CHAPTER I
AN INTRODUCTION TO FERRITES

CHAPTER - I
AN INTRODUCTION TO FERRITES

1.1 THE PAST, PRESENT AND FUTURE OF FERRITE

Magnetic materials have played a prominent role in the development of modern technology. Ferrites, ceramic ferromagnetic materials, have been considered as highly important electronic materials for more than half a century.

Magnetoceramics, which are mainly composed of ferric oxide ($\propto$- Fe_2O_3) and certain divalent metal oxides, are called "Ferrites". Hilpert[1] was first in preparing Fe_3O_4. Magnetite, Fe_3O_4 a natural mineral, is a genuine ferrite and it is said that ancient people had recognized its magnetism and that it was used as a mariner's compass in China more than two thousand years ago. However, the first attempt to prepare ferrites was not made until the beginning of this century. Actual commercialization of ferrites started about 60 years ago. However, the commercial ferrites did not attract much attention because of the fact that their magnetic properties were considerably inferior to those of ferromagnetic alloys. Around the same time, physicists and electronics engineers worldwide became greatly interested in the unique magnetism and the expanded high frequency applications of ferrites.

Recently researchers in chemistry, ceramics and metallurgy have been engaged in the development of new ferrites, enhancement of existing ferrite properties and improvement of ferrite manufacturing processes. The ferrite production has increased enormously in the recent years.

1.2   FERRITE INDUSTRY IN INDIA

Present Indian ferrite industry has come a long way. Commercial production of ferrites started in sixties.[2] The production of ferrites was about 7000 MT in 1990 and about 15000 MT in 1995. Indian ferrite industry is now poised for big jump and getting ready to compete in the world market. The growth pattern of ferrite production for soft and hard categories for the last 10 years is shown in Fig. 1.1.

1.3   HISTORICAL DEVELOPMENTS

The history of Asia Minor, another cradle of civilization, claims that the loadstone was discovered as a natural magnet in magnesia more than 3500 years ago. The stone was called magnes lapis, which means magnesian stone. Magnet and magnetism were derived from the word magnesian.

Many reports are available on the historical development of the science and technology of ferrites. The first systematic study on

PRODUCTION GROWTH
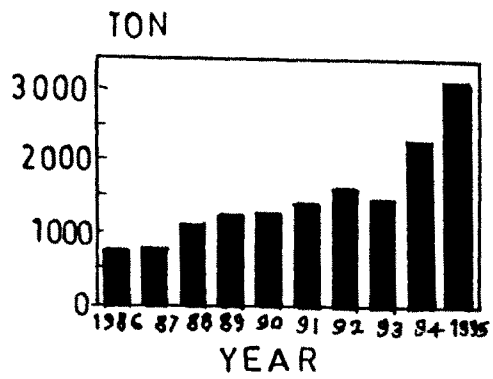
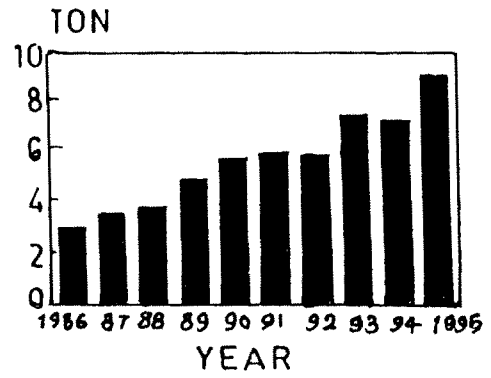SOFT FERRITE   HARD FERRITE

Fig. 1·1   GROWTH PATTERN OF INDIAN FERRITE INDUSTRY .

the relationship between chemical composition and magnetic properties of ferrites was reported by Hilpert in 1909. Hilpert successfully prepared copper, cobalt, magnesium and zinc ferrites. Forestier, in 1928, prepared ferrites by basic precipitation from chloride solutions and subsequent heat treatment. Several Japanese investigators took active part in ferrite preparation in the early thirties. Neel[3] was the first to explain the basic theory of spin-spin interaction. Anderson[4] and Van Vleck[5] developed the superexchange theory for the extensive study of basic interactions. Yafet and Kittel[6] introduced the triangular spin arrangements to extend superexchange theory. Gilleo[7] proposed the method of determining cation distribution from Curie temperature.

