Building blocks and system architecture for mm-wave imaging radar

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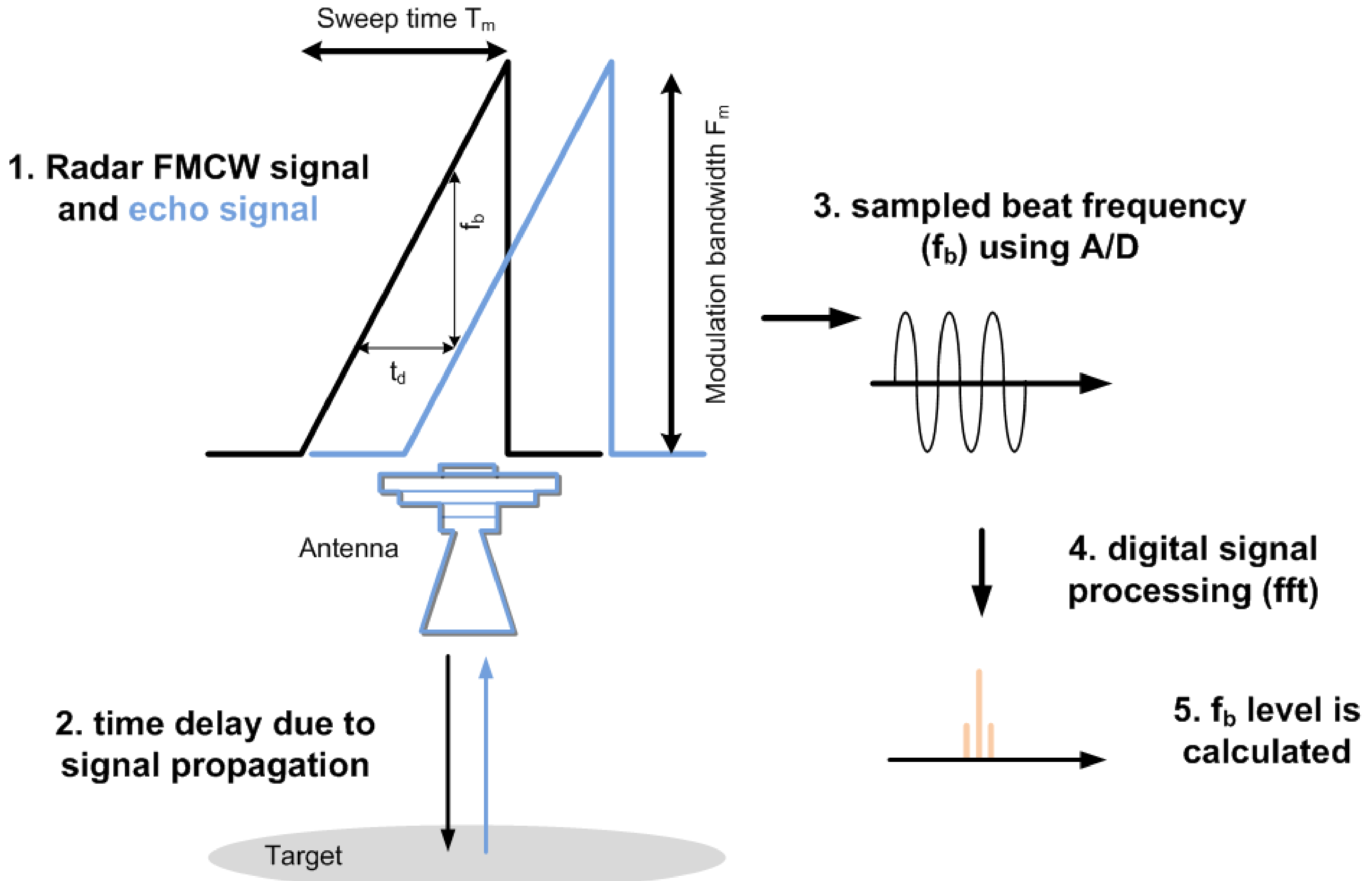
Outline

- Motivation
- Frequency scanning FMCW
- Integrated waveguide technology
- Antenna interface
- Frequency scanning antenna
- System assembly demonstrator
- Broadband building blocks
  - mm-wave digital PLL (DPLL)
  - power combining mm-wave PAs
- Conclusions

Motivation

- Unlicensed mm-wave bands allow for high resolution imaging radars to be integrated in small form factor systems.
  - Image (lateral) resolution related to $\lambda=c/f$ (3mm at 100GHz) in diffraction limited systems.
  - Antenna size on the order of $\lambda_g/2$ (i.e., resonant antenna)
  - Antenna spacing close to $\lambda/2$ (linear array)
- Advanced SiGe technology to realize high-performance broadband front-ends interfacing with the radiating elements.

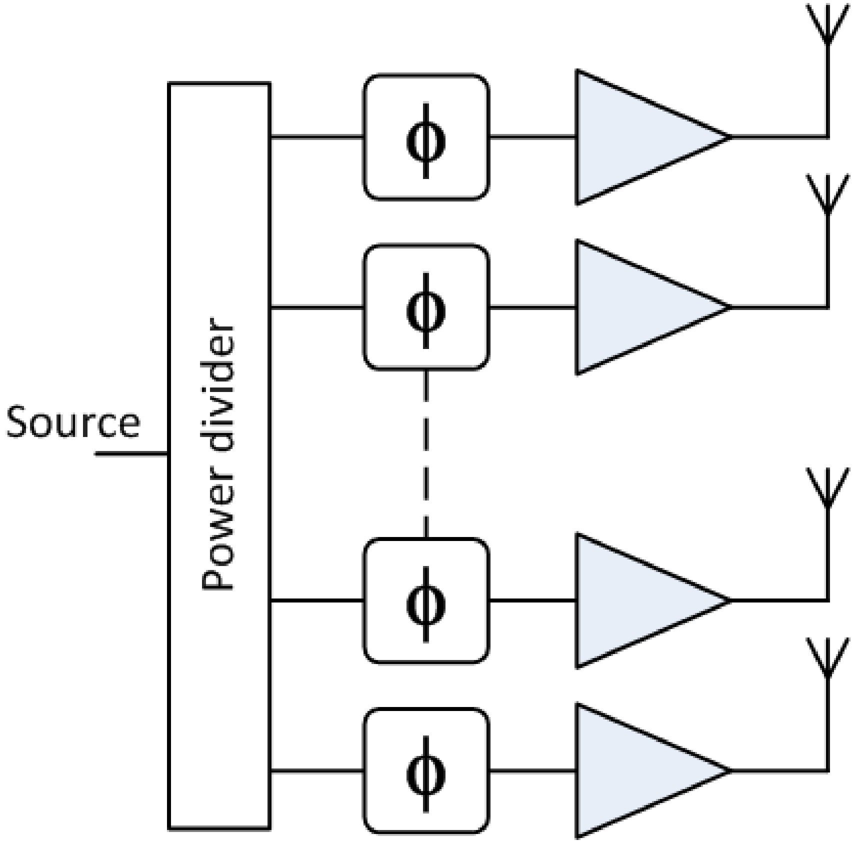
Frequency-modulated continuous-wave radar



FMCW imaging radar

In order to create 2D images of an object, beam steering along one axis is implemented.

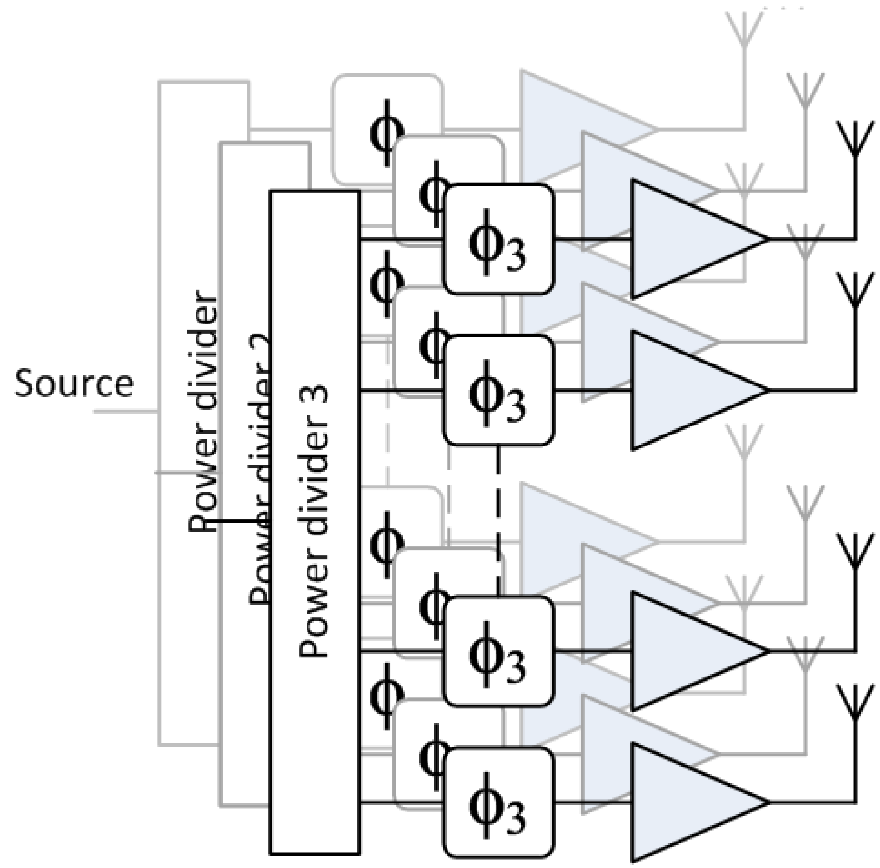
Delay elements or phase shifters can be employed.



FMCW imaging radar

To obtain 3D images, beam steering capabilities also on the other axis (i.e., y) are implemented.

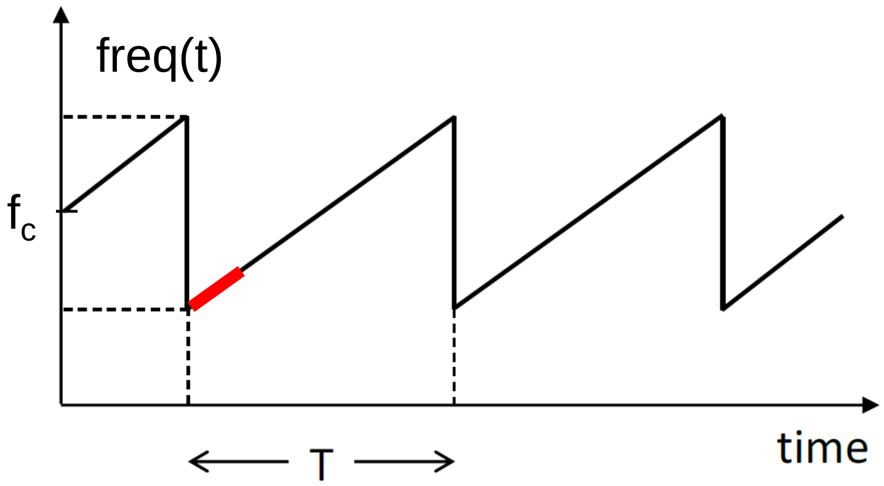
Bi-dimensional beam steering requires a phase-shifter or true-time delay for every radiating element.

