

CHAPTER 15

Ferrite Materials

15.1 Introduction

Ferrites are mixed crystals of various metallic oxides and may be considered to consist of oxygen ions in a closed-packed structure with *cations* filling the interstices. They have a general formula: $MOFe_2O_3 \cdot xH_2O$ where M is a divalent metallic ion such as Mn^{2+} , Fe^{2+} , Co^{2+} , Ni^{2+} , Zn^{2+} , Mg^{2+} , and Cd^{2+} . In general, the magnetic saturation intensity of ferrites is lower than that of various metallic magnetic alloys, but the ferrites have very high resistivity and as such are insulator-like. Therefore, the power loss in ferrites is very small especially at high frequencies. Further, ferrites have a narrow hysteresis (BH) loop and can be made with square-loop characteristics. These properties permit their applications in high frequency devices and for switching (memory) cores.

Ferromagnetic materials such as steel which have wide applications in electrical engineering have a disadvantage in that they have low electrical resistivity. The laminations used for electrical machines, for example, have a resistivity of about 14×10^{-6} ohm-cm and the highest value obtainable in ferromagnetic alloys is less than 10^{-4} ohm-cm. This disadvantage of ferromagnetic materials limits their application in the high frequency alternating current applications. High *eddy current losses* occur in metallic sheets even at low frequencies. Ferrites, on the other hand, with useful magnetic properties have d.c. resistivity of many orders higher than in iron and are used at frequencies up to microwaves.

Ferrites are essentially *ferrimagnets*. That is, if the net magnetization of magnetic sublattices is not zero, the material exhibits ferrimagnetism and possesses a net *magnetic moment*. (This moment disappears above the Curie temperature T_c analogous to Néel temperature at which thermal energy randomizes the individual magnetic moments and the material becomes *paramagnetic*.)

Ferrites (ferrimagnetic materials) in general, as mentioned earlier, are complex oxide compounds of various metals and oxygen. Ferrites are derived from *magnetite* by replacing the divalent iron atom by an atom of another metal. The formula for magnetite is $(Fe^{2+}O, Fe_2^{3+}O_3)$.

The general properties of ferrites as compared to metallic soft-alloy materials are listed in Table 15.1.

Many of the useful ferrites are isomorphic (similar structure) with the mineral *spinel* with the formula $(MO Fe_2O_3)$, M being the replacement metal as mentioned earlier. Usable replacement metals as mentioned earlier are divalent metals such as manganese, magnesium, nickel, copper, cobalt, zinc, and cadmium. The properties of final ferrite depend on the nature of the replacement metal and on its properties. When Zn or Cd are the replacement for Fe, the ferrite obtained is nonmagnetic. When it is entirely replaced by one of the other metals mentioned above, the material is magnetic with a high permeability but large hysteresis losses. Complex ferrites are also possible when the iron atoms are replaced by two divalent atoms at the same time. Typical examples are : Manganese-magnesium, nickel-zinc, nickel-cobalt, nickel-aluminum ferrites. The chemical formula for nickel-zinc ferrite is $(\alpha NiO \beta ZnO Fe_2O_3)$, $(\alpha + \beta) = 1$. In some cases the trivalent atoms of iron in Fe_2O_3 are replaced by atoms of another trivalent metal such as Al.

The intense intrinsic magnetization of ferrites is due to the ion distribution of the inverse spinel type and also an anti-parallel alignment of the spins on the A and B sites as shown in Figure 15.1.

Table 15.1 Ferrite versus Metallic Alloys: General Magnetic Properties

Material	μ_T (Initial)	μ_T (Max)	H_C (oersted)	B_S (gauss)	Saturation BH loss (erg/cm ²)	ρ (ohm-cm)
Grain-oriented Si-Fe 3% Si, 97% Fe	1500	40000	0.1	20000	700	47
Supermalloy 5% Mo, 79% Ni	100000	10 ⁶	0.002	7900	8	60
Ferroxcube3 Mn-Zn Ferrite	1000	1500	0.01	2500	130	10 ⁸

Remarks: μ_T = Relative permeability.
 H_C = Coercive magnetic field intensity.
 B_S = Saturation value of magnetic flux density.
 ρ = Resistivity.

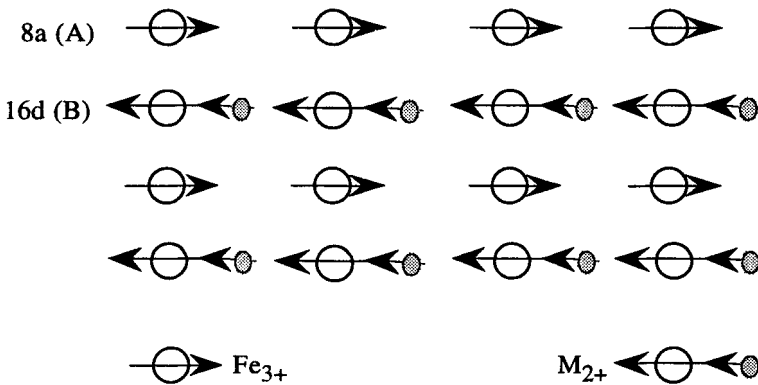
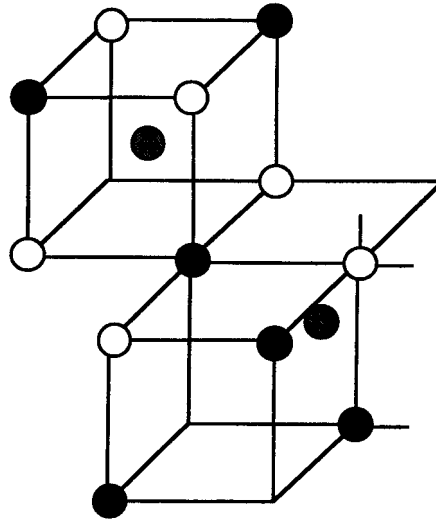


Figure 15.1 Spin-arrangement in inverse spinel structure.

The opposing Fe³⁺ at A and B sites cancel each other being M²⁺ ions at the B sites to yield an effective moment. The extent of this effective moment depends on the maximum spin magnetic moment attained by the alignment of 3d spins in the transition metal. The absolute saturation moment of a simple ferrite per unit cell is denoted by M/M_B .

