RF & Microwave Circuits for Wireless Communications

8/10/2020

- Welcome!
- Agenda today:
  - Introductions
  - Course overview, what's in it for you
  - Review of syllabus & lab stuff, key details
  - And on to the technical material

Introductions

- 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
  – I am happy to meet in person, by zoom, …

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

Lab Component

- The lab work cuts across these topics
- Focus mostly on measurement techniques & design; some circuit construction
  - **Make sure you're registered for both lecture and lab** (40458 and 41458)
- 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
- **We need to adjust the lab sections: please remind me if I forget to bring this up again later…**

Syllabus

- Heidi has two handouts- syllabus and lab policy
- Walk through a few key parts—this course is not "normal" in a few important ways…

EE 40458 | **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, and additional material is also available on Sakai. Some of the material is also available at http://www.nd.edu/~hscdlab (but Sakai is more complete)

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. 10 laboratory sessions)
1. High frequency performance of circuit components
2. Measurement basics; reflectometry, spectrum analysis
3. Vector network analyzer operation and error correction
4. Scattering parameter measurements of active devices
5. Matching network design, fabrication, and characterization
6. Project design, layout, construction, characterization, and analysis
7. Nonlinear characterization of active circuits; intermodulation and compression
8. Noise figure measurement of amplifiers

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

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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, transmission lines. Introduction to ADS microwave CAD software.
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Labs and Design Project

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

Laboratory and Design Project: (approx. 10 laboratory sessions)
1. High frequency performance of circuit components
2. Measurement basics; reflectometry, spectrum analysis
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7. Nonlinear characterization of active circuits; intermodulation and compression
8. Noise figure measurement of amplifiers

- Labs are a mix of "normal" labs (follow a procedure to learn a technique) and "design" labs that are open-ended
- The "Lab page" in Sakai has guide sheets for each lab, and a *tentative* schedule
- Read the guides **before** lab
  - Watch the lab videos before lab too; some stuff is easier show than write about
- 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

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

Sakai and course web site has some useful stuff on it

- Homeworks will be posted in Sakai (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."

Lab Administrative Stuff

- Lab starts next week (Aug. 19-20)
- Advance preparation is required
  - Go to the “Lab page” section of the Sakai site
    - Get the handout, and read it before lab
    - Watch the video
  - Read the Lab Policy and Notebook Guidelines document
- Bring a lab notebook, ready to go, to the lab – you **must** have this for your first lab.

Lab Policy Overview:

Please read (really!)

We do not run the lab for this course like a normal lab class.

EE 41458 | **RF and Microwave Circuits for Wireless Communications Laboratory**

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

Laboratory Policy:
1. Attendance at all scheduled labs is expected; the instructor should be informed of any conflicts or issues in advance so that suitable arrangements for an alternate time can be found.
2. Be on time–the beginning of each lab session will contain a brief discussion and important notes regarding the lab to be performed.
3. An engineering notebook must be kept. The specific format and guidelines are outlined below.
4. Notebooks will be collected several times (possibly unannounced) during the semester, and after the final exam.
5. No eating, or drinking is permitted at the test benches in the microwave measurements lab.

Notebook Guidelines:

An engineering notebook is intended to act as the engineer's diary of ideas, theories, measurements and results, comments, and any other details related to the work being done. Notebooks are to be kept such that a technically literate person not specifically involved in your work could duplicate the work at a later time.

For this class, **the notebook does not consist of a collection of formal lab reports–there are no such reports for this class**. The notebook itself is the final product of the course, and most of the work on the notebook should be done during the lab period as you are doing the work.

Notebook Requirements:
1. You must include **all** data in your notebook –using separate sheets of paper for data collection ***is not permitted***. Be sure to include units with all measurements. Securely fasten any plots, graphs, or computer-generated tables in the notebook with tape or glue so that they cannot fall out.
2. The notebook must be bound, with consecutively numbered pages.
3. The first page or two should be set aside for use as a table of contents; add entries to the table as appropriate, including a label, range of page numbers, and date for a particular section or experiment.
4. All entries must be in ink. If an error is made, cross out the error with a single line, and continue. **Do not erase or obliterate errors**. Be neat enough so that others can follow what you are doing.
5. The entries in an engineering notebook must be consecutive–**you may not leave blank spaces for later entries**, or insert or remove pages. A line should be drawn through any blank space remaining on a page.
6. If you find that you have made an error on a previous page, do not return to that page and make corrections. Instead, leave the original erroneous entries as they are, and make a note on the current page as to the nature of the error, and include any corrections or new measurement data.
7. You may use both sides of the page or front sides only at your discretion, but be consistent throughout the notebook.
8. Please include sample calculations when they will enhance the clarity of your notes, but the decision as to how much detail to include is up to your own judgment.
9. For computer coding or simulation-based work, be sure to document your thoughts, plans, and intermediate results **as you go along**. This will help enormously if problems come up.
10. Each section in the notebook should begin on a new page, and should follow the following general format outlined below. This is not a report, but note that these steps form an orderly progression through a typical laboratory experiment; each of these steps should be completed before going on to the next step.
    - Title of section
    - Brief statement of the purpose of work to be performed
    - Equipment set-up, including equipment type and models, block diagrams of equipment configuration
    - Measurement and other procedures, including calibration procedures if applicable
    - Measured data and results
    - Analysis, discussion of applicable theory, and summary

Lab Policies & Procedures

- Show up on time. If “something comes up,” let me know in advance so that we can work something out
- Notebooks:

  The notebook is an important part of the lab. **Read and follow the guidelines.**

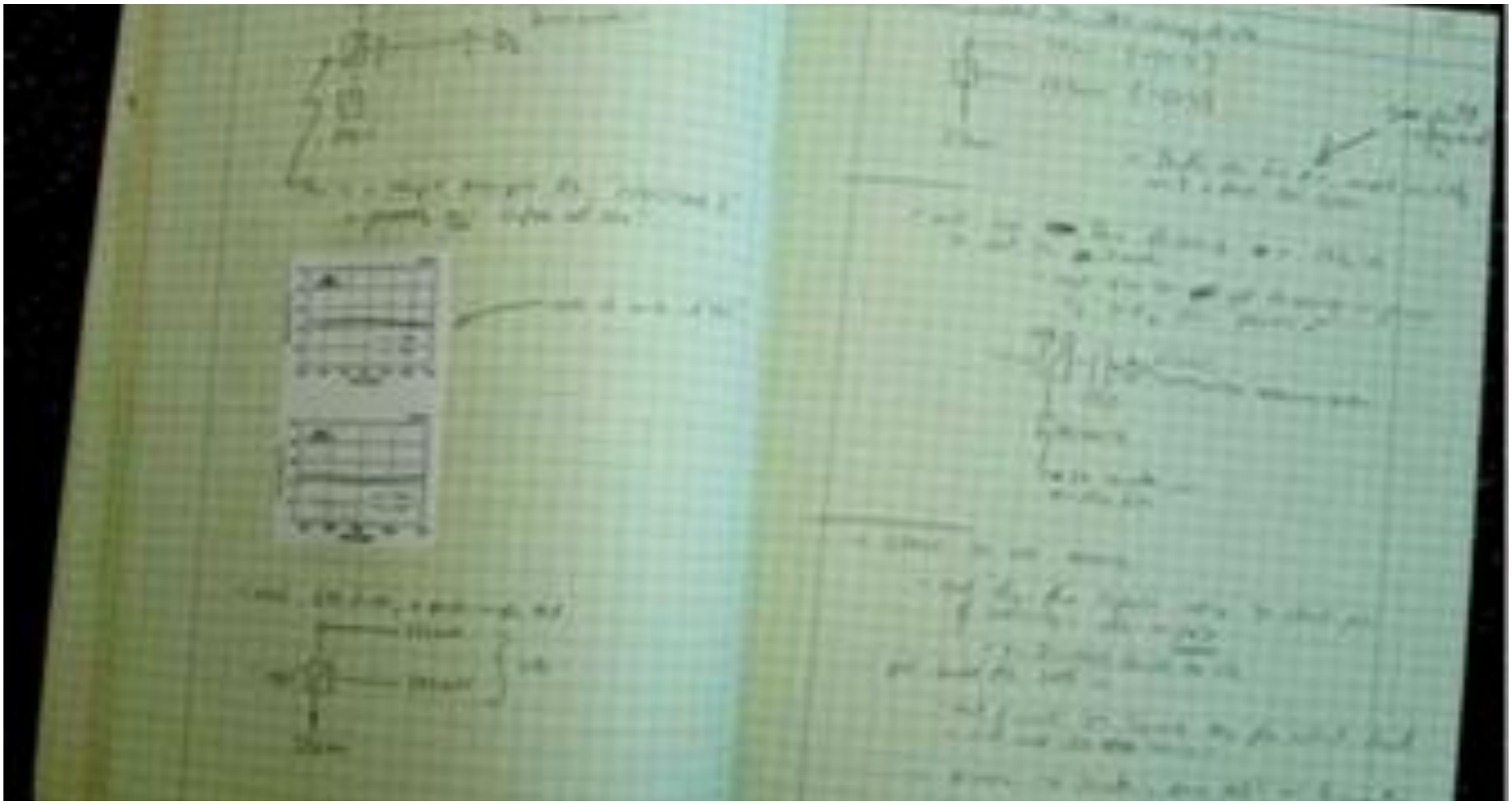
  - **The notebook is not a collection of reports**. It is a “working document” that you use to keep track of what you did, the data you collected, etc.
  - Leave a couple pages at the front for a table of contents
  - All data goes in the notebook. **No scrap paper. No re-copying data over.** Record the data as collected.
  - Must be bound; then number the pages
  - All writing in ink. Mistakes are ~~crossed out lightly~~. No erasing, no white-out, no obliteration.
  - No leaving blank space. If you’re going to include a graph (to be made in the future, for example) say so, then put the graph at the end.

Lab Policies & Procedures (cont.)

