Microwave Engineering
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Lecture No. 31
Ferrite Devices

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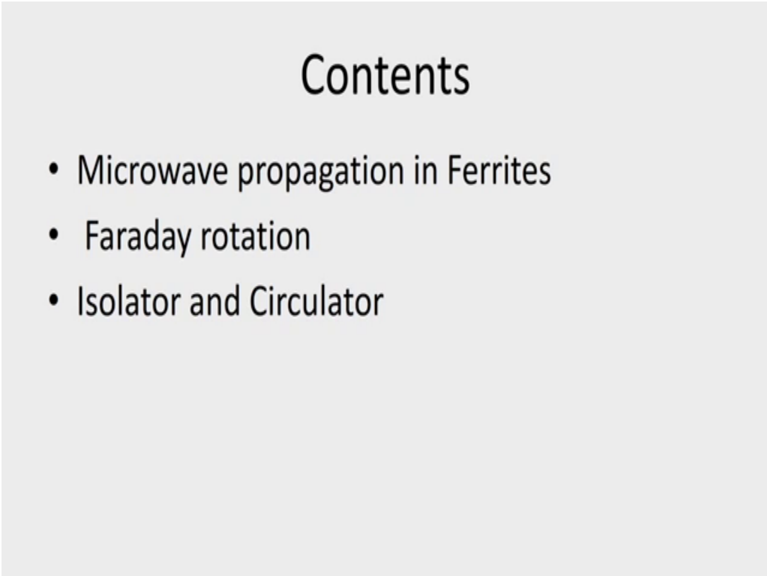

We started new module ferrite devices. In this module, we are going to cover basics of microwave propagation in ferrites. Then we will discuss the concept of Faraday rotation, and then we will discuss how this Faraday rotation effect is utilized in designing devices called isolator and circulator.

Isolator and circulator they have non-reciprocal transmission characteristics. The isolator will allow transmission of signal in one direction only, and these types of devices and the circulator actually it can be a clockwise circulator or a counter-clockwise circulator, as we have already mentioned, and it can transmit signal from one port to the next port, other port remaining isolated. So, these types of devices are realized using Faraday rotation effect, and ferrite materials are used in the design of such devices.

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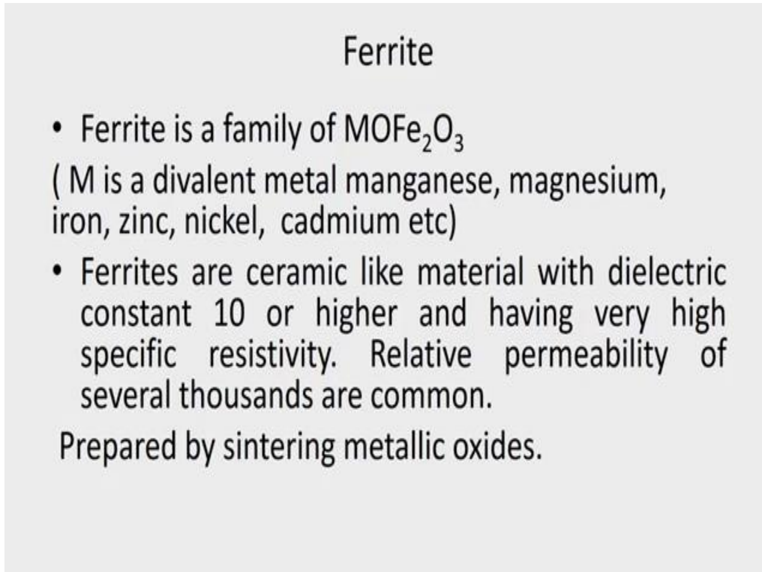

We start our discussion by briefly describing what a ferrite material is. A ferrite is a family of MOFe2O3, Fe2O3 is ferric oxide, M here is a divalent metal, and O is the oxide again. So, M is a divalent metal which can be manganese, magnesium, iron, zinc, nickel, cadmium, etcetera. Now, these ferrites are ceramic-like material with dielectric constant usually 10 or higher and having very high specific resistivity. And relative permeability of several 1000s is very common for this type of material. Now, they are prepared by sintering metallic oxides.

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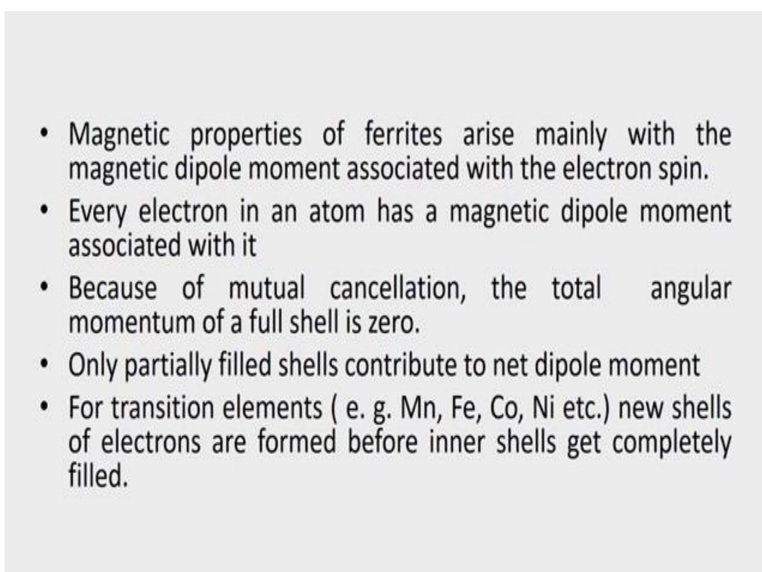

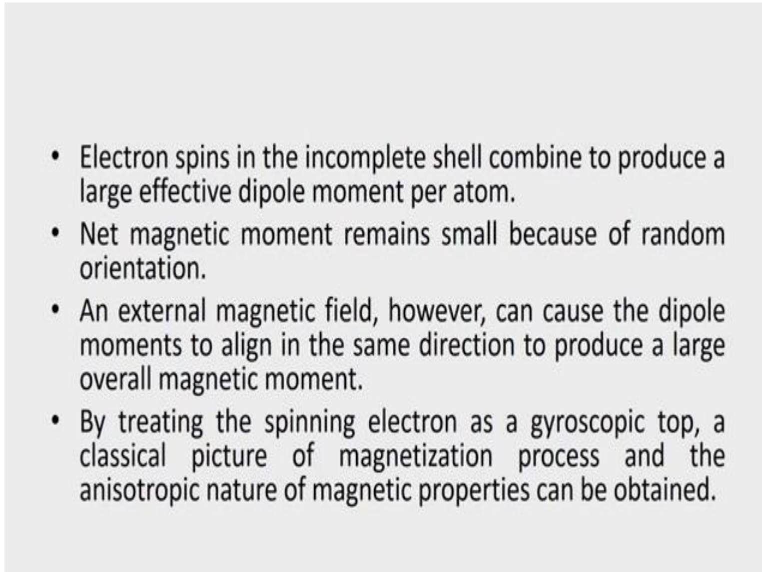

The magnetic properties of ferrites arise mainly with the magnetic dipole moment associated with the electron spin. Every electron in an atom has a magnetic dipole moment associated with it. Because of mutual cancellation, the total angular momentum of a full shell is 0. So, if a shell of an atom is fully filled, then these magnetic dipole moments cancel out each other.

