Chapter 1:

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1.1 OVERLAY:

A new area of research "Study of overlay at microwaves" was added in last three decades. Due to its importance in industry, agriculture, engineering etc. the field is picking up momentum. This work is also one of these activities. Primary information of overlay and a survey of work on overlay are presented in this chapter. The chapter deals with the information in two parts

(i) Introduction and the theoretical background of overlay and overlay effects

(ii) Transmission line structures on which overlays are kept.

1.1.1. Introduction to overlay:

Laying of some material on some microwave passive component like transmission line structure or resonating structure is called as an overlay. Laying material may vary is thickness, in size, in shape and its nature. An overlay material can be of different dielectric constants, different permeability and different conductivity etc. The overlay material is kept on some surface of the transmission line. The overlay may be of single material or composite material. It may also be kept on conductor face or dielectrics of closed structure or it may also be kept on conductor or dielectric of open structure.

The overlay may be solid, liquid and may be available naturally or developed in the laboratory. The overlay may be of single material or composite materials; overlay may be regular or irregular in shapes.

Due to varieties of overlay material and their geometrical structure, overlay can be classified in many ways. Overlay classification can be made on the basis of its material properties, size and orientation. The material properties
may include electromagnetic properties, natural availability, biological and composite nature. We discuss below these in brief.

1.1.2 Overlay Types:

**Basis of electromagnetic properties of material**: Basically, it is the group of electromagnetic properties that exhibits effect of overlay. The materials with dielectric constant different from air but relative permeability $\mu=1$, form dielectric overlay. Piece of glass, drop of water are examples of such overlay. Materials with much higher value of $\mu$ like ferrites, form magnetic overlay.

**Basis of natural availability of material**: The overlay material may be naturally available or may have to be obtained artificially by some chemical process. Soil, Wood, seed, leaf, water are the examples of naturally available materials, where as paper, rubber, soap, glass, paint etc., are examples of artificially made overlay materials.

**Basis of biological nature material**: The overlay material may be of biological origin and to distinguish them from other overlay materials; these will be classified as biomaterial overlays. Leaf, seed, milk part of human body or plant etc. form such a class.

**Basis of number of materials in the overlay structure**: The overlay may be a single material or multi-material body. Mostly an overlay will consist of single material and to distinguish an overlay with materials more than one from the overlay with only one material, a composite overlay classification is used. Overlay consisting of two layers of two different dielectrics is an example of composite overlay.

**Basis of thickness**: Thickness of overlay forms one more point of classification among overlays. If overlay is in the form of film and is having thickness of the order of few micron, then it is called as thin film overlay. For film with higher thickness, overlay is called as thick film overlay. When the overlay is not suitable to be called as film it is known as bulk overlay. The film deposited by
evaporation, colour painting by brush and heap of powder are the examples of thick film and bulk overlay respectively.

**Basis of area coverage:**

When an overlay covers the entire surface of ring resonator, exposed to surroundings, then the overlay is complete overlay. In case of partial area with overlay the overlay is called partial overlay.

**Basis of Volume:**

According to quantity of overlay, Overlays with large volume, large number grains are also grouped as bulk overlay.

**1.1.3 Overlay effects:**

An electromagnetic field show interaction with dielectric material / magnetic material which can be used in varieties of microwave application. The properties of microwave components are found to change due to overlay. Changes in dielectric constant, conductivity, permeability, thickness and nature of overlays produce changes in the characteristics of the microwave components. Important properties of microwave components are cut-off frequency, attenuation, band width, Q factor, impedance, power loss etc.

These properties can be changed or controlled with overlay of materials with adjustable overlay properties. Dielectric bulk overlay creates region of high dielectric constant material above the microwave structure that confines the fringing field to the substrate and thus enhances transmission. The complete overlay as well as partial overlay, both, affect the fringing field of microstrip line but to a different extent.

**1.1.4. Literature Survey:**

As there are changes in the properties of microwave components when overlay is kept on them. The material kept on microstrip transmission line structures, resonator or coated surface, coating of waveguide change the properties of the corresponding component. Chun [1] analysed using numerical method circular waveguide coated with a lossy material to study the attenuation
properties as a function of coating material thickness of layer and frequency. Further they studied the propagation constant, wave number and cut-off frequencies in magnetic material coated waveguide as well as in a dielectric coated waveguide.