In 1932, Japanese chemists, Kato and Takei[8] discovered that solid solutions of magnetite and cobalt ferrite were strongly magnetized at $\cong 300^{c}C$ and that the solid solution had practical applications. The early achievements in ferrites are concentrated in the period 1935-1970.

1.4 STRUCTURE OF SPINEL FERRITES

The structure of spinel ferrite was determined by Bragg[9] and Nishikawa.[10] The compounds with the general formula AB_2O_4 crystallize with the same structure as the mineral spinel, $MgAl_2O_4$ (Fig. 1.2a). The three important parameters associated with atomic

arrangement of spinel are, the lattice parameter 'a', oxygen parameter 'u' and cation inversion parameter 'i'. Oxide spinels are used as examples to explore the interrelationship between these parameters.

The general chemical formula for spinel ferrite is $M^{2+}Fe_2^{3+}O_4^{2-}$ (where M is a divalent metal ion and Fe is a trivalent (ferric) iron ion. In the formula AB_2O_4, A and B refer to tetrahedral and octahedral cation sites respectively. The oxygen anions are arranged in a face centered cubic lattice. Each unit cell contains 8 formula units with O^{2-} anions in the 32(b) sites and Fe^{3+} and M^{2+} cations occupying the 16(d) and 8(a) sites. The space group of ferrites is Fd_3m O_h^7 and lattice parameters are typically of the order of 8.3 A^0. The relative positions of the A and B cations with respect to neighbouring oxygen anions is quite important for strong superexchange, which is dependent on both the cation-anion-cation bond angle and the interatomic distance between the cations and anions.

The metal ions occupy the interstitial positions of four fold (a) and six fold (d) oxygen co-ordination. In one, magnetic ion is surrounded by four oxygen ions at the vertices of tetrahedron and is called tetrahedral or A site, (Fig.1.2b) whereas in the other it is surrounded by six oxygen ions at the vertices of an octahedron and is called octahedral site or B site (Fig. 1.2c).
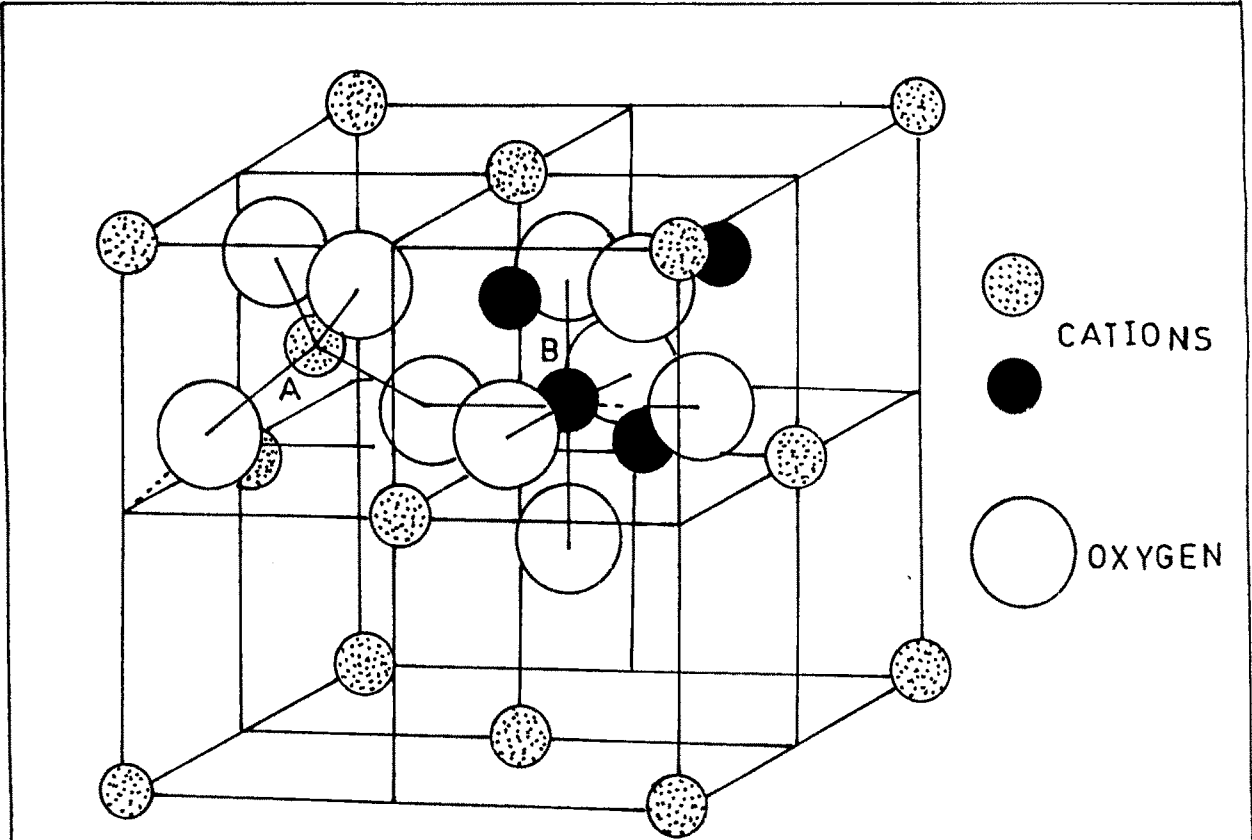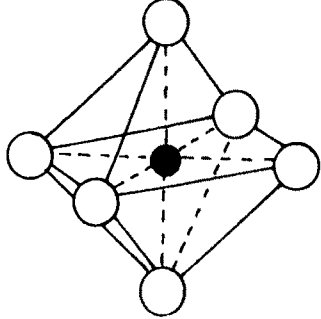
(a)