Ferrites have largely spinel or inverse spinel structures. (However, garnet and perovskite structures are also not excluded as will be detailed later.) The spinel structure is illustrated in Figure 15.2.

As an example, considering MOFe₂O₃ ferrite the divalent metal M²⁺ ions reside at the interstitial 8a-sites (A sites) and Fe³⁺ ions reside at 16d sites (B sites). This is a *simple* or *normal ferrite*. The oxygen ions in this lattice touch each other and form a close-packed face-centered cubic lattice.



- Oxygen ions forming fcc lattice
- Metal ions at tetrahedral sites (8a-sites):A sites
- Metal ions at octahedral sites (16d-sites):B sites

Figure 15.2 Spinel structure.

In another crystalline structure known as *inverse spinel structure*, half of the Fe^{3+} ions reside at A sites and the remaining half as well as all the M^{2+} ions are located at B sites.

In normal spinel-type structure, the spinel unit cell of a ferrite consists of a close-packed cubic array of 32 oxygen anions between which there are 96 spaces or interstices: 24 are filled with cations, and the remaining 72 are empty. The sites occupied by the cations are of two kinds, tetrahedral or A sites and octahedral or B sites. The A sites (of which eight are occupied), are surrounded by four oxygen anions, and B-sites (of which sixteen are occupied) are surrounded by six oxygen anions.

General magnetic and electric properties of ferrites can be enumerated as follows:

- A very high resistivity, generally, in excess of 10^5 ohm-cm
- Dielectric constant of the order of 10–12 at high frequencies (microwaves) with extremely low dielectric loss
- Permeability of several tens
- Saturation magnetization is appreciable, but significantly smaller than that of ferromagnetic materials
- Low coercive force
- Curie temperature varies from $100^{\circ}C$ to several hundred $^{\circ}C$
- Mechanically hard, brittle, and not easily machinable

Ferrimagnetic domains in certain materials can be altered in their shape by the application of an external field. These domains can be used to store information. The materials of interest in such a category are the rare-earth *orthoferrites* and the rare-earth *iron garnets*.

The orthoferrites are not ferrimagnets but antiferromagnets in which the direction of the sublattice magnetizations make a small angle with each other giving rise to a magnetic state called *weak ferrimagnetism*. In such materials, domain pattern can be altered by applying a field normal to the crystal face to become a set of individual cylindrical domains known as *magnetic bubbles*.

Rare-earth iron garnets, for example, $\text{Er}_3\text{Fe}_5\text{O}_{12}$ (erbium-iron-garnet), holmium-iron-garnets, etc. also show bubble domain characteristics; and hexagonal ferrites $\text{BaFe}_{12}\text{O}_{19}$ and $\text{PbFe}_{12}\text{O}_{19}$ have also been used as domain materials.

Anisotropic properties in ferrimagnetic materials made by pressing and sintering *ceramic powder* can be obtained by applying a magnetic field appropriately during the firing and cooling processes. These are cost-effective materials and can be used *in lieu* of metallic magnets to realize high resistivity and low eddy current losses.

Maximum magnetic moment of a ferrite is $5 M_B$, (where M_B is the Bohr magneton moment) with inverse spinel structure. This value can be increased by adding some amount of normal spinel ferrite, for example, ZnFe_2O_4 . The Zn^{2+} ions would then occupy the A sites and force the same number of Fe^{3+} ions from A to B sites; and this will result in additional magnetization of B sites. By adding a fraction of ZnFe_2O_3 to the fraction $(1-x)$ of $(\text{Fe}^{3+})_O \cdot (\text{Fe}^{3+} + \text{M}^{2+})\text{O}_3$, the resulting structure $(\text{Fe}_{1-x}^{3+}\text{Zn}_x^{2+})_O \cdot (\text{Fe}_{1+x}^{3+} \text{M}_{1-x}^{2+})\text{O}_3$ will have $M = [n + (10-n)x] M_B$ where n is the number of Bohr magnetons of M^{2+} moment. Thus with Zn^{2+} ions, M_B increases to $10 M_B$. Experimental evidence indicates such an increase with a small concentration of the added ferrite. At higher concentrations deviations from the increase are observed (Figure 15.3) [1].

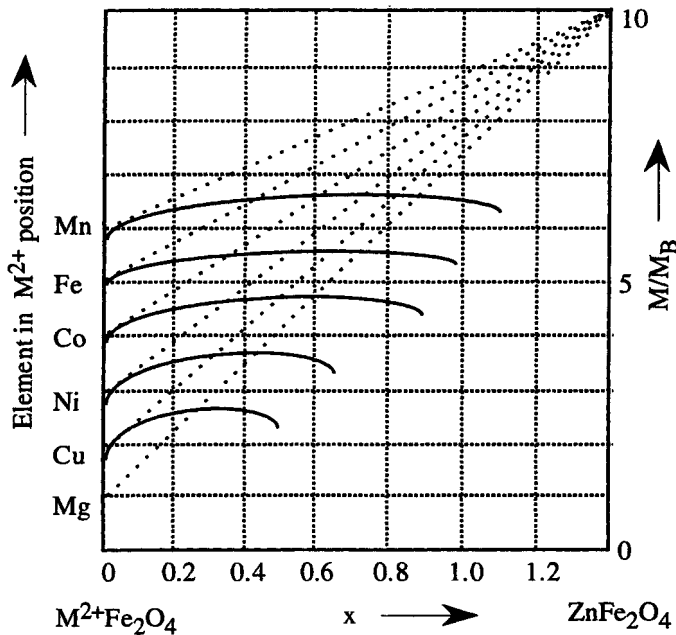


Figure 15.3 Fractional addition of normal spinel ferrite *versus* enhancement of magnetic moment of $\text{M}^{2+}\text{Fe}_2\text{O}_4$.

15.2 Temperature Dependency of Intrinsic Magnetization of Ferrites

This is described by the *Néel theory*. Considering the proportion of Fe^{3+} ions on A sites as α and on B sites is β (so that $\alpha + \beta = 1$), then $\alpha = 0$, $\beta = 1$ specifies a *normal*

spinel; and $\alpha = \beta = 0.5$ refers to *inverse spinel*. Since M^{2+} ions occupy the remaining sites, the distribution of ions over A and B sites can be indicated by:



The total intensity (I) of magnetization is $\alpha I_A + \beta I_B$ where I_A and I_B are contributions from sites A and B, respectively, at thermal equilibrium. These depend on exchange interactions between both atoms of different sites and atoms on the same site. Hence above the Curie temperature, by consideration of *Langevin's theory of paramagnetism**, the magnetic susceptibility χ_m , versus temperature (T) can be written as:

$$(1/\chi_m) = [(T/C) + (1/\chi_o)] - [\sigma/(T - \theta)] \tag{15.2}$$

where C , σ , and θ are constants for a material and $(1/\chi_o)$ is the y-intercept of $(1/\chi_m)$ versus T curve shown in Figure 15.4.

