Millimeter-wave Metamaterial Antenna in Standard CMOS Technology

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Background and Objective

Background

Wireless communication system
- ✓ Bands of 2.4 and 5 GHz crowded

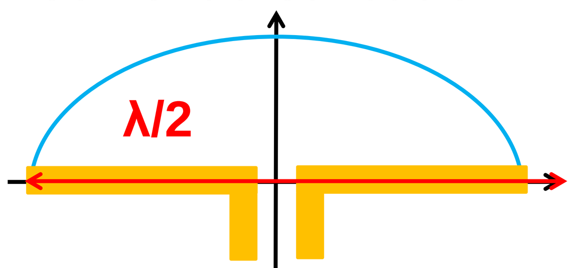
Solutions

- ✓ Millimeter-wave regions (e.g., 60 GHz)
- ✓ High gain Si on-chip antenna to reduce cost

Problems

Principle of dipole antenna

Current distribution

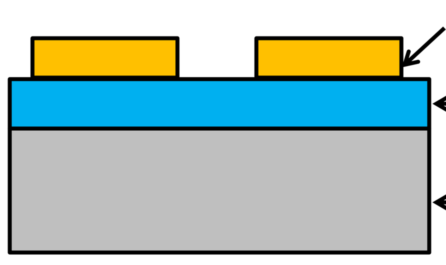


λ/2 = 2.5 mm (at 60 GHz)

➡ Large antenna size

On-chip antenna

Cross section view of CMOS chip



Low resistivity of Si substrate

➡ Low antenna gain

Objective

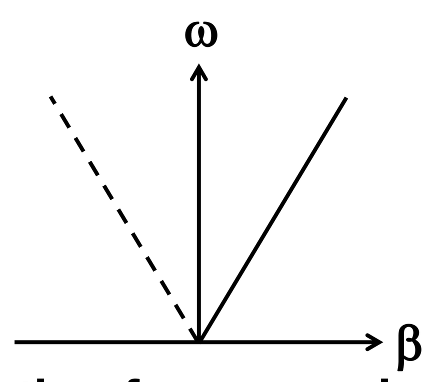
Design and fabricate MM-wave high-gain, small-size on-chip antenna