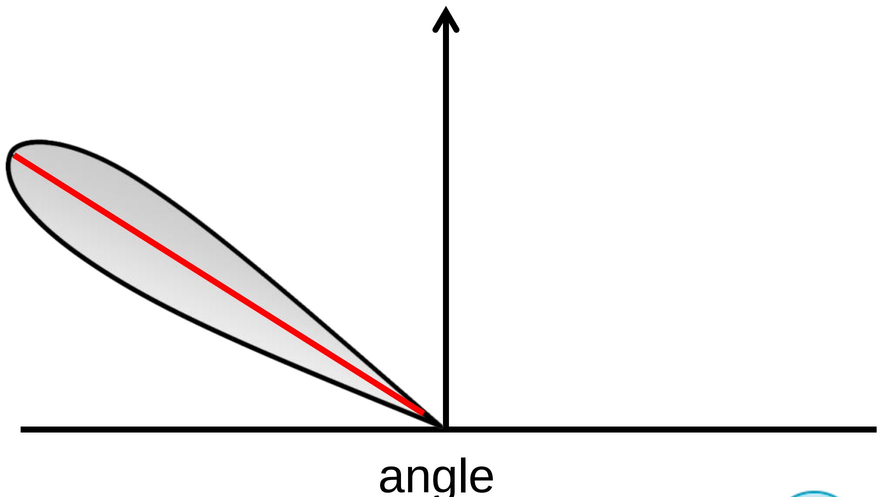


N^2 delay elements required for NxN antenna matrix

Frequency scanning FMCW concept

To reduce the system complexity (i.e., number of delay elements) in high resolution systems, the beam can be steered along one axis using frequency modulation, which is called frequency scanning.





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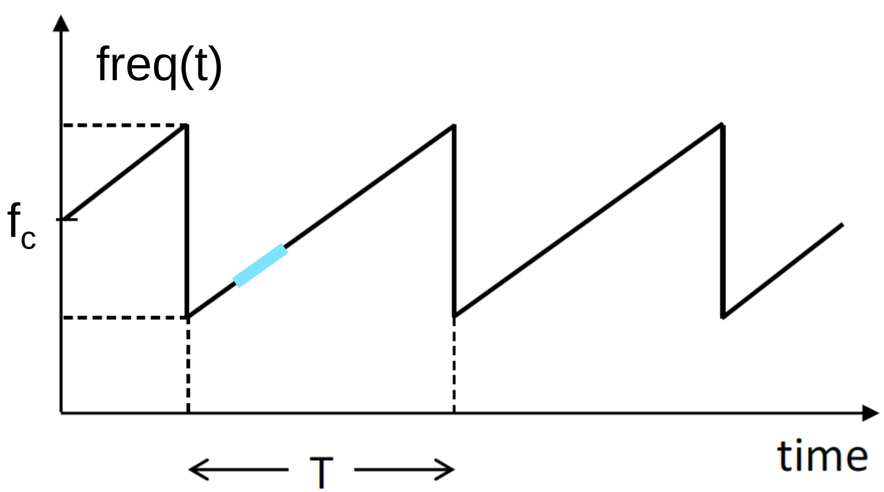

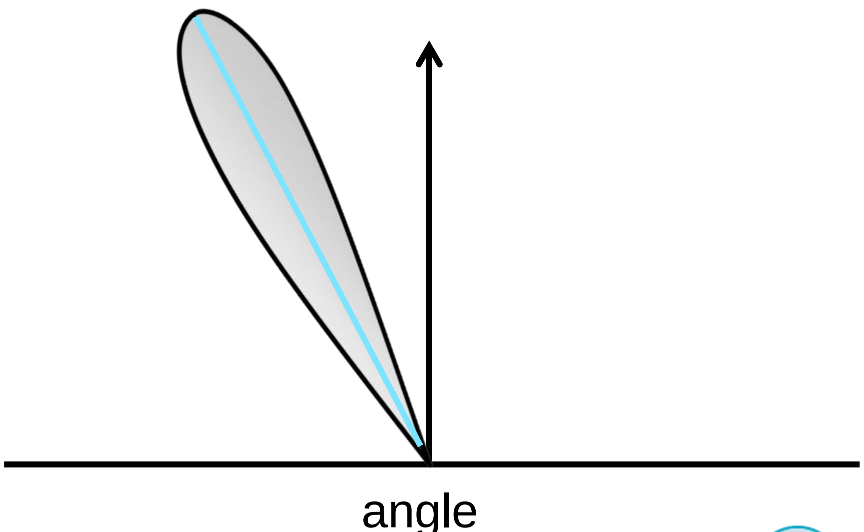

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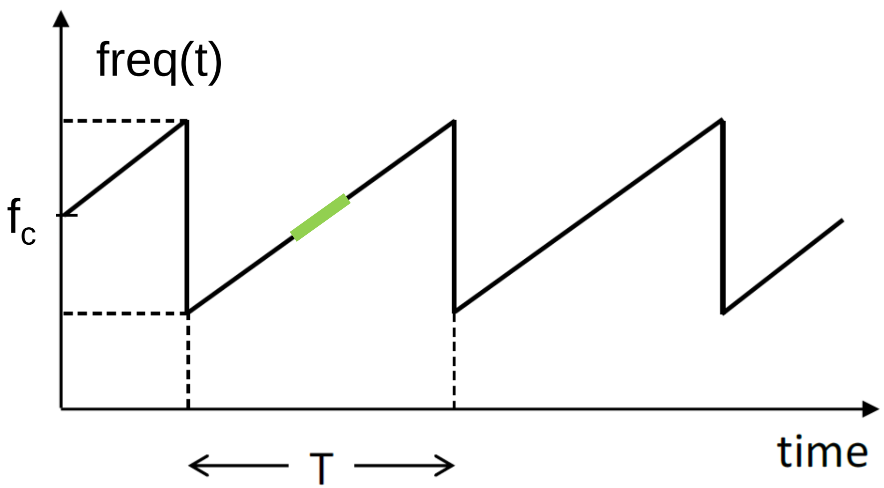

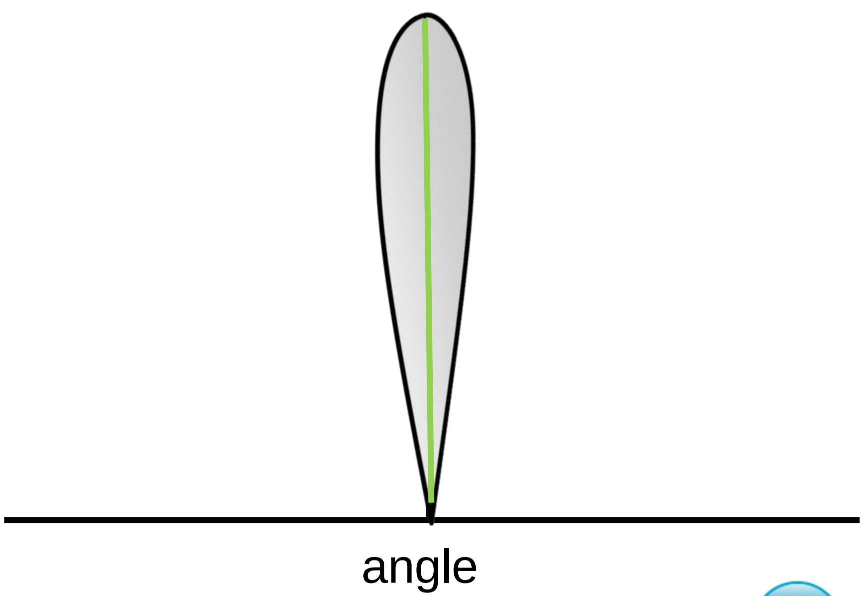

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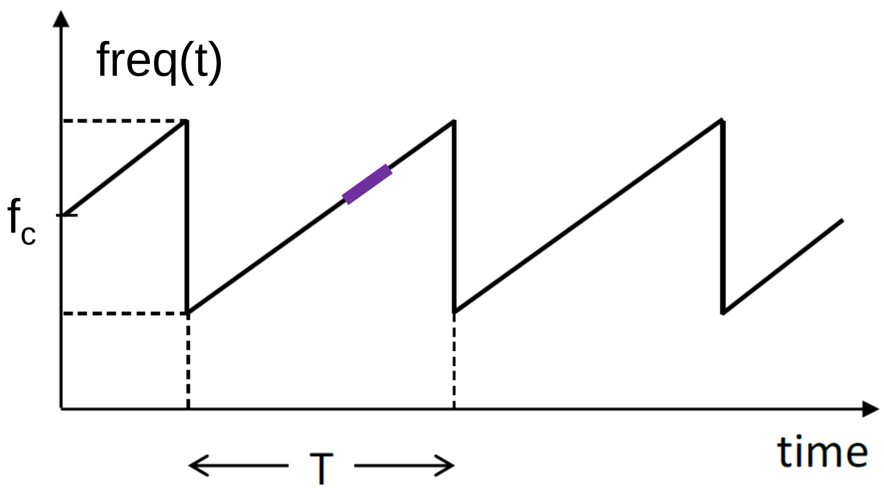

