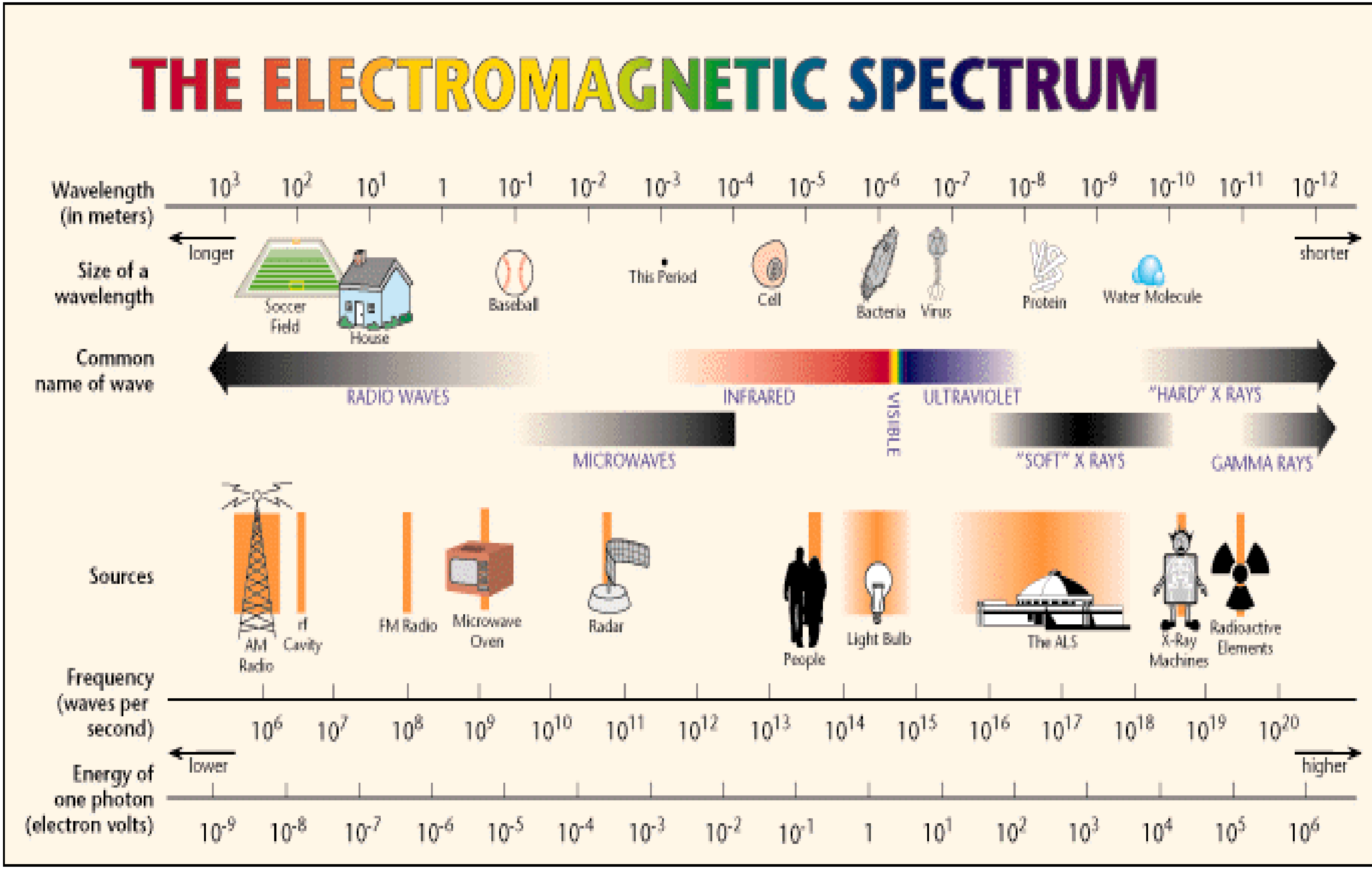
A BRIEF HISTORY OF MICROWAVE ENGINEERING