Only partially filled shells contribute to the net dipole moment. Now, for transition elements, like manganese, iron, cobalt, nickel, etcetera, new shells of electrons are formed before inner shells get completely filled. So, we have the formation of outer shells even when inner shells are not fully filled and giving rise to partially filled shells.

Electron spins in the incomplete shell combine to produce a large effective dipole moment per atom. Now, when these moments, they are randomly oriented, the net dipole moment remains small as they cancel each other’s effect. An external magnetic field, however, can cause the dipole moments to align in the same direction to produce a large overall magnetic moment. By treating the spinning electron as a gyroscopic top, a classical picture of the magnetization process and the anisotropic nature of magnetic properties can be obtained.

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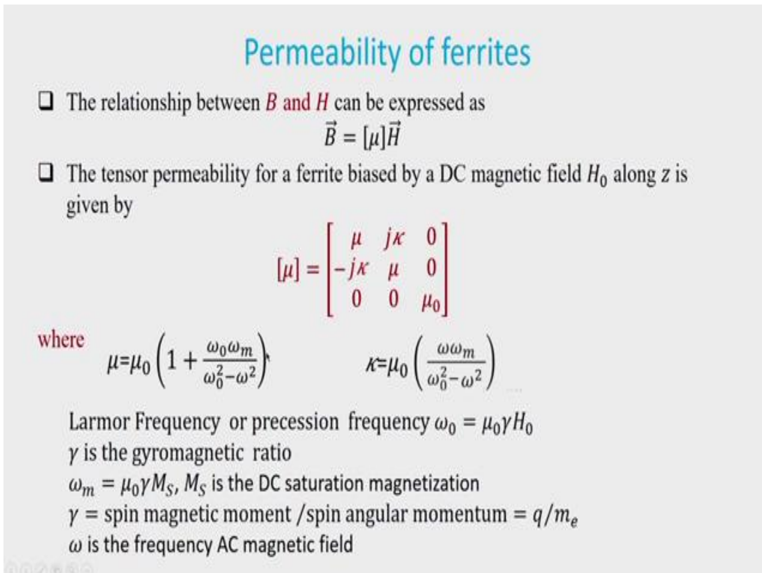
$$\vec{B} = [\mu]\vec{H}$$

$$[\mu] = \begin{bmatrix} \mu & j\kappa & 0 \\ -j\kappa & \mu & 0 \\ 0 & 0 & \mu_0 \end{bmatrix}$$

$$\mu = \mu_0 \left(1 + \frac{\omega_0 \omega_m}{\omega_0^2 - \omega^2}\right)$$

$$\boldsymbol{\kappa} = \boldsymbol{\mu_0} \left(\frac{\boldsymbol{\omega \omega_m}}{\boldsymbol{\omega_0^2 - \omega^2}}\right)$$



Let us now have a look at the permeability of ferrites. The relationship between B and H for a ferrite material can be expressed as B here mu is a tensor permeability as we will see H and the tensor permeability for a ferrite biased by a DC magnetic field H naught along z naught is given by this matrix, mu j kappa 0 minus j kappa mu 0, 0 0 mu naught.

Now, in ordinary non-magnetic material, the permeability is a scalar constant where B is equal to mu H. Similarly, for many magnetic materials this relationship holds but when it comes to ferrite, the permeability becomes a tensor permeability, and from this relationship we see that every component, suppose only H_x is present, H_y, and H_z is 0 then also we will get Bx, By, Bz.

So, each filled component actually contributes to all flux density components. So, this type of behavior comes because of the anisotropy present in ferrite material, and this mu kappa, they are defined as mu is equal to mu naught 1 plus omega naught omega m by omega naught square minus omega square. Kappa is equal to mu naught omega m divided by omega naught square minus omega square.

Now, let us see the parameters, omega naught is called the Larmor frequency or precession frequency and it is given by mu naught gamma H naught, H naught is the bias field that is applied, magnitude of the bias field and gamma it is the gyromagnetic ratio, and it is the ratio of the spin magnetic moment to the spin angular moment.

Now, electron spin is associated as we have told with a magnetic moment, and it is also associated with an angular momentum, which is given by H by 2. Now, this angular momentum and the moment due to spin, they are oppositely directed, and this ratio, gyromagnetic ratio can be calculated as q divided by m_e, q is the electronic charge, and m_e is the effective mass of the electron.

When this ferrite material, when a bias field is applied to a ferrite material, what happens, this magnetic dipole moment they try to align along the applied field and if the strength of the applied bias field is kept on increasing, a scenario will come when all this dipole moments, they get aligned, and this condition corresponds to a saturation condition of magnetization. So, this is denoted by M_s and omega m is mu naught gyromagnetic ratio gamma into M_s.

Now, in ferrite material, we will have waves propagating, and omega is the frequency of the AC magnetic field component that is present. So, we see that the magnetic field and the flux density in a ferrite medium, they are related by this permeability tensor mu.

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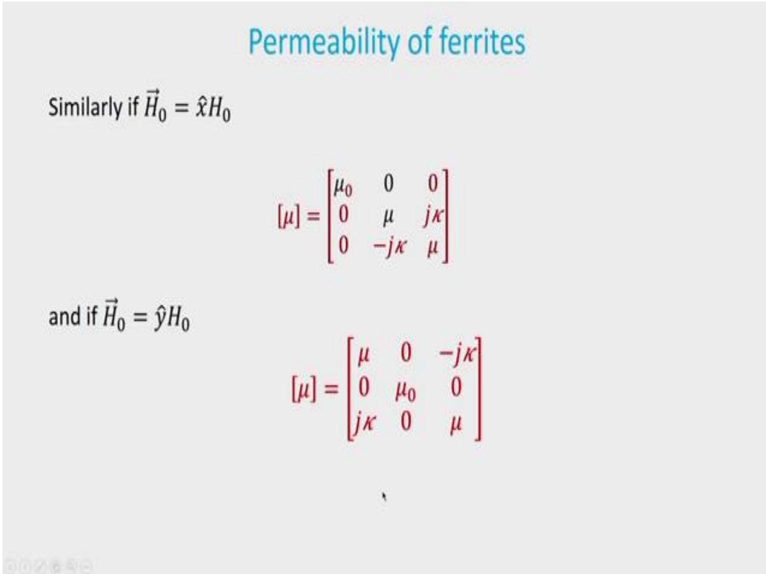
Similarly if $\vec{H}_0 = \hat{x}H_0$

$$[\mu] = \begin{bmatrix} \mu_0 & 0 & 0 \\ 0 & \mu & j\kappa \\ 0 & -j\kappa & \mu \end{bmatrix}$$

and if $\vec{H}_0 = \hat{y}H_0$

$$[\mu] = \begin{bmatrix} \mu & 0 & -j\kappa \\ 0 & \mu_0 & 0 \\ j\kappa & 0 & \mu \end{bmatrix}$$



If you change the bias, for example, if the biasing magnetic field is now placed along x-direction, then we will get mu to be equal to mu naught 0 0, 0 mu j kappa, 0 minus j kappa mu. Similarly, we can apply this biasing field also along y-direction and we get the corresponding permeability tensor as shown.