THE SPINEL STRUCTURE (SCHEMATIC)
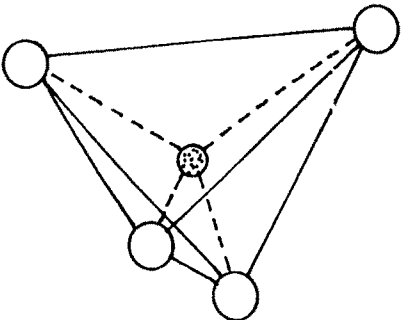
(b)

TETRAHEDRAL SITE

(c)

OCTAHEDRAL SITE

FIG 1·2

There are 96 interstices between the anions in the unit cell of AB_2O_4 compound. Of which only eight tetrahedral and sixteen octahedral sites are occupied by the cations. The equilibrium distribution of cations in the spinel structure depends on ionic radii, electronic configuration, electrostatic energies and polarization effects.

1.5 CLASSIFICATION OF FERRITES

The ferrites are classified on the bass of cation distribution. Barth and Posjank[11] have observed different types of cation distribution in ferrites.

a. Normal Spinel Ferrites

In normal spinel ferrites all the M^{2+} ions occupy the tetrahedral sites, while Fe^{3+} ions occupy the octahedral sites. In these ferrites there is no A-B interaction as A sites do not contain any magnetic ion. The B-B interaction lines up with half the magnetic ions in one direction so that alternate planes of B sublattice are magnetised in opposite direction. This results in the nonmagnetic character of the ferrite. $ZnFe_2O_4$ and $CdFe_2O_4$ are the ferrites with the normal spinel structure. The cation distribution for normal spinel ferrite is given by
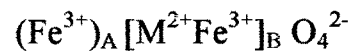
$$(M^{2+})_A [Fe_2^{3+}]_B O_4^{2-}$$
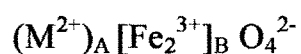
For normal spinel inversion parameter i = 0

b. Inverse Spinel Ferrites

When the divalent cations are on B sites and the trivalent ions are equally divided between A and a B site, the structure is called an inverse spinel structure. The cation distribution for inverse spinel ferrite is

$$(Fe^{3+})_A [M^{2+}Fe^{3+}]_B O_4^{2-}$$

The inverse spinel ferrites show ferrimagnetic behaviour.

e.g. $MgFe_2O_4$, $CoFe_2O_4$ show inverse spinel structure.

