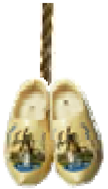


Antennas and packaging for millimeter-wave phased-array transceivers

J.A.G. Akkermans[1] and D. Liu[2]

(1) Eindhoven University of Technology, The Netherlands

(2) Thomas J. Watson research center, IBM, USA

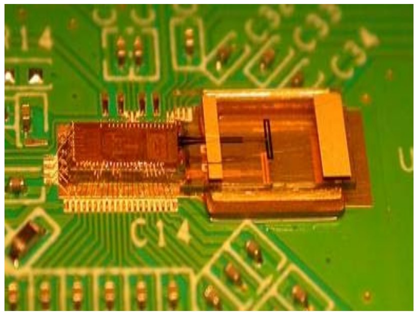
technische universiteit eindhoven

Outline

- Introduction
- Antenna considerations
  - antenna requirements
  - radiation efficiency
- Packaging considerations
  - package requirements
  - material characterisation
- Examples
  - single-element
    - PCB
    - LTCC
    - Silicon-based
  - antenna array
- Conclusions

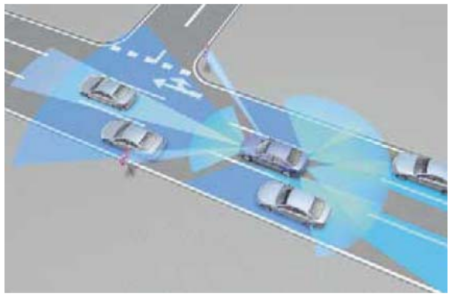
Introduction

- Millimeter-wave antennas
  - Applications
    - wireless gigabit ethernet (60 GHz, 80 GHz)
      - indoor / outdoor (point to point)
    - car radar (77 GHz)
    - imaging (94 GHz)



IBM

ref: ezwireless.us

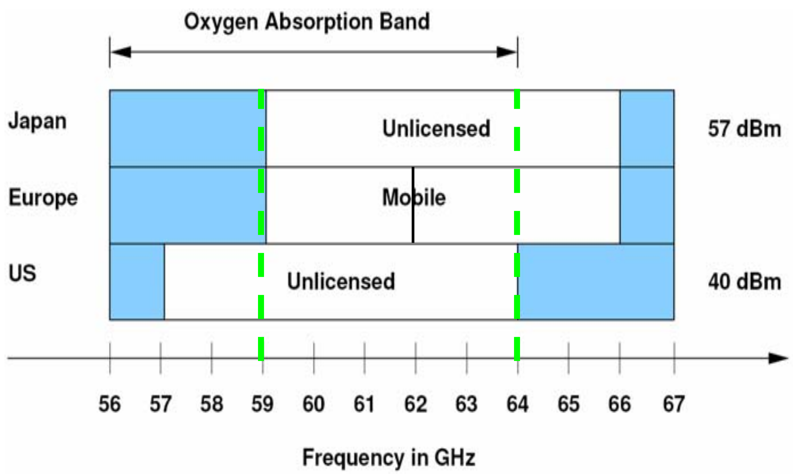


ref: Siemens.com

ref: Science Vol. 297, 2 Aug. 2002.

Introduction

- Broadband communication in the 60 Ghz band
  - Worldwide 5 GHz unlicensed bandwidth
  - Data rate > 1 Gbps
  - Applications
    - wireless USB2.0
    - wireless gigabit ethernet
    - wireless video (HDTV)
    - telecom backhaul



Introduction

- Link budget example
  - transfer speed: 2 Gbps
  - distance: 10m
  - coded OFDM (BER = 1e-6)
- Required antenna gain
  - > 12 dBi

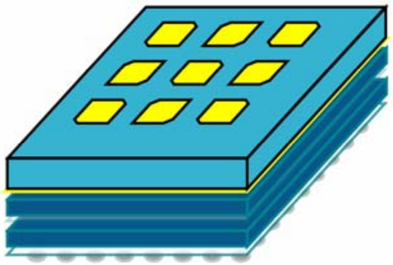
transmit power	12 dBm
antenna gain at transmitter	12 dBi ←
path gain (LOS) @ 10 meter	-88 dB
antenna gain at receiver	12 dBi ←
received power	**-52 dBm**
equivalent noise temperature	290 K
equivalent noise bandwidth	2 GHz
receiver noise figure	7 dB
receiver noise power	**-74 dBm**
obtained signal-to-noise ratio	22 dB
required signal-to-noise ratio*	10 dB
fading and implementation margin	**12 dB**

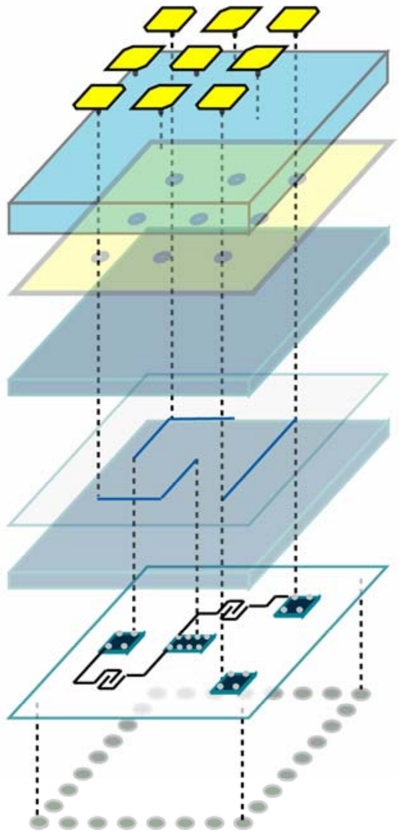
* for OFDM + QPSK + 3/4 conv. coding and BER of 1E-6

Adaptive beam-forming antennas needed!

Introduction

- Integrate into one package
  - transceiver chip-set
  - antenna
  - other passive components





Introduction

- Why is this difficult?
  - wavelength is small
    - high-precision technology is needed
  - vias do not work well
    - relatively large
      - mismatch
      - loss
  - feed-line loss
    - large wire inductance (~ ωL)
  - dielectric loss (~ ω)
    - high-quality materials needed

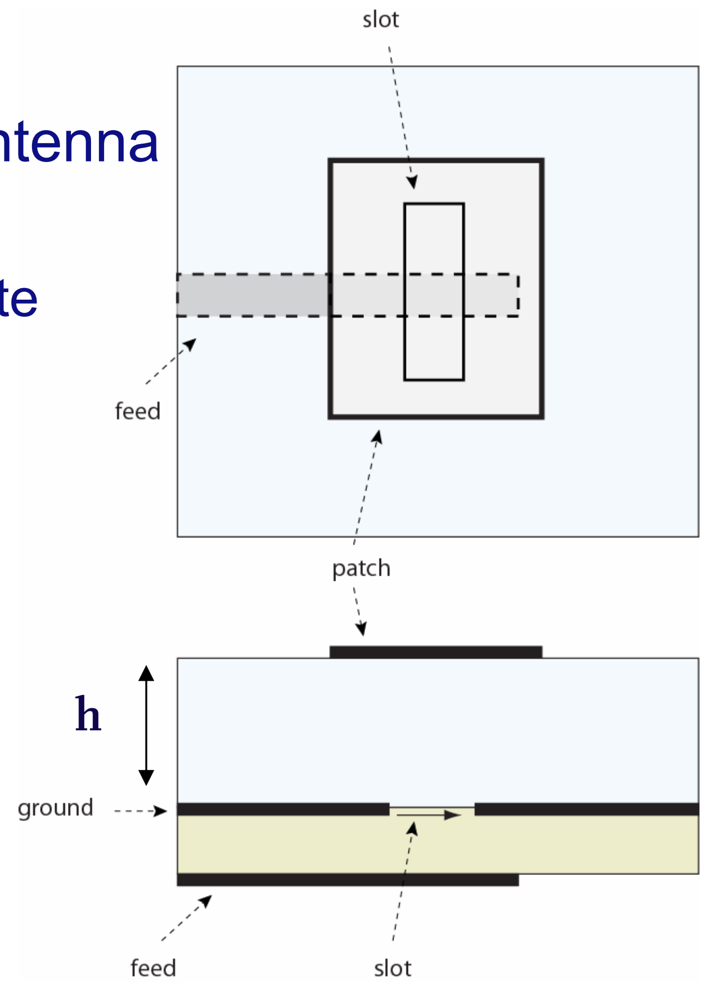
How to do low-cost packaging at mm-wave frequencies?

Antenna considerations

- Antenna requirements
  - broadband operation
    - minimum 5 GHz bandwidth
  - high radiation efficiency
    - low dielectric constant
  - hemispherical radiation pattern antenna element
    - large scan range antenna array
  - low interconnect loss with Tx/Rx chip
    - coplanar feed
  - easy integration into package
    - planar technology

Antenna considerations

- Planar antennas
  - E.g. Aperture-coupled patch antenna
    - feed substrate can be chosen different from antenna substrate
    - bandwidth ~ $\dfrac{h}{\sqrt{\varepsilon_r}}$

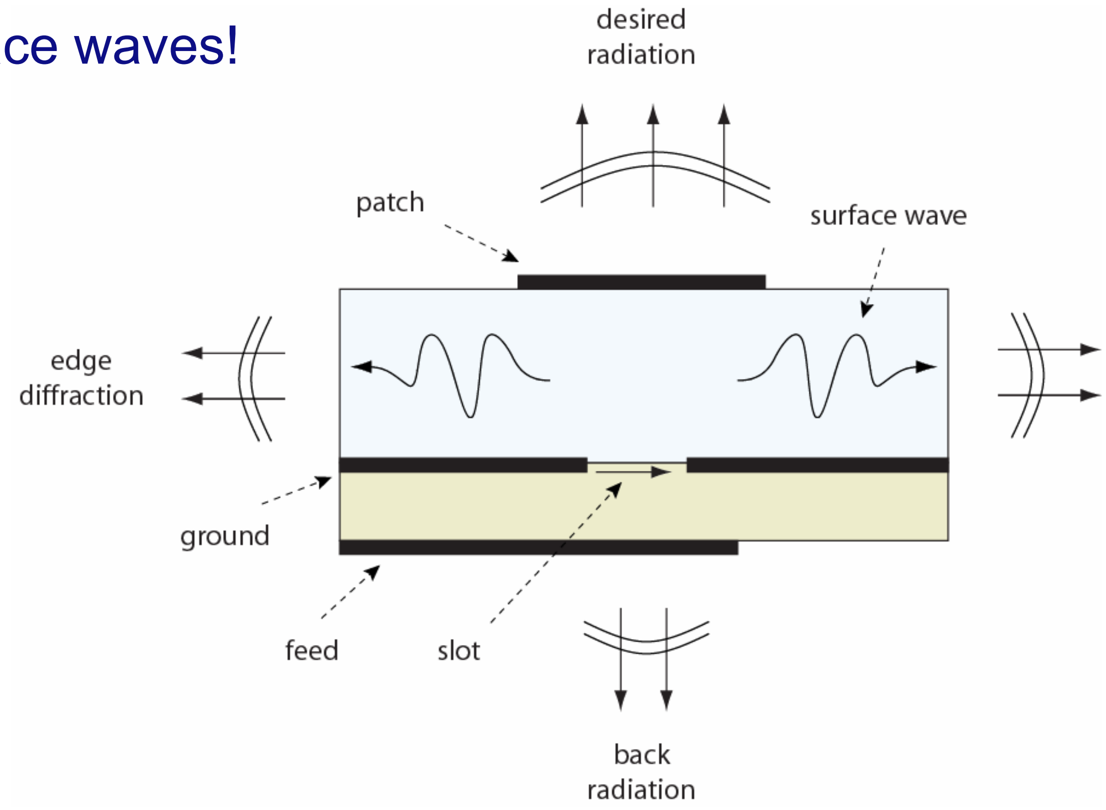


Antenna considerations

- Radiation mechanisms
  - challenge of planar antennas
    - control surface waves!

