Microwave Engineering
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Lecture 01
Introduction to Microwave Engineering and Transmission line theory

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Welcome to this first lecture of the course microwave engineering, in this lecture, we give a brief introduction to microwave engineering and transmission line theory. The contents covered in this lecture are brief history of microwaves, we have a discussion on different microwave frequency bands, different applications of microwave and then I will briefly introduce the microwave transmission lines and the lumped elements circuit model used to represents such transmission line.

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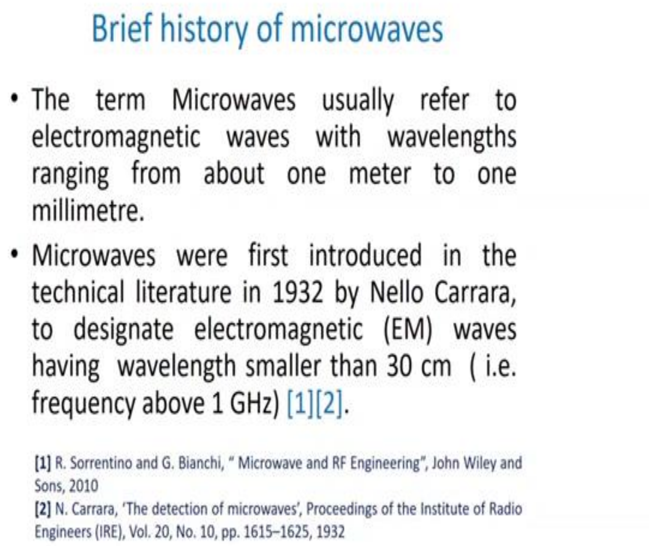

The term microwaves usually refer to electromagnetic waves with wavelengths ranging from about one metre to one millimetre. Microwaves were first introduced in the technical literature in 1932 by Nello Carrara to designate electromagnetic waves having wavelength smaller than 30 cm, that is frequency about 1 GHz. The detection of microwaves appeared in the proceedings of institute of radio engineers in the 1932.

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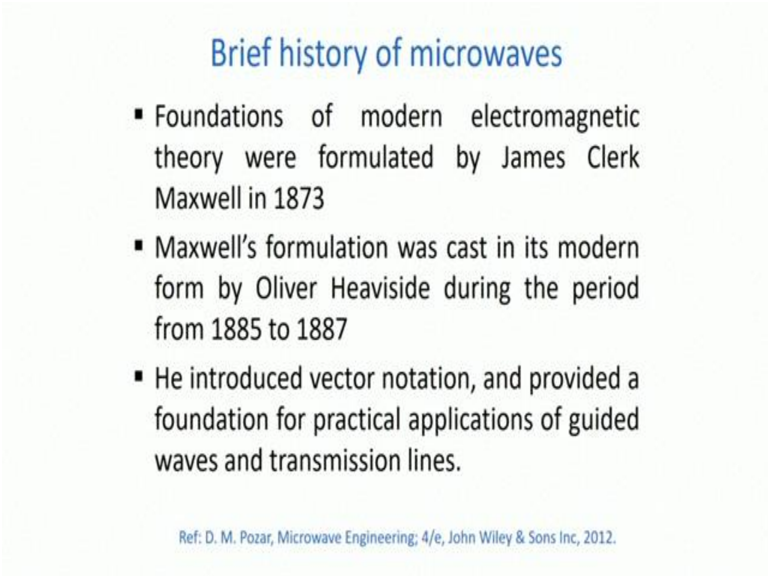

Foundation of modern electromagnetic theory was formulated by James Clark Maxwell in 1873, Maxwell's formulation was cast in its modern form by Oliver Heaviside during the period from 1885 to 1887. He introduced vector notation and provided a foundation for practical application of guided waves and transmission lines.

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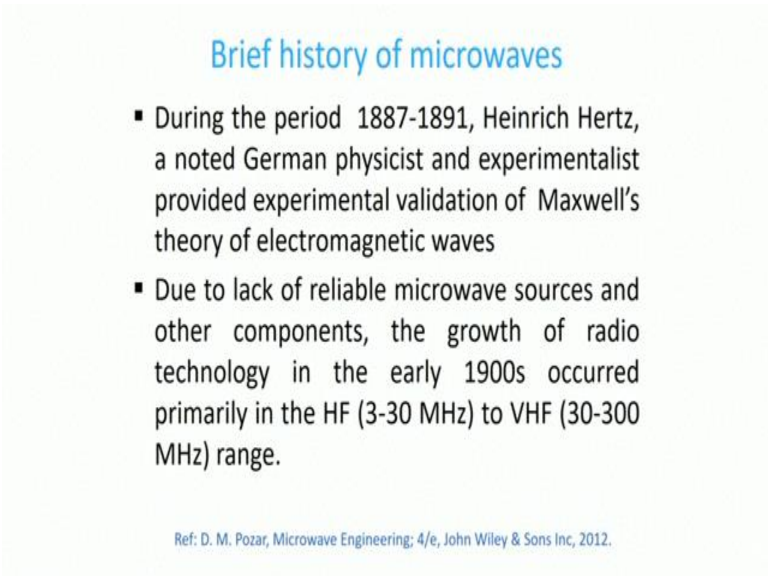

During the period 1887 to 1891, Heinrich Hertz a noted German physicist and experimentalist provided experimental validation of Maxwell's theory of electromagnetic waves. Due to the lack of reliable microwave sources and other components, the growth of radio technology in early 1900s occurred primarily in the high-frequency (HF) band, which covers 3 to 30 MHz to very high-frequency or VHF band which covers 30 to 300 MHz range.

