RF & Microwave Circuits for Wireless Communications

- Welcome!
- Agenda today:
  - Introductions
  - Overview of this course, what’s in it for you
  - Review of syllabus, key details
  - Keysight certification option
  - And on to the technical material

Introductions

- First: an apology. I didn't plan to have such a weird start to the semester…
  - My thanks to Heidi for setting up the teleconference
  - My thanks to you for your understanding
- My contact details:

  pfay@nd.edu, 631-5693

  Office: 261 Fitzpatrick Hall
- Email is the best way to reach me, or just drop by my office any time

Course Overview

- Course focuses on high-frequency circuits for wireless communications
  - What functions are needed for systems
  - How to design circuits for these functions
  - How to measure them
    - Do they do what we want?
    - Do they do other things too? Maybe things we don’t want?
  - Augmented with labs: you’ll measure circuits, design your own, build your own, and test them

Functions Needed

- Develop a “big picture” understanding of the processing done on signals in wireless communication systems
- We’ll focus completely on the high-frequency, analog parts; baseband and DSP-based processing won’t be discussed (but it is important)
- But “block diagram” type thinking is not enough—lots of critical details
  - Limitations on block diagrams, what else must be considered, how to really make something that actually works

Circuit Design

- Take functions and do detailed designs – convert transistors, resistors, capacitors, etc., plus interconnects & wiring, into something useful
  - What is the same and what is different from “regular old” circuit design?
  - Develop models for components appropriate for high frequencies
  - Develop a detailed understanding of interconnects and how to design them—this is probably the biggest change in design
- Approaches: hand calculation, computer-aided
  - Multiple levels of sophistication: circuit-model based, electromagnetics-based, nonlinear approaches

Measurement Techniques

- Measurement takes on added importance in RF/ microwave circuits
- Design tools are pretty good, but…
  - Most modern circuit designs are digital; “on/off” behavior makes design & validation much simpler; simple frequency dependence
  - Most RF/microwave designs are dominated by analog; details and small effects matter *a lot*
    - Example: an amplifier. Gain, input and output resistances are just the starting point. Useful, but leaves a lot out…
    - Why? an example: huge range in signals present. Your phone sees the signal from another phone just a few feet away, and has to be able to also see the signal from a base station up to 10 miles away. These signals are many orders of magnitude different in amplitude, and both signals have to be properly processed

Measurement Techniques (cont).

- So we need measurement capabilities to capture both "big picture" and nuances in circuit function
- A complication: frequencies are high
  - Circuit probing (e.g. oscilloscopes) don't work well
  - Adding the probe changes the circuit (details matter…), and changes the performance. Sometimes (usually) a lot
  - Need to accurately measure extremely high frequency signals, often at very low amplitudes.

6 GHz probes: Weird looking; discontinued

Result: different techniques

- Workhorse tools become vector network analyzer, spectrum analyzer; mostly work in frequency domain
- Often must analyze circuits "from the outside"—and infer from that what is going on inside
- Lab is well-equipped; you'll get first-hand experience

Lab Component

- The lab work cuts across these topics
- Focus mostly on measurement techniques & design; some circuit construction
  - Hands-on; work in small groups (usually 2)
  - **Make sure you're registered for both lecture and lab** (undergrads: 40458 and 41458; grads 60558 and 61558)
- The lab is your chance to get real hands-on experience with RF/microwave test & measurement hardware, as well as industrial-strength CAD software
  - About $300k worth of toys (not counting the software; a single license for that is $250k)—take advantage of it

Syllabus

- Hardcopies available with Heidi
- Walk through a few key parts—this course is not necessarily “normal”

EE 40458/60558 | **RF and Microwave Circuits for Wireless Communications**

Instructor: Patrick Fay
261 Fitzpatrick Hall
631-5693
pfay@nd.edu
http://www.nd.edu/~hscdlab

Text: David M. Pozar, *Microwave Engineering, 4th. ed.*, John Wiley & Sons, 2012.
Supplementary reading:
Guillermo Gonzalez, *Microwave Transistor Amplifiers, 2nd. ed.*, Prentice-Hall, 1997.
Class notes, handouts. Additional material is also available on the course web page at http://www.nd.edu/~hscdlab
Prerequisites: EE 30348, EE 30358 or consent of instructor
Catalog Description: (2-3-3)
This course is an introduction to RF and microwave circuit design and analysis techniques, with particular emphasis on applications for modern wireless communication and sensing systems. An integrated laboratory experience provides hands-on exposure to specialized high-frequency measurement techniques. Students will develop an enhanced understanding of circuit design and analysis principles as applied to modern RF & microwave circuits, as well as gain familiarity with design techniques for both hand analysis and computer-aided design. A design project will be designed, built, and tested using the computer-aided techniques and instrumentation in the lab.
Course Outline:
- Review of electromagnetics; Maxwell's equations, plane wave solutions, transmission lines. Introduction to ADS microwave CAD software
- Types of transmission lines and their properties; coaxial lines, rectangular waveguides, microstrip.
- Network analysis; scattering matrix, transmission matrix formulations. Flow graphs, Mason's rule.
- Matching networks: lumped element designs and limitations, single and double-stub tuned designs. Quarter-wavelength transformers, multisection matching transformers.
- Active microwave circuit design, characteristics of microwave diodes and transistors. Linear and nonlinear behavior and models.
- Amplifier design; gain and stability, design for noise figure.
- Noise in microwave circuits; dynamic range and noise sources, equivalent noise temperature, system noise figure considerations.

Laboratory and Design Project: (approx. 11 laboratory sessions)
1. High frequency performance of circuit components
2. Measurement basics; reflectometry, spectrum analysis
3. Scalar network analyzer measurements
4. Vector network analyzer operation and error correction
5. Scattering parameter measurements of active devices
6. Matching network design, fabrication, and characterization
7. Project design, characterization, and analysis
8. Nonlinear and noise characterization of active circuits

Homework:
Homework will be assigned and collected (approximately) weekly.
Examinations:
1 in-class midterm examination, cumulative final exam

Grading:		
	Homework	20 %
	Mid-term exam	25 %
	Laboratory (includes design project)	25 %
	Final exam	30 %

Text Book

Key point #1: be careful about text book editions.

- We will use Pozar's **4th edition, 2012**
- Older ones are organized differently, are missing material
- International versions are not the same. Do not use them—we have found many sneaky changes
- There are two versions of Pozar—a "thin" and "thick" version. Both are OK—only difference is portability
- Gonzales' book is an excellent resource, provides good alternative approaches if Pozar is unclear

http://www

Text: David M. Pozar, *Microwave Engineering, 4th. ed.*, John Wiley & Sons, 2012.
Supplementary reading:
Guillermo Gonzalez, *Microwave Transistor Amplifiers, 2nd. ed.*, Prentice-Hall, 199
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http://www.nd.edu/~hscdlab
Prerequisites: EE 30348, EE 30358 or consent of instructor
Catalog Description: (2-3-3)

Course Outline

Have a look…that way you won't be surprised about what we're doing or where we're going next

•This is not "text book order"—we'll jump around

•Don't worry (too much) about the electromagnetics part; we'll focus on designs and circuits much more

Course Outline:

- Review of electromagnetics; Maxwell's equations, plane wave solutions, transmis
  Introduction to ADS microwave CAD software
- Types of transmission lines and their properties; coaxial lines, rectangular wavegu
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  system noise figure considerations.

Labs and Design Project

Key point #2: the lab is a big part of this course

> **Laboratory and Design Project:** (approx. 11 laboratory sessions)
> 1. High frequency performance of circuit components
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> 3. Scalar network analyzer measurements
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> 5. Scattering parameter measurements of active devices
> 6. Matching network design, fabrication, and characterization
> 7. Project design, characterization, and analysis
> 8. Nonlinear and noise characterization of active circuits

- Labs are a mix of "normal" labs where you follow a procedure to learn a technique and "design" labs that are much more open-ended
- The course web page has guide sheets for each lab, and a tentative schedule
- Read the guides *before* the lab. It'll make your time in the lab a lot more productive and fun
- Schedule is subject to revision—but we always find a way to make it work

Grades & Stuff

Key point #3: the lab is a big part of this course, and so is the homework

- Homework is 20% of your grade
- Labs are 25% of the total grade
- This weighting reflects where the learning really takes place—you'll learn these techniques best doing them
- Net result: do the homework, and do the labs
- One more detail: for grad. students **only**, this year this course is a "qualifying exam" course. Students in the grad version will get extra homework problems. These give you the extra depth you need for the qual exam. Courtesy of Prof. Chisum. Enjoy?

Homework:

Homework will be assigned and collected (approximately) weekly.

Examinations:

1 in-class midterm examination, cumulative final exam

Grading:	Homework	20 %
	Mid-term exam	25 %
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More Important Stuff

Course web site has some useful stuff on it

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4th. ed., John Wiley & Sons, 2012

- Homeworks will be posted there (with solutions)
- Lab procedures and write-ups, files that are helpful for the lab and computer work (design model files, etc.). Look on the “lab” page
- Other aids: copy of the syllabus, lab policy sheet, Smith charts, old tests. Look on the “homework” page

Keysight Certification Option

- Students that do well in this class can also receive Keysight Technologies' "Ready for Industry" certification
- This is entirely optional, but if you're considering an RF/microwave career, it might help in interviews
- Main emphasis is on experience/competence with test & measurement gear and techniques, and design/simulation tools and techniques
- The course more than satisfies the "level 1" requirements
- More details are online—but don't focus on their requirements. I take care of the details for you

Keysight RF & Microwave Industry-Ready Student Certification Program

The RF & Microwave Industry-Ready Student Certification Program creates a collaboration between universities and industry to recognize and acknowledge students that have demonstrated RF/MW design and measurement expertise.

"40 of the top engineering universities in the U.S. and Europe are participating in the RF and microwave certification program," said Todd Cutler, vice president and general manager of Keysight EEsof EDA. "The curriculum and labs at each university focuses on the design, building, measurement and analysis of RF/MW components to help students gain real-world understanding in design and measurement techniques. Students completing the program receive recognition as qualified Keysight RF/MW Industry-Ready Students."

Questions on Administrative Stuff?