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We consider an infinite ferrite medium with a DC bias field $\vec{H}_0 = \hat{z}H_0$

$$\nabla \times \vec{E} = -j\omega[\mu]\vec{H} \qquad \nabla \cdot \vec{D} = 0$$
$$\nabla \times \vec{H} = j\omega\epsilon\vec{E} \qquad \nabla \cdot \vec{B} = 0$$

Wave propagation is considered in the z-direction and $\frac{\partial}{\partial x} = \frac{\partial}{\partial y} = 0$. Let the fields be of the form

$$\vec{E} = \vec{E}_0 e^{-j\beta z} \quad \vec{H} = \vec{H}_0 e^{-j\beta z}$$

$j\beta E_y = -j\omega\left(\mu H_x + j\kappa H_y\right)$

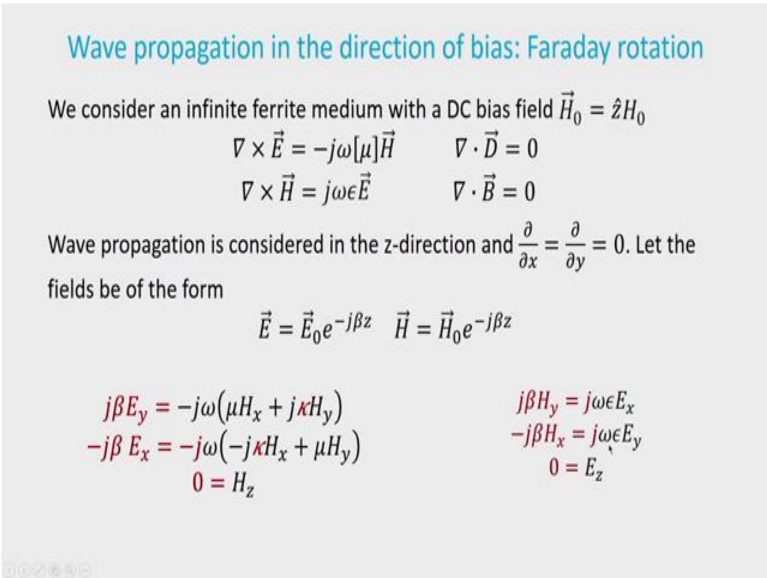
$-j\beta\, E_x = -j\omega\left(-j\kappa H_x + \mu H_y\right)$

$0 = H_z$

$$j\beta H_y = j\omega\epsilon E_x$$

$$-j\beta H_x = j\omega\epsilon E_y$$

$$0 = E_z$$



Let us now consider the wave propagation in the direction of bias and which gives rise to Faraday rotation. Faraday rotation is essentially a rotation of the wave polarization as the wave propagates in the media. So, this effect is utilized in the design of devices like isolators. So, let us first consider an infinite ferrite medium with a DC bias field H naught is equal to z bar into H naught.

Now, we can write Maxwell's equation in this ferrite media where we have included this tensor mu. Remaining equations are the same. Now, we consider the wave, a plane wave propagating along z, and for a plane wave propagation we will have del del x is equal to del del y equal to 0. And also let us assume that the propagating fields can be described by E bar is equal to E naught bar e to the power minus j beta z, H bar is equal to H naught bar e to the power minus j beta z, so we are only considering the phases.

Now, in this (())(15:52) expression, we will have del del x del del y 0, and therefore only del del z will be present and derivative with respect to z will give minus j beta. So, we can write j beta Ey is equal to minus j omega, and then we will have mu Hx plus j kappa H y. This will come from this term, and once we write the filled components separately, we get these 3 equations.

Similarly, from (())(16:57) H equal to j omega epsilon E, we will get this set of equations. Now, from this set of equations, we observe that the wave admittance H_y by E_x is equal to omega epsilon by beta. Similarly, minus H_x by E_y is also omega epsilon by beta.

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$$Y = \frac{H_y}{E_x} = -\frac{H_x}{E_y} = \frac{\omega\epsilon}{\delta}$$

$$j\omega^2\epsilon\kappa E_x + (\beta^2 - \omega^2\mu\epsilon)E_y = 0$$

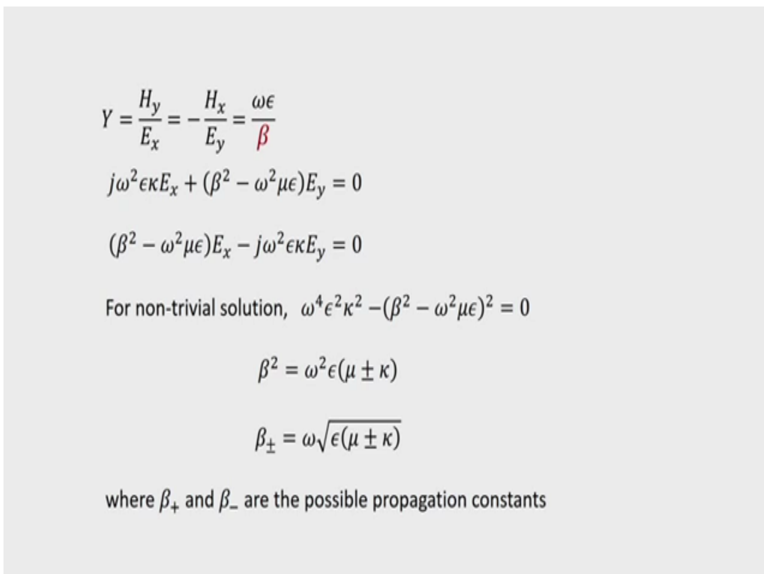
$$(\beta^2 - \omega^2\mu\epsilon)E_x - j\omega^2\epsilon\kappa E_y = 0$$

