5.5 Faraday Rotation – Ferromagnetic properties

Module:5 Microwave Passive components

Course: BECE305L – Antenna and Microwave Engineering

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CHENNAI

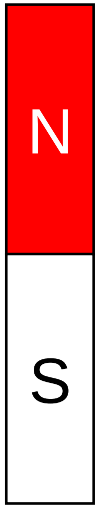
Module:5 Microwave Passive components 6 hours

- Microwave Networks - ABCD, 'S' parameter and its properties. E-Plane Tee, H-Plane Tee, Magic Tee and Multi-hole directional coupler. Principle of Faraday rotation, isolator, circulator and phase shifter.

- Source of the contents: Pozar

1.Basics of Magnetic permeability

- Magnet – North and South



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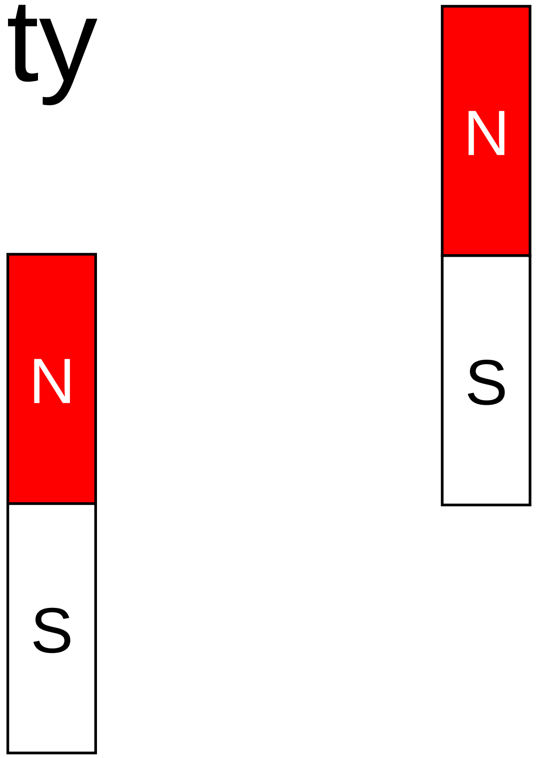

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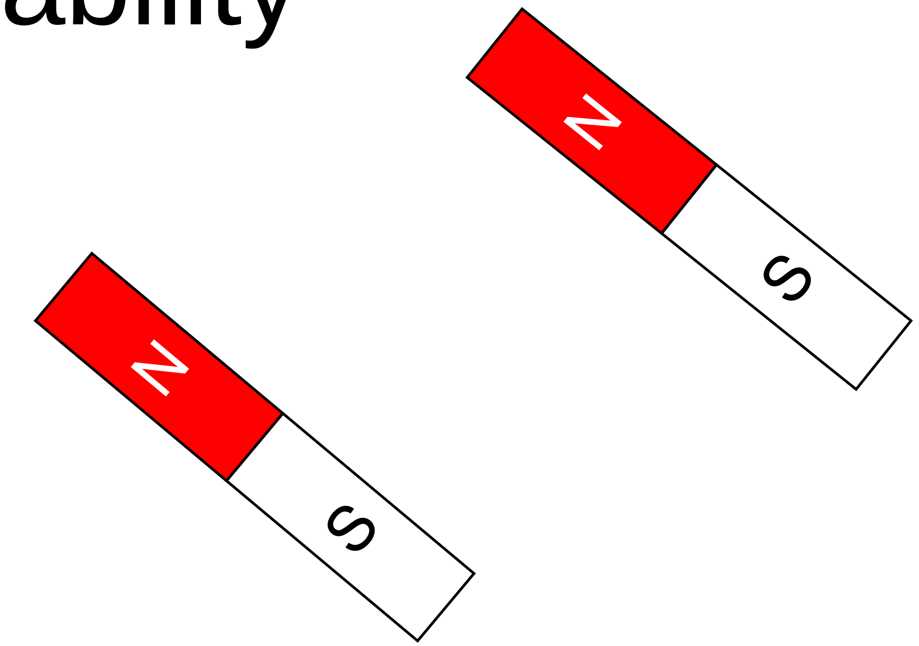

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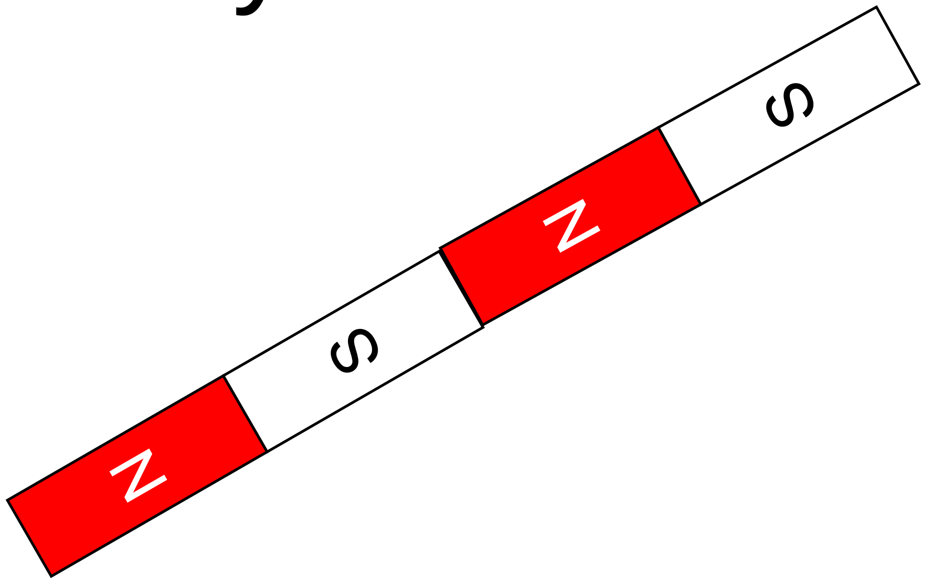

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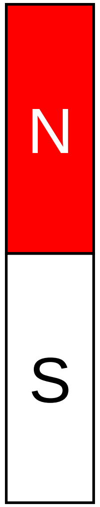

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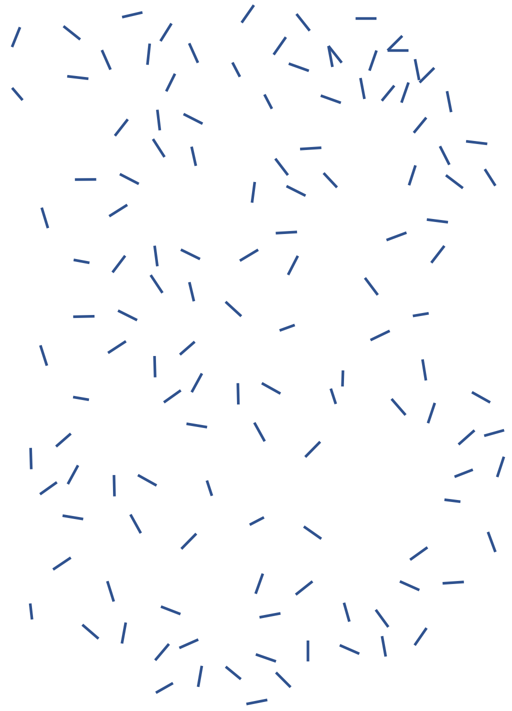

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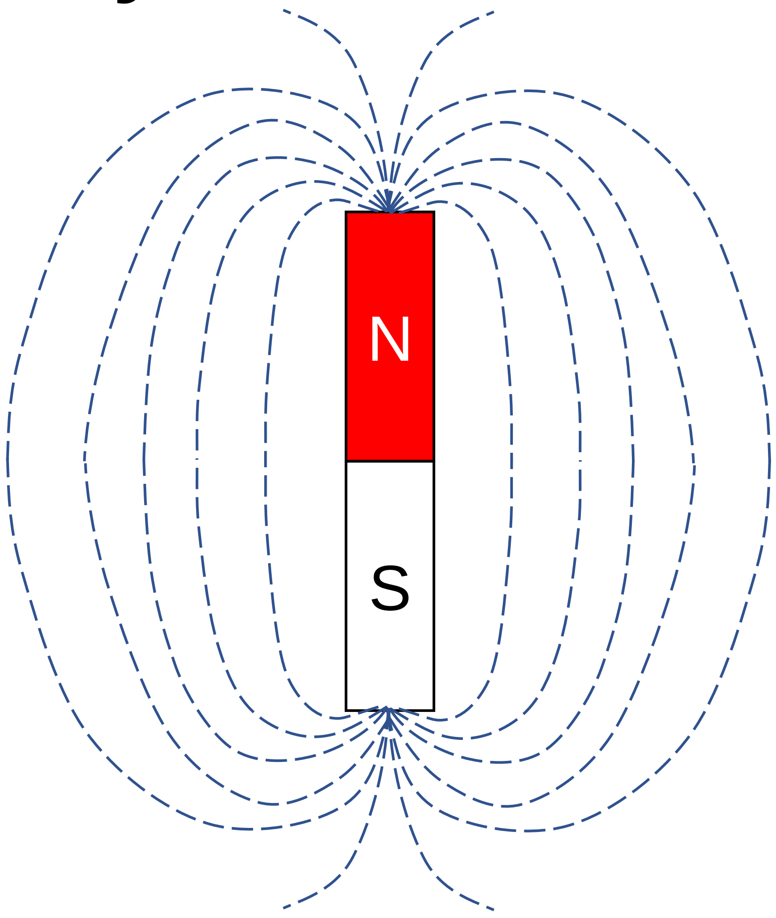

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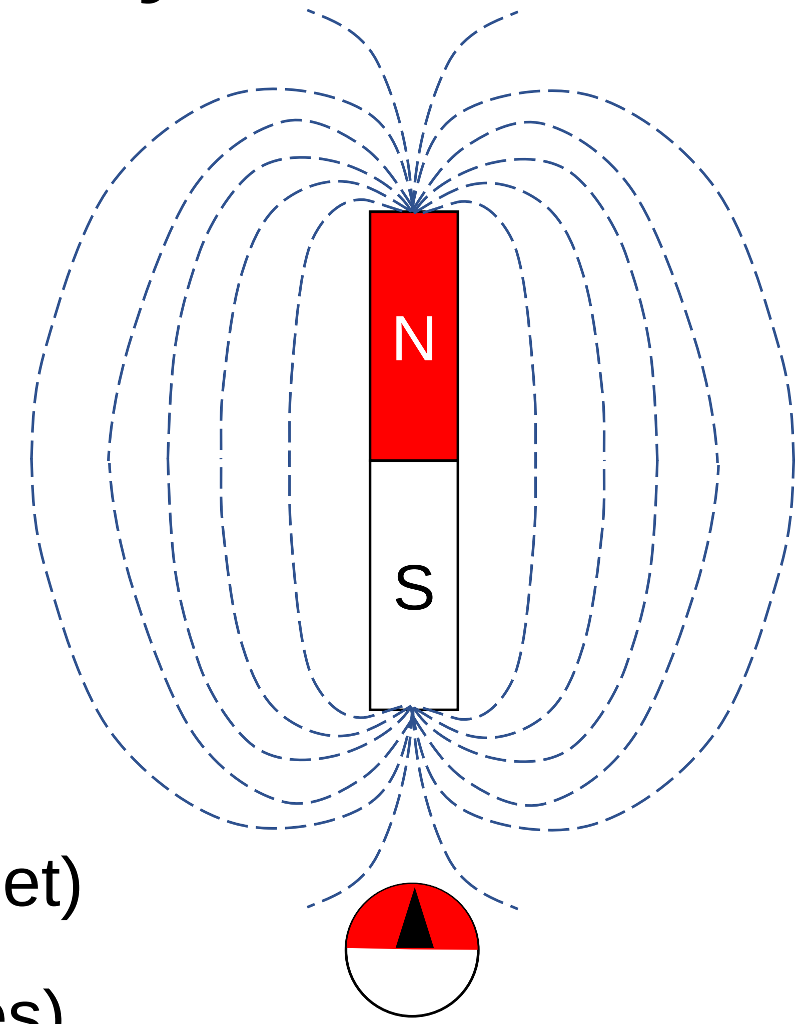

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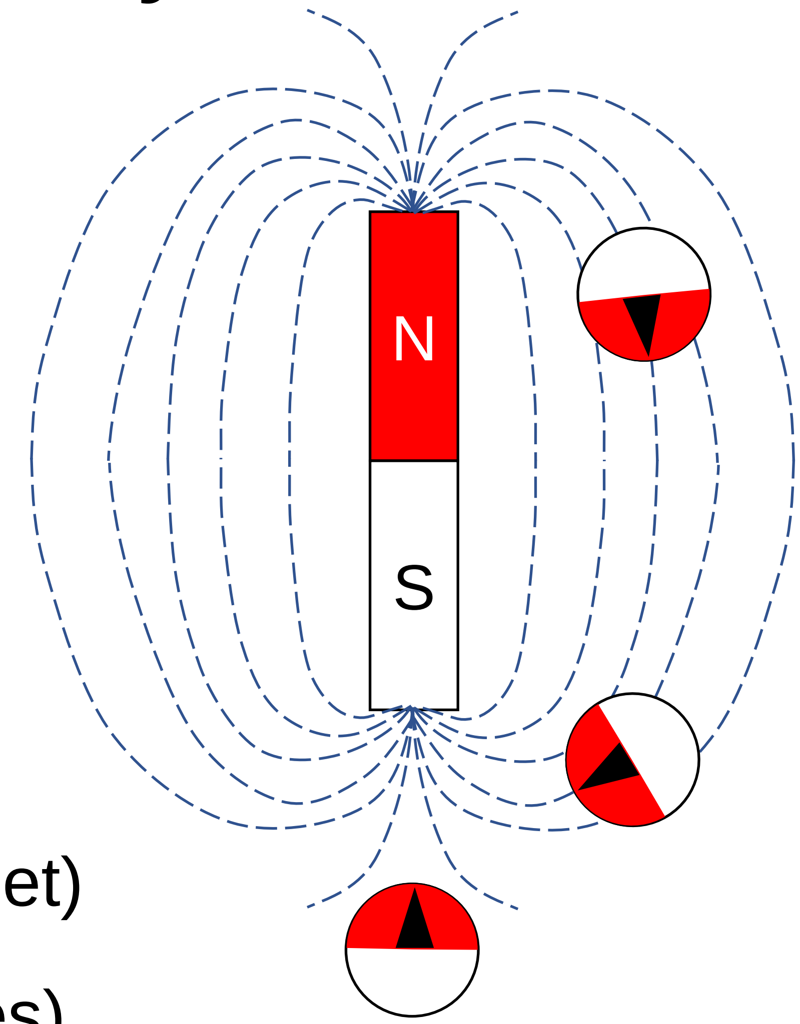