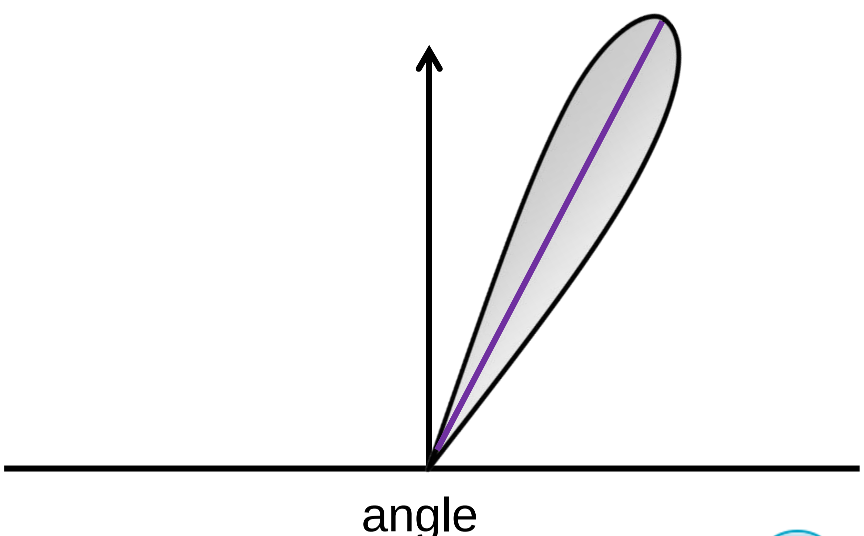

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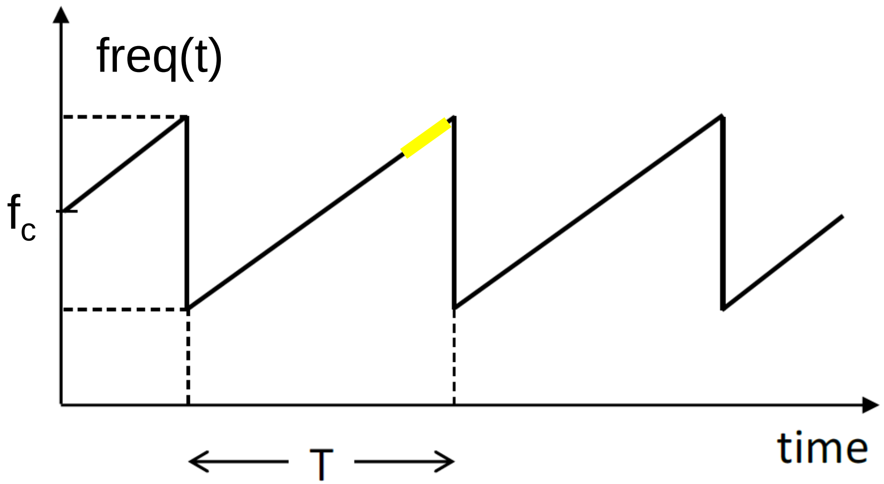
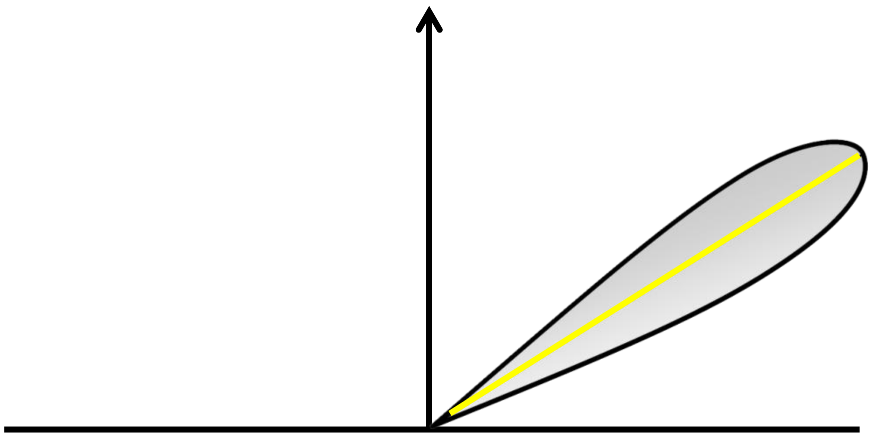
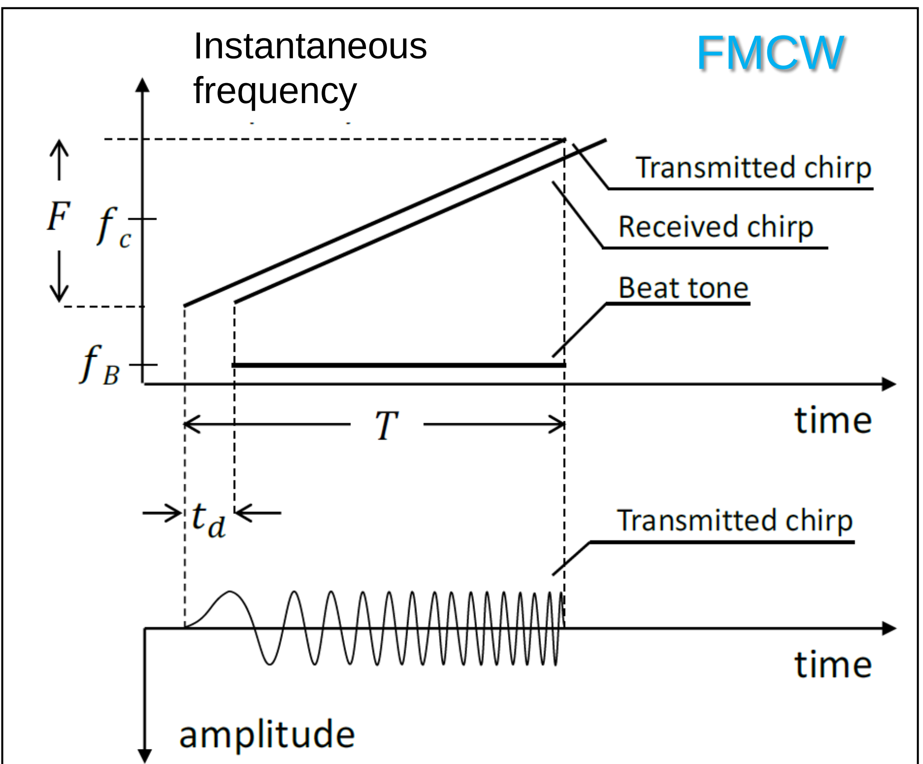


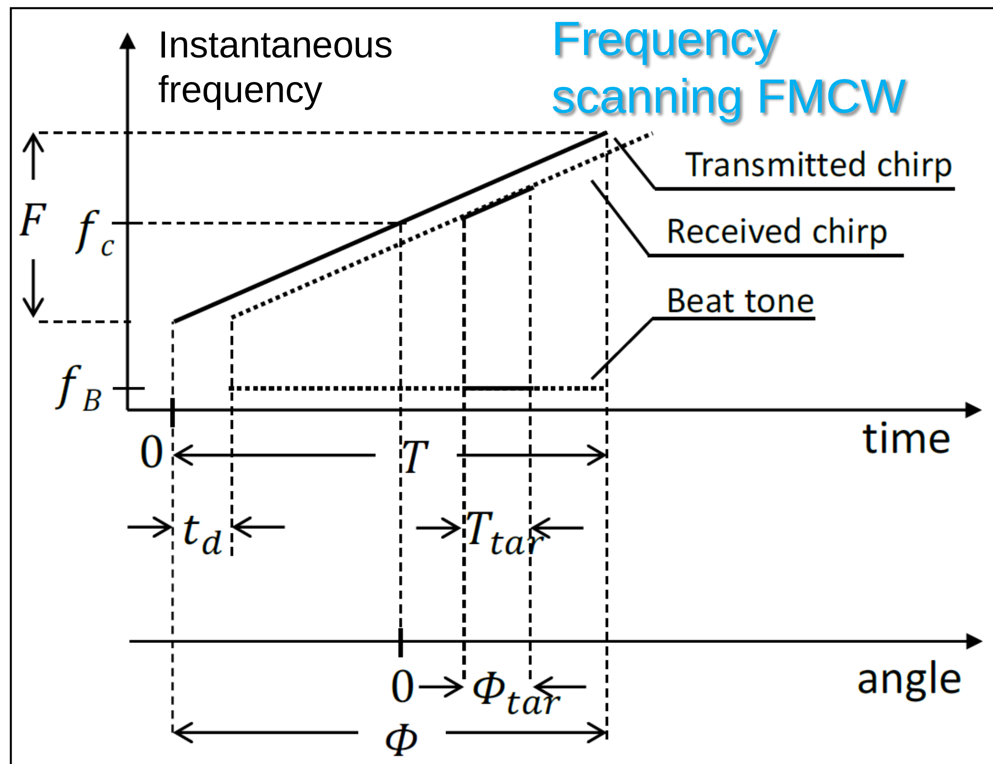


Frequency scanning FMCW detection

Angle information:

- FMCW provided by phase shifter settings
- Frequency scanning FMCW provided by time of arrival





Frequency scanning FMCW, detection

When analysing the detection equation we have:

$R_{\min\_r} = \frac{c}{2F}$ (improves with large modulation BW)

$T_{tar} \propto \Phi_B$

$\Phi_{resolution} \propto \frac{1}{\Phi_B}$ (improves with antenna gain and number of elements)

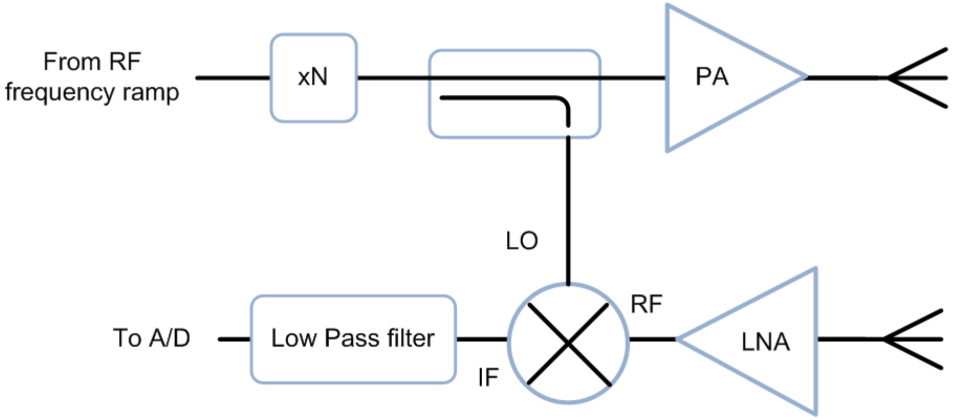
Where:

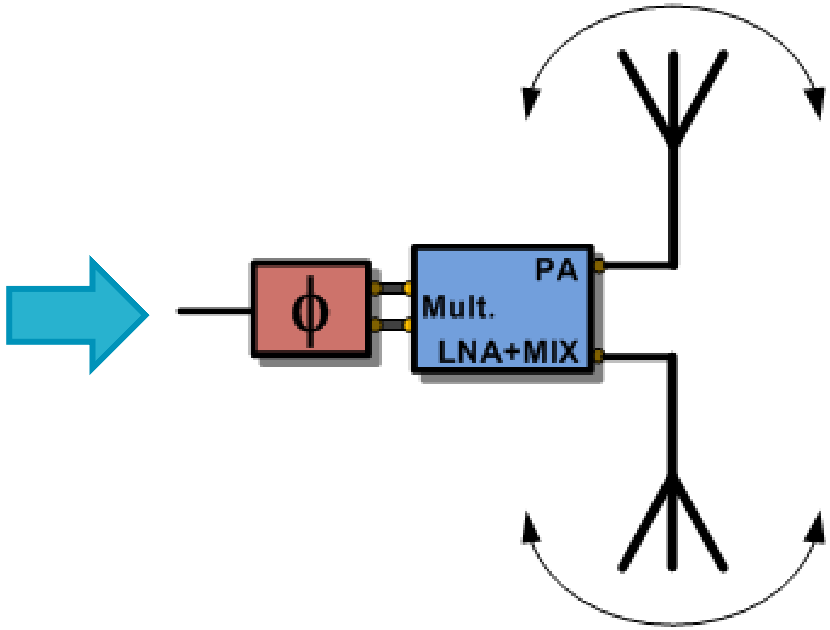
$\Phi_{tar} \cong \frac{D}{R}(180/\pi)$ (target's angle seen by antenna in degrees)

Φ_B (beam width of main lobe)