- On to technical discussion…

RF and Microwave Circuits for Wireless Communications

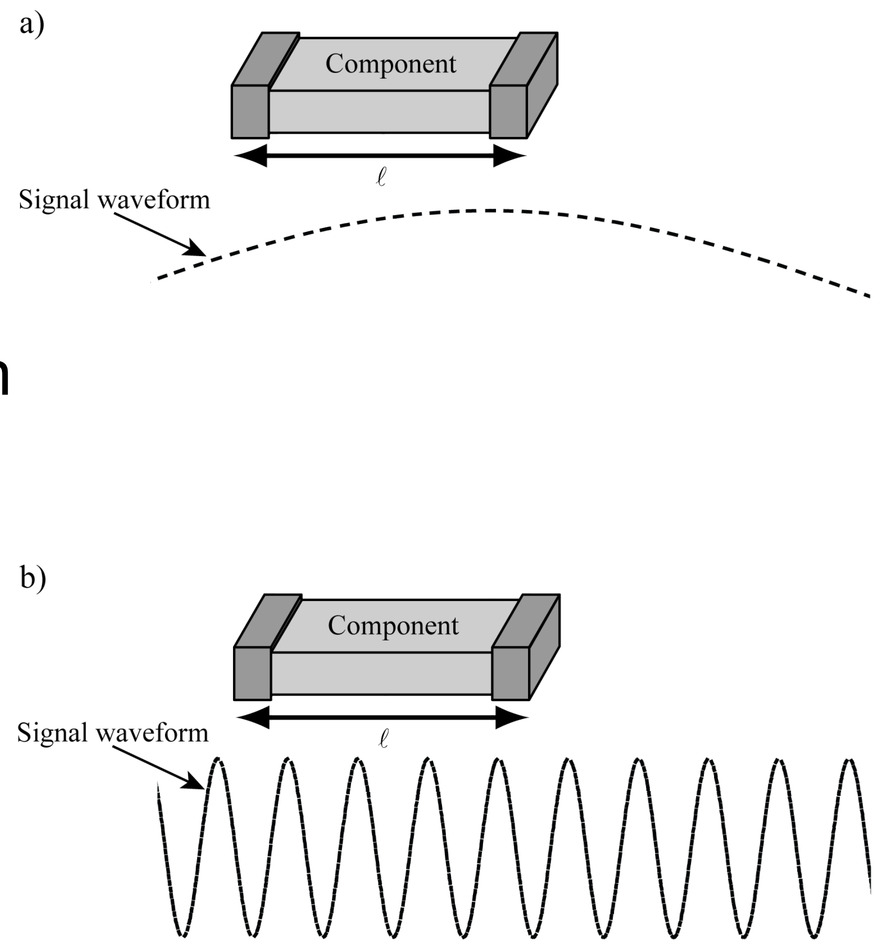
- Modern wireless communications relies on high-performance, high-frequency circuits
- Lots of other applications do too…
  - Radar
  - Medical therapies (RF-induced hyperthermia treatments for cardiac arrhythmia)
  - Imaging for avionics, security (airport scanners, theft prevention at warehouses)
  - Digital circuits
- Our job: figure out how to make circuits that do what is needed

RF and Microwave Design

- So what's the big deal? How is this any different from "regular old" circuit design?
- Key issue: at high frequencies, some fundamental (maybe even forgotten) assumptions in "regular old" circuit design fall apart
  - Normally, circuit layout is not so important; at RF/microwaves, layout is *very* important
  - RF/microwave: basically short-hand for "high frequency"—RF is ~10 MHz – 1 GHz; microwave is 1 GHz and up
- Where does this come from? Finite speed of light
- "Regular old" circuit design assumes that changes in signals propagate instantly. But we know really this isn't possible—nothing, not even signals, moves faster than light. So why does this break at high frequencies?

What's Different about Microwave Circuits?

- As frequency increases, size of "components" becomes comparable to wavelength
- Provides both complication as well as opportunity for design
- "Applied electromagnetic engineering"
- Another way: we were just lucky before that all of our components were much smaller than a wavelength

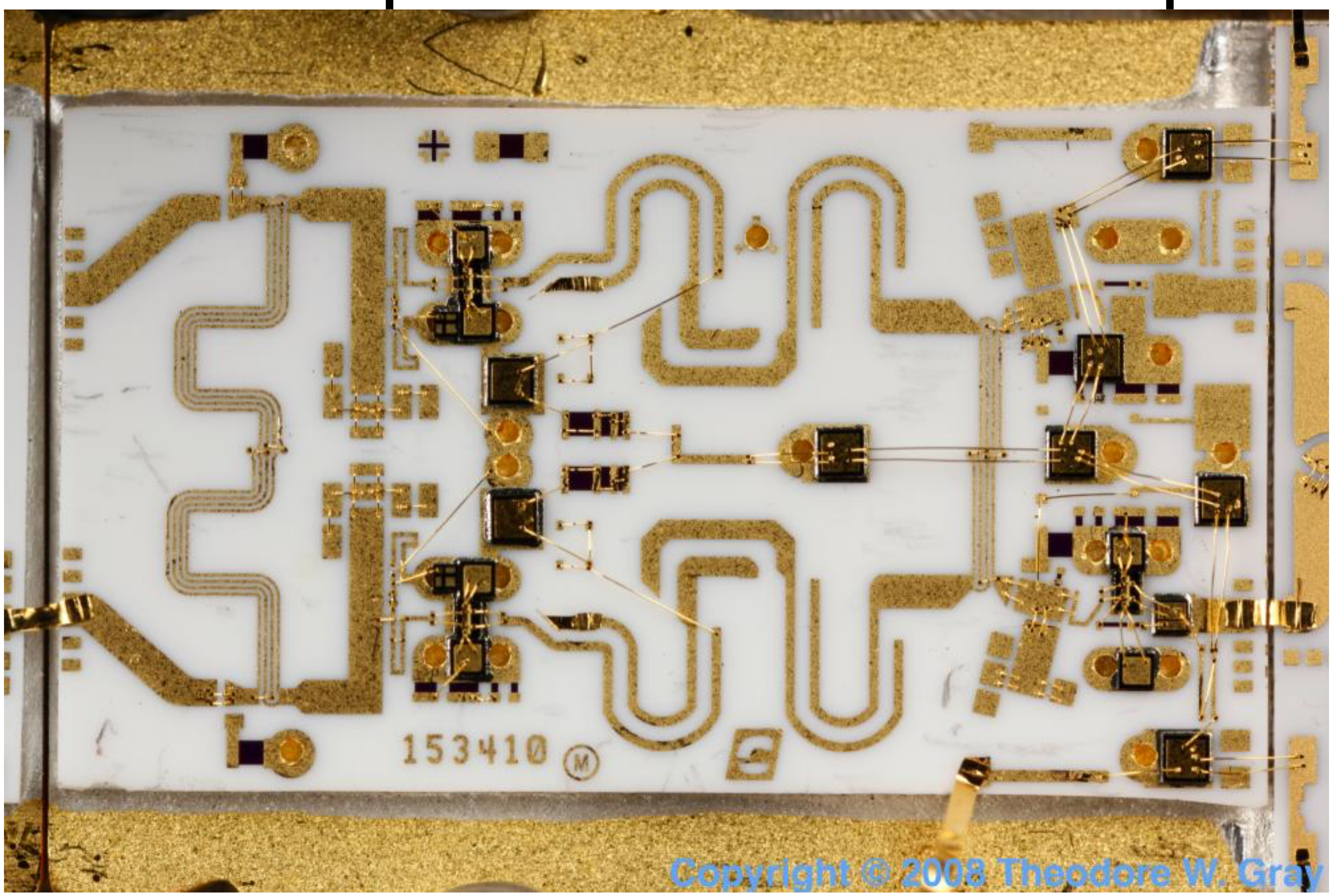


Conclusion: “nodes” aren’t nodes anymore…

- Wires, interconnections matter—a lot
- Shape of the circuit matters—a lot
  - Makes for funny-looking circuits
  - Opens up many design opportunities
  - “Distributed” circuit concepts—explicitly use wave propagation to do things that “shouldn’t work”
- Many technologies can be used
  - CMOS, BJTs, more exotic III-V electronics, vacuum tubes (honest!), magnetic devices
  - Classic engineering—use what is available, just make it work (and on time and under budget)