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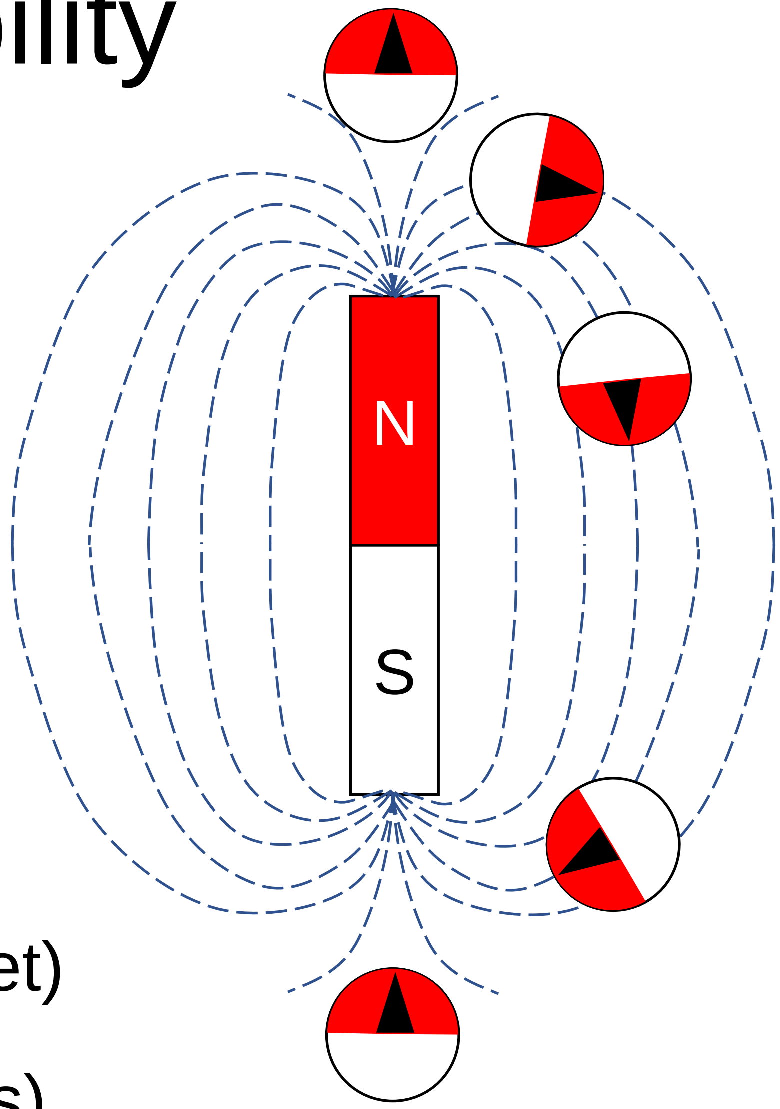

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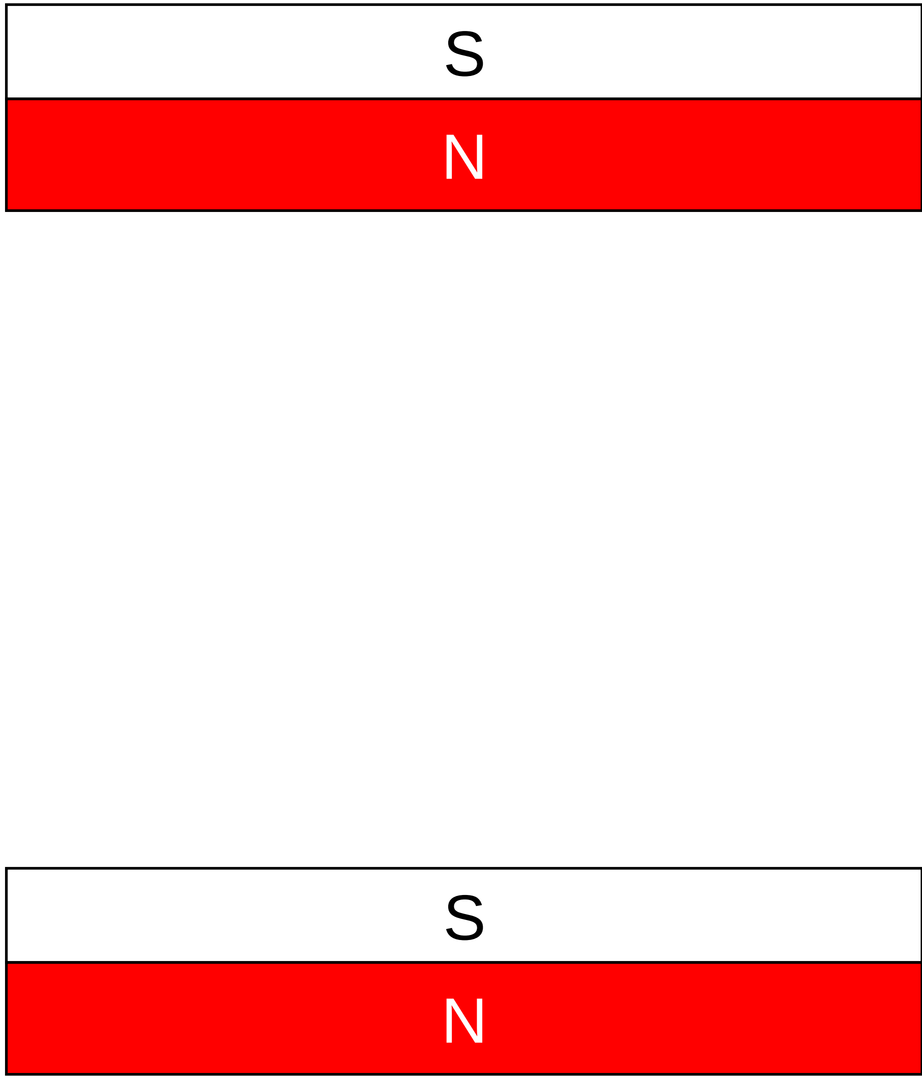

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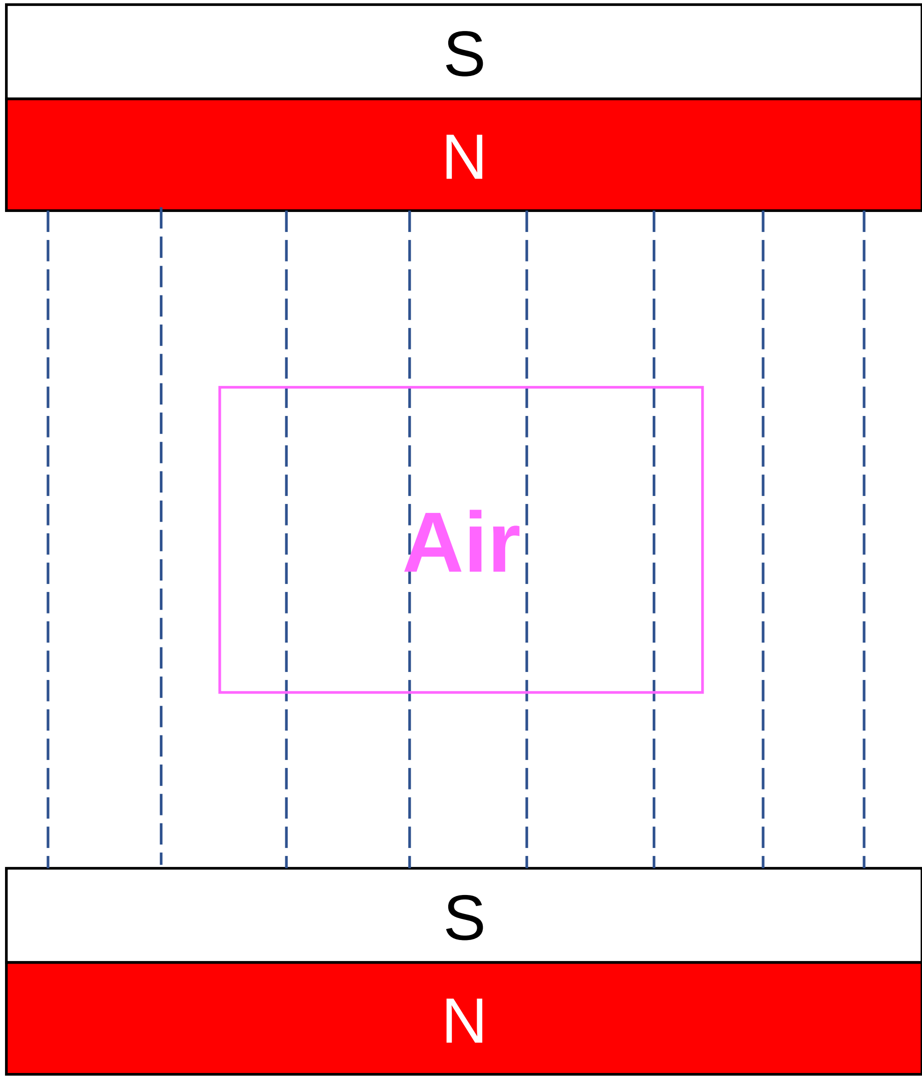
- In air medium/vacuum, the field lines remain the same.
  Air/vacuum allows/permits the magnetic fields to pass through normally.
  And so does many other materials.
  μ_0: Ability of vacuum to create internal magnetic fields



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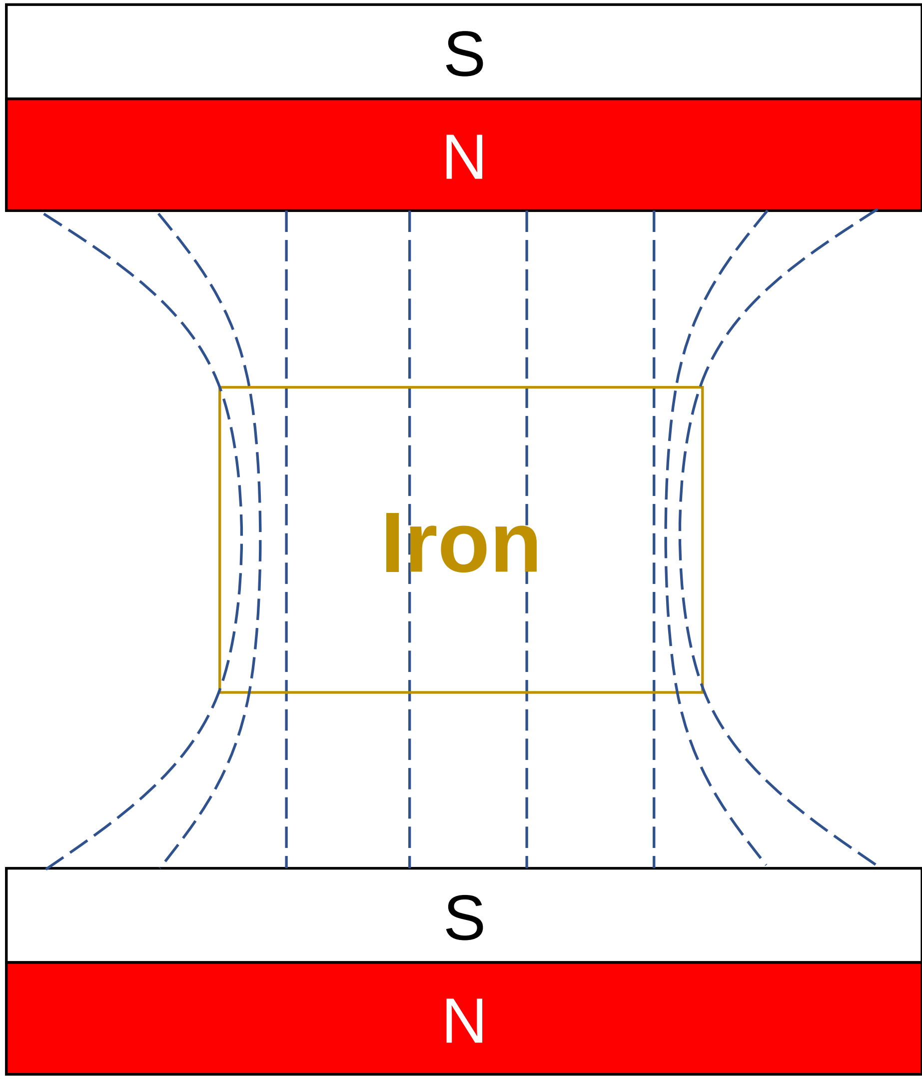
- For **iron**, the magnetic fields are warped into the medium.
  This is because, fields are formed inside the material.
  $\mu = \mu_0 \mu_r$: Ability of Iron to create internal H field



1.1 Introduction - Until now

- Reciprocal networks (Response of network was independent of direction of signal flow - $S_{ij} = S_{ji}$)
- Component was passive, and materials were isotropic.

1.2 Introduction – Non-reciprocity

- Anisotropic materials and active devices produce non-reciprocal behaviour.
- Nonreciprocity - a useful property in devices like circulators and isolators.
- Nonreciprocity – an ancillary property in devices like transistor amplifiers, ferrite phase shifters.

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- Most practical materials for some microwave applications – Ferrimagnetic compounds known as ferrites.
  Example: Yttrium iron garnet (YIG) and materials composed of iron oxides, various elements like aluminium, cobalt, manganese and nickel.

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- Ferromagnetic materials (iron, steel)
- Ferrimagnetic compounds have high resistivity and significant anisotropy at microwave frequencies.

1.2 Introduction – Non-reciprocity

- **Magnetic anisotropy** is induced by applying a DC magnetic bias field.
- **Field aligns the magnetic dipoles** in **ferrite material** to produce a net(zero) **magnetic dipole moment**
  Causing the magnetic dipoles to **precess(change in orientation of rotation axis**) at **frequency controlled by strength of the bias field**.

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- A circularly polarized microwave signal when in the same direction as this precession, will interact strongly with dipole moments.
- Oppositely polarized field interacts less strongly.
- **For a given direction of rotation, sense of polarization changes with direction of propagation,**
  Microwave signal will propagate through magnetically biased ferrite differently in different directions. (Used in circulators, isolators, gyrators)

1.2 Introduction – Non-reciprocity

- **Interaction** with applied microwave signal – **controlled by adjusting the strength of the bias field**.
  Leads to control devices: **phase shifters**, **switches**, **tunable resonators** and filters.

1.3 **Para-electric materials**

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- Paraelectric materials – variable phase shifters and other control components.
- Isotropic and reciprocal.
- **High dielectric constants and loss tangents** when used in **bulk form**, modern **generally use thin films of paraelectric material layered on a substrate**.
- Advantage: Need for large and heavy magnet or biasing coil is eliminated.