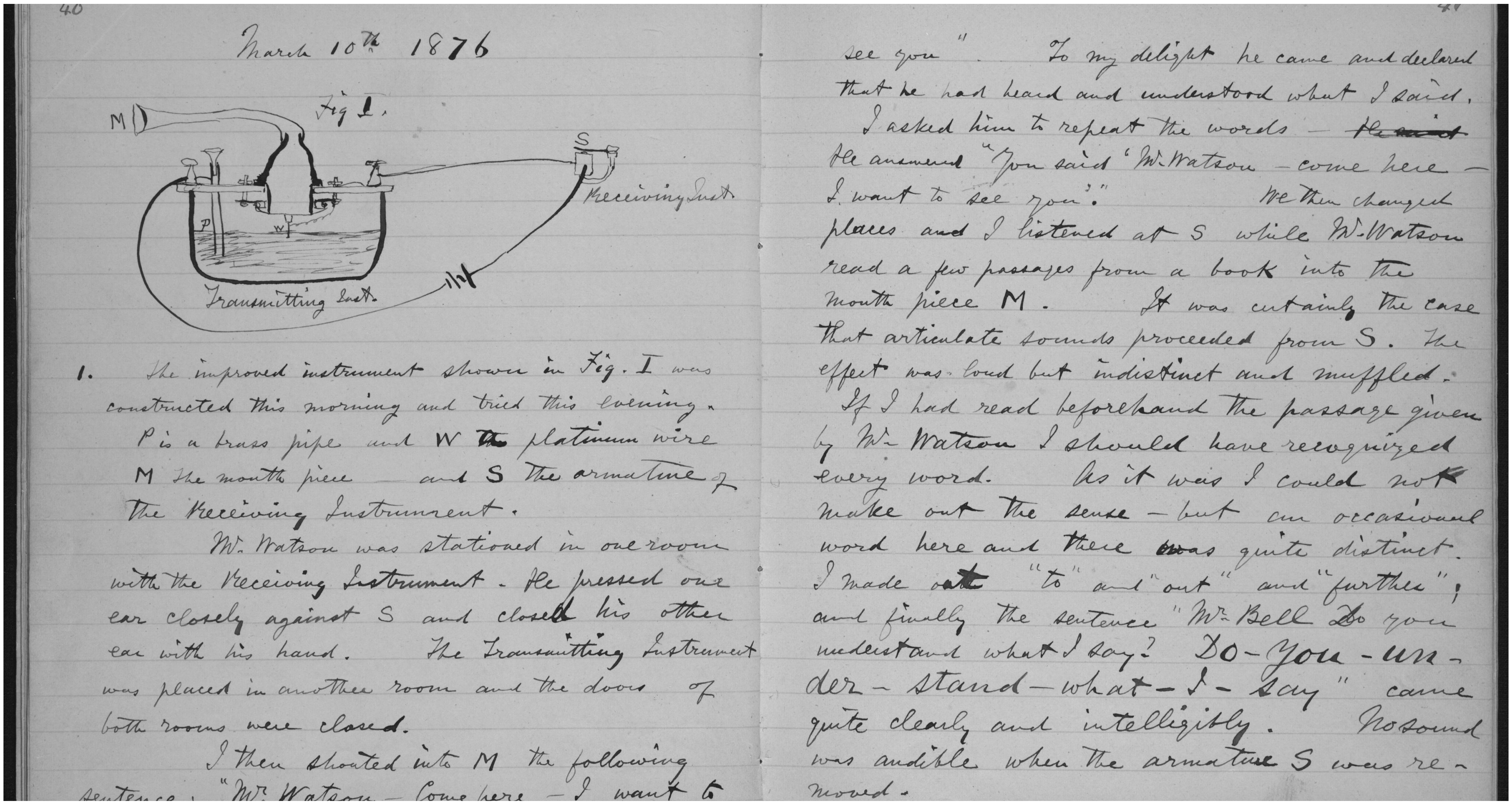
- Notebooks (cont.):
  - If you realize you made a mistake on an earlier page, no problem. Just leave the original (wrong) data as it is. Make a note of it (where you are in the book) and enter the corrections.
  - Include derivations or example calculations to illustrate your thought process.
  - **For computer simulations, code writing: take notes as you go.** It'll help you debug when things go bonk.
  - Each section of the lab should start on a new page, with a few remarks at the beginning to set things up:
    - Title
    - Purpose of the work
  - Then switch to a "narrative" format where you document your work **as you do it**:
    - Set-up of the equipment/experiment, software, etc.
    - Measurement or experimental procedures, design process and goals
    - Measured data, results
    - Analysis

➢ **READ THE LAB POLICY DOCUMENT AND FOLLOW IT**

An example:



Another example:



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March 10th 1876

Fig. 1.

M — S — Receiving Inst. — P — W — Transmitting Inst.

1. The improved instrument shown in Fig. I was constructed this morning and tried this evening.

P is a brass pipe and W ~~the~~ platinum wire M the mouth piece and S the armature of the Receiving Instrument.

Mr. Watson was stationed in one room with the Receiving Instrument. He pressed one ear closely against S and closed his other ear with his hand. The Transmitting Instrument was placed in another room and the doors of both rooms were closed.

I then shouted into M the following sentence: "Mr. Watson — Come here — I want to

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see you". To my delight he came and declared that he had heard and understood what I said.

I asked him to repeat the words — ~~He said~~ He answered "You said 'Mr. Watson — come here — I want to see you.'" We then changed places and I listened at S while Mr. Watson read a few passages from a book into the mouth piece M. It was certainly the case that articulate sounds proceeded from S. The effect was loud but indistinct and muffled.

If I had read beforehand the passage given by Mr. Watson I should have recognized every word. As it was I could not make out the sense — but an occasional word here and there ~~was~~ quite distinct. I made out "to" and "out" and "further"; and finally the sentence "Mr. Bell Do you understand what I say? Do — you — un-der — stand — what — I — say" came quite clearly and intelligibly. No sound was audible when the armature S was removed.

Questions on Administrative Stuff?

- On to technical discussion…

RF and Microwave Circuits for Wireless Communications

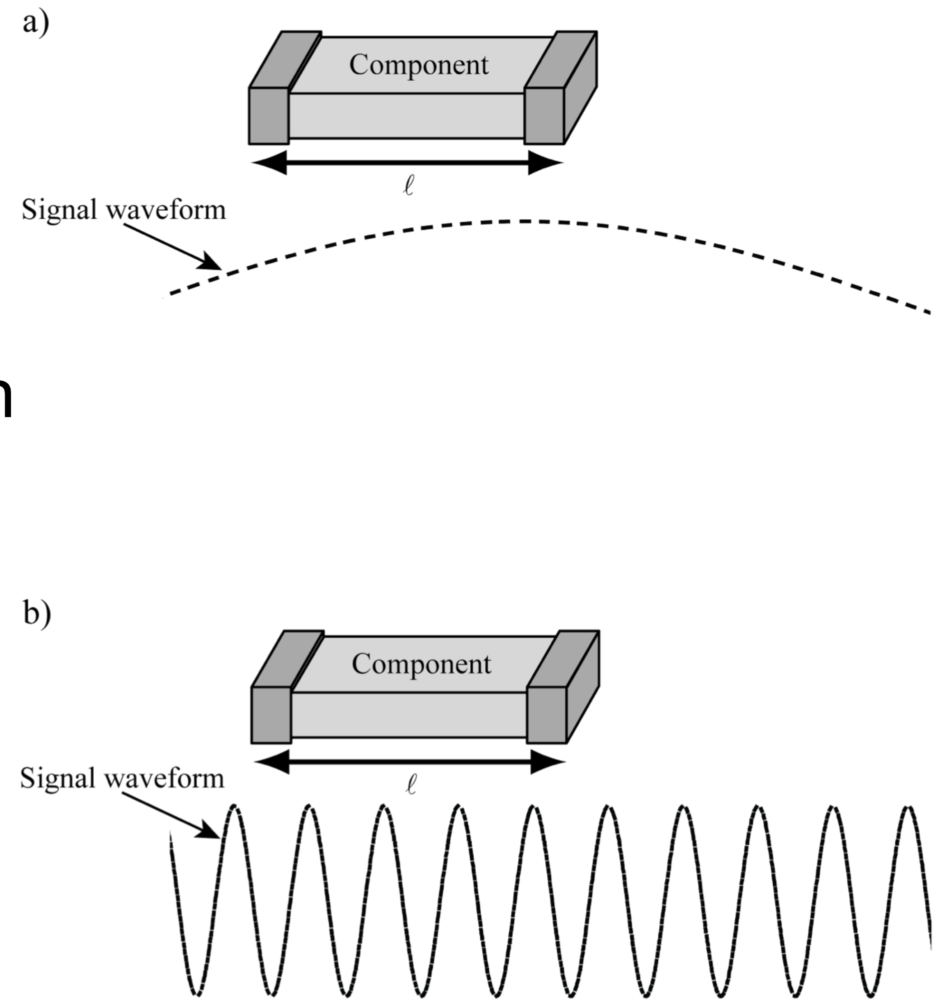
- Modern wireless communications relies on high-performance, high-frequency circuits
- Lots of other applications do too…
  - Radar
  - Medical therapies (RF-induced hyperthermia treatments for cardiac arrhythmia)
  - Imaging for avionics, security (airport scanners, theft prevention at warehouses)
  - 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

