Building blocks and system architecture for mm-wave imaging radar
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Motivation

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

1. Radar FMCW signal and echo signal
2. Time delay due to signal propagation
3. Sampled beat frequency ($f_b$) using A/D
4. Digital signal processing (FFT)
5. $f_b$ level is calculated
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.
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 \( N \times N \) 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.

![Diagram of frequency scanning FMCW concept](image)
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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:

\[ R_{\text{min}, r} = \frac{c}{2F} \]  
\[ T_{\text{tar}} \propto \Phi_B \]  
\[ \Phi_{\text{resolution}} \propto \frac{1}{\Phi_B} \]  

(improves with large modulation BW)

(improves with antenna gain and number of elements)

Where:

\[ \Phi_{\text{tar}} \approx \frac{D}{R} \left( \frac{180}{\pi} \right) \]  
\[ \Phi_B \]  

(target’s angle seen by antenna in degrees)

(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.

Integrated waveguide technology

**Process features:**
- Continuous metal side walls
- Size reduction (silicon $\varepsilon_r$)
- Photolithographic accuracy
- Planar feed

![Graph showing simulated and measured loss versus frequency](image)

- Simulated
- Measured
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.

![Graph](image)

94 GHz

- $|E_{\text{norm}}|$ (dB)
- Scanning angle (°)
- Side lobe level (dB)

- simulated
- measured

- theoretical
- simulated
- measured
System demonstrator IC

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

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.
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.

Broadband building blocks, DPLL

DPLL implemented in 65-nm TSCM CMOS
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.

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.
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References

Backup slides
Radiated power demonstrator

\[ P_r = P_t + \left( \frac{\lambda}{4\pi d} \right)^2 G_t G_r - I_{\text{trans}} - I_{\text{wav}} \]

Pr at 5cm
-53.5dBm

P at chip computed from

Antenna gain
13.4dBi