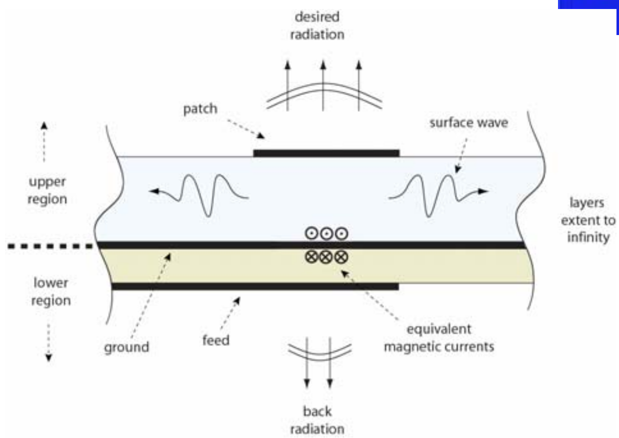
Surface waves:

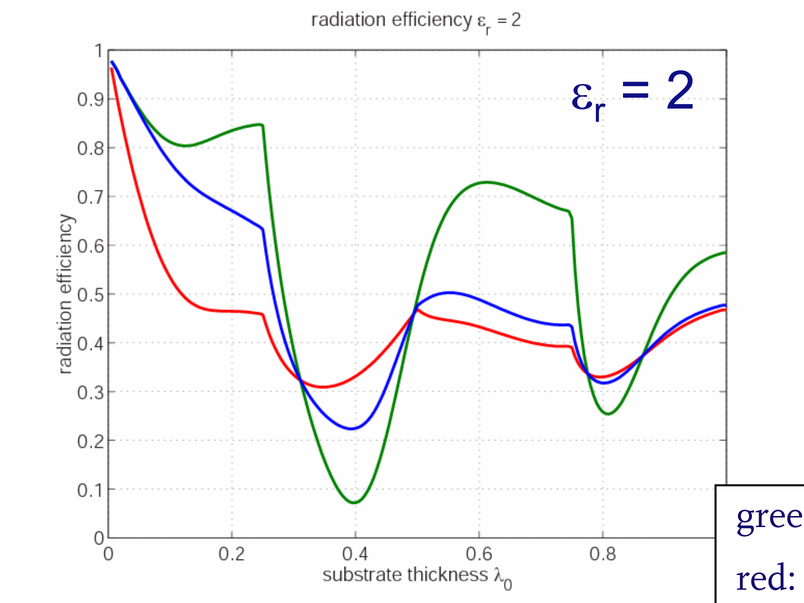
- **reduce efficiency**
- **distort radiation pattern**
- **increase mutual coupling in array configuration**

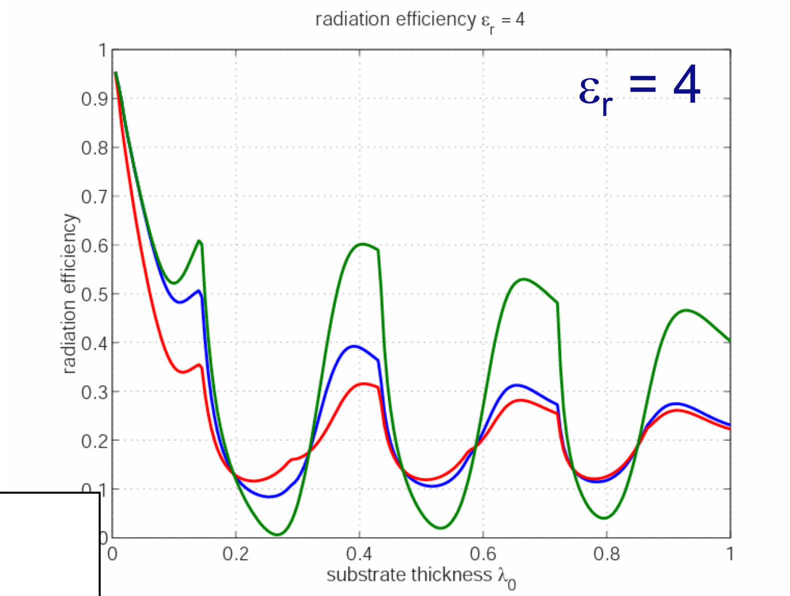


Antenna considerations

- Radiation efficiency
  - Surface waves
    - upper region
    - radiation efficiency = P^{rad} / P^{tot}



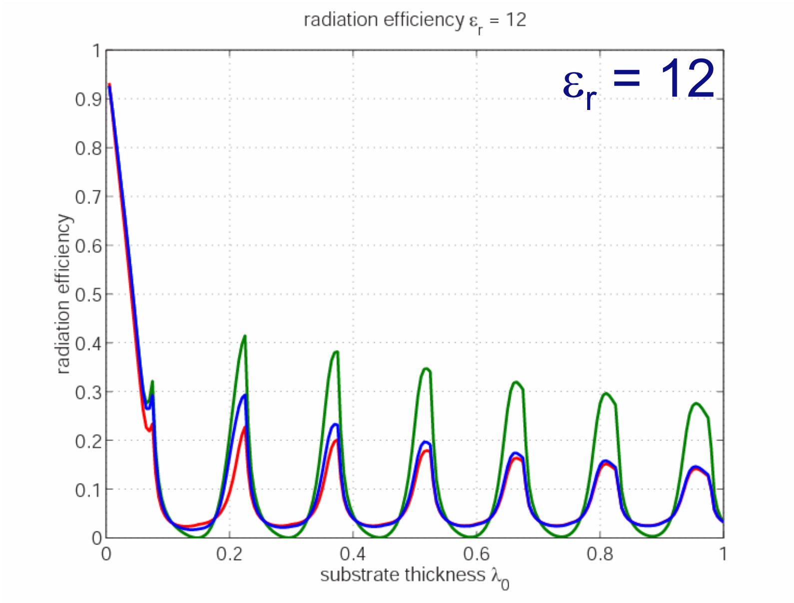




green: patch
red: slot
blue: slot + patch

Antenna considerations

- Antenna on chip?
  - bandwidth ~ $\dfrac{h}{\sqrt{\varepsilon_r}}$



green: patch
red: slot
blue: slot + patch

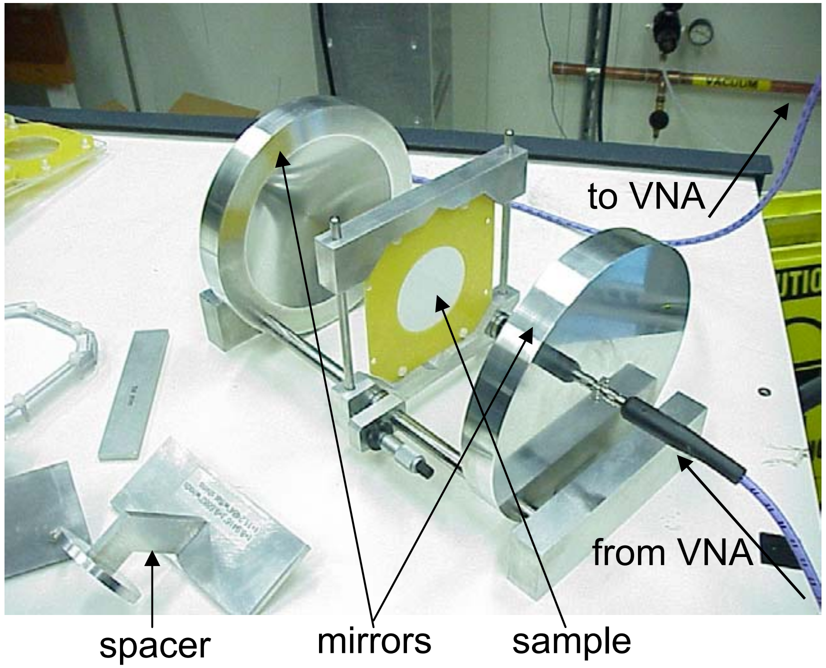
Package considerations

- Package requirements
  - standard planar manufacturing technology
    - low-cost
  - small feature size
    - low tolerances
  - accurate alignment
  - candidates
    - advanced PCB
      - thin-film
    - LTCC
    - Silicon-based