A three component finite element method is used by M-Fana [2] to study rectangular waveguide behavior loaded with dielectric on the broader wall. Theoretical investigation on changes in propagation characteristics of waveguide due to loading of its surface with dielectrics is carried by many workers and finite element method is the prominent method used for this purpose. Tuptim [3] used an efficient formulation of FEM to find dispersion characteristics of dielectric loaded rectangular waveguide and ferrite loaded rectangular waveguide.

Jain Ming Jin and Valvis V. Liepa [4] studied the electro magnetic scattering (E-polarization and H-Polarization) by coating / painting (rectangular and circular) cylinders with dielectric and / or magnetic materials by applying the hybrid Finite Element method analysis.

The LSM and LSE modes are identified and their dispersion curves are obtained. Chung [5] and others analysed the LSE and LSM modes and obtained various propagation characteristics such as phase constant, useful band width, power handling capacity, attenuation constant for rectangular waveguide loaded with a slave of parabolic dielectric profile.

Bardi [6] used a numerically efficient finite elements formulation for analysis of rectangular and elliptic cross section waveguide loaded with anisotropic, dielectric and magnetic ferrite materials. In this the dispersion characteristics, dissipation power propagation are studied [1]. J. P. Webb, [9] kept a cylindrical metal post in rectangular wavguide, and studied the transmission coefficient as a function of height of cylindrical post using FEM and FDM methods. The cylindrical post is kept parallel to electrical field of dominant TE_{10} mode.
Bernice M Dhillon and John P. Webb [8] had calculated (7) the cutoff waveguide numbers of first three modes in the rectangular waveguide partially loaded with lossless dielectric on its broader side and also with shorter side. Boundary integral formulation is employed to study dispersion curve for dominant and higher modes for dielectric loaded rectangular waveguide. The basic study of effect of dielectric material loading on the conducting wall of a rectangular waveguide is by Collin. [10]

1.2 WAVEGUIDES:

Waveguides are used for transmitting electromagnetic fields in UHF and microwave frequency region (3-300 GHz). A waveguide is a hollow metallic tube of rectangular or circular cross-section. Generally waveguides are constructed from brass, copper or aluminum. In the microwave region the coaxial cables become inefficient due to skin effect and dielectric losses, waveguides are used to obtain larger bandwidth and lower signal attenuation. The coaxial cables are capable of guiding energy from point to point in TEM mode, where as transmission of energy in TE and TM modes can be achieved by use of waveguide. Frequencies above $f_c$, cutoff frequency, of a waveguide will be propagated and all lower frequencies will be attenuated. Thus, waveguides acts as high-pass filters. The wave is propagated by reflections from the inner walls of the waveguide hence the inner walls of waveguides are smooth, moisture-free and often silver coated.

There are various types of waveguides. Electromagnetic waves can travel through any shape of cross section of a waveguide having same cross-section along the length. Waveguides with irregular shapes of cross-section are different to analyse and are rarely used. Rectangular waveguide and circular waveguide are easily analysed and commonly used in microwave frequency range. The ridge waveguide is a modification of rectangular waveguide with single, double or multiple ridges on the longer side of rectangular waveguide. It may be present on
top or bottom side of the rectangular waveguide. Elliptical waveguide is a form of circular waveguide.

The electromagnetic wave to be transmitted travel longitudinally down the length of the waveguide. The conducting walls of the waveguide keep the electromagnetic field within waveguide limits and guide the wave. The wave is reflected between the walls and due to multiple reflections number of distinct field configurations can exist in waveguides. Each of these field configuration is called a MODE.

Circular waveguide, due to rotational symmetry, allow the use of rotating joints and are used with rotating antennas in radars. Elliptical shape is often preferred in flexible the waveguide section should be capable of movement, like bending stretch in or twisting. A copper tube having an elliptical cross section is a good example of a flexible waveguide.