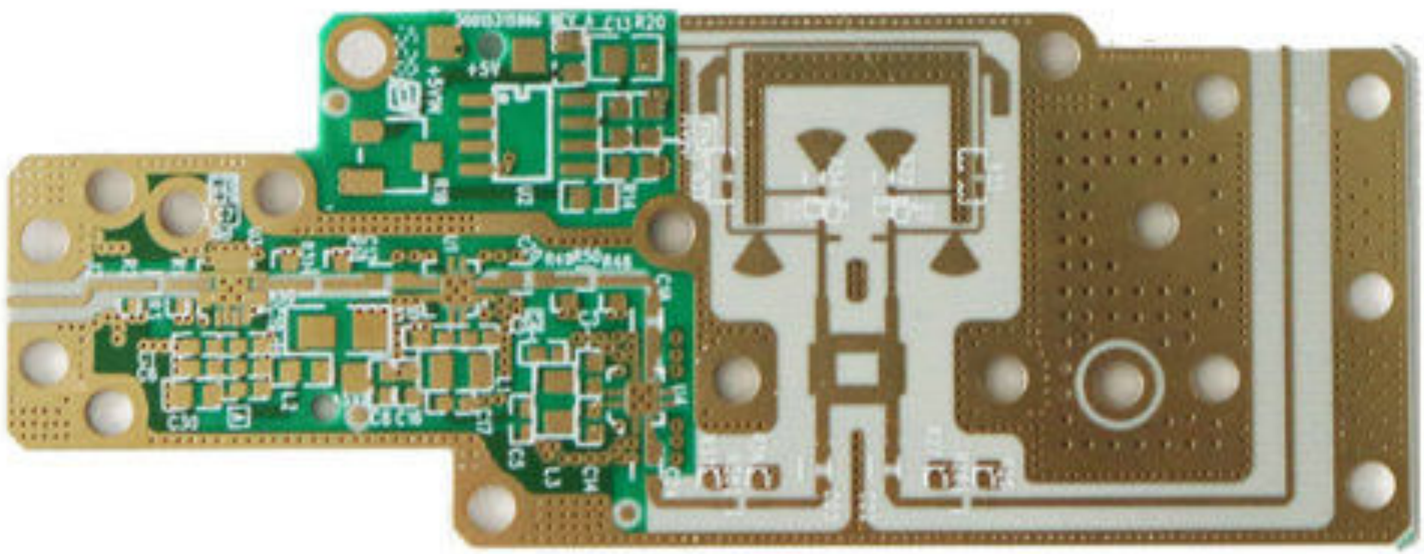
Board-level

- A few examples…GaAs FET amp



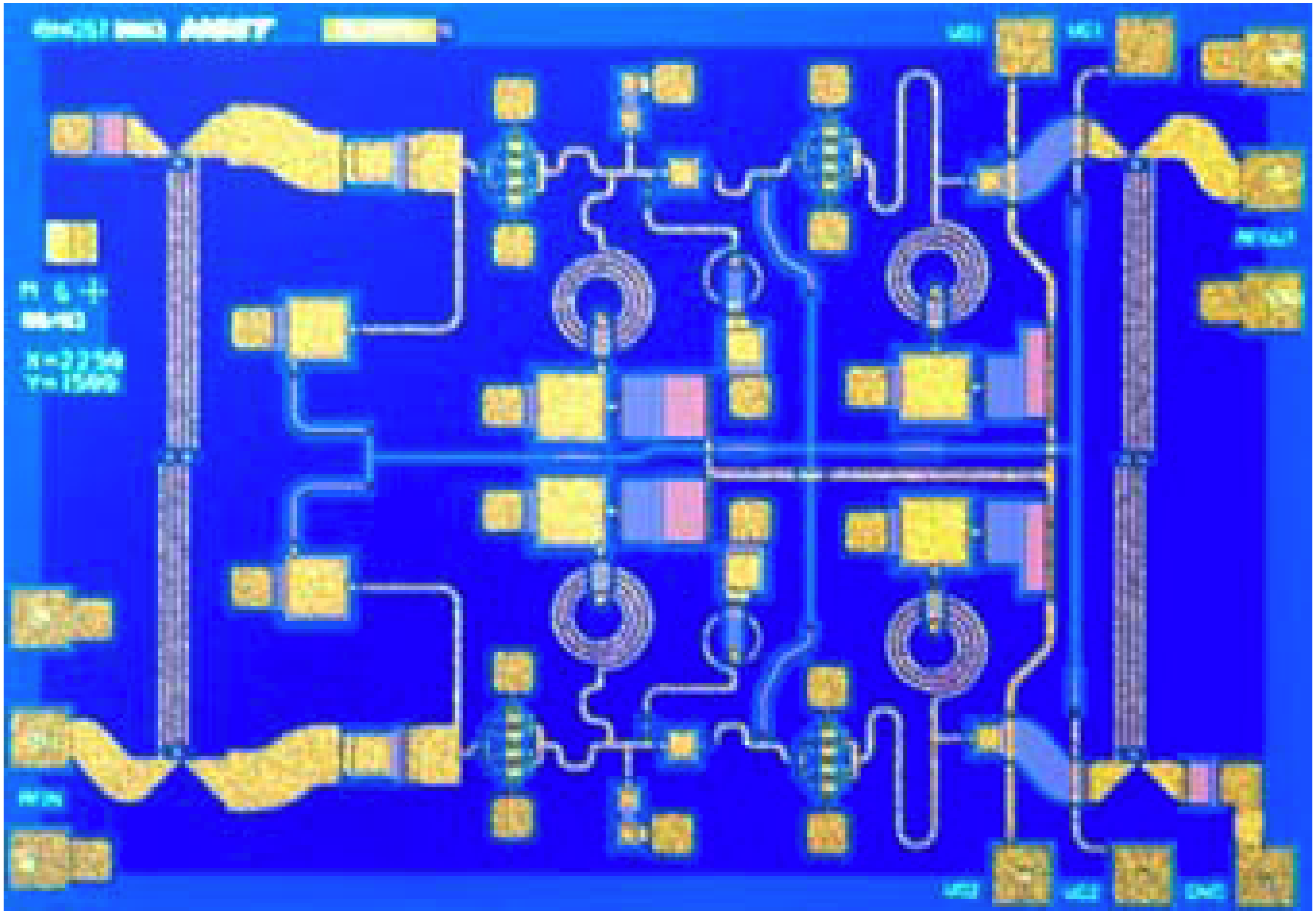
Board-level

- A few examples…Coupler & splitter, plus a few other things…

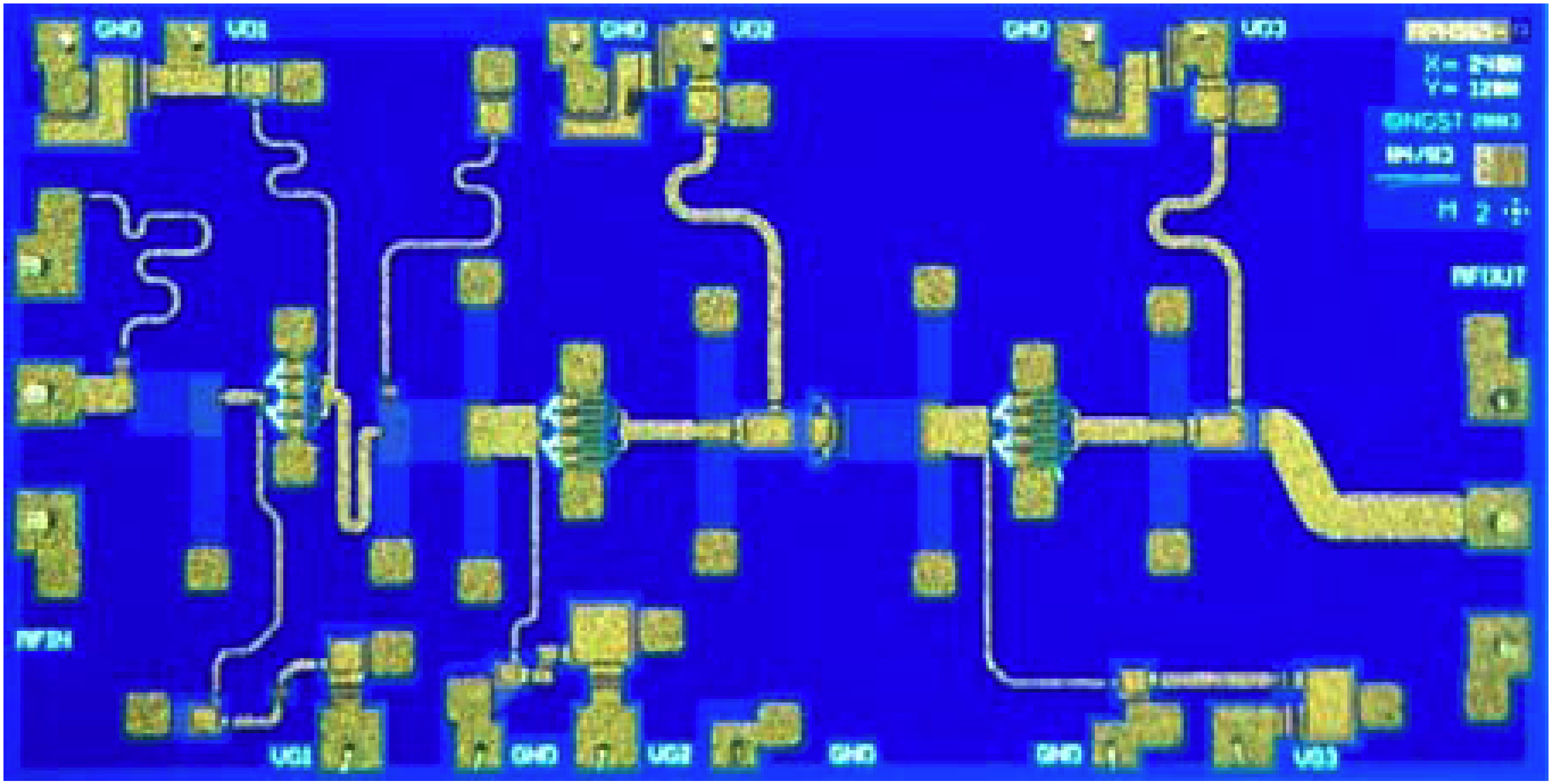


- I have a bunch of examples—they are much easier to see in person

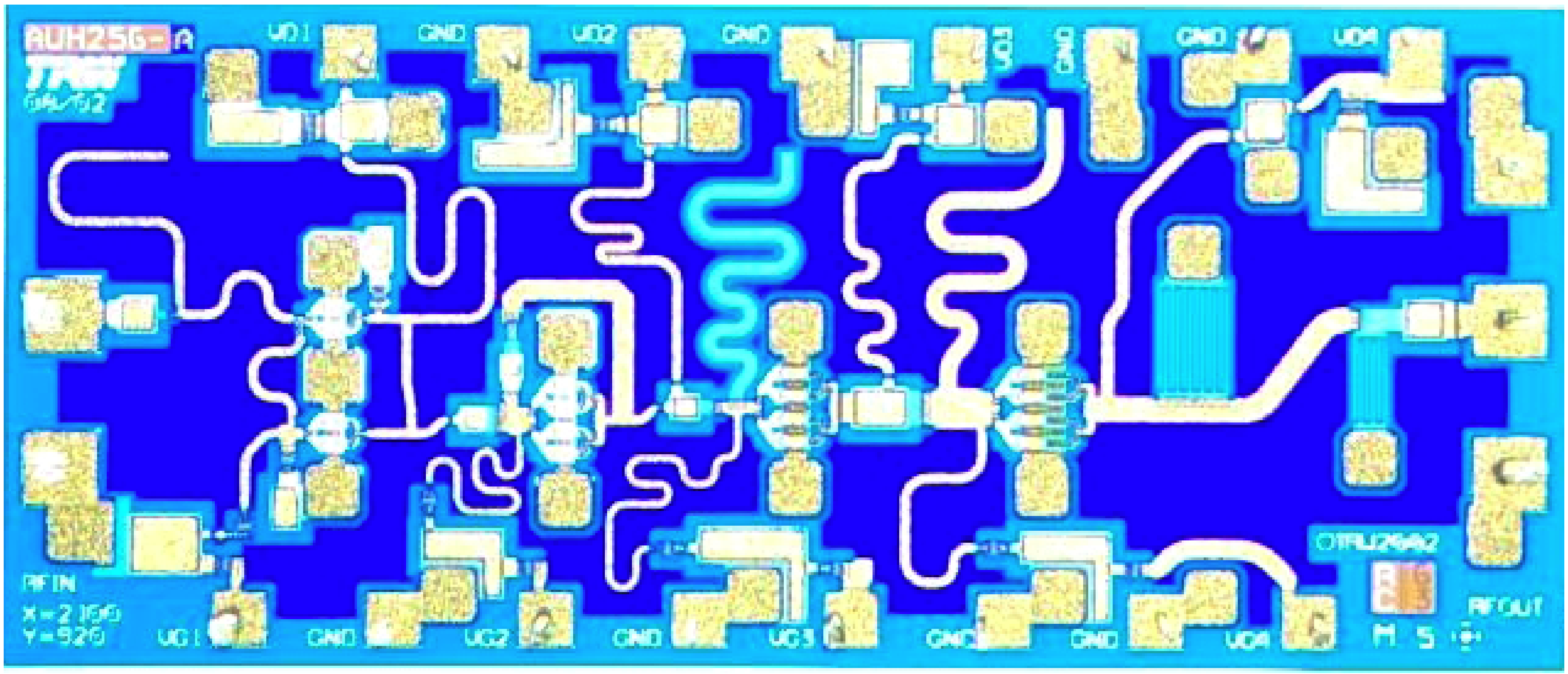
And on chip:
14-27 GHz Low Noise Amp



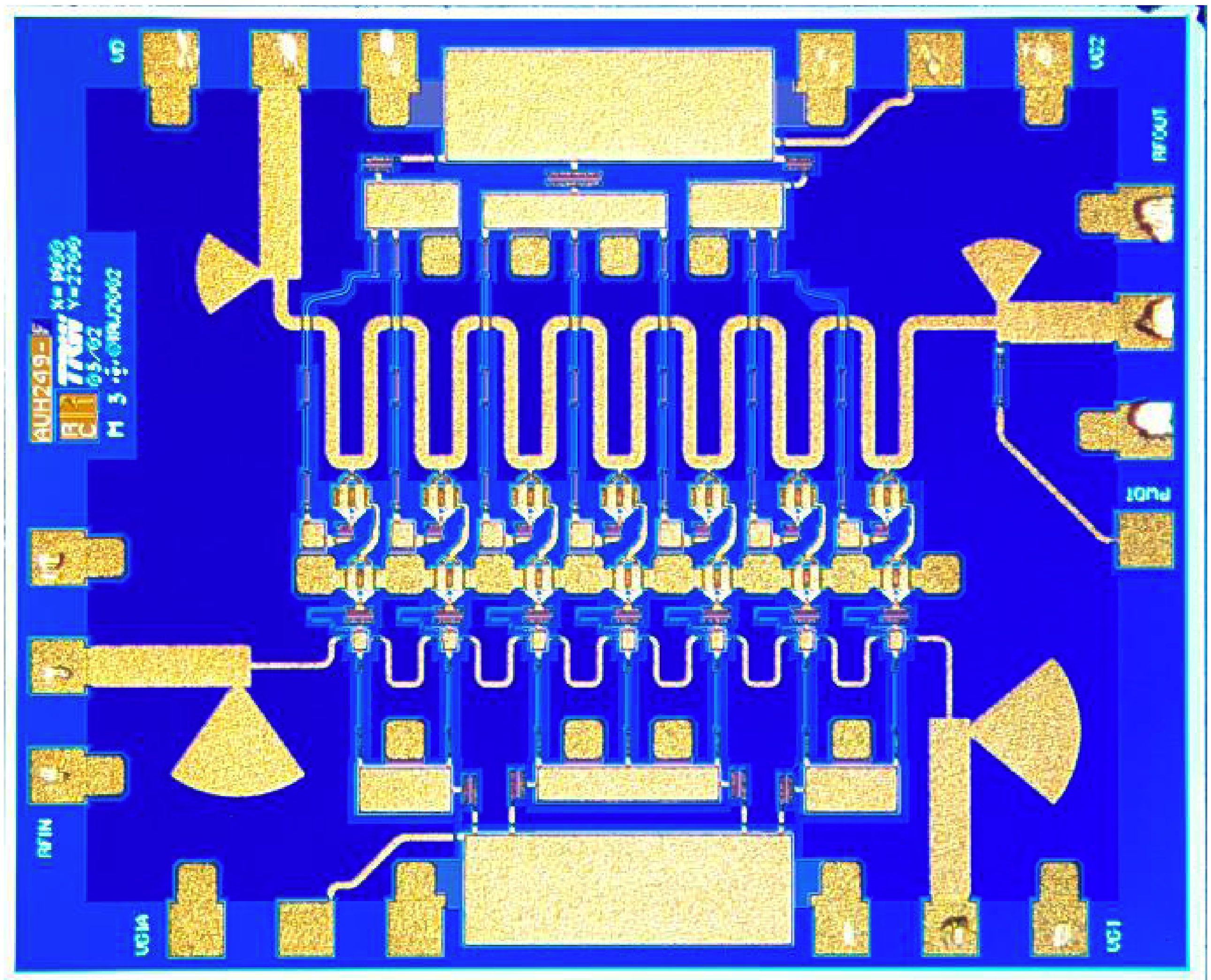
43-46 GHz Medium Power Amplifier



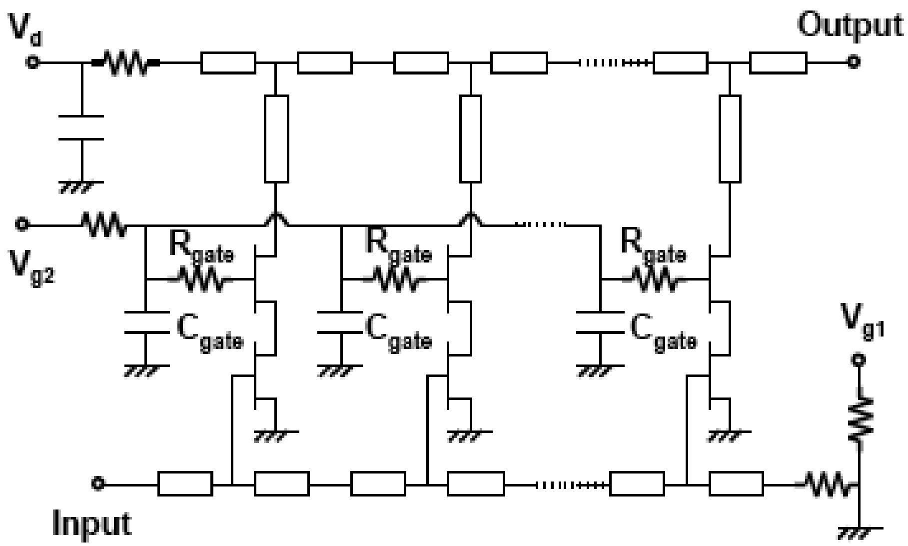
17.5-41 GHz Broadband amp

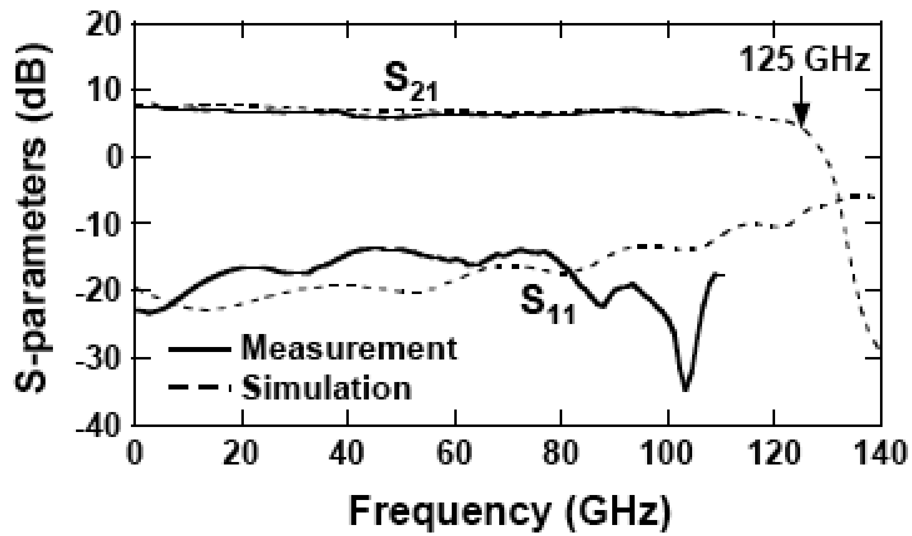