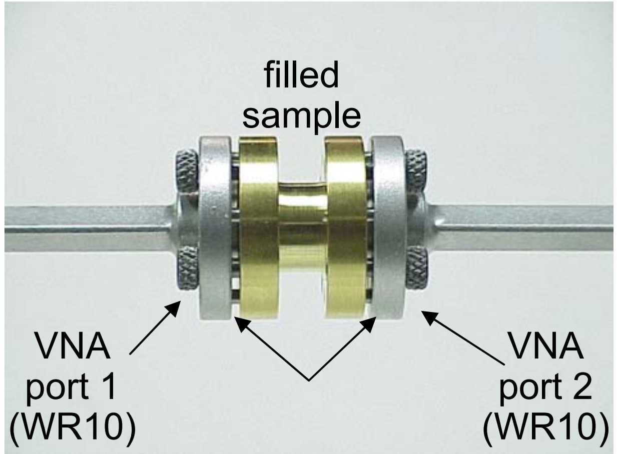
Package considerations

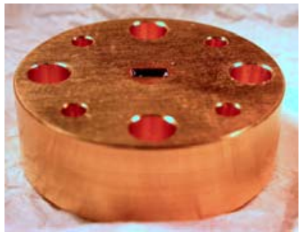
- Material characterisation

open resonator (20-80 GHz)



waveguide setup





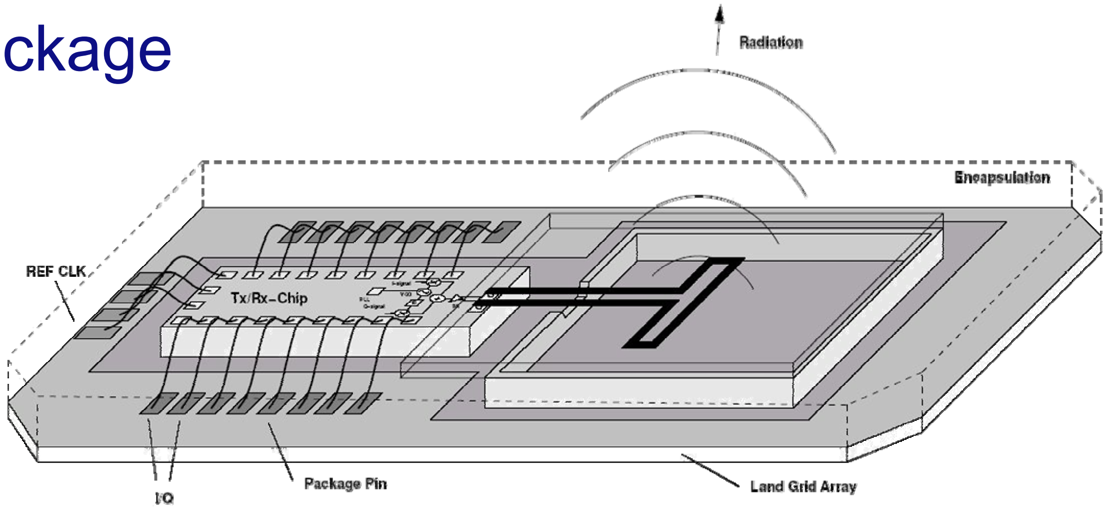
6811 encapsulant

teflon

T. Zwick, etc., “Determination of the complex permittivity of packaging materials at millimeter-wave frequencies,” IEEE Trans. Microwave Theory Tech.. Vol. 54, No. 3, pp. 1001-1010, Mar. 2006.

Example: Cavity-backed superstrate antenna

- Chip-on-board package

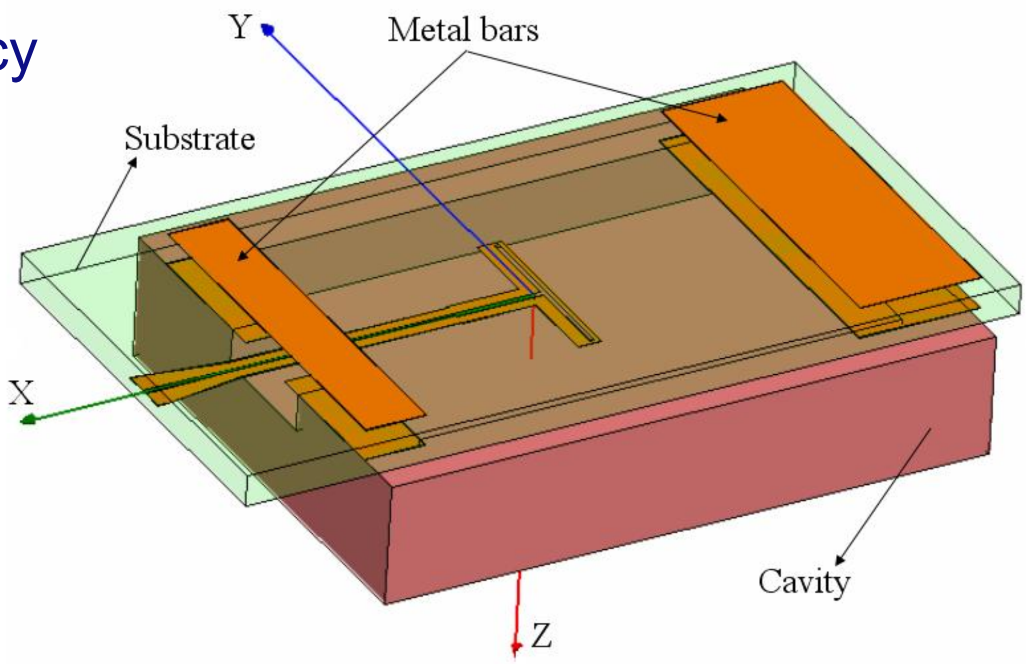


  - package base acts as ground plane for antenna
  - standard wire-bonding except for 60GHz signal
  - antenna is flipped on the mm-wave circuit

U. R. Pfeiffer, etc., “A chip-scale packaging technology for 60-GHz wireless chipsets,” IEEE Trans. Microwave Theory Tech., vol. 54, No. 8, pp 3387-3397, Aug. 2006.

Example: Cavity-backed superstrate antenna

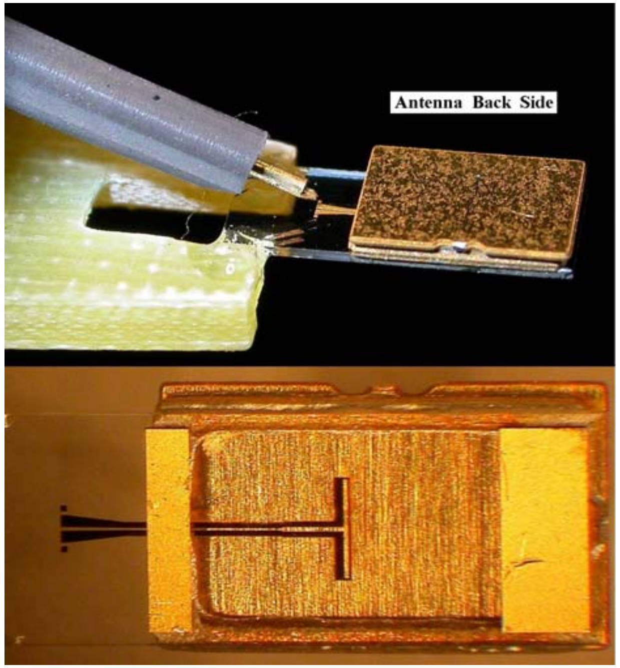
- Superstrate antenna
  - high radiation efficiency
  - large bandwidth
  - packaging still difficult
  - not suitable for array configurations

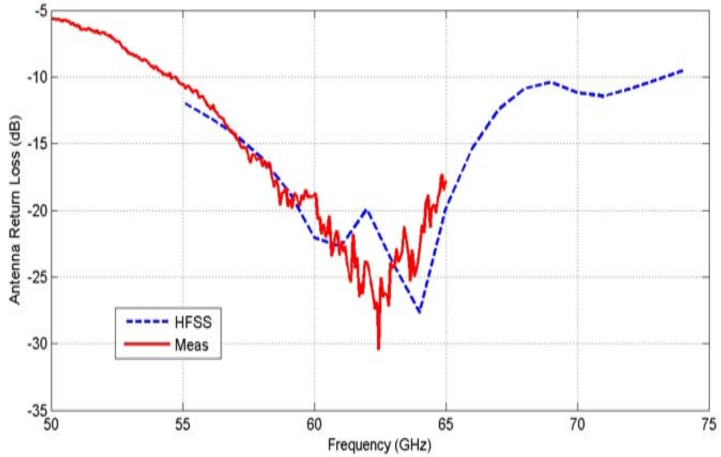


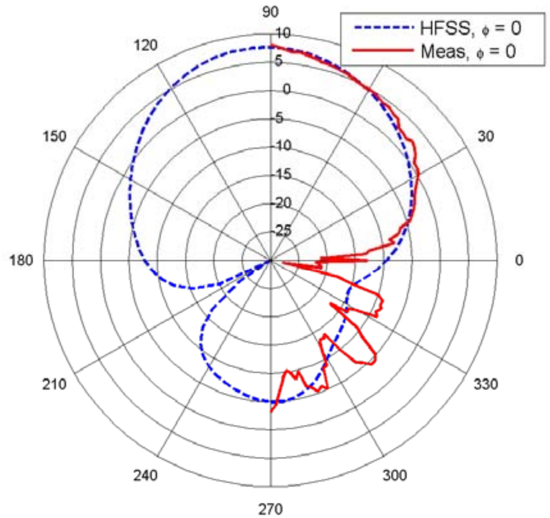
J. Grzyb, etc., “Wideband cavity-backed folded dipole superstrate antenna for 60 GHz applications,” in Proc. IEEE AP-S International Symposium and UNSC/URSI and AMEREM Meetings, pp. 3939-3942, Albuquerque, New Mexico, July 9-14, 2006.