Ridging is a convenient method of reducing the waveguide dimensions and increasing the critical wavelength. However, the presence of ridge has the disadvantage of increased attenuation, reduced power handling capacity and introducing distortions. The frequency range of the waveguide is increased by ridging. It also helps, in reducing the phase velocity.
1.3 RECTANGULAR WAVEGUIDE

A rectangular waveguide is a conducting pipe characterised by rectangular cross-section having its wider dimension ‘a’ and narrow dimension ‘b’.

There are two types of modes of propagation of electromagnetic waves in a rectangular waveguide. i) TM mode (Transverse Magnetic) ii) TE mode (Transverse Electric)

In TM mode, magnetic lines are entirely transverse to the direction of propagation of electromagnetic wave and electric field has a component in the direction of propagation.
In TE mode, the electric field lines are entirely transverse to the direction of the propagation where as magnetic field has a component along the direction of propagation.

The propagation modes for both TM and TE are designated by two subscripts. The first subscript indicates the number of half wave variations of the electric field in the wide dimension 'a' of the wave guide where as second subscript indicates the number of half wave variations of the electric field along the narrow dimension of the waveguide 'b'.

Depending on the integer values of m and n, a mode is denoted by TE_{mn} or TM_{mn} mode. For m = 0 and n = 0, i.e. the number of half wave variations on wide dimension and narrow dimensions are zero; therefore all the field components vanished inside the waveguide making the mode non-existing.

Cutoff wavelength is the wavelength of the signal below which the propagation of wave occurs and above which there is attenuation or no propagation. The cutoff wavelength is denoted by \( \lambda_c \).

The cutoff wavelength for rectangular waveguides for both TE_{mn} and TM_{mn} is given by

\[
\lambda = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}} \quad (1.3.1)
\]

i.e.

\[
\lambda_{cm,n} = \frac{2ab}{\sqrt{m^2b^2 + n^2a^2}} \quad (1.3.2)
\]

The frequency associated with cutoff wavelength is called cutoff frequency (\( f_c \)) and is given by

\[
f_c = \frac{1}{2\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \quad (1.3.3)
\]

Dominant mode or fundamental mode is a mode which offers highest cut off wavelength (\( \lambda_c \)) or lowest cutoff frequency (\( f_c \)) in a particular waveguide among
all modes. $TE_{10}$ is the dominant mode of rectangular waveguide with cutoff wavelength.

$$\lambda_{c01} = \frac{2ab}{\sqrt{a^2}} = 2b$$ \hfill (1.3.4)

and cutoff frequency of fundamental mode is

$$f_{c10} = \frac{1}{2\sqrt{\mu}a}$$ \hfill (1.3.5)

Field pattern for $TE_{mn}$ modes in rectangular waveguide are shown in the Fig. 1.3 and in Fig.1.4.
Fig.1.4 Field patterns for some higher-order TE modes in rectangular waveguide
Wave impedance is defined as the ratio of transverse electric field to transverse magnetic field at any point in the waveguide. For TM wave in rectangular waveguide.

\[ Z_{TM} = \eta \sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \quad (1.3.6) \]

Wave impedance for TE wave in rectangular waveguide

\[ Z_{TM} = \frac{\eta}{\sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2}} \quad (1.3.7) \]

where \( \eta \) = Intrinsic impedance for free space =120\pi

Since \( \lambda_0 \) is always less than \( \lambda_c \) for wave propagation \( Z_{TM} < \eta \)

1.4 CIRCULAR WAVEGUIDE:

Circular waveguide is the next most commonly used waveguide and is as shown in fig. 1.5.

![Circular waveguide](image)

**Fig. 1.5 Circular waveguide**

A circular waveguide is a tubular, circular conductor. A plane wave propagating through a circular waveguide results in a transverse electric (TE) or transverse magnetic (TM) modes. Just as in rectangular waveguides, the modes in circular waveguides are \( \text{TE}_{m,n} \) and \( \text{TM}_{m,n} \) due to the circular rather than rectangular configuration of the waveguide, the subscripts \( m \) and \( n \) have other meanings. The \( m \) term indicates the number of full wavelengths around the
circumference of the guide and the \( n \) term indicates the number of one-half wavelengths across the diameter of the circular waveguide.