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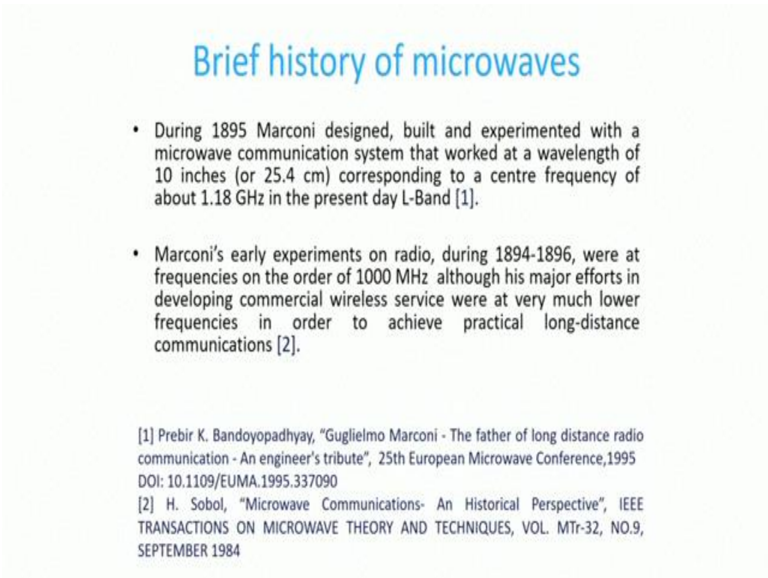

During 1895 Marconi designed, built and experimented with a microwave communication system that worked at a wavelength of 10 inches, which corresponds to a centre frequency of about 1.18 GHz in the present day L band. So initial work of Marconi were in the microwave frequency band, Marconi's early experiment on radio, during 1894 to 1896, were at frequencies on the order of 1000 MHz, although his major efforts in developing commercial wireless device were read very much lower frequencies in order to achieve practical long-distance communication.

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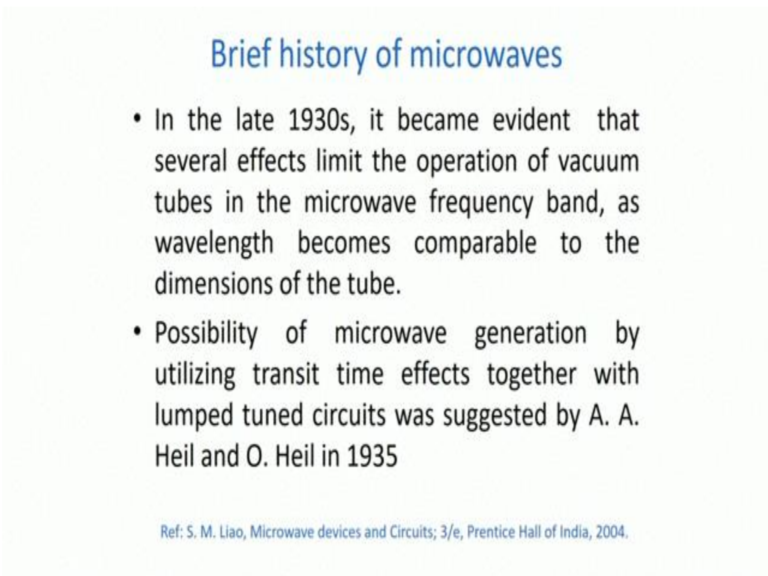

In the late 1930s, it became evident that several effects limit the operation of vacuum tubes in microwave frequency band, as wavelength becomes comparable to the dimension of the tube. Possibility of microwave generation by utilizing transit time effects together with lumped circuits were suggested by A. A. Heil and O. Heil in 1935. In conventional tube, the transit time from cathode to anode become an issue and to reduce the transit time, if the inter-electrodes spacing is reduced, then it increases the inter-electrode capacitance. So this effort to utilise transit time in microwave frequency generation it created a new direction.

