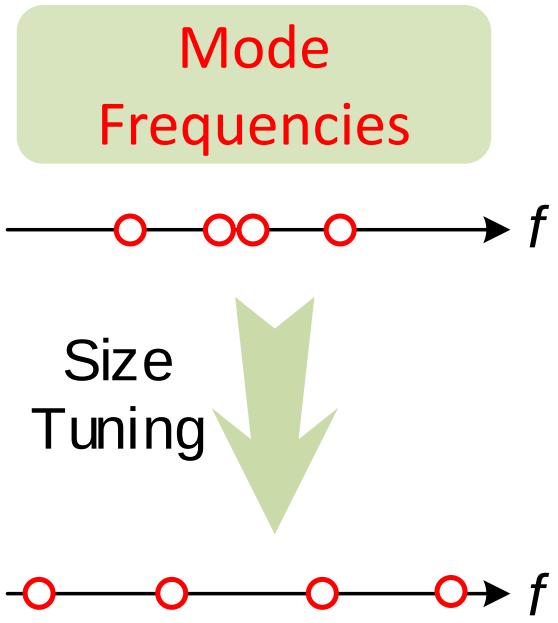


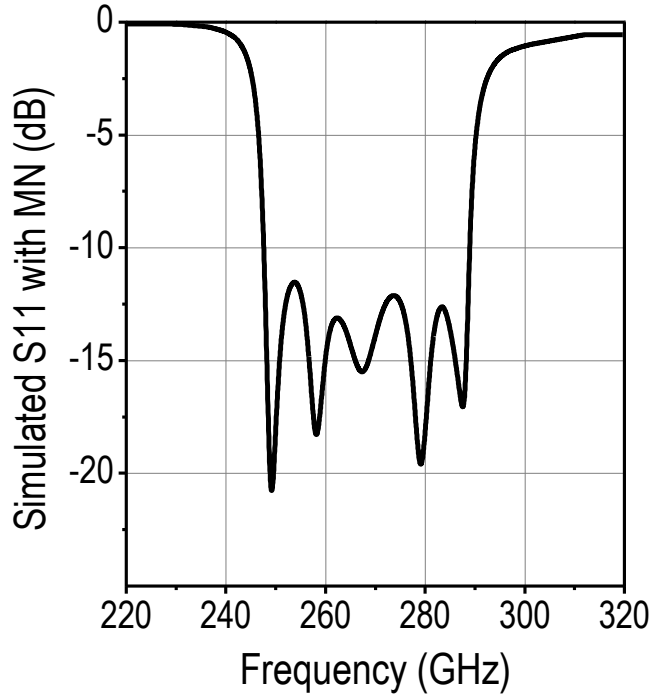


SIW Orthogonal Slot Antenna

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

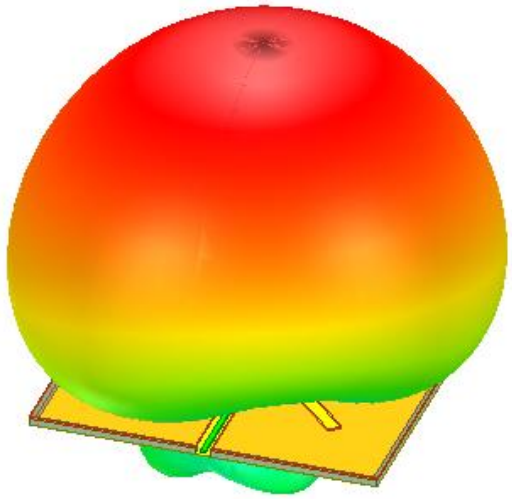


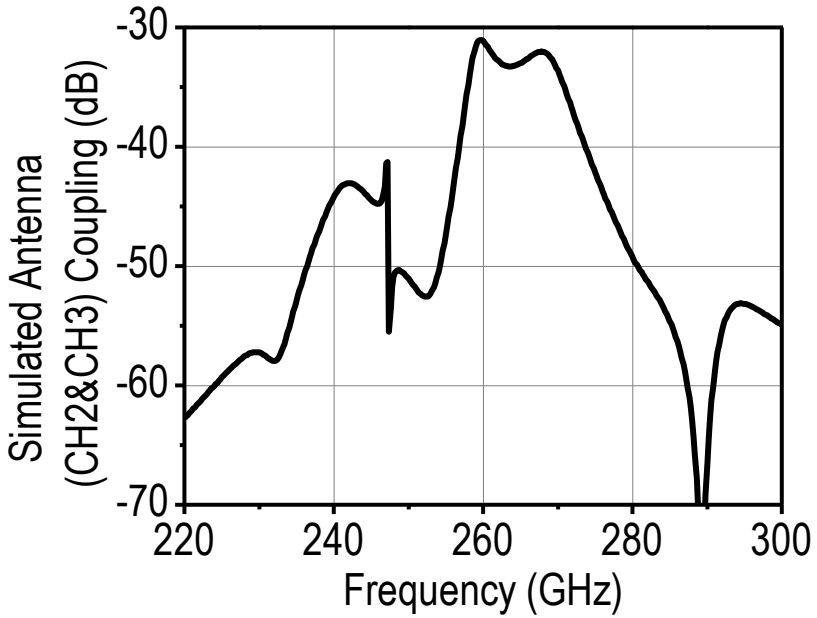


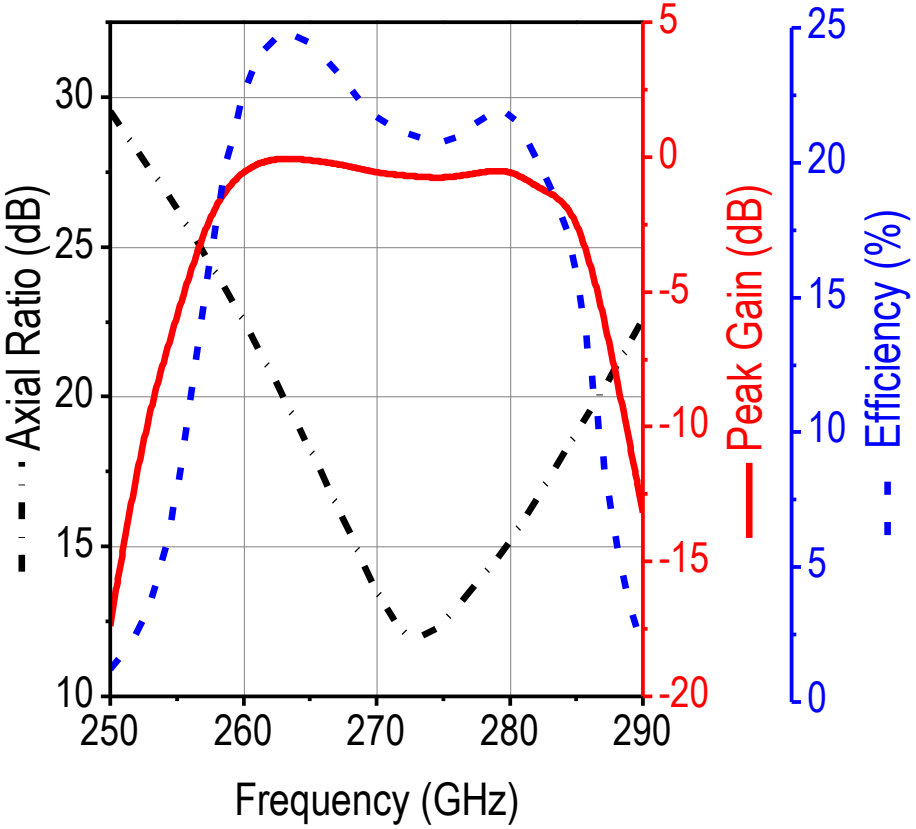


SIW Orthogonal Slot Antenna

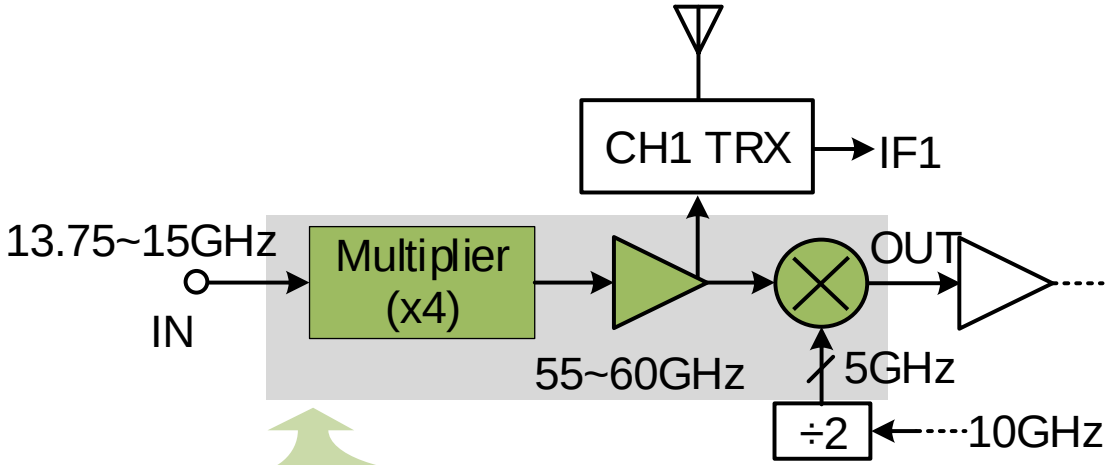
- Wide bandwidth (~40GHz, 14.8%)
- 0dBi peak gain
- Linear polarization (axial ratio > 11.6dB)
- Low coupling (< -31dB)
- 20.5% efficiency