Example: Cavity-backed superstrate antenna

- Measurement results

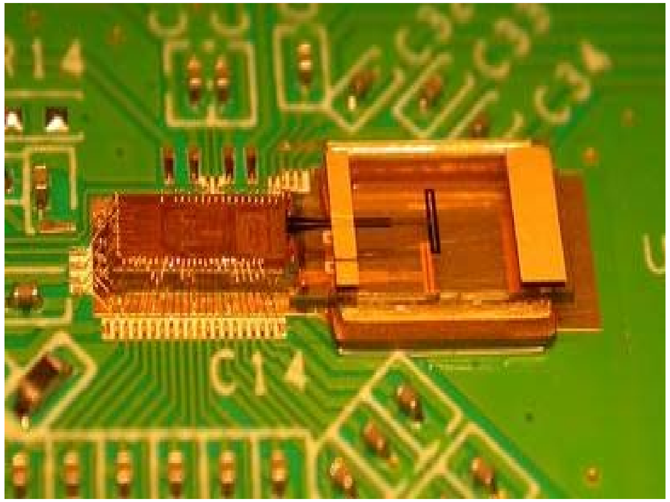


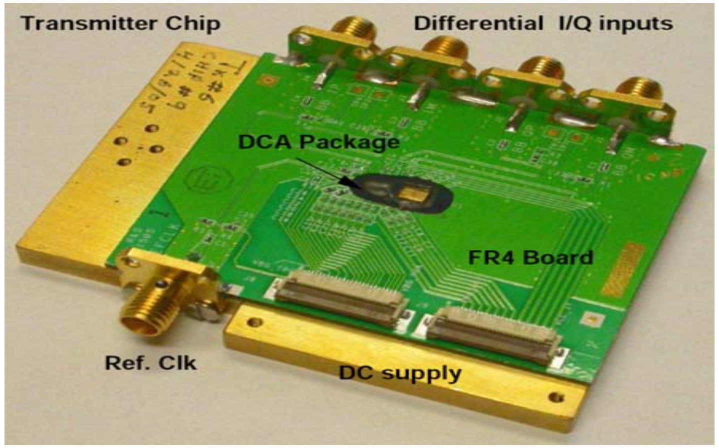




Example: Cavity-backed superstrate antenna

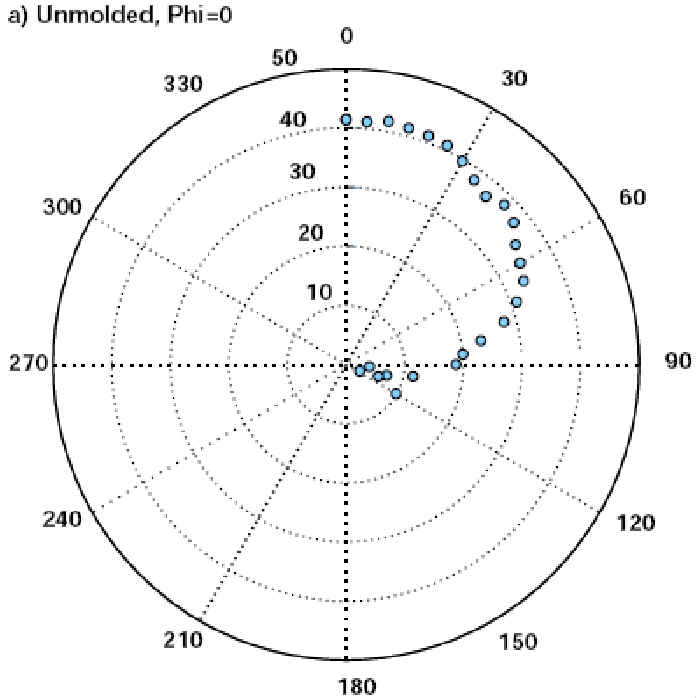
- Chip is molded with standard glob-top material
- Optional antenna window.

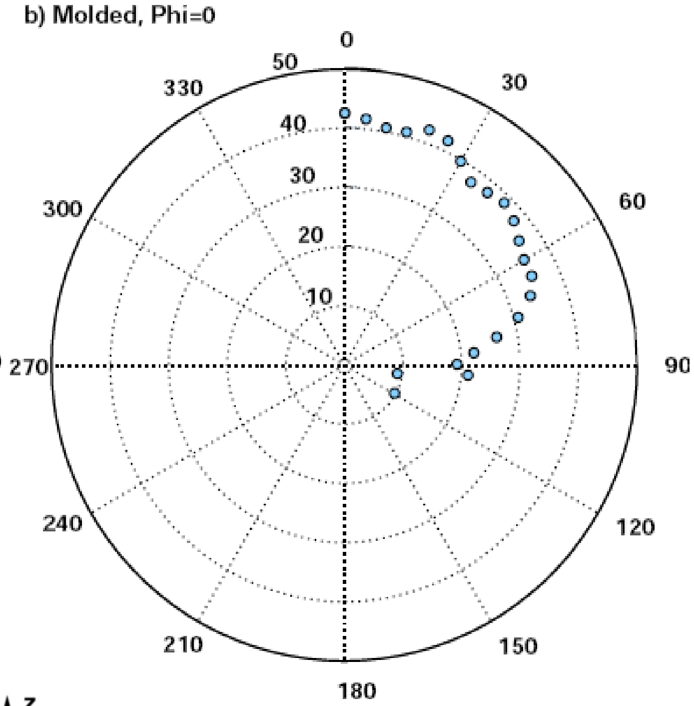


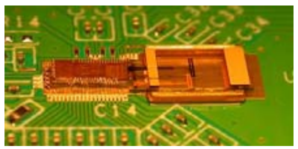


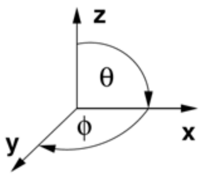
Example: Cavity-backed superstrate antenna

- Measured pattern in system





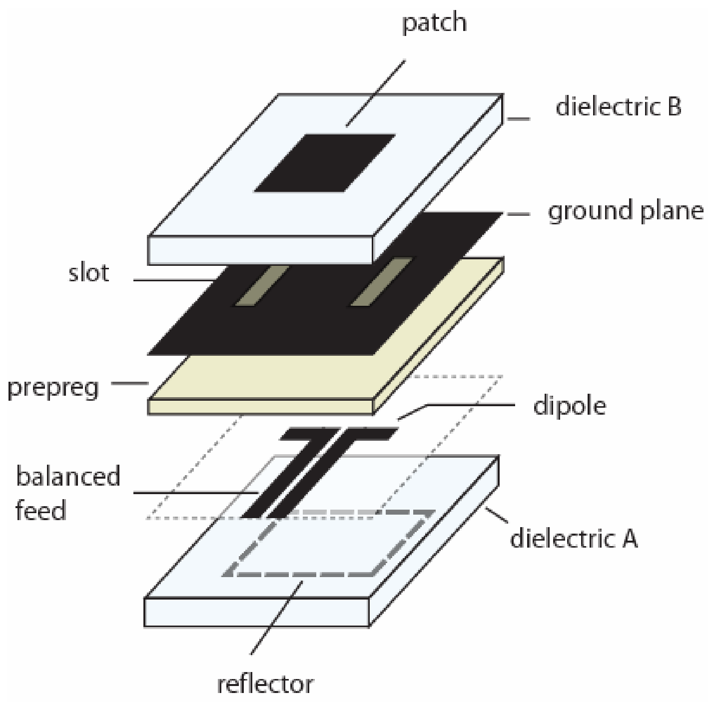


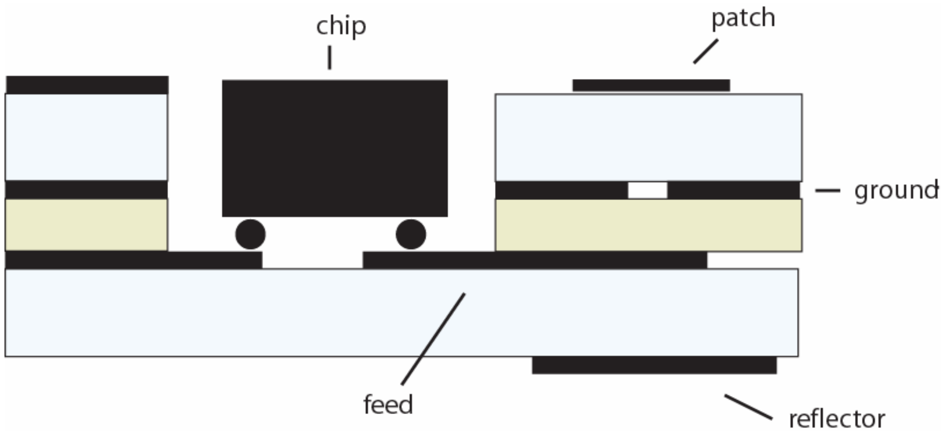


U. R. Pfeiffer, etc., “A chip-scale packaging technology for 60-GHz wireless chipsets,” IEEE Trans. Microwave Theory Tech., vol. 54, No. 8, pp 3387-3397, Aug. 2006.

Example: Balanced-fed aperture-coupled patch antenna

– PCB technology
– no vias
– high radiation efficiency
    • >80%
– bandwidth
    • 10-15 %

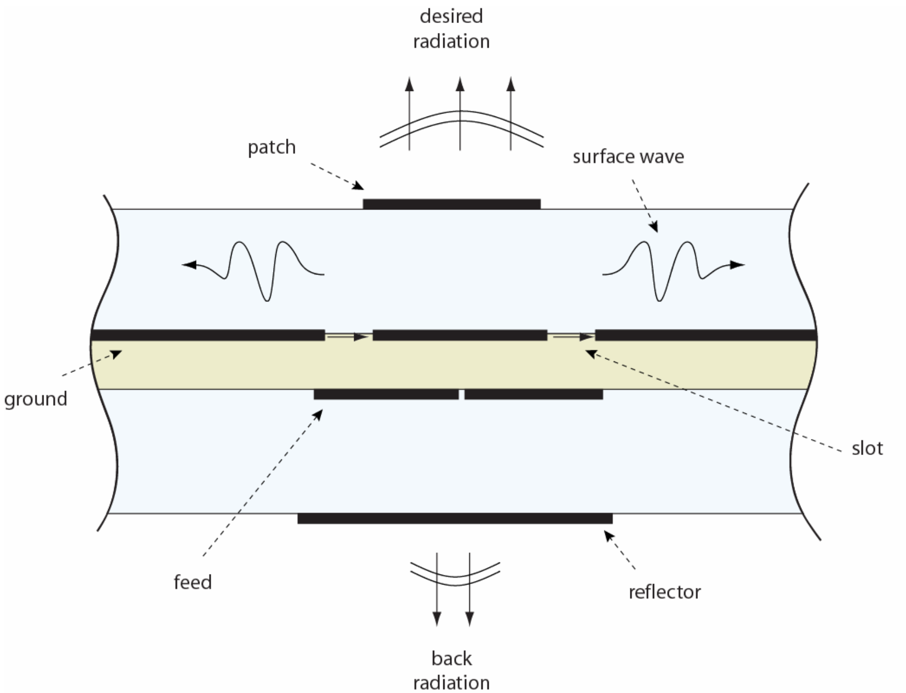


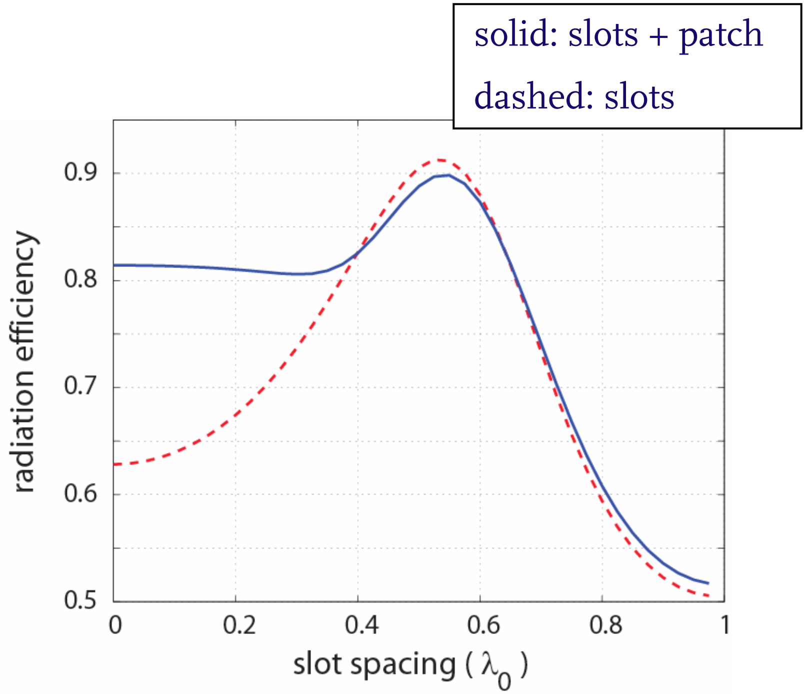


J.A.G. Akkermans, etc., "Design of a millimeter-wave balanced-fed aperture-coupled patch antenna" in proc. EuCAP, ESA SP626, (Nice, France), November 2006.