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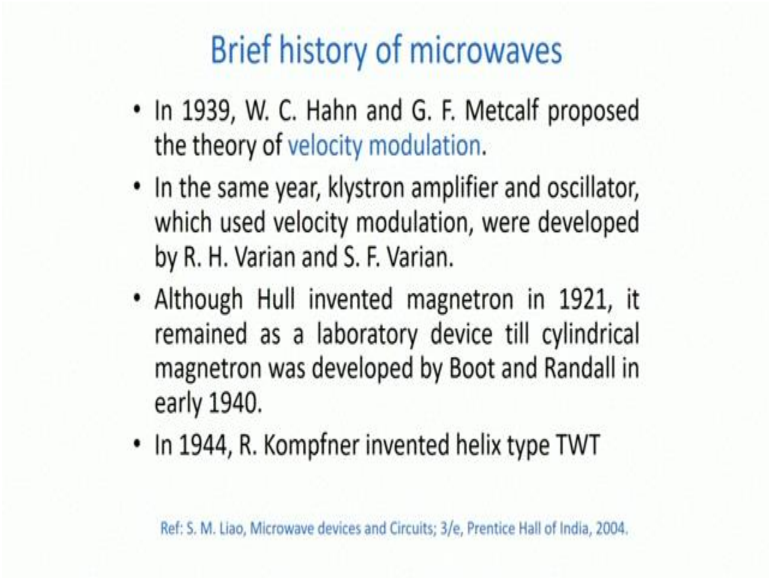

In 1939 W.C. Hahn and J. F. Metcalf proposed the theory of velocity modulation. In the same year, klystron amplifier and oscillator, which use velocity modulation, were developed by R.H. Varian and S.F. Varian. Another very popularly used microwave source is magnetron, although Hull invented magnetron in 1921, it remained as a laboratory device till cylindrical magnetron was developed by Boot and Randall in early 1940. In 1944, R. Kompfner invented helix type travelling wave tube.

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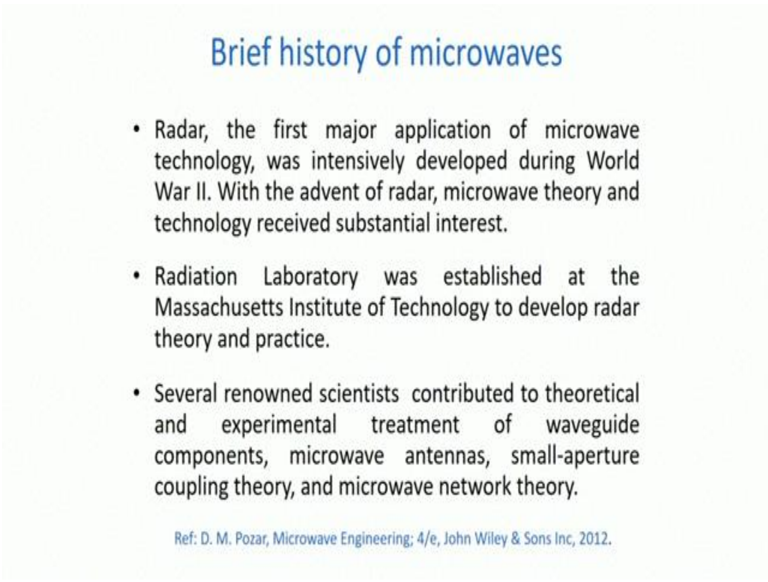

Radar, radio detection and ranging, the first major application of microwave technology, was intensively developed during World War II, with the advent of radar, microwave theory and technology received substantial interest. Radiation laboratory was established at the MIT to develop radar theory and practice, several renowned scientists contributed to the theoretical and experimental treatment of waveguide components, microwave antennas, small aperture coupling theory, and microwave network theory.

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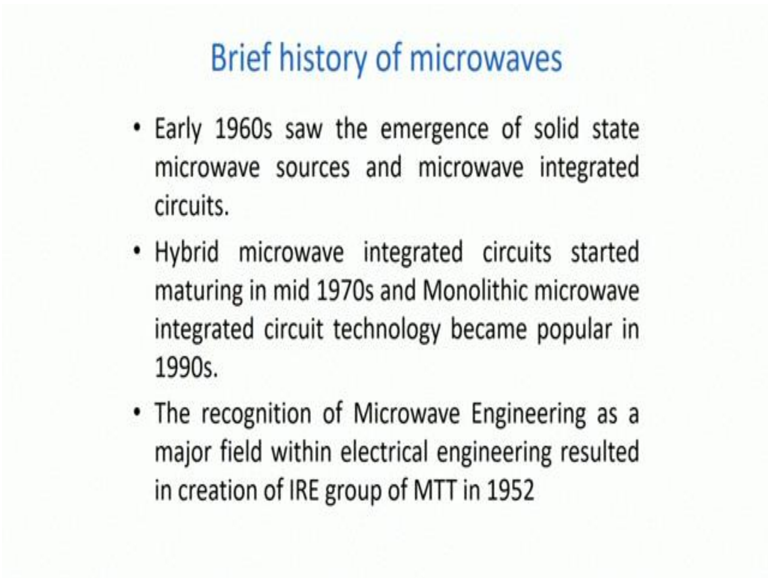

Early 1960s saw the emergence of solid-state microwave sources and microwave integrated circuits. Hybrid microwave integrated circuits started maturing in mid-1970s and monolithic microwave integrated circuits, known as MMIC, such technology became popular in 1990s, in hybrid MIC the conductor and the transmission line, these are printed on the substrate, while the district components are bonded to the substrate. In MMIC both active and passive components are fabricated together on the substrate and semiconductor substrates are used. The recognition of microwave engineering as a major field within electrical engineering resulted in creation of IRE group of MTT in 1952, IRE later became IEEE.