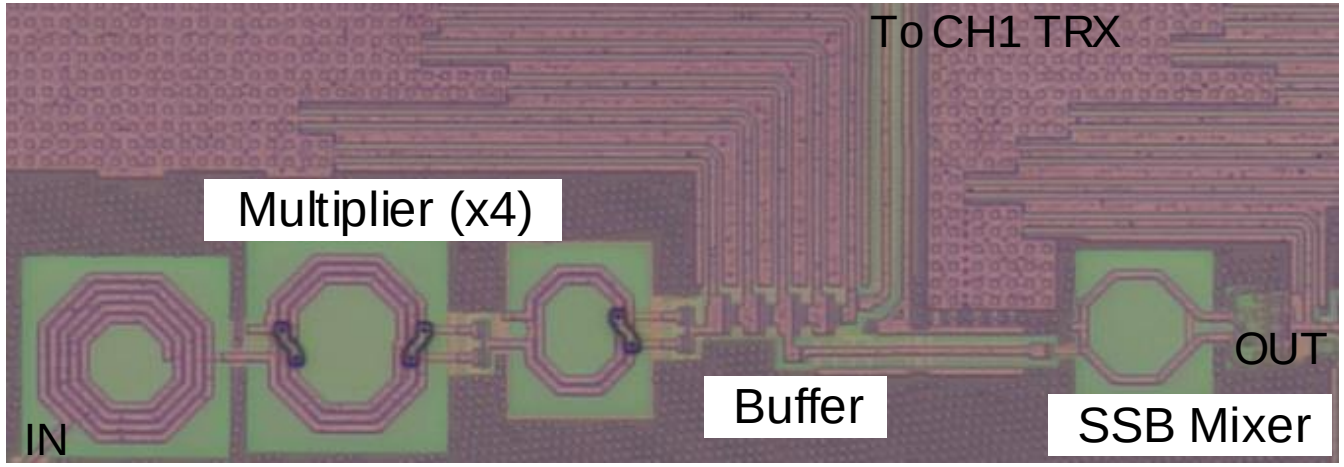


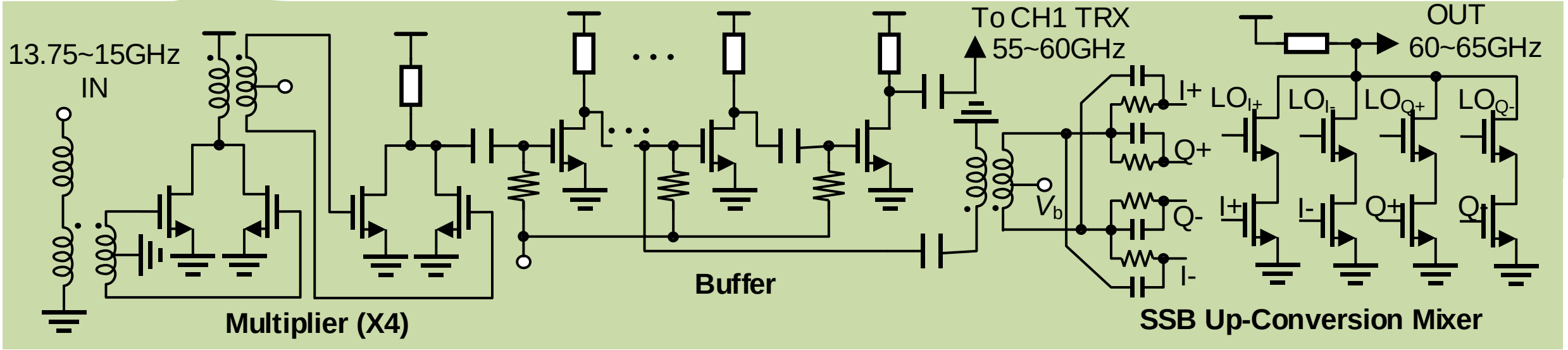




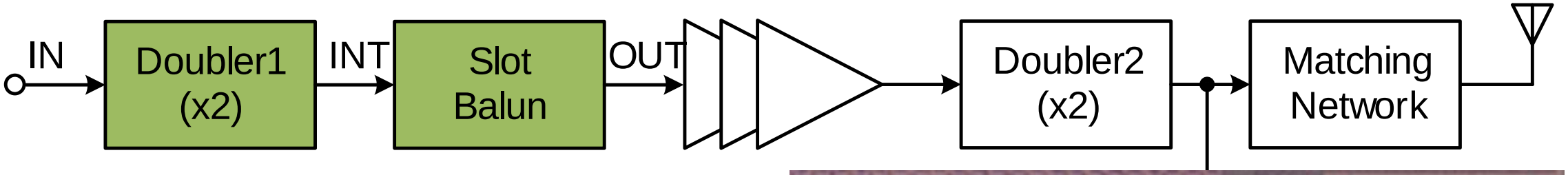
Input Multiplier, Buffer, and SSB Mixer

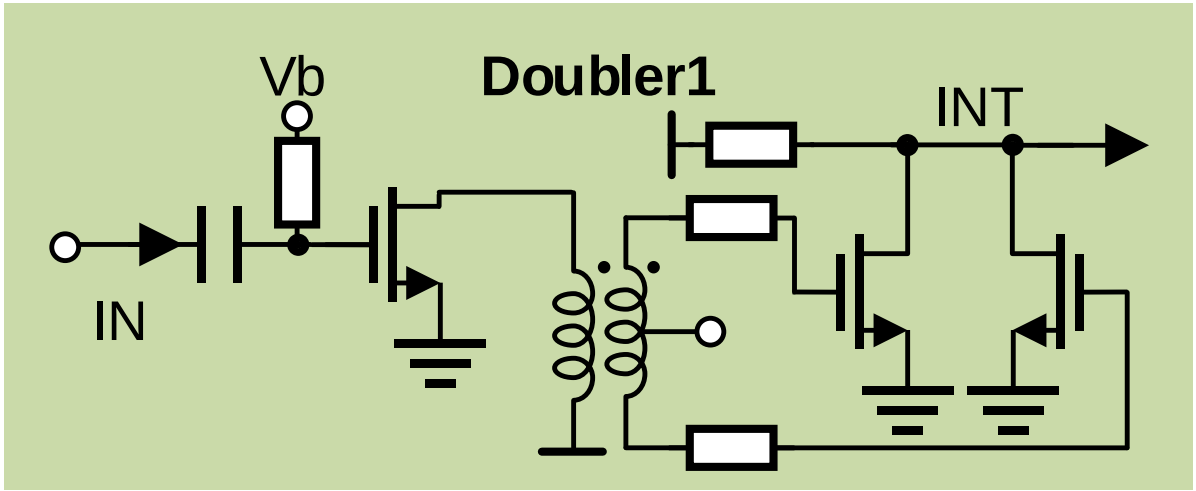


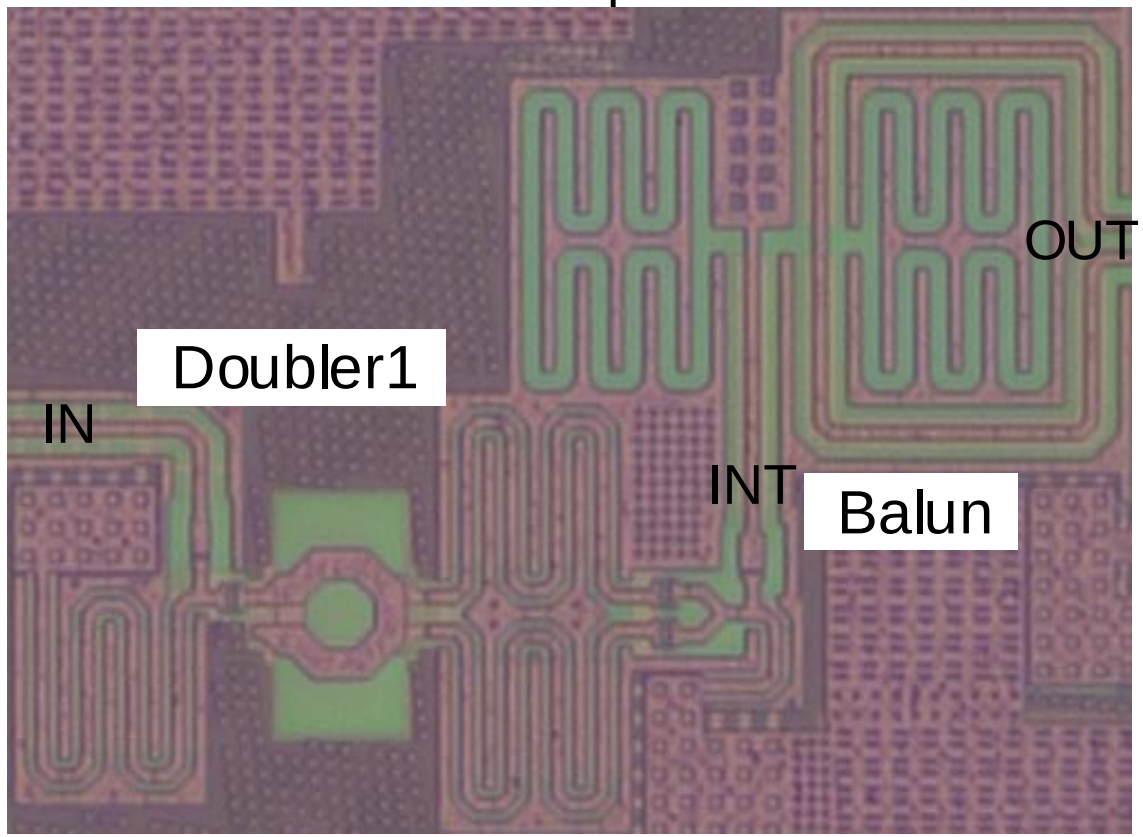




Doubler1 and Folded Slot Balun

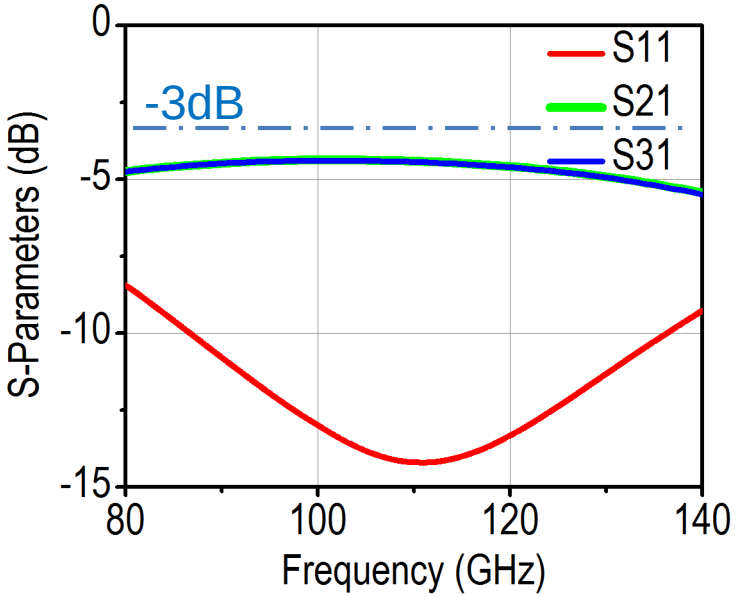


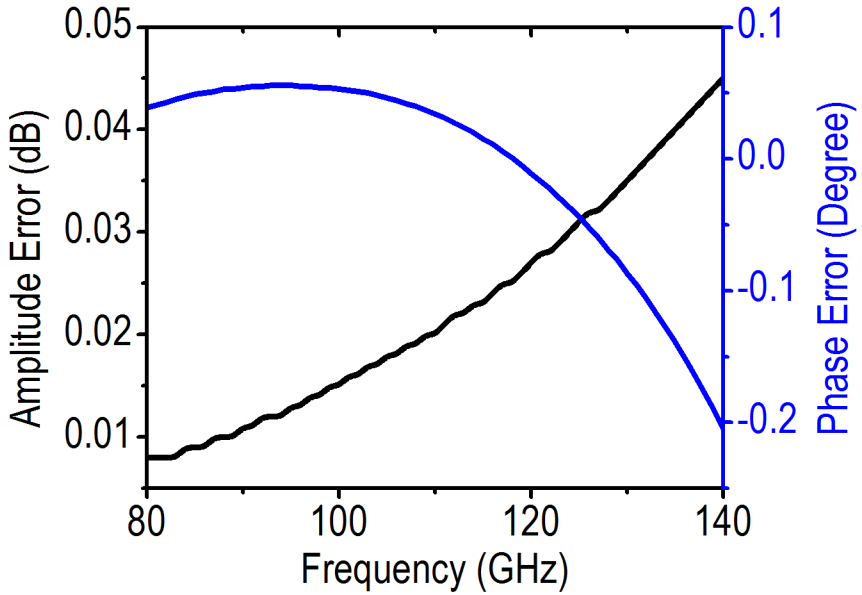


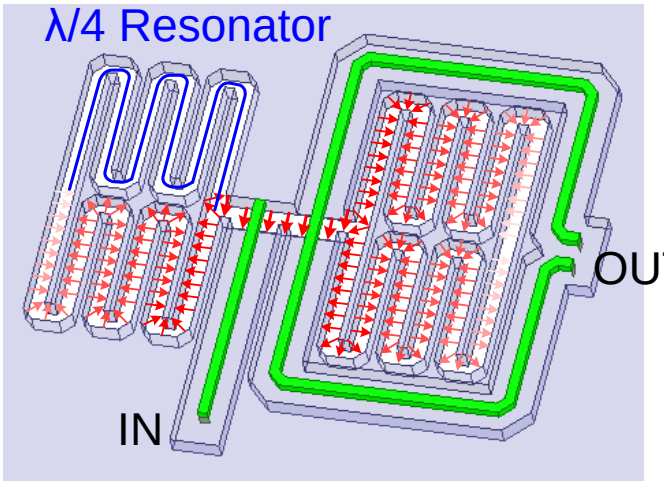


