Microwave Engineering: Lecture #1

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Dr. Ghassan Nihad Jawad

University of Baghdad

ghassan.jawad@coeng.uobaghdad.edu.iq

Definition of Microwaves

In general, the term *Microwaves* refers to the Alternating Current (AC) signals with frequency range between 300 MHz and 300 GHz. This frequency range corresponds to a wavelength ($\lambda = \frac{c}{f} = \frac{3\times10^8}{f}$) between 1 m and 1 mm. Figure (1) illustrates the location of the microwave frequencies within the electromagnetic spectrum. Microwave frequencies are further divided into bands, each having a designated letter as illustrated in Table (1).

Reasons for Studying Microwave Engineering

The main reason for studying microwave theory and technique as a dedicated branch of Electrical engineering is the relationship between the wavelength of operation (λ) and the dimensions of the circuit elements.
Generally speaking, Maxwell's equations are the universal tool that can be used to analyze any circuit regardless of its dimensions in terms of its electromagnetic fields. However,

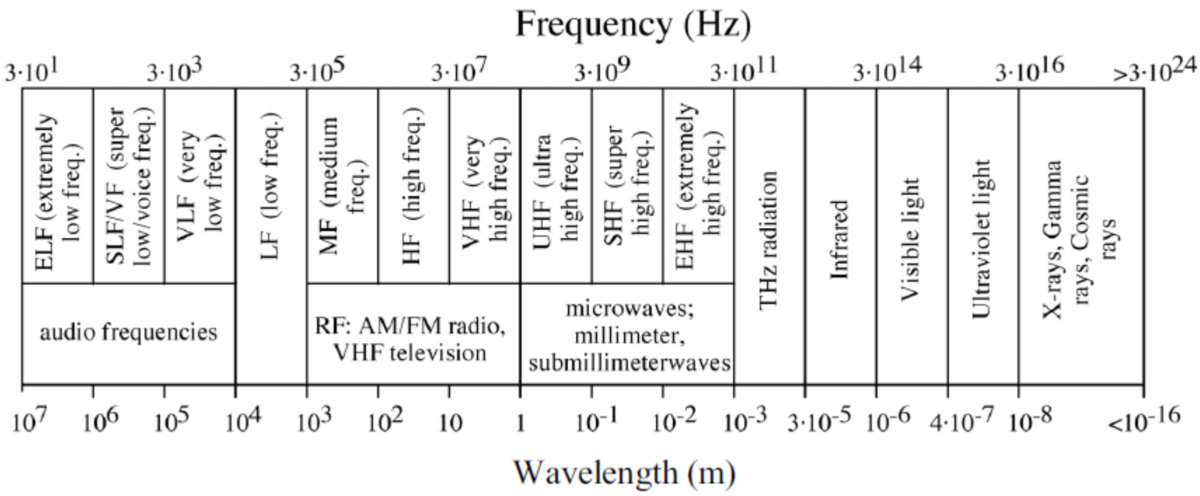
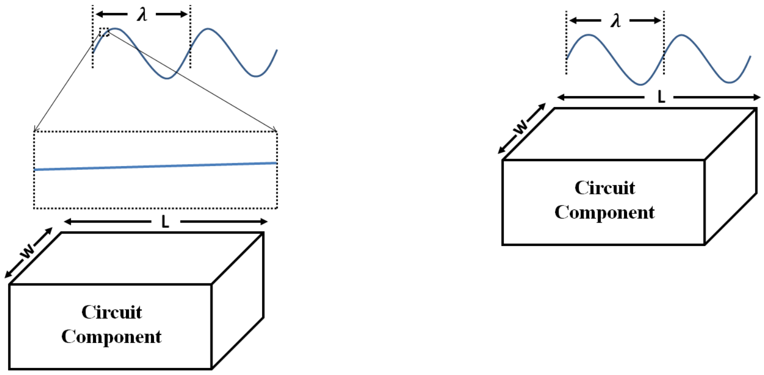


Figure 1: The location of the microwave frequency range within the electromagnetic spectrum

Table 1: Microwave frequency bands

Band Designator	Frequency (GHz)
UHF	0.3 to 1
L band	1 to 2
S band	2 to 4
C band	4 to 8
X band	8 to 12
Ku band	12 to 18
K band	18 to 27
Ka band	27 to 40
V band	40 to 75
W band	75 to 110
mm-Wave band	110 to 300



(a) Low frequency ($\lambda \gg$ circuit dimensions). (b) High frequency ($\lambda \ll$ circuit dimensions).

Figure 2: A comparison between the wavelength of a microwave signal and the dimensions of an arbitrary circuit component

solving Maxwell's equations is an extremely hard task, and it takes experts very long time to provide a solution for any electrical circuit based on the solution of Maxwell's equations. Hence, a number of approximations had to be introduced to simplify circuit analysis and provide a fast, easy to use methodologies to study and design electrical circuits.

In the case of circuits operating with wavelengths much larger than their own dimensions, the time taken for the electromagnetic field to propagate from one point of the circuit to another is a small fraction of its period. Hence, the simple *lumped circuit theory* is applied, which represents a simplification of Maxwell's equations.

In the opposites case, i.e., when the objects of the circuit elements are much larger than the wavelength, *optical laws*, which are another type of simplification of Maxwell's equations, are applied. In this approximation, electromagnetic fields are treated as optical traces and the circuit components are no longer treated as lumped elements.

The microwave range corresponds to those cases when the wavelengths are *of the same order* (roughly, from one-tenth to 10 times) as the circuit dimensions (as shown in Figure (2b)), so that neither one nor the other approximation is permissible: Maxwell's equations must be solved in their entirety.