The cut-off wavelength for TE and TM waves is given by,

\[
\lambda_c = \frac{2\pi a}{P_{nm}} \tag{1.4.1}
\]

where \( P_{nm} \) is the \( m \)th root of \( J_n(P) = 0 \) for TM mode and \( J'_n(P) = 0 \) for TE mode. TE11 is the dominant mode in circular waveguide with cutoff wavelength

\[
\lambda_{c11} = \frac{2\pi a}{1.841} \tag{1.4.2}
\]

Typical electric and magnetic field patterns for TE_{m,n} and TE_{m,n} modes in the circular waveguides are shown in fig. (1.6).

\[(a) \ TE_{0,1} \ Mode \quad (b) \ TM_{0,1} \ Mode \]
\[(c) \ TE_{1,1} \ Mode \quad (d) \ TM_{1,1} \ Mode \quad (e) \ TE_{2,1} \ Mode \]

*Fig. 1.6 filed patterns in circular waveguide*

Due to the symmetry of circular waveguides, rotation of the guide has no effect on the wave. Rotation of rectangular waveguides is not possible because of its lack of symmetry.

Wave impedance in TE mode

\[
Z_{\text{TE}} = \frac{\omega \mu}{\beta} = \frac{\eta}{\sqrt{1 - (\lambda_o / \lambda_c)^2}} \tag{1.4.3}
\]
Wave impedance in TM mode
\[ Z_{\text{TM}} = \frac{\beta}{\omega \mu} = \eta \sqrt{1 - (\lambda_0 / \lambda_c)^2} \] (1.4.4)

Similar to rectangular waveguides, it is possible to determine the attenuation in a circular waveguide for TE and TM modes. The attenuation in an air filled circular waveguide is due to finite conductivity of the guide walls and is given by.

\[ \alpha = \frac{\text{Power loss/unit length}}{2(\text{Average power transmitted})} \] (1.4.5)

The attenuation constant \( \alpha \) for TE and TM modes can be written as:

\[ \alpha_{\text{TM}} = \frac{R_s}{\alpha Z_0 \sqrt{1 - (f_c / f)^2}} \] (1.4.6)

For TM\( m \) modes, attenuation falls off as \( f^{3/2} \) as per

\[ \alpha = \frac{R}{\alpha Z_0 f(t^2 - f_c^2)^{-1/2}} \] (1.4.7)

This rapid decrease of attenuation with frequency of TE\( 01 \) mode helps it to be useful for long low loss waveguide communication links. However, all modes above dominant mode (TE\( 11 \)), result in mode conversion leading to signal distortion.

1.5 RIDGE WAVEGUIDE:

Instead of rectangular cross-sectional waveguides if we consider deformation of waveguide with deformed cross-section, by some means, characteristics of propagation of wave through waveguide changes. Such deformed waveguide may be formed by central ridge either at top or bottom or both of rectangular sections then deformed rectangular waveguide is called ridge waveguide (fig 1.7).
The rectangular guide can also be manufactured with either a single or double ridge. The cross sectional view of double ridge waveguide is shown in fig. 1.8.

Ridged waveguide uniformly loads the waveguide and has the advantage of lowering the characteristic impedance and increasing the bandwidth of the waveguide. Phase velocity is also lowered, which results in a lower cutoff frequency for the dominant mode. This allows the use of a smaller, ridged waveguide rather than the larger, rectangular waveguide for the same application. With ridged waveguide, the characteristic impedance of the line can be varied over a large range of values. Ridged waveguide can be tapered to match two waveguides of different of different characteristic impedances. Another advantages is an increase in band-width, which is useful in some applications. A disadvantage of ridged waveguide is an increase in attenuation that restricts its
use to short line lengths. Ridged waveguide is available in standard sizes and is compatible with standard rectangular waveguide.

1.6 PLANAR TRANSMISSION LINES:

Planar transmission lines have geometry that allows to control the characteristic impedance of the line by controlling its dimension. The complete transmission line circuit can be fabricated in one step by thin film technology and photolithography techniques. Several configurations of planar transmission lines can be possible. Some commonly used configurations are stripline, microstrip, slotline and coplanar lines.