S.N. SINHA

PROFESSOR

DEPT. OF ELECTRONICS & COMPUTER ENGINEERING

IIT ROORKEE


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6

Multiple	Name	Symbol	Multiple	Name	Symbol
10^{0}	**hertz**	Hz			
10^{1}	decahertz	daHz	10^{-1}	decihertz	dHz
10^{2}	hectohertz	hHz	10^{-2}	centihertz	cHz
10^{3}	kilohertz	kHz	10^{-3}	millihertz	mHz
10^{6}	megahertz	MHz	10^{-6}	microhertz	µHz
10^{9}	gigahertz	GHz	10^{-9}	nanohertz	nHz
10^{12}	terahertz	THz	10^{-12}	picohertz	pHz
10^{15}	petahertz	PHz	10^{-15}	femtohertz	fHz
10^{18}	exahertz	EHz	10^{-18}	attohertz	aHz
10^{21}	zettahertz	ZHz	10^{-21}	zeptohertz	zHz
10^{24}	yottahertz	YHz	10^{-24}	yoctohertz	yHz

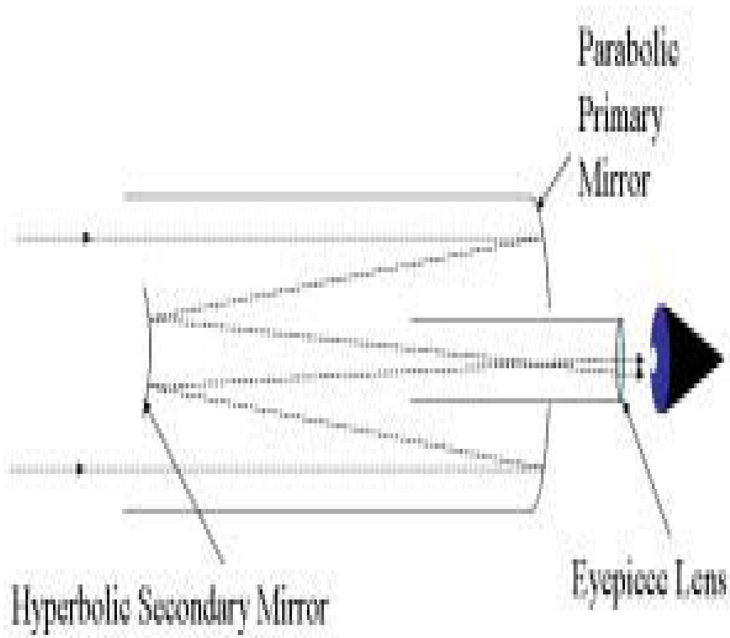
CLASS	FREQUENCY	WAVELENGTH	ENERGY
γ	300 EHz	1 pm	1.24 MeV
HX	30 EHz	10 pm	124 keV
SX	3 EHz	100 pm	12.4 keV
	300 PHz	1 nm	1.24 keV
EUV	30 PHz	10 nm	124 eV
NUV	3 PHz	100 nm	12.4 eV
NIR	300 THz	1 μm	1.24 eV
MIR	30 THz	10 μm	124 meV
FIR	3 THz	100 μm	12.4 meV
EHF	300 GHz	1 mm	1.24 meV
SHF	30 GHz	1 cm	124 μeV
UHF	3 GHz	1 dm	12.4 μeV
VHF	300 MHz	1 m	1.24 μeV
HF	30 MHz	1 dam	124 neV
MF	3 MHz	1 hm	12.4 neV
LF	300 kHz	1 km	1.24 neV
VLF	30 kHz	10 km	124 peV
VF	3 kHz	100 km	12.4 peV
ELF	300 Hz	1 Mm	1.24 peV
	30 Hz	10 Mm	124 feV

- John Napier, born in 1550
- Developed the theory of logarithms, in order to eliminate the frustration of hand calculations of division, multiplication, squares, etc.
- We use logarithms every day in microwaves when we refer to the decibel
- The Neper, a unitless quantity for dealing with ratios, is named after John Napier

John Napier

Laurent Cassegrain

- Not much is known about Laurent Cassegrain, a Catholic Priest in Chartre, France, who in 1672 reportedly submitted a manuscript on a new type of reflecting telescope that bears his name.
- The Cassegrain antenna is an an adaptation of the telescope



- Hans Christian Oersted, one of the leading scientists of the nineteenth century, played a crucial role in understanding electromagnetism
- He showed that electricity and magnetism were related phenomena, a finding that laid the foundation for the theory of electromagnetism and for the research that later created such technologies as radio, television and fiber optics
- The unit of magnetic field strength was named the Oersted in his honor.