For inverse spinel structure inversion parameter i = 1.

C. Random Spinel Ferrites

When all the divalent and trivalent iron ions are distributed randomly over A and B sites then resulting ferrite is called random spinel ferrite.

The cation distribution of random spinel ferrite is expressed as-

$$[M_x^{2+} Fe_{1-x}^{3}]_A [M_{1-x}^{2+} Fe_{1+x}^{3+}]_B O_4^{2-}$$

where x   = coefficient of normalcy

1-x = coefficient of inversion

Inversion parameter i = $^2/_3$ corresponds to a random distribution of cations.

1.6 TYPES OF FERRITES

The spinel ferrites are classified depending upon their chemical compositions as follows.

a. Simple Ferrites

When a divalent ferrous ion in Fe_3O_4 is replaced by another divalent metal ion like Mn, Co, Ni, Cu, Zn, Cd or Mg the resulting ferrite is called simple ferrite e.g. $MnFe_2O_4$, $CuFe_2O_4$ $ZnFe_2O_4$.

b. Mixed Ferrites

When a ferrous ion in Fe_3O_4 is replaced by two other divalent metal ions like Cu, Co, Cd, Ni etc. without altering the stoichiometry of the system, the resulting ferrite is called mixed ferrite.

e.g. $Zn_x Co_{1-x} Fe_2O_4$, $Cd_x Mg_{1-x} Fe_2O_4$

c. Substitutional Ferrites

When the divalent metal ions as well as trivalent iron ions are replaced by other magnetic or non-magnetic ions in the spinel structure, the resulting ferrite is called substitutional ferrite.

e.g. $Ni_{1-x} Zn_x Fe_2O_4$, $Ni Fe_{2-x} Al_xO_4$.

The net magnetization in such a ferrite depends on the site occupancy of the substitution.

1.7 PROPERTIES OF FERRITES

1.7.1 Electrical Properties

Spinels have a wide range of resistivity[12] from 10^{-5} to $10^{12} \Omega$ cm Physical and chemical properties of ferrites depend on the mechanism of charge transport. The conduction mechanism can be studied from the measurement of electrical conductivity, thermoelectric power, magneto resistance and Hall effect. The charge transport can vary with the composition and the method of preparation of ferrites. The conductivity in ferrite depends upon purity of compound, stoichiometry, sintering temperature, time, atmosphere, physico-chemical history, density, porosity, grain size and chemical homogeneity[13].

The temperature dependence of resistivity is given by

$$\rho = \rho_o \exp (\Delta E/ kT) \qquad \ldots \qquad (1.1)$$

where k = Boltzmann constant

ΔE = activation energy

T = absolute temperature

The plots of log ρ vs ^{1}/T show a straight line and break occurs closely at the ferrimagnetic Curie temperature.[14] The high value of ΔE is associated with high resistivity at room temperature. During the preparation of polycrystalline ferrites, oxygen dissociation sets

up above 1200^0 giving rise to Fe^{2+} ions. The Fe^{2+} ions are responsible for the electron conduction.

The ions having two valance states get distributed randomly over the crystallographically equivalent sites. The high conductivity of ferrites is due to the presence of Fe^{2+} and Fe^{3+} ions on the identical lattice sites in the spinel structure. In this situation, the electron can move from trivalent iron ion to divalent iron ion and back within the octahedral position. The transition does not cause a charge in the energy state of the crystal.

1.7.2 Dielectric Properties

In ferrites eddy currents may flow due to dielectric displacement. Ferrite show abnormally high dielectric constant and dispersion of dielectric constant and resistivity in the frequency range from a few Hz to MHz. Koops[15] described the phenomenological theory of dielectric dispersion in ferrites at low frequencies. The theory of dielectric dispersion is based on the assumption of parallel resistance and capacitance of material. The theoretical and observed frequency variations of dielectric constant and resistivity are in good agreement for some samples. Activation energy observed by Kamiyoshi[16] and Fairwheather[17] from temperature variation with relaxation time agrees will with those obtained with temperature variation of

resistivity. The high dielectric constant arising at low frequency may be due to oxygen ions, which have three B-site, and one A site neighbours. This is justified in view of the fact that oxygen possesses the maximum polarizability. Abnormally high dielectric constant have been reported by several workers as a result of lower frequency.[18]