2. Propagation of Microwaves in Ferrite

- To develop many microwave non-reciprocal devices.
- Ferrites: Complex solids represented by $\mathrm{M^{+2}O.Fe_2O_3}$.
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- Specific resistance of ferrites: order of $10^7 - 10^8 \Omega m$ (10^{14} times than that of metal)
- Relative permittivity $\varepsilon_r \sim 10 - 15$
- Loss tangent $\tan\delta \approx 10^{-4}$ (low loss at microwave frequencies)

2. Propagation of Microwaves in Ferrite

- For **magnetically saturated ferrite**, magnetized in z direction with **RF field propagating in $z - direction$**

  Permeability of ferrite: (It is asymmetric tensor) $\tilde{\mu} = \mu_0 \begin{bmatrix} \mu & -jK & 0 \\ jK & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix}$

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- **Non-reciprocal electrical properties** (for microwave propagation)

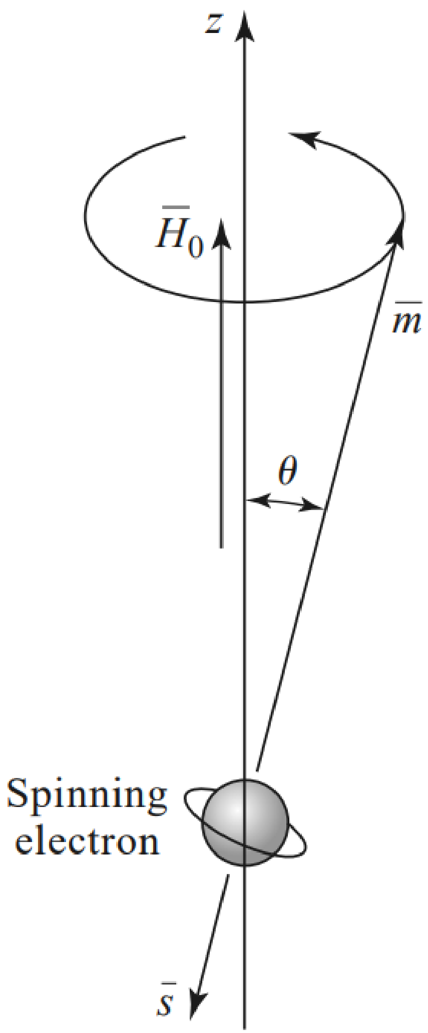
  1) The **transmission coefficient** is **not same for different direction**

  2) **Non-reciprocal rotation of the plane of polarization**.

2.1 Magnetic dipole moment of an atom

- ***Magnetic properties of ferrites*** results from **magnetic dipole moment $\mathbf{m}$ due to the electron spin**.

- Permeability tensor:
  Existence of magnetic dipole moments (due to primarily from electron spin)



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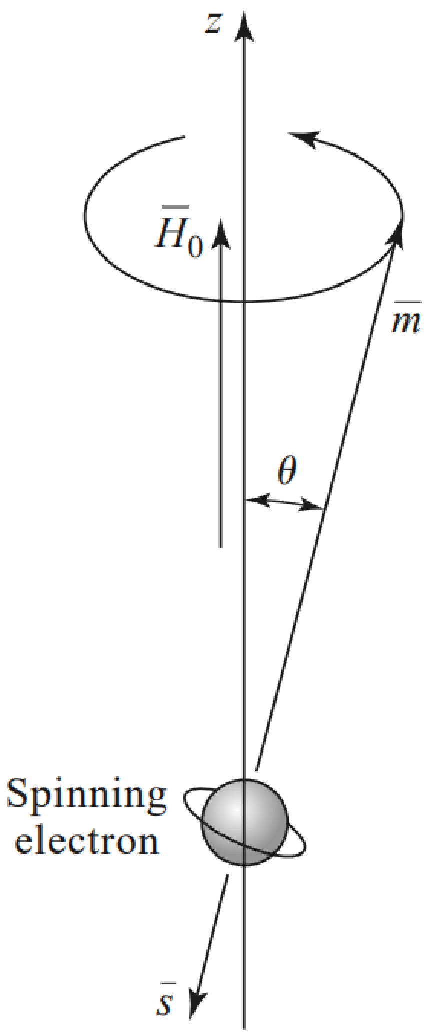
- **Magnetic dipole moment of an electron due to its spin**

$$m = \frac{qh}{2m_e} = 9.27 \times 10^{-24}\mathrm{A} - \mathrm{m}^2$$

h: Plank's constant by 2π.
q: Electron charge
m_e: mass of the electron



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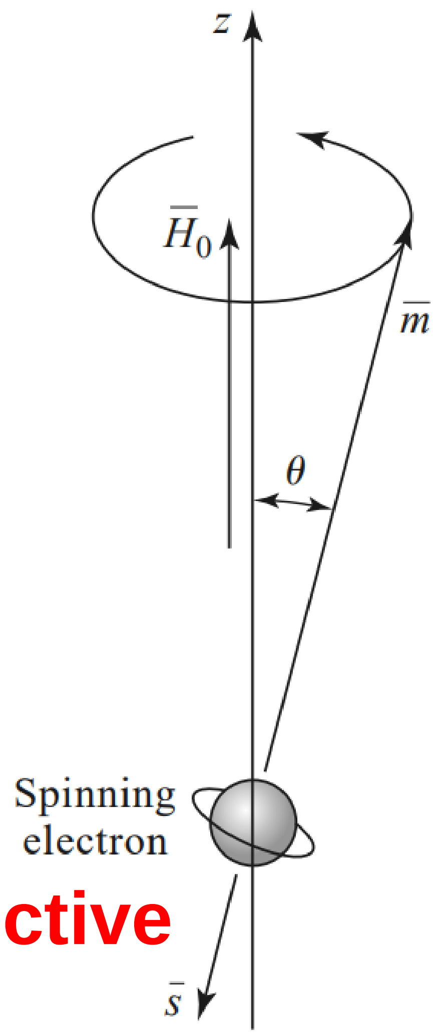

- **An electron in orbit around a nucleus gives rise to an effective current loop**, thus an **additional magnetic moment**.

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- Ferrite: **Can be considered as collection of N effective spinning electrons per unit volume**.
- Total magnetic dipole moment $\mathbf{M} = N\mathbf{m}$.

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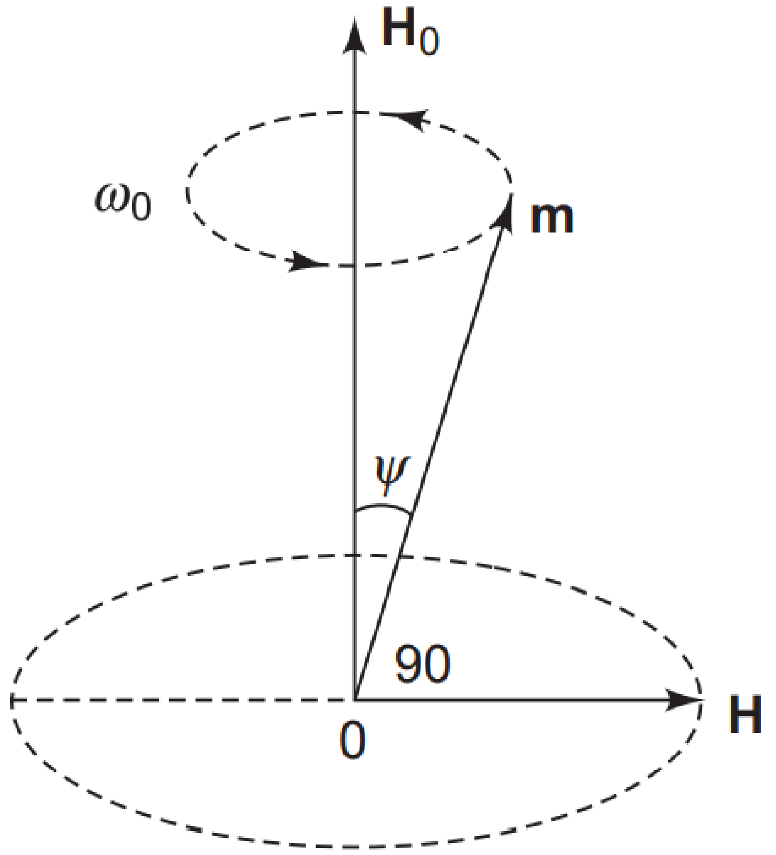

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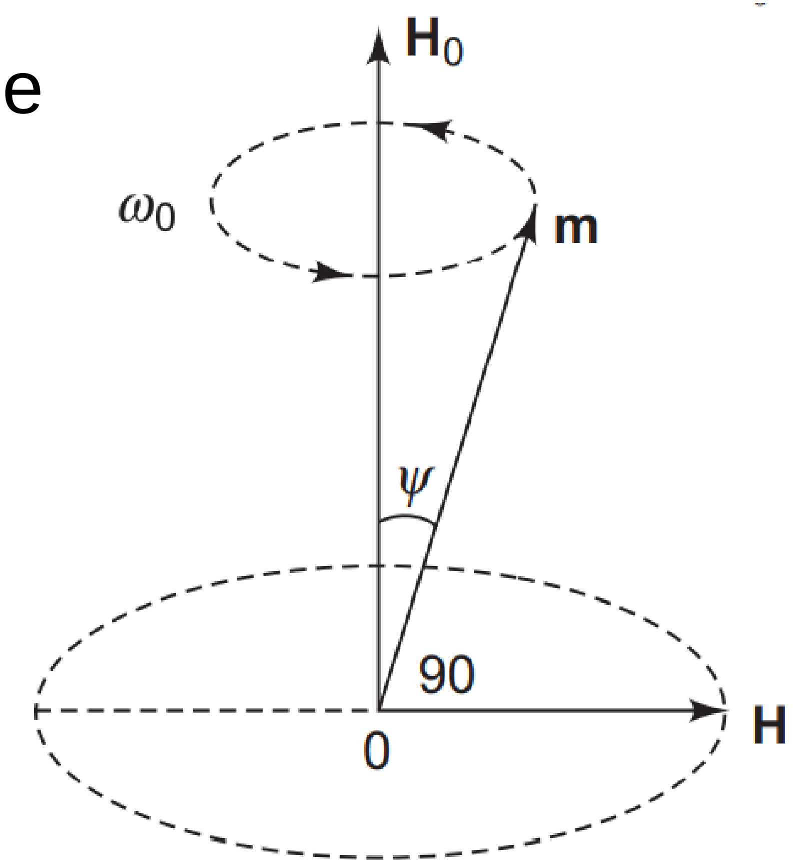

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- If **Steady external magnetic field** $\mathbf{H}_0$ is present in the direction other than that of $\mathbf{m}$ of an electron, m precesses gyromagnetically around H_0 due to the torque

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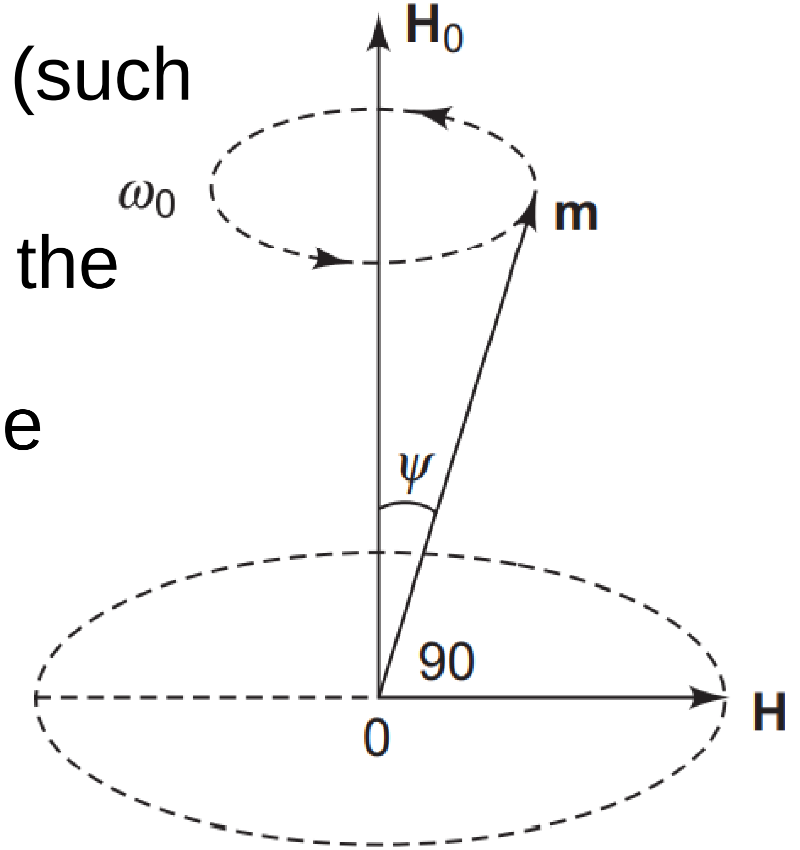
And trends to align the electron spin with $\mathbf{H}_0$.



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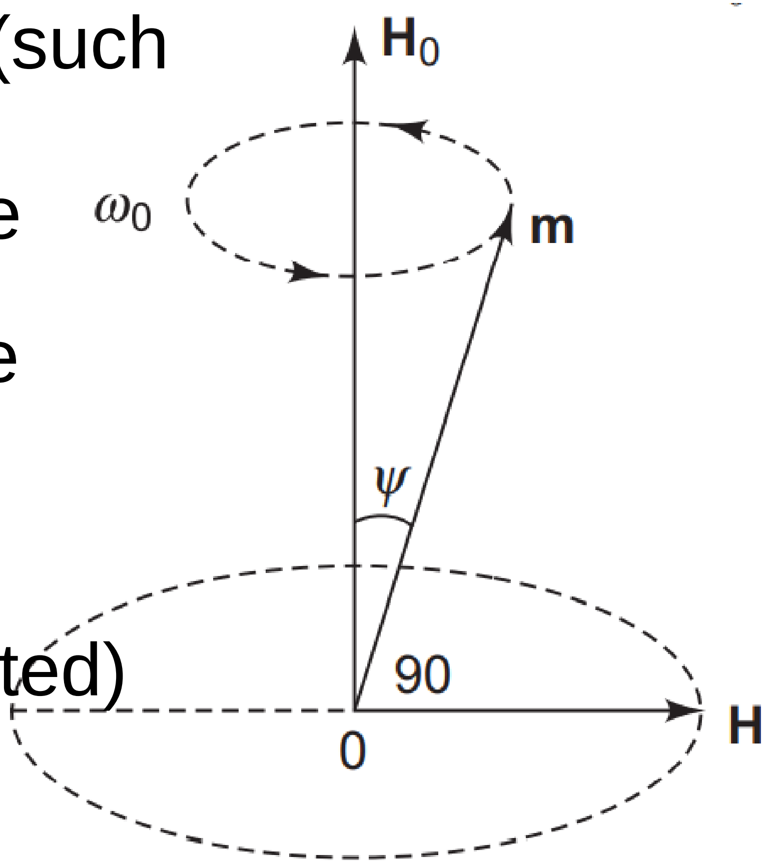
Gyromagnetic ratio $= \gamma = 2.8\ MHz/oersted$



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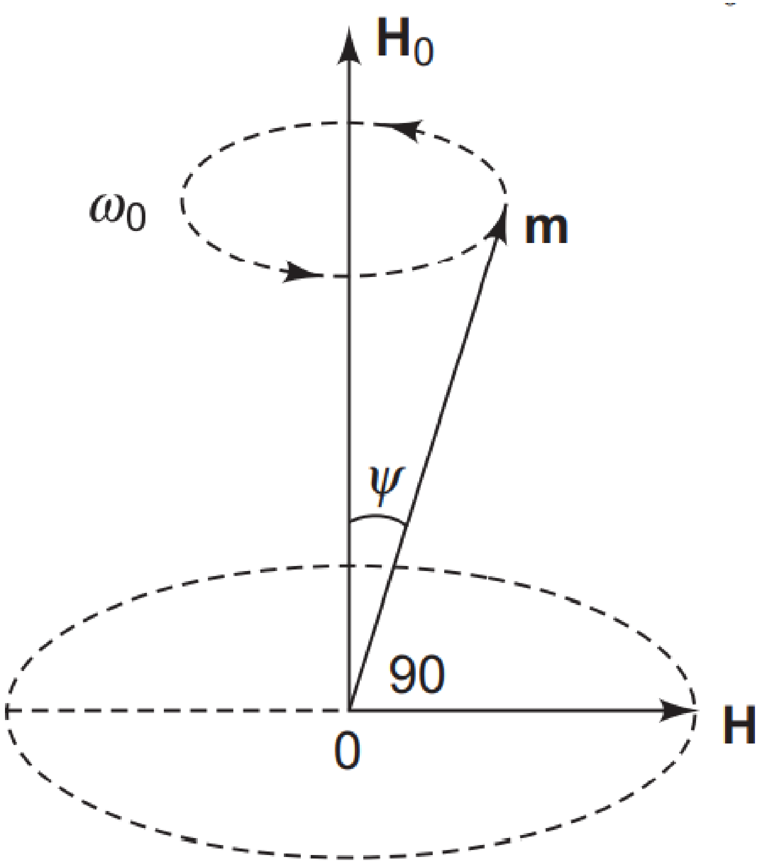
- Angle of precession, $\psi = \angle \mathbf{H_0} \mathbf{m}$ decreases due to friction.