Principle

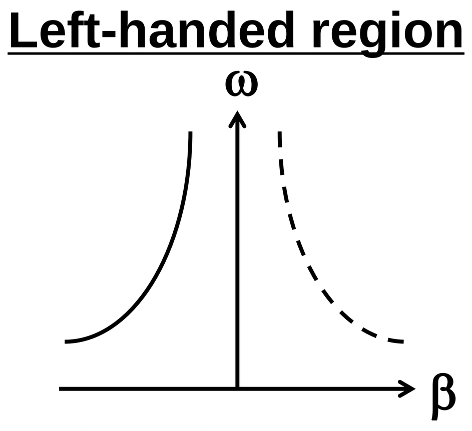
Metamaterial

Artificial materials that show electromagnetic properties not existing in nature

Right-handed region



Left-handed region



Radiation frequency inversely proportional to phase constant

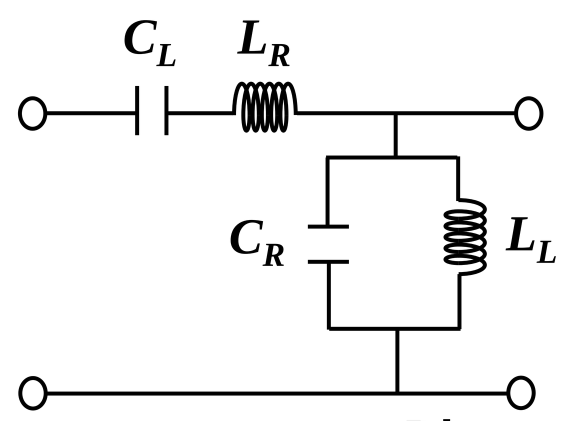
⇒ Miniaturized antenna size

⇒ Increased gain due to reduction in silicon substrate loss

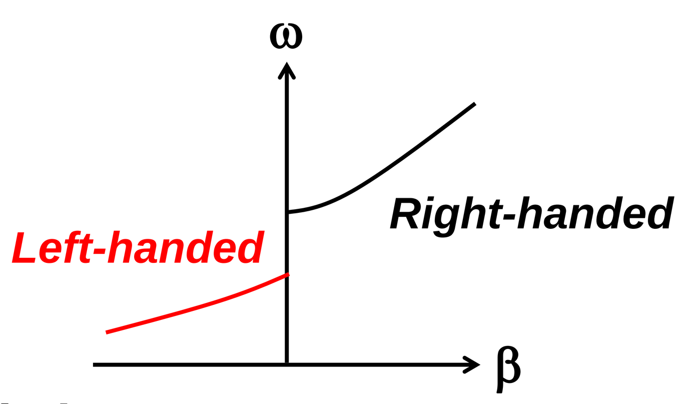
✓ Pure left-handed transmission line impossible to fabricate

Composite right/left-handed (CRLH) theory

CRLH transmission line



Dispersion diagram of CRLH

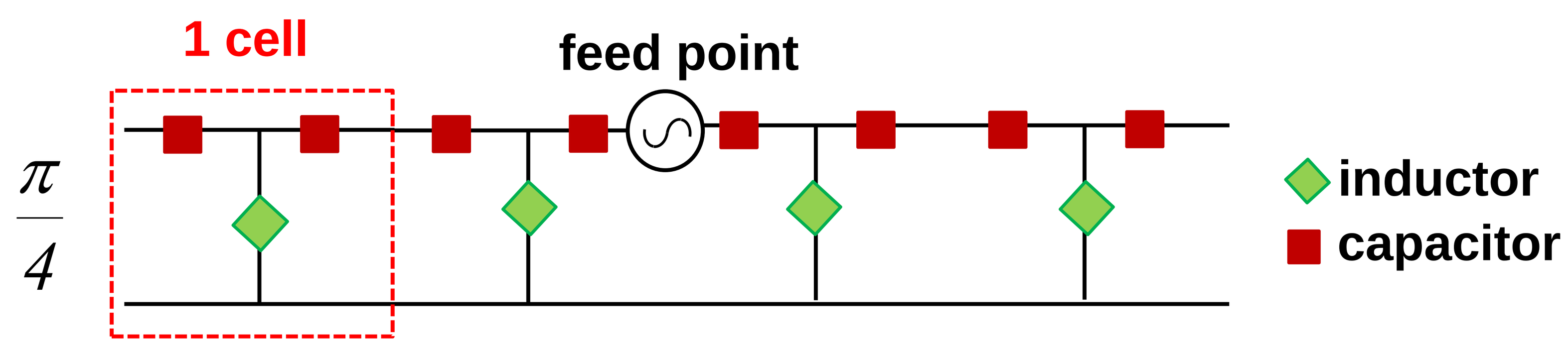


Dispersion relation

$$\beta p = \cos^{-1}\left[1-\frac{1}{2}\left(\omega L_R-\frac{1}{\omega C_L}\right)\left(\omega C_R-\frac{1}{\omega L_L}\right)\right]$$

β : phase constant p : length of unit cell

Structure of metamaterial antenna



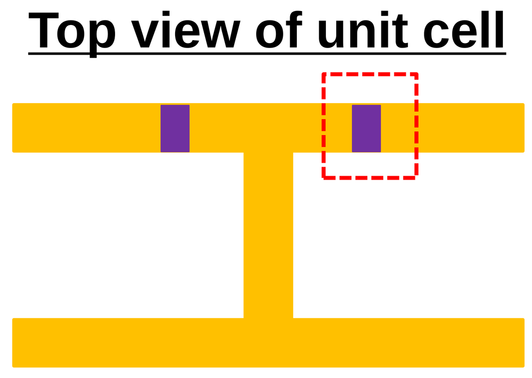
Phase difference between two open ends equals π at 60 GHz