Example: Balanced-fed aperture-coupled patch antenna

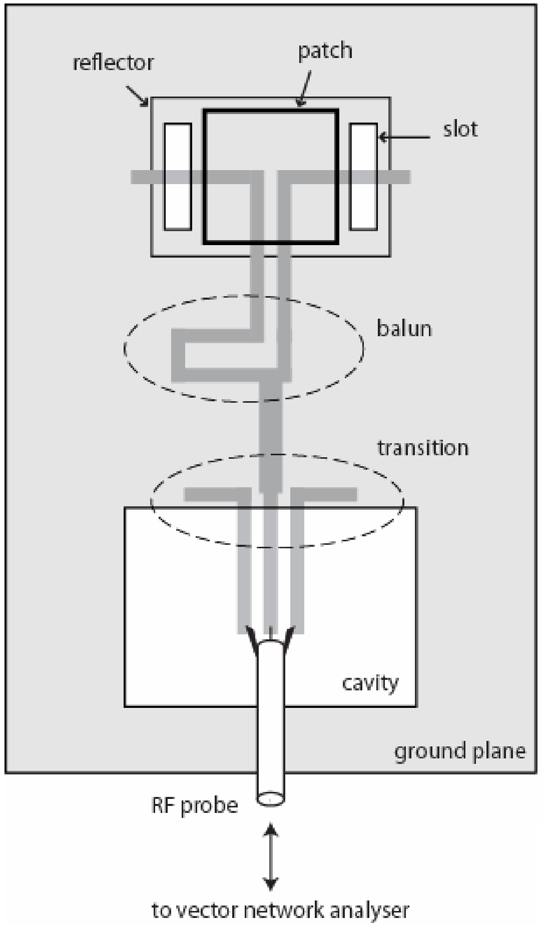
- Radiation efficiency
  - slot spacing
    - cancel surface waves
    - efficiency > 80 %

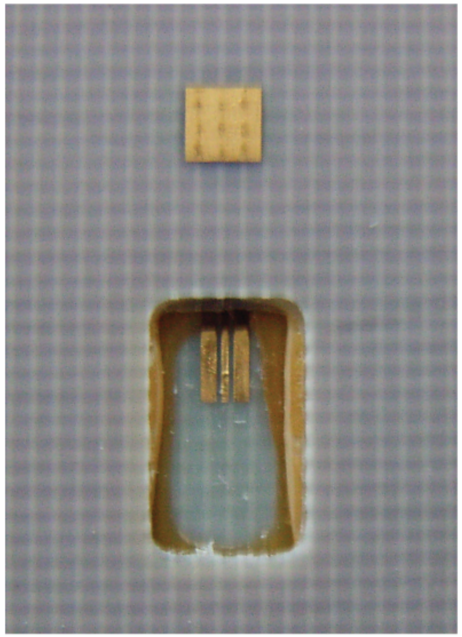




Example: Balanced-fed aperture-coupled patch antenna

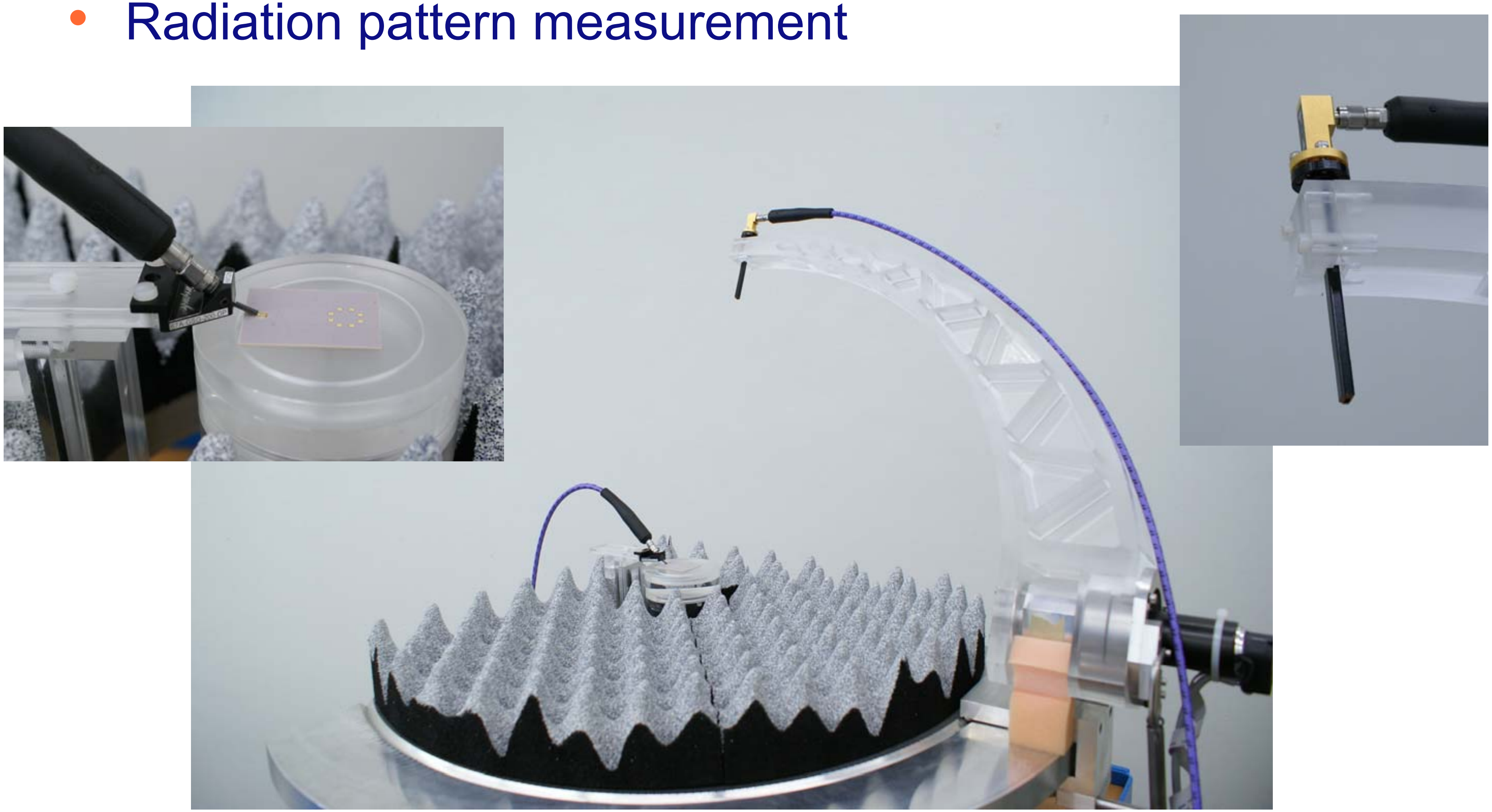
- Measurement setup
  - RF probe
  - transition
    - CPW - MS
  - balun
  - problem: flow of adhesive into open cavity





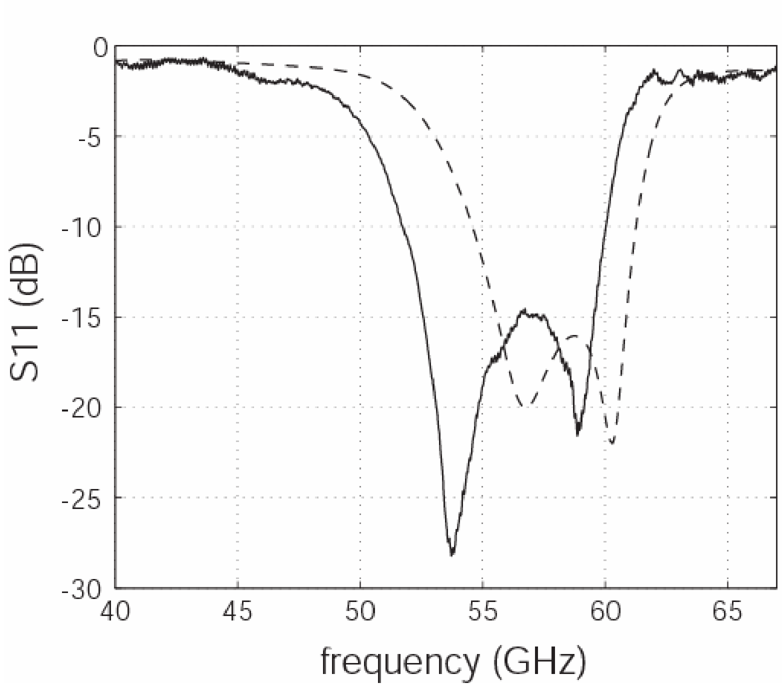
Example: Balanced-fed aperture-coupled patch antenna