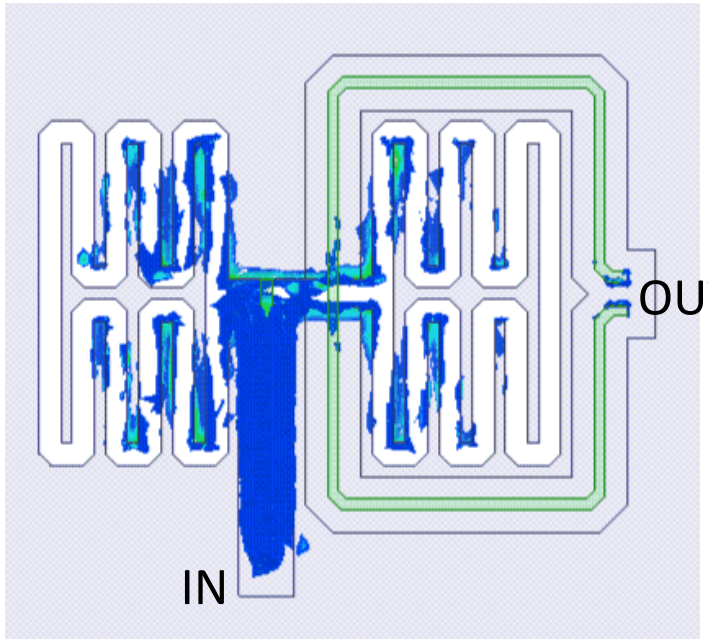
Folded Slot Balun

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

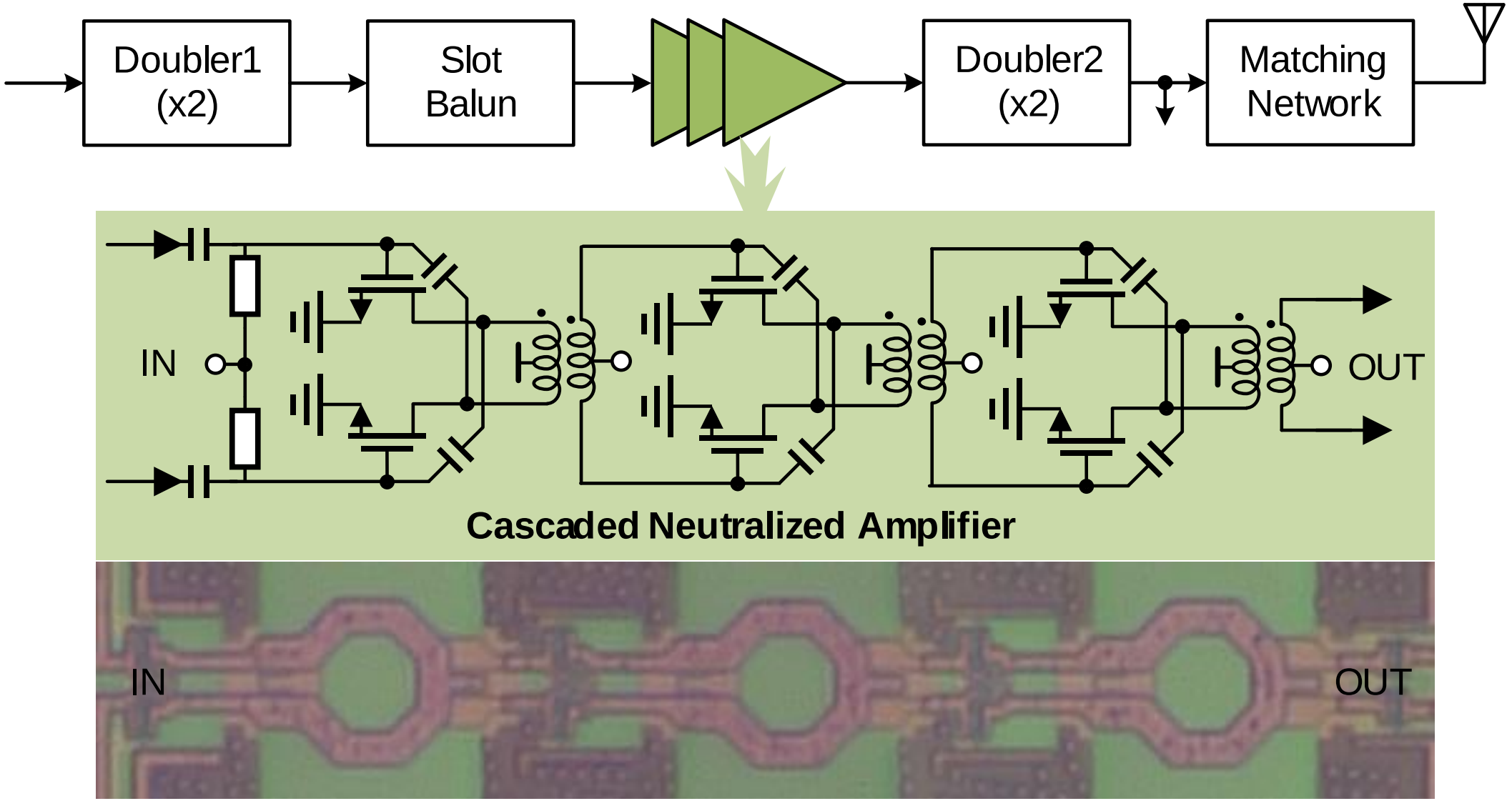




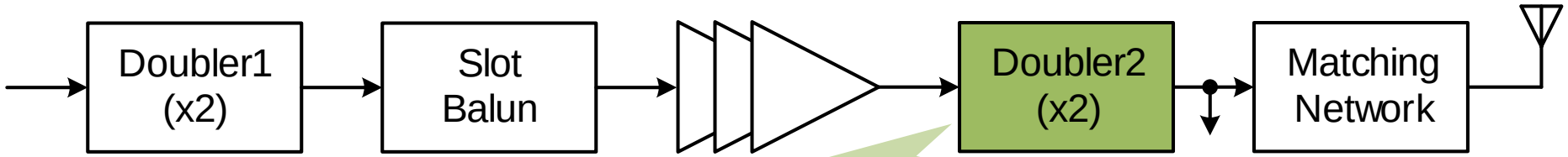


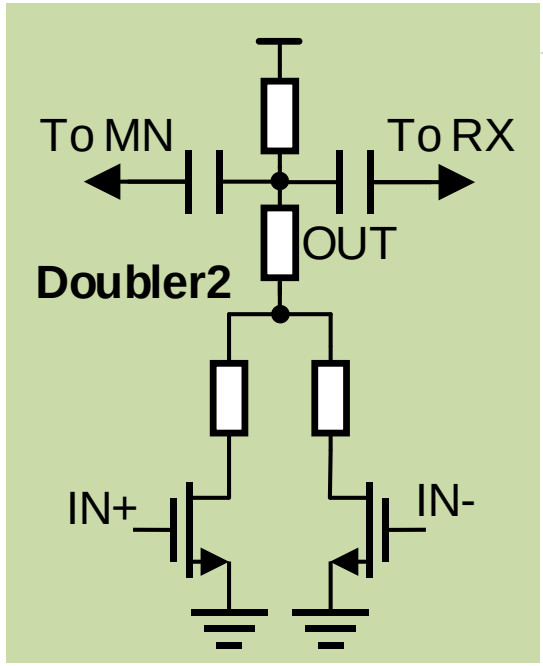


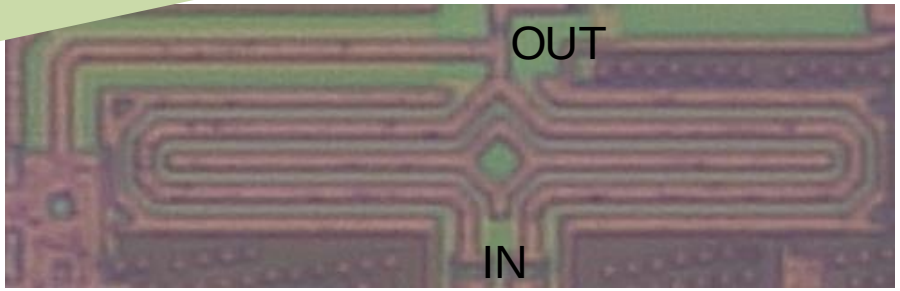
Cascaded Neutralized Amplifier

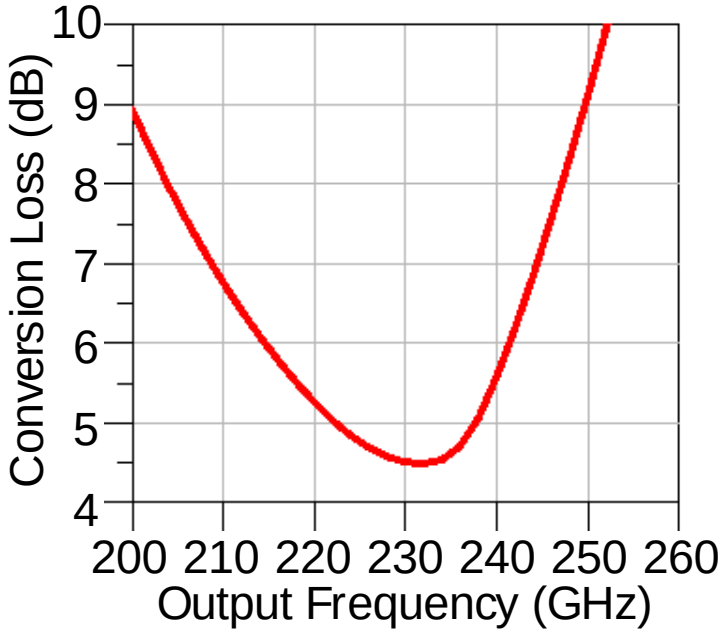


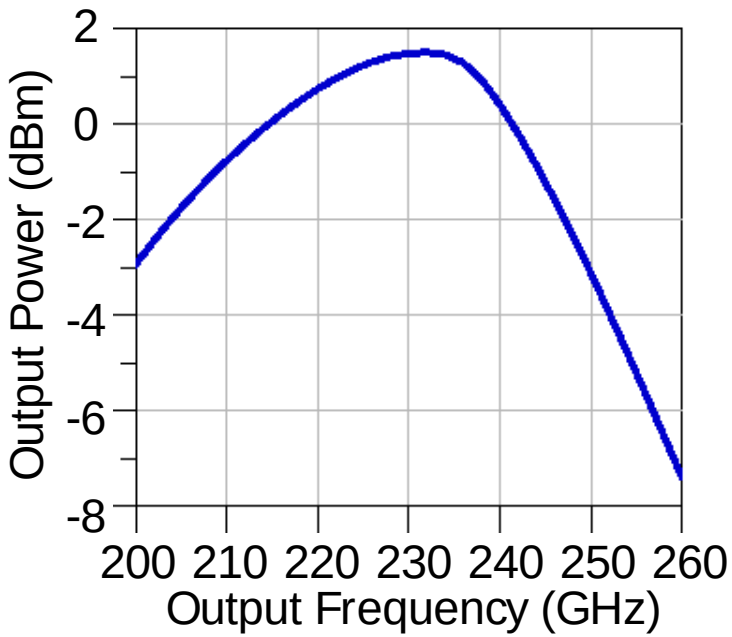
Doubler2



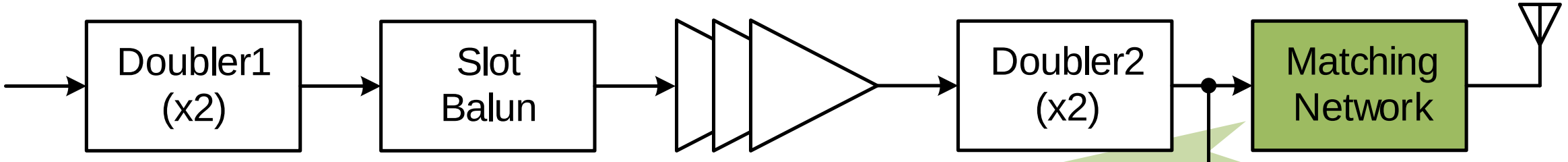