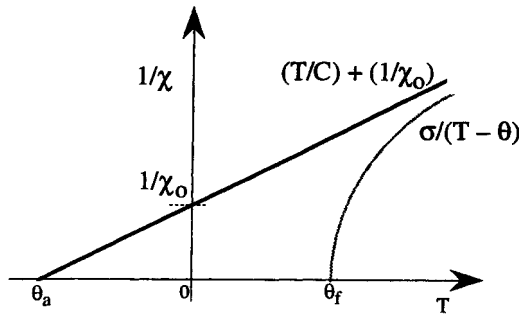


Figure 15.4 Temperature versus magnetic susceptibility of a ferrite.

Referring to Figure 15.4, the constant C and θ_a are related by the equation $\theta_a = (-C/\chi_o)$ and θ_a is designated as the *asymptotic Curie point*. Further, θ_f is the temperature at which $1/\chi_m$ becomes zero and at the same time a spontaneous magnetization appears and is referred to as *ferrimagnetic Curie point* or *Néels temperature*. If $\theta_f < 0$, there is *paramagnetism* for the whole temperature range whereas if $\theta_f > 0$, there is *ferrimagnetism* below this temperature.

* *Langevin's theory of paramagnetism* refers to a simple model specifying the net atomic moments being zero in the absence of an applied field due to their mutual cancellation as a result of isotropic random orientation. With an applied field, the atomic moments tend to align along the field and the resulting orientation of the moments (with the counteraction due to thermal agitation) is partially anisotropic. This partial anisotropic orientation of the atomic moments yields a small susceptibility. With increase in temperature, the thermal agitation upsetting this partial anisotropy leads to a decrease in susceptibility. Quantitatively, the relative magnetization (M/M_o) is governed by the *Langevin function* $L(a)$ equal to $\text{Coth}(a) - 1/a$ where $a = \mu H/k_B T$. Here, μ is the permeability, H is the magnetizing external field, k_B is the Boltzman constant, and T is the temperature.

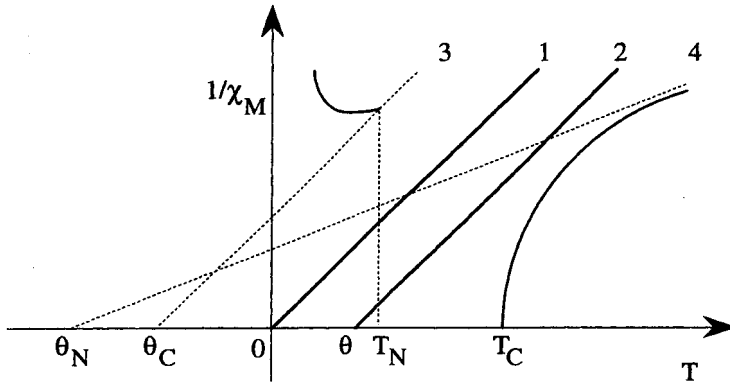


Figure 15.5 Reciprocal of magnetic susceptibility as a function of temperature for various types of magnetic materials.

As a summary, Figure 15.5 depicts the variation of reciprocal magnetic susceptibility (χ_m) as a function of temperature for various magnetic materials. The curves shown are:

1. Paramagnet-Curie law: $\chi_m = C/T$
2. Ferromagnet-Curie-Weiss law: $\chi_m = C/(T - \theta)$; $T > \theta$ where θ is Curie temperature.
3. Antiferromagnet-Curie-Weiss law: $\chi_m = C/(T + \theta_N)$; at $T > T_N$
 θ_N Extrapolated Néel temperature
 T_N Néel temperature
4. Ferrimagnet-Curie-Weiss law: $\chi_m = C/(T + \theta_o)$; $T > T_o$
 T_o Ferrimagnetic Curie temperature
 θ_o Extrapolated Curie temperature

15.3 Magnetization Characteristics of Ferrites

When ferromagnetic or ferrimagnetic materials are magnetized, the direction of magnetization will be rotated from its preferential direction. This corresponds to an anisotropic behavior. On removing the magnetizing force, the total magnetization will in general have a non-zero value. The above characteristics are due to crystal stress and shape anisotropies, respectively.

Crystal anisotropy: Crystal anisotropy does not yield a variation of permeability in a ferrite with the direction of applied magnetizing force because the bulk material consists of an aggregate of crystals whose axes are randomly oriented.

Stress anisotropy: Simple ferrites (with the exception of Fe_3O_4) have a negative *magnetostriction constant*; that is, upon magnetization the ferrites contract in the direction of magnetization. Therefore under a compressive force they can be magnetized most easily in the direction of magnetization and under tension they magnetize easily in a direction perpendicular to the direction of magnetization. Thus useful properties can be infused into ferrites under controlled stresses. However, occurrence of arbitrary stresses is undesirable and is avoided. As such, while preparing the ferrites, care has to be exercised to reduce any unspecified stresses to a minimum.

Shape anisotropy: A ferromagnetic body is magnetized most easily in the direction of its largest dimension. Non-magnetic inclusions and voids in the body have a similar influence producing a local preferential direction of magnetization parallel to its largest dimension. Different degrees of porosity exist in ferrites depending upon the method of preparation. Ferrites are therefore especially prone to the internal shape anisotropy. Hence, it

is often endeavored to make these materials less porous because shape anisotropy impairs their usefulness for many applications. The effect of porosity on the magnetization curve and the hysteresis loop of a ferrite is shown in Figure 15.6.