Frequency scanning FMCW

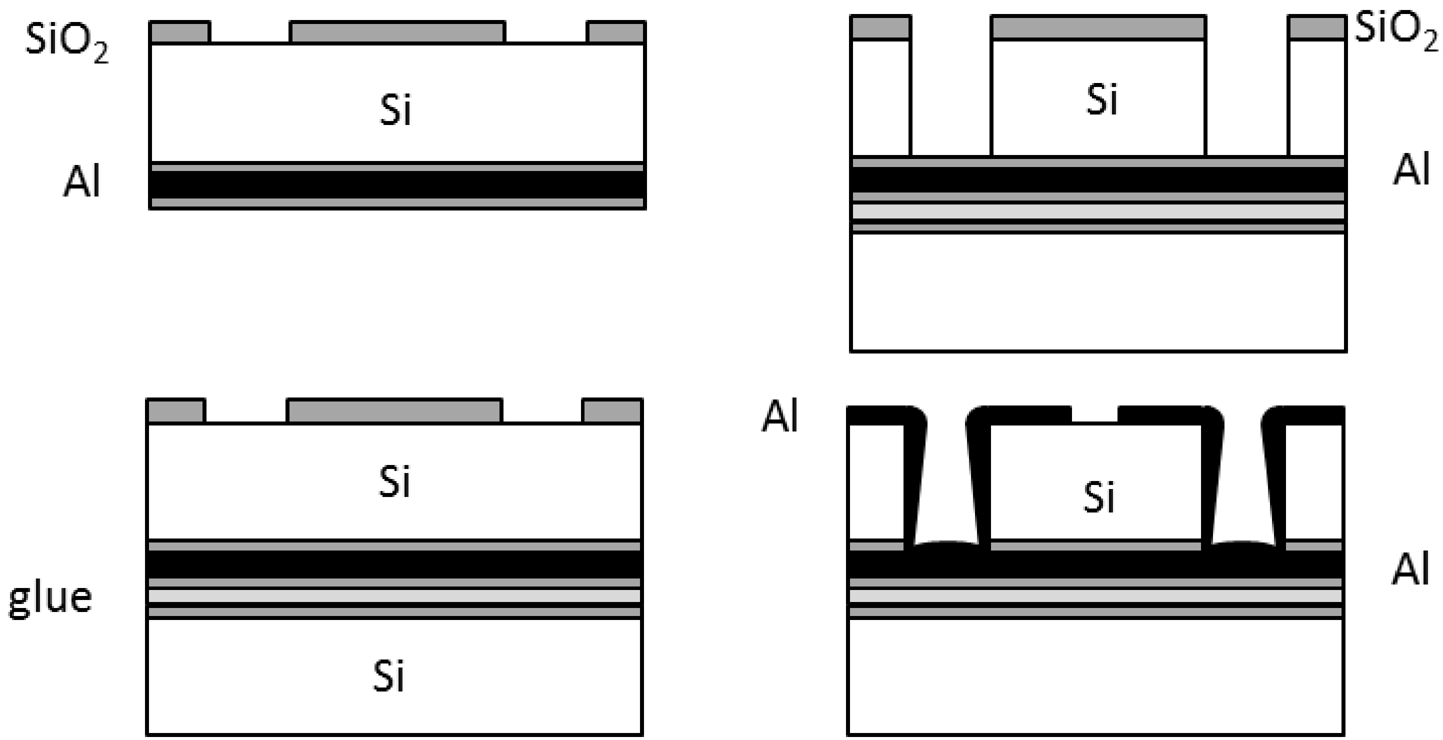
To enable integrated, high performance frequency scanning systems the required building blocks (ICs) need to be interface over a broadband with frequency scanning antennas.





Integrated waveguide technology

The DRIE waveguide process to integrate silicon filled waveguide.

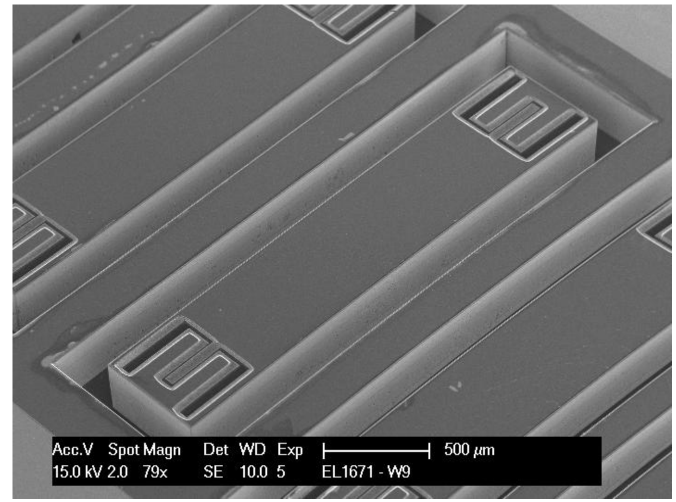


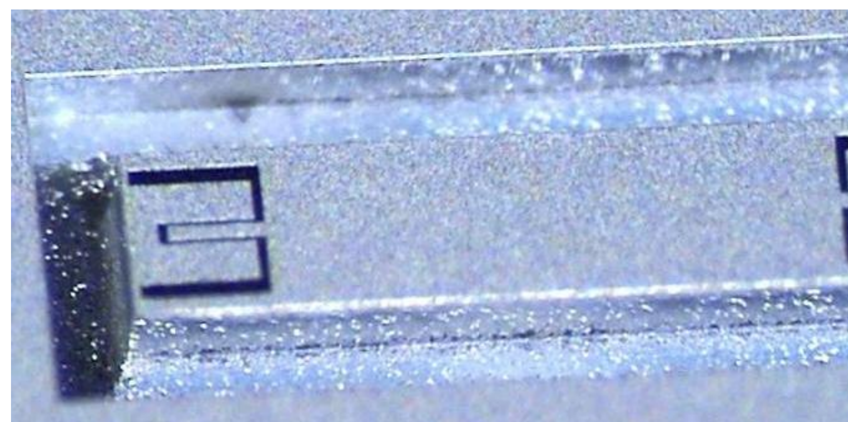
G. Gentile, V. Jovanovic, M.J. Pelk, L. Jiang, R. Dekker, P. Graaf, B. Rejaei, L.C.N. Vreede, L.K. Nanver, M. Spirito, "Silicon-Filled Rectangular Waveguides and Frequency Scanning Antennas for mm-Wave Integrated Systems," Antennas and Propagation, Early Access Articles 2013.

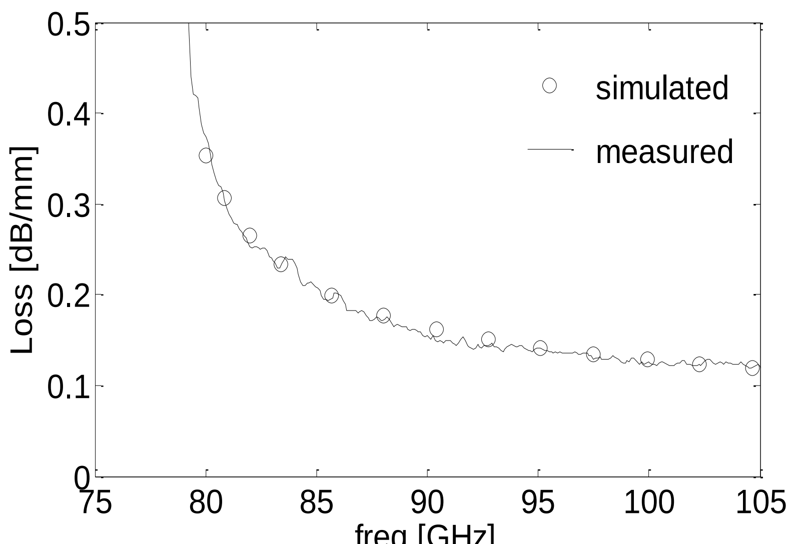
Integrated waveguide technology

Process features:

- Continuous metal side walls
- Size reduction (silicon ε_r)
- Photolithographic accuracy
- Planar feed

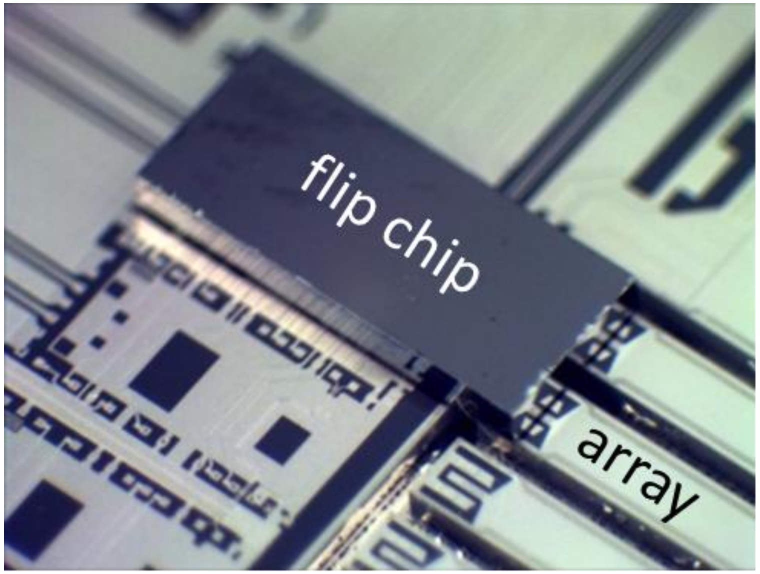


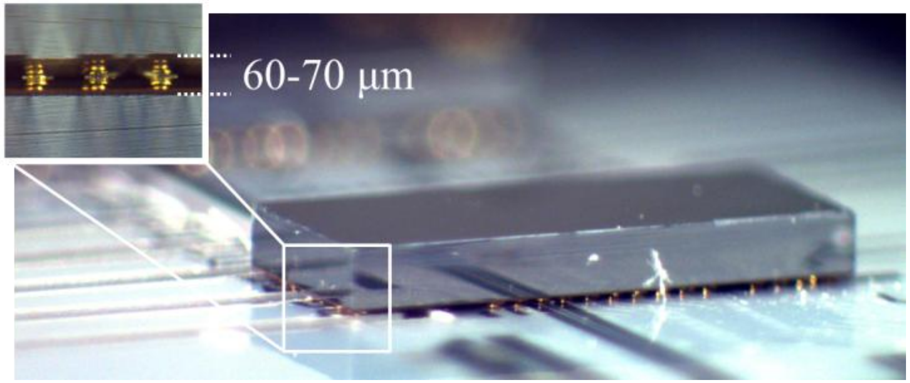




Antenna interface, on-to-off chip

To achieve high system performance requires a wide FM bandwidth. To properly deliver the realized signal to the radiator, a broadband antenna interface needs to be realized.

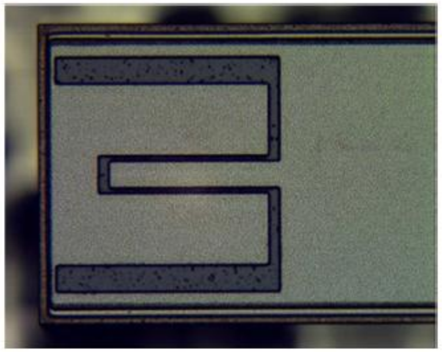


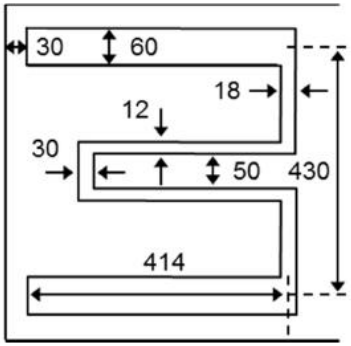


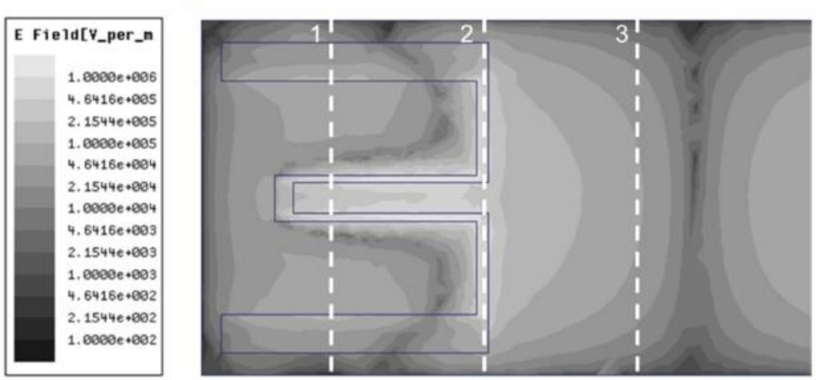
Low inductance (56 pH) flip-chip transition employed.