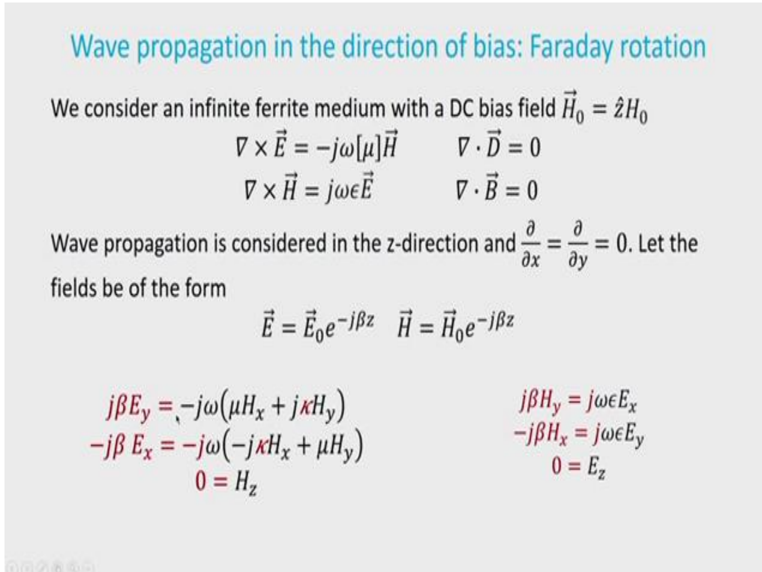
For non-trivial solution, $\omega^4\epsilon^2\kappa^2 - (\beta^2 - \omega^2\mu\epsilon)^2 = 0$

$$\beta^2 = \omega^2\epsilon(\mu \pm \kappa)$$

$$\beta_\pm = \omega\sqrt{\epsilon(\mu \pm \kappa)}$$

where β_+ and β_- are the possible propagation constants





So, we write Y equal to H_y by E_x, which is equal to minus H_x by E_y is equal to omega epsilon by beta. Now, once we substitute, for example here we can substitute H_x in terms of E_y and H_y in terms of E_x, similarly in the second equation also we can substitute H_x and H_y in terms of E_x and E_y and once this is done we get a set of 2 equations, j omega square epsilon kappa E_x plus beta square minus omega square mu epsilon E_y equal to 0. Similarly, beta square minus omega square mu epsilon E_x minus j omega square epsilon kappa E_y equal to 0.

Now, we have the set of these 2 equations, and for this equation to give a non-trivial solution we must have this determinant formed by the coefficient of E_x and E_y has to be 0, and therefore we get omega to the power 4 epsilon square kappa square minus beta square omega square mu epsilon whole square must be equal to 0.

So, from this condition, if we solve for beta we get two possible propagation constants. We denote them by beta plus and beta minus. So, the beta plus will be omega root epsilon mu plus kappa, and beta minus will be omega root epsilon mu minus kappa. So, we see that in the same media, now we have two propagation constants. And this beta plus and beta minus will give rise to wave propagation with different velocities.

We will see how we can infer Faraday rotation, which corresponds to rotation of polarization of the wave with distance by considering these beta plus and beta minus. So, we find that when a plane wave it propagates in a biased ferrite media and the bias is applied along the direction of propagation, we get two values of propagation constants, which are denoted by beta plus and beta minus.

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$$\beta_+ = \omega\sqrt{\epsilon(\mu + \kappa)}$$

$$j\omega^2\epsilon\kappa E_x + (\beta^2 - \omega^2\mu\epsilon)E_y = 0$$

Substituting β_+ we get,

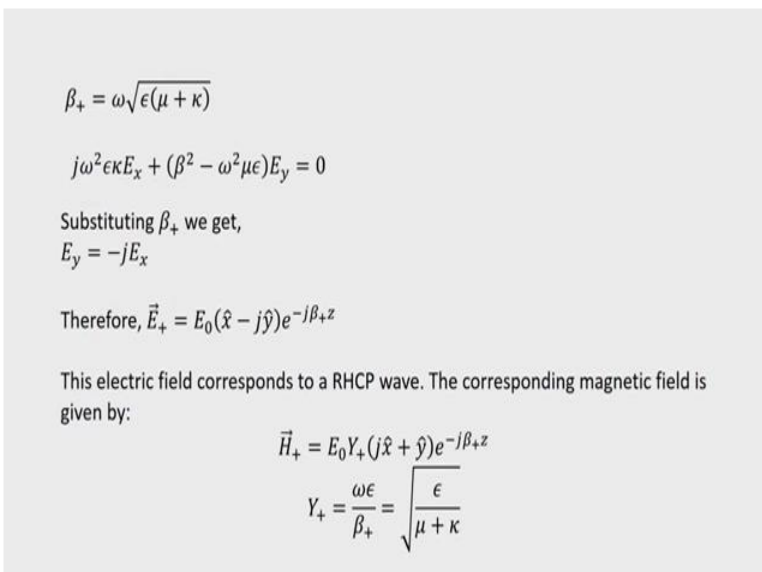
$E_y = -jE_x$

Therefore, $\vec{E}_+ = E_0(\hat{x} - j\hat{y})e^{-j\beta_+ z}$

This electric field corresponds to a RHCP wave. The corresponding magnetic field is given by:

$$\vec{H}_+ = E_0 Y_+(j\hat{x} + \hat{y})e^{-j\beta_+ z}$$

$$Y_+ = \frac{\omega\epsilon}{\beta_+} = \sqrt{\frac{\epsilon}{\mu + \kappa}}$$



Let us now consider the field corresponding to beta plus, beta plus is given by omega root epsilon mu plus kappa and when this substituting beta plus in this equation we get Ey is equal to minus j Ex and therefore we can now write, the electric field corresponding to beta plus as E plus equal to E naught x cap minus j y cap e to the power minus j beta plus z, now these are unit vectors

Now, this electric field corresponds to a right-hand circular polarized wave or an RHCP wave, and we can get the corresponding magnetic field as H plus equal to E naught Y plus j x cap plus y cap e to the power minus j beta plus z. Here Y plus is the wave admittance corresponding to beta plus and is given by omega epsilon by beta plus, which can be written as root of epsilon by mu plus kappa.