Hans Christian Oersted

- George Simon Ohm was born in Erlangen, Bavaria on March 16, 1787.
- Ohm's Law (V=IR) is as basic to the study of electronics, as Newton's Law (F=mA) is to classical physics.
- Semiconductors have been known to bend Ohm's law, but it took more than a century for this to happen
- Ohm's colleagues apparently dismissed his work, causing him both poverty and humiliation
- He died in 1854, but his name is still used approximately one billion times each day!

George Simon Ohm

Johann Carl Friedrich Gauss
1777 - 1855

- **Gauss** worked in a wide variety of fields in both mathematics and physics including number theory, analysis, differential geometry, magnetism, astronomy and optics.
- His work has had an immense influence in many areas.
- Gauss Theorem (Divergence Theorem)
- Gauss's Law

$$\int_{c.s.} \mathbf{D} \cdot d\mathbf{A} = \int_{c.s.} \epsilon_0 \mathbf{E} \cdot d\mathbf{A} = q = \int \rho \, d\mathbf{V} \qquad \nabla \cdot \mathbf{D} = \rho \quad \text{or} \quad \nabla \cdot \mathbf{E} = \rho / \epsilon_0$$

- Gaussian distribution
- And Many other contributions

Ampère, André (1775-1836)

- French mathematician and physicist who extended Oersted's results by showing that the deflection of a compass relative to an electrical current obeyed the right hand rule.
- Ampère argued that magnetism could be explained by electric currents in molecules, and invented the solenoid, which behaved as a bar magnet.
- Ampère also showed that parallel wires with current in the same direction attract, those with current in opposite directions repel.
- The law formulated by him forms one of the Maxwell's equations.

- Michael Faraday, born in 1791, is credited as the discoverer of magneto-electric induction, the law of electrochemical decomposition, the magnetization of light, and diamagnetism, among many other contributions to chemistry and physics.
- He did his research at the Royal Academy at London, for a stipend of 300 pounds per year from the British government!
- Faraday's name is immortalized in the Farad, the unit of capacitance.

Michael Faraday

- Christian Andreas Doppler was born in Austria in 1803
- He learned mathematics at the Vienna Polytechnic Institute.
- His theory of the apparent shift in frequency when source or observer was in motion relative to the other was proved using musicians on trains and train platforms listening for what notes the others were playing.
- He correctly predicted that the concept would prove valuable in astronomy in determining celestial motion because of color shifts
- Doppler radar is used everyday
- He died young at age 49.

Christian Andreas Doppler

- At the same time Faraday was working on E-M theory, Princeton Professor Joseph Henry was also playing with large electromagnets
- One of Henry's experiments "illustrates most strikingly the reciprocal action of the two principles of electricity and magnetism"
- His work on self-induction is remembered today because the unit of inductance is the Henry

Joseph Henry

- In 1873, country-boy misfit James Clerk Maxwell laid the foundations of modern electromagnetic theory in his work, "A Treatise on Electricity and Magnetism" in Scotland, which he wrote as a retired college professor.
- Born in 1831, Maxwell theorized that, if combined, electrical and magnetic energy would be able to travel through space in a wave
- If Maxwell were here today, he would be pleased to see his equations routinely solved many thousands of times per second by today's three-dimensional structural simulators using finite element analysis

James Clerk Maxwell

- Several years later, German Heinrich Hertz conducted experiments that proved Maxwell's theories were correct.
- Hertz began testing these theories by using a high-voltage spark discharge (a source rich in high-frequency harmonics) to excite a half-wave dipole antenna.
- A receive antenna consisted of an adjustable loop of wire with another spark gap
- When both transmit and receive antennas were adjusted for the same resonant frequency, Hertz was able to demonstrate propagation of electromagnetic waves.

Heinrich Hertz

- In another experiment, Hertz used a coax line to show that electromagnetic waves propagated with a finite velocity
- He discovered basic transmission line effects such as the existence of nodes in a standing wave pattern, a quarter wavelength from an open circuit and a half wavelength from a short circuit
- He then went on to develop cylindrical parabolic reflectors for directional antennas, as well as a number of other radio frequency (RF) and microwave devices and techniques.