- Radiation pattern measurement

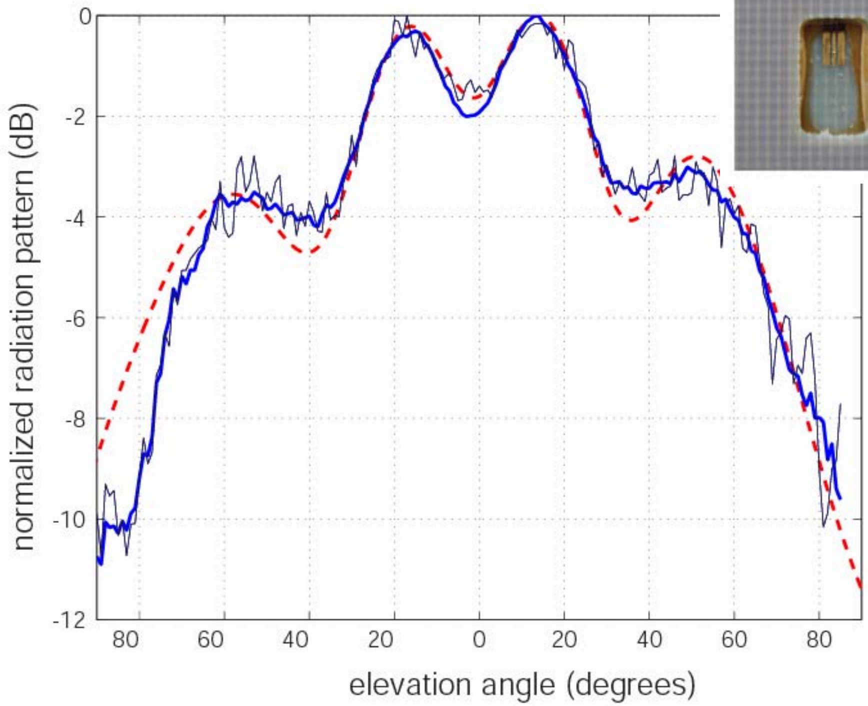


Example: Balanced-fed aperture-coupled patch antenna

- Measurement results



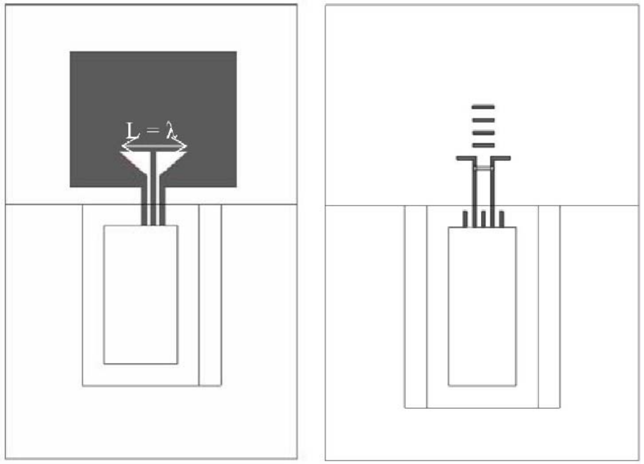
- simulation (dashed)
- measurement (solid)

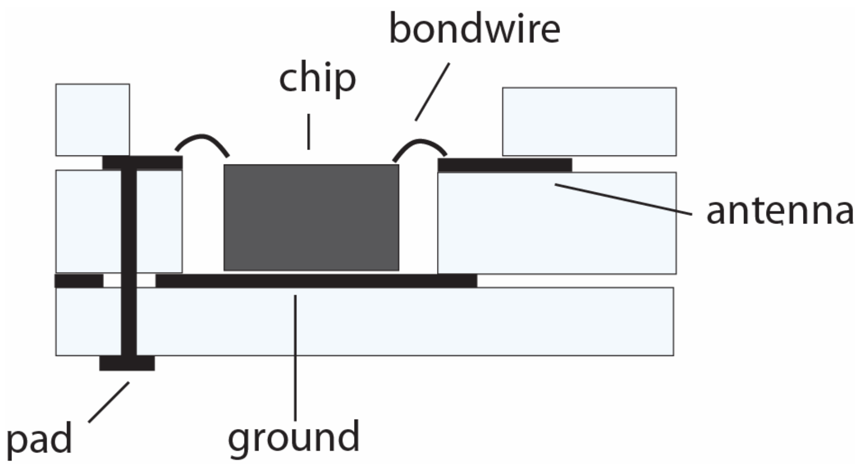


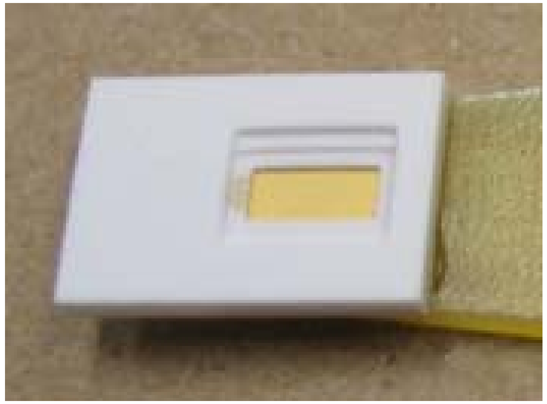
- simulation (red)
- measurement (black)
- time-gated measurement (blue)

Example: LTCC package effort

- LTCC antenna-in-package
  - slot dipole (differential)
  - yagi (single-ended)
- chip interconnect with bondwires



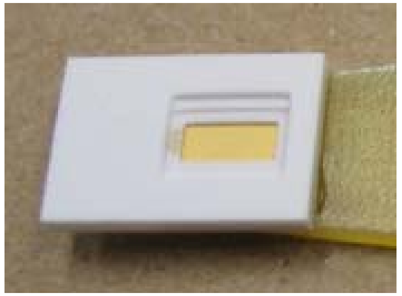


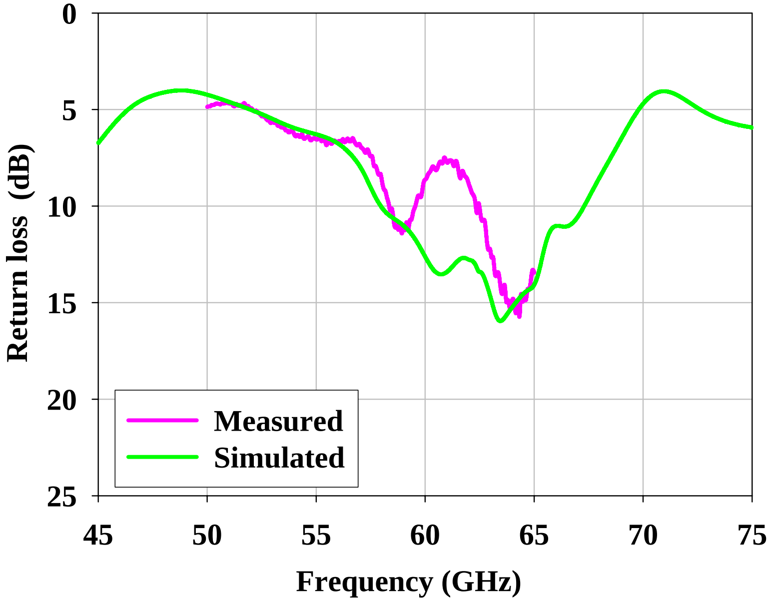


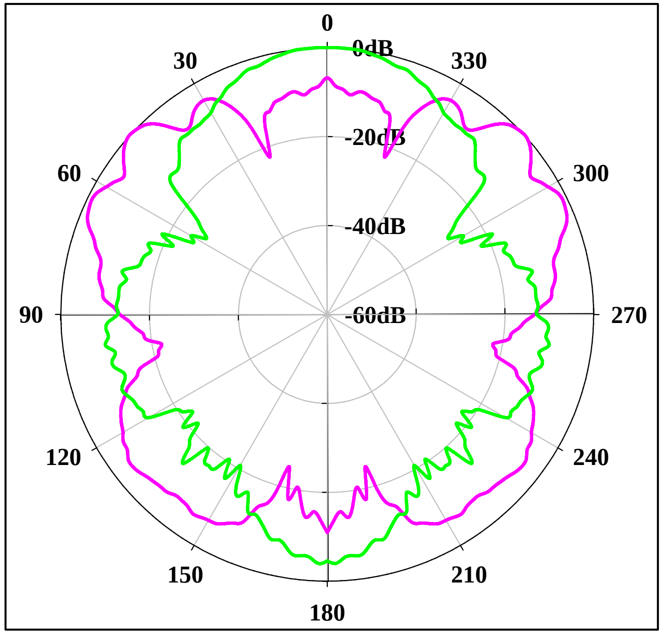
Y. P. Zhang, etc., ``Antenna-in-package in LTCC for 60 GHz radio," in Proc. IEEE International Workshop on Antenna Technology, Cambridge, UK, March 21-23, 2007.