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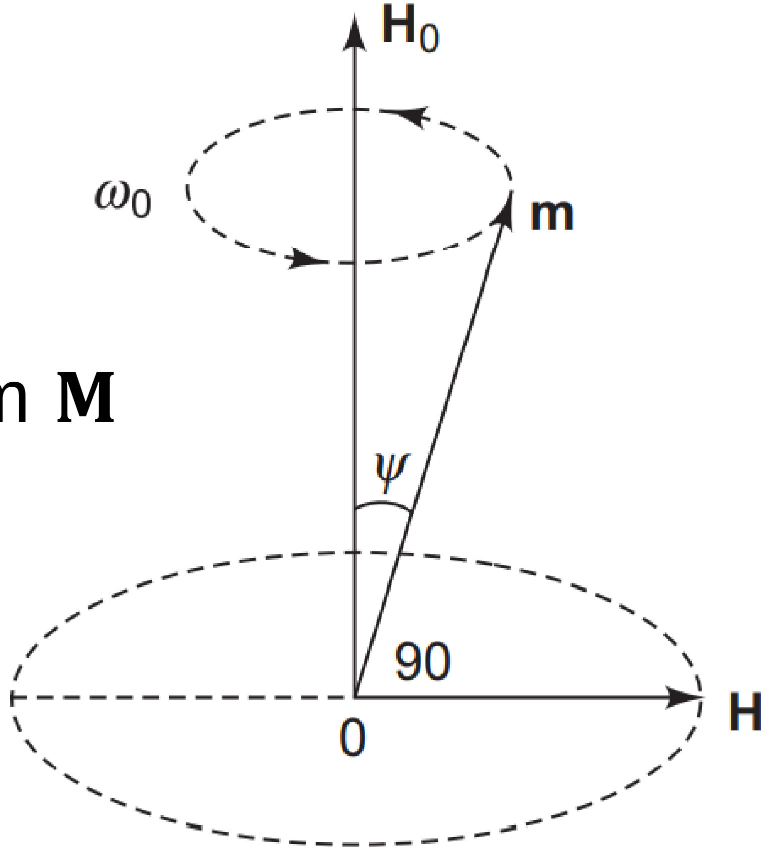
- Ferrite is magnetized with magnetization momentum $\mathbf{M}$ when the electron spins are aligned with $\mathbf{H_0}$.



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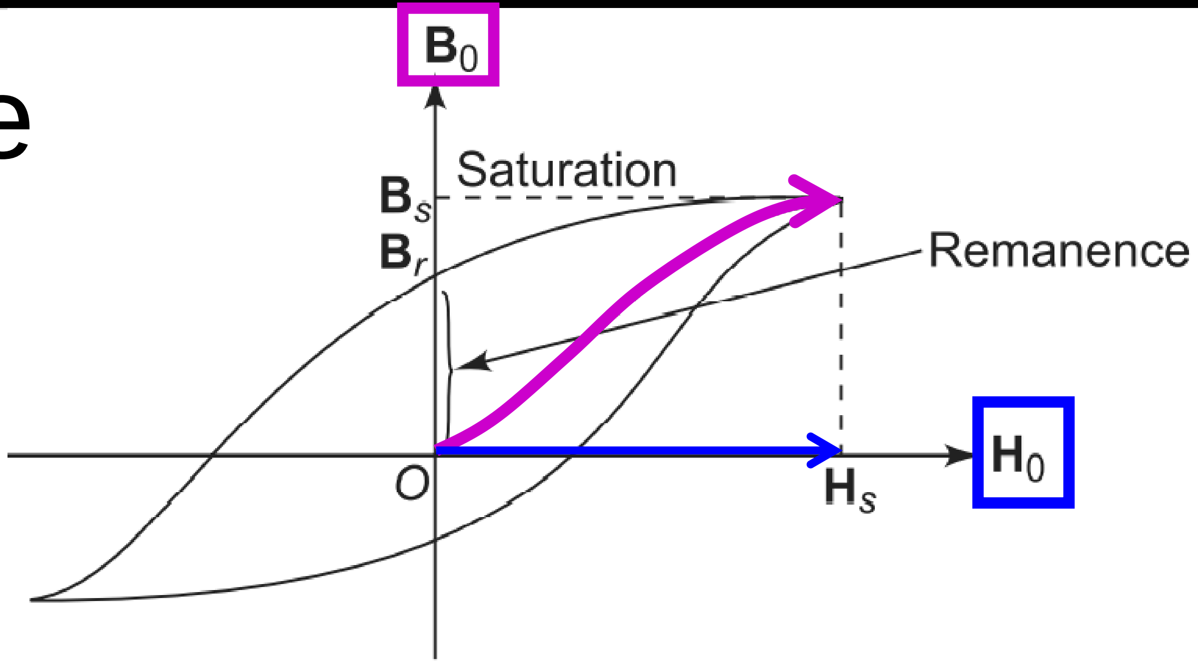
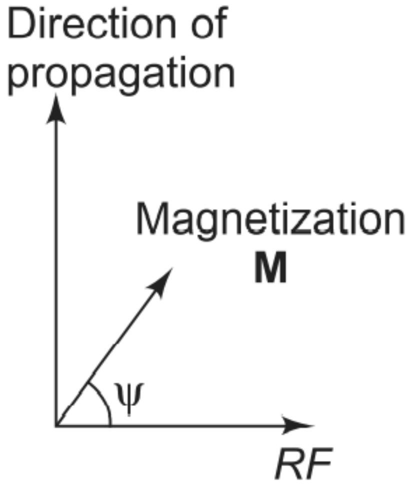
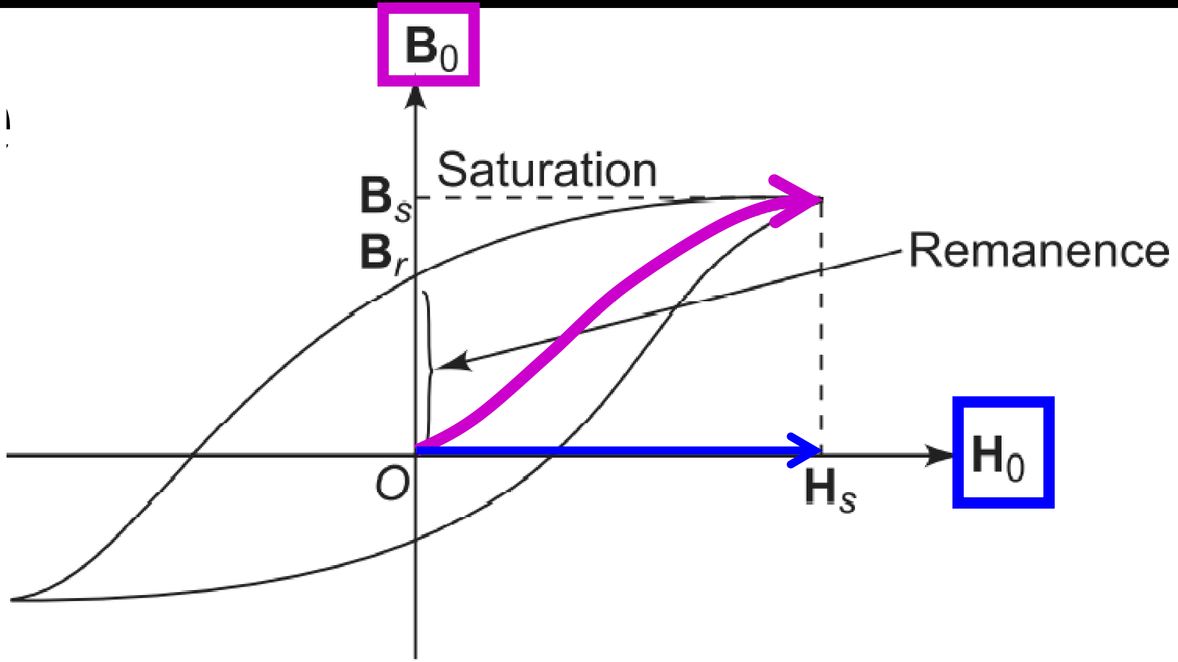
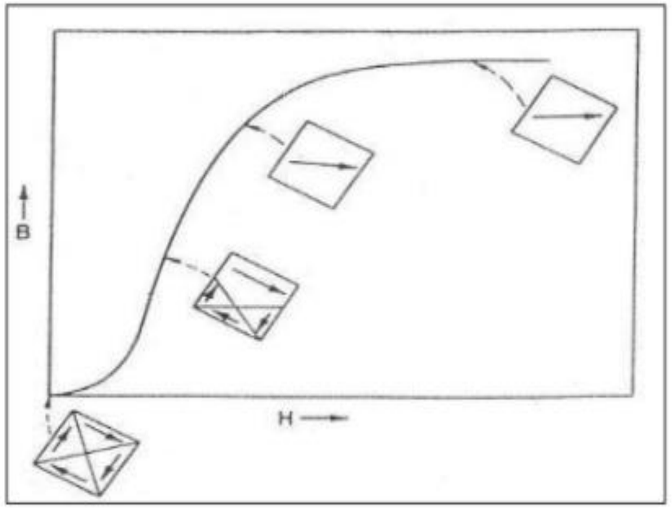
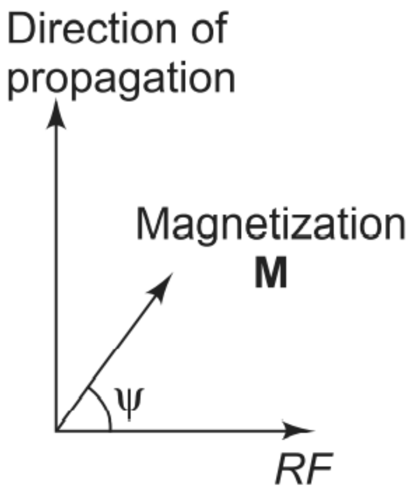


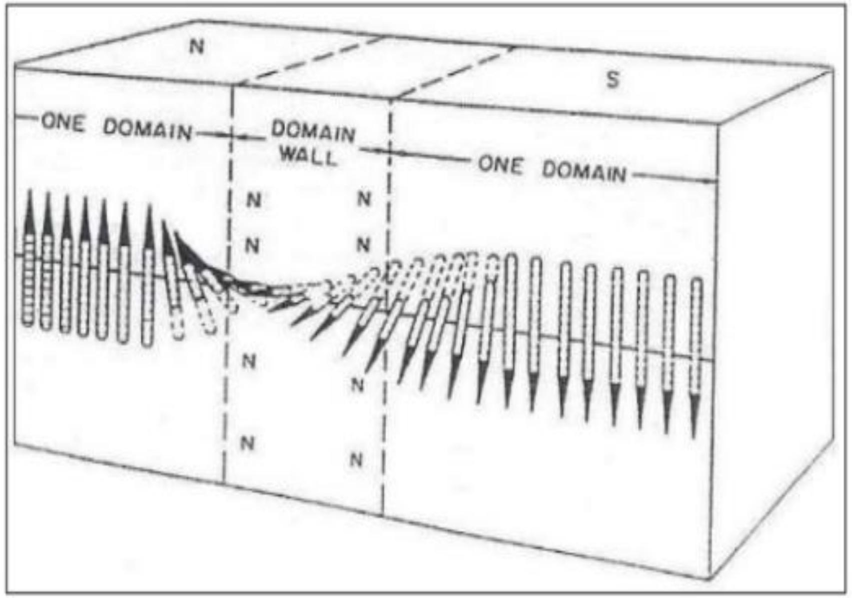




Schematic Illustration of Domain Structure at Various Stages of the Magnetization Process







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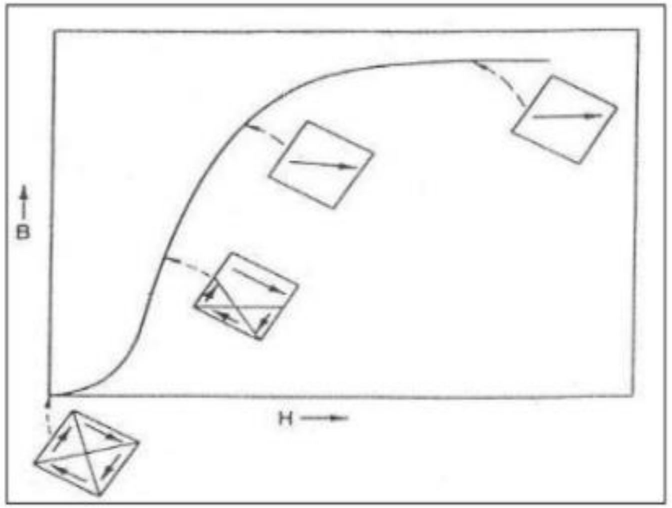