Fabrication Method

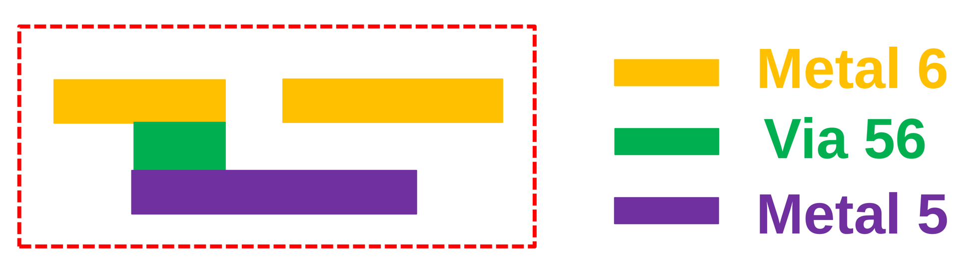
Antenna Design

Process : TSMC 0.18-μm 1P6M mixed signal/RF CMOS

Top view of unit cell



Cross-sectional view of series capacitor

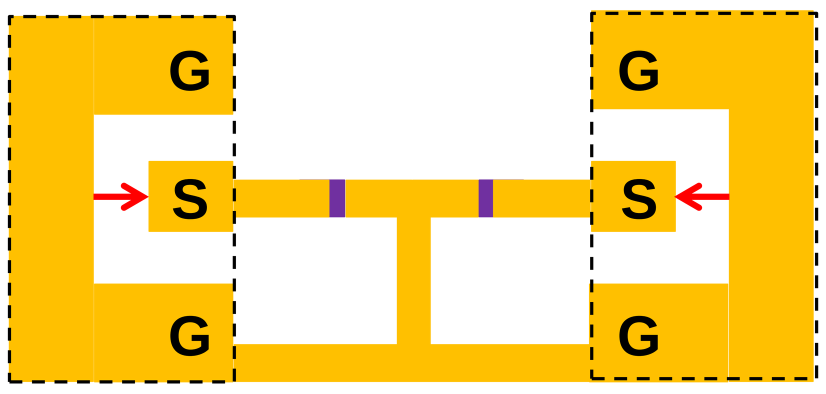


- ✓ Thick top metal used as antenna element (to reduce wire loss)
- ✓ C_L : MIM capacitor between Metal 5 and Metal 6
- ✓ L_L : straight line of Metal 6

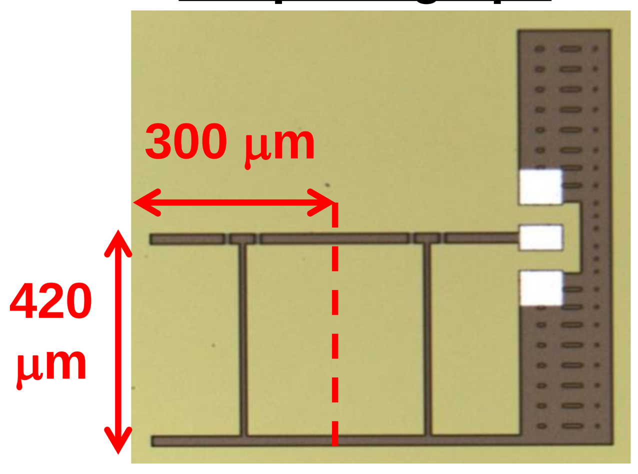
EM Simulation

Simulator : EMpro (Keysight Tech.) using Finite-difference-time-domain (FDTD) method