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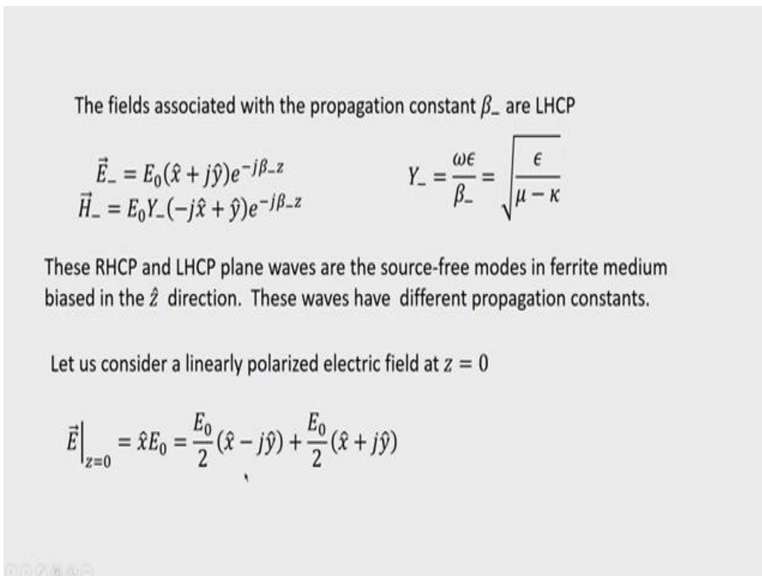
$$\vec{E}_- = E_0(\hat{x} + j\hat{y})e^{-j\beta_- z}$$

$$\vec{H}_- = E_0 Y_-(-j\hat{x} + \hat{y})e^{-j\beta_- z}$$

$$Y_- = \frac{\omega\epsilon}{\beta_-} = \sqrt{\frac{\epsilon}{\mu - \kappa}}$$

$$\vec{E}\Big|_{z=0} = \hat{x}E_0 = \frac{E_0}{2}(\hat{x} - j\hat{y}) + \frac{E_0}{2}(\hat{x} + j\hat{y})$$



In the same manner, we can find that the fields associated with the propagation constant beta minus are LHCP or left hand circularly polarized. And therefore we can write E for beta minus E and H expression as shown, and Y minus the wave admittance corresponding to beta minus is given by under root epsilon by mu minus kappa. These RHCP and LHCP plane waves are the source-free modes in ferrite medium biased in the z-direction. These waves have different propagation constants.

Now, let us consider a linearly polarized electric field at z is equal to 0. So, at z is equal to 0 the electric field E, which is directed along x can be written in this form.

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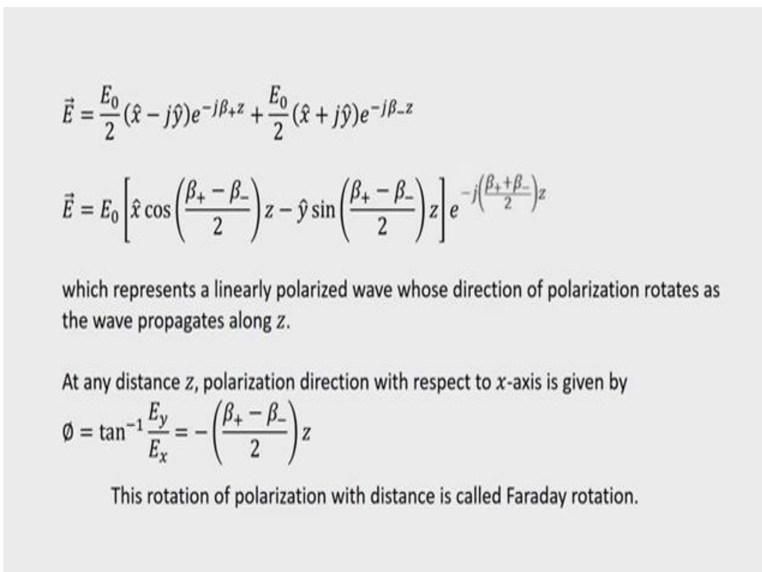
$$\vec{E} = \frac{E_0}{2}(\hat{x} - j\hat{y})e^{-j\beta_+ z} + \frac{E_0}{2}(\hat{x} + j\hat{y})e^{-j\beta_- z}$$

$$\vec{E} = E_0\left[\hat{x}\cos\left(\frac{\beta_+ - \beta_-}{2}\right)z - \hat{y}\sin\left(\frac{\beta_+ - \beta_-}{2}\right)z\right]e^{-j\left(\frac{\beta_+ + \beta_-}{2}\right)z}$$

which represents a linearly polarized wave whose direction of polarization rotates as the wave propagates along z.

At any distance z, polarization direction with respect to x-axis is given by

$$\emptyset = \tan^{-1}\frac{E_y}{E_x} = -\left(\frac{\beta_+ - \beta_-}{2}\right)z$$



And therefore, at any z we can write E as E naught by 2 x cap minus j y cap e to the power minus j beta plus z plus E naught by 2 x cap plus j y cap e to the power minus j beta minus z. And this can be rearranged in this manner, E is now actually summed of an RHCP, and an LHCP wave and the electric field expression can be rearranged in this manner. So, when this e to the power j beta plus plus beta minus 2z is combined with this term, we get this expression.

So, the total electric field now can be written as E is equal to E naught x cap cos beta plus minus beta minus by 2 z minus y cap sin beta plus minus beta minus by 2 z e to the power minus j beta plus plus beta minus by 2 z. And this represents a linearly polarized wave whose direction of polarization we will see rotates as the wave propagates along z.

Now, the angle phi, which represents the direction of polarization with respect to x-axis is given by tan inverse Ey by Ex, and this will be minus beta plus minus beta minus by 2 z. So, as the wave progresses the direction of the electric field rotates with z and this type of rotation of polarization with distance. This is called Faraday rotation. Now, this Faraday rotation is an important property of (())(27:56) biased by a magnetic field, and we will see how this property is utilized in designing microwave devices such as isolator and circulator.

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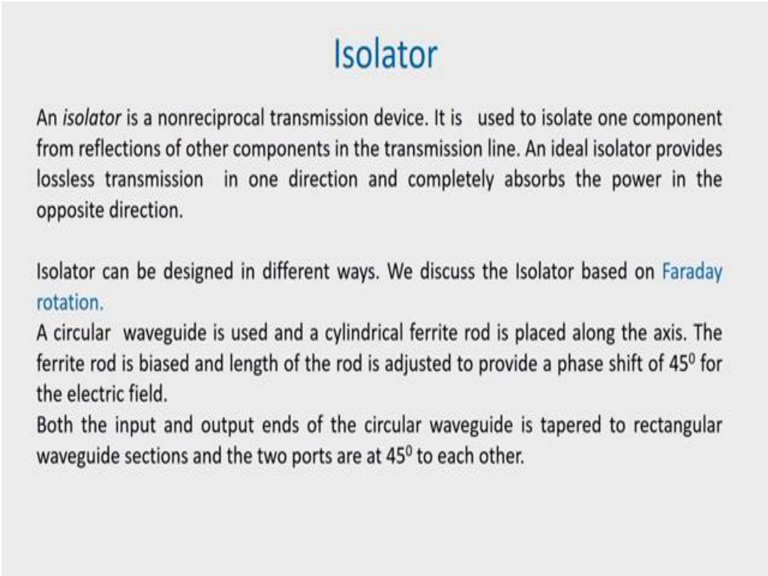

An isolator is a nonreciprocal transmission device. It is used to isolate one component from the reflection of other components in the transmission line. An ideal isolator provides lossless transmission in one direction and completely absorbs the power in the opposite direction. Isolators can be designed in different ways. We will discuss the isolator based on Faraday rotation.