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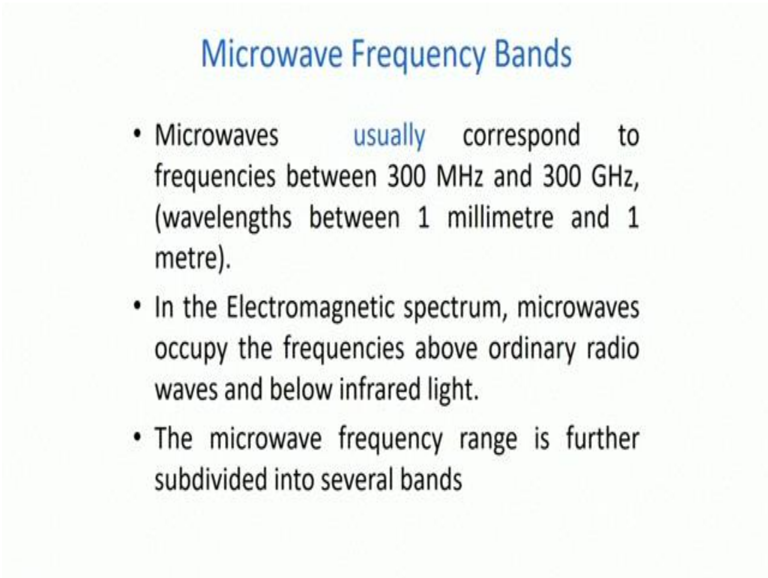

Microwaves occupy the frequency band from 300 MHz to 300 GHz which correspond to wavelengths between 1 millimetre and 1 metre. In the electromagnetic spectrum, microwaves occupy the frequencies above ordinary radio waves and below the infrared light. Now 300 MHz to 300 GHz is a huge frequency band and the microwave frequency range is further subdivided into several bands. Although there are different band designations, we will follow the microwave frequency bands which are recommended by IEEE.

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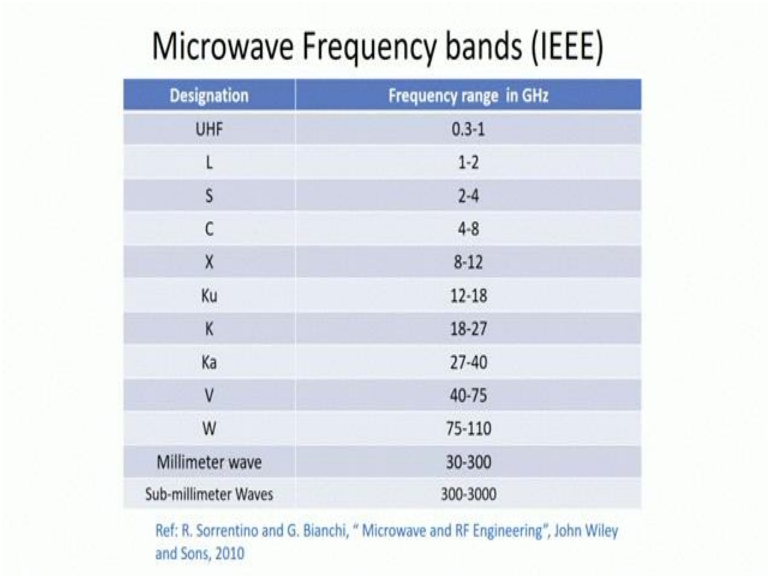

Microwave Frequency bands (IEEE)

Designation	Frequency range in GHz
UHF	0.3-1
L	1-2
S	2-4
C	4-8
X	8-12
Ku	12-18
K	18-27
Ka	27-40
V	40-75
W	75-110
Millimeter wave	30-300
Sub-millimeter Waves	300-3000

Ref: R. Sorrentino and G. Bianchi, " Microwave and RF Engineering", John Wiley and Sons, 2010

The frequency range from 0.3 to 1 GHz is designated as UHF, L band is from 1 to 2 GHz, S band is from 2 to 4 GHz, C band is from 4 to 8 GHz, X band is 8 to 12 GHz, Ku band is from 12 to 18 GHz and K band is from 18 to 27 GHz, Ka 27 to 40 GHz, V band is from 40 to 75 GHz and W band is from 75 to 110 GHz. Usually the frequency band from 30 to 300 GHz are called millimetre wave and 300 to 3000 GHz these are submillimetre waves.