Analysis model for unit cell



Die photograph

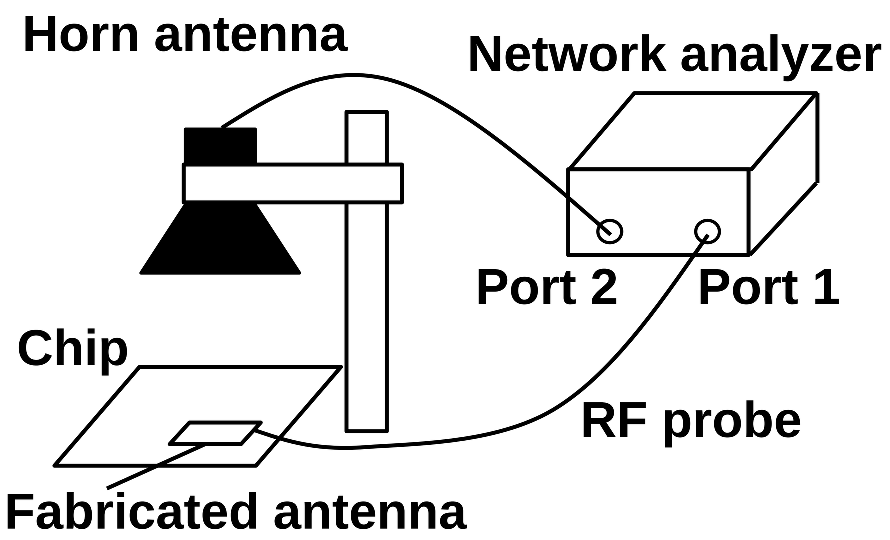


- ✓ Feed points assumed to be GSG pads
- ✓ Calculated rigorous dispersion diagram
  ⇒ Adjust component sizes