When a dielectric material is subjected to an a.c. electric field, there is a relative displacement of positive and negative ions resulting in an electric dipole moment. The dipole moment per unit volume is called polarization. The total polarization of dielectrics can be represented as

$$P = Pe + Pi + Po + Ps \qquad \ldots \quad (1.2)$$

where   Pe = electric polarization

            Pi = ionic polarization

            Po = orientational polarization

            Ps = interfacial or space charge polarization

These polarizations are shown in Fig. (1.3a). The frequency range of each of these polarization is as shown in Fig. (1.3b).

1.7.3 Magnetic Properties

a. Magnetisation in Ferrites

The magnetisation in ferrites results from the distribution and alignment of magnetic ions on the octahedral and tetrahedral sites.

No Field   Field applied
                          ← E
              Electronic Polarization

Ionic Polarization
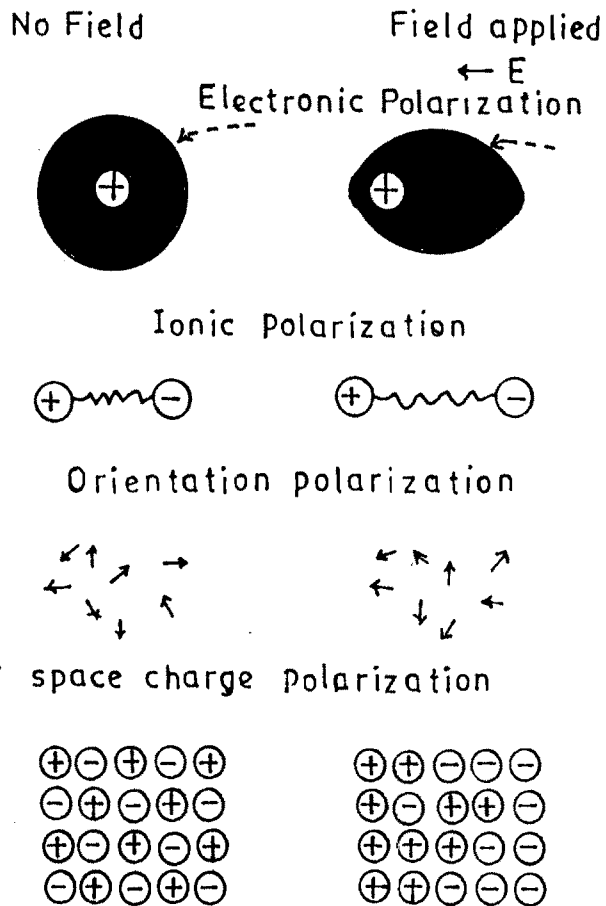
Orientation polarization

space charge Polarization

FIG. 1·3 ᵃ — SCHEMATIC REPRESENTATION OF DIFFERENT
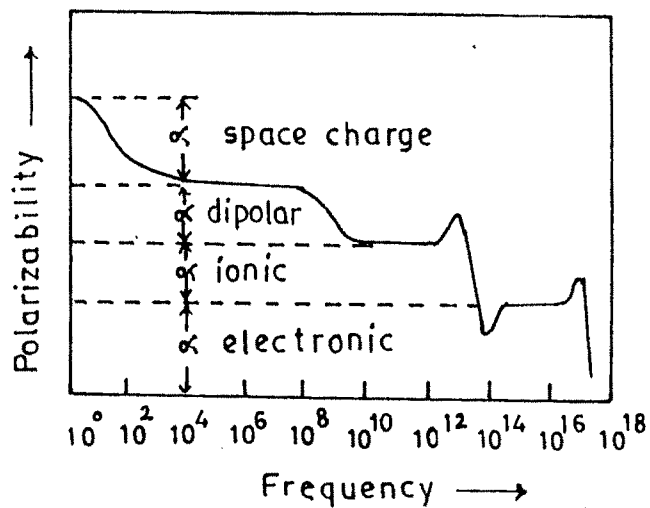
MECHANISMS OF POLARIZATION.