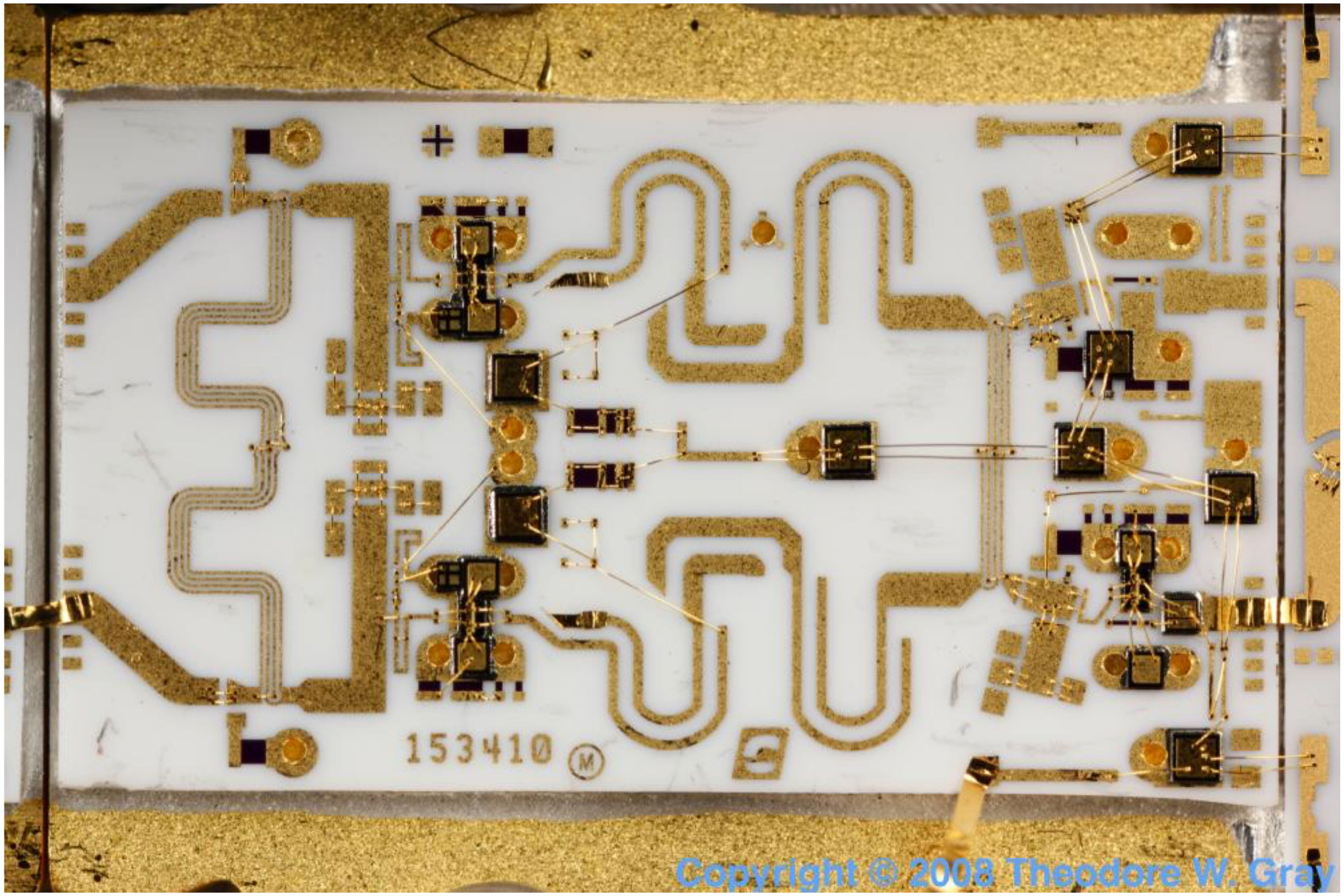


Conclusion: “nodes” aren’t nodes anymore…

- 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)