The letters used to designate microwave bands has their connection to World War II times, L refers to long, S refers to short, K refers to the German word Kuds, similarly Ku is K under, Ka is K above.

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Let us now come to the application of microwaves. Microwaves have wide range of applications, one major area of application is commutation, microwave frequencies are used for terrestrial commutation, in the form of microwave links, cellular wireless commutation and WLAN. Satellite commutation takes place in the microwave frequency band. Another major application of microwave is in radar. Radars may be of different types. Civilian applications of radar include air traffic control, ship traffic control, car traffic control, remote sensing, whereas military application of radar include surveillance, navigation, weapon guidance, electronic warfare.

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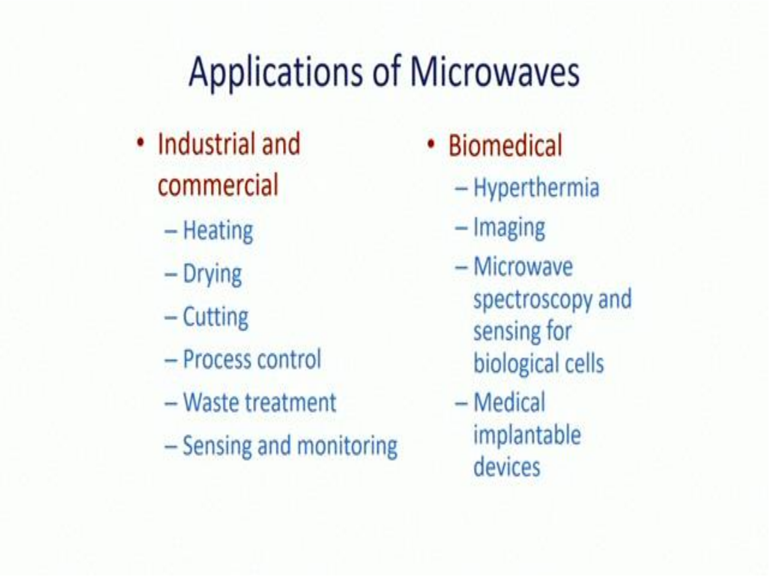

Microwaves also have industrial and commercial application in heating, drying, cutting, process control, waste treatment, sensing and monitoring. Microwave frequencies find application in biomedical field, the examples are hyperthermia, imaging, microwave spectroscopy and sensing for biological cells, medical implantable devices.

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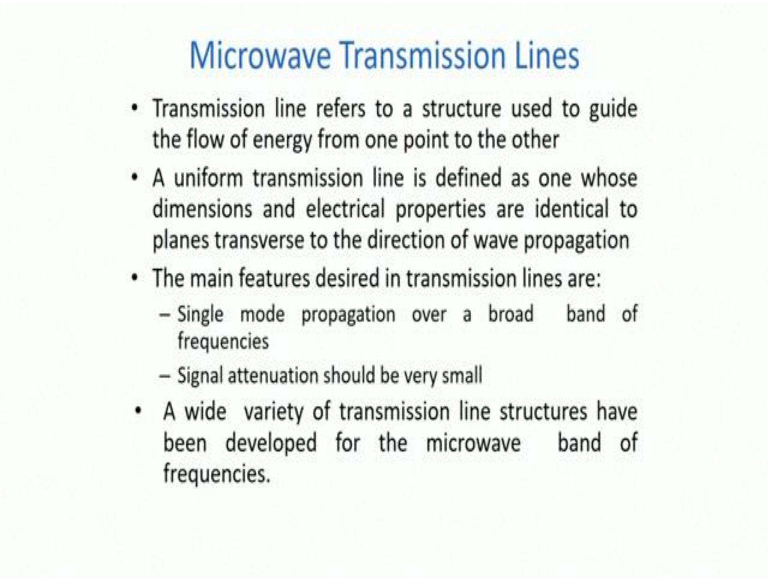

Let us now come to the microwave transmission lines. Transmission line refers to a structure which is used to guide the flow of energy from one point to the other. A uniform transmission line is defined as one whose dimensions and electrical properties are identical to the planes transverse to the direction of wave propagation. Now in transmission line the flow of energy takes place because of the propagation of wave and in uniform transmission line the dimensional electrical properties remain identical to the plane of planes transverse to the direction of propagation.

The main features desired in transmission lines are, single more propagation over a broad band of frequencies, normally will see two conductor transmission lines they have TEM mode of propagation, whereas later on, we will consider transmission structure which use other modes of propagation like TE and TM. The signal attenuation should be very small, a wide variety of transmission line structures have been developed for microwave band of frequencies.