Distributed Amp - DC-35 GHz



“Counter-intuitive” Circuit Layout – Improved Performance





What is the (frequency) limit?

368 IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 21, NO. 7, JULY 2011

Low Noise Amplification at 0.67 THz Using 30 nm InP HEMTs

William. R. Deal, *Senior Member, IEEE*, K. Leong, *Member, IEEE*, V. Radisic, *Senior Member, IEEE*, S. Sarkozy, B. Gorospe, J. Lee, P. H. Liu, W. Yoshida, J. Zhou, M. Lange, R. Lai, *Fellow, IEEE*, and X. B. Mei, *Member, IEEE*

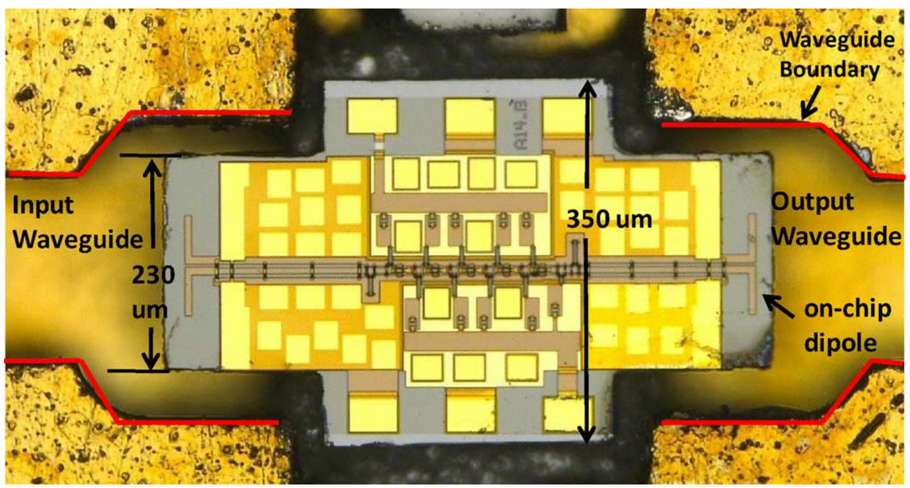


Fig. 1. Microphotograph of 670 GHz LNA in split block housing.