FIG. 1·3 b — FREQUENCY DEPENDENCE OF SEVERAL

CONTRIBUTION TO THE POLARIZABILITY ·

Certain characteristic features of the ferrite can be explained on the basis of their magnetic properties. The susceptibility, permeability, saturation magnetisation, Curie temperature depends upon the concentration of divalent ions on both the cation sites and these properties are called intrinsic properties. The properties, which depend upon the structure of ferrite, are called structure sensitive properties e.g. coercive force. The intrinsic properties of polycrystalline ferrite are influenced by pinned wall domains due to porosity at the grain boundaries.

The exchange interaction between the magnetic moments of neighbouring ions is responsible for the magnetization in ferrites. The interaction is positive when the moments are parallel and negative when the moments are antiparallel. The interaction arises from an indirect exchange mechanism in which magnetic ions are coupled through electron transfer with intermediate anions. This concept of indirect exchange has been forwarded by Kramers[18] and then developed by Anderson[4] in the form of superexchange interaction. The idea of superexchange interaction is used to account for the magnetization in normal and inverse spinel ferrites.

b. Magnetic Interaction in Ferrites

The various possible magnetic interaction were studied by Gorter.[19] As metal ions occupy two different sites viz. tetrahedral
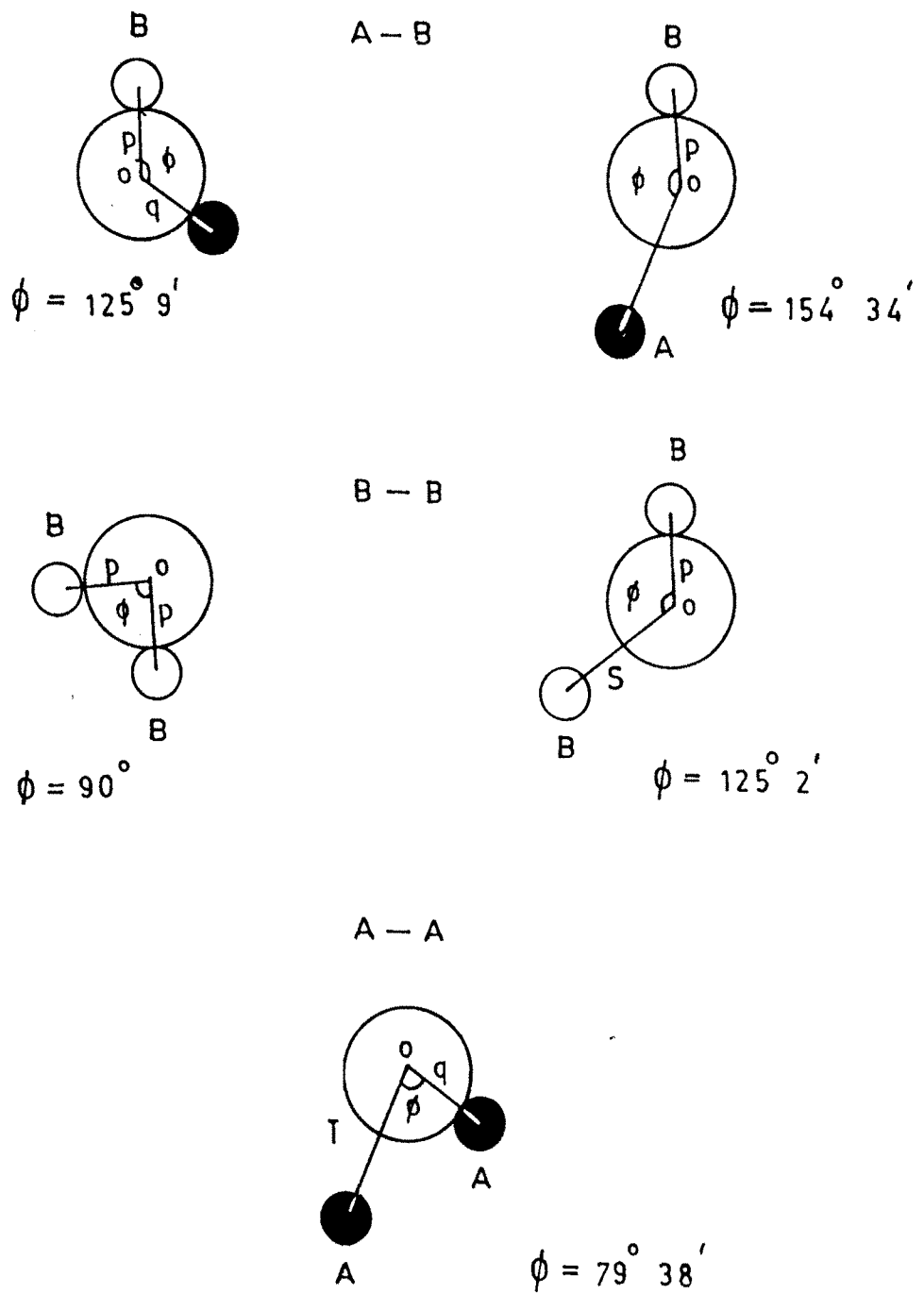
FIG. 1·4 — ANGLE BETWEEN A—A , B—B & A—B
CATIONS IN A SPINEL STRUCTURE.