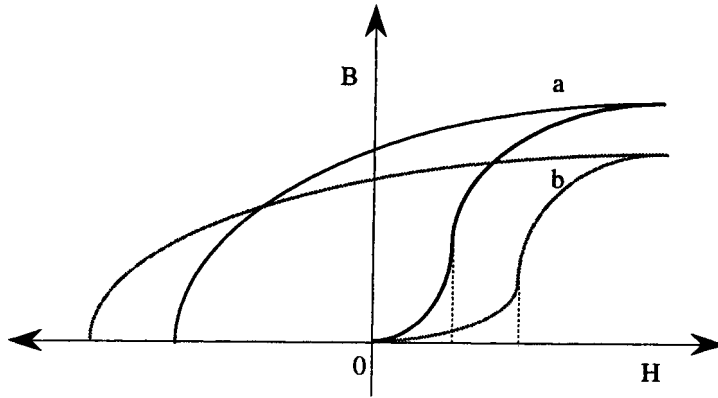


Figure 15.6 Effect of porosity on the magnetization curve of a ferrite. (a) Non-porous material; (b) Same ferrite with substantial porosity.

The porous material has less remnant magnetism than the non-porous material but the demagnetization field required to reduce the magnetism to zero is larger for a porous material than for the non-porous one.

Ferrites are hard and brittle materials and as mentioned earlier they cannot be shaped by ordinary machining processes. In general, a diamond impregnated slitting wheel is necessary for cutting the ferrite rods.

The mechanical and thermal properties of ferrites are compared with those of iron in Table 15.2.

Table 15.2 Properties of Ferrite and Iron

	Ferrite (Ferrox-cube) TM	Iron
Specific gravity	4.30	7.80
Young's modulus lb/sq.in.	21×10^6	31×10^6
Tensile strength lb/sq.in.	2,600	43,000
Crushing strength lb/sq. in.	10,400	43,000
Coefficient of linear expansion $^{\circ}\text{C}^{-1}$	11×10^{-6}	12×10^{-6}
Specific heat	0.17	0.11
Thermal conductivity Cal/cm-sec- $^{\circ}\text{C}$	8×10^{-3}	0.18

Table 15.2 shows that ferrites have a lower tensile strength and a lower thermal conductivity as compared to iron. Ferrite component should not, therefore, be subjected to tension. Low thermal conductivity may result in high local temperature and large temperature gradients in the ferrite subjected to rapid reversals of magnetic fields. Apart from mechanical fracture which may take place due to high temperature gradients, the magnetic performance may also be seriously impaired if the Curie temperature is approached at any of the hot spots within the material.

15.4 Magnetic Resonance in Ferrites and Faraday Rotation

A rotating body will produce a *kinetic moment* along the axis of rotation. This kinetic moment is proportional to the speed of rotation. The rate of change of the kinetic moment with time is equal to the couple of the applied force.

An electron having a mass and spin will give rise to both magnetic moment and kinetic moment. If M is the magnetic moment and P is the kinetic moment, then the *gyromagnetic ratio* is given by:

$$\gamma = |M/P| \quad (15.3)$$

The electron rotates in a fixed direction along the axis OC (Figure 15.7) when an external field is applied. If an external field H is applied along the OZ axis, this magnetic field would exert a couple C on moment M ; that is, $C = M \times H = dP/dt$. Further, since $dP/dt = (-1/\gamma) dM/dt$, it follows that $M \times H = (-1/\gamma) dM/dt$. This is the differential equation of motion of the moment M . The tip of the M vector will rotate in a circle lying in a plane perpendicular to OZ. The corresponding angular velocity is given by: $\omega = 2\pi f$ where $f = (\gamma/2\pi)H = 2.8 \times 10^6 H$ for electrons.

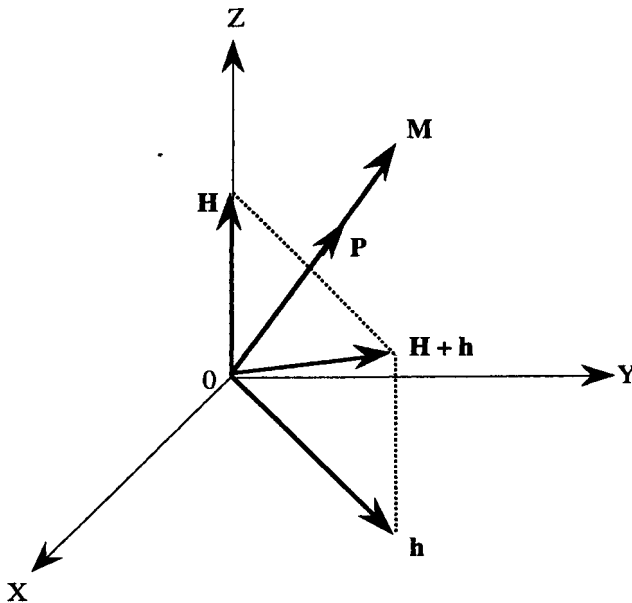


Figure 15.7 Illustration of the axes pertinent to magnetic resonance phenomenon.

When a circularly polarized high frequency field h is applied, this field will rotate in the plane of magnetic polarization which is the plane XOY in Figure 15.7. Under this condition, the vector $(H + h)$ describes a cone carrying the moment M with which it acquires a *precessional motion* around it. If the sense of rotation of h is such that the resultant vector

$(\mathbf{H} + \mathbf{h})$ rotates in the same sense as that of precession and if the frequency of \mathbf{h} is the same as that of the precession, then there will be a synchronization of the two phenomena resulting in the *magnetic resonance*. This will cause absorption of energy from the high frequency field. This phenomenon is known as *gyromagnetic resonance*. On the other hand, if the sense of rotation of the field \mathbf{h} is such that the resultant vector rotates in the opposite sense to that of the precession, then there is no synchronization and hence no magnetic resonance will take place.

For a circularly polarized high frequency wave the sense of rotation depends on the direction of propagation. Resonance occurs only in one direction of propagation. In the other direction there is no resonance and hence no significant absorption.

The effective permeability of the ferrite in respect to the above two cases (that is, with a circularly polarized field in the positive sense and that in the negative sense) can be designated by μ^+ and μ^- , respectively. Further, these permeabilities are assumed as complex quantities to represent the losses. Hence it follows that:

$$\mu^+ = (\mu')^+ - j(\mu'')^+ \tag{15.4a}$$

$$\mu^- = (\mu')^- - j(\mu'')^- \tag{15.4a}$$

Typical variations of the real and imaginary parts of the permeabilities with the applied magnetic field for the positive and negative cases are shown in Figure 15.8. The application of ferrites at microwave frequencies is to make use of their nonreciprocal behavior so that the wave transmission properties depend on the polarization and the direction of incident electromagnetic wave. The most widely used such devices are *isolators* and *circulators* constructed in waveguide, coaxial or stripline geometries. In the forward direction these devices pose a low loss (usually 3.0 dB or less) and in the reverse direction the loss is 20-30 dB or more. The choice of ferrite material for a resonance isolator depends upon the factors like dielectric loss, resonance line width, saturation magnetization, and Curie temperature.