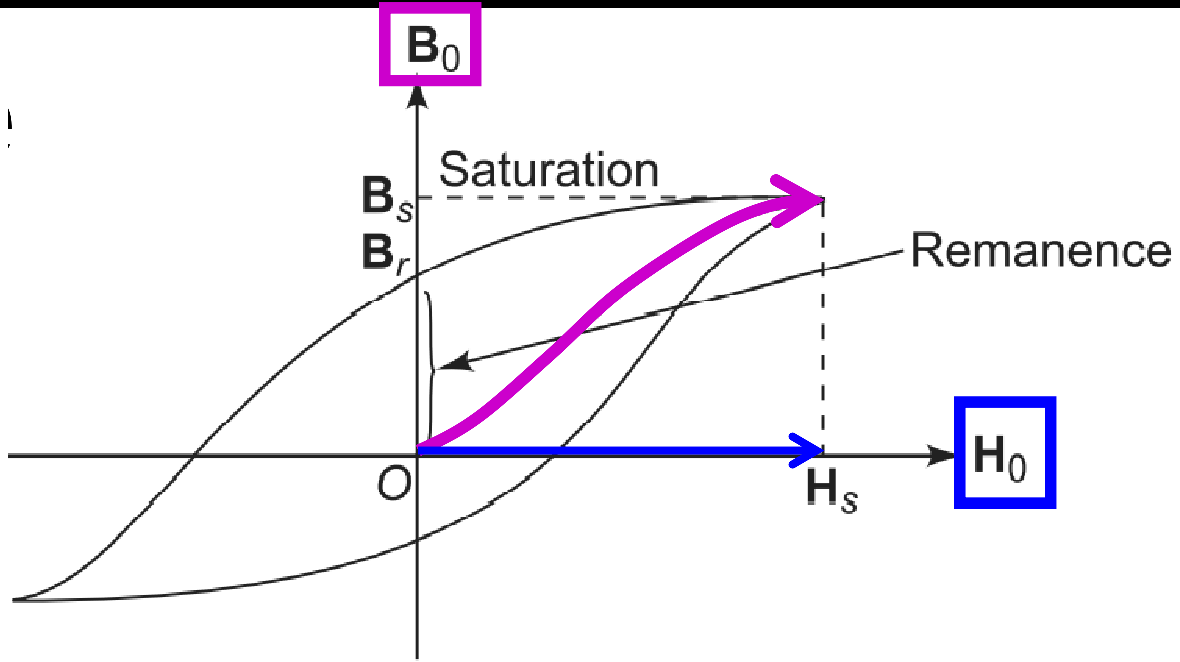

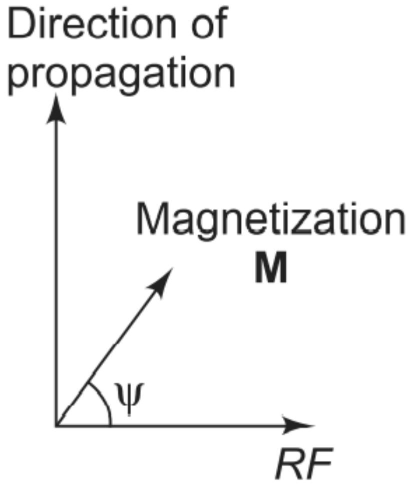

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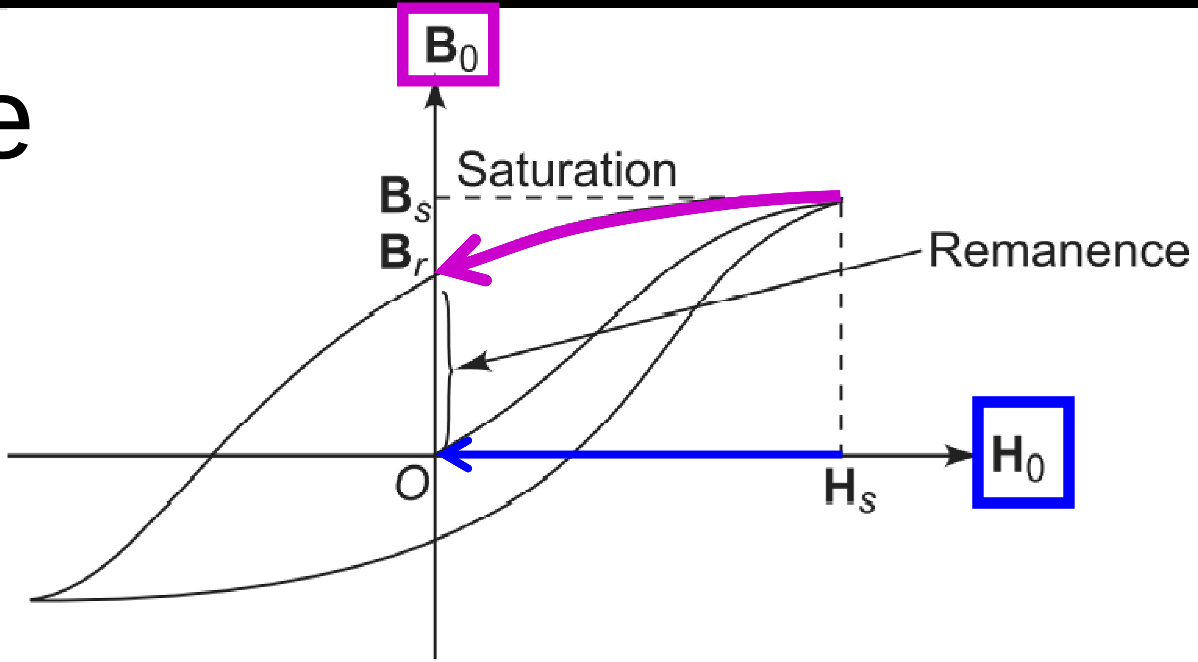

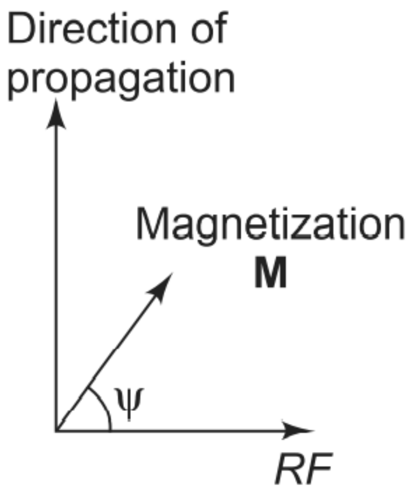

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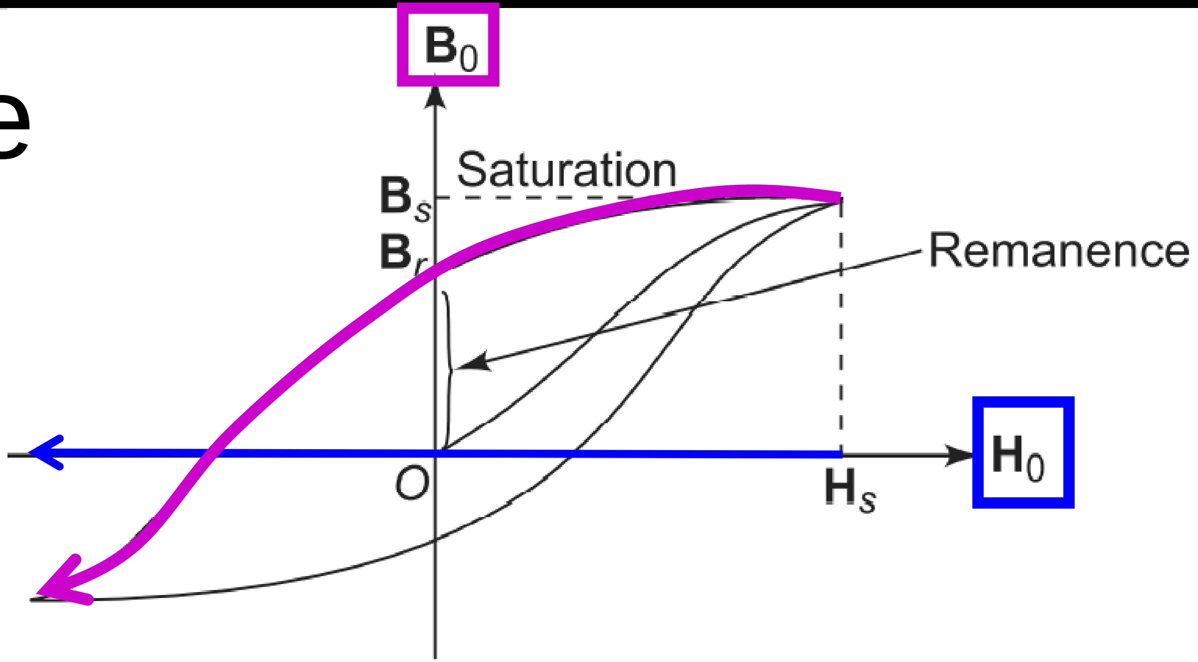

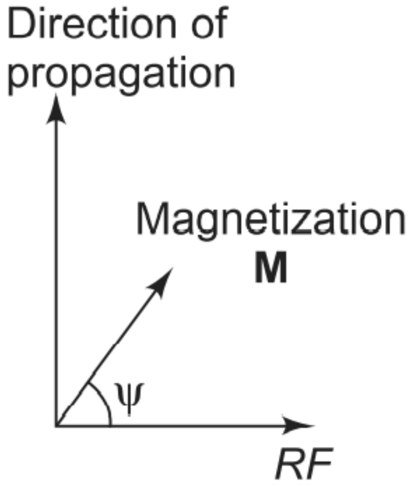

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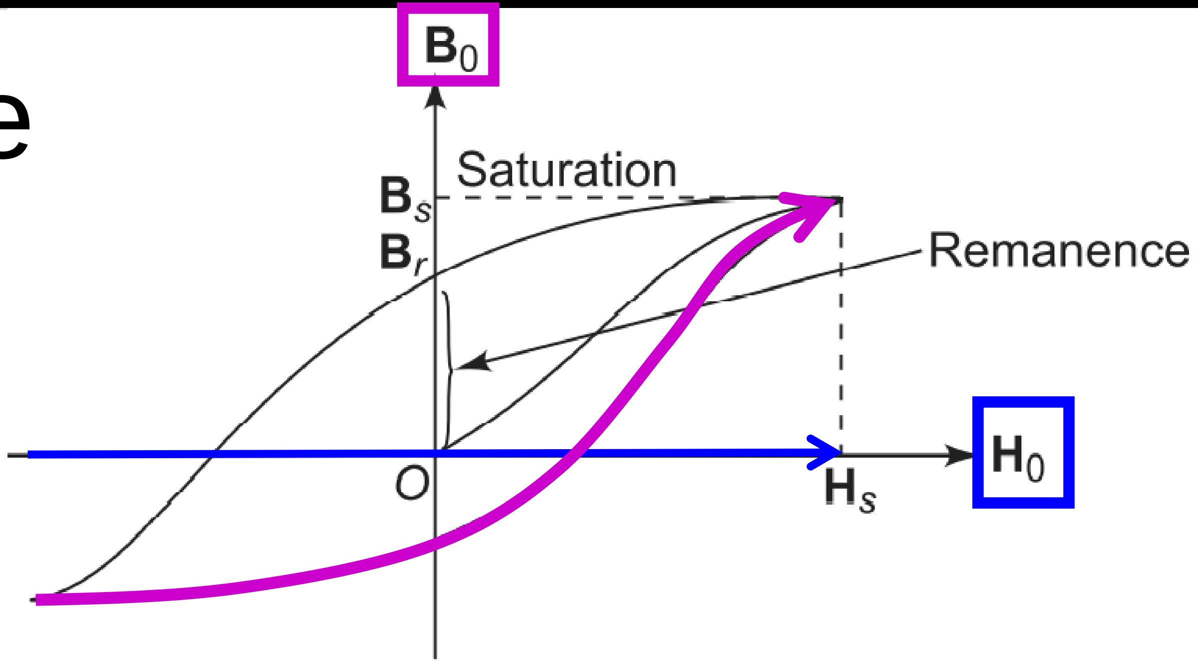

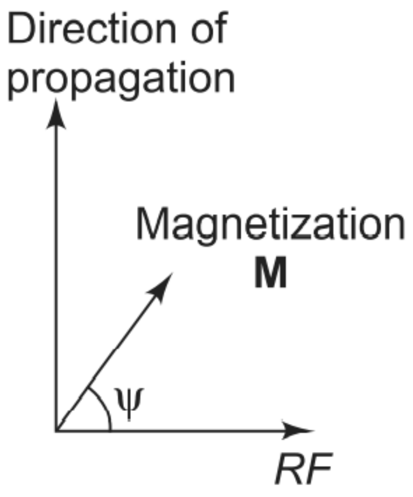

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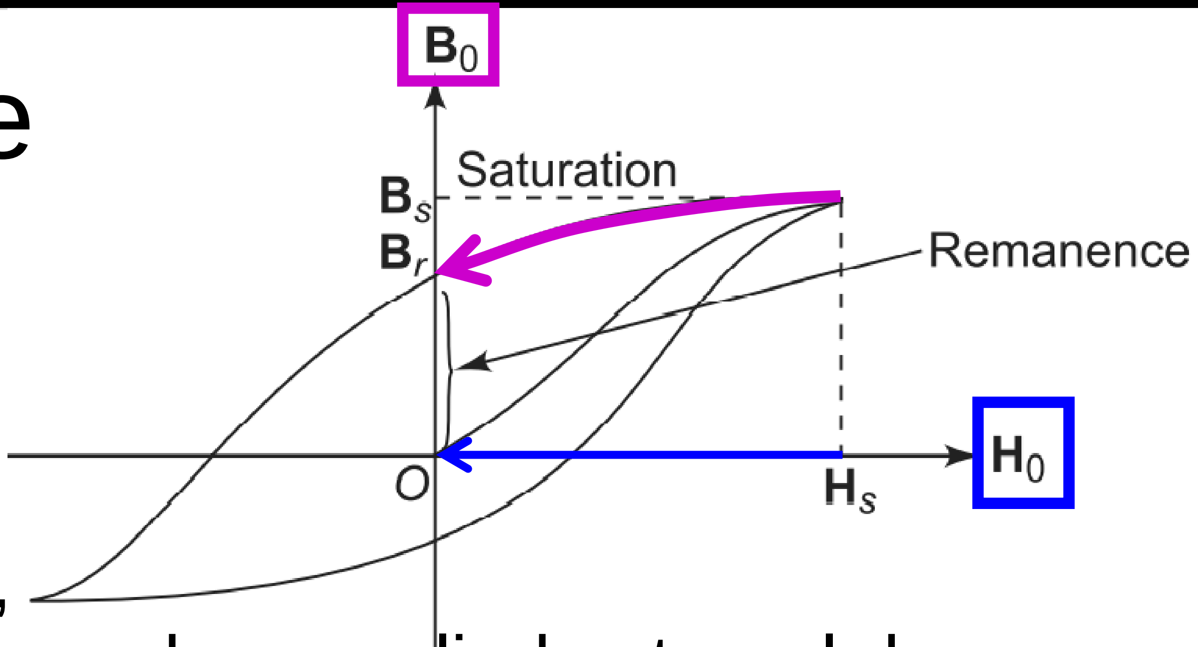
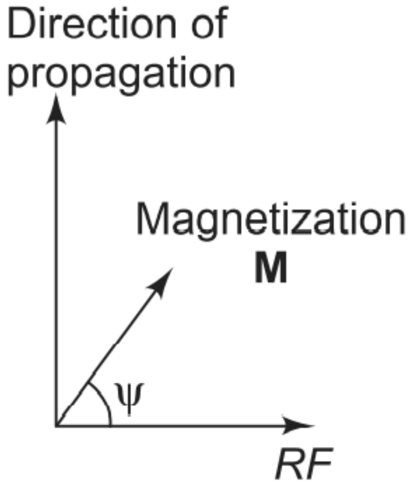
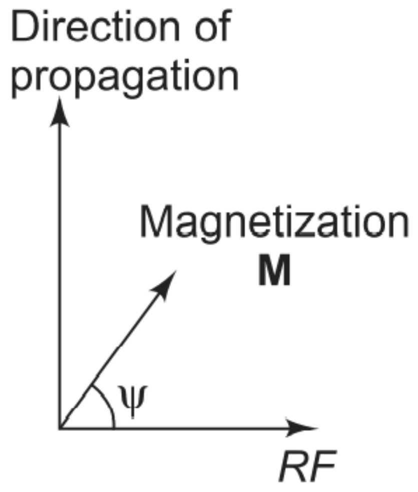


- Hysteresis: The behaviour of magnetization and demagnetization of ferrite.
- Ferrite has high **remanence value**, $\boldsymbol{B_r}$: sample remains magnetized even when applied external dc magnetic field $\mathbf{H_0}$ is reduced to zero from its saturation magnetization $\mathbf{H_s}$.