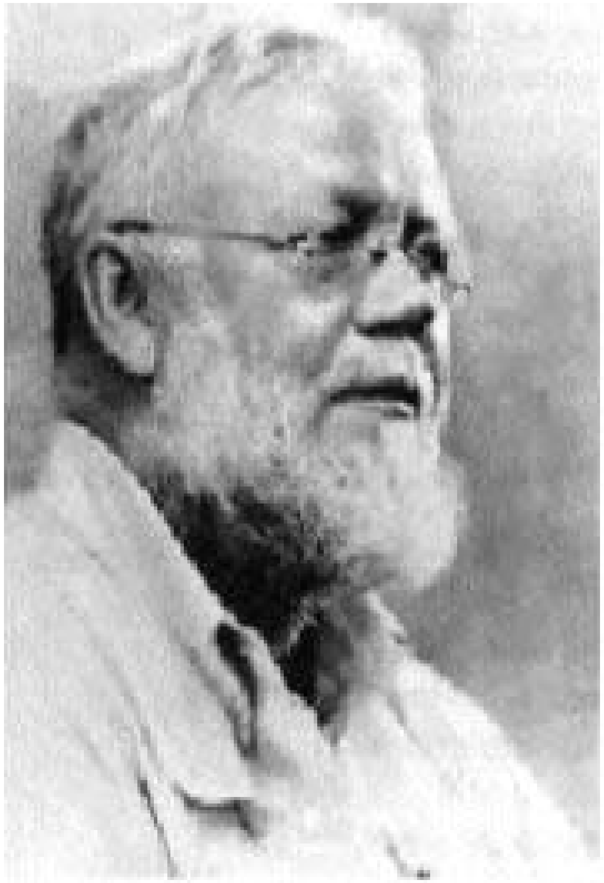
Heinrich Hertz

- Other scientists built on Hertz's work.
- In 1894, Guglielmo Marconi began experiments in Italy sending a signal using Morse code
- He formed a company, G.E.C. Marconi, that is still around today.
- His early experiments proved that it was possible to send waves not just across a room, but around the world.
- Marconi received the Nobel prize of 1909 for his work, shared with German Ferdinand Braun

Guglielmo Marconi

- Reginald Aubrey Fessenden, born in Canada in 1866, was a huge pioneer of wireless.
- He was the first inventor to demonstrate transmission of *voice* in December 1900 (Marconi thought that Morse Code was good enough for all communication needs), and his first transmission involved a weather report
- He was the first to think in terms of continuous wave (CW) transmissions instead of the pulsed spark-gap transmitters of the day

Fessenden



KARL FERDINAND BRAUN

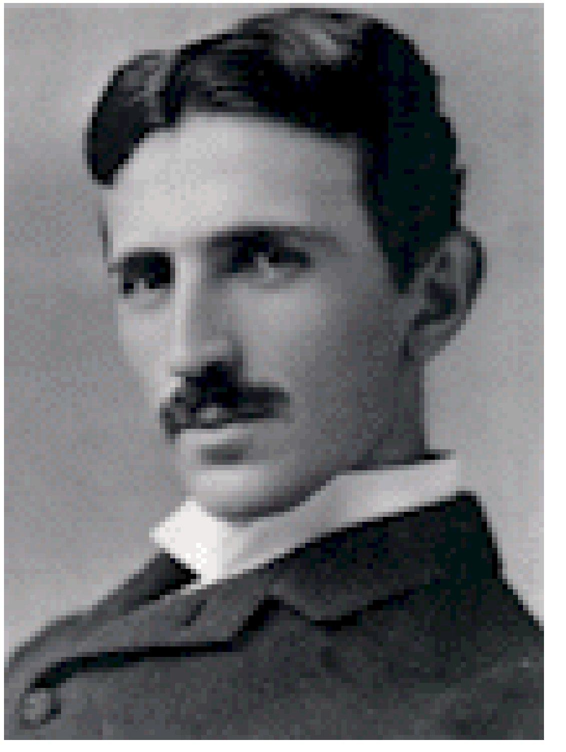
- Karl Ferdinand Braun's work on wireless telegraphy included the invention of the first semiconductor, the point-contact diode used in "crystal" radios
- He also invented the first cathode-ray tube to provide a visual display, the precursor to radar screens, oscilloscopes and video screens alike.