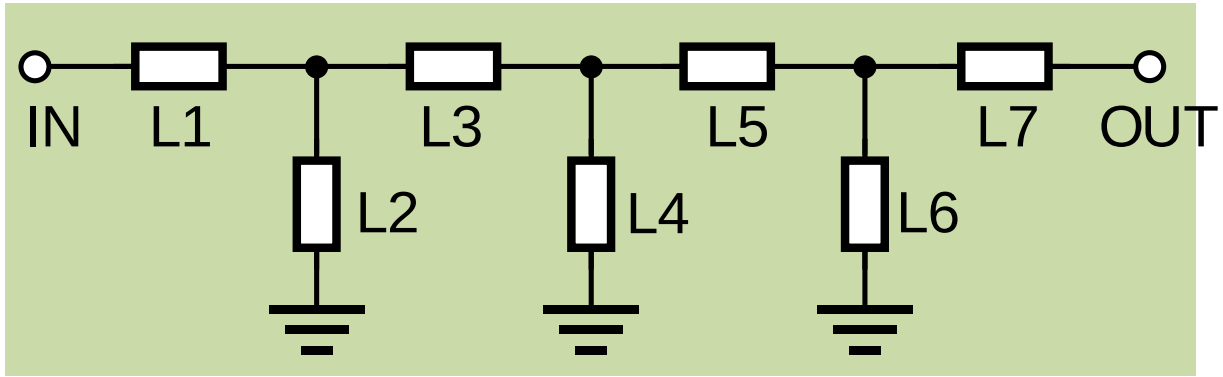


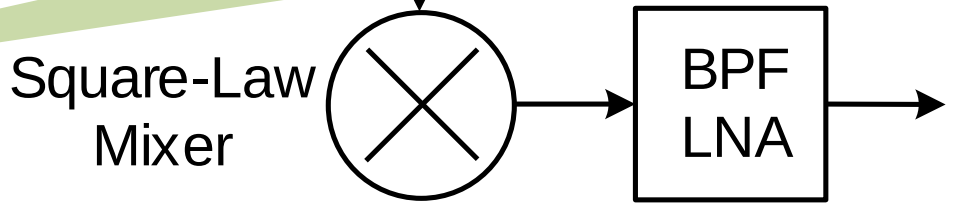


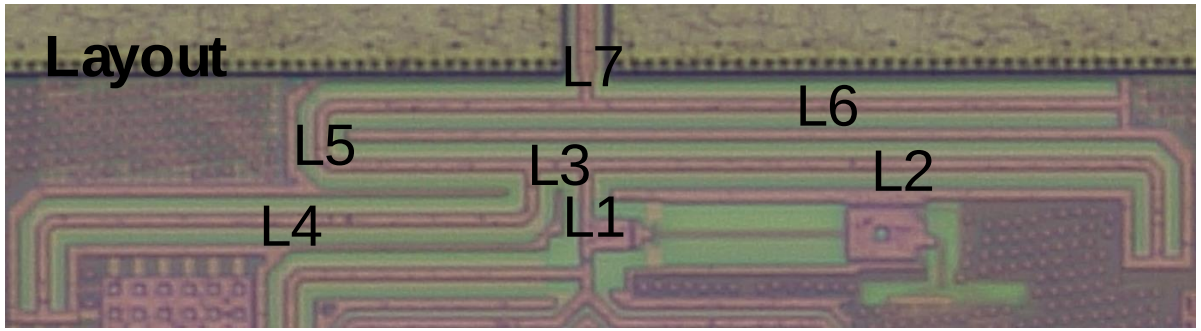


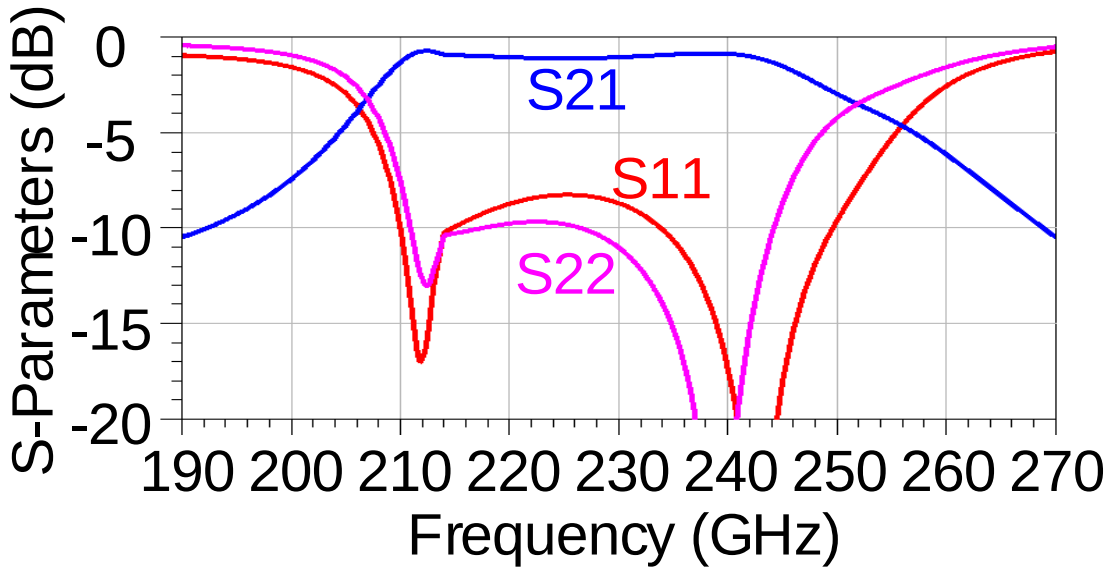
Multi-Stub Matching Network



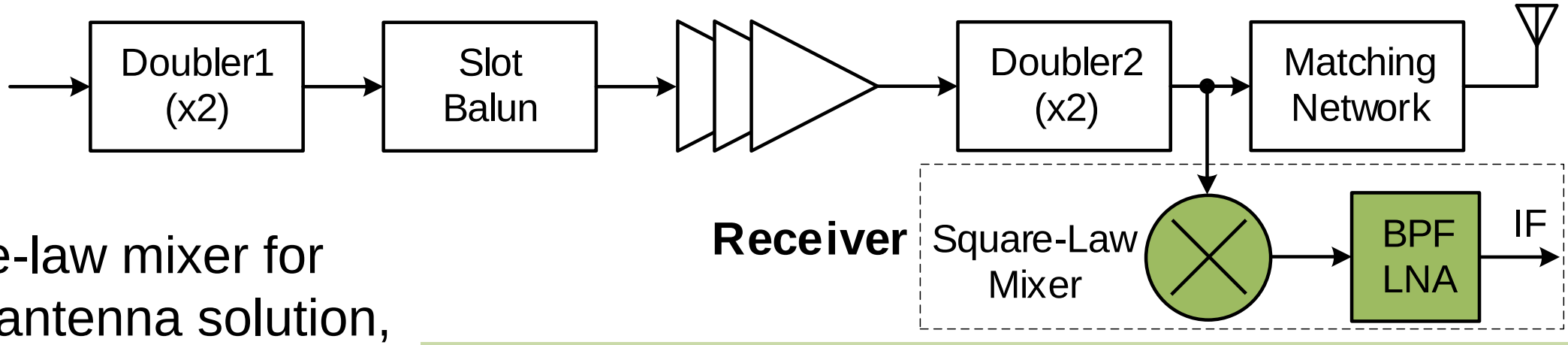




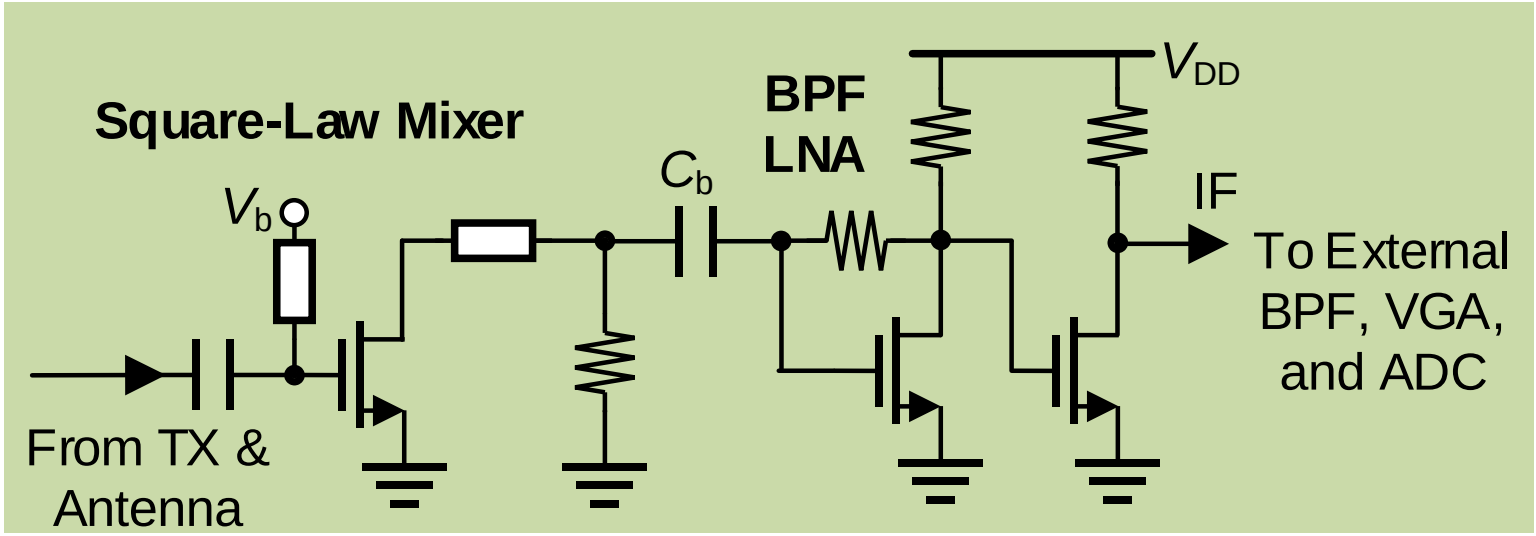




Receiver



- 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

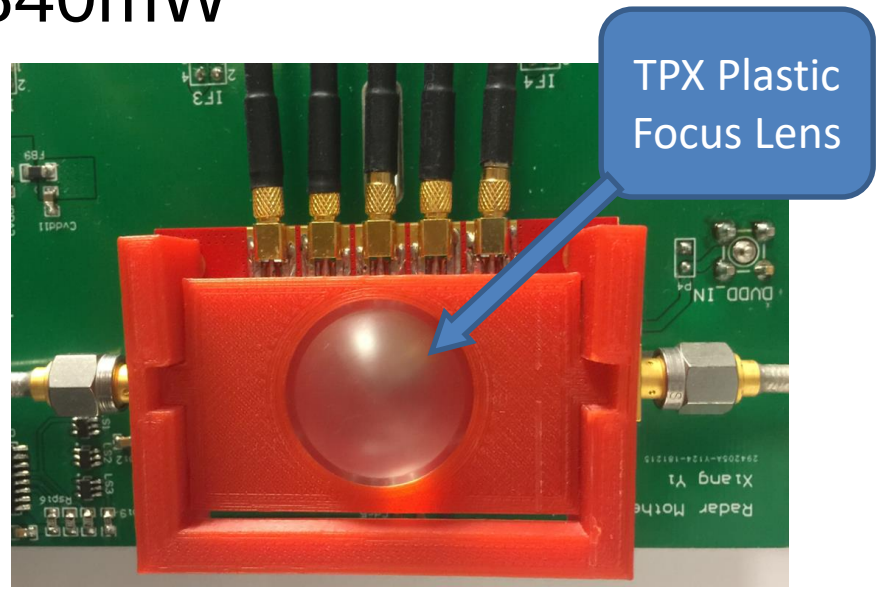


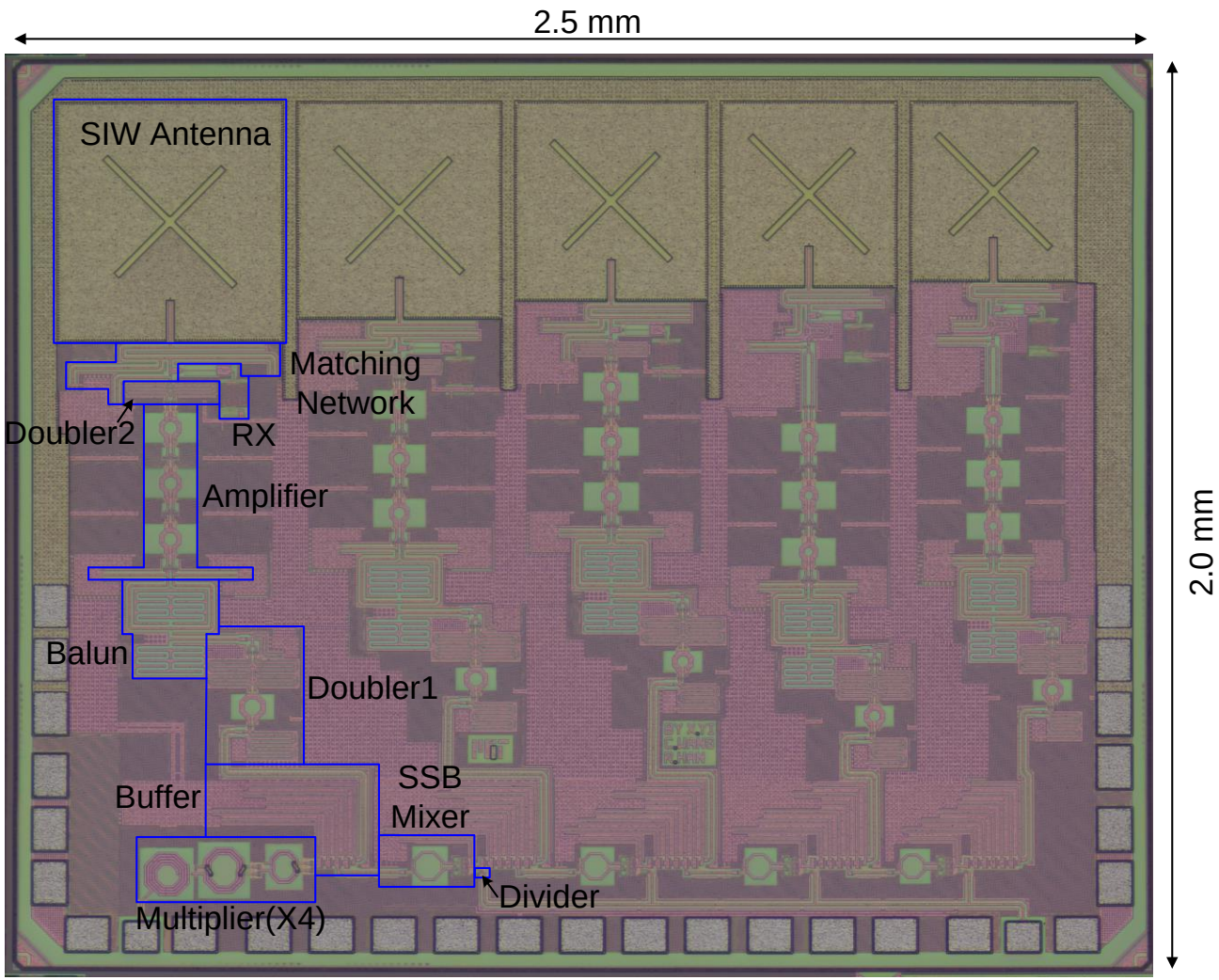