3. TEM wave in ferrite

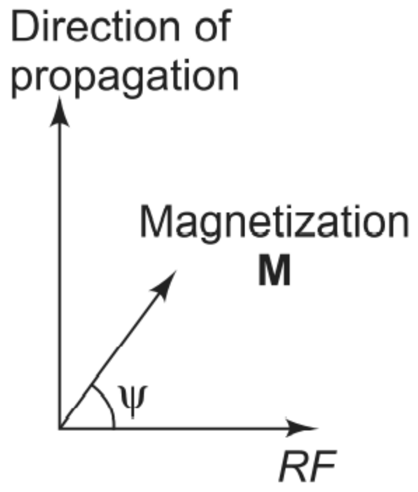


1) If Ferrite sample is magnetized to saturation in its plane, in direction to RF magnetic field $\psi = 0°$,
then for small RF signal strength, minimum interaction between ferrite and RF magnetic field.

- Effective RF relative permeability $\mu_r \approx 1$

2)

3. TEM wave in ferrite



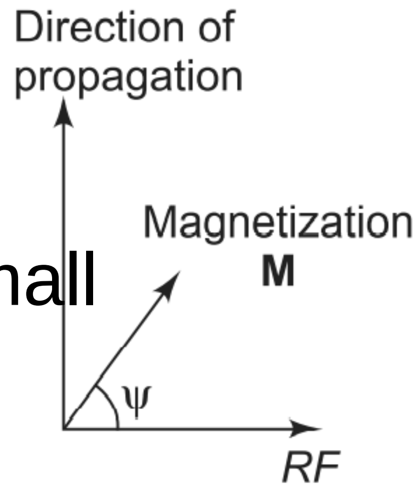
1) If Ferrite sample is magnetized to saturation in its plane, in direction to RF magnetic field $\psi = 0°$, then for small RF signal strength, minimum interaction between ferrite and RF magnetic field.

- Effective RF relative permeability $\mu_r \approx 1$

2) If Ferrite sample is magnetized to saturation in direction perpendicular to RF magnetic field $\psi = 90°$, maximum interaction takes place between ferrite medium and RF magnetic field.

- Effective RF relative permeability $\mu_r = \frac{\mu^2 - K^2}{\mu^2}$ where μ and K are components of permeability tensor $K = \frac{\gamma_m 4\pi M_s}{\omega}$.

3. TEM wave in ferrite



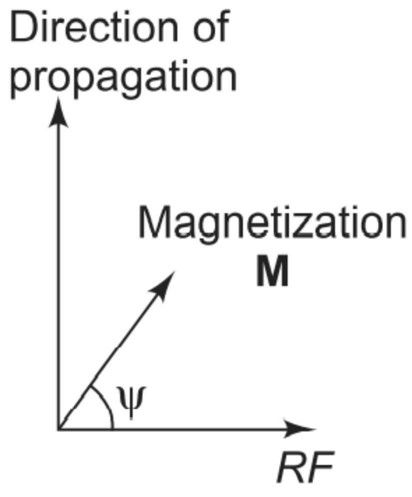
In the frequency range of interest where $\frac{\gamma_m 4\pi M_s}{\omega} < 1$, and with small applied magnetic field, the effective RF relative permeability becomes:

$$\mu_r \approx 1 - \left(\frac{\gamma_m 4\pi M_s}{\omega}\right)^2$$

Where the ferrite's magnetization= $4\pi M_s$.

When $\omega = \gamma_m 4\pi M_s$, magnetic loss becomes significant and the μ_r equation changes.

3. TEM wave in ferrite



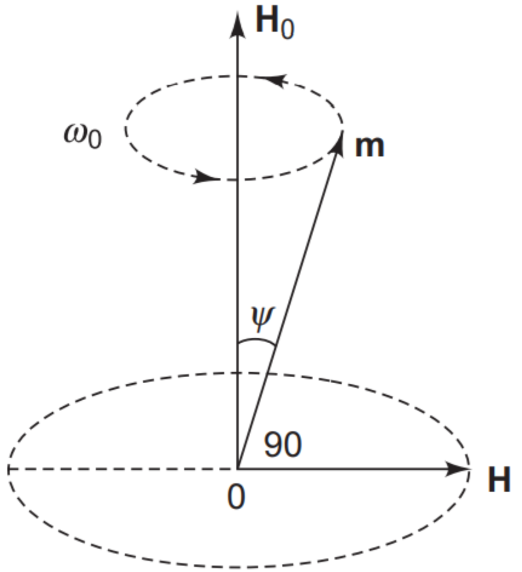
- The propagation constant of TEM wave in ferrite
  $\beta = \omega\sqrt{\mu_r \mu_0 \varepsilon_r \varepsilon_0}$
- When the ferrite is magnetized with

$$\mu_r = \begin{cases} 1, & non\ interacting\ state \\ \frac{\mu^2 - K^2}{\mu^2}, & Interacting\ state \end{cases}$$

- Propagation constant changes its state with the direction of magnetization.

4. Gyromagnetic resonance

- In addition to external steady magnetic field, if RF or microwave circularly polarized magnetic field $\mathbf{H}$ at frequency $f \approx f_0$ is applied perpendicular to $\mathbf{H_0}$,



4. Gyromagnetic resonance

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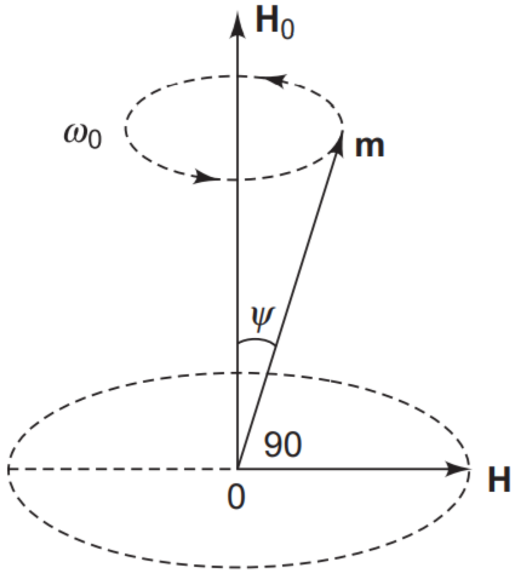
  if RF or microwave circularly polarized magnetic field $\mathbf{H}$ at frequency $f \approx f_0$ is applied perpendicular to $\mathbf{H_0}$,
  <u>When the direction of rotation of $\mathbf{H}$ and $\mathbf{M}$ coincide</u>:
  the angle of precession ψ of $\mathbf{M}$ and also the amplitude of induced precession will tend to increase at $f = f_0$ and reach a steady state due to magnetic frictional loss.
  The energy continuously supplied by the RF field is dissipa
  the ferrite.



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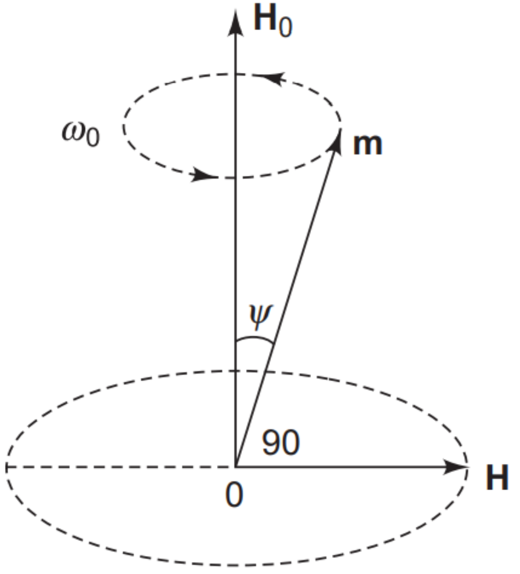

<u>When the interaction between RF/Microwave field and electrons is reduced</u>: Low losses in ferrite.

4. Gyromagnetic resonance

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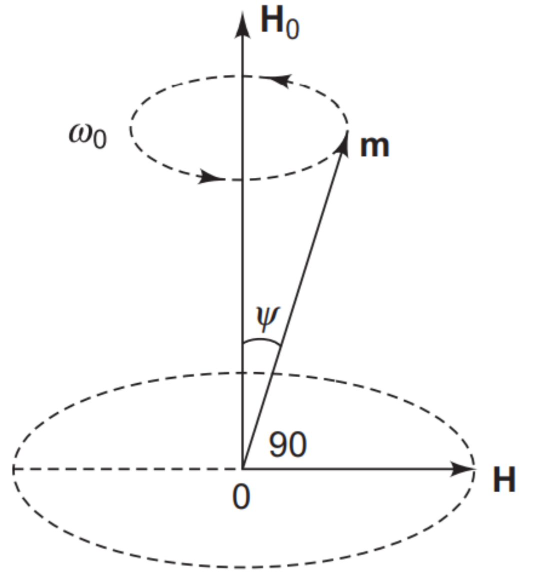
When the direction of rotation of $\mathbf{H}$ and $\mathbf{M}$ coincide:
the angle of precession ψ of $\mathbf{M}$ and also the amplitude of induced precession will tend to increase at $f = f_0$ and reach a steady state due to magnetic frictional loss.
The energy continuously supplied by the RF field is dissipated as heat in the ferrite.

When the interaction between RF/Microwave field and electrons is reduced: Low losses in ferrite.

When $\mathbf{H}$ and $\mathbf{M}$ rotate in opposite direction:
Ferrite dissipates no time averaged power, and hence exhibits low losses.

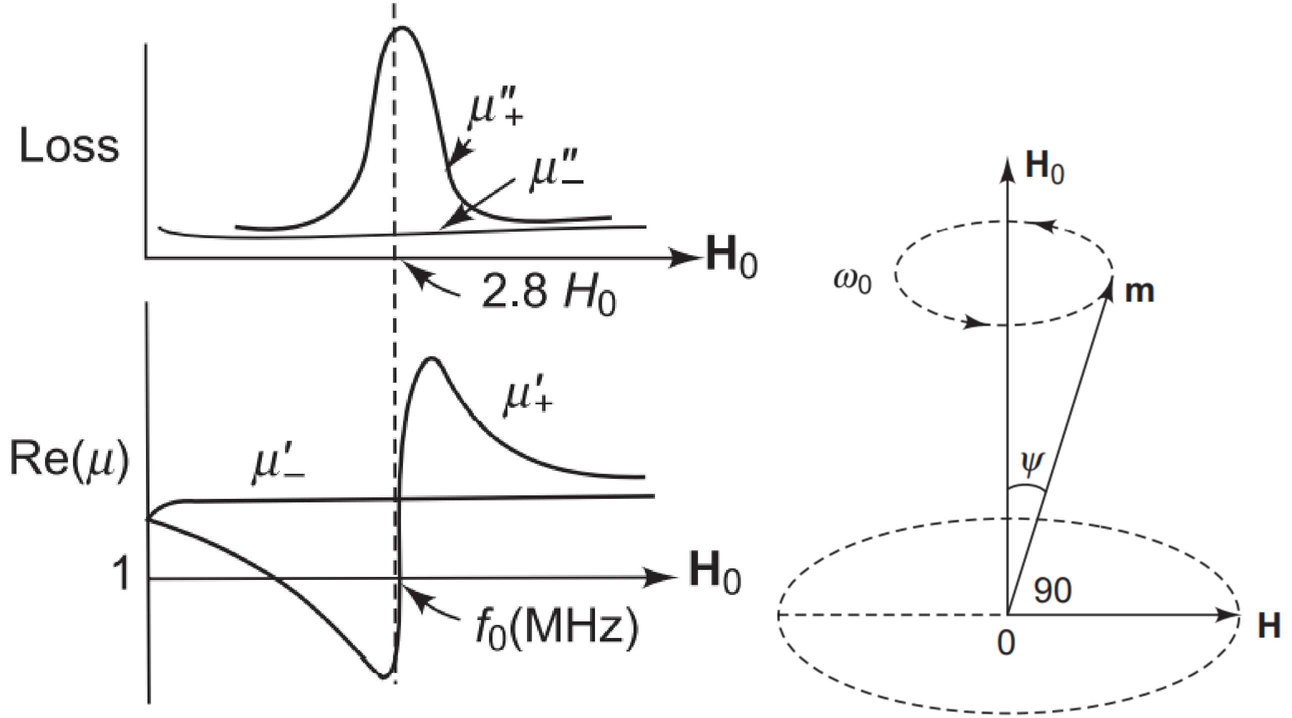


4. Gyromagnetic resonance

- Hence a resonance (gyromagnetic) with

  a peak of loss exists for microwave propagation in ferrites, for clockwise polarization of $\mathbf{H}$ coinciding with M

  a flat low loss for opposite polarization



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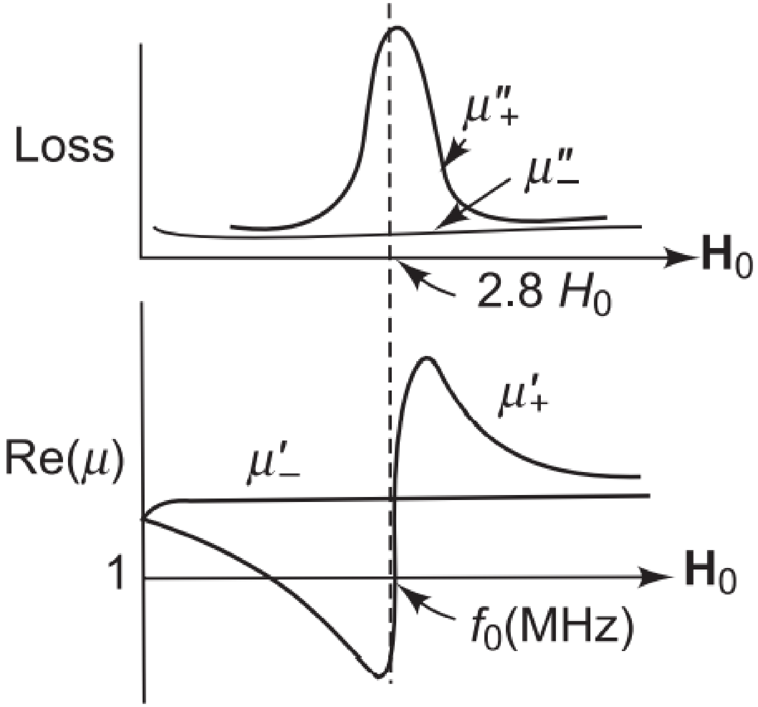
Clockwise polarization:

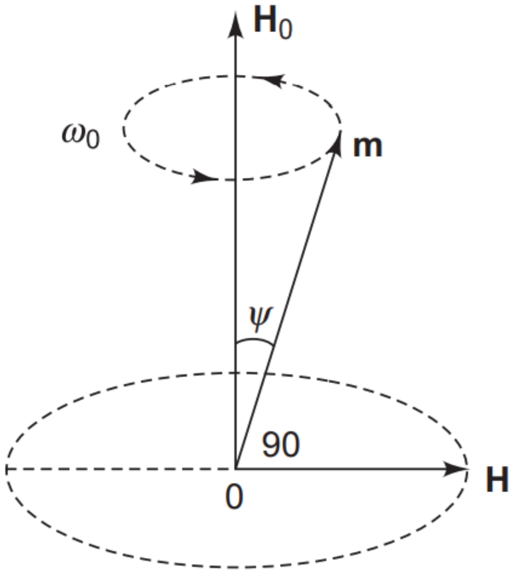
$$B_t^+ = \mu_0 M^+ + B^+ = \mu_+ H^+$$

Anticlockwise polarization

$$B_t^- = \mu_0 M^- + B^- = \mu_- H^-$$

Two complex permeabilities μ_+, μ_-





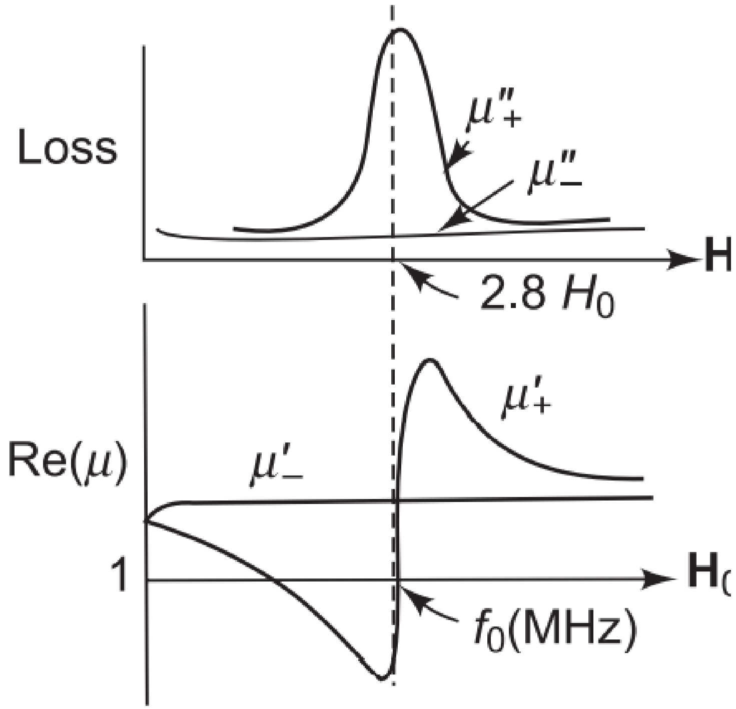
4. Gyromagnetic resonance

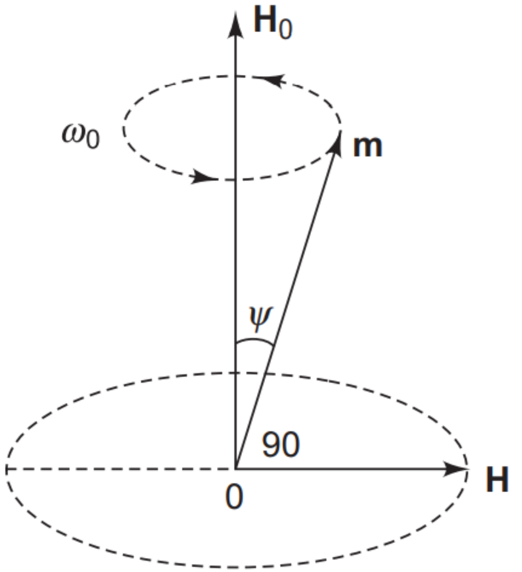
$$\mu_+ = \mu'_+ - \mathrm{j}\mu''_+$$

$$\mu_- = \mu'_- - j\mu''_-$$

Real and imaginary parts of μ_-: are independent of applied steady magnetic field.

μ_+: Resonant behaviour at $\mathbf{H_0}$ **value**





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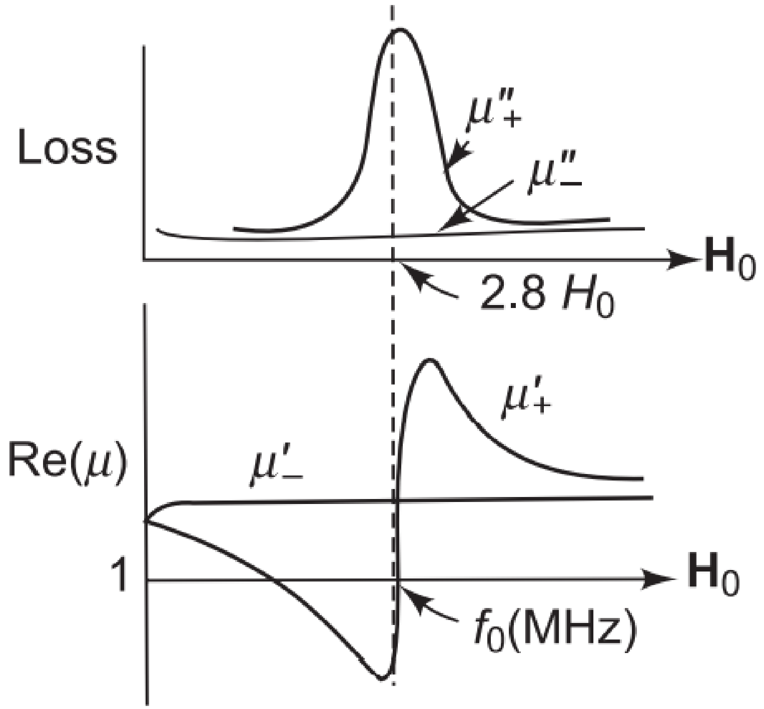
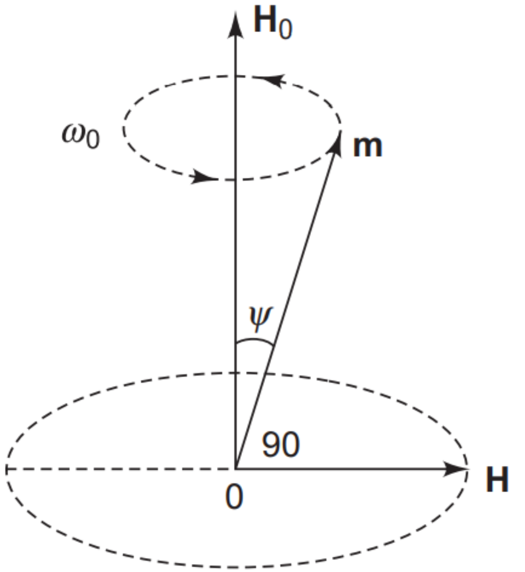
$$\mu_- = \mu'_- - j\mu''_-$$

Real and imaginary parts of μ_-: are independent of applied steady magnetic field.

μ_+: Resonant behaviour at $\mathbf{H_0}$ **value**

Linearly polarized: Combination of Two circularly polarized. Therefore Non-reciprocal behaviour of ferrite materials to microwave propagation.





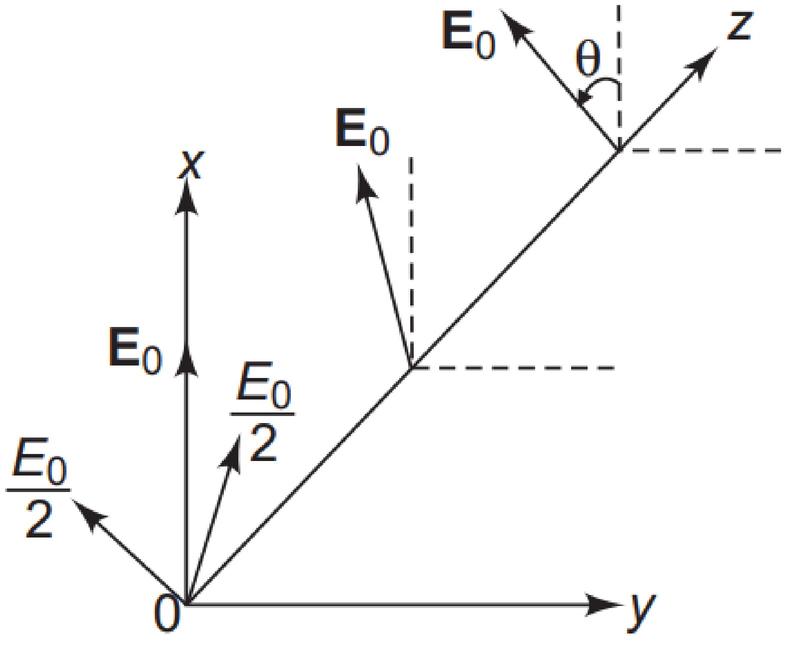
5. Faraday Rotation

$\mu_+ = \mu'_+ - j\mu''_+ \qquad \mu_- = \mu'_- - j\mu''_-$

Plane circularly polarized wave propagating in $\mathbf{H_0}$ direction will have **two propagation constants**

$\beta^+ =$

$\beta^- =$



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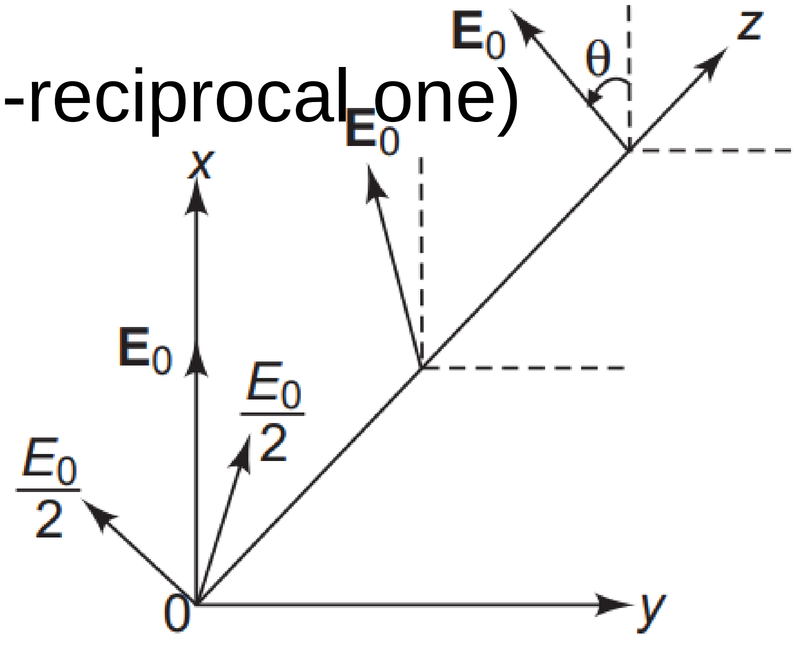
$\mu_+ = \mu'_+ - \mathrm{j}\mu''_+ \qquad \mu_- = \mu'_- - j\mu''_-$

Plane circularly polarized wave propagating in H_0 direction will have two propagation constants

$\beta^+ = \omega\sqrt{\varepsilon\mu_+} = \frac{2\pi}{\lambda^+}$ Clockwise

$\beta^- = \omega\sqrt{\varepsilon\mu_-} = \frac{2\pi}{\lambda^-}$ AntiClockwise

Which results in plane of polarization to rotate. (Non-reciprocal one)



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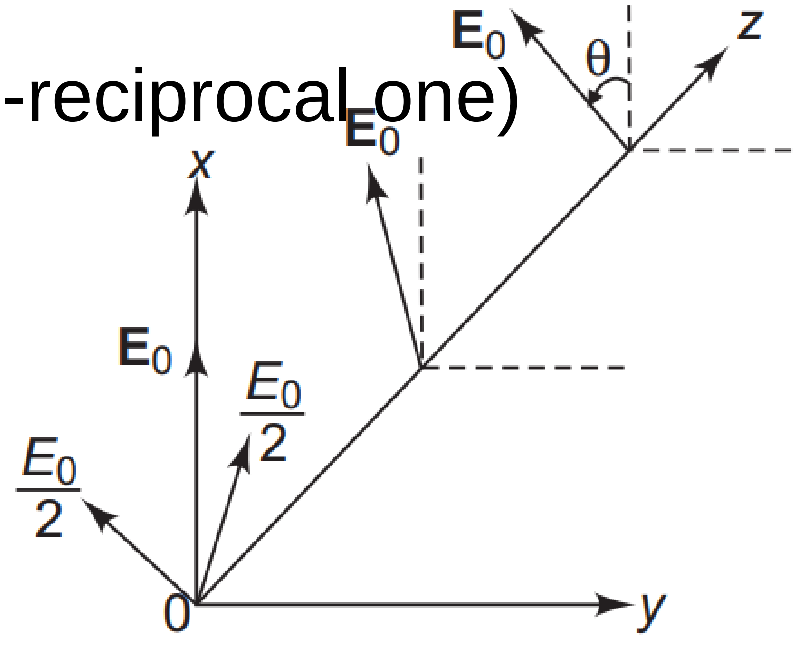
Which results in plane of polarization to rotate. (Non-reciprocal one)

Rotation of Electric field of linearly polarized wave passing through a magnetized ferrite is
<u>Faraday rotation in ferrites.</u>

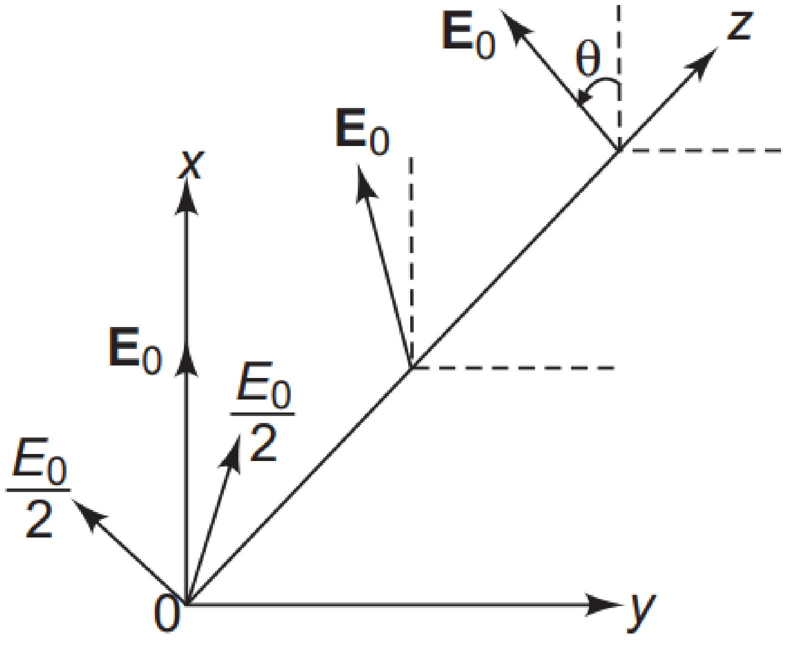


5. Faraday Rotation

$\mu_+ = \mu'_+ - j\mu''_+ \qquad \mu_- = \mu'_- - j\mu''_-$ with $\beta^+ = \omega\sqrt{\varepsilon\mu_+} = \frac{2\pi}{\lambda^+}$ (CW) , $\beta^- = \omega\sqrt{\varepsilon\mu_-} = \frac{2\pi}{\lambda^-}$ (CCW)

Linearly polarized TEM wave propagates in ferrite along $+z$ axis.