- Mad scientist Oliver Heaviside's research in transmission-line theory was first applied to telegraphs, including the transatlantic cable, but microwave engineers use his concepts to this day.
- A mathematician, he rewrote Maxwell's messy equations into their simple, vector-calculus form.
- He predicted the E-layer of the ionosphere, which allows propagation of electromagnetic waves around the curvature of the earth.
- He painted his nails pink!

Oliver Heaviside

- Although Marconi was awarded the Nobel prize in 1907 for his "wireless telegraphy" work , the U.S. Supreme Court revoked Marconi's patents since Serbian-American genius Nikola Tesla had taken out a patent for radio communications as early as 1897.
- Tesla's life has taken on legendary status, having obtained more than 700 U.S. patents.
- Discovered the rotating magnetic field, the basis of most alternating-current machinery. He invented the Tesla coil, an induction coil widely used in radio technology. His other inventions are: a telephone repeater, rotating magnetic field principle, polyphase alternating-current system, induction motor, alternating-current power transmission, Tesla coil transformer, wireless communication, radio, fluorescent lights

Nikola Tesla

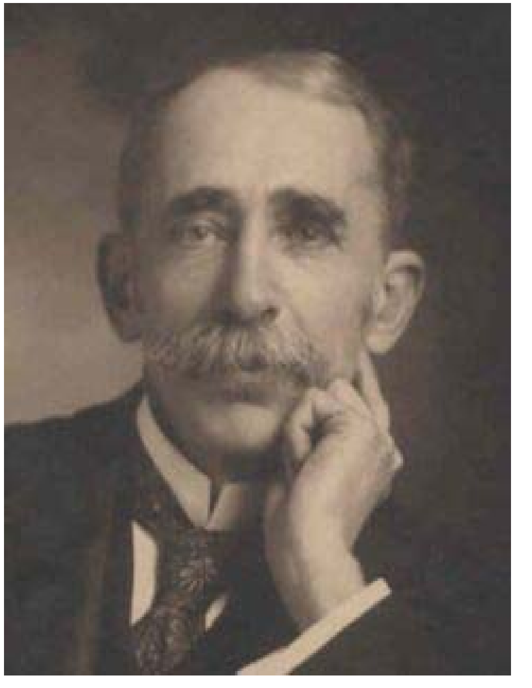


Oliver George

- By 1894, Sir Oliver George was conducting experiments noting that directional radiation was obtained when he surrounded a spark oscillator with a metal tube.
- In 1897, Lord Rayleigh proved mathematically that waves could be propagated inside a hollow metal tube.
- Rayleigh also noted the infinite set of modes of the TE or TM type which were possible, and the existence of a cutoff frequency.
- Waveguide was essentially forgotten, however, until it was rediscovered independently in 1936 by George C. Southworth at AT&T (Bell Telephone Labs) and W.L. Barrow at MIT.

J.A. Fleming

- A lot was happening in microwaves around the previous turn of the century.
- J.A. Fleming, who had worked with Maxwell, Marconi, and Thomas Edison, invented an "electrical valve", better known today as a diode tube, which was used as detector
- Fleming also came up with an equation that expressed the impedance characteristics of high frequency transmission lines in terms of measurable effects of electromagnetic waves.



J.C. Bose

- In India, however, J.C. Bose was working with shorter and shorter waves.
- In 1895 Bose gave his first public demonstration of electromagnetic waves, using them to ring a bell remotely and to explode some gunpowder.
- The wavelengths he used ranged from 2.5 cm to 5 mm.
- Think about that. He was playing at 60 GHz over one hundred years ago!
- Bose's investigations included measurement of refractive index of a variety of substances.
- He also made dielectric lenses, oscillators, receivers, and his own "polarization device."

Jan Czochralski

- A scientist from Poland, Jan Czochralski, was many years ahead of his time.
- In 1916 he developed a method for growing single crystals, which was basically forgotten until after World War II.
- Today the semiconductor industry depends on the Czochralski method for manufacturing billions of dollars worth of semiconductor materials.
- He was accused of being a Nazi sympathizer but was later acquitted and died in Poland in 1953.
- What a strange world, Bill Gates is the richest man on earth and most people don't even know how to pronounce "Czochralski!"

Walter Schottky

- Walter Schottky's name is embedded in solid-state physics (Schottky effect, Schottky barrier, Schottky contact, Schottky diode).
- Born in 1878 in Germany, he was a contemporary of Einstein and Max Planck.
- His work included superheterodyne receivers, noise theory, and radio tube work such as invention of the tetrode
- But his most important contribution to microwaves is no doubt his investigation of metal-semiconductor rectifying junctions (published in 1938), which is the basis for the gate contact of all MESFETs.