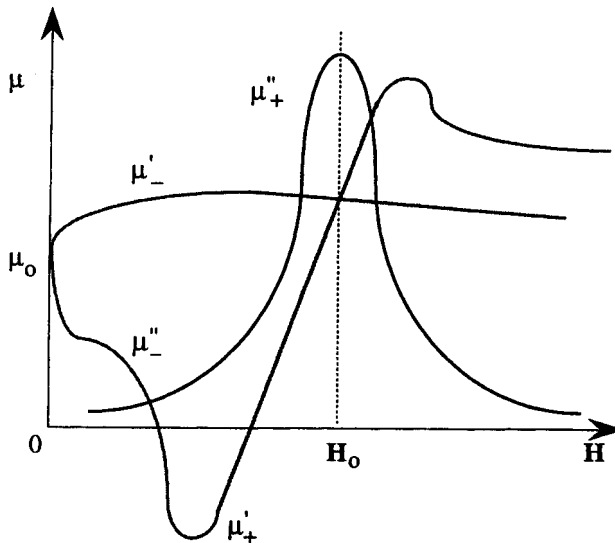


Figure 15.8 Magnetic permeability components as functions of applied field H.

15.5 Classification of Ferrites and Their Subclasses

15.5.1 Spinel structure ferrites

As mentioned earlier, the general formula for a ferrite can be expressed as $MO \cdot xFe_2O_3$ where M is a divalent metal ion. Various constants of simple ferrites are presented in Table 15.3. Unit cells of these ferrites have spinel structure.

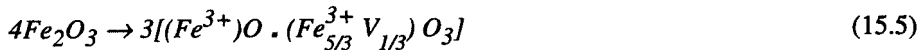
Table 15.3 Constants of Simple Ferrites [1]

Ferrite	M/M _B	θ _f (°C)	Density (gm/cc)	Saturation Magnetization (kilogauss)	Initial Permeability
MnFe ₂ O ₄	4.6-5.0	300	5.00	5.20	250
FeFe ₂ O ₄	4.1	585	5.24	6.20	70
CoFe ₂ O ₄	3.7	520	5.29	5.00	
NiFe ₂ O ₄	2.3	585	5.38	3.40	10
CuFe ₂ O ₄	1.3	455	5.38	1.70	
MgFe ₂ O ₄	1.1	440	4.52	1.40	10
Li _{0.5} · Fe _{2.5} O ₄	2.5-2.6	670	4.75	3.90	

Practical ferrites of this category are made by two constituent mixtures. For example, Zn-Fe ferrite has a stoichiometric formulation $Zn_{\alpha}Fe_{1-\alpha}(Ni_{1-\alpha}Fe_{1+\alpha})O_4$ where α and $(1 - \alpha)$ are the molecular fractions of Zn and Fe ferrites, respectively, and the symbols inside the parenthesis indicate ions occupying octahedral positions (*inverted type*). (Normally, the divalent ions otherwise occupy the tetrahedral positions.)

15.5.2 γFe_2O_3 ferrites

These refer to an oxide called *maghemite* (a natural oxide) which also forms a spinel lattice. The chemical formula of this oxide is:



where V is a vacancy in the lattice.

15.5.3 Ferrites of corundum-type oxides

Hematite (αFe_2O_3) and ilmenite ($FeTiO_3$) are natural oxides like magnetite (Fe_3O_4) which exhibits rhombohedral lattice symmetry with metal ions occupying various sites as illustrated in Figure 15.9.

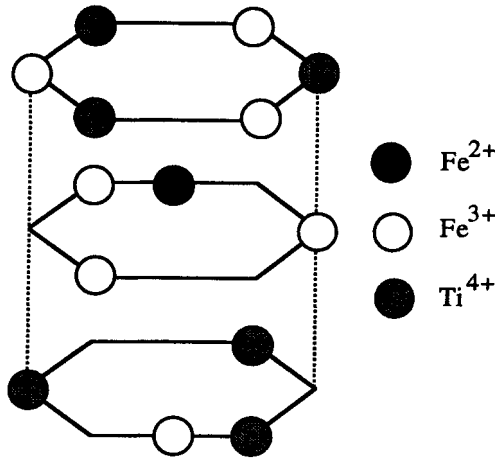


Figure 15.9 Ilmenite lattice structure.

15.6 Ferrites of Magnetoplumbite-Structured Oxides

These have a lead-based composition given by $\text{PbFe}_{11}\text{AlO}_{19}$ or with a generic formula $\text{MO} \cdot 6\text{Fe}_2\text{O}_3$ where M represents a divalent ions such as Ba^{2+} , Sr^{2+} , or Pb^{2+} . This type of oxide has hexagonal structure composed of stacked spinel ionic layers with interspaced ionic layers of M^{2+} , O^{2-} , and Fe. These types of oxide ferrites have extensive magnetocrystalline anisotropy due to their low crystal symmetry. A typical example of this ferrite is the barium ferrite which is popularly used in making permanent magnets.

Another class of oxides which resemble magnetoplumbite with hexagonal crystal structure are known as *W-type*, *Y-type*, and *Z-type* ferrites as indicated below:

- W-type: $1\text{BaO} \cdot 2\text{MO} \cdot 8\text{Fe}_2\text{O}_3$
- Y-type: $2\text{BaO} \cdot 2\text{MO} \cdot 6\text{Fe}_2\text{O}_3$
- Z-type: $3\text{BaO} \cdot 2\text{MO} \cdot 12\text{Fe}_2\text{O}_3$

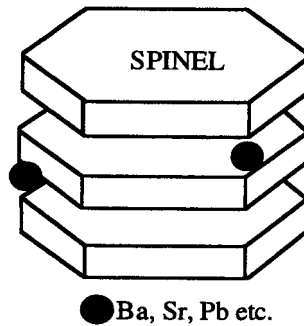


Figure 15.10 Magnetoplumbite.

where again M denotes a divalent metal ion such as Mn^{2+} , Fe^{2+} , Co^{2+} , Ni^{2+} , Zn^{2+} , or Mg^{2+} . Among these, Co_2Z and Mg_2Y exhibit negative anisotropy constant (meaning a basal plane with an easy plane of magnetization). Hence, they are useful as excellent high frequency magnetic materials. Saturation magnetization range of magnetoplumbite oxides is similar to spinel ferrites and the Curie points range from 400 to 500°C.