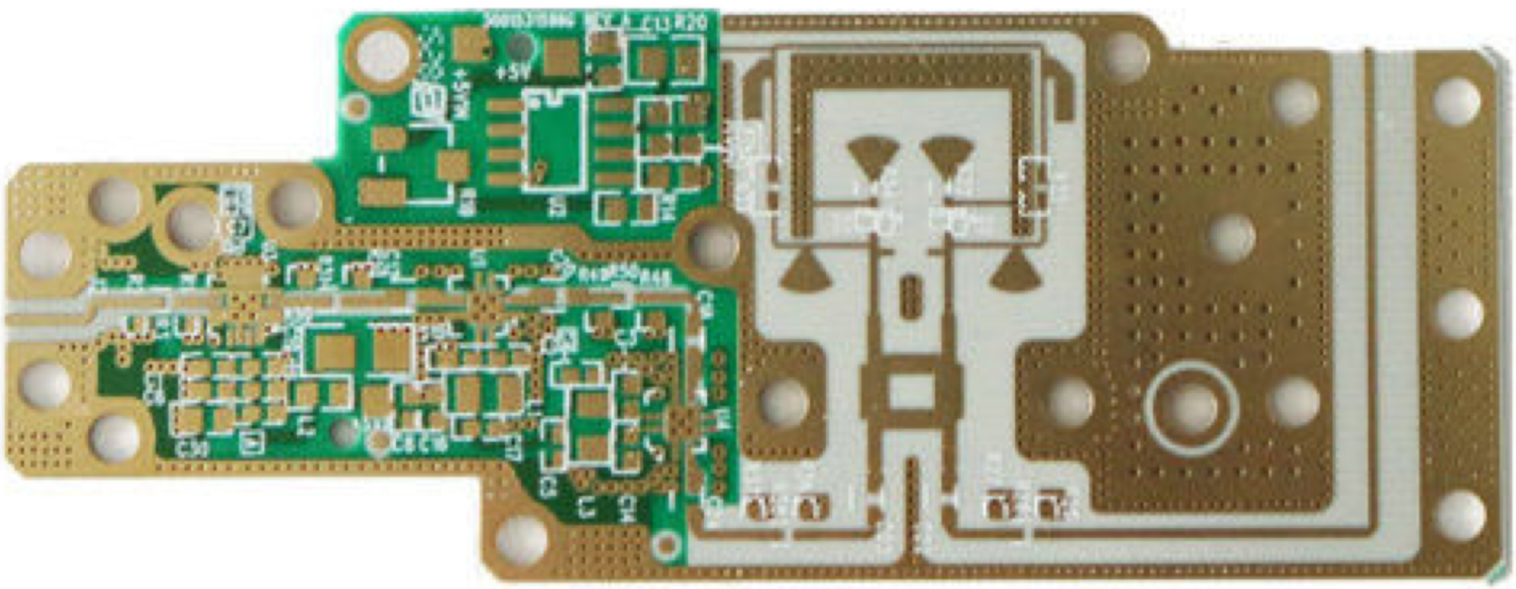
Board-level

- A few examples…GaAs FET amp

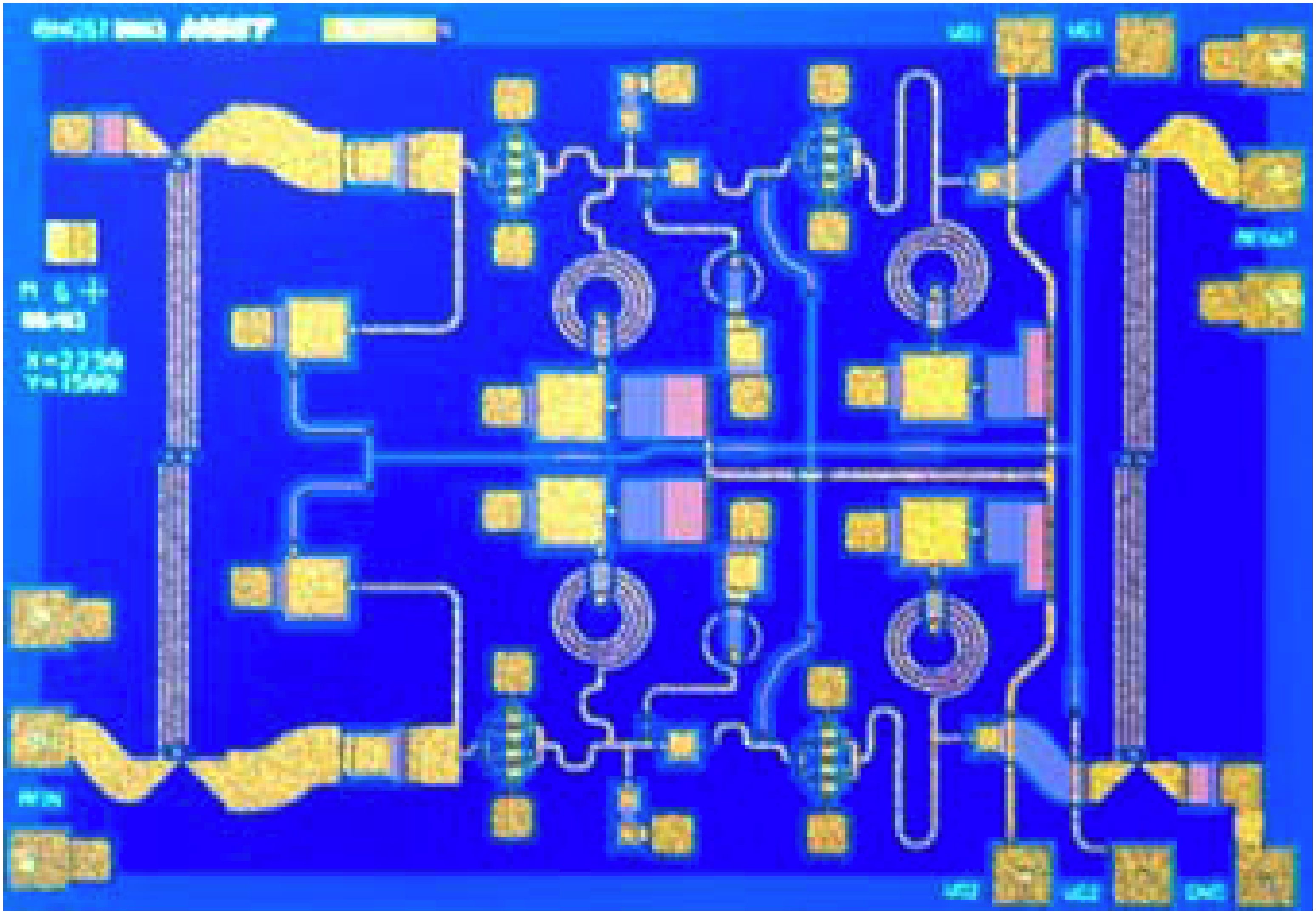


Board-level

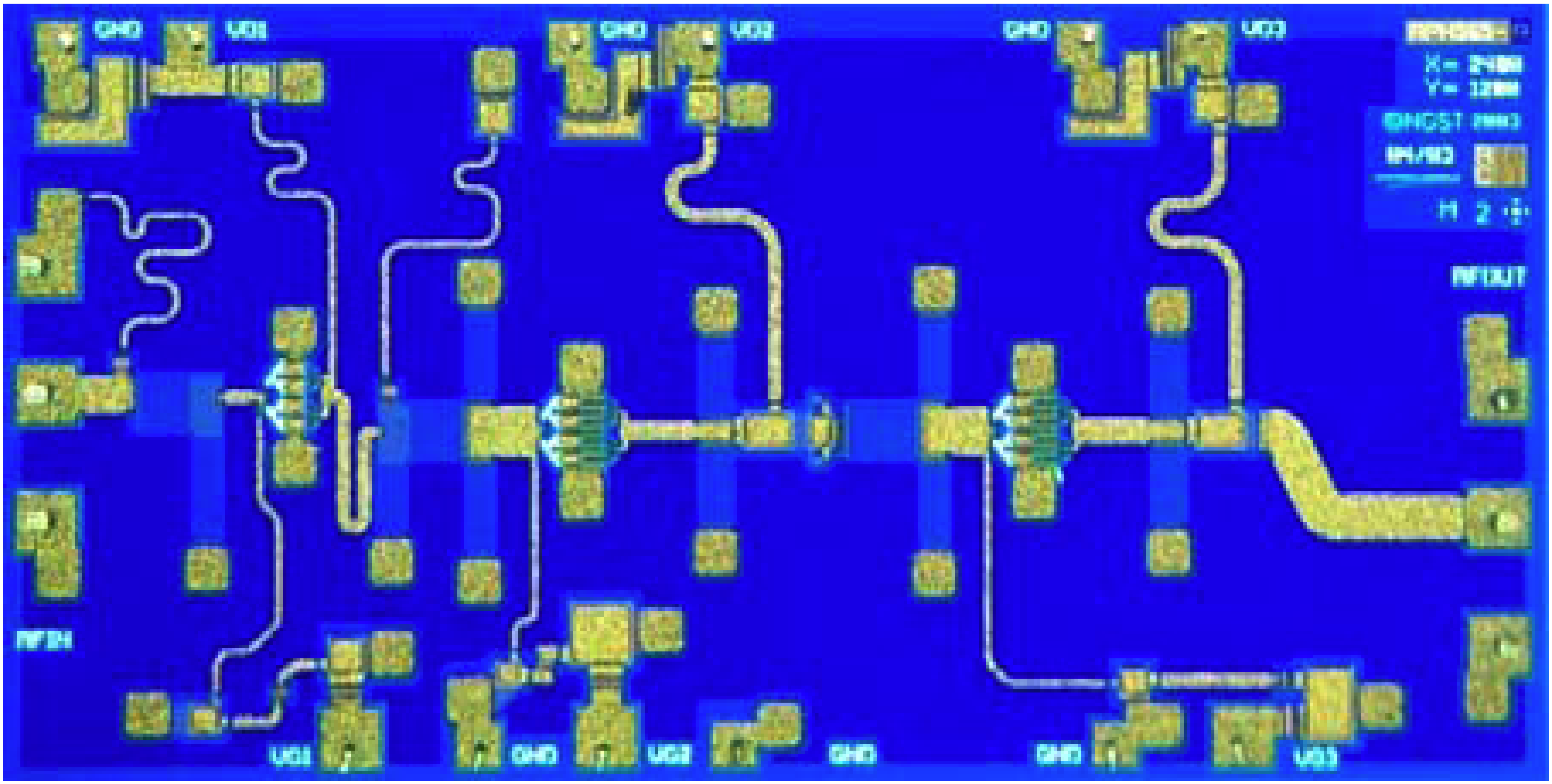
- A few examples…Coupler & splitter, plus a few other things…



