A 200-TO-257GHZ AUTODYNE FMCW PHASED-ARRAY RADAR WITH 2D BEAM-STEERING IN 55NM BICMOS

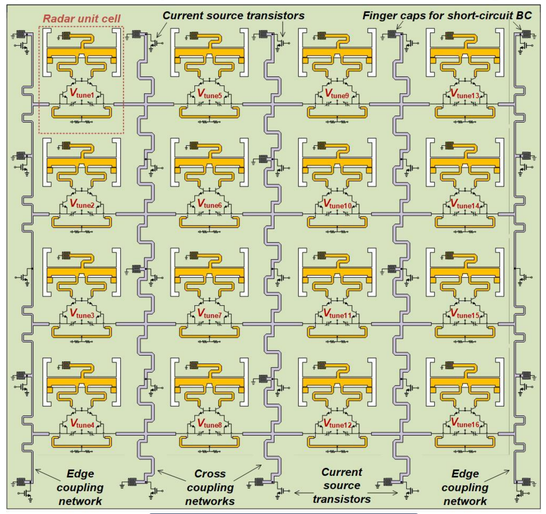
STUDENTS: XIANGYU ZHAO, ZI ZHANG

Abstract

- This project proposed a 4x4 autodyne FMCW phased-array radar with a center frequency of 228 GHz and a wide tuning range of 57.4 GHz. The radar unit cell integrates all transmitter (TX), receiver (RX), and antenna components in a compact area. Injection locking between unit cells is achieved via compact edge and cross-coupling network. Measurement results shows continuous beam steering of 30° in both the E- and H-planes with the range resolution and accuracy of 2.7 mm and 38 um, making it suitable for precise and rapid sub-THz imaging.

Introduction

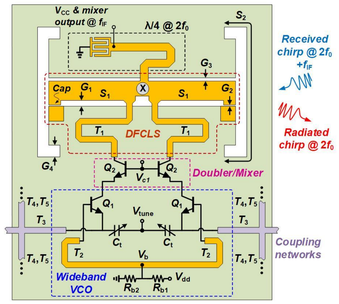
- Why sub-THz FMCW phased array radars?
  - **Frequency modulated continuous wave (FMCW)** radars in **sub-THz/THz band** provide higher resolution than their mm-wave counterparts
  - **Phased array** enables electronic beam steering without mechanical parts, good for rapid scanning
- Challenges
  - Traditional top-side radiation method is narrow-band
  - Back-side radiation requires small radar unit cell of $\frac{\lambda}{2n} \times \frac{\lambda}{2n}$, where n is silicon refractive index. Hard to integrate both TX and RX
  - Back-side radiation introduces beam tilting issue
- Our solutions
  - **Miniaturized radar unit cell** with a multifunctional EM structure satisfies area limits of back-side radiation
  - **Autodyne** topology is adopted to have TX/RX re-use the same circuit block
  - An **optimized off-chip silicon lens** is used to fix beam tilting issue



4x4 Autodyne FMCW radar array

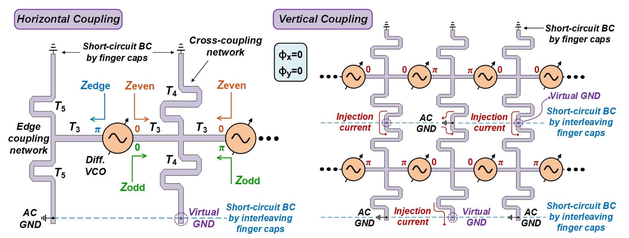
Circuit Architecture

- Transmitter
  - Differential Colpitts voltage-controlled oscillator (VCO) is wideband
  - Transistor Q2 acts as **doubler** to generate $2f_0$, radiated via DFCLS; f_0 is cancelled at node X
  - Multi-functional Double-fed capacitive loaded slot (DFCLS): impedance matching, radiation and reception
- Receiver
  - Signal $2f_0 + f_{IF}$ is received by DFCLS
  - Transistor Q2 acts as **mixer** in receiver mode to generate intermediate frequency (IF) current
  - IF signals are combined via VCC line from all unit cells and extracted using off-chip bias-T and transimpedance amplifier