For microwave frequencies, the finite propagation velocity of electromagnetic waves can lo longer be neglected. For these frequencies, the time delay associated with signal propagation from one end of a component to the other is an appreciable fraction of the signal period, and thus lumped-element description are no longer adequate to describe electrical behavior. The time delay associated with finite wave propagation velocity that gives rise to the *distributed circuit effects* is a distinguishing feature of the mindset of Microwave Engineering.

In addition to the above, other physical effects that are negligible at lower frequencies become increasingly important at high frequencies. Two of these effects are the *skin effect* and *radiation losses.* The skin effect is a function of frequency; the depth of penetration is given by $\delta_s = \frac{1}{\sqrt{\omega\mu\sigma}}$ where μ is the permeability, f is the frequency and σ is the conductivity of the material. As the expression indicates, δ_s decreases with increasing frequency, and so the electromagnetic fields are confined to the regions increasingly near the surface as the frequency increases. This results in the microwave currents flowing exclusively along the surface of the conductor, significantly increasing the effective resistance (and thus the loss) of metallic interconnections. *Radiation loss* also become increasingly important as the signal wavelengths approach the component and interconnection dimensions. For conductors and other components of comparable size to the signal wavelengths, standing waves caused by reflection of the electromagnetic waves from the boundaries of the components can greatly enhance the radiation of electromagnetic energy. These standing waves can be easily established either intentionally (in the case of antennae and resonant structures) or unintentionally (in the case of abrupt transitions, poor circuit layout, or other imperfections). Careful attention to transmission line geometry, placement relative to other components, transmission lines, and ground planes, as well as circuit packaging is essential for avoiding excessive signal attenuation and unintended coupling due to radiation effects.

A Brief History of Microwave Engineering

The foundations of modern electromagnetic theory were formulated in 1873 by the Scottish scientist James Clerk Maxwell. All of the practical applications of electromagnetic theory owe their existence to the theoretical work of Maxwell.

During the 1880s, German scientist Heinrich Hertz has conducted experiments that proved Maxwell's theories. For the first time, Hertz has used operation frequencies around 500 MHz, where the physical dimensions of the experimental apparatus were a significant fraction of the wavelength.

In 1894, Guglielmo Marconi began experiments in Italy sending a signal using Morse code [1]. Later, Marconi received Nobel prize after successfully sending a message across the Atlantic Ocean from England to USA in 1901.

In the beginning of the 1900s, most of the radio technology was in the high frequency (HF) and very high frequency (VHF) range due to the lack of components working at the microwave frequency range. However, in 1932, Robert Watson-Watt came up with the idea of Radio Direction Finding (RDF) technique, which was later called RAdio Detection And Ranging, or RADAR. During the 1940s, the development of radar for the use in the World War II gave Microwave theory and technology substantial interest.

The successful record of radar systems WWII urged many scientist in the United States to start researching in the field of microwave technology. This led to establishing the Radiation

[1] Morse code: Is a system of sending messages that uses long and short sounds or dots and dashes to represent letters and numbers. The video here will show you the history of this system.

Laboratory (or RadLab) at Massachusetts Institute of Technology (MIT). By the end of the 1904s, scientist at Radlab were able to develop the radar technology by improving the efficiency of the microwave sources.

During that period, Percy Spencer, one of the scientists at RadLab, noticed that a chocolate bar in his pocket melted when he walked in front of a high-power microwave source. This led to the invention of the microwave oven in 1949.

During the 1950s and the 1960s, communications systems using the microwave technology began to be developed, benefiting from the work originally made for the radar systems. By the 1970s, Computer-Aided design industry began to help engineers designing and optimizing microwave passive and active circuits.

In 1975, Ray Pengelly proposed a new class of microwave circuits called the Microwave Monolithic Integrated Circuits, or MMIC. This technology combines various semiconductor and metallization layers on a single wafer of gallium arsenide or silocon to provide a circuit in a very small area. This led to a huge reduction in the cost of microwave circuit fabrication, and marked the beginning of the modern satellite and mobile communications revolution.

Applications of Microwave Engineering

The use of microwave frequencies is spurred by a number of advantages. One of the major advantages is the reduced dimensions of the circuit components. Antennas, for example, can be miniaturized when using higher frequencies since the antenna size is inversely proportional to the frequency of operation. In addition, the speed of data transmission depends on the frequency band employed. Hence, the use of higher frequencies allows one to increase the channel capacity and thus to increase the data transmission rate.

Line-of-sight propagation is another advantage of microwave signals, which makes satellite and terrestrial communication links with very high capacities possible, with frequency reuse at minimally distant locations.

Microwave applications can be divided into five main sectors, as follows:

1. **Communications:** This includes satellite and mobile communications, Wireless Local Area Networks (WLAN), Local Multipoint Distribution Systems (LMDS) and Multipoint Multichannel Distributed System (MMDS).

2. **Radar:** Radar systems can be divided into two sectors: the first is dedicated for Military applications, such as surveillance, navigation and guidance of weapons. The second sector is used for civilian purposes. Such applications include air traffic control, ship traffic control, remote sensing and weather forecasting.

3. **Industrial:** Microwave technology can be used for process control, monitoring, sensing and food processing.

4. **Biomedical:** Microwave imagining is used for investigation and diagnosis of different types of diseases. Microwave hyperthermia is also used for cancer treatment.

5. **Scientific:** Microwaves are utilized in many scientific fields, such as radio astronomy for space exploration, and for remotely monitoring water resources.