Outline

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

Chip and PCB Photograph

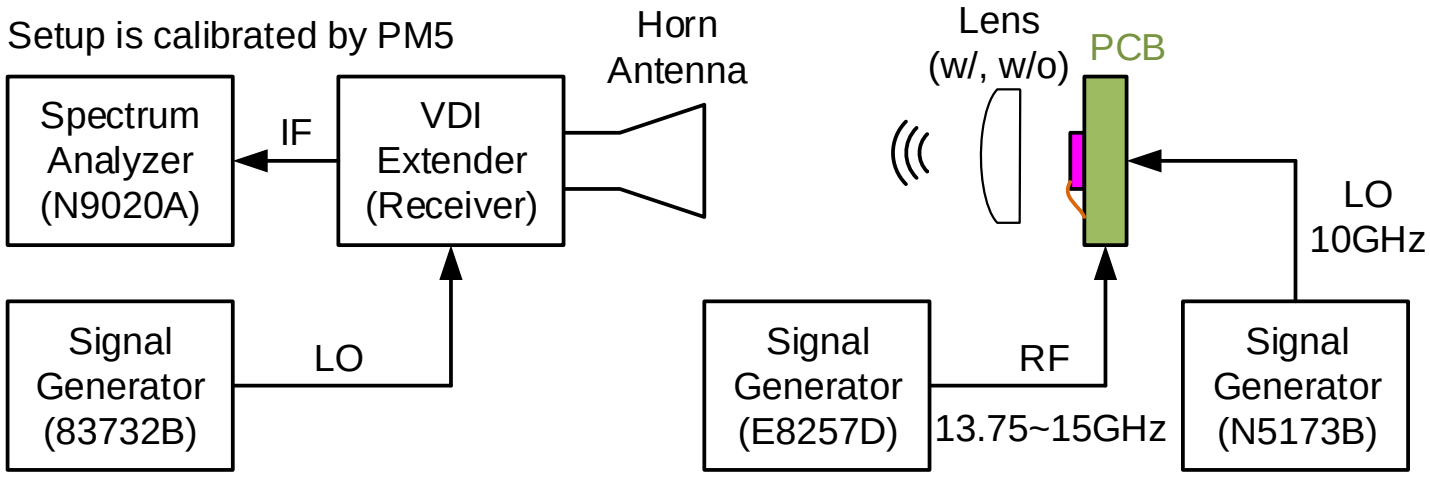
- TSMC 65nm bulk CMOS technology
- Area: 2.5mm by 2.0mm
- Total power consumption: 840mW

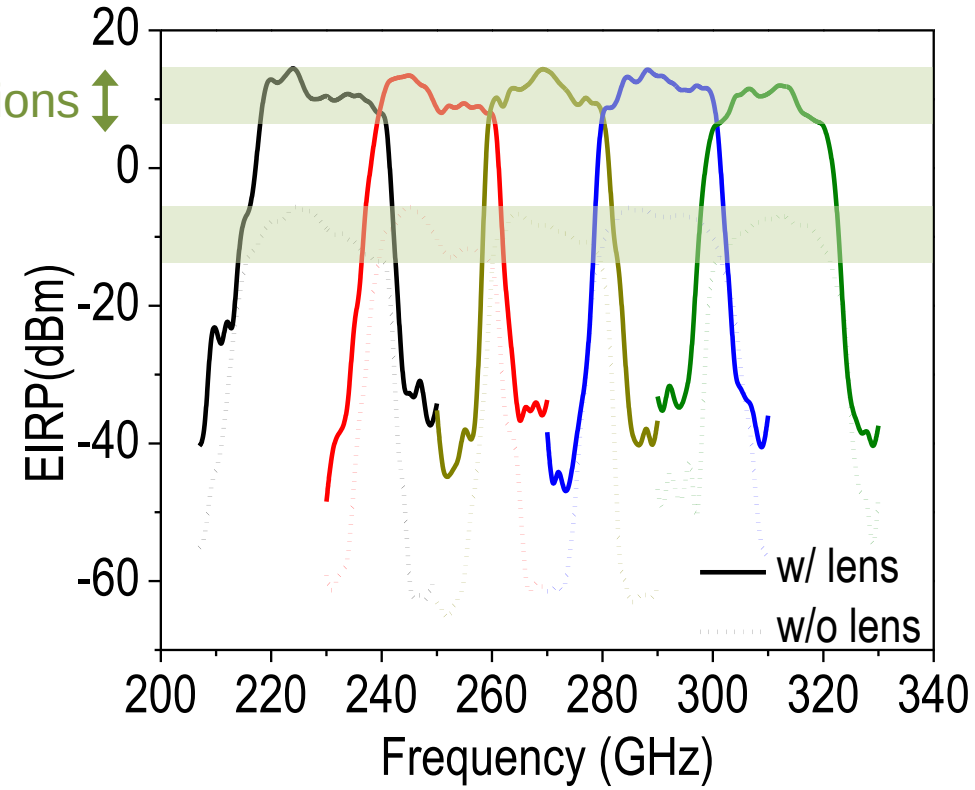




Transmitter Mode Measurement

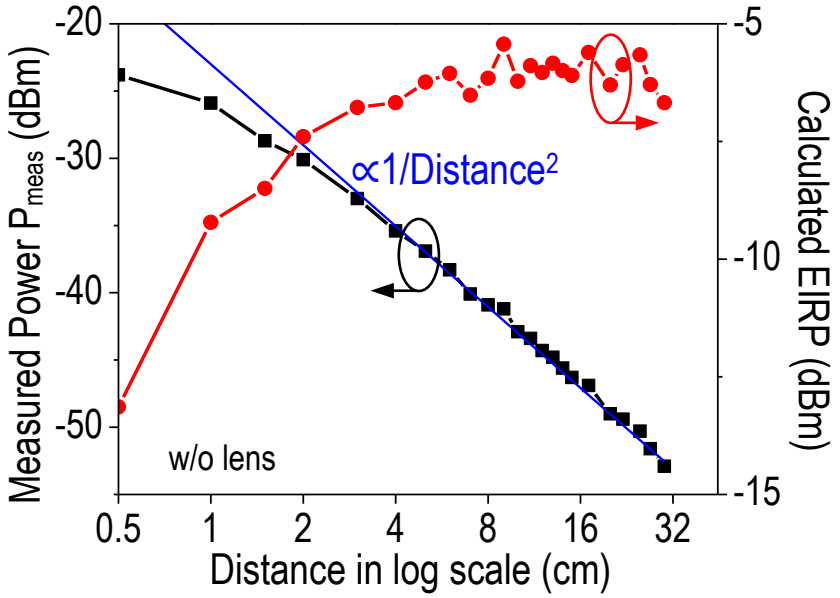
- Total EIRP without lens: 0.6dBm
- Total EIRP with lens: 20dBm
- Fluctuations: within 8.8dB