Radar unit cell

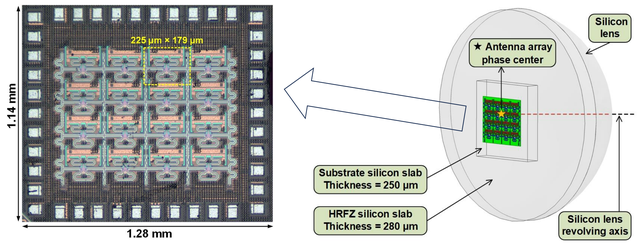
- 2-D Injection Locking Mechanism
  - To form a phased array, each unit cell should function in **the desired mode and phase distribution**
  - Edge & cross-coupling networks couples a unit cell with its neighboring cells in the 2-D direction (horizontal & vertical)
  - Transmission lines T3, T4, T5 and finger caps creates **boundary conditions** required for the desired operating mode



Horizontal coupling (X) / Vertical coupling (Y) — Radar unit cell

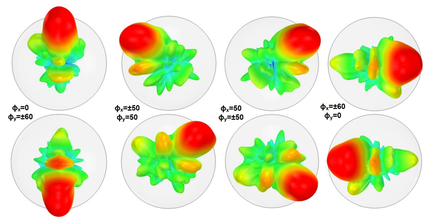
0	π	π+Φ_x	Φ_x	2Φ_x	π+2Φ_x	π+3Φ_x	3Φ_x
π+Φ_y	Φ_y	Φ_x+Φ_y	π+Φ_x+Φ_y	π+2Φ_x+Φ_y	2Φ_x+Φ_y	3Φ_x+Φ_y	π+3Φ_x+Φ_y
2Φ_y	π+2Φ_y	π+Φ_x+2Φ_y	Φ_x+2Φ_y	2Φ_x+2Φ_y	π+2Φ_x+2Φ_y	π+3Φ_x+2Φ_y	3Φ_x+2Φ_y
π+3Φ_y	3Φ_y	Φ_x+3Φ_y	π+Φ_x+3Φ_y	π+2Φ_x+3Φ_y	2Φ_x+3Φ_y	3Φ_x+3Φ_y	π+3Φ_x+3Φ_y

Phase distribution at f_0

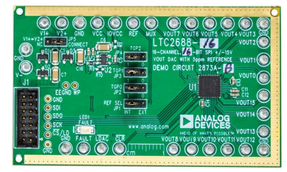


Experimental Results

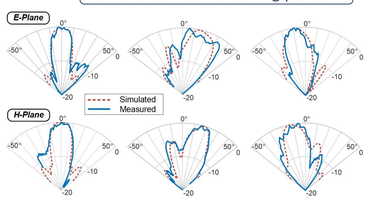
- Beam steering measurement
  - Vtune of 16 VCOs were adjusted by a 16-channel digital-to-analog (DAC) controller
  - **30 degrees of beam steering** were measured in both E- and H-planes



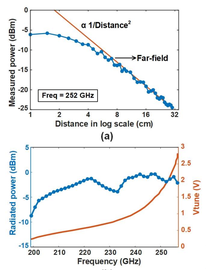
Simulated beam steering pattern

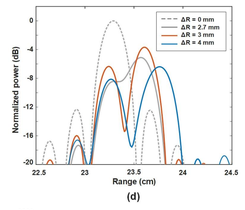


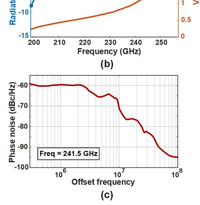
DAC evaluation board

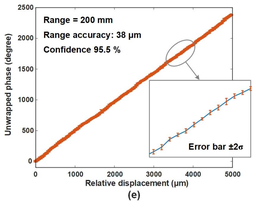


Measured beam steering pattern









- Other measurements
  - DC power: 0.475W

a) Far-field power

b) Radiated power and frequency tuning range: 199.3GHz to 256.7GHz

c) Phase noise

d) Range resolution: 2.7 mm

e) Range accuracy: 38 um

Conclusion

- In this project, a 4x4 autodyne FMCW phased-array radar operating in the frequency range of 199.3 to 256.7 GHz has been designed, fabricated, and measured. The system incorporates a miniaturized and broadband radar unit cell and a compact coupling network that enables continuous beam steering with the high range resolution and accuracy required for rapid and precise sub-THz imaging. This work represents **the first demonstration of a broadband, fully integrated FMCW phased array radar operating in the sub-THz/THz range**.

References

[1] H. Jalili et al., "A 436-to-467GHz Lens-Integrated Reconfigurable Radiating Source with Continuous 2D Steering and Multi-Beam Operations in 65nm CMOS," in IEEE ISSCC, vol. 64, 2021, pp. 326–328.

[2] S. M. H. Naghavi et al., "A 250GHz Autodyne FMCW Radar in 55nmBiCMOS with Micrometer Range Resolution," in IEEE ISSCC, vol. 64,2021, pp. 320–322.

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