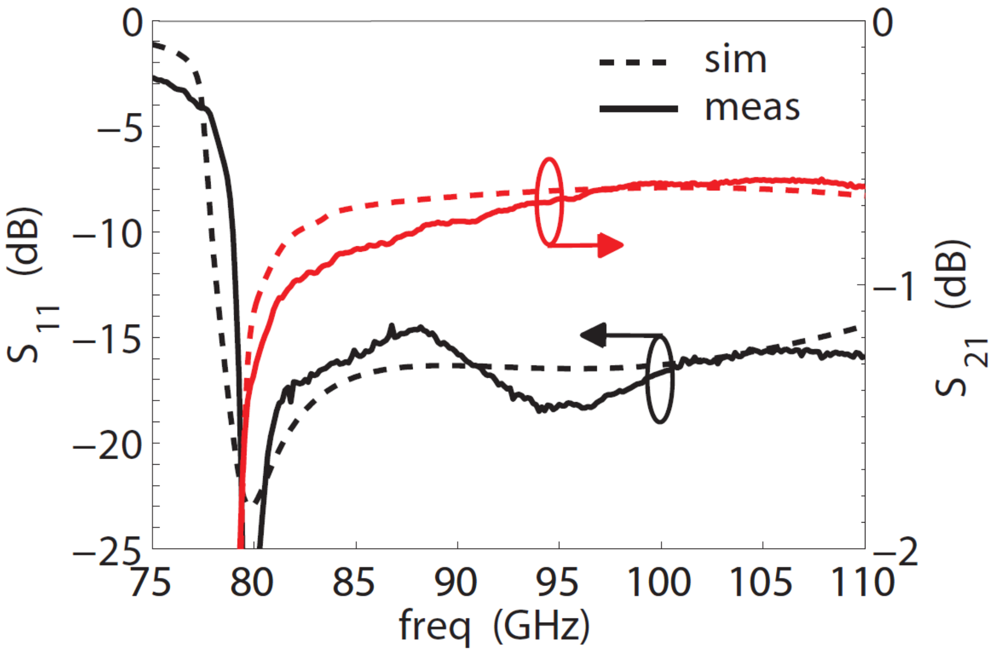
Antenna interface, waveguide feed

The broadband feed of the rectangular waveguide is realized via a coplanar slot antenna with parasitic longitudinal slots.



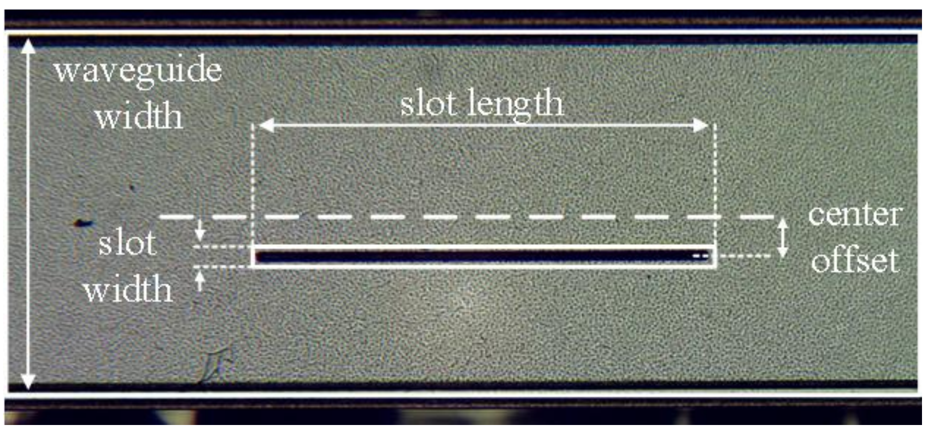


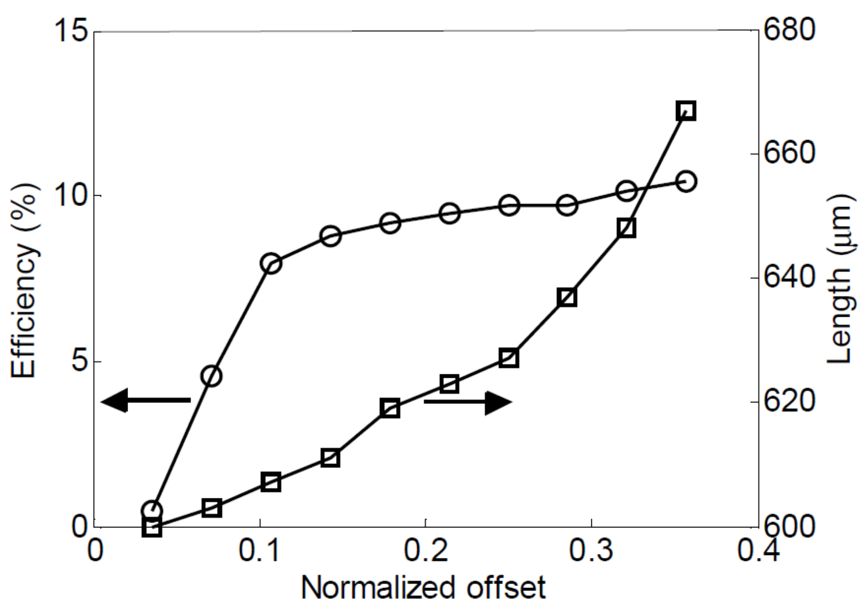




Frequency scanning antenna

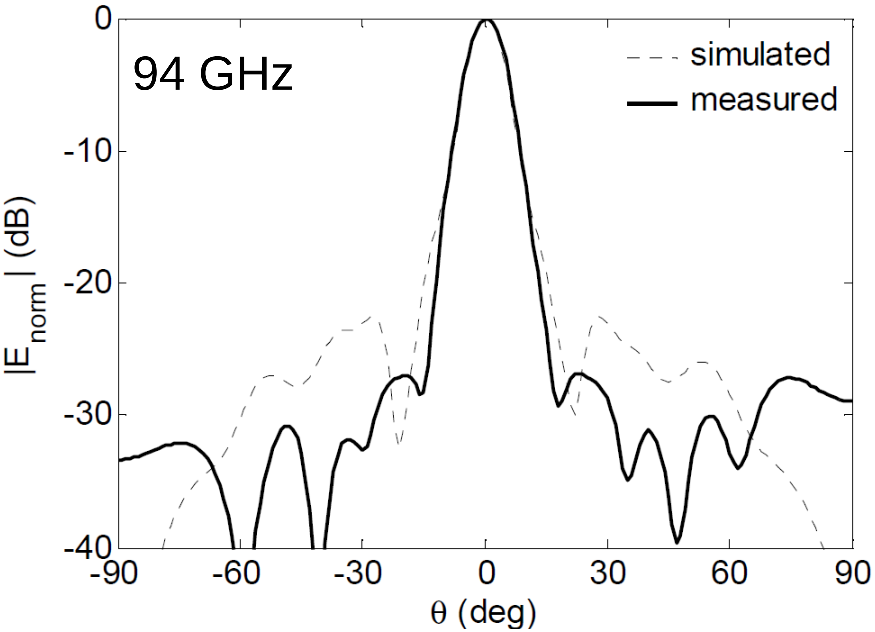
Slots with different dimensions and offsets enable scanning frequency antenna, simplifying the system architecture.

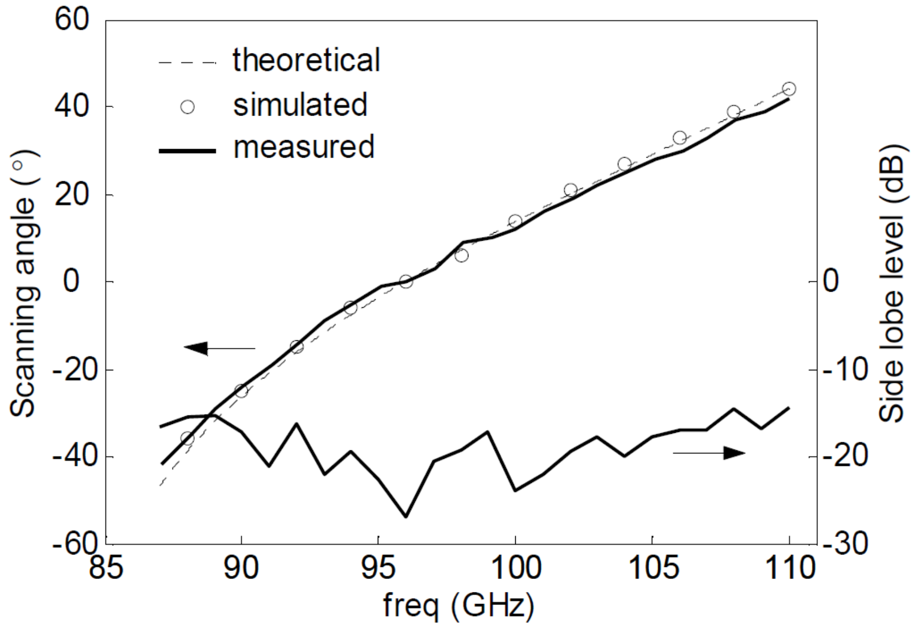




Frequency scanning antenna

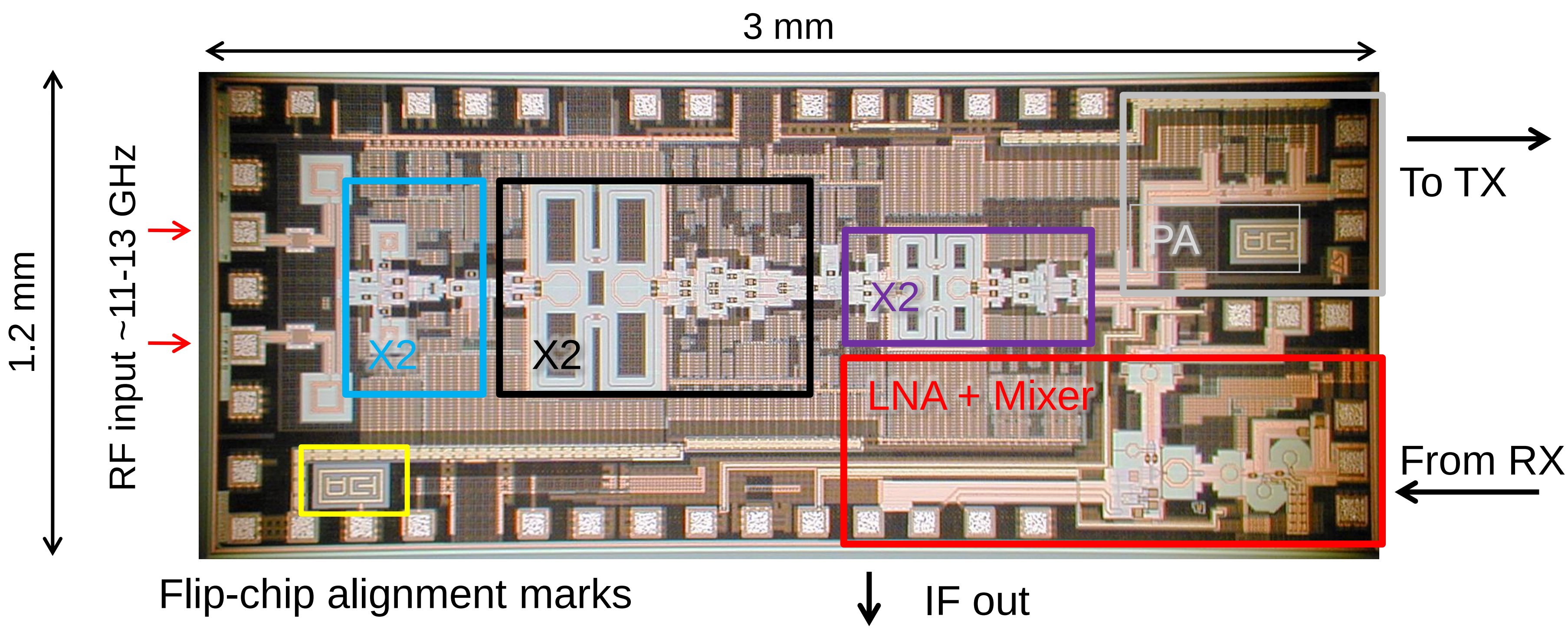
Employing a Tschebyscheff distribution of the radiated power by each slot high gain, low side-lobes antennas can be integrated.