15.7 Ferrites of Perovskite-Type Oxides

Perovskite is a Calcium titanate (CaTiO_3)-based mineral. If Ti is replaced by Fe, a magnetic perovskite-type oxide with a formula MFeO_3 is realized where M represents a large metal ion such as La^{3+} , Ca^{2+} , Ba^{2+} , or Sr^{2+} . These oxides have cubic structure as illustrated in Figure 15.11.

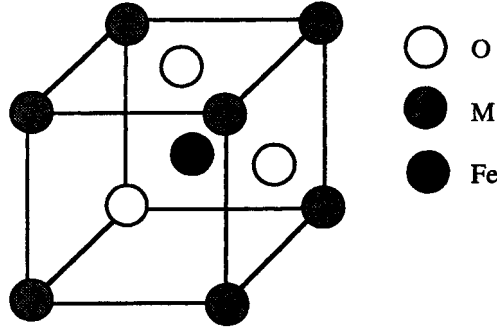


Figure 15.11 Perovskite-type metal oxide.

Another class of ferromagnetic materials of this type are obtained by solutions of $(\text{M}_1^{3+} \text{Mn}^{3+}\text{O}_3 + \text{M}_2 \text{Mn}^{4+}\text{O}_3)$ where $(\text{M}_1$ and $\text{M}_2)$ are (La, Ca, Sr, or Ba), (although single oxides are invariably antiferromagnetic).

15.8 Garnet-Structured Ferrimagnets

Garnets are minerals with pyrope composition, namely, $\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$. If Si is replaced by Fe, a family of ferrimagnetic garnets with stoichiometric formulation $3\text{M}_2\text{O}_3 \cdot 5\text{Fe}_2\text{O}_3$ are obtained where M represents a rare-earth element, namely, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, or Y.

Ferrimagnetic garnets have complex cubic crystalline structure. Properties of these materials are listed in Table 15.4.

Table 15.4 Properties of Typical Garnets

Rare-earth Element (M) in the Garnet	Curie Point (K)	M/M_B	Density (gram/cm^3)
Sm	560	9.30	6.235
Eu	570	5.00	6.276
Gd	564	30.00	6.436
Tb	568	31.40	6.533
Dy	563	32.50	6.653
Ho	567	27.50	6.760
Er	556	23.10	6.859
Tm	549	2.00	6.946
Yb	548	0	7.082
Lu	539	8.30	7.128
Y	560	9.44	5.169

Garnet-type ferrites exhibit high resistivity due to the absence of divalent metal ions. Therefore, they are low-loss materials at microwave frequencies.

15.9 NiAs-Type Compounds

Pyrotite compound (Fe_xS) is a typical example of this material which is ferrimagnetic. The index x may range from 0.90 to 0.875. Another example is Cr_yS (with y = 1.17) which is ferrimagnetic between -114°C and its Curie point, 40°C. The (MnSb-CrSb) system also shows ferrimagnetic properties with Néel points varying with the volume fractions of the composition.

15.10 Hard and Soft Ferrites

On the basis of hysteresis performance of a ferrite it can be classified as *hard* or *soft* as follows:

- Soft ferrite: $H_c \rightarrow 0$; $B_r \rightarrow 0$ and $B_m \rightarrow$ large value
- Hard ferrite: $H_c \rightarrow$ high value; $B_r/B_m \rightarrow 1$ (squareness) and $B_m \rightarrow$ large value.

Typical characteristic parameters of hard and soft ferrites are listed in Table 15.5.

Table 15.5 Properties of Soft and Hard Ferrites

Type	Ferrite	B _m	H _c	B _r	μ _r
Soft	0.8Ni + 0.2 Fe	0.38	0.10	~0.60	50,000
	Mn Zn				
	Co ₁₀ Fe ₅ Si ₁₅ B ₁₀	0.24	0.02	~0.40	5,000
		0.31	0.10	~0.50	10,000
Hard	γ-Fe ₂ O ₃	0.24	250-450	~0.25	~120
	CrO ₂	0.24	450-600	~0.60	120
	BaO . 6Fe ₂ O ₃	0.18	800-3,000	~0.25	320
	Sm CO ₃	0.50	40,000	~1.40	720
	Sm ₂ CO ₁₇	0.60	17,000	~1.75	920
	Fe ₁₄ B Nd ₂	~0.60	12,000	~2.00	310

All values relative to those of Fe.

15.11 Applications of Ferrites

Ferrimagnetic materials are used widely in storing data (as memories) in computers and in high frequency applications. Based on their, applications ferrites can be classified into the following categories:

- Ferrites for permanent magnets: Hard ferrites
- Ferrites for transformers and inductors: Soft ferrites
- Data storage: Rectangular loop ferrites
- Microwave applications: Ferrites and garnets

As permanent magnets, barium or strontium ferrite materials are mostly used (BaFe₁₂O₁₉ and SrFe₁₂O₁₉, respectively). These materials have high value of uniaxial anisotropy field, high coercive force, and high resistivity. They are used as focusing magnets in television tubes. Typical commercial versions of barrium ferrite permanent magnets (ceramic materials) are Ferroxdure™, Magnadur™, and Feroba™. For the BaFe₁₂O₁₉ ferrite

permanent magnet, the value of $(BH)_{\max}$, remanence, and coercivity are 8 Joule/meter³, 0.21 weber/meter², and 14000 ampere/meter, respectively.

Another major application of ferrites refers to the category of soft ferrites. They are used as inductor cores, transformer cores, television transformers and rod aerials. For these applications, ferrites should have high permeability, low coercive force, low eddy current losses, and ability to operate up to frequencies of 10 MHz and with special requirements extending up to 1000 MHz. The ferrites used for this purpose are manganese zinc ferrites and nickel zinc ferrites.