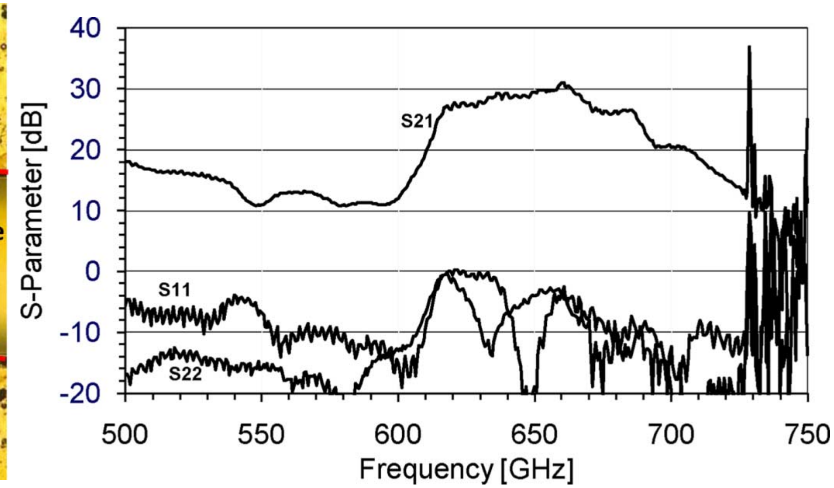
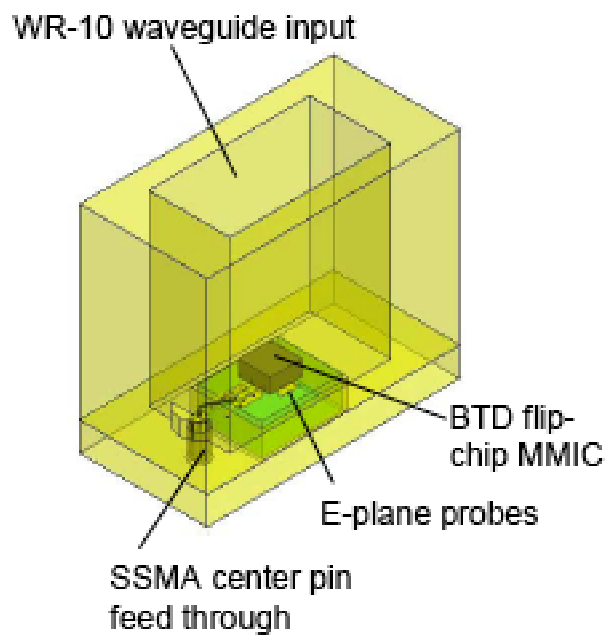
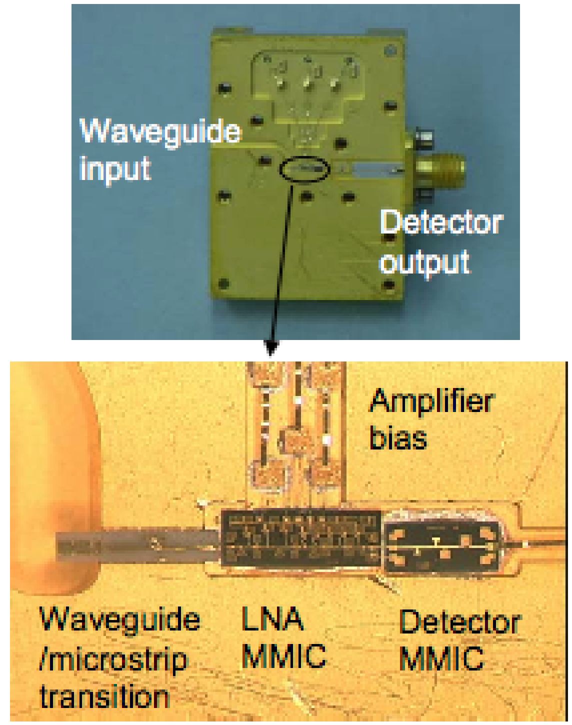


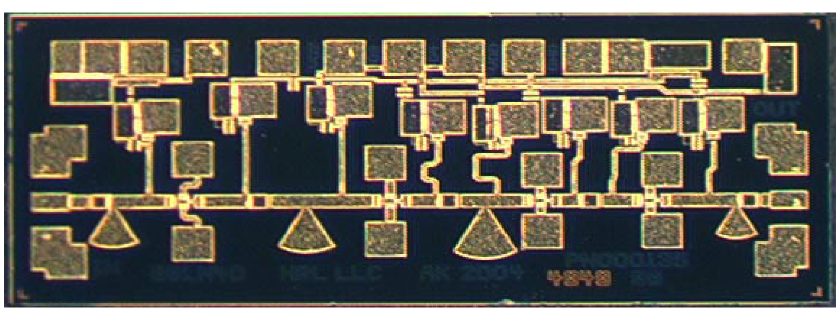
Fig. 6. Measured on-wafer S-Parameters of 10-stage LNA.

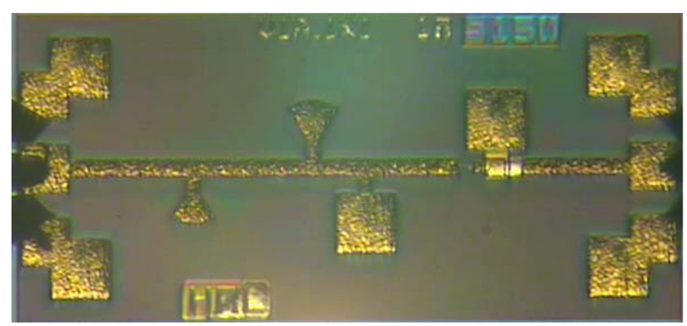
Everything still "works" to 670 GHz…and transistors over 1 THz have been demonstrated. Maxwell's equations are just fine…

Not just amplifiers - detectors(example: 94 GHz)





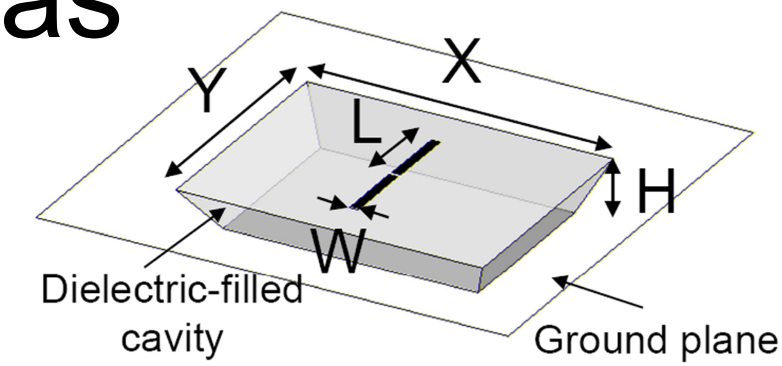


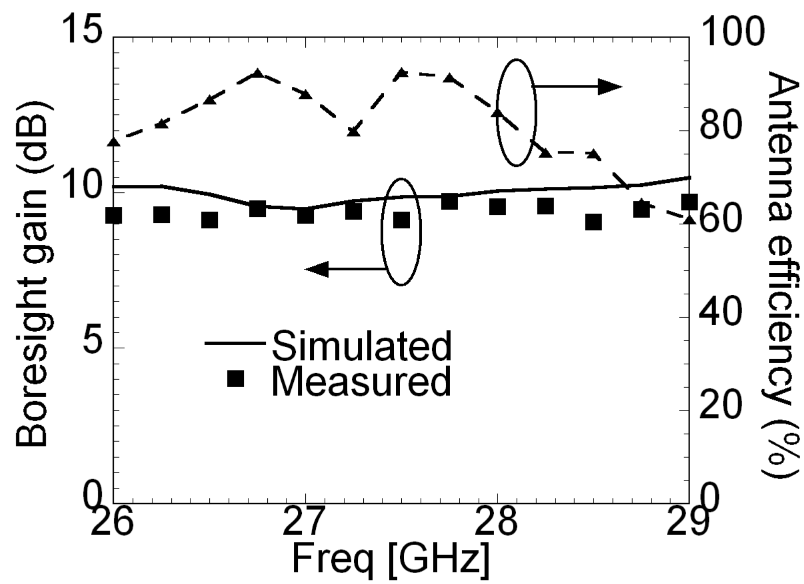


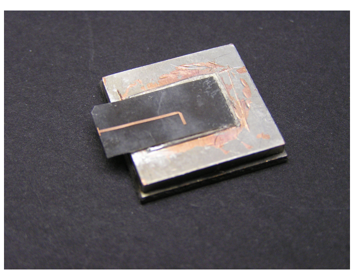
Not Just Circuits - Integrated Antennas

In-Package and On-Wafer Antenna Designs

- Compact, efficient designs for imaging, phased arrays
- Cavity-backed dipoles demonstrated at Ka band for in-package integrated antennas
- High directional gain (10 dB) obtained; 6 dB improvement over theoretical optimum for planar dipole
- At W-band and above, design scalable for on-wafer integration