System demonstrator IC

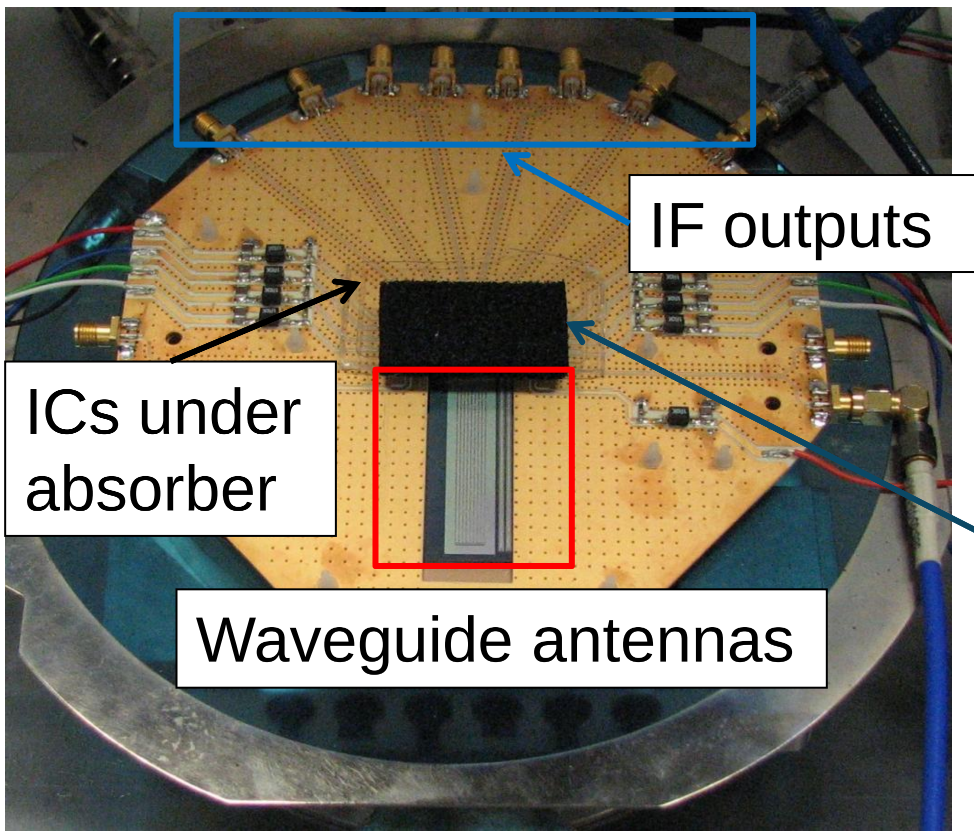
Single-chip 94 GHz up-conversion and receiver in 0.13 um Bi-CMOS, integrated in ST 9MW technology (230/280, F_t/F_{max}).



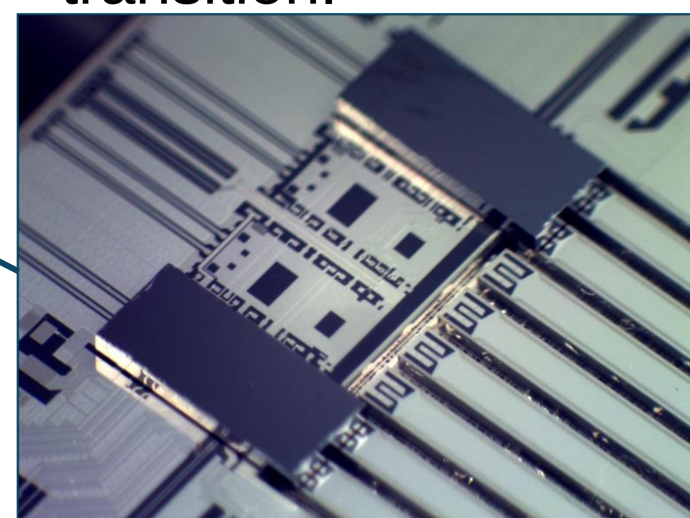
8x frequency up-conversion + down-converting mixer

System assembly demonstrator

Complete demonstrator with 20 horizontal radiators providing 8.5° half power beam width, and 4 vertical channels.

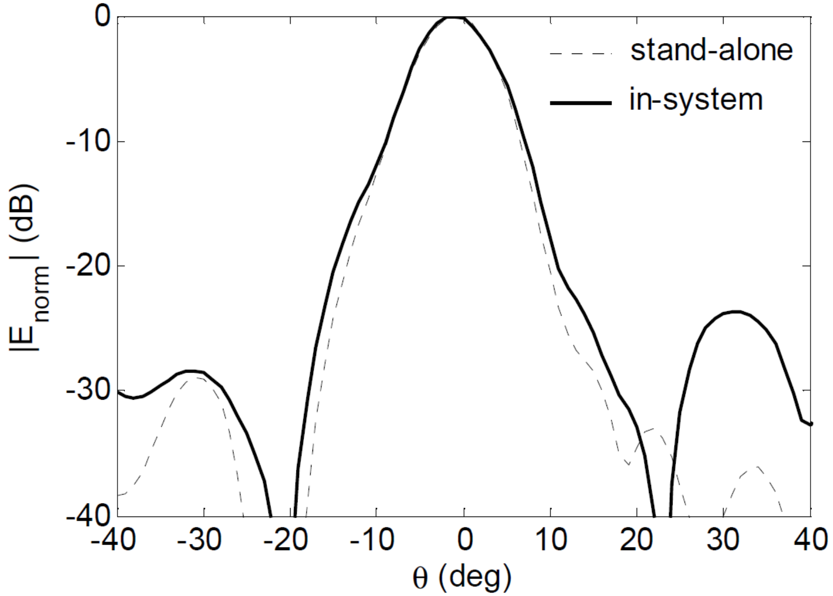


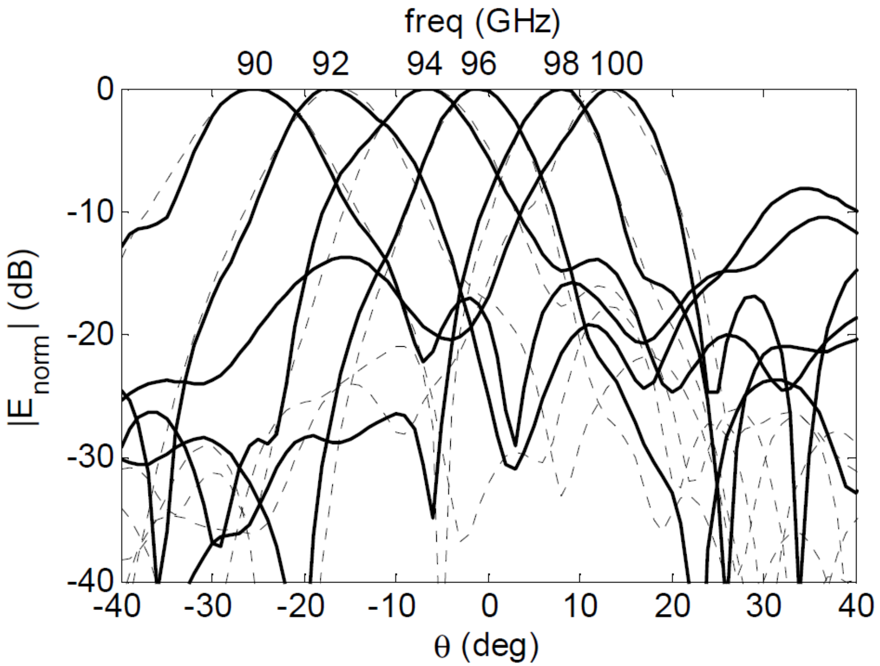
Absorber used to minimize radiation disturbance due to transition.



System, testing under static FMCW

The demonstrator was tested (input ~12GHz) and benchmarked versus stand-alone antenna measurements.





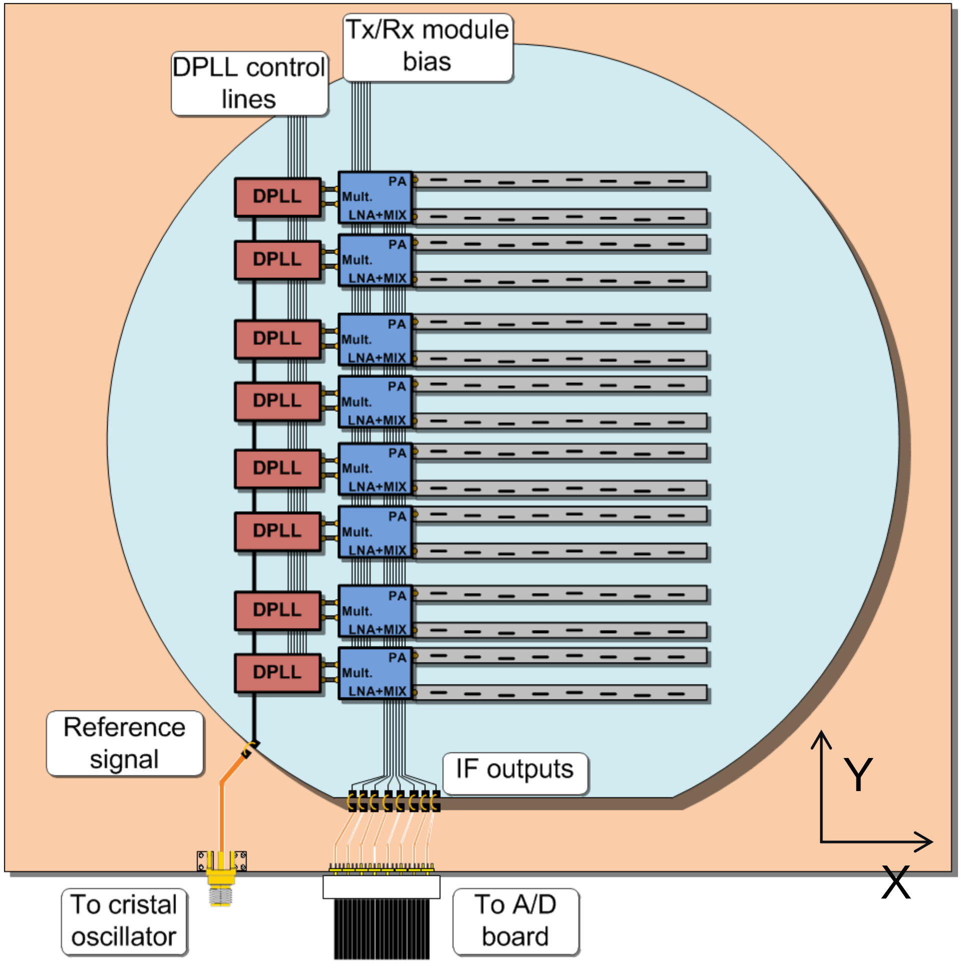
Reduced complexity imaging system

High resistivity silicon provides the integration platform.