Some ferrites have hysteresis loops which are almost rectangular in shape. This property makes them suitable for use in a *magnetic memory core* in computers. Figure 15.12 shows an ideal rectangular hysteresis loop of a ferrite. The two points $-P$ and $+P$ represent two stable states of magnetization of a ferrite material which is usually in the form of a small toroid. These states can represent a "zero and one" in digital storage of binary information. The loop can only be traversed in anticlockwise direction and the state $-P$ can be changed rapidly to $+P$ by the application of a field greater than or equal to H_a . In the same way $+P$ can be changed to $-P$ by the application of a field less than or equal to $-H_d$. The switching time is on the order of 1 microsecond.

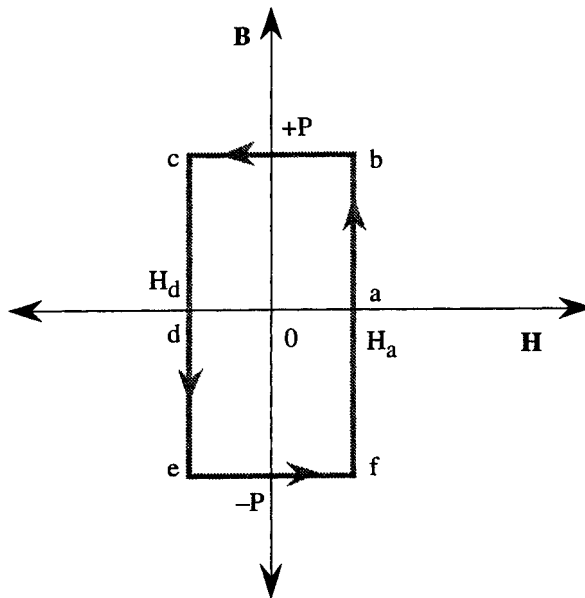


Figure 15.12 Ideal hysteresis loop (BH curve) of a ferrite core.

Figure 15.13 shows a two-dimensional matrix array of toroidal ferrite core loops used to store binary information. If current corresponding to a field $H_a/2$ is passed through an X and a Y wire, only where they intersect will the field be of sufficient magnitude to switch that core, should it be in state $-P(0)$; otherwise, if it is in state "1" already, it will remain in that state. A negative current corresponding to a field $-H_d/2$ in both wires will cause the core at the intersection to change from "1" to "0", if state "1" prevails at the intersection, but will have no effect if it is in state "0". In actual practice, a three-wire system is used for a three-dimensional matrix array of ferrite cores. Normally a fourth wire is used to inhibit the reading of states which are not required. Ferrites commonly used for this application are manganese-magnesium type, manganese copper ferrite, and lithium nickel ferrite. In practice the loops look more like Figure 15.14.

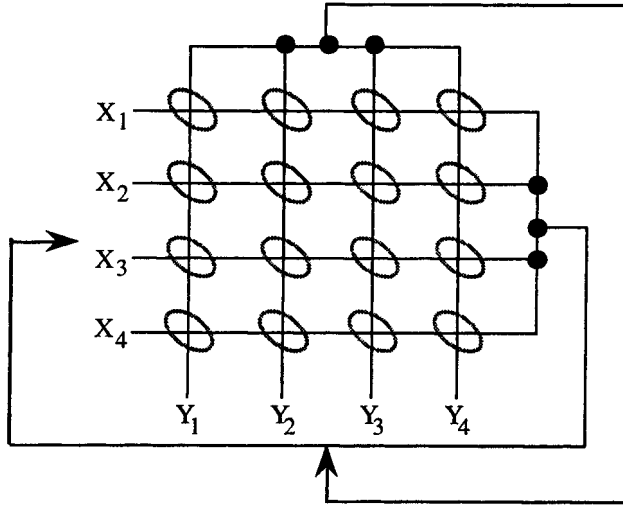


Figure 15.13 A matrix array of ferrite cores.

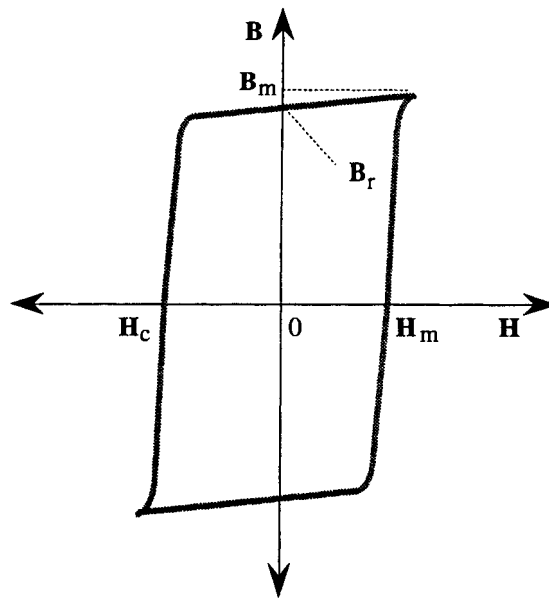


Figure 15.14 Actual hysteresis loop of a ferrite core.

A $MnMgZn$ ferrite has a maximum flux density, $0.25 \text{ weber/meter}^2$; remanent flux density, $0.21 \text{ weber/meter}^2$; coercive force, $23.8 \text{ ampere/meter}$; H_m , $43.7 \text{ ampere/meter}$, T_c , 160°C ; and permeability μ_r , 260 (initial) and 4500 (maximum).

Microwave ferrites are used in the frequency range of 1-100 GHz. In this range of frequency, electromagnetic waves interact with the spin magnetic moments in the ferrite. As discussed in Section 15.4, the process which takes place is called *Faraday rotation*. This is the rotation of the plane of polarization of a plane electromagnetic wave as it travels through a ferrite in the direction of an applied magnetic field.

Application of Faraday rotation is in waveguides to accept or reject polarized microwaves. These are known as *nonreciprocal microwave devices*. Thus (unwanted) reflected signals are prevented in the so-called *isolators* and rotation of the plane of polarization is achieved in the devices known as *gyrators*. Ferrites are also used in *phase shifters* and *circulators*. Some of the microwave ferrites are: Single crystalline; MnFe_2O_4 , NiFe_2O_4 , CoFe_2O_4 , $5\text{Fe}_2\text{O}_4$, $3\text{Y}_2\text{O}_3$, etc.; commercial ceramic ferrites-nickel ferrite, magnesium ferrite, etc.; and commercial garnets -YIG, YI(Al)G, YI(Al, Gd)G.