and octahedral sites, three kinds of magnetic interactions between metal ions are possible via intermediate O^{2-} ions by superexchange mechanism, namely A-A, A-B and BB interactions (Fig. 1.4). In the superexchange interaction, there is an excitation of oxygen ion from its ground state.[20] The superexchange interaction increases rapidly with the decrease in the distance between the ions. The A-B interaction is the only predoment interaction in ferrites. It is observed that the interaction energies between two magnetic ions A and B depend on the distance of these ions from the oxygen ion through which interaction occurs and the angle between A-O-B. The angle of 180^{0} gives maximum interaction energy. The spinels of A and B site ions, will oppositely magnetize the sublattices A and B giving resultant magnetic moment equal to the difference between those of A and B site ions. In general, value of saturation magnetic moment for B site (M_B) is greater than that of the A site (M_A). The resultant saturation magnetization (Ms) can be written as-

$$Ms = \mid M_B - M_A \mid \qquad \qquad \dots \quad (1.3)$$

1.8 APPLICATIONS OF FERRITES

Ferrites have vast applications from microwave to radio frequencies (Fig. 1.5a, 1.5b). The low frequency applications of soft ferrites include magnetic heads, inductors, transformer cores, filter cores etc. High frequency applications include a large number of

Ferrite cores

- Cu–Zn ══ Ni–Cu–Zn (Bulk, Thick film)
- Mn–Zn (High μ, Low loss)
- Ni–Zn
- Mn–Mg–Zn

Magnetic recording

Floppy disk

- Media | γ–Fe$_2$O$_3$ CrO Fe$_3$O$_4$ Co dope or Coat
- Head materials | Hot pressed | Mn–Zn single crystal

Microwave ferrite

- YIG (Single crystal, Polycrystal, Thick film)
- Ni–Zn, Mn–Mg, Ba

Ferrite memory core

- Mn–Mg

Ferrite magnet

- Fe–Co | Ba–ferrite | Sr–ferrite

Fig. 1·5 (a) — APPLICATIONS OF FERRITES.

| Cu – Zn | | Ni-Cu-Zn (Bulk, Thick, film) |

| Mn-Zn (High μ, Low loss) |

Low loss and high stability materials

$Tan\ \delta = 1{\sim}2 \times 10^{6}$ at 100 kHz

$TC = 0{\sim}2 \times 10^{-6}\ [/^{\circ}C]$

$DF = 2{\sim}5 \times 10^{-6}$

Filters for 10~800 kHz range

High permeability materials

$\mu_1 = 3000$ at 100 kHz (~500 kHz)

$\mu_1 = 20,000$ at 10 kHz (~100 kHz)

Inductors
Transformers
Choke coils
Magnetic heads

High saturation magnetic flux density materials

$B = 500{\sim}590$ mT, at $20^{\circ}C$

Power source transformers
Choke coils
Magnetic heads

Others

Temperature sensitive read switch
Ferrite electrode
Electro-magnetic wave absorber
Magnetic toner for copiers