Edwin Howard Armstrong

- In 1912, he invented a feedback circuit based on Lee DeForest's three-terminal audion tube that provided the first usable electrical amplifier
- Before Armstrong, the only "amplifiers" that existed were the mechanical relays used to boost voltage on long telegraph lines
- Armstrong invented the super-heterodyne receiver and frequency-modulation(FM) broadcasting.

Albert Wallace Hull

- Albert Wallace Hull was born in Connecticut in 1880. He earned a Ph.D. in physics at Yale, then worked at General Electric's research lab in NY.
- He was a noted vacuum tube inventor. One of his tubes used magnetic control; it was called the magnetron.
- Hull's magnetron only operated at kHz frequencies, but it cranked out 15,000 watts of power and could be used as both an amplifier or an oscillator.
- By WW II, the magnetron became an important component of many radar systems.
- Today, all commercial microwave ovens use mass-produced magnetrons

Robert A. Watson-Watt

- In 1932, Sir Robert A. Watson-Watt came up the idea of “RDF”, Radio Direction Finding.
- He wrote a paper (with A.F. Wilkins) describing this new technique of Radio Detection and Ranging giving it the code name of "radar” in 1935.
- It was proved that the theory would work, but with a range of only 8 miles using the state-of-the-art devices of the day.
- By the autumn of 1938 radar systems were in place along the south coast of Britain.
- Watson-Watt became scientific advisor to the British Air Ministry in 1940 and in 1941 went to the United States to set up radar systems there.

George C. Southworth

- Also at Bell Telephone Labs in the 1930s, Dr. George C. Southworth discovered that radio waves could be transmitted efficiently through a hollow copper pipe.
- He and his team at Bell found that electromagnetic energy traveling through an enclosed structure moved in distinct patterns that we all know and love called "modes", and that the optimum diameter for a waveguide pipe was slightly greater than one-half wave length.
- They also experimented successfully with square, rectangular and oval waveguides.

VARIAN BROTHERS

- In 1937, funded by $100 by Stanford University, Sigurd (top of photo) and Russell Varian demonstrated the first klystron tube
- Later they founded Varian Associates, one of the very first technology-based companies in what would soon become silicon valley.
- Variations of their klystron tube provide millimeter-wave power today.

Philip Smith

- By the end of the thirties, secret work was afoot in both the USA and the United Kingdom.
- At Bell Telephone's Radio Research Lab in New Jersey, Philip Smith, born in Lexington Massachusetts, developed a circular chart form in 1939 that shows the entire universe of complex impedances in one convenient circle.
- The Smith chart is still in wide use today, and will be around long after we're all gone.
- Philip Smith submitted an article on his development to the IRE, which was rejected !

Influence of WW-II

- Radio Proximity Fuze was developed during World War II as a method was needed for detonating a shell near the target.
- It consisted of four major parts: A miniature radio transceiver, complete with amplifier and capacitor; a battery; an explosive train; and the necessary safety devices.
- The theory was that the fuze transmitter, alone, would not produce sufficient signal intensity, to trigger a thyratron tube switch. However, as the projectile approached a target the radio waves reflected by the target would gradually increase and come more and more into phase with the fuze-generated signal. Once the signal level was high enough, the fuze would know that the shell could do a maximum amount of damage, and the thyratron tube switch would be triggered releasing the energy in a charged capacitor and thus igniting the shell.

Chain Home and the Battle of Britain

- World War II began in September 1939, when Germany invaded—and quickly defeated—Poland. By the summer of 1940, less than a year later, nearly all of Western Europe was under Nazi control
- The British had been driven from the shores of Dunkirk and watched France crumble from across the English Channel.
- Now, Hitler turned his attention to Great Britain and began planning an invasion. To do so Hitler needed to gain control of the English Channel.
- The German Navy couldn’t do it, so Hitler hoped to destroy the British Navy, and any coastal resistance, with air superiority.
- Hitler had great faith in his undefeated Luftwaffe, and with good reason. Comprised of more than 2400 fighters and bombers, it would face Britain’s 900 fighters.