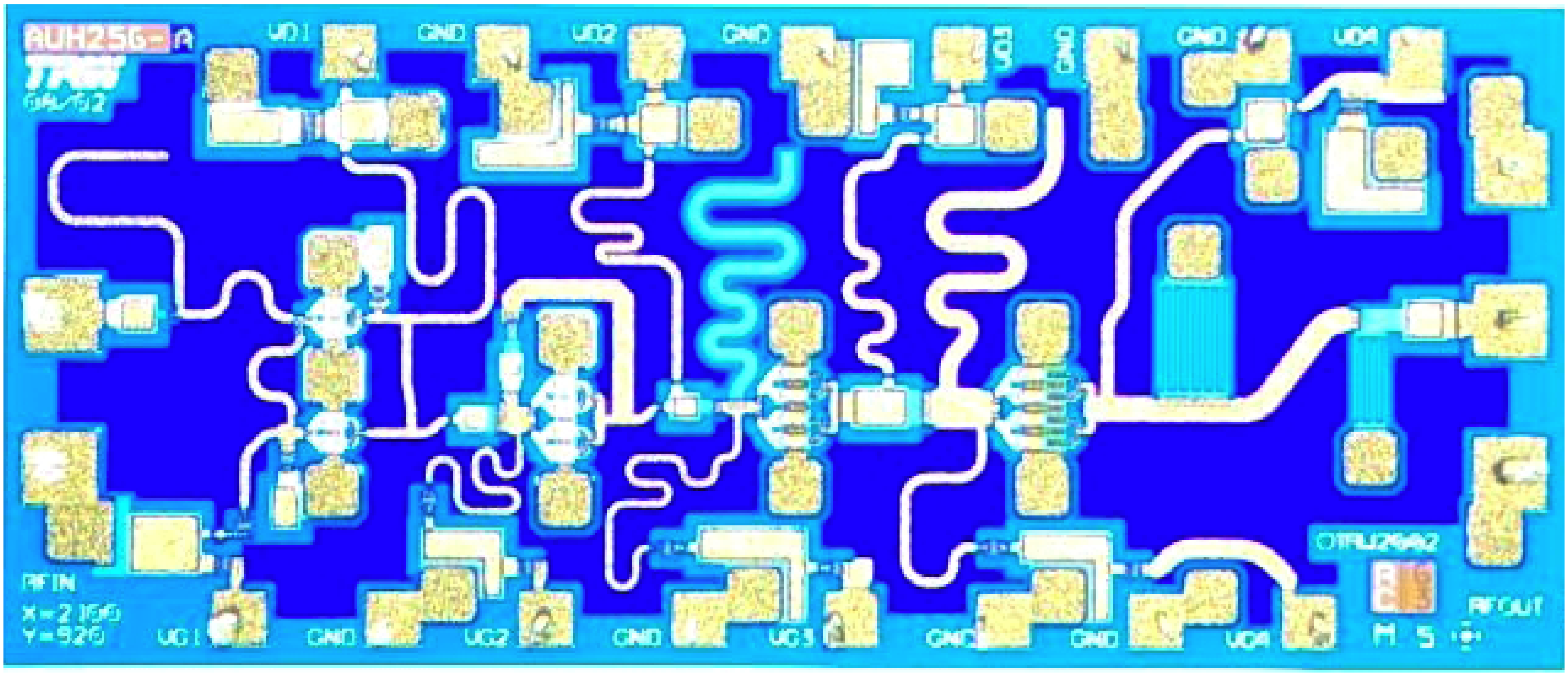
And on chip:
14-27 GHz Low Noise Amp



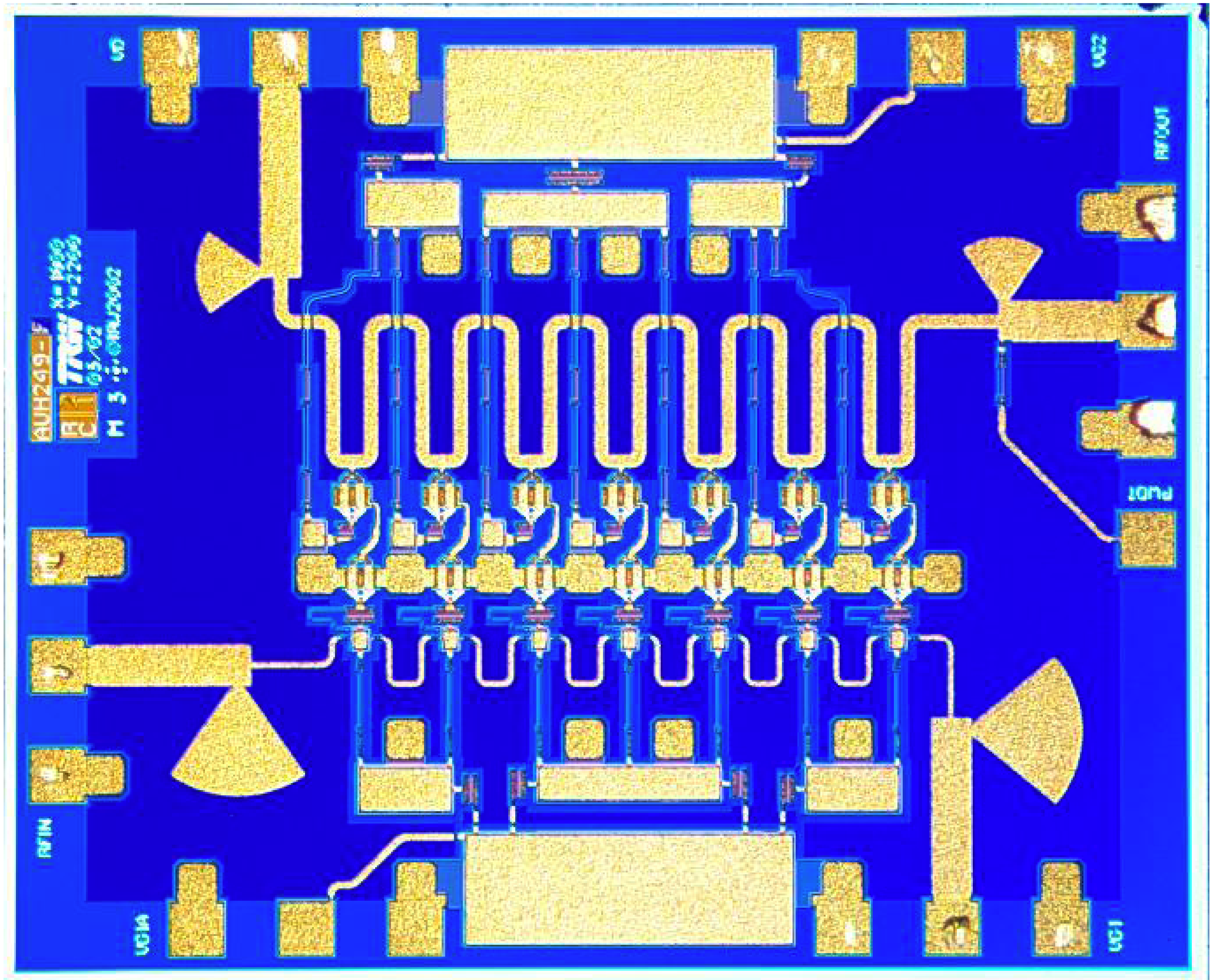
43-46 GHz Medium Power Amplifier



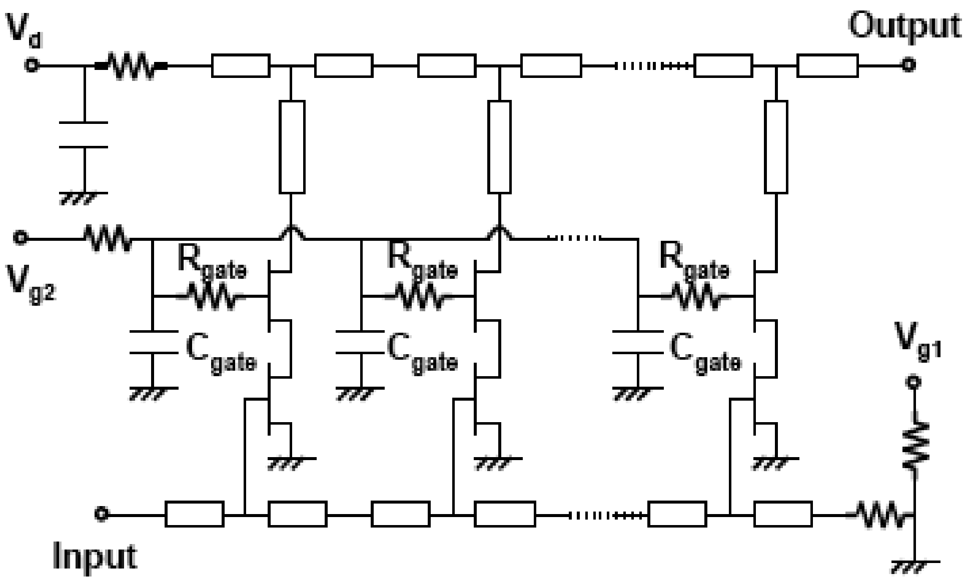
17.5-41 GHz Broadband amp

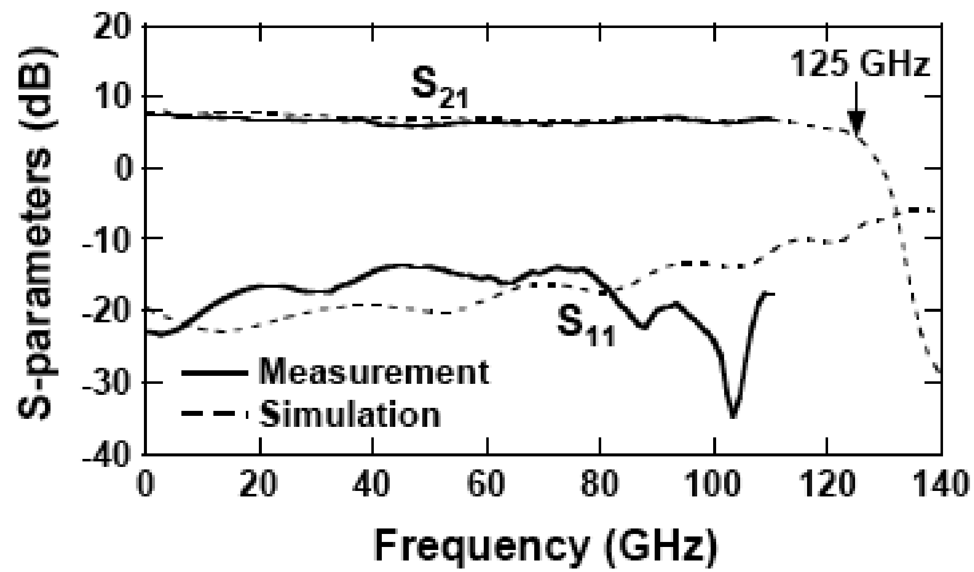


Distributed Amp - DC-35 GHz



“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*

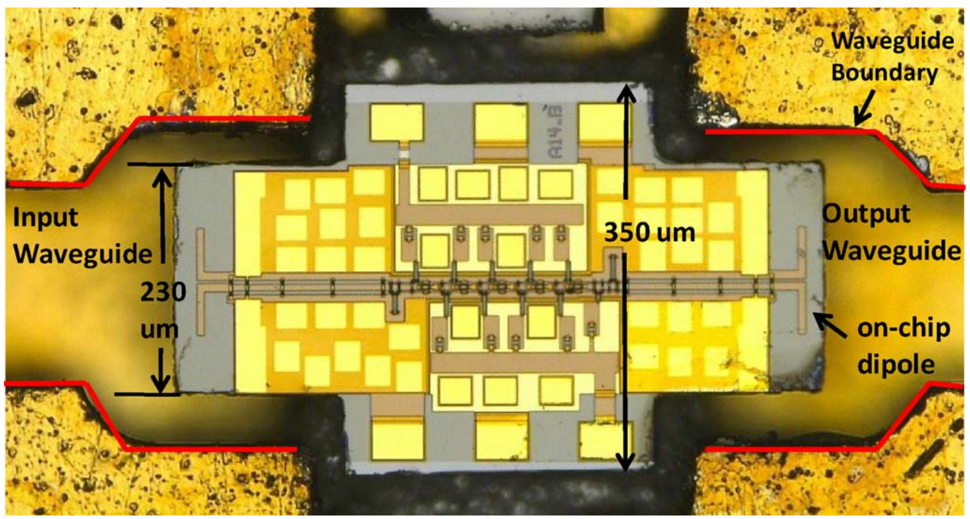


Fig. 1. Microphotograph of 670 GHz LNA in split block housing.

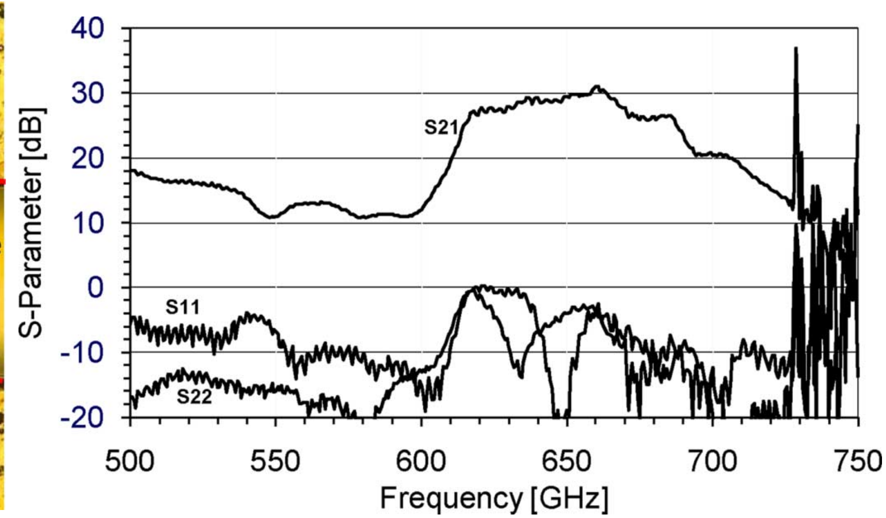
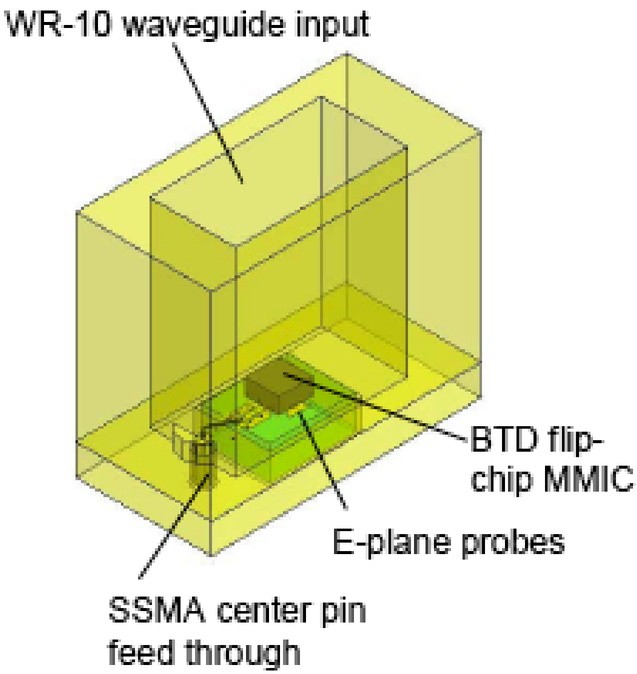
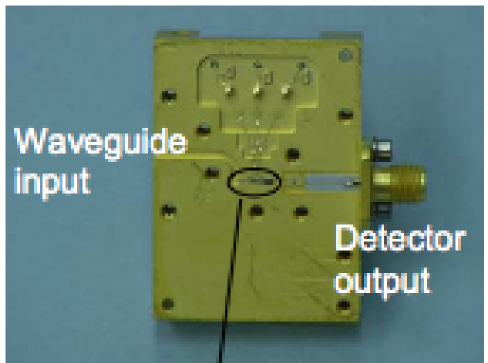


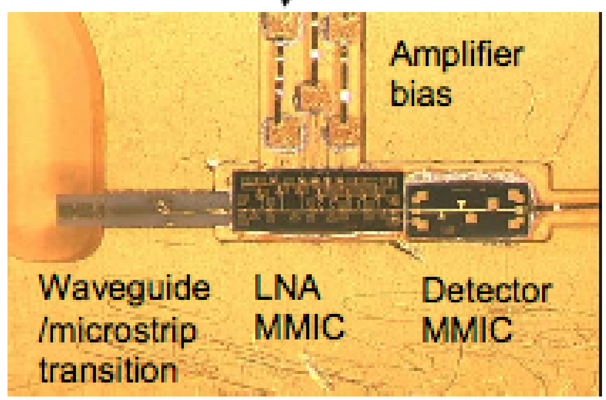
Fig. 6. Measured on-wafer S-Parameters of 10-stage LNA.

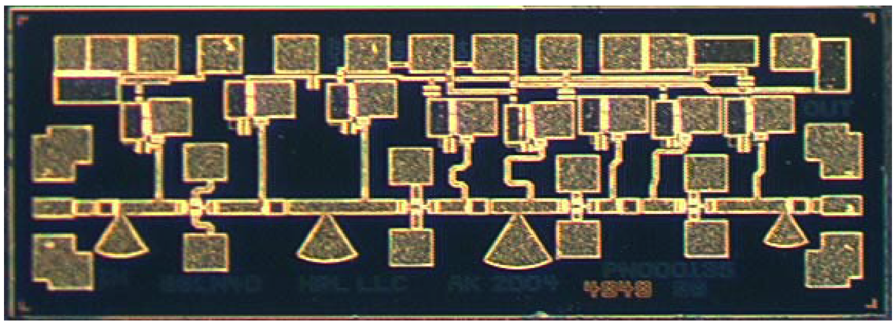
Everything still "works" to 670 GHz…and transistors over 1 THz have been demonstrated. Maxwell's equations are just fine…

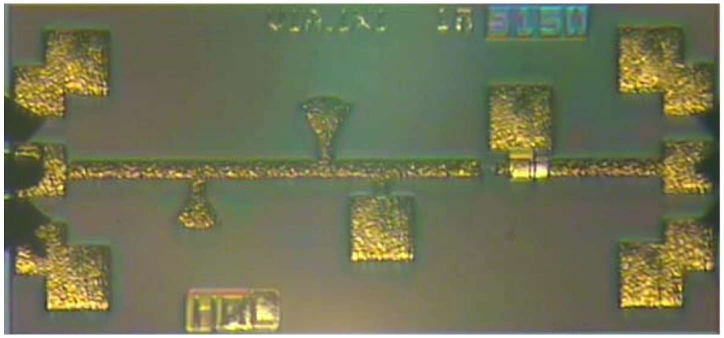
Not just amplifiers – detectors (example: 94 GHz)