FM provides beam steering along X direction.

Delays in the DPLL frequency ramps provide beam steering along Y direction.

Linear multiplier (i.e., x2 with 60GHz input) to access the desired operating frequency.



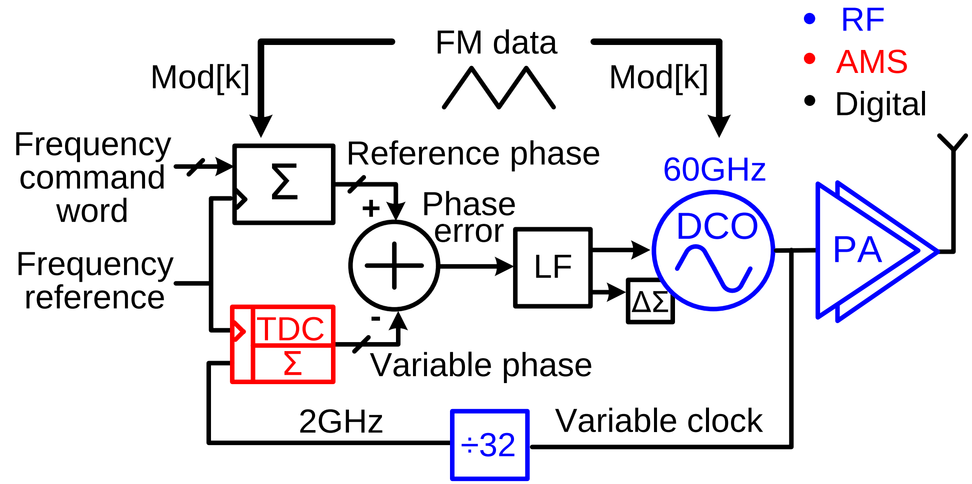
Advanced building blocks SiGe enabled

Digital intensive PLL enables a high level of programmability and built-in calibration/self-test capabilities.

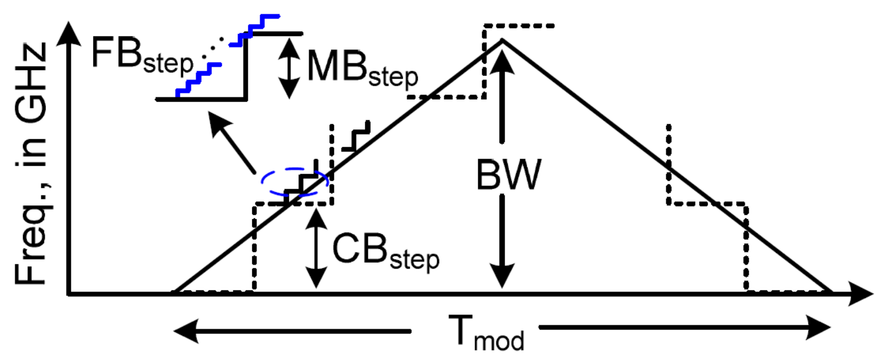
Millimeter-wave DPLL reduces the number of in-band spurs and relaxes isolation requirements on the following stages.

Broadband building blocks, DPLL

FMCW transmitter with multirate, two-point, wideband frequency modulation capability using a DPLL.



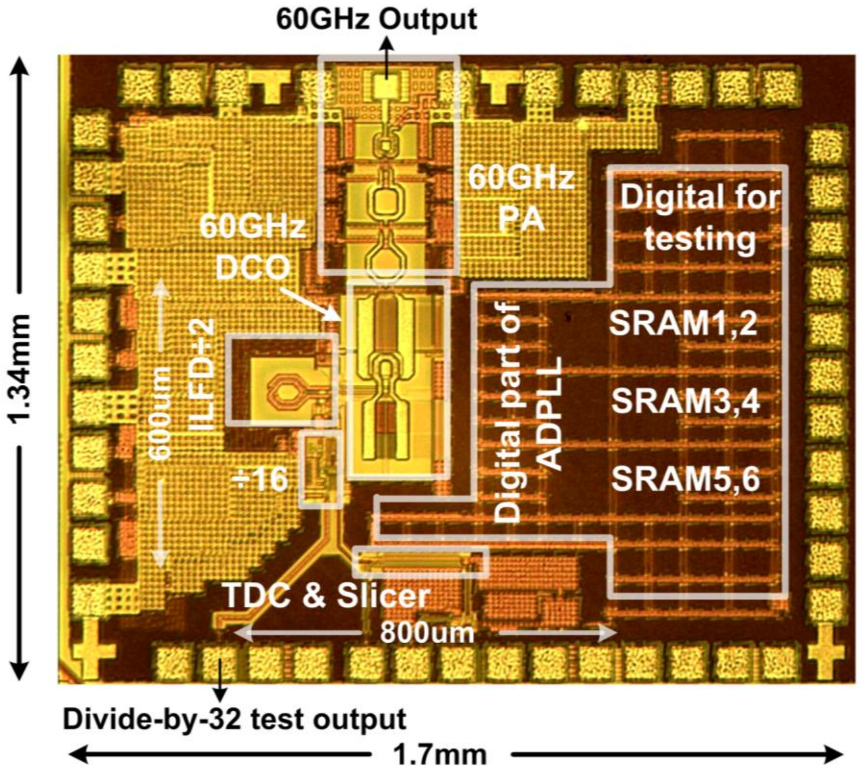
DCO tuning segmented into coarse (CB), mid-coarse (MB), and fine tuning (FB) banks for high resolution and wide tuning range.

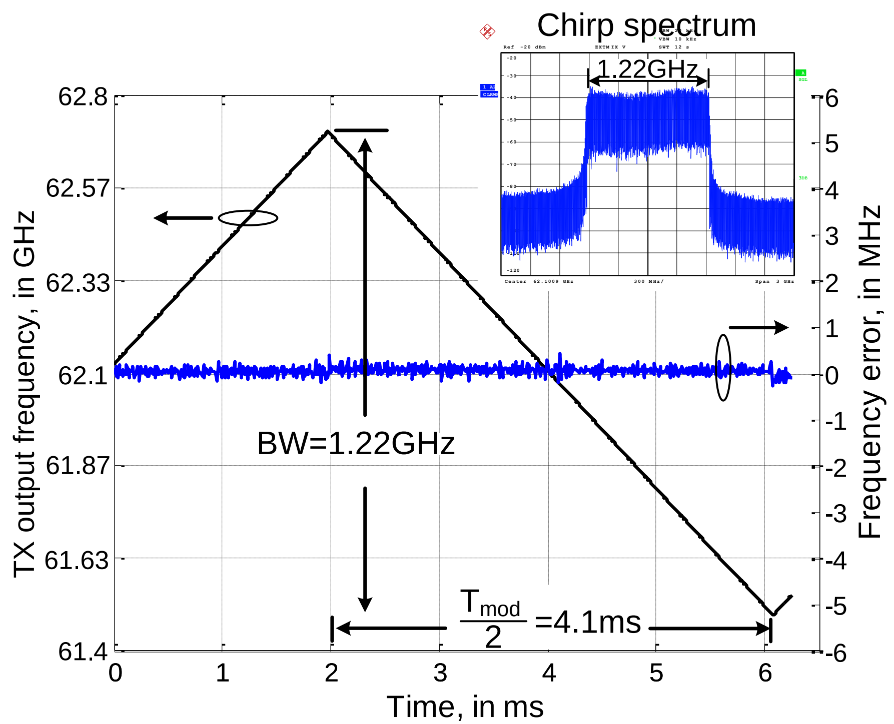


W. Wanghua, Bai Xuefei, R.B. Staszewski, J.R. Long, "A mm-Wave FMCW radar transmitter based on a multirate ADPLL," Radio Frequency Integrated Circuits Symposium (RFIC), 2013 IEEE , vol., no., pp.107,110, 2-4 June 2013

Broadband building blocks, DPLL

DPLL implemented in 65-nm TSCM CMOS

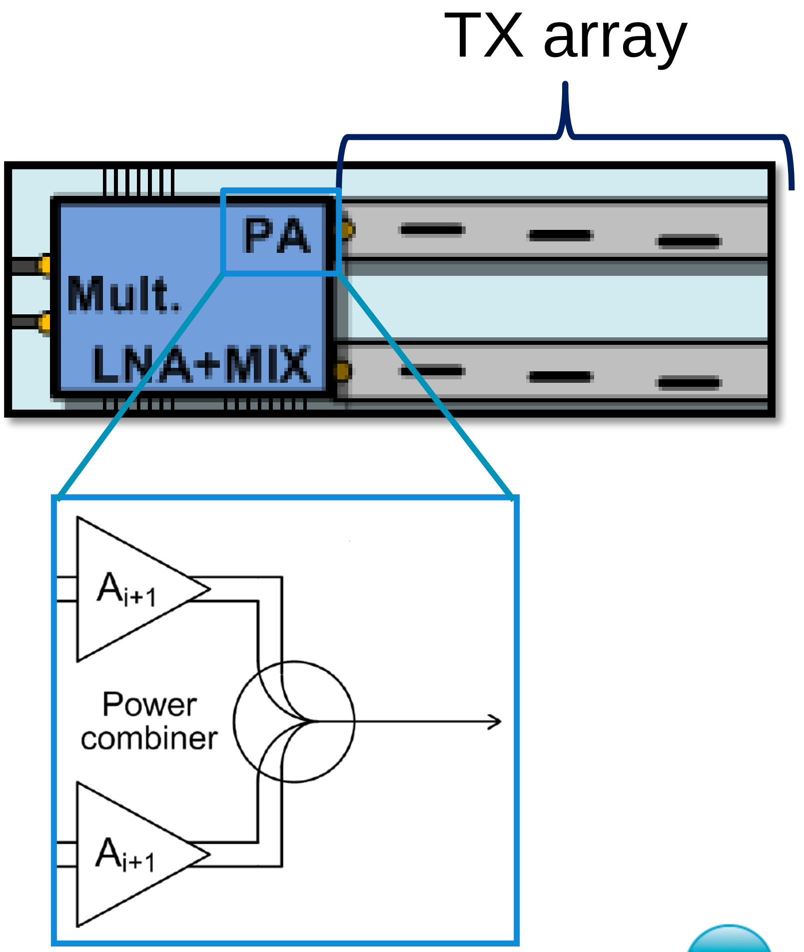




Advanced building blocks SiGe enabled

Increasing operating frequencies will allow for higher resolution images and higher gain antennas.

Frequency scanning FMCW requires higher power, when compared to NxN beam steering approaches (due to spatial power combining), and efficient PAs operating in the mm-wave band.