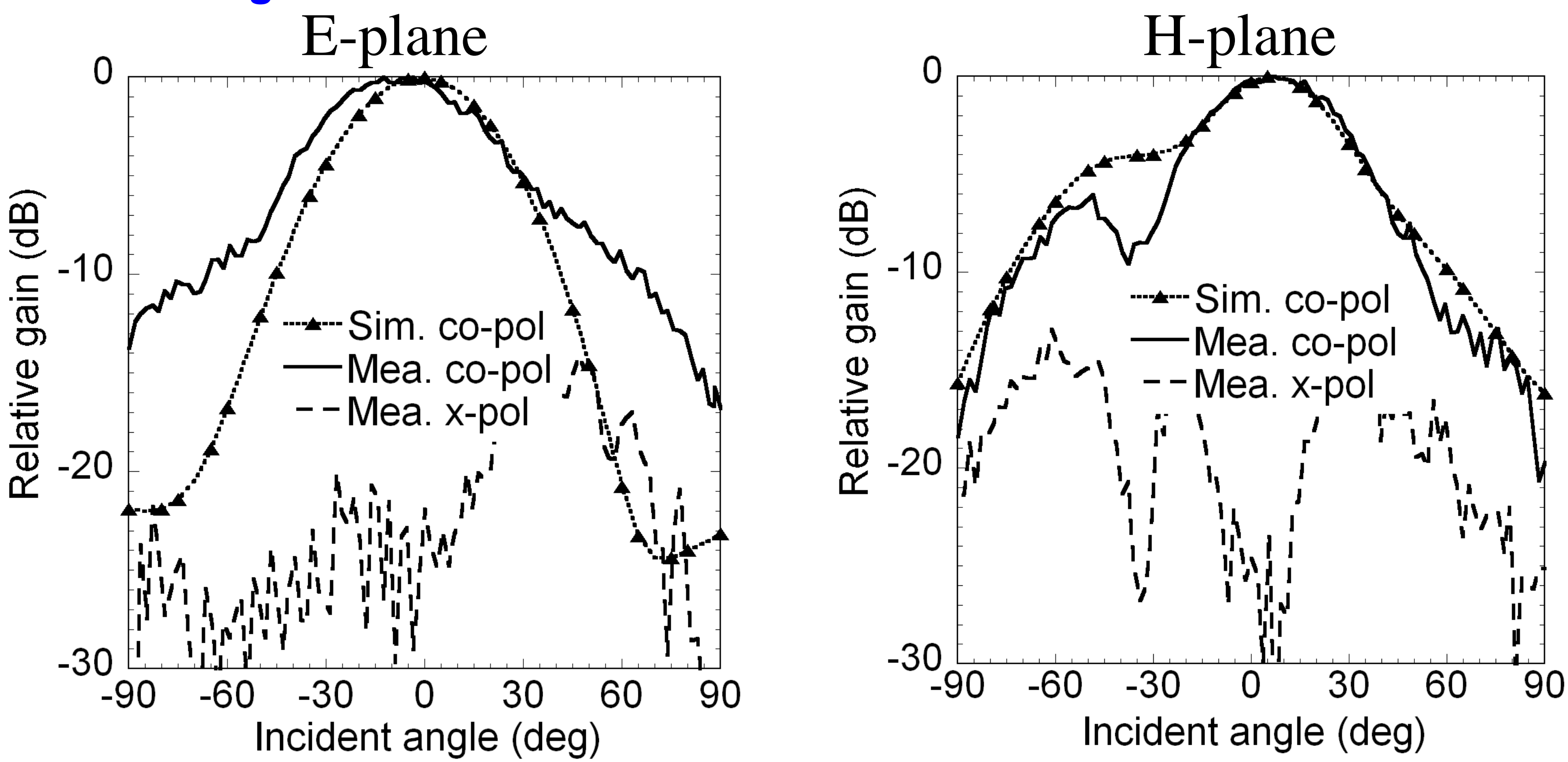




Z. Sun et al., IEEE Antennas and Wireless Prop. Lett., vol. 5, pp. 459-461, 2006.

Radiation Performance

In-Package Ka-band Antenna Performance

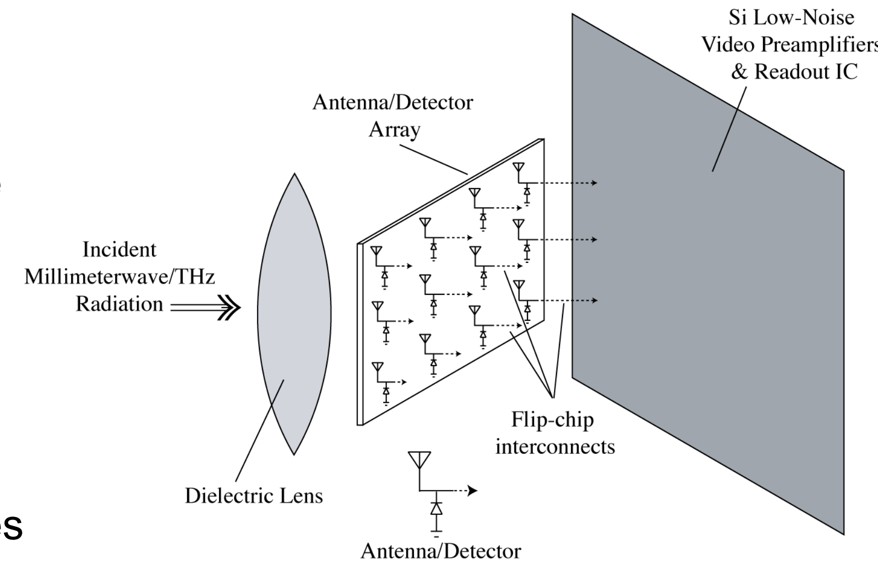


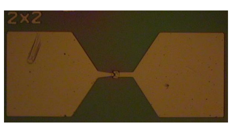
- 3D electromagnetic simulations indicate similar performance possible through W-band

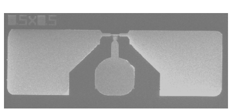
New System Concepts

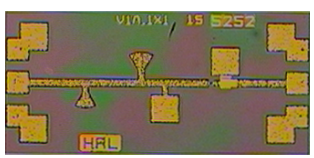
Imaging:

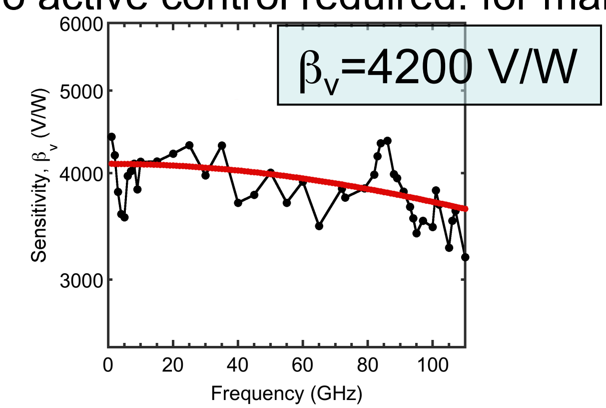
- Focal plane array, pupil-plane arrays
- Direct detection: “rectification” of mm-wave incident radiation, producing DC output
- High integration level for parallel receiver chains (MMIC)
- High instantaneous detection bandwidth; f_c > 800 GHz
- No bias required
- Lower 1/f noise than competing technologies
  - Reduced/eliminated LNA requirements
  - Reduction in cost, size & weight
- Insensitive to temperature - no active control required: for many applications, no cooling required

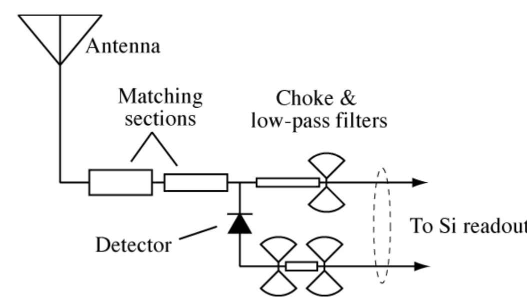






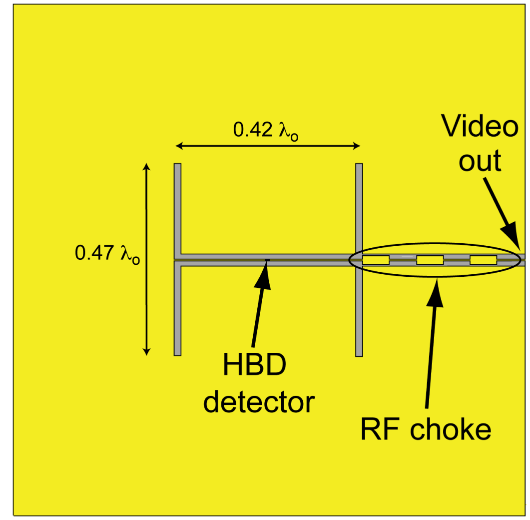


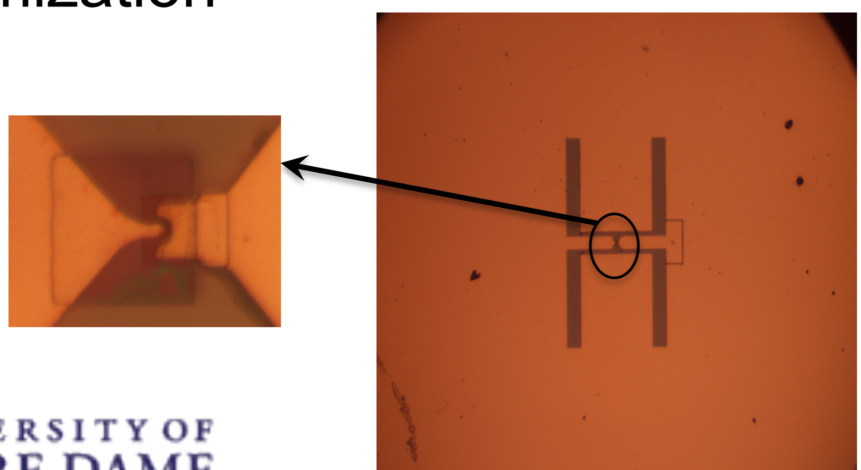


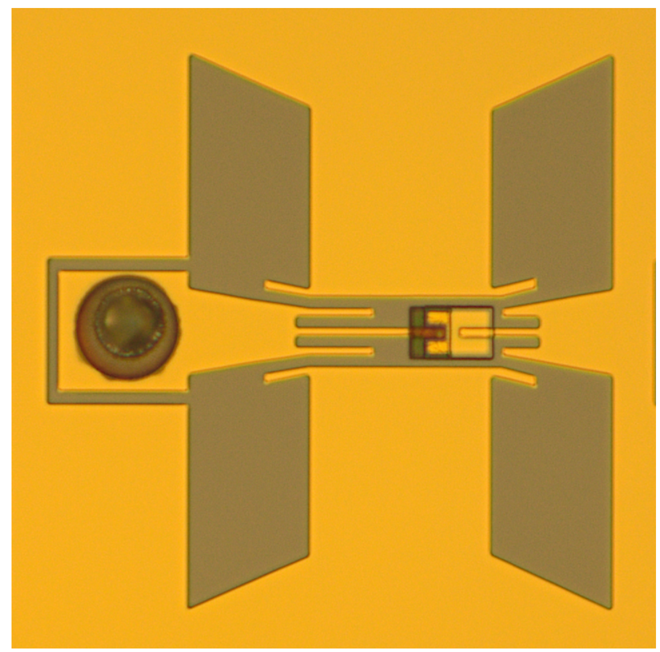


Integrated Pixels

- Low NEP enables passive focal plane array
- Monolithic antenna/detector integration demonstrated
- Versions with & without impedance matching tested to > 600 GHz
- > 20,000 V/W possible with optimization