1.6.1 Stripline:

Stripline is a three conductor transmission line and is a modification of two wire lines and co-axial lines used at frequencies from 100 MHz to 100 GHz. It consists of a strip and two ground planes and its cross section is shown in Fig. 1.9. The width of the strip (w) is much greater than its thickness (t) i.e. \( w \gg t \). The space between two ground plane is filled with a homogeneously dielectric medium, the strip is embedded in this dielectric medium.

![Fig. 1.9 Cross-section of stripline](image)

The dominant mode of propagation in strip line is a pure transverse electromagnetic (TEM) i.e. the electric and magnetic field components are transverse to the direction of propagation. The field lines are concentrated near
the strip and decay exponentially towards ground planes which are at zero potential. The electric and magnetic field distribution is shown in Fig. 1.10

![Electric and Magnetic Field Distribution](image)

**Fig. 1.10 E and H field distribution of strip-line**

The dimensions of stripline are chosen so as to operate in TEM mode with minimum losses. Higher order modes are not allowed to propagate this can be ensured by keeping distance between ground planes less than $\lambda_d/2$ where $\lambda_d$ is wavelength in dielectric medium. Teflon and Polystyrene are commonly used dielectrics.

1.6.2 Microstrip:

Microstrip line consists of single dielectric substrate with ground plane on one side and a strip on the other face. Fig. 1.11 shows cross sectional view of a microstrip.

![Microstrip Cross Section](image)

**Fig. 1.11 Cross section of microstrip**
The upper ground plane in stripline is not present in microstrip; hence microstrip is called as openstripline. The mode of propagation in microstrip is quasi-TEM. Approximate distributions of the electric and magnetic fields in a microstrip are sketched in Fig. 1.12 (a) and 1.12 (b) respectively. Because of the concentration of electric field in the dielectric region below the strip most of the energy of the wave is concentrated there. The distribution of the electric field lines Fig. 1.12 (a) indicates that E lines approach the air-dielectric interface obliquely, and thus there are at least two components of the electric field.

![Fig. 1.12 (a)](image1)

![Fig. 1.12 (b)](image2)

However, since the major portion of electric field lines is concentrated below the strip, the electric flux crossing the air dielectric boundary is small. Therefore, the deviation from the TEM mode is small and may be ignored for most of the circuit design applications. Due to easy access to the top surface it is easy to mount discrete (active or passive) devices. But the openness of the structure leads to higher radiation loss or interference with nearby conductors. The use of high dielectric constant of substrate reduces phase velocity (and guide wavelength) and consequently the circuit dimensions.

There are various types of microstrip lines used in practice as embedded microstrip, standard inverted microstrip, suspended microstrip and slotted transmission line as shown in fig. 1.13.
Characteristics impedance of microstrip with strip width \( W \) and substrate height \( h \) is given by

\[
Z_0 = \frac{42.4}{\sqrt{\varepsilon_r} + 1} \ln \left\{ 1 + \left( \frac{4h}{W} \right) \left( \frac{14 + 8/\varepsilon_r}{11} \right) \left( \frac{4h}{W} \right) + \sqrt{\left( \frac{14 + 8/\varepsilon_r}{11} \right)^2 \left( \frac{4h}{W} \right)^2 + \frac{1 + 1/\varepsilon_r - \pi^2}{2}} \right\}
\]

(1.6.1)

The Q-factor of a microstrip is given as

\[
Q = 0.63h \sqrt{\sigma f}
\]

(1.6.2)

where \( \sigma \) = conductivity of dielectric and \( f \) = operating frequency.
1.7 AIM OF PRESENT WORK:

The aim of the present work is to study the effect of overlay on the propagation properties of different types of wave guiding structures. The structures considered are

- Rectangular wave guide
- Circular waveguide
- Ridge wave guide
- Microstrip

The dispersion characteristics of the guiding structures will be studied together with their cutoff frequencies for fundamental and first higher mode. Band-width variations with overlay is another point of study.

The Finite Element Method will be used to deal with these problems.
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