A circular waveguide is used in the design, and a cylindrical ferrite is placed along the axis. The ferrite rod is biased, and the length of the rod is adjusted to provide a phase shift of 45 degrees for the electric field. We have seen that Faraday rotation will rotate the polarization of the electric field, so the length of the rod and the biased it is adjusted so that the polarization rotates by 45 degrees. Both the input and the output ends of the circular waveguide, it is tapered to rectangular waveguide sections, and the two ports are at 45 degrees to each other.

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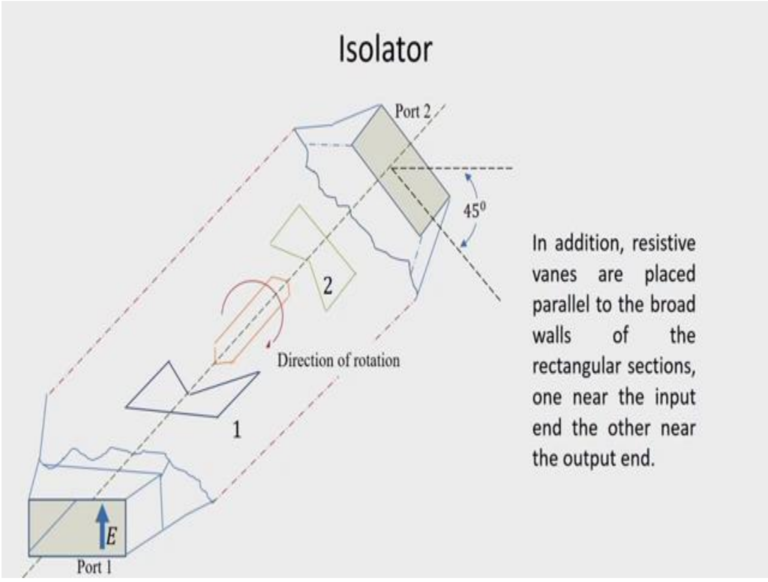

So, the structure is shown here. We have a circular waveguide section which is tapered to rectangular waveguide at the two ends, and this port 1 and port 2 are at 45 degrees to each other. We have a magnetized ferrite placed here also we have 2 vanes denoted by 1 and 2. These are placed parallel to the broad walls of the rectangular sections, so this one is parallel to this broad wall and vane 2 is parallel to the broad wall of port 2. 1 near the input end and another near the output end. Now, let us try to understand how the device is shown actually works as an isolator.

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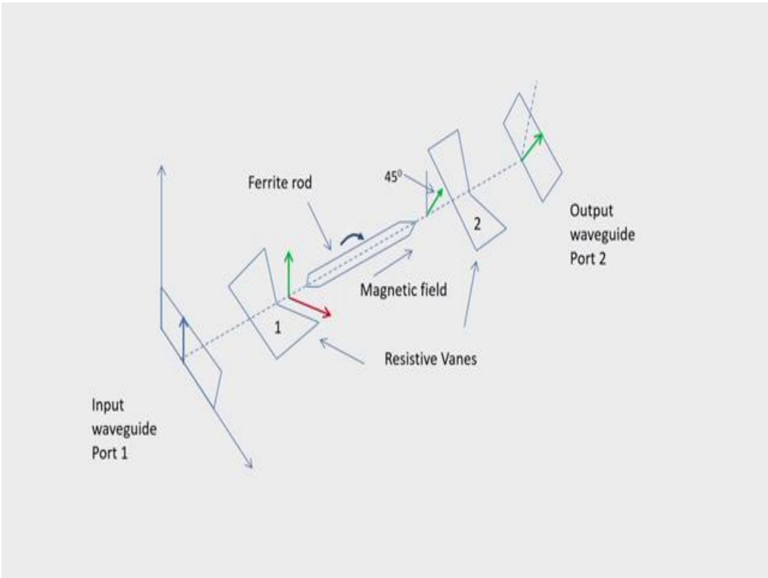

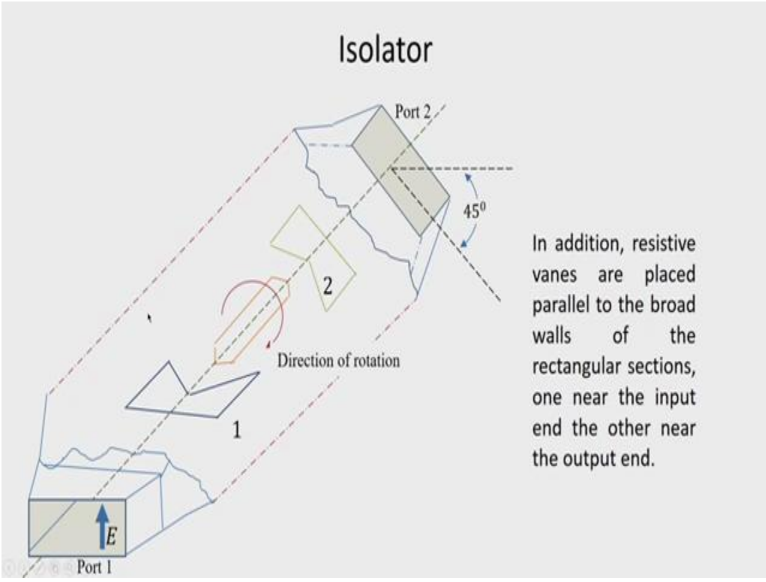

This is illustrated with the diagram shown in the figure. At the input port let us suppose this is the polarization of the wave, now when this propagates and enters the circular section of the waveguide through this transition, this TE_{10} mode will give rise to TE_{11} mode in the circular waveguide but its polarization will remain same as before and here this electric field is perpendicular to this resistive vane.

Now, these types of resistive vanes actually absorb the wave if it is, the electric field is parallel to such vanes. So, here this electric field being perpendicular, it passes unattenuated, it enters in the ferrite media where it undergoes 45-degree rotation, and this is shown here. Now, after this 45-degree rotation, this vane 2 is placed with its plane parallel to this edge, and therefore this field will appear perpendicular to this vane, and it will pass unattenuated, and finally because of the transition present here, the wave will appear in the output port 2 unattenuated.

Now, if we consider a wave incident in port 2, which may be because of some mismatch, some reflected signal appears at port 2. This will now undergo a rotation of 45 degrees, please note that bias, in this case, is opposite to the direction of propagation, so with respect to the wave propagation the rotation will be now counter-clockwise and as a result after passing through this ferrite rod, the electric field component, the reflected field component will become parallel to this resistive vane.

And it will get absorbed by this vane and will not appear in port 1. Now when this field is incident at vane 1, if there is any reflection from here, this will be rotated by 45 degrees by this ferrite rod, and it will come in parallel to vane 2, and it will get absorbed.