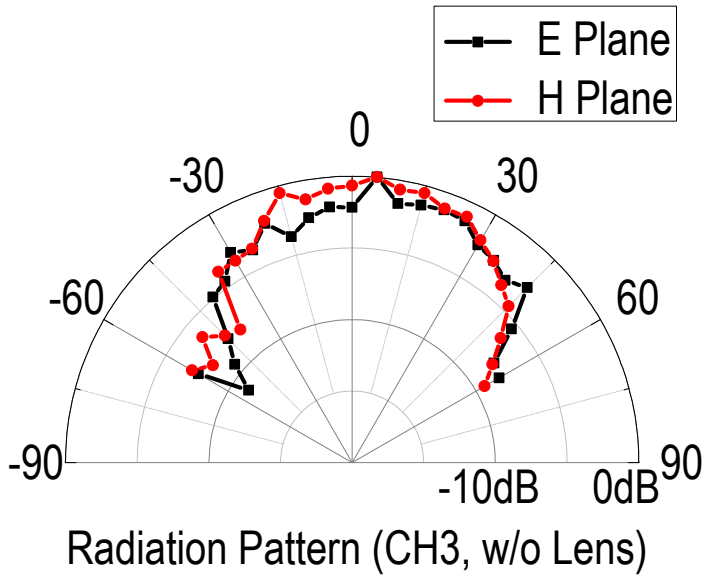


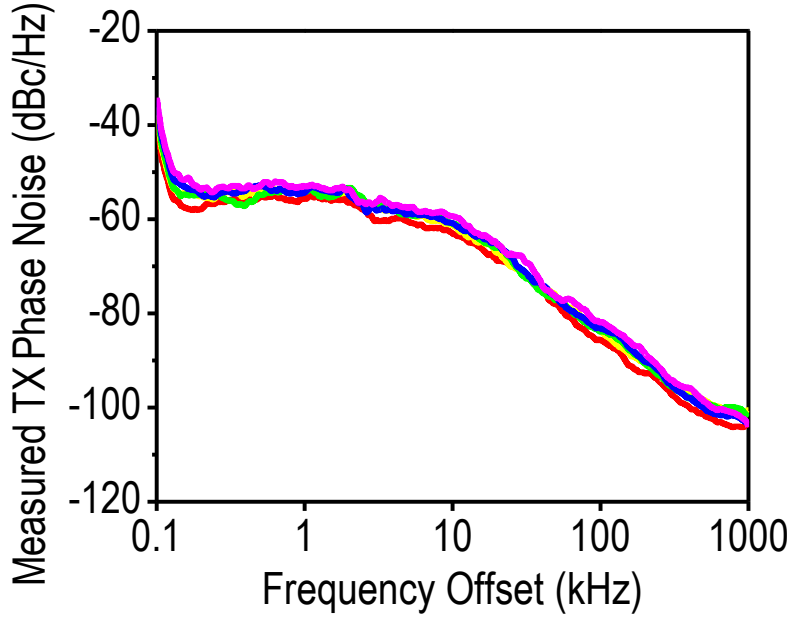


Transmitter Mode Measurement

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

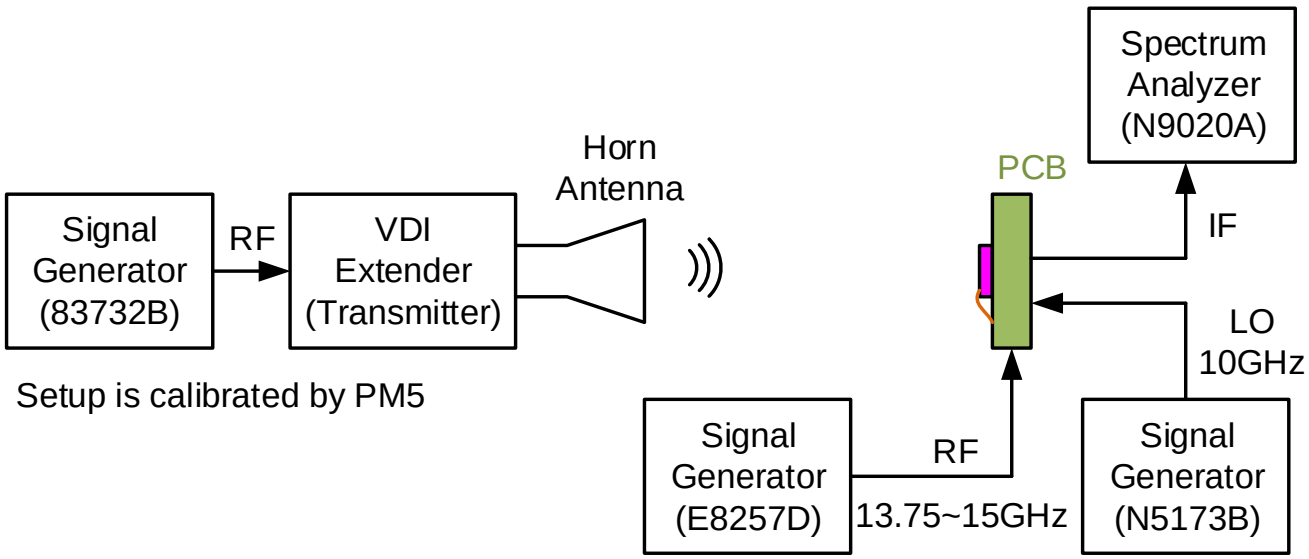


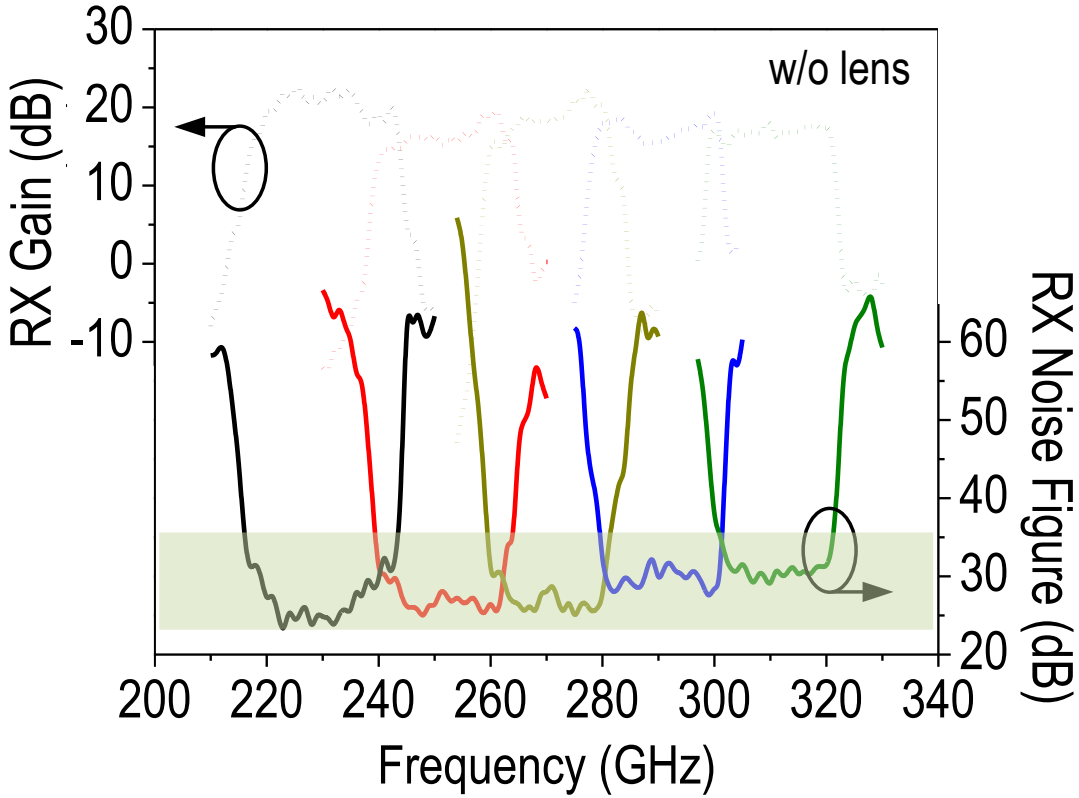




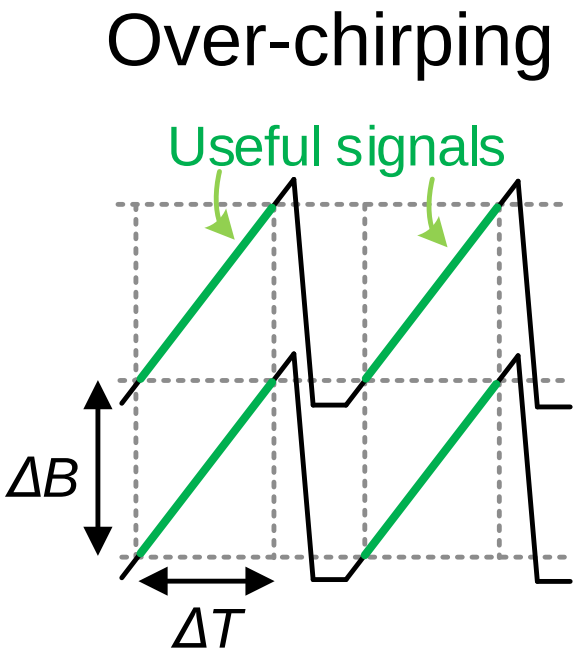
Receiver Mode Measurement

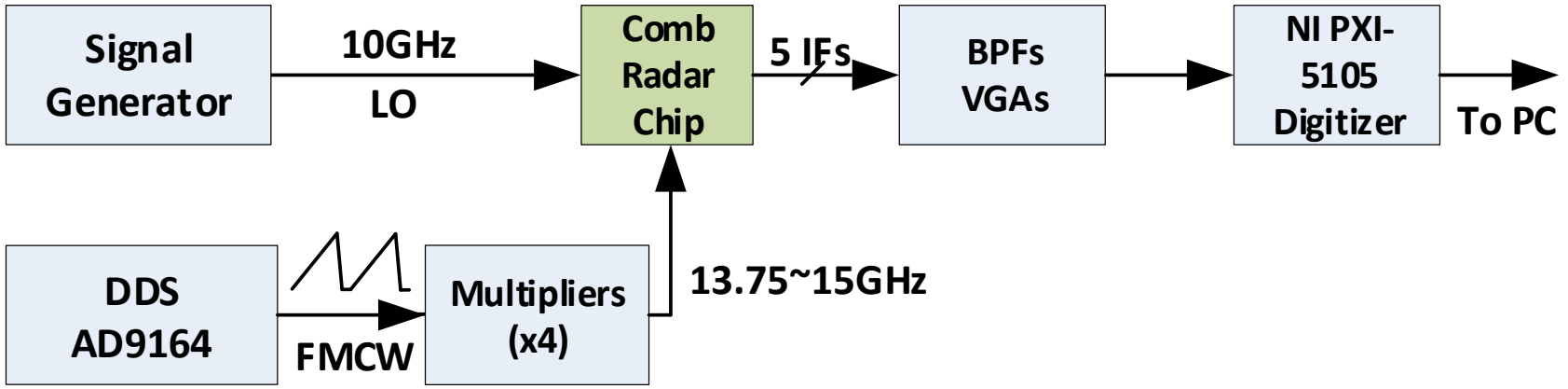
- Minimum SSB NF including antenna loss: 22.8dB
- Fluctuation of NF: 14.6dB
- Receiver gain: 22.2dB