Chain Home and the Battle of Britain

- With these dismal odds, the British needed an early warning system, one that would disclose the German air position and take away their element of surprise.
- This system would also allow British pilots to conserve precious time in-flight and remove the necessity of mounting constant air patrols over the entire English East Coast.
- It was through the extraordinary foresight of radio researcher Sir Robert Watson-Watt that the British had in place in 1940 an entire network of long-range early-warning radar stations whose reports were tightly integrated by Fighter Command.
- This was the Chain Home radar system, the first radar-based air defense system, which was ready just in time for the Battle of Britain

Chain Home and the Battle of Britain

- In the late 1930s the technology to generate high-power pulsed radio energy at wavelengths short enough to make narrow beams did not exist.
- Instead, Chain Home relied on antennas that illuminated a huge area, like a floodlight. These antennas did not move or scan at all.
- Rather, Chain Home radar operators chose a target ("blip") on their screen and turned the knob of a special coil-like instrument to null out or minimize the blip. Then they could read the direction to this target from a scale around the knob.
- This device (called a radio goniometer) electronically steered the nulls from a pair of simple fixed receiving antennas.
- This idea was invented during the first decade of radio technology development and was used by Watson-Watt to track radio static generated by thunderstorms years before the war.

Chain Home and the Battle of Britain

- Although it required intense human interaction both to direction-find on each target and to filter the reports from many radar stations into a coherent air picture, the Chain Home system was highly effective, especially during those critical months in the summer and fall of 1940.
- Still, the Battle of Britain was a costly conflict. By the end of the battle, the Luftwaffe had lost some 1700 aircraft and nearly all their crew.
- Thanks to the early warning and raid locations provided to Fighter Command by the Chain Home radar, and the rapid production of replacement fighters, the British lost just over 900 aircraft and saved about half their pilots—and most importantly, forced the Germans to abandon their plans to invade England.

CAVITY MAGNETRON

- At the Battle of Britain in 1940 the British were able to detect enemy aircraft at any time of day and in any weather conditions, proving the value of microwaves to the world. The Massachusetts Institute of Technology (MIT) opened the Radiation Laboratory to research applications for radar early in the 1940s.

- Two British scientists, HAH Boot and JT Randall at the University of Birmingham had devised a tube which could generate 1000 times the power of any other existing microwave generator at the time. They named it the "cavity magnetron". The problem was that it took them a month to create a dozen of the complex units. Watson-Watt suggested they talk to MIT, and MIT in turn suggested that the British meet with a small company called Raytheon, which had been founded by an ex-MIT professor, Vannevar Bush

MIT Radiation Lab

- The **Radiation Laboratory** or often **RadLab** at Massachusetts Institute of Technology was in operation from October 1940 until December 31, 1945
- The lab was initially set up as a joint Anglo-American project, largely inspired by the British development of simple radar and that of the cavity magnetron pioneered by John Randall and Boot at the University of Birmingham in 1940
- In 1940, the technology of radar was exported to the United States for further development and production
- The lab's activities eventually encompassed physical electronics, electromagnetic properties of matter, microwave physics, and microwave communication principles, and the lab made fundamental advances in all of these fields

- One of Raytheon's engineers, Percy Spencer, figured out a new manufacturing process that cut manufacturing time to a mere fraction of what it was AND improved the power efficiency
- Throughout the war years, new efficient sources were rapidly developed for transmitting microwave radar pulses which by the end of the war had reached peak power levels as great as several million watts.
- Just after the war, Percy Spencer was still working with magnetrons when he noticed that a chocolate bar in his pocket melted when he walked in front of the magnetron. He had invented the microwave oven!!!