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Wave incident on the input port excites TE_{11} mode of circular waveguide with electric field polarization same as that of incident wave.

Electric field of incident wave being perpendicular to the resistive vane 1 is not effected by it.
The electric field polarization is rotated by 45^0 (CW with respect to direction of propagation) by the ferrite rod biased by a magnetic field in the direction of propagation.

After rotation, the field is perpendicular to vane 2 and therefore not effected. Since the orientation of output port is 45^0 with respect to input port, the wave passes unattenuated to output port.
For any wave incident at port 2, after travelling past the ferrite, the electric field vector rotates CCW by 45^0 , becomes parallel to resistive vane 1 and gets absorbed. Any reflected wave from vane 1, if present, gets absorbed in vane 2.

So, let us summarize the wave incident on the input port excites TE_{11} mode of the circular waveguide with electric field polarization same as that of the incident wave. The electric field of incident wave is perpendicular to the resistive vane 1 is not affected by it. The electric field polarization is rotated by 45 degrees clockwise with respect to the direction of propagation by the ferrite rod biased by a magnetic field in the same direction of propagation.

After rotation, the field is perpendicular to vane 2 and, therefore, not affected. Since the orientation of the output port is 45 degrees with respect to the input port, the wave passes unattenuated to the output port. For any wave incident at port 2, after travelling past the ferrite, the electric field vector rotates counterclockwise by 45 degrees, becomes parallel to resistive vane 1, and gets absorbed. Any reflected wave from vane 1, if present will get absorbed in vane 2. So, this is how this type of Faraday rotation isolator will provide only unidirectional transmission from port 1 to port 2 and not from port 2 to port 1.

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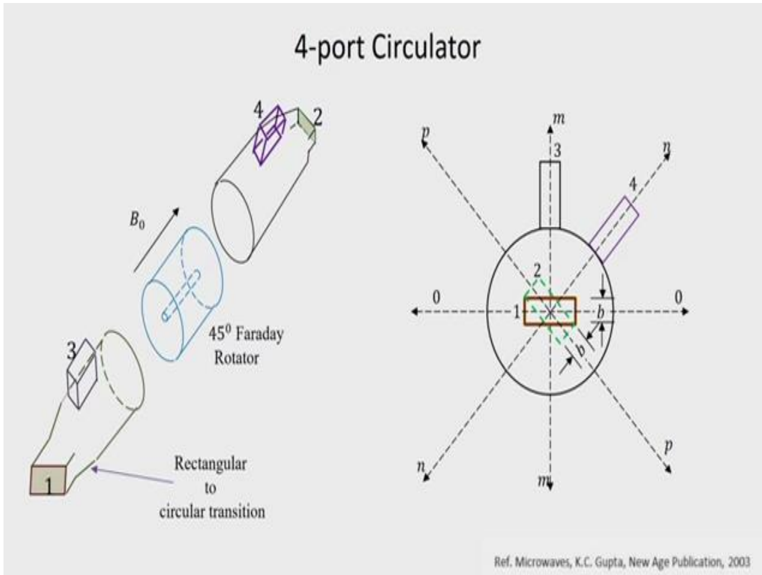

We have seen the operation of an isolator based on the Faraday rotation in ferrite. Now, let us see how this Faraday rotation effect in ferrite can be used to realize a 4 port circulator. Here we show the schematic of a 4 port circulator, and different sections are shown. So, we have a rectangular port, and from this rectangular port we have a transition to circular waveguide section. Within the circular waveguide, we have a ferrite rod which provides 45-degree rotation and axial magnetic field biases this ferrite.

Next, we have the port 2, which is again a transition from circular to rectangular but this time at an angle of 45 degrees with respect to the port 1. We have 2 additional rectangular ports that are on the circular waveguides, and the positioning of these ports are as shown. So port 1, with reference to port 1 we can see that port 2, which is 45 degrees placed, and the angle between 3 and 4 are again 45 degrees. So, let us see how this 4 port circulator operates.

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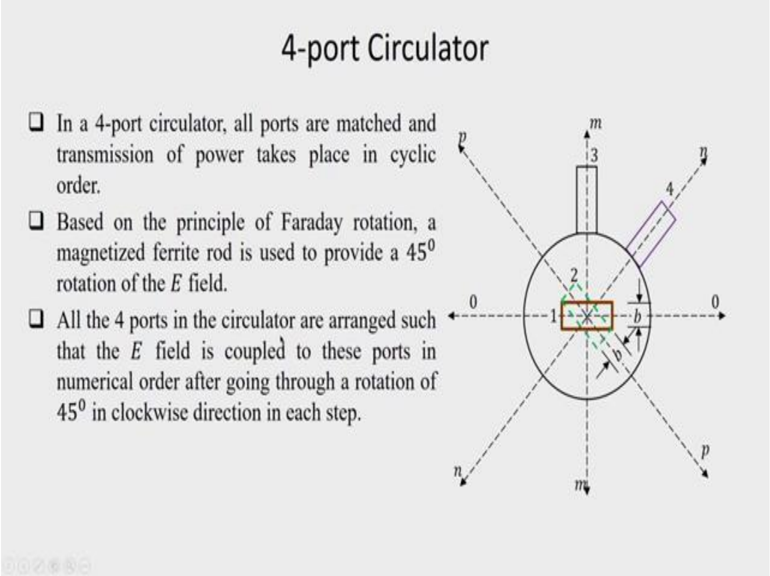

So, in this 4 port circulator, all ports are kept matched, and transmission of power takes place in cyclic order. That means 1 to 2, 2 to 3, 3 to 4, like that. Based on the principle of Faraday rotation, a magnetized ferrite rod is used to provide a 45-degree rotation of the electric field. All 4 ports in the circulator are arranged such that E field is coupled to these ports in numerical order after going through a rotation of 45 degrees in clockwise direction.

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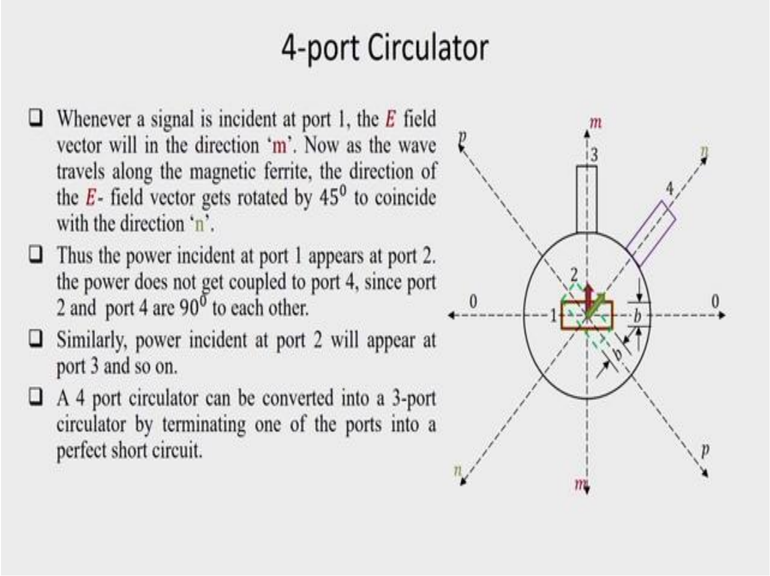

So, referring to this figure, whenever a signal is an incident at port 1, E field vector will in the direction of m, so this is the E field vector. Now, as the wave travels along the magnetic ferrite the direction of E field vector gets rotated by 45 degrees and it coincides with n, and therefore the power incident at port 1 will now appear at port 2.