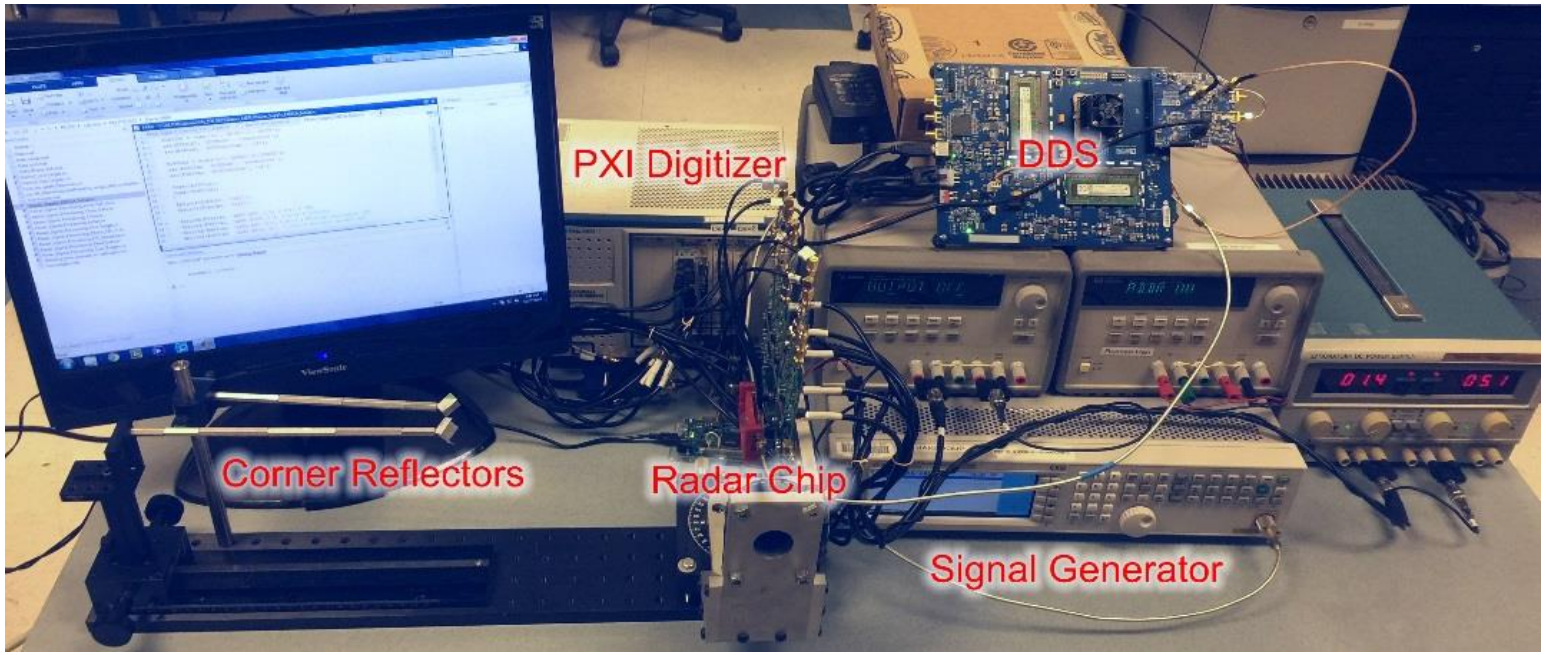




FMCW Radar Measurement Setup

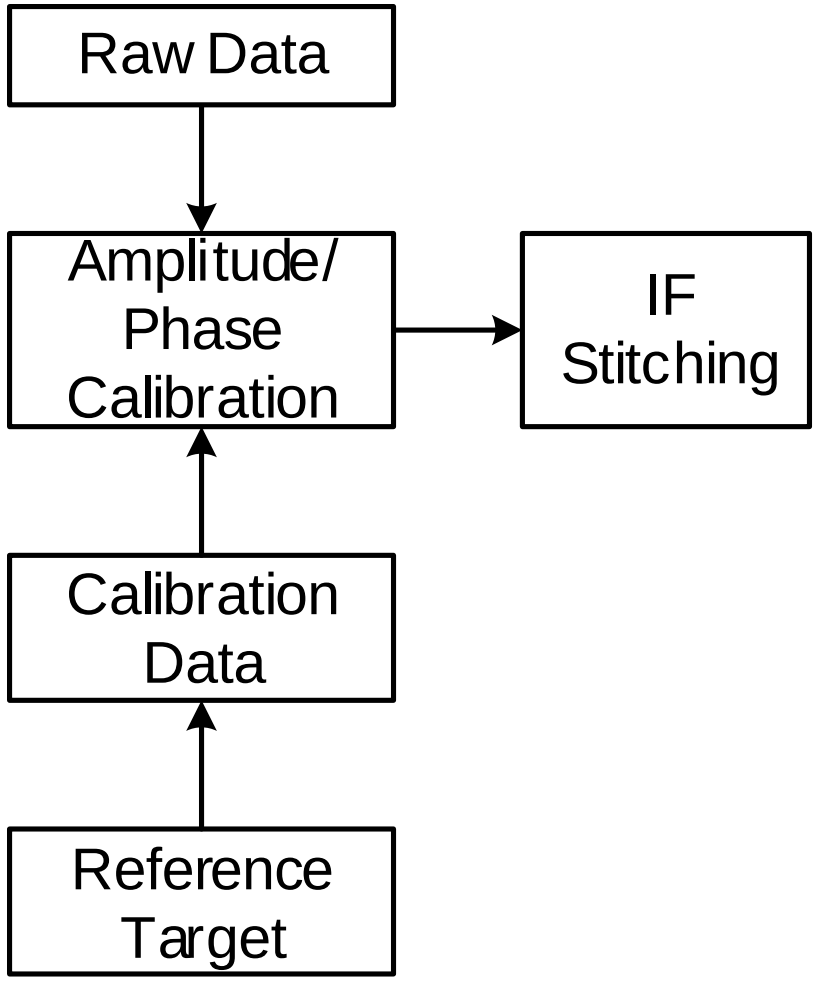






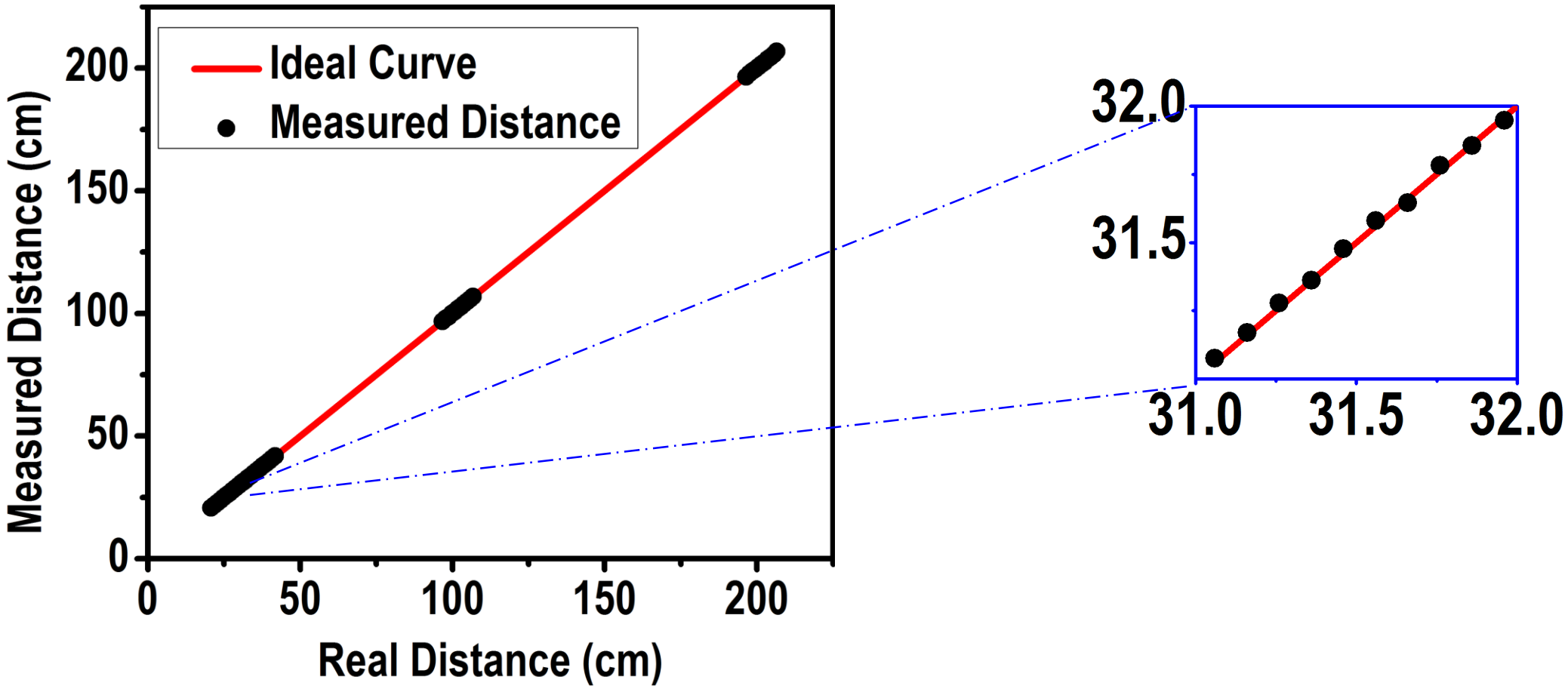
Radar Signal Calibration

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



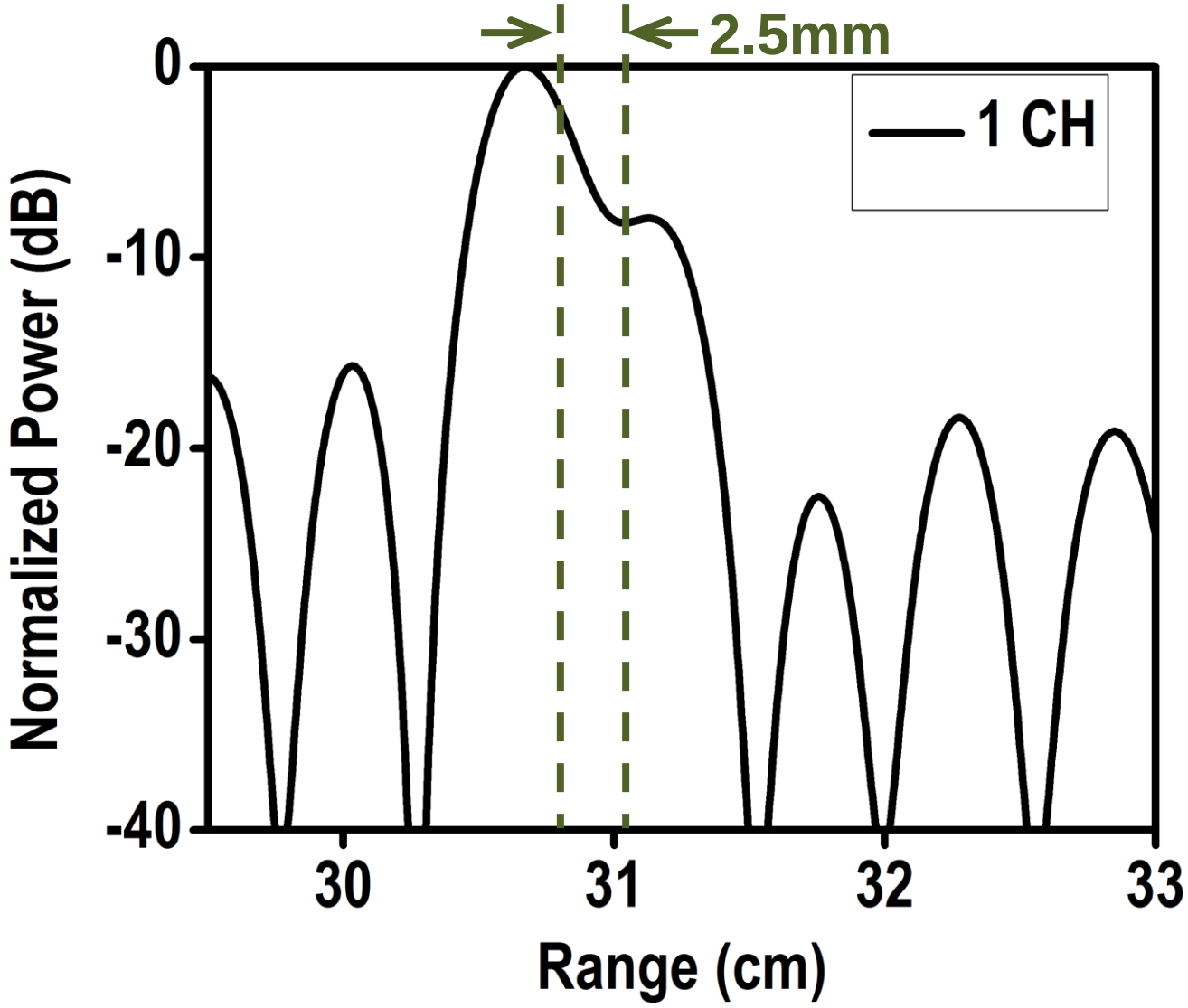
Range Accuracy Measurement

- Measured distance matches real distance



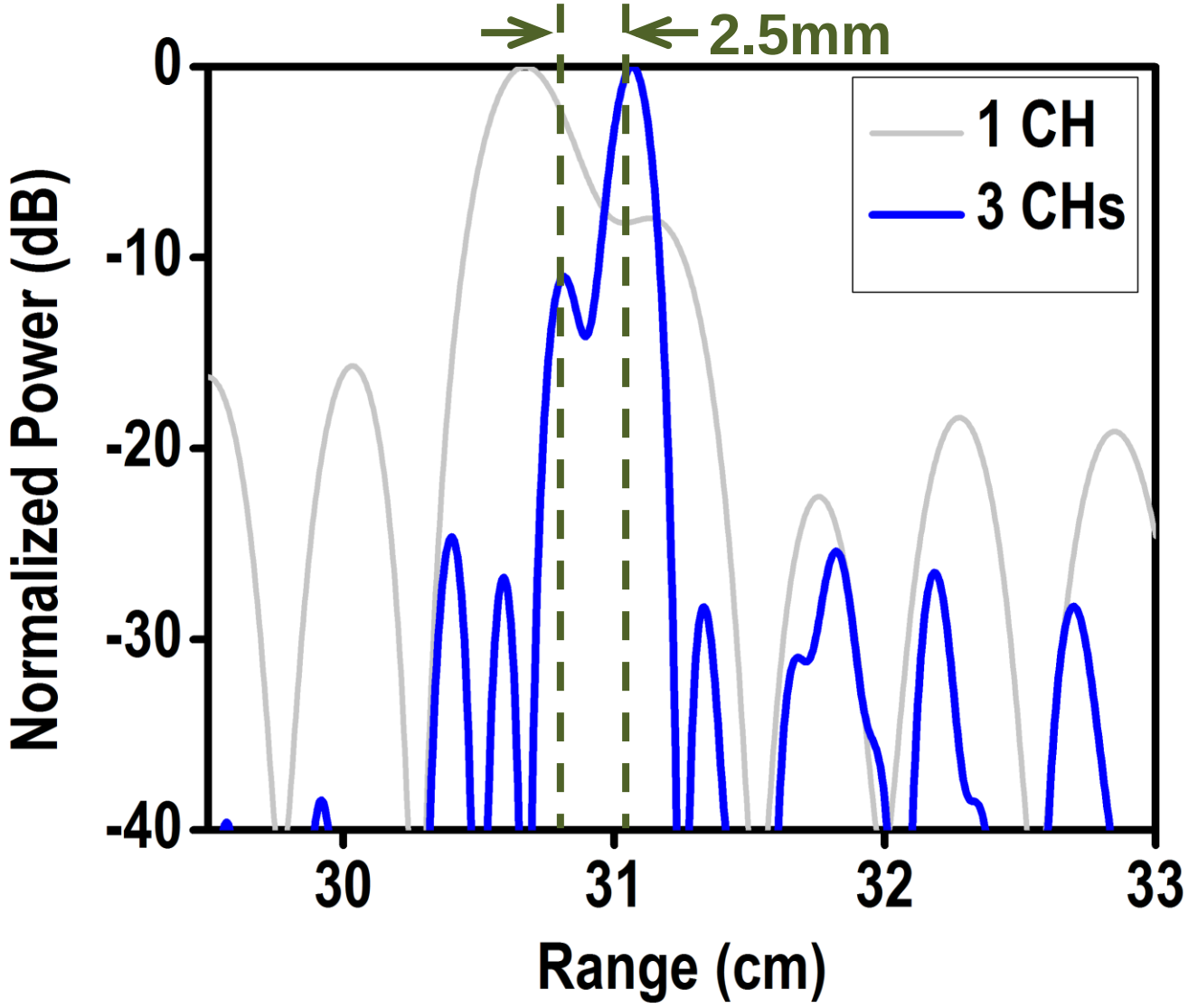
Range Resolution Measurement

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



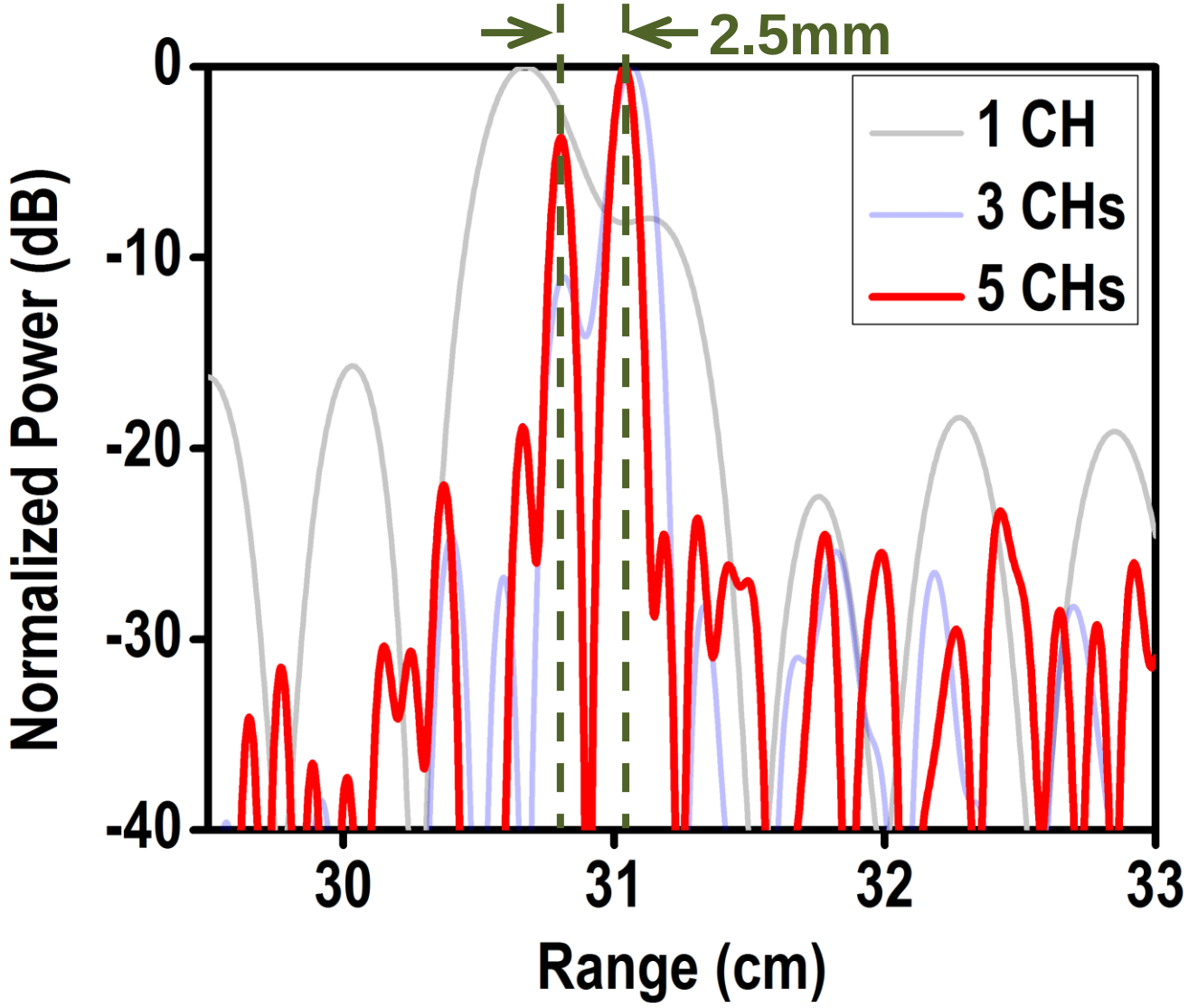
Range Resolution Measurement

- 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.

Outline

- Introduction
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Conclusion

- **Comb radar for wideband THz applications**
  - Flatter frequency responses
  - More linear chirp signal
  - Finer velocity resolution
  - Improved SNR
  - Scalable bandwidth extension

- **A five channel comb radar with 100GHz bandwidth was demonstrated in 65nm bulk CMOS technology**

Acknowledgements

- Chip fabrication: TSMC University Shuttle Program
- Measurements: Prof. Charlie Sodini, Prof. Tomás Palacios, Qingyu Yang, Mohamed I. Ibrahim, and Nathan Monroe (MIT); Pu Wang, and Rui Ma (Mitsubishi Electric Research Labs)
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