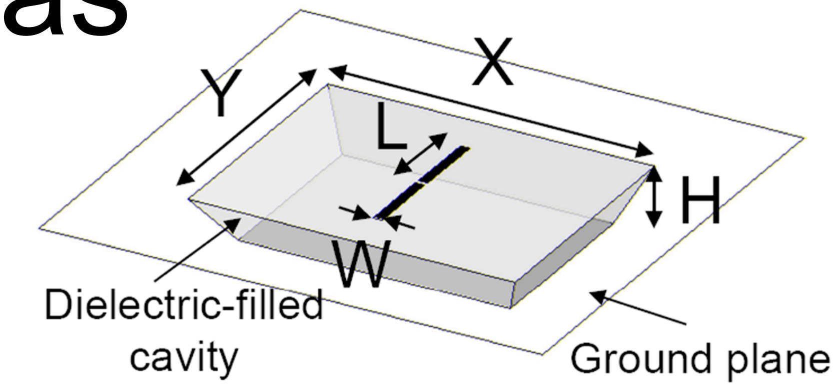


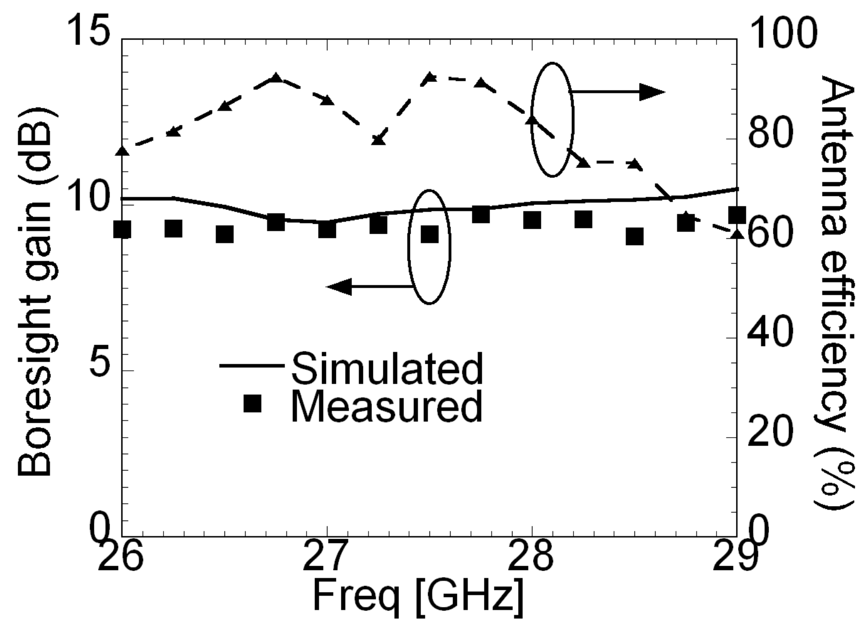


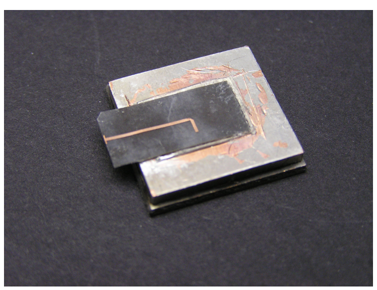
Not Just Circuits - Integrated Antennas

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



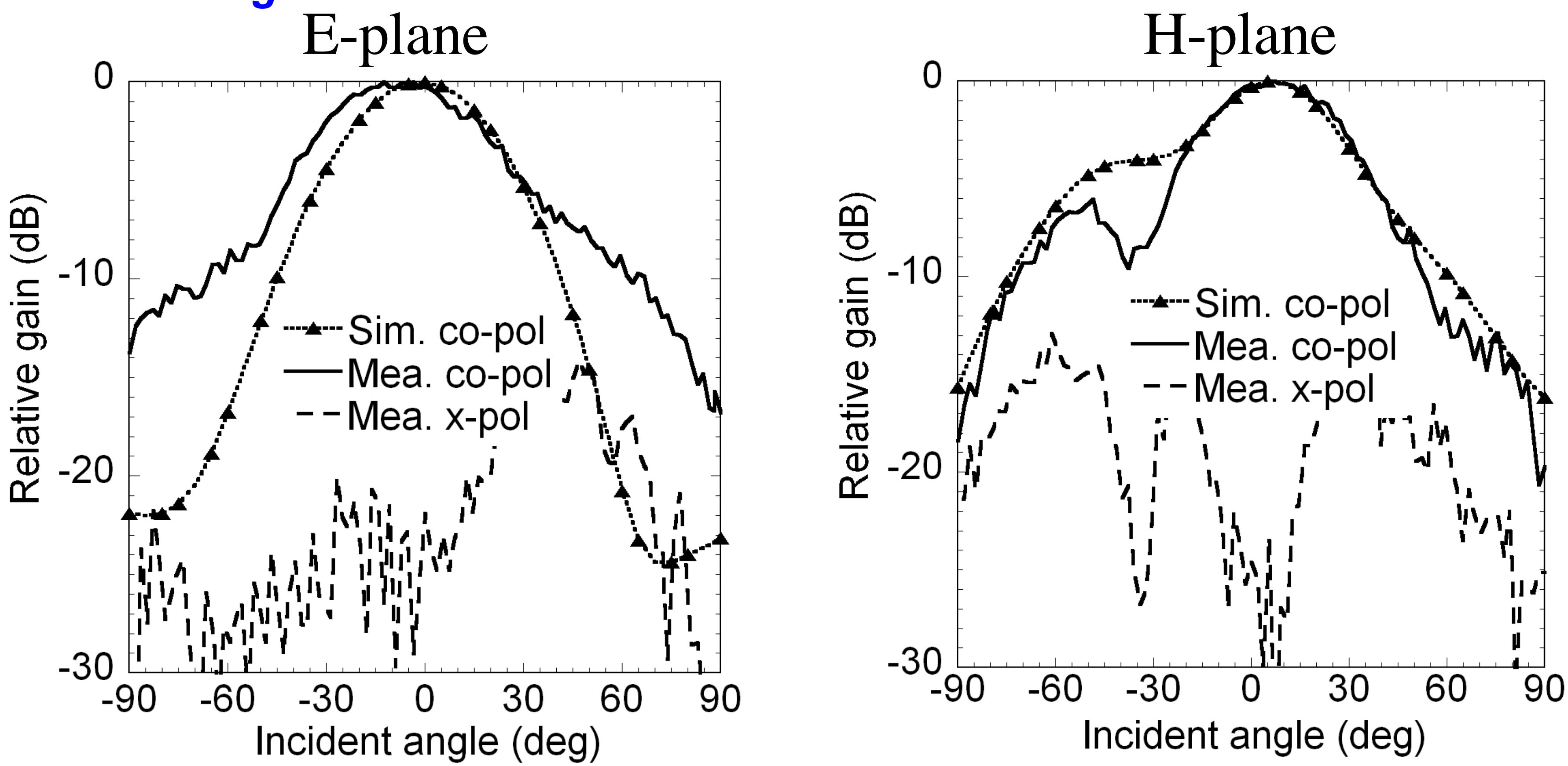




Z. Sun et al., IEEE Antennas and Wireless Prop. Lett., vol. 5, pp. 459-461, 2006.

Radiation Performance

In-Package Ka-band Antenna Performance

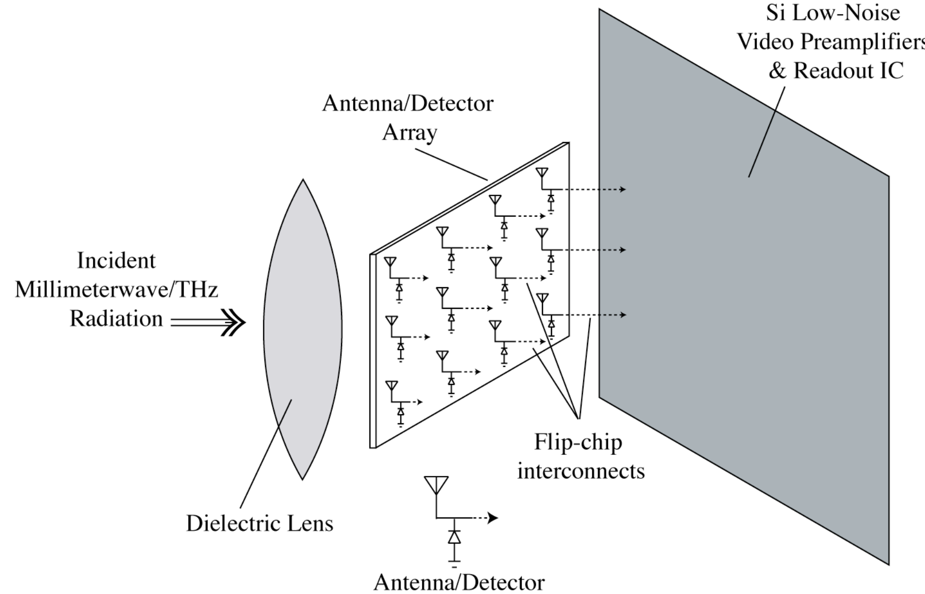


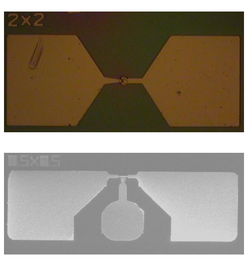
- 3D electromagnetic simulations indicate similar performance possible through W-band

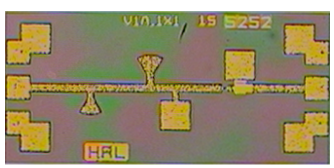
New System Concepts

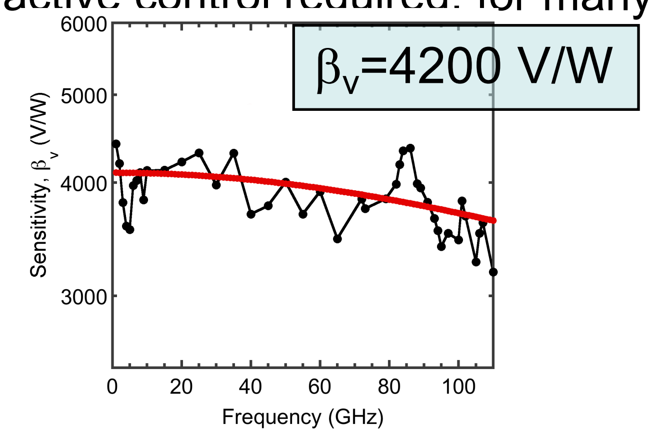
Imaging:

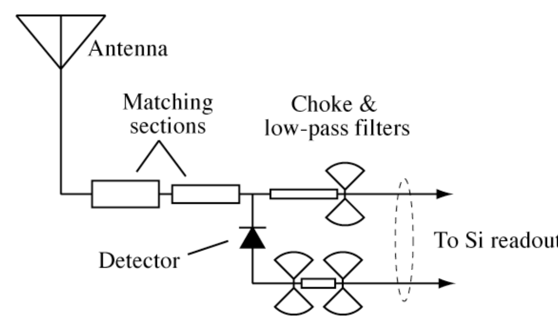
- Focal plane array, pupil-plane arrays
- Direct detection: “rectification” of mm-wave incident radiation, producing DC output
- High integration level for parallel receiver chains (MMIC)
- High instantaneous detection bandwidth; f_c > 800 GHz
- No bias required
- Lower 1/f noise than competing technologies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









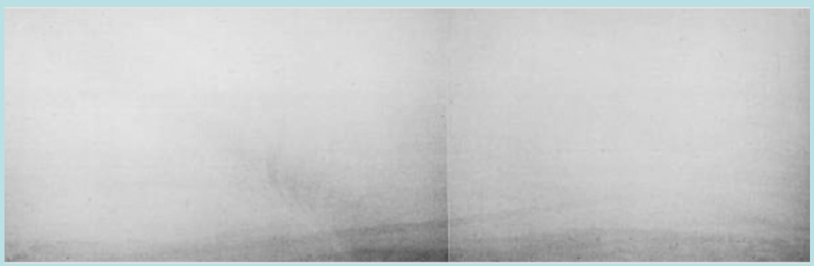


Why Millimeter-wave/THz Imaging?

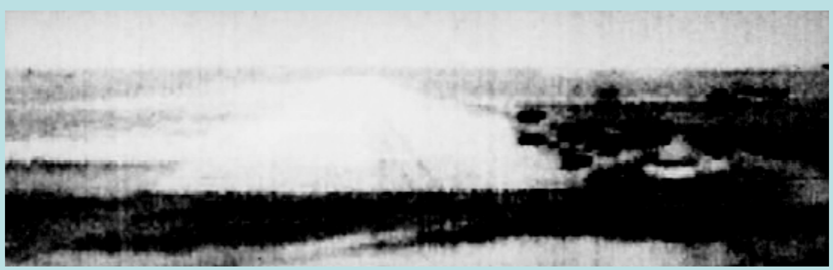
Avionics:

Visible, clear day

A little foggy

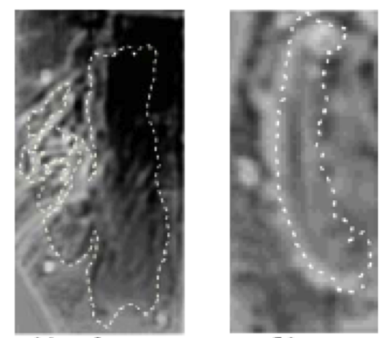


W-band image in fog



Security:

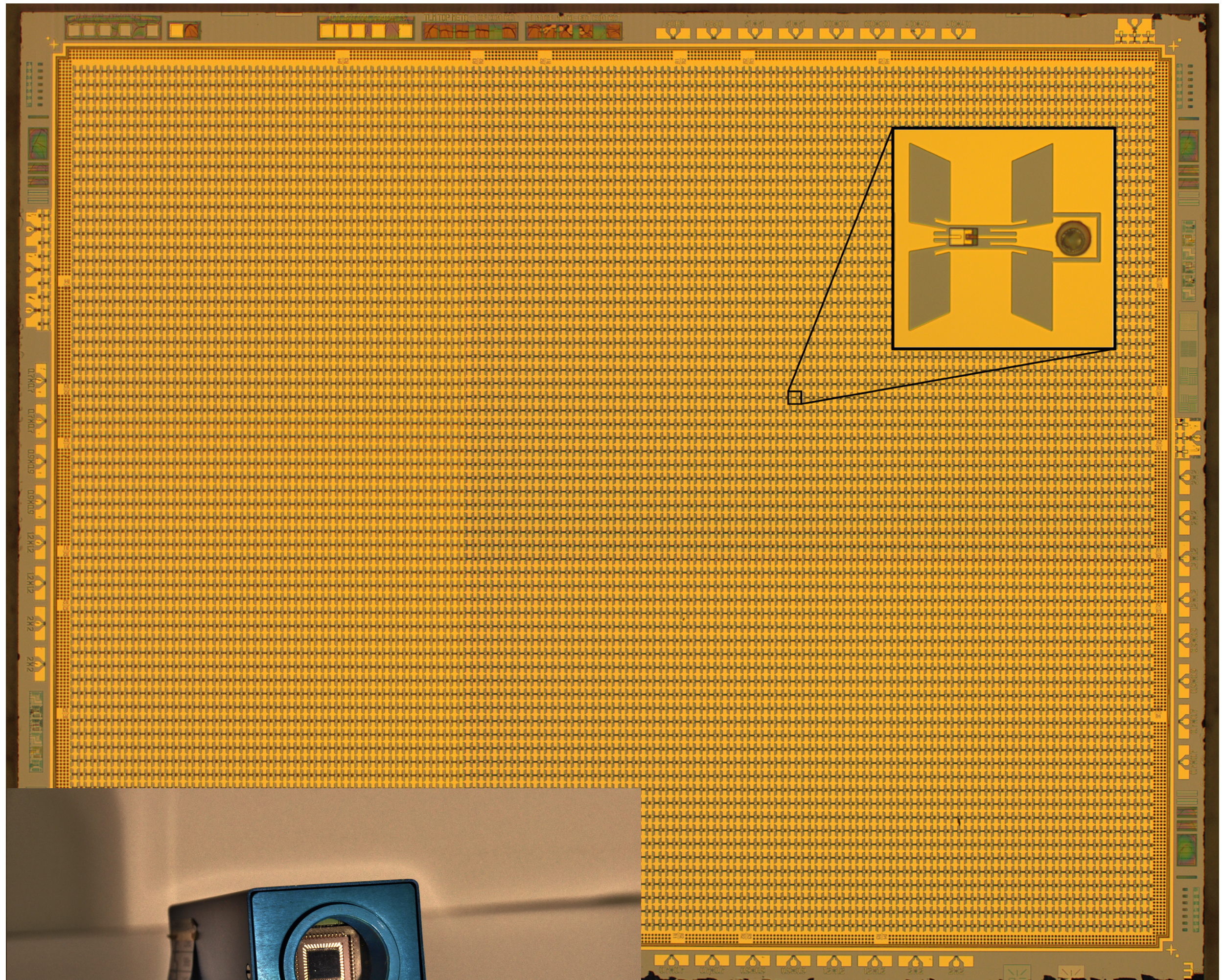
Medical:

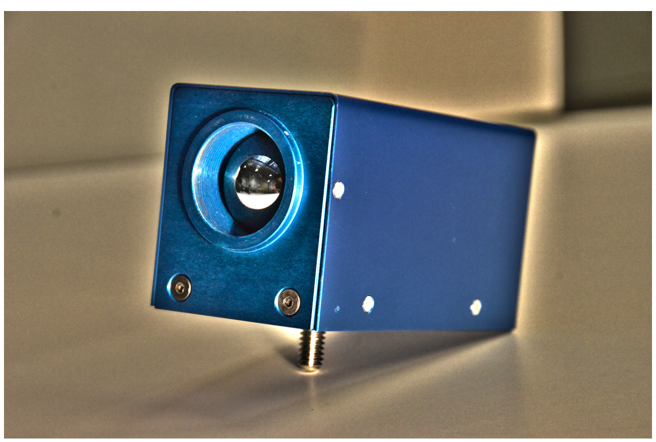


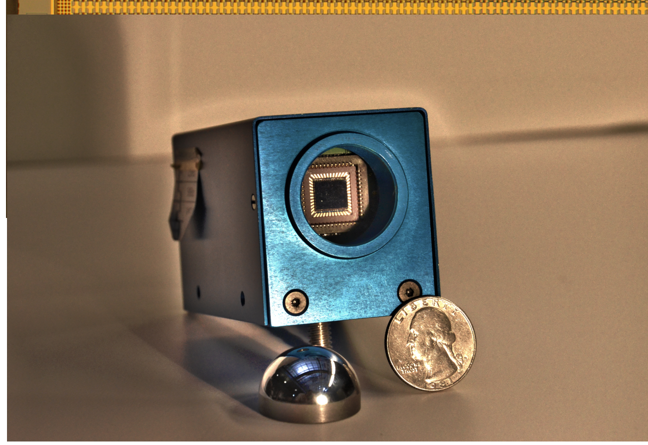
(a) melanoma (b) nevus

A Focal Plane Array…

- 80x64 pixel array
- Integrated into camera







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

Up Next—Some Definitions

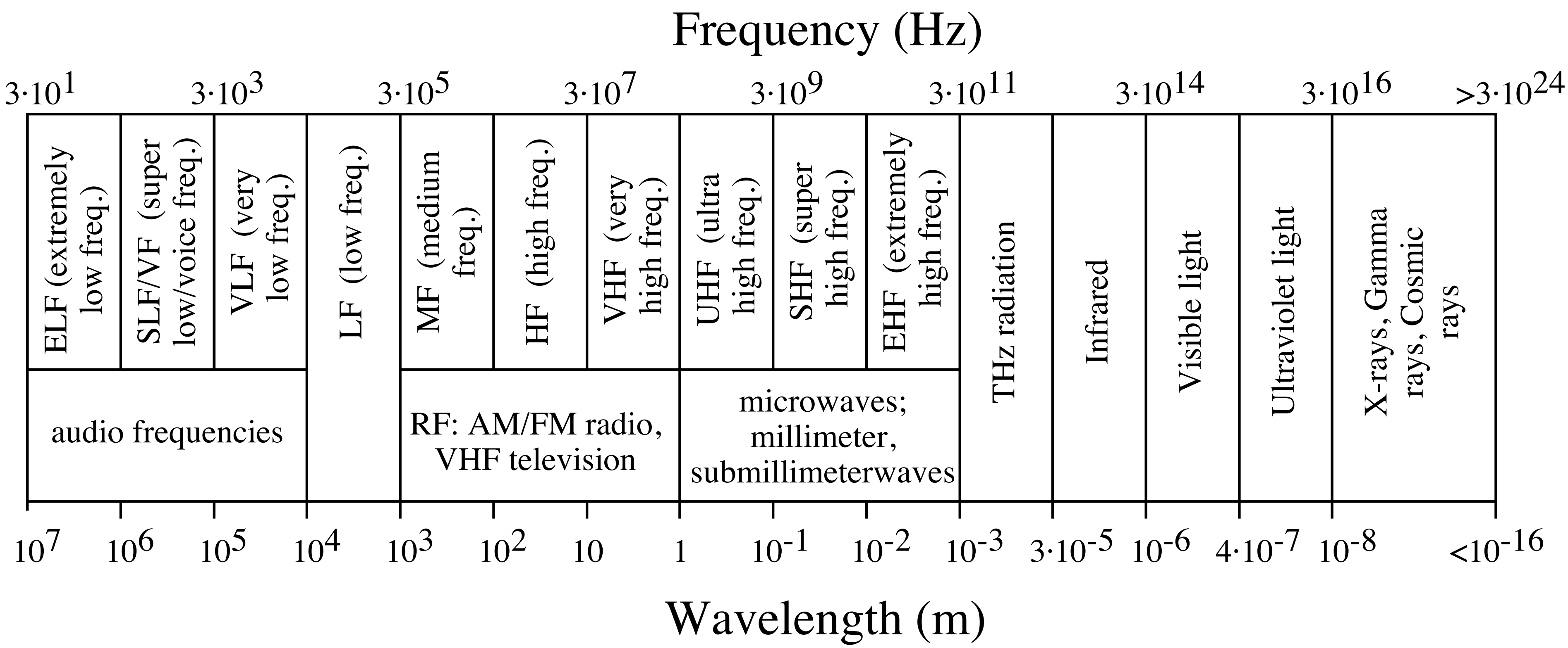
- Our focus is communications systems—so a few definitions
- All wireless systems work by broadcasting a signal, which propagates as electromagnetic waves before being picked up and reconverted into useful signals
- We're going to focus on electronics for the transmit and receive part; generating the 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

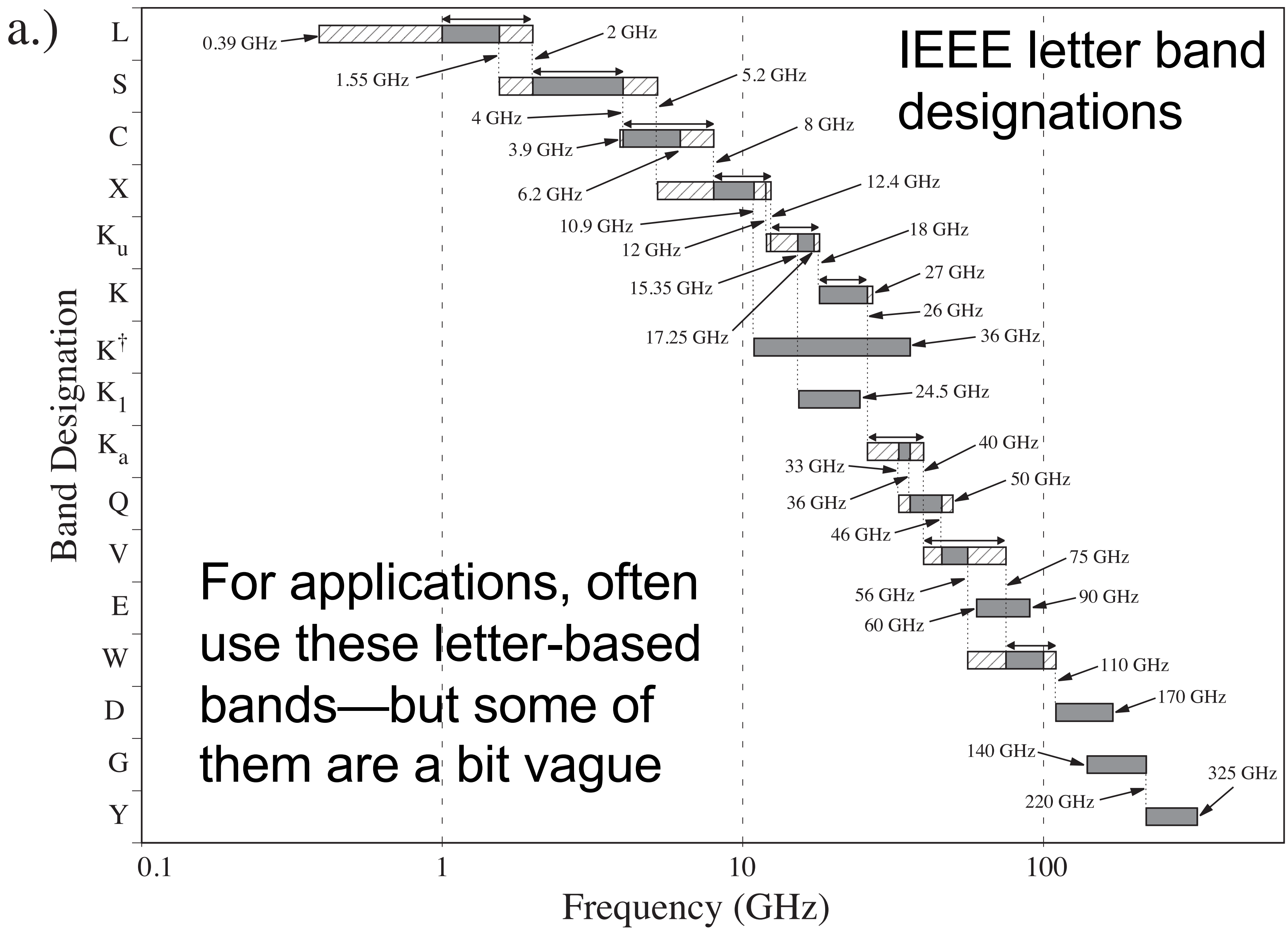
Frequency Bands

One pretty common set of labels:



But these categories are too broad for many uses

Frequency Bands



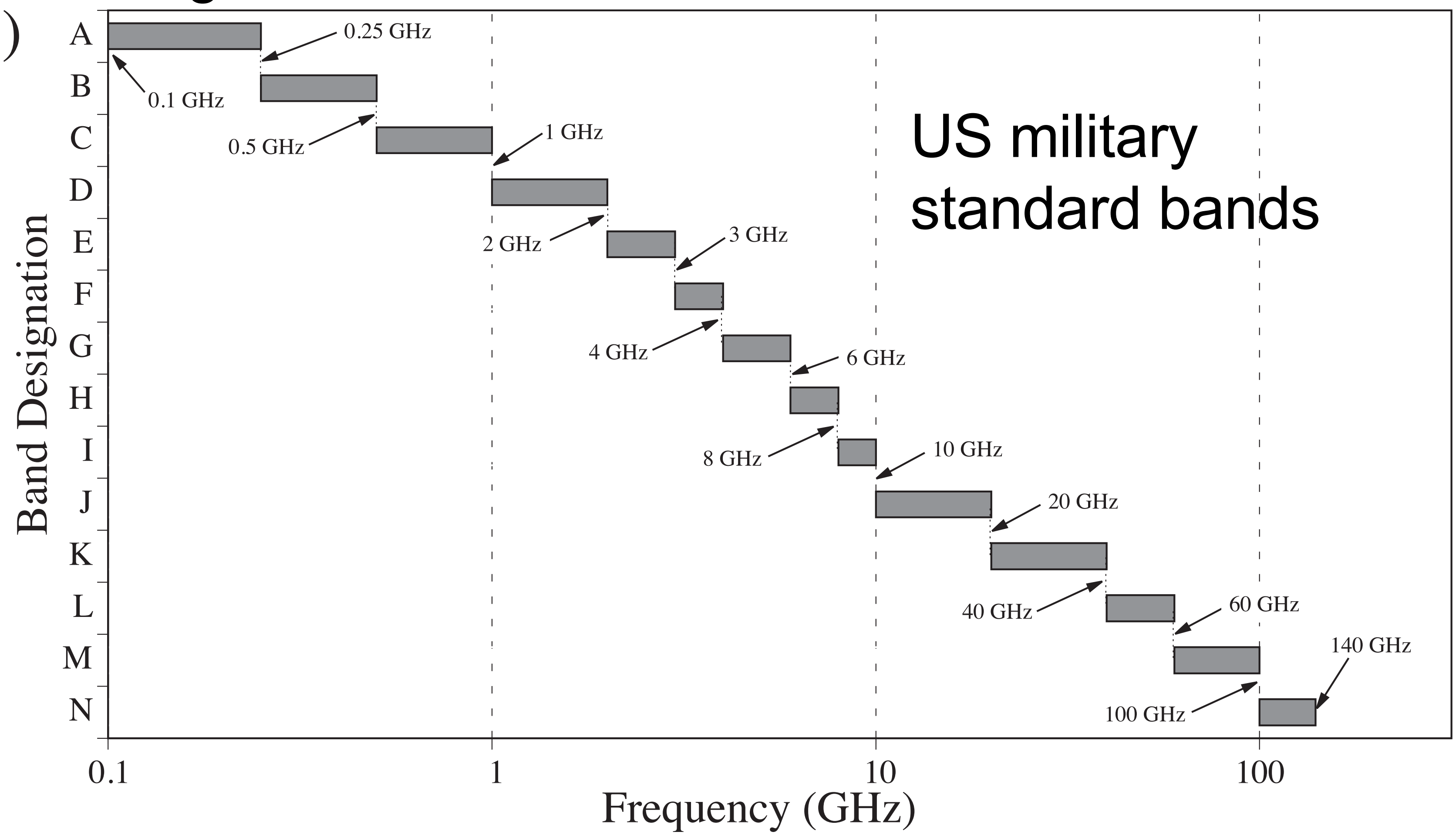
IEEE letter band designations

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 lab this week—but there is lab next week, and there are things to read and videos to watch before lab**

- An administrative issue:
- We need to adjust the lab sections to preserve "social awkwarding"
  - Looks like 8 of you are signed up, 3 on Wednesday, 5 on Thursday.
    - Can anyone volunteer to switch sections from Thursday to Wednesday? We need to "balance" as much as possible

Students:

You must report your permanent seat location using

here.nd.edu/seat

All seats have been numbered for your convenience.

Log in to enter your course/section, room, and seat number.

Course: EE 40458, Section: 01
Room: Nanovic-Jenkins B062

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