Measurement

Measurement System

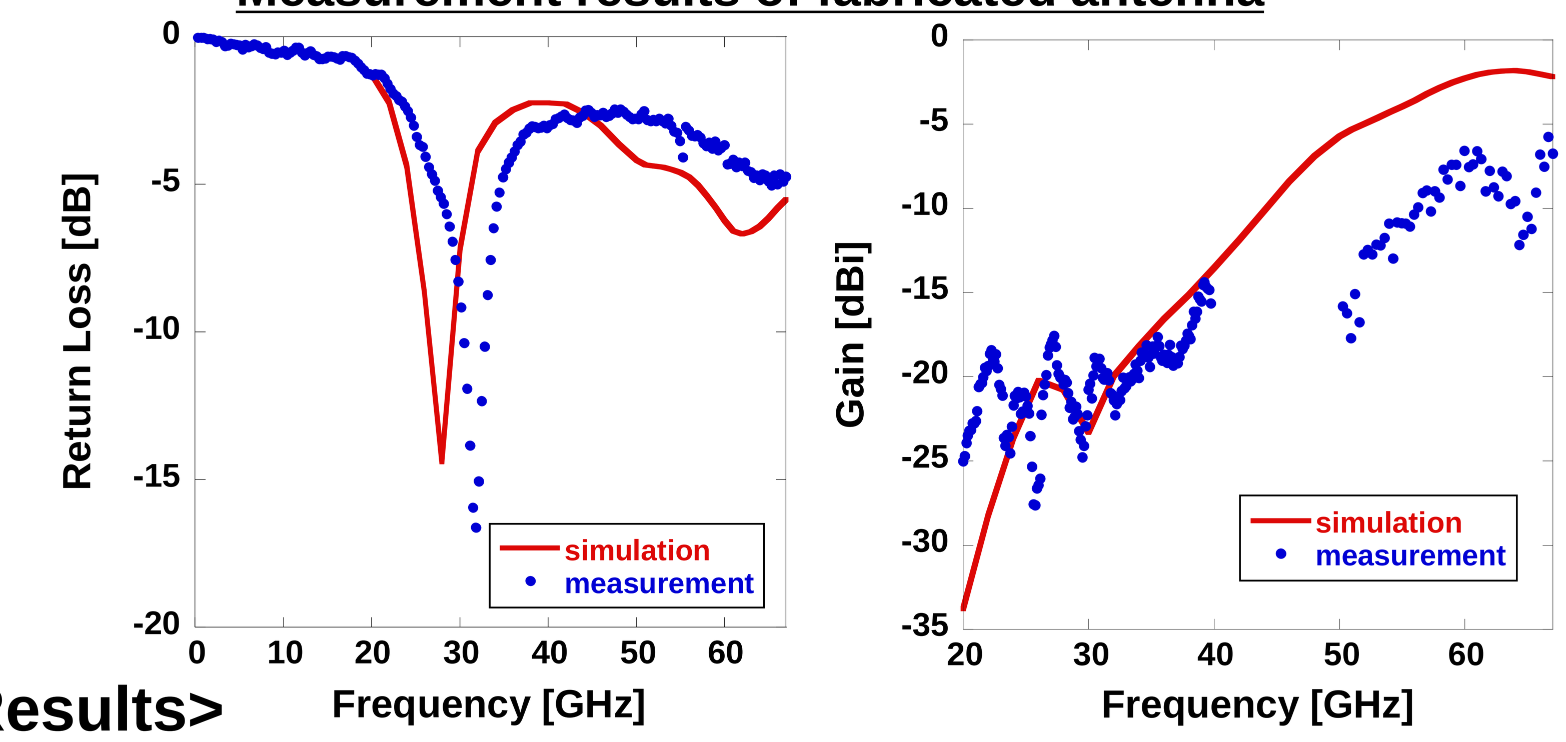
Experimental setup



- ✓ Two types of horn antennas (20 - 40 GHz and 50 - 67 GHz)
- ✓ Return loss measured with 1-port calibration method
- ✓ Gain evaluated by taking into account S_{21} between two horn antennas and gain of horn antenna

Results and Discussion

Measurement results of fabricated antenna



<Results>

	LH mode		RH mode	
	simulation	measurement	simulation	measurement
S_{11}	-14.4 dB (28 GHz)	-16.6 dB (31.8 GHz)	-6.7 dB (62 GHz)	-5.0 dB (65.3 GHz)
Gain	-20.8 dBi (28 GHz)	-14.4 dBi (39.3 GHz)	-1.83 dBi (65 GHz)	-5.8 dBi (66.7 GHz)

<Discussion>

- ✓ Measured S_{11} shifted about 3 to 6 GHz to higher frequency compared with simulated one
- ✓ Measured gain ~7 dB smaller than simulation in 50 - 67-GHz range

⇒ Different radiation patterns between horn antenna and fabricated antenna and/or difference between fabricated silicon substrate resistivity and value (10 Ω-cm) assumed in simulations

Conclusion

Performance comparison

	Process	Gain	Size	Configuration
This work	180-nm CMOS	-5.8 dBi	600 μm × 420 μm	CRLH monopole
[1]	65-nm CMOS	-10 dBi	1000 μm × 300 μm	Dipole
[2]	180-nm CMOS	-10.6 dBi	1100 μm × 950 μm	Yagi
[3]	90-nm CMOS	-6.0 dBi	1300 μm × 1100 μm	Slot on AMC

[1] T. Hirano, T. Yamaguchi, N. Li, K. Okada, J. Hirokawa, and M. Ando, "60 GHz on-chip dipole antenna with differential feed," *Proc. 2012 APMC*, Dec. 4-7, 2012, pp. 304-306.
[2] S. –S. Hsu, K. –C. Wei, C. –Y. Hsu, and H. R. –Chuang, "A 60-GHz millimeter-wave CPW-fed Yagi antenna fabricated by using 0.18-mm CMOS technology." *IEEE Electron Device Lett.*, vol. 29, no 6, pp. 625-627, 2008.
[3] K. Kang, F. Lin, D. –D. Pham, J. Brinkhoff, C. –H. Heng, Y. X. Guo, and X. Yuan ., "A 60-GHz OOK receiver with an on-chip antenna in 90 nm CMOS." *IEEE J. Solid-State Circuits*, vol. 45, no.9 pp. 1720-1730, 2010.

Successful design and fabrication of MM-wave high gain, small-size on-chip antenna

Acknowledgement

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