Ferrites can also be used in the fabrication of EMI shields (Chapter 21) and EM absorbing materials (Chapter 22).

A detailed description of microwave applications of ferrites is available in [5].

15.12 Semiconductor Ferrites

Ferrites with semiconducting properties may exhibit the *Hall effect*. For example, Mn-Zn ferrite, under controlled (isothermic) conditions has been shown to produce a Hall electromotive force (EMF). Semiconducting ferrites (which are distinct from insulating or dielectric ferrites) are characterized by a magnetic arrangement which yields a Hall EMF (E_H) given by:

$$E_H = R_o H + R_A M \quad (15.6)$$

where R_o is the *Hall coefficient* and H is the intensity of external magnetic field. Further, R_A is the analogous *Hall coefficient* and M is the magnetization. Typically ($R_A M / R_o H$) ratio is about 6 in Mn-Zn ferrites. The flow of charge carriers due to the Hall effect is controlled by the *Hall mobility* μ_H .

The temperature dependency of the electrical conductivity (σ) in semiconductor ferrites is given by:

$$\sigma = \sigma_o \exp[-\Delta E_\sigma / k_B T] \quad (15.7)$$

where ΔE_σ is the activation energy for electrical conduction as dictated by hopping of electrons and/or holes. The mobility (μ) of charge carriers in semiconductor ferrites is given by:

$$\mu = (C/k_B T) \exp(-\Delta E_h / k_B T) \quad (15.8)$$

where C is a constant characteristic of the type of crystal and ΔE_h is the activation energy associated with the hopping process. The mobility that corresponds to charge conduction mechanism is labeled as the *drift mobility* (μ_D) which is on the order of 10^{-3} - 10^{-7} $\text{cm}^2/\text{volt-sec}$.

Typical electrical parameters of semiconducting ferrites (with spinel structure are tabulated in Table 15.6 [2].

Table 15.6 Electrical Parameters of Semiconducting Ferrites

Ferrite	ΔE_σ (ev)	ΔE_h (ev)	Gap Energy E_g (ev)	μ_H at 300° ($\text{cm}^2/\text{volt-sec}$)
Fe_2O_4	0.3-0.05	0.03-0.95		1
CoFe_2O_4	0.2	0.2	0.6	1

(continued...)

Ferrite	ΔE_{σ} (ev)	ΔE_h (ev)	Gap Energy E_g (ev)	μ_H at 300° (cm ² /volt-sec)
MgFe ₂ O ₄	0.35			
NiFe ₂ O ₄		0.1	1.1	
MnFe ₂ O ₄	0.05-0.08	0.05-0.08	0.3	10 ⁻¹
ZnFe ₂ O ₄	0.17	0.12		10 ⁻¹

15.13 Ferrite Dielectrics

The dielectric properties of ferrites depend on: Preparation of the mixed medium, chemical composition, grain structure and/or size of the constituent particulates, and type of sintering. In general, the dielectric response of a ferrite is characterized by a complex permittivity ($\epsilon' - j\epsilon''$). The real part is mainly decided by the average grain size of the specimens in the ferrite composition and ϵ'' refers to the frequency dispersion. The corresponding relaxation occurs at a low frequency due to the conducting grains in the medium being specified by the insulating layers. (This corresponds to a model of a heterogeneous dielectric structure.) There are also high frequency relaxations due to the presence of low conducting surface layers on the grains of the ferrite. Like any dielectric, as presented in Chapter 2, the relaxational attributes of a ferrite can be described by its conductivity (σ) and the dielectric constant (ϵ') as follows:

$$\sigma = \sigma_o + (\sigma_o - \sigma_{\infty}) / (1 + \omega^2 \tau^2) \tag{15.9a}$$

$$\epsilon' = \epsilon_{\infty} + (\epsilon_o - \epsilon_{\infty}) / (1 + \omega^2 \tau^2) \tag{15.9b}$$

where the subscript *o* indicates the static values and ∞ refers to the high frequency (optical) limit. Further, τ depicts the relaxational time constant.

15.14 Conclusions

Ferrites as a class constitute a major subset of magnetic materials and are of vital engineering utility in modern high-tech applications. Especially at high frequencies, ferrites offer unique application potentials. Generically being a composite material, there is an abundant niche to search for newer ferrite compositions to yield better performance characteristics. Ferrites being ceramic in nature constitute the nonconducting class of magnetic materials distinctly different from conventional metallic/alloy-type magnetic materials, and they offer great potentials for further studies and technological utilities.

References

[1] S. Chikamuzi and S. H. Charap: *Physics of Magnetisms*. (John Wiley and Sons Inc., New York: 1959).

[2] B. Viswanathan and V. R. K. Murthy: *Ferrite Materials*. (Springer-Verlag/Narosa Publishing House, New Delhi: 1990).

[3] A. Nussbaum: *Electric and Magnetic Behavior of Materials*. (Prentice-Hall Inc., Englewood Cliffs, NJ: 1967).

[4] R. C. Dorf (Ed.): *The Electrical Engineering Handbook*. (CRC Press Inc., Boca Raton, FL: 1993), pp. 816-818.

- [5] R. F. Soohoo: *Theory and Application of Microwave Ferrites*. (Prentice-Hall Inc., Englewood Cliffs, NJ: 1971).

Defining Terms

Antiferromagnetism: Clustering of oppositely oriented ions with parallel spins in a lattice structure having random spins, leading to nil magnetic susceptibility of the material.

Faraday rotation/effect: Change of plane of polarization of EM wave being transmitted upon reflection by the direction of magnetization of the surface of the material.

Ferrimagnetism: Refers to antiferromagnetism with incompletely cancelled spins.

Ferrites: Mixed metal oxides exhibiting ferrimagnetic properties and are antiferromagnets with incompletely cancelled spin system.

Garnets: Ferrimagnetic materials composed of oxides of iron and a rare-earth element.

Inverse spinel-structured ferrites: Ferrites with a spinel structure with half of Fe-ion at A sites and the remaining Fe-ion as well as divalent metal ions at B sites.

Néels temperature: Critical temperature above which thermal agitation destroys antiferromagnetic alignment.

Spinel structure: A lattice structure in which each oxygen ion surrounded by one tetrahedral ion (A-ion) and 3 octahedral ions (B-ions) constitutes a basic unit. Spinel-structured ferrites have divalent metal ions at A site and iron ions at B sites.