Example: LTCC package effort

- Measurement results

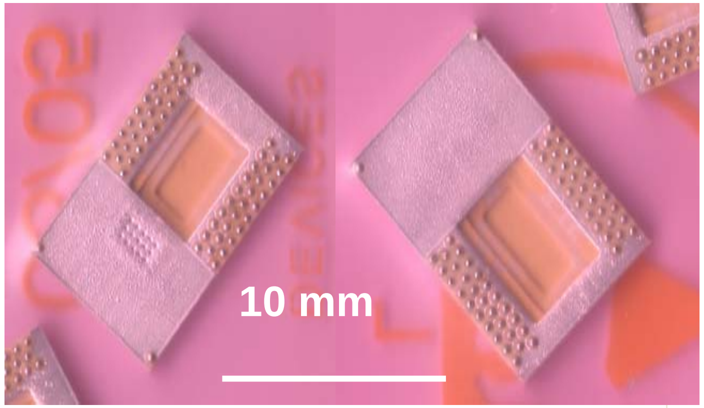


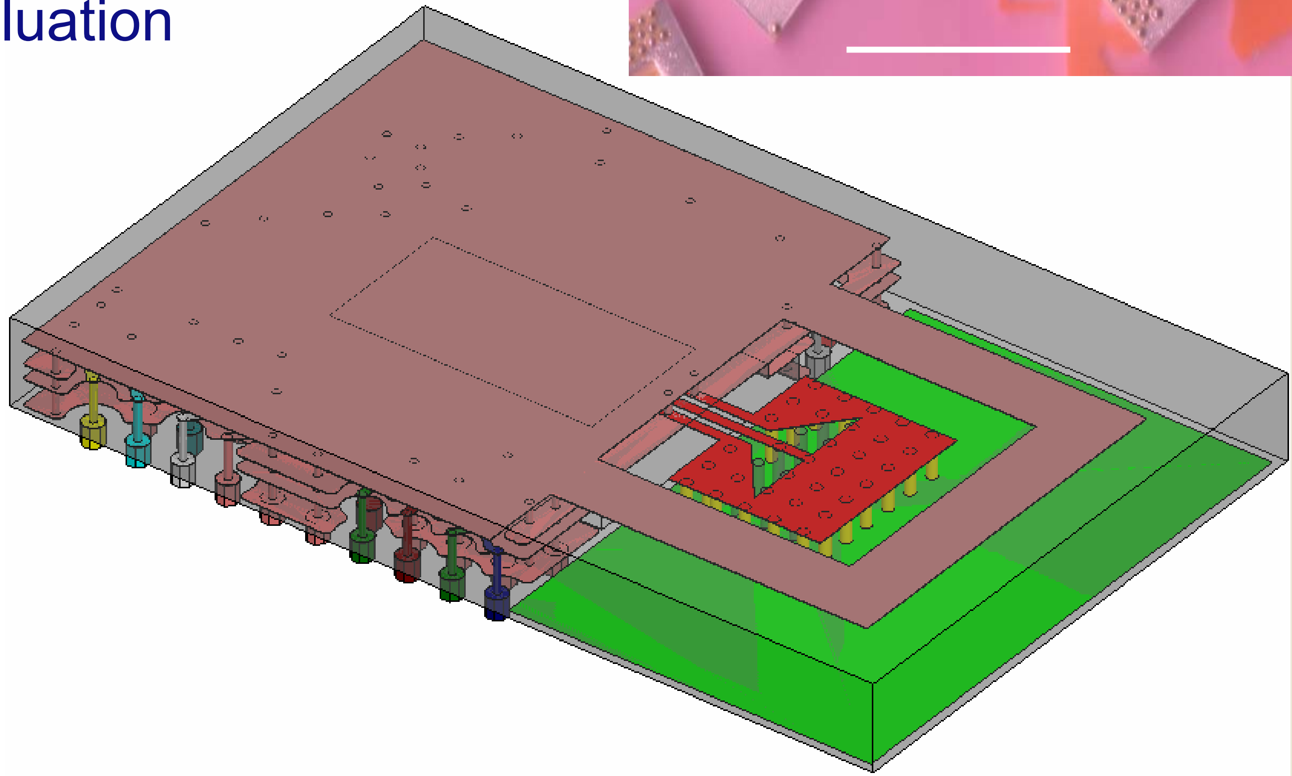




Example: LTCC package effort

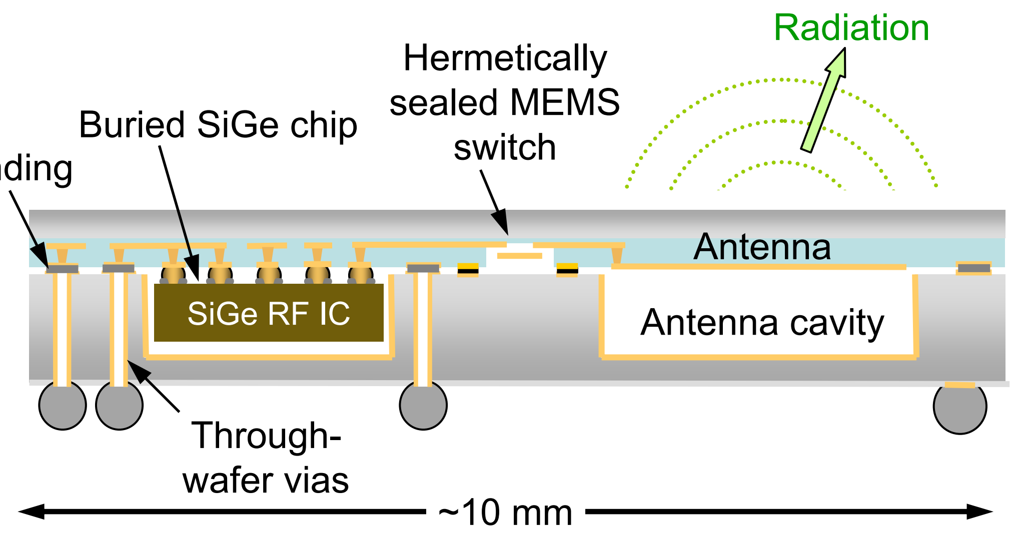
- 2^{nd} generation
  - holes to reduce effective dielectric constant
  - under evaluation



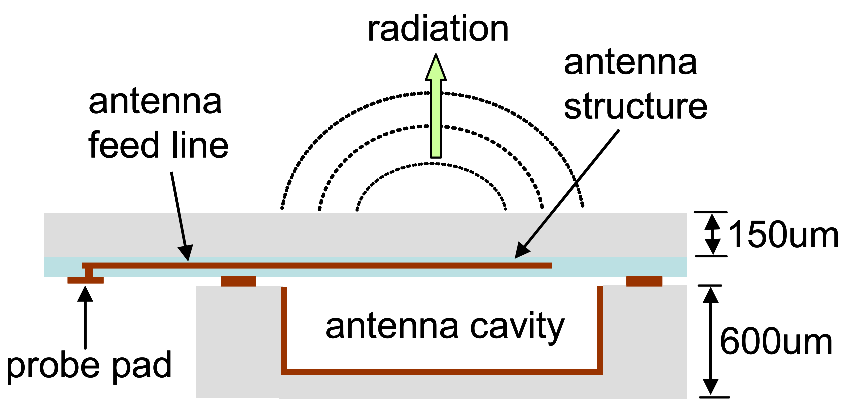


Example: Si-based packaging

- package concept
  - cavity-backed antenna
  - high-resolution process



- antenna test structure

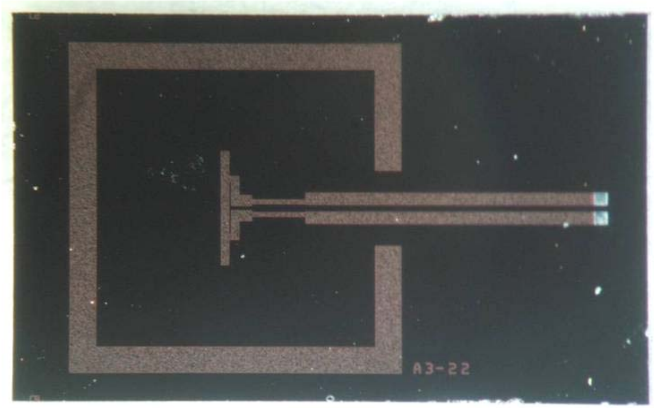


N. Hoivik, etc., "High-efficiency 60 GHZ antenna fabricated using low-cost silicon micromaching techniques," in Proc. IEEE AP-S International Symposium, pp. 5043-5046, Honolulu, Hawaii, June 10-15, 2007.

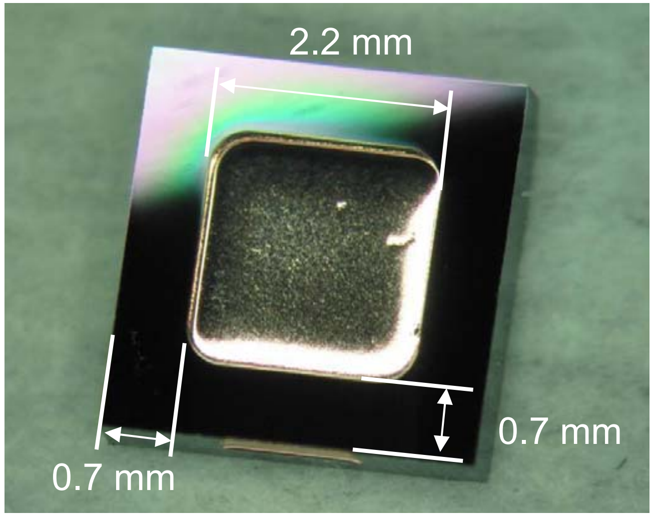
Example: Si-based packaging

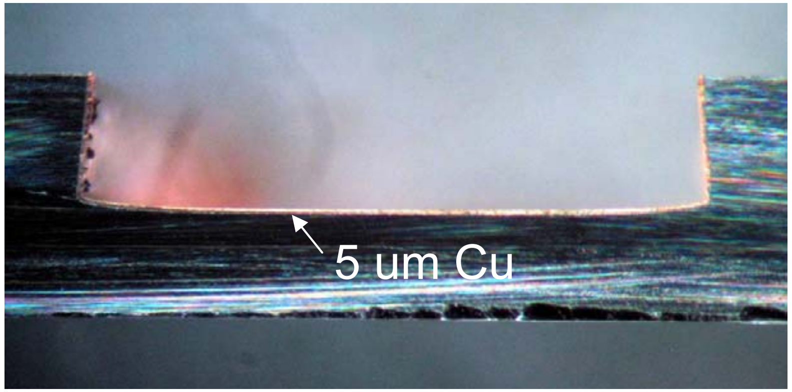
- The antenna is fabricated using 1.2 µm thick Cu
- Si wafers were thinned after processing from 725 µm to 150 µm using a back-side grinding process

Top view of antenna – High resistivity Si



Antenna cavity – doped Si

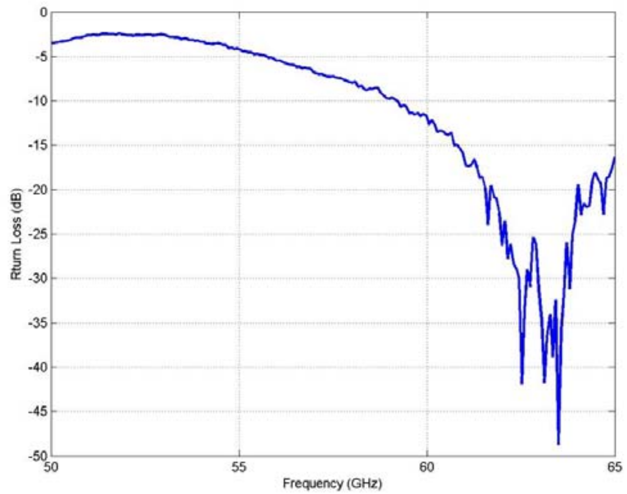


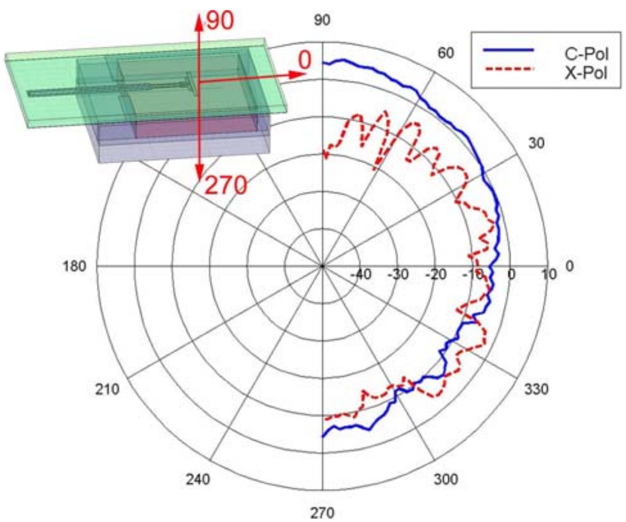


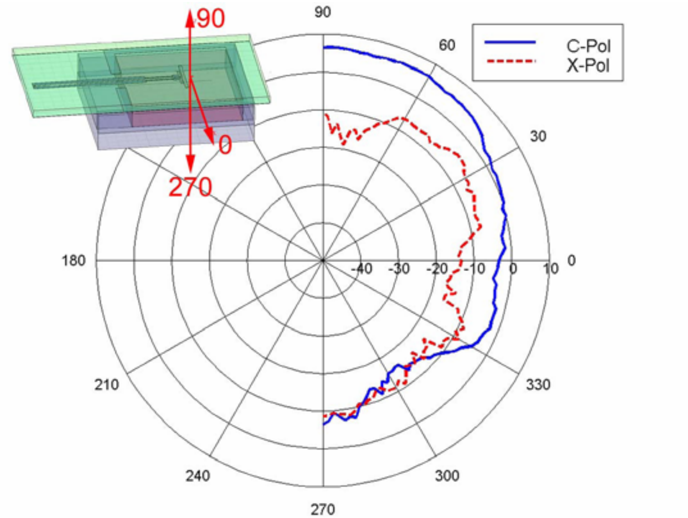
Antenna cavity

Example: Si-based packaging

- Measurement results
  - S_{11} in good agreement with simulations
  - high efficiency
  - gain 6-8 dBi