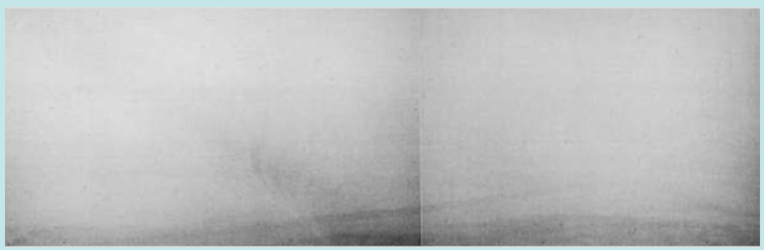
UNIVERSITY OF NOTRE DAME

Why Millimeter-wave/THz Imaging?

Avionics:

Visible, clear day

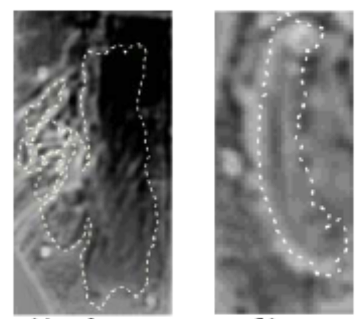
A little foggy



W-band image in fog

Security:

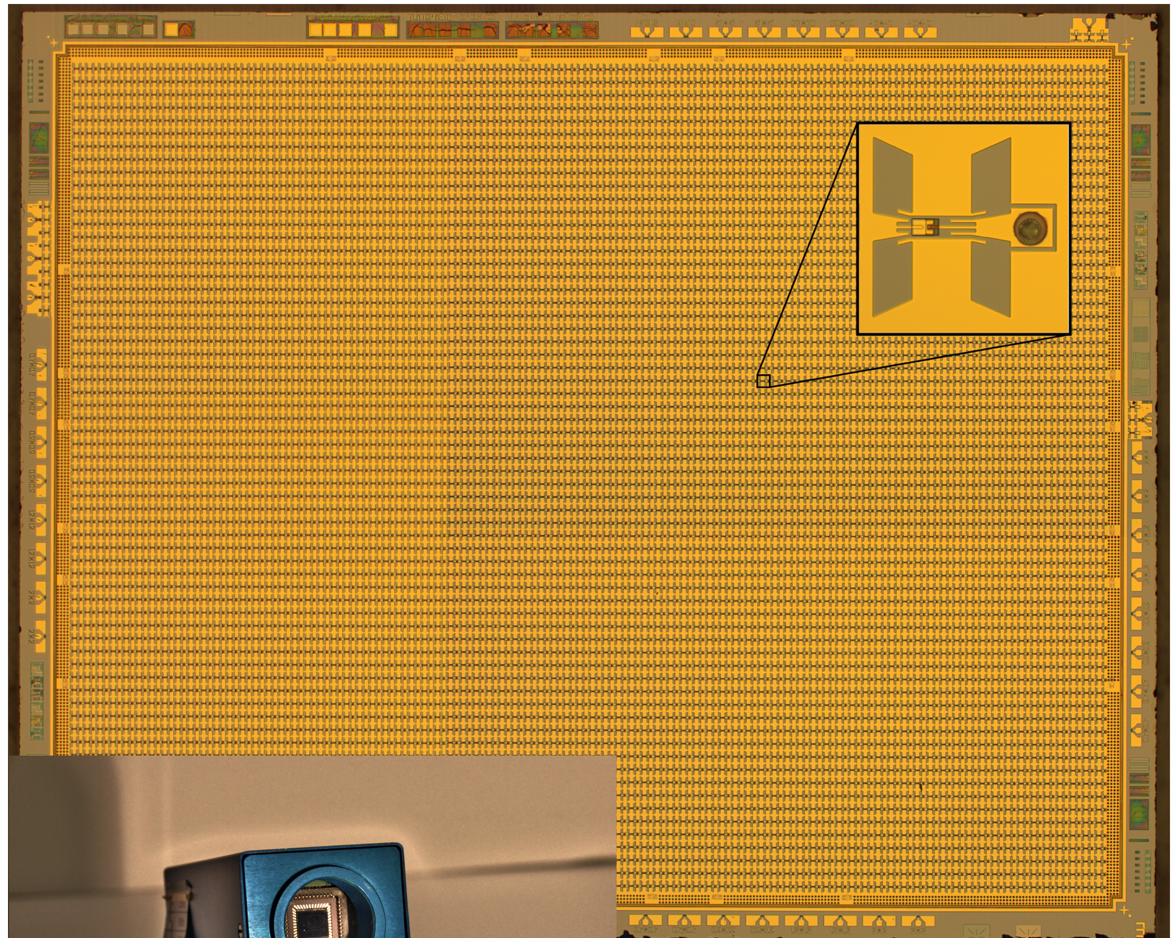
Medical:

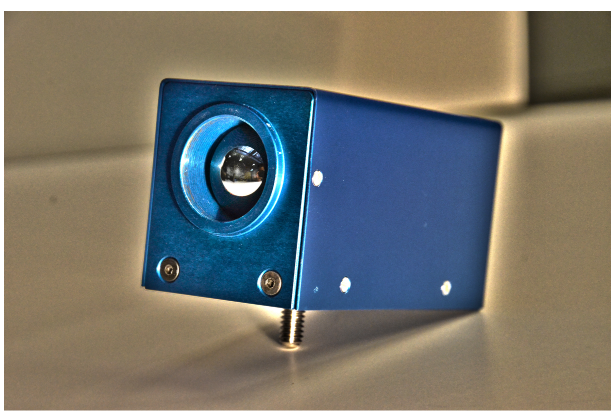


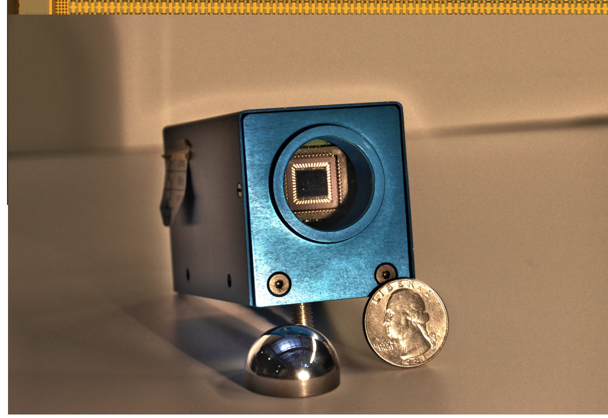
(a) melanoma (b) nevus

A Focal Plane Array…

- 80x64 pixel array
- Integrated into camera







Up Next—Some Definitions

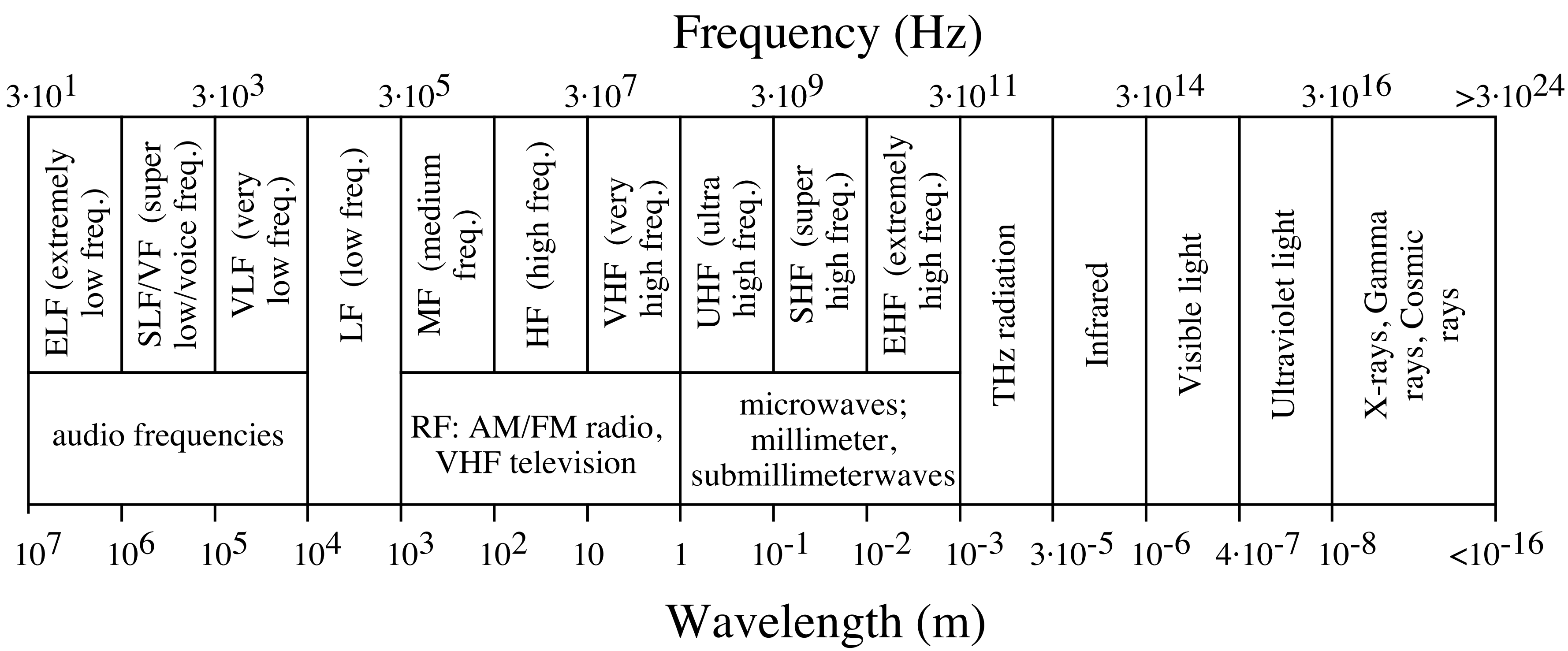
- Our focus is communications systems—so a few definitions
- All wireless systems work by broadcasting a signal, which propagates as electromagnetic waves before being picked up and reconverted into useful signals
- We're going to focus on electronics for the transmit and receive side; generating the data, etc., is somebody else's problem
  - In modern systems, nearly always digital signal processing; more code than circuit design