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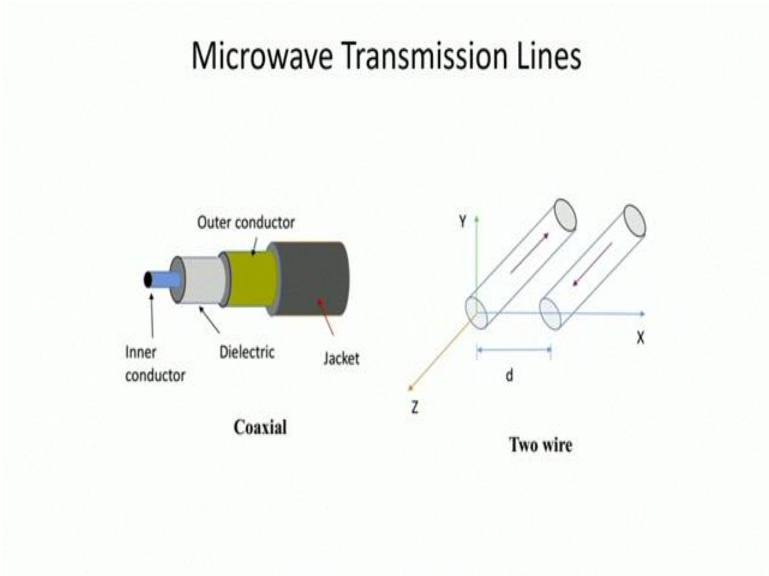

Here will consider examples of some TEM transmission lines or quasi TEM transmission lines. A very popular transmission line is a coaxial transmission line, where we have the inner conductor and an outer conductor in the form of concentric cylinders separated by a dielectric media. Another form of transmission line is a two-wire transmission line, here we have a set of parallel wires and these are used to guide electromagnetic wave from source to destination.

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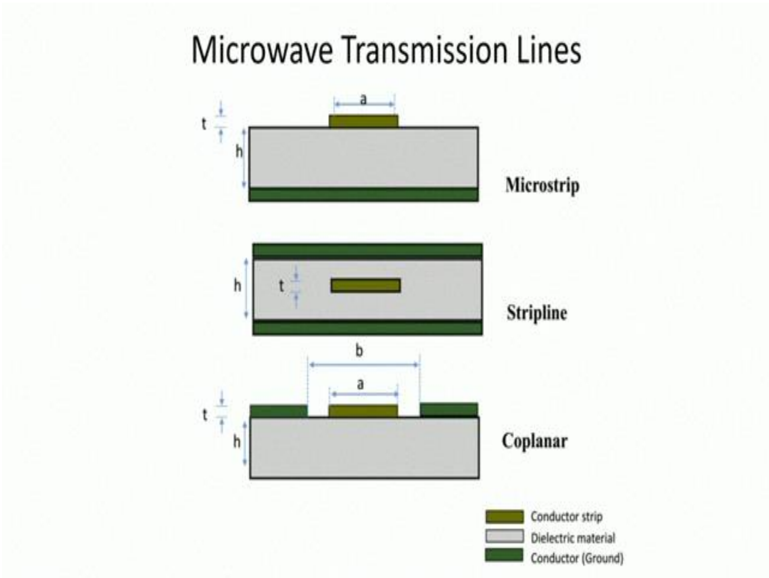

Microwave transmission lines are also designed in the planar form, and this type of transmission lines are often compatible with the microwave integrated circuits. Some basic forms of planar transmission lines are microstrip lines, where the line is separated from a ground plane by a dielectric layer, then strip line the central conductor has ground plane on both above and below and the dielectric fields are space in between. In a coplanar line, the central conductor is surrounded by the ground plane, but all are in the same plane.

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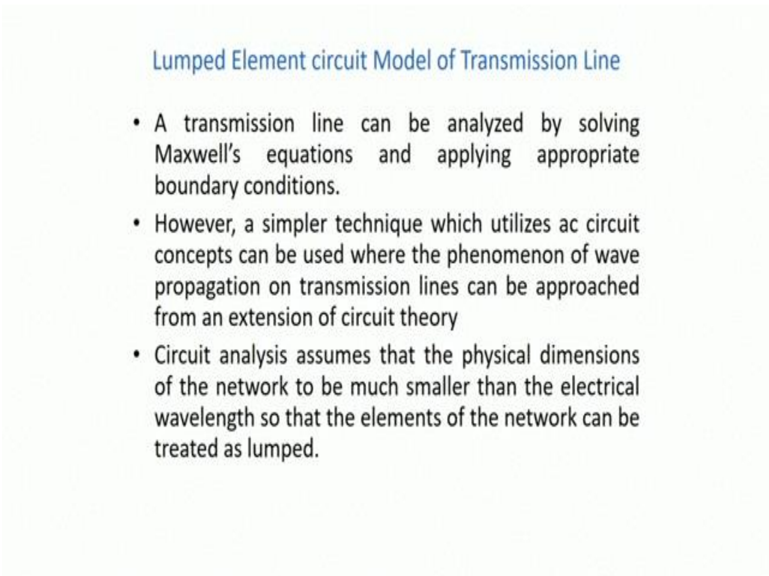

Let us now come to the lumped elements circuit model of transmission line. A transmission line can be analysed by solving Maxwell's equations and applying appropriate boundary conditions on the conductors and the conductor dielectric interface. However, a simpler technique which utilizes ac circuit concepts can be used where the phenomena of wave propagation on transmission lines can be approached from an extension of circuit theory. Circuit analysis assumes the physical dimensions of the network to be much smaller than the electrical wavelength so that the elements of the network can be treated as a lumped element.