Percy Spencer

Hewlett and Packard

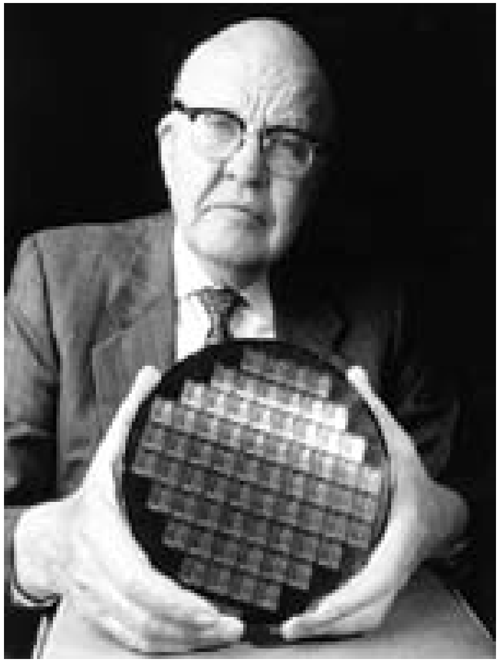
- In 1939 Bill Hewlett and Dave Packard started a business in Dave's garage using $538.
- Their first successful product was an audio oscillator.
- Another California entrepreneur, Walt Disney, was one of their first big contracts when his company ordered a few oscillators for use in creating the film "Fantasia".
- Now known as Agilent, HP products have been used by generations of microwave engineers and have always presented a problem during capital equipment requests, because this is equipment that never dies, so why would you ever need to replace it?

- Leo Esaki (born in 1925), researched heavily doped silicon and germanium while working for Sony Corporation in Japan, and invented the Esaki tunnel diode during the 1950s.
- This device constitutes the first quantum electron device, and today it is used in many microwave detectors and oscillators (due to its negative resistance region).
- Later as an IBM employee, Esaki pioneered other semiconductor quantum structures such as man-made superlattices. He won the Nobel Prize for Physics in 1973.

Leo Esaki

- Jack Kilby (born in 1923), working for Texas Instruments, is credited with the invention of the integrated circuit, which ranks up there with "fire" and "wheel" as an invention that changed the world.
- The first public announcement of a "solid circuit" was made at the IRE conference in 1959.
- Not three months later, Robert Noyce independently came up with the same idea at Fairchild, and the patent feud brought corporate lawyers for all the way to the supreme court.
- Jack's insistence that he was a "co-inventor" with Noyce speaks volumes about the man, and later the two shared the Nobel Prize in Physics in year 2000.

Jack Kilby



J.B. Gunn

- In 1963 John Gunn invented the diode that bears his name, while working for IBM. The negative-resistance Gunn diode has been used to build cheap oscillators up to 100 GHz.

George Matthaei, Leo Young, and EMT Jones

- In 1964, George Matthaei, Leo Young, and EMT Jones published a little book called "Microwave Filters, Impedance-Matching Networks, and Coupling Structures".
- The best filter designers still refer to this masterpiece, four full decades later. These three researchers worked together at Stanford Research Institute, in Menlo Park California, when the book was written and published by McGraw Hill.
- Leo Young was born in Austria but came to America to get his PhD at JHU. Matthaei and Young were both born in the USA.

- Kaneyuki Kurokawa was born in Japan in 1928. While on leave of absence from from his position at University of Tokyo, he worked during the early 1960s at Bell Labs in New Jersey.

- His March 1965 IEEE paper entitled *Power Waves and the Scattering Matrix*, makes Kurokawa the first to popularize the concept of S-parameters.

- This profound yet simple idea is one of the concepts sets microwave engineers apart from other "normal" electrical engineers.

Kaneyuki Kurokawa

- Les Besser started the microwave computer-aided design industry in 1973 when he created COMPACT software (Computerized Optimization of Microwave Passive and Active CircuiTs).

- Amazingly, his original submission to the IEEE of a paper describing COMPACT was turned down

Les Besser

- In 1975, a paper published by Ray Pengelly and James Turner entitled "Monolithic Broadband GaAs F.E.T. Amplifiers" sealed their fate as the inventors of the MMIC.

- Working at Plessey, their little single-stage amplifier provided 5 dB of gain at X-band using 1 micron optically-written gates. They used computer optimization to design their lumped element matching structures, which included capacitors and inductors, but no DC blocking on the input/output

Ray Pengelly

Herb Kroemer

- Herb Kroemer's semiconductor work from the 1950s proposed what are now called hetero-structures, but it took several decades to realize the technology to build them.
- He was one of the pioneers of molecular beam epitaxy, in part, to realize some of his invented structures.
- One outcome of his work known to all microwave engineers is the hetero-junction bipolar transistor (HBT), which has given the microwave field-effect transistor a run for its money in recent years.
- Dr. Kroemer won the Nobel Prize in 2000 for his work, and currently is a professor at University of California, Santa Barbara

AND A LOT MORE IS TO COME IN THE FORESEEABLE FUTURE !!!!

THANK YOU
FOR YOUR PATIENCE