Frequency Bands

- Important to have a handle on what bands are used for what purposes; cell phones ≠ satellite uplinks ≠ GPS ≠ …
- And there are things that are not communications that we have to worry about too—radar, microwave ovens (i.e., kW transmitters at 2.45 GHz)
- To keep all of this straight, “standardized” band designations have been developed—sort of

Frequency Bands

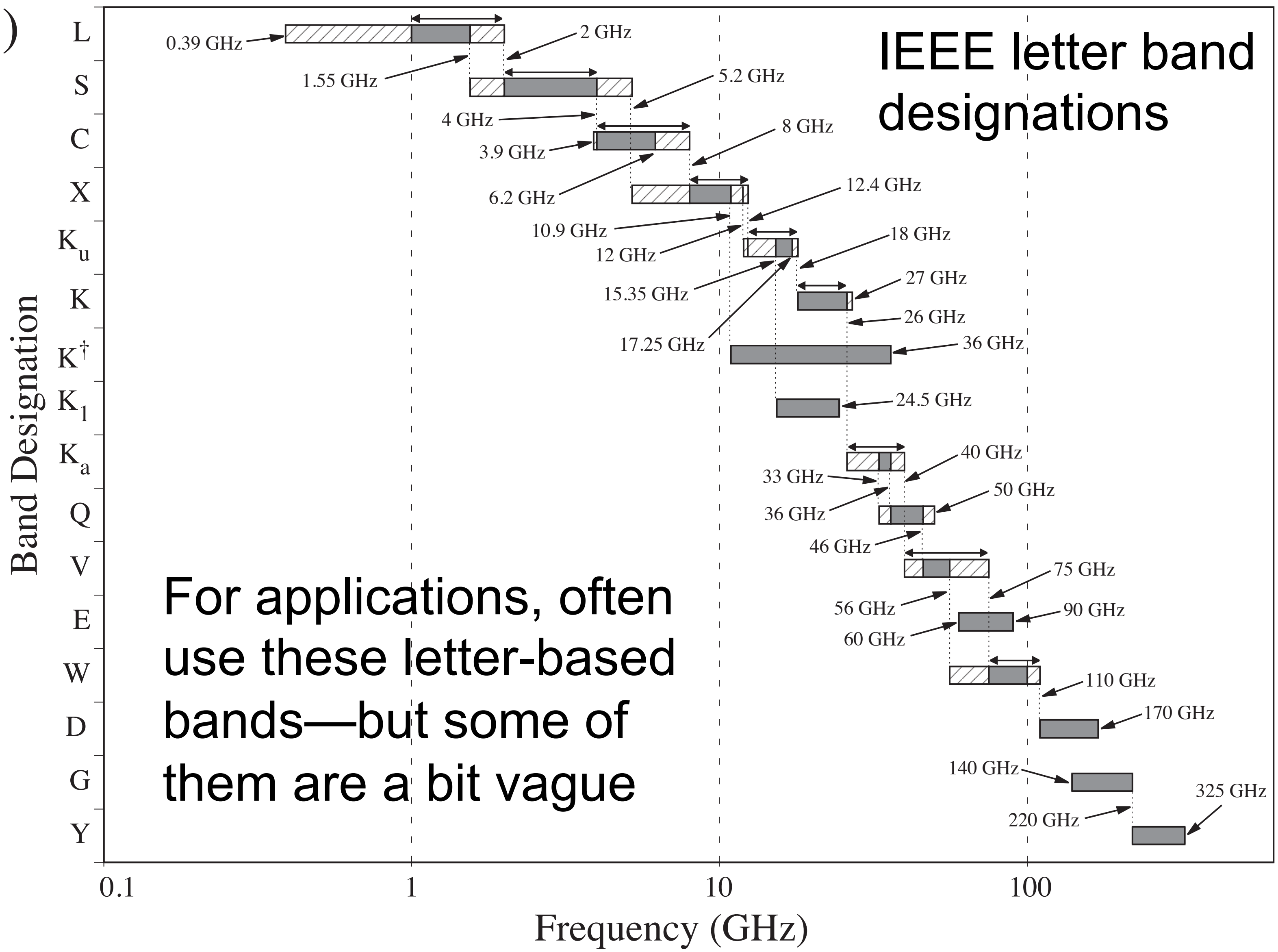
One pretty common set of labels:



But these categories are too broad for many uses

Frequency Bands

a.)



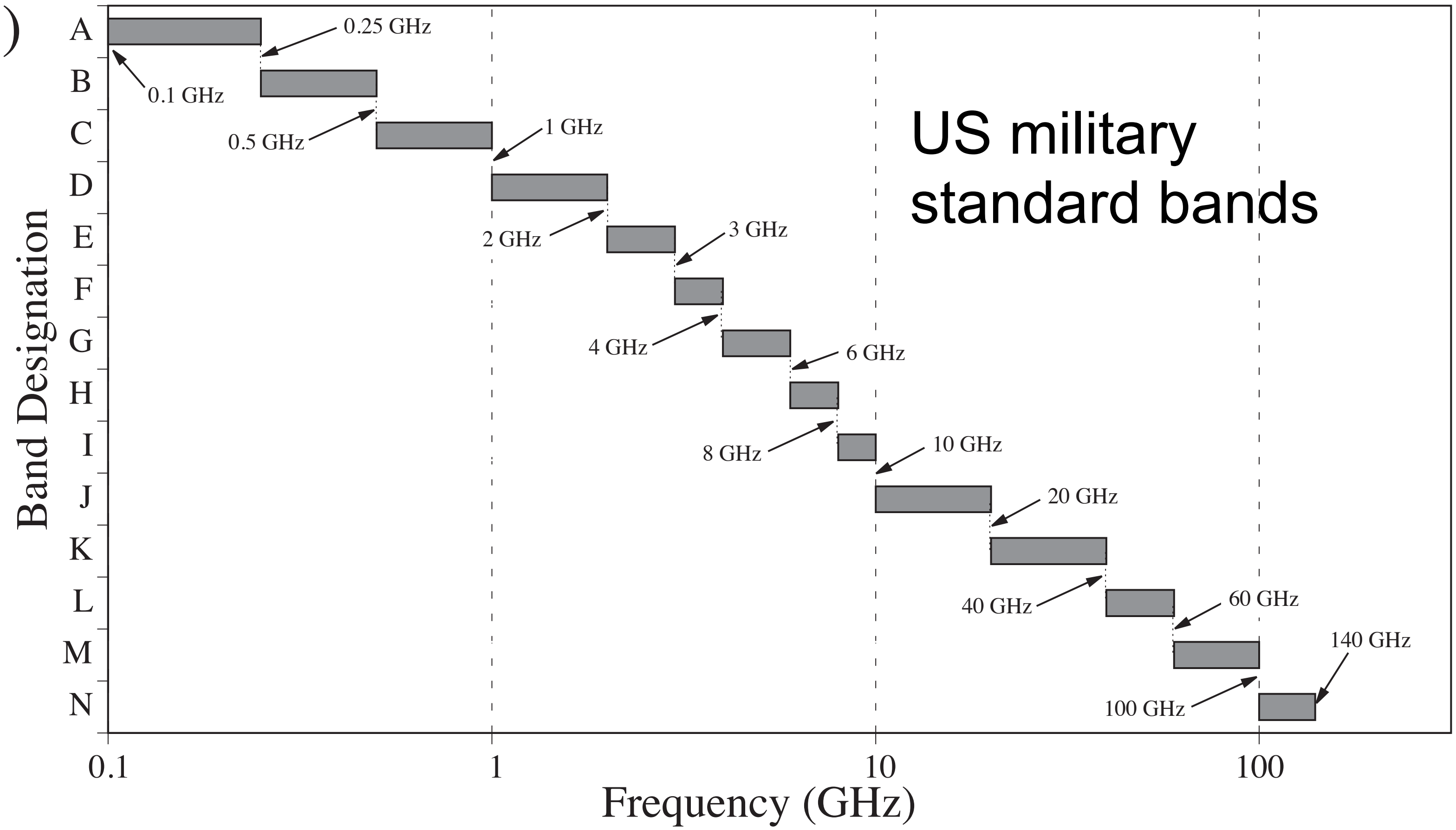
IEEE letter band designations

For applications, often use these letter-based bands—but some of them are a bit vague

Frequency Bands

And of course they don't agree with other "standard" designations:

b.)



Bottom line: standards aren't really—context matters.

Administrative Wrap-Up

- Be sure you're registered for the course and lab (40458 and 41458)
- **No class on Thursday**
- **No lab this week, no lab next week**
- Thursday lab is too crowded—would Tuesday work?
- Plan is to have class again (by Zoom) on Tuesday (this time, from Brazil). After this, back to "normal."
- **Question:** would it be possible to "stretch" classes by 10 minutes (2:00-2:50 → 2:00-3:00)? If we do this, we can recover from my stupid travel schedule without make-up classes. I will follow up with email—if this is a problem, be sure to let me know