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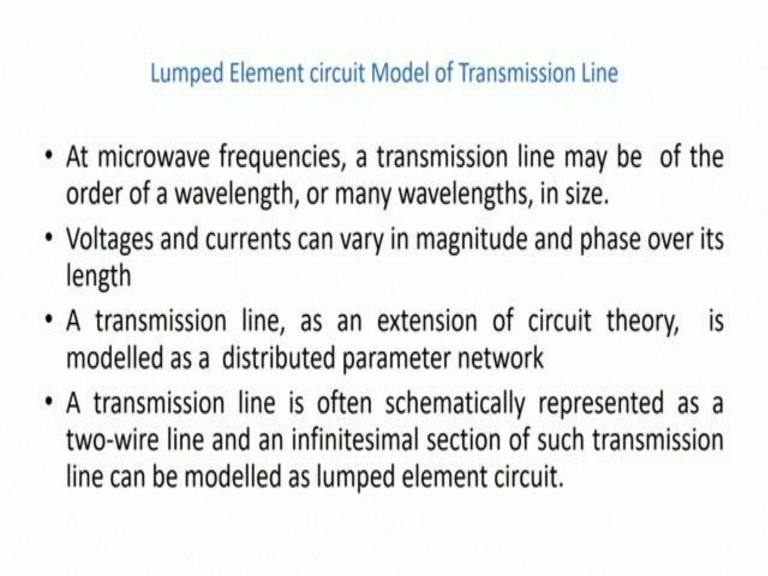

When it comes to microwave frequencies, a transmission line may be of the order of a wavelength or many wavelengths in size. The voltages and currents can vary in magnitude and phase over its length. A transmission line as an extension of circuit theory is modelled as a distributed parameter network. It is often schematically represented as a two-wire line and an infinitesimal section of such transmission line can be modelled as lumped elements circuit.

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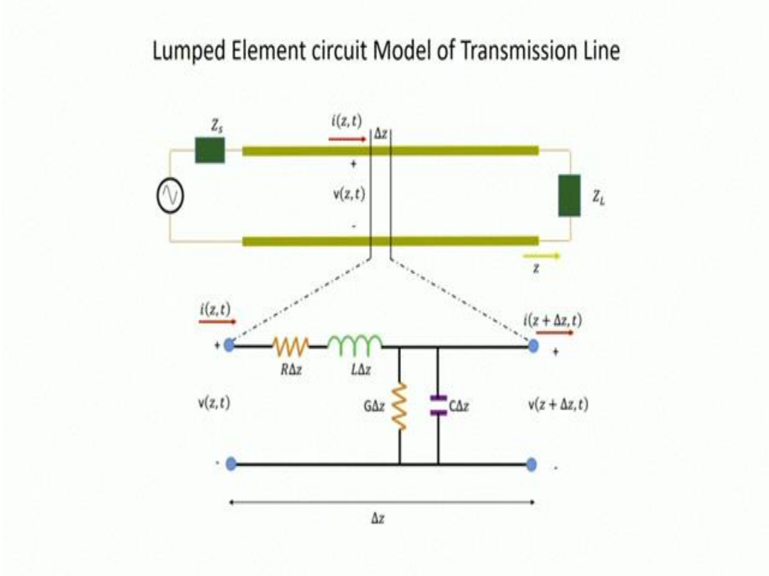

Next we show the representation of some such long elements circuit. Here we see a source is connected to a transmission line and the other end of the line is connected to the load, we considered a very small section ΔZ of this transmission line, since the dimension of ΔZ is now much smaller compared to the wavelength, this section can be modelled through lumped element representation. So here we have a resistance represented by $R\Delta Z$.

Inductance $L\Delta Z$, $G\Delta Z$ represents the conductance and $C\Delta Z$ represents the capacitance. It should be noted that this quantities R, L, G, and C, these are per unit length quantities. The current and voltages, these are functions of both distance and time. So the current at any time T at a distance Z will be different from the current at the other end of the element that is at a distance of $Z + \Delta Z$. Similarly the voltage $V(z, t)$ and $V(z + \Delta z, t)$ will be different. With this representation we can use the circuit theorems to model the transmission line.