The power does not get coupled to port 4 since port 2 and 4 are at 90 degrees with respect to each other. Similarly, if power is incident at port 2, it will appear at port 3 after Faraday rotation of 45 degrees, this vector will be parallel to the opening of port 3, and it will excite port 3. And what we can do a 4 port circulator can be converted through a 3 port circulator, we studied already 3 port circulator, basic 3 port circulator while discussing S parameter, so a 4 port circulator can be converted through a 3 port circulator by terminating one of the ports into a perfect short circuit.

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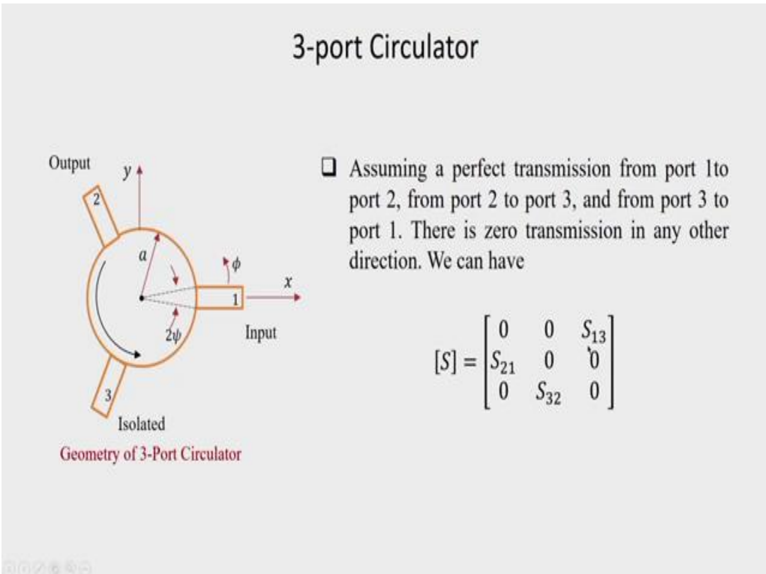

Here we show the schematic of a 3 port circulator when port 1 is input is given at port 1. The power appears at port 2, while port 3 remains isolated. So, we have perfect transmission from 1 to 2, 2 to 3 and from 3 to 1. And we do not have 0 transmissions in the other direction. Then we will have the S parameters, S 1 to 2, S 2 to 3, and S 3 to 1.

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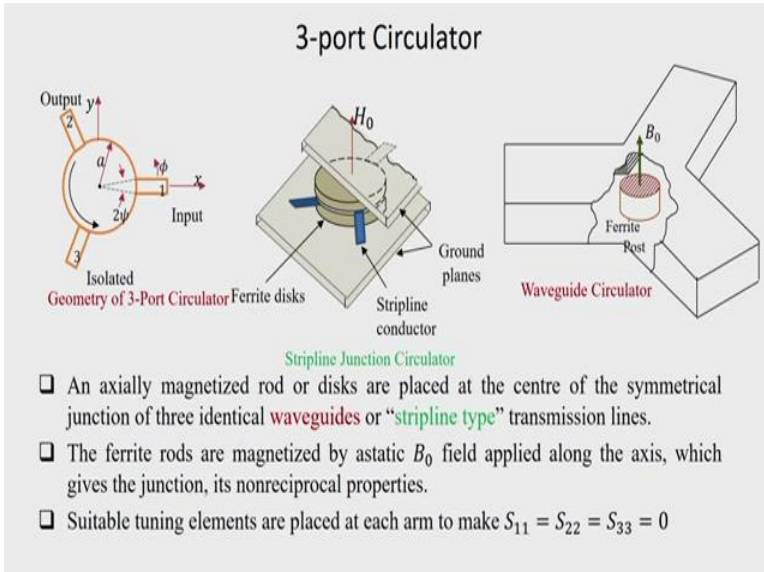

All these S parameter magnitudes will be unity. Now, this type of 3 port circulators can be realized either in the form of stripline junction, in the form of a y junction or in the form of a waveguide circulator. In case of a stripline junction circulator, we have the ground planes on the top and bottom, and between the stripline conductor and the ground plane are the ferrite discs, and the magnetic field is applied along the axis of this disc.

Similarly, in case of a waveguide circulator, we have a ferrite post. Once again, an axially magnetized rod or disc is placed at the center of the symmetrical junction of 3 identical waveguide or stripline type transmission lines, as shown in the figure. The ferrite rods are magnetized by a static B naught field applied along the axis, which gives such junctions nonreciprocal properties.

And suitable tuning elements are placed at each arm to make S_{11}, S_{22}, and S_{33} equal to 0, so as to obtain a matching. For the stripline case as we have seen, 2 ferrite discs fill the space between the center metallic disc and the ground planes of the stripline. The stripline conductors form a junction and at the 120-degree interval. Now, in the absence of any bias field, the ferrite discs, they form dielectric resonator and has a single lowest order mode with a cos phi or sin phi type dependence.

When the ferrite is magnetically biased, this mode breaks into 2 resonance modes having slightly different resonance frequencies. The operating frequency of the circulator can then be chosen so that the superposition of the 2 modes, add at one port and cancel at another port. So, in that way, when one port is excited, the power gets couples to one port, and other ports remain isolated. So, this is in brief, the operation of 3 port stripline type circulator.

So, in this lecture we have mainly discussed the properties of ferrite materials, we have seen how we can have 2 different propagation constants in a biased ferrite media and then we have seen how the polarization of the electric field rotates as it propagates in a biased ferrite media giving rise to what is known as Faraday rotation. And then, we have discussed how this Faraday rotation effect can be utilized in realizing an isolator and a 4 port circulator. Apart from 4 port circulator, 3 port circulators based on ferrite are also very popular, and we have discussed the basic construction of such circulators.

So, with this discussion, we come to the end of this module, and in the next module we will discuss some basics of microwave integrated circuits, we will discuss different types of planar transmission lines that are used in MICs. Then we will discuss some of the discrete components such as inductor, capacitor, and resistors. We will see how hybrid and monolithic microwave integrated circuits are realized using this type of planar transmission lines and components.