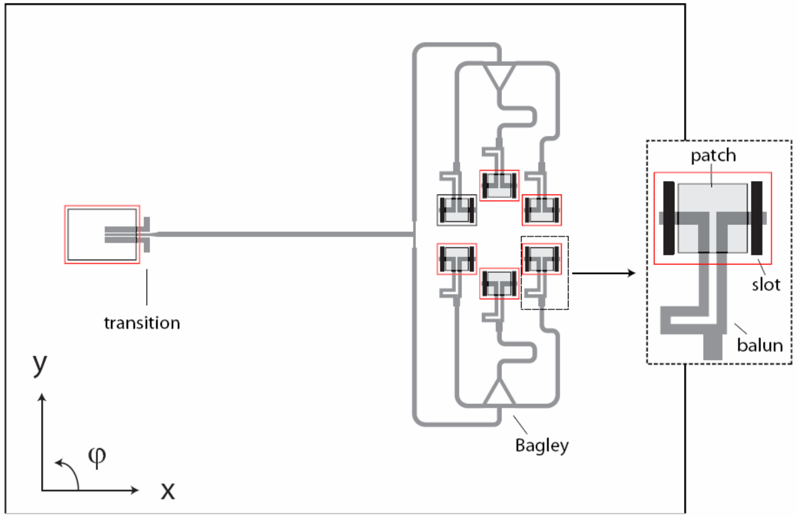


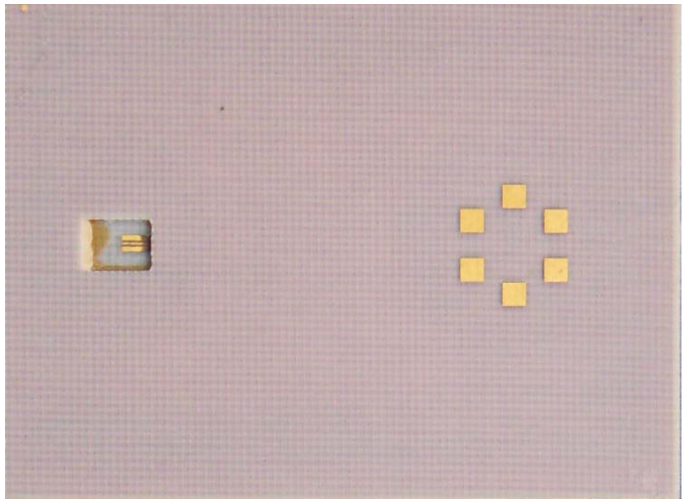


EuMIC 2008 38TH EUROPEAN MICROWAVE CONFERENCE 2008 IBM TU/e technische universiteit eindhoven

Example: Beam-forming antenna array

- Beam-forming antenna array
  - 6-element circular array
  - feed network designed for scan to θ = 0, 30, 60 degrees
  - problem: large feed-line losses (1.3 dB/cm)

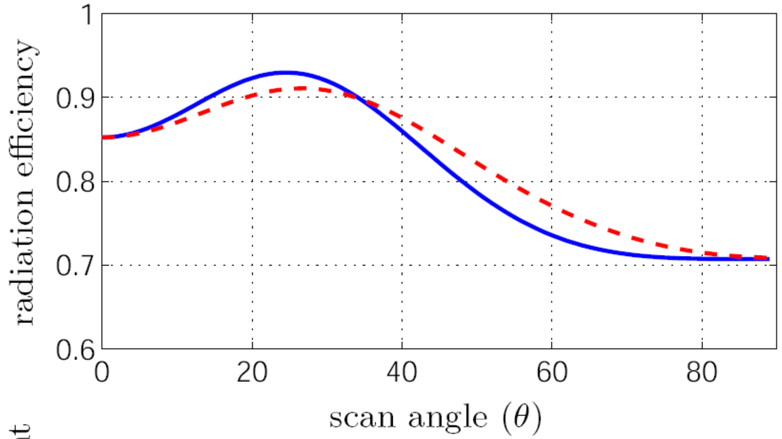


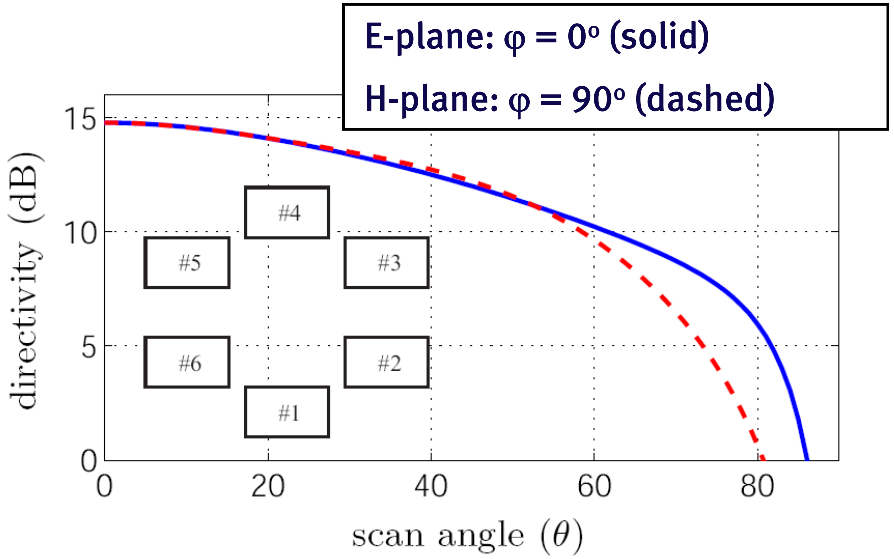


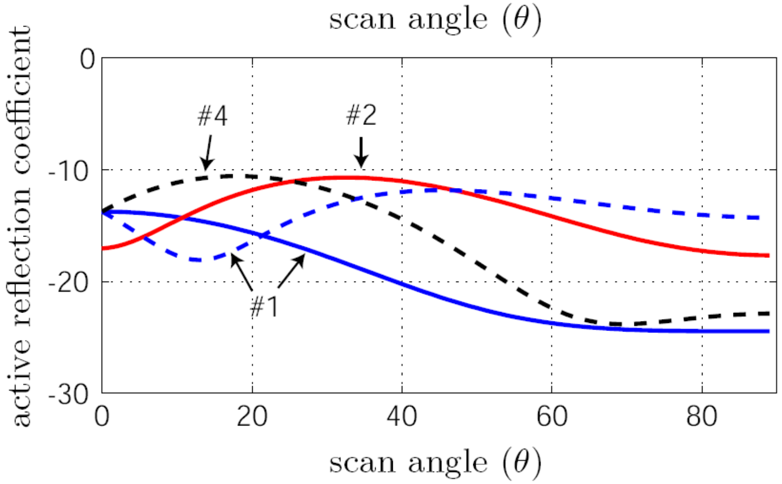
J.A.G. Akkermans, etc., "Planar beam-forming array for broadband communication in the 60 GHz band", EuCAP 2007, Edinburgh, UK, November 2007

Example: Beam-forming antenna array

- Performance as function of scan angle
  - no feed network!
  - directivity
  - radiation efficiency
  - reflection coefficient

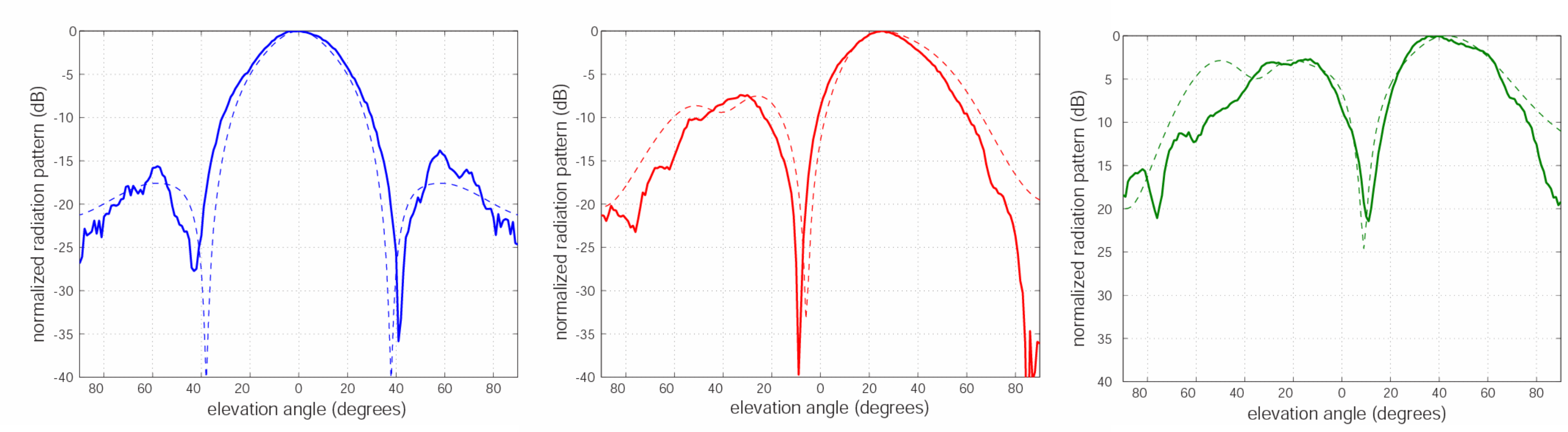






Example: Beam-forming antenna array

- Measurement results
  - beam-forming to 0, 30, 45 degrees



- simulation (dashed)
- measurement (solid)

EuMIC 2008 · 38th European Microwave Conference 2008 · IBM · TU/e technische universiteit eindhoven

Conclusions

- A lot of work is going on in millimeter-wave packaging
- Challenges
  - low-cost solution
    - planar technology
  - efficient
    - control surface waves
    - coplanar feed
  - flexible
    - support antenna arrays
- The all-in-one solution is not presented yet!