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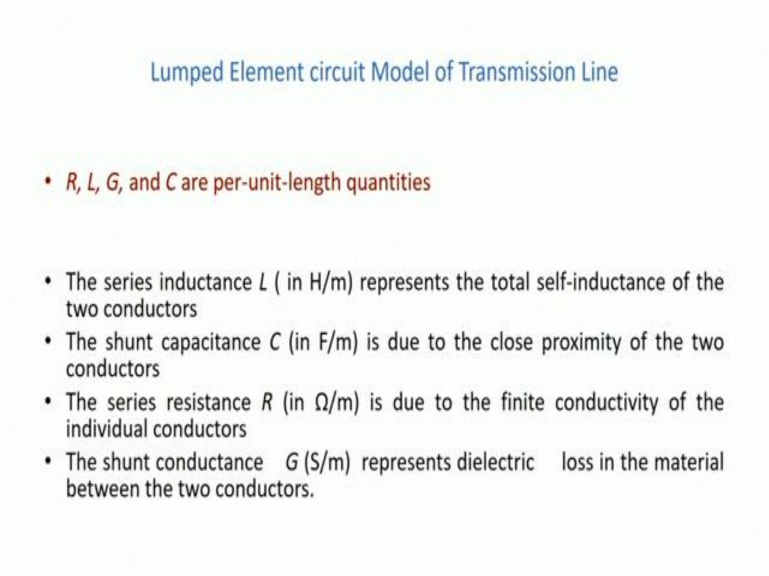

As already mentioned R, L, G, C are per unit length quantities, the series inductance L which is in Henry per metre represents the total self-inductance of the two conductors. Similarly the shunt capacitance C in Farad per metre is due to the close proximity of the two conductors. The series resistance R in ohm per metre is due to the finite conductivity of the individual conductors. It may be noted that R accounts for the loss of power in both the conductors. The shunt conductance G in Siemens per metre represents the dielectric loss in the material between two conductors.

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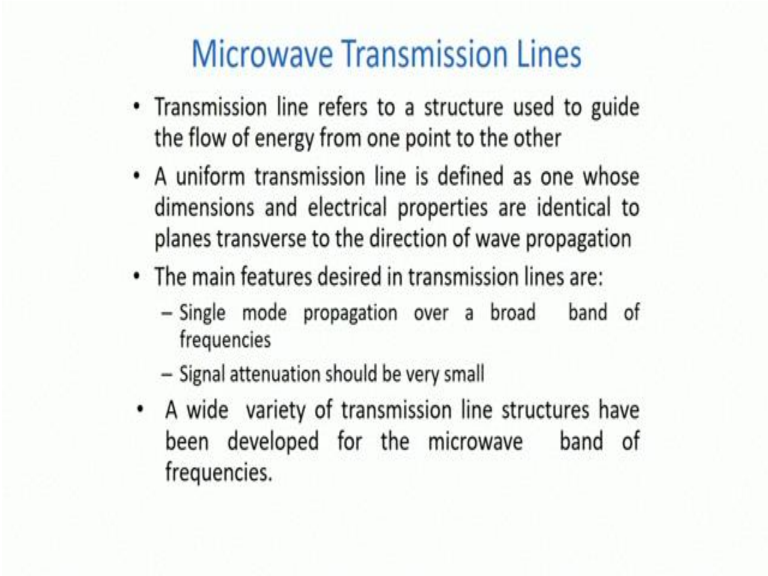

This quantities R, L, G, and C can be computed. This can be determined for simple line geometries through field analysis of transmission lines.

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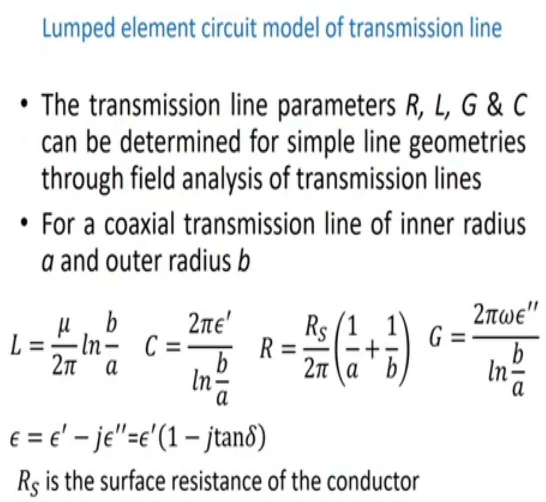

For example if we take a coaxial transmission line, having an inner radius a and outer radius b, then the parameter L is given by $L = \frac{\mu}{2\pi} ln\frac{b}{a}$, capacitance C is $C = \frac{2\pi\epsilon'}{ln\frac{b}{a}}$, R is $R = \frac{R_S}{2\pi}\left(\frac{1}{a}+\frac{1}{b}\right)$ and G is $G = \frac{2\pi\omega\,\epsilon''}{ln\frac{b}{a}}$. Here ω which is $2\pi f$ represents the angular frequency, μ is the permeability and for non-magnetic material μ_r will be 1, so μ will be equal to μ_0. ϵ represents the complex permittivity and the imaginary part of this is related to 10δ and that accounts for the power loss in the substrate, power loss in the dielectric, R_S is the surface resistance of the conductor. So once these parameters are found out, we can use these values in the transmission line, lumped parameter model and a distributed parameter model for the transmission line can be developed.