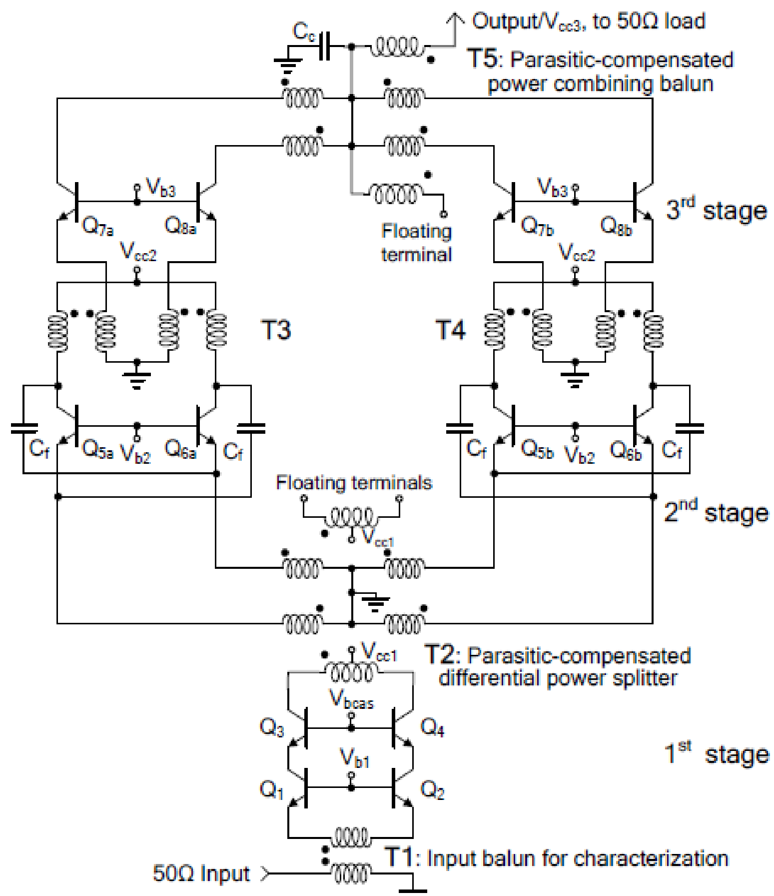
Enabled by DOT7 BiCMOS technology

Power combining mm-wave PAs

Three-stage transformer-coupled multi-path PA developed.

Power splitter and combiner utilizes parasitic-compensation to reduce interwinding capacitance effects.

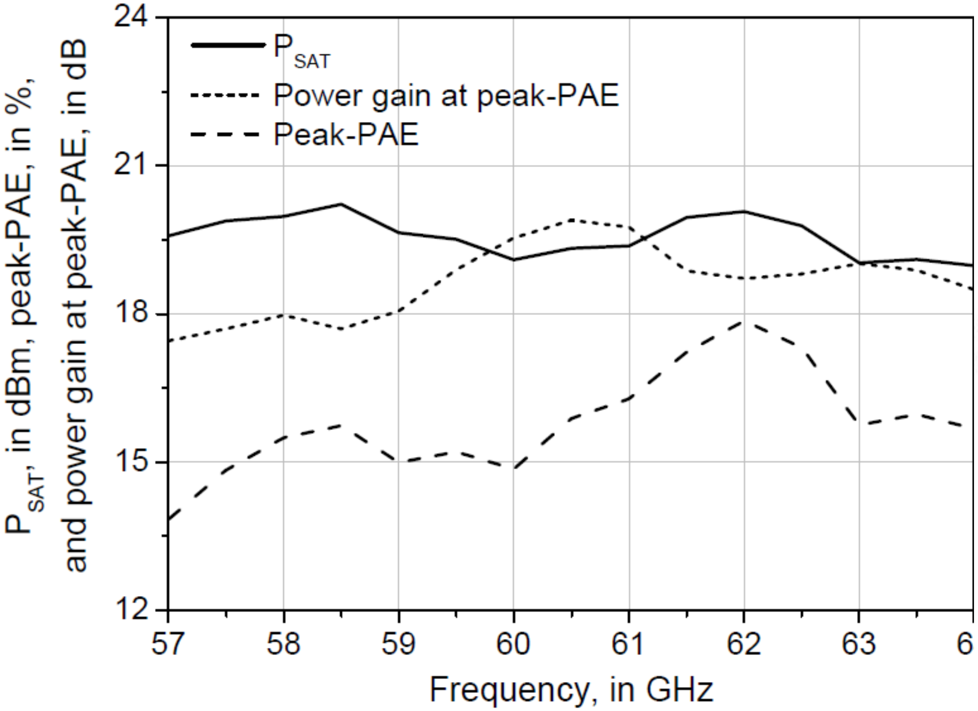
Topology uses neutralized differential common-base (CB) pairs and a cascode driver stage to achieve high gain and output power.

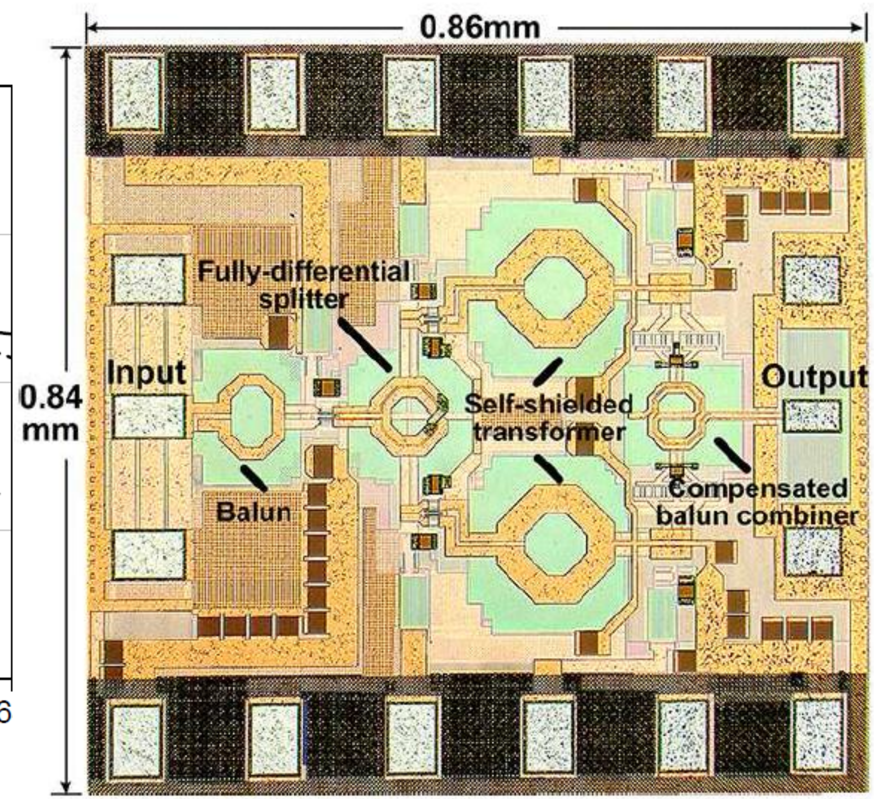


Y. Zhao, J. R. Long, and M. Spirito, "A 60GHz-band 20dBm power amplifier with 20% peak PAE," in *Proc. of IEEE-RFIC*, Jun. 2011, pp. 1–4.

Power combined mm-wave PAs

PA implemented in ST 130nm SiGe BiCMOS.





Conclusions

- A system level architecture to reduce the complexity of imaging system described.
- Broadband antenna interface and high-gain antennas have been realized using flip-chip assembly and silicon integrated waveguide technology.
- A first prototype of highly-integrated radar imaging system based on a frequency scanning FMCW concept was realized.
- The potential for advanced building blocks and system integration arising from advanced SiGe BiCMOS technology is identified.
- State of the art building blocks enabling true time delays, frequency sweeping and power amplification in CMOS and BiCMOS technologies developed and benchmarked.

Acknowledgements

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The SIW technology was developed in the DIMES at The Delft University of Technology by Prof. Lis Nanver.

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References

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[6] Gentile, G.; Spirito, M.; de Vreede, L.C.N.; Rejaei, B.; Dekker, R.; de Graaf, P., "Silicon integrated waveguide technology for mm-wave frequency scanning array," *Microwave Integrated Circuits Conference (EuMIC), 2012 7th European* , vol., no., pp.234,237, 29-30 Oct. 2012.
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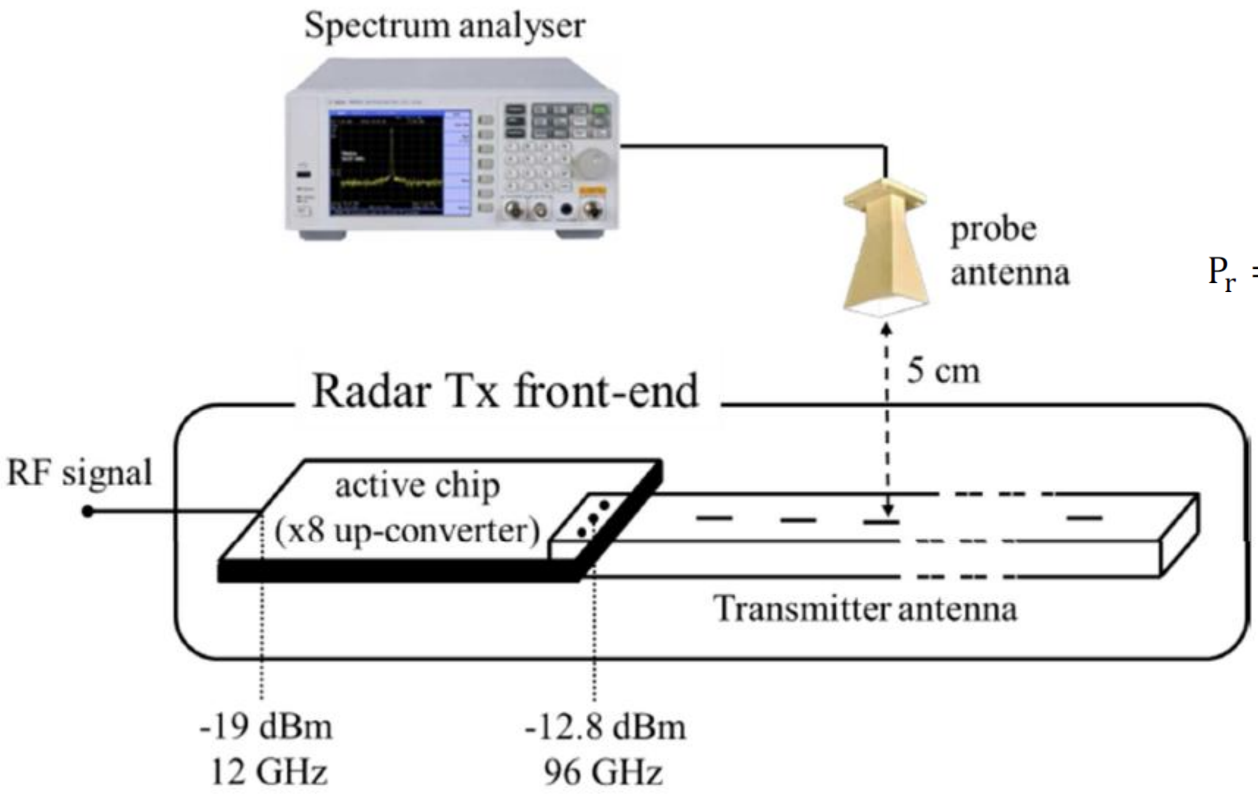
Backup slides

Radiated power demonstrator



Pr at 5cm
-53.5dBm
P at chip computed from

$$P_r = P_t + \left(\frac{\lambda}{4\pi d}\right)^2 G_t G_r - IL_{trans} - IL_{wav}$$

Antenna gain
13.4dBi