$\mathbf{E} = \bar{a}_x E_x$ at $z = 0$



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The linearly polarized wave – decomposed into sum of CW and CCW circularly polarized waves.

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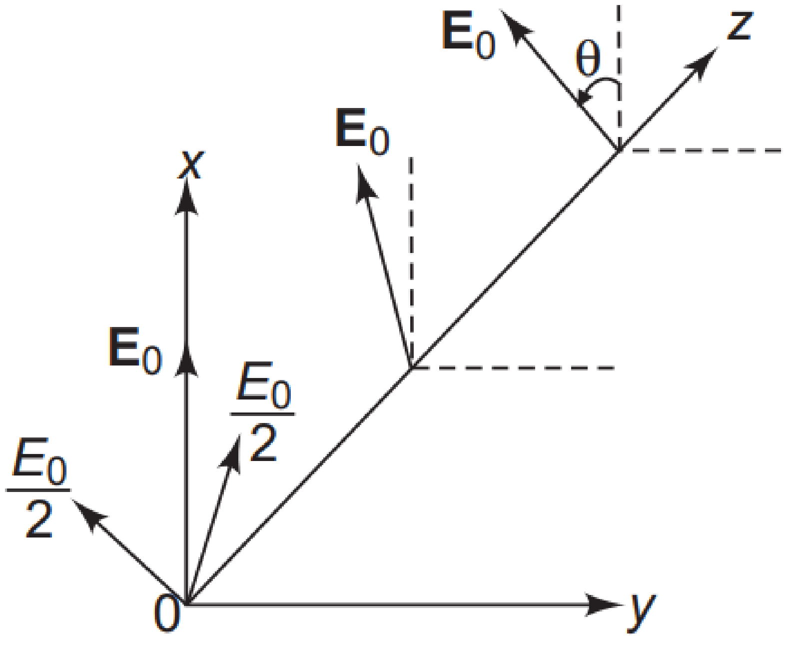

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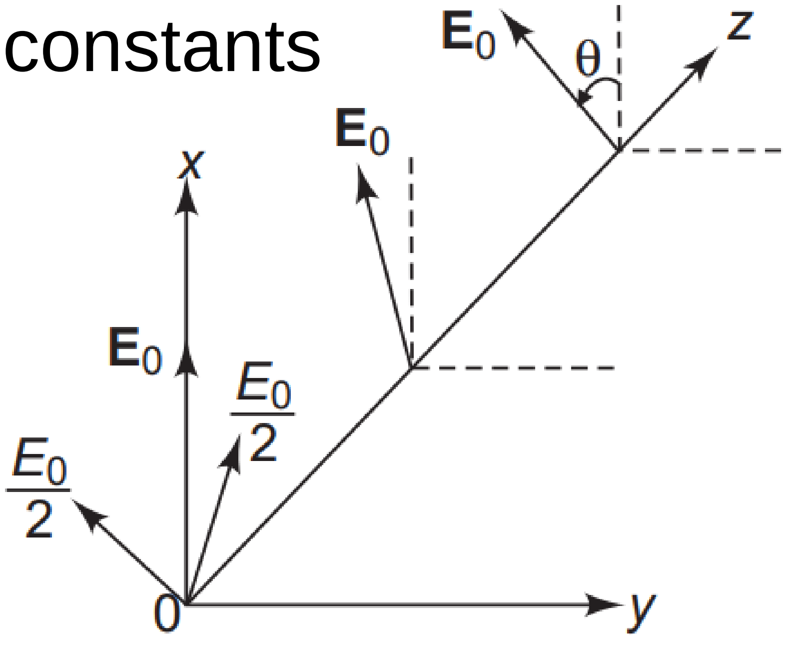
The linearly polarized wave – decomposed into sum of CW and CCW circularly polarized waves.

The component waves propagate at different phase constants β^+, β^-.

Two electric field vectors rotate at different rates.



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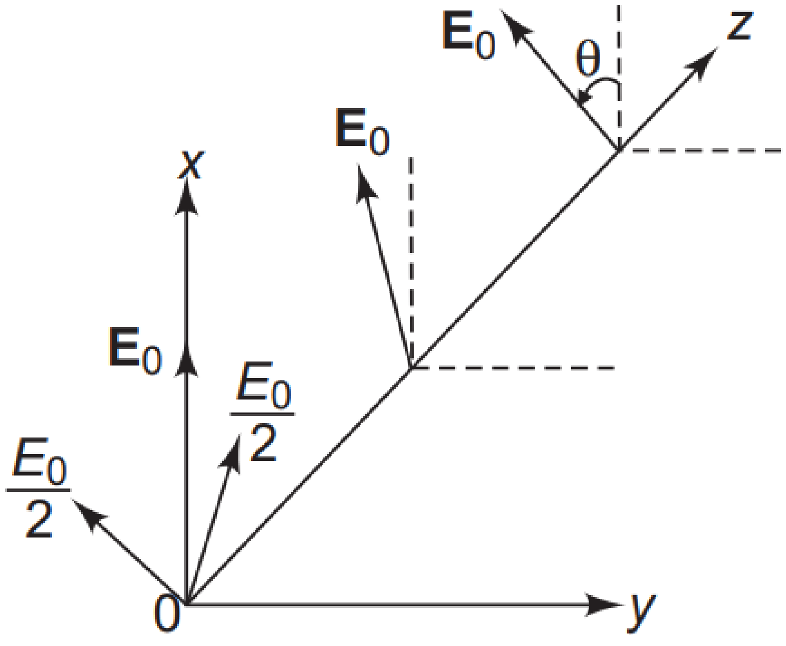
Over a distance λ, resultant polarized wave undergoes phase shift of $(\beta^+ + \beta^-)\lambda = 4\pi$

$\lambda = \frac{4\pi}{\beta^+ + \beta^-} = \frac{2\lambda^+\lambda^-}{\lambda^+ + \lambda^-}$ with angle $\frac{(\beta^+ - \beta^-)\lambda}{2} = \frac{(\beta^+ - \beta^-)}{(\beta^+ + \beta^-)}2\pi$

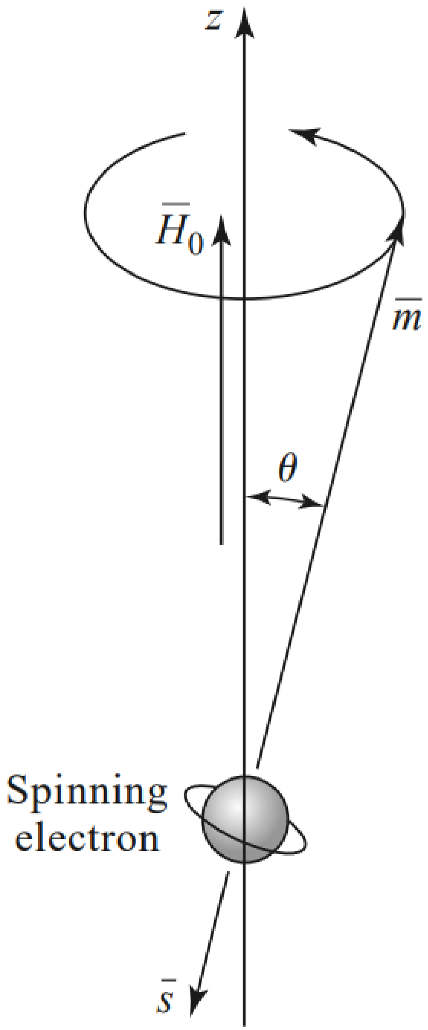
Rotation per unit distance $\theta = \frac{(\beta^+ - \beta^-)\lambda}{2}$

Application in ferrite isolators



2.1 Basic properties of Ferrimagnetic materials

- Permeability tensor:
  Existence of magnetic dipole moments (due to primarily from electron spin)



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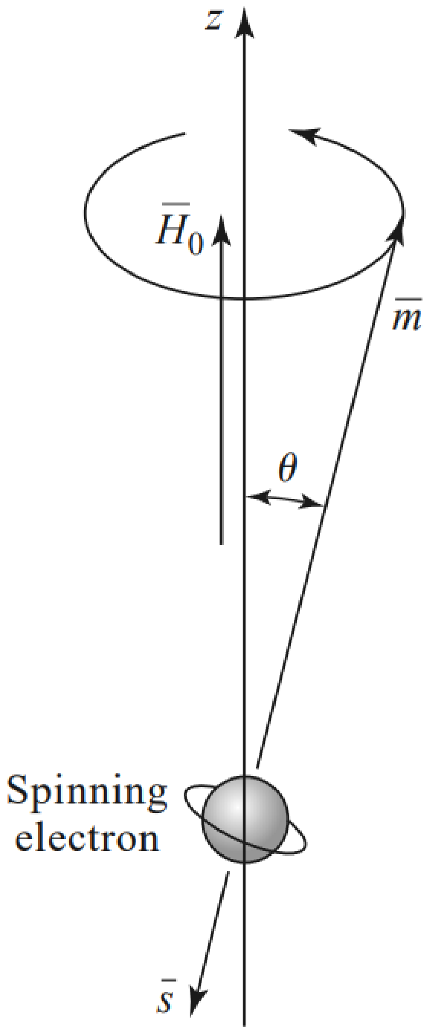
- Permeability tensor:
  Existence of magnetic dipole moments (due to primarily from electron spin)
- Magnetic dipole moment of an electron due to its spin

$$m = \frac{qh}{2m_e} = 9.27 \times 10^{-24}\mathrm{A} - \mathrm{m}^2$$

h: Plank’s constant by 2π.
q: Electron charge
m_e: mass of the electron



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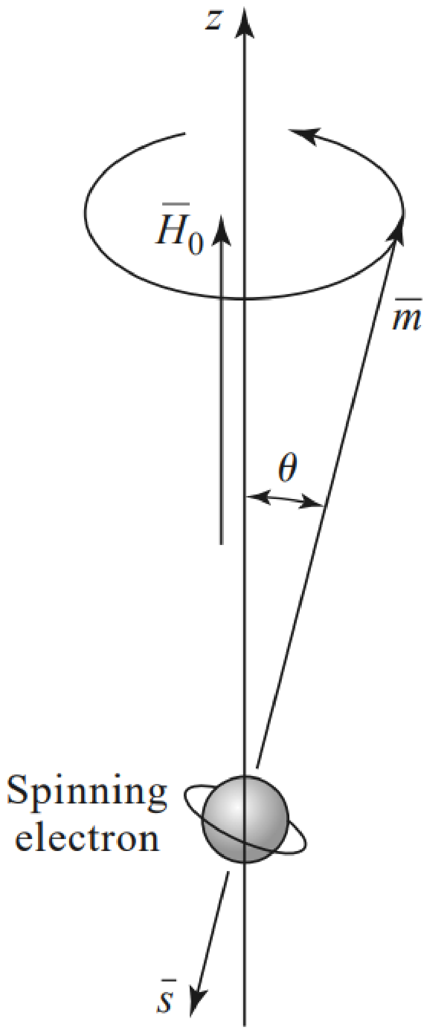
- An electron in orbit around a nucleus gives rise to an effective current loop, thus an additional magnetic moment.



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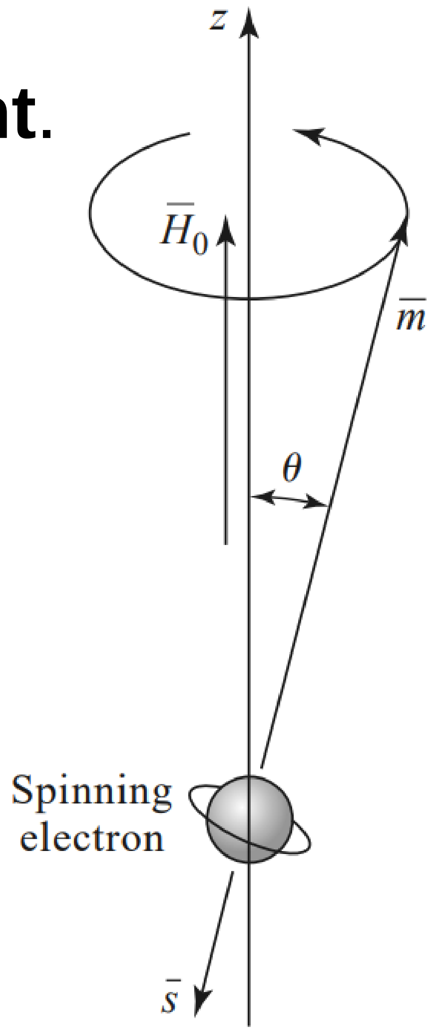
- **An electron in orbit around a nucleus** gives rise to an **effective current loop**, thus an **additional magnetic moment**.
- This is generally insignificant when compared to magnetic moment due to spin.



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- An electron in orbit around a nucleus gives rise to an effective current loop, thus an additional magnetic moment.
- This **is generally insignificant** when **compared to magnetic moment due to spin**.
- $Lande'g\ factor$: measure of relative contributions of orbital moment and the spin moment to the total magnetic moment

$g = 1$ *when* moment is due only to orbital motion.
$g = 2$ *moment is due to spin only.*

Most ferrite materials: g: *in the range of* $1.98 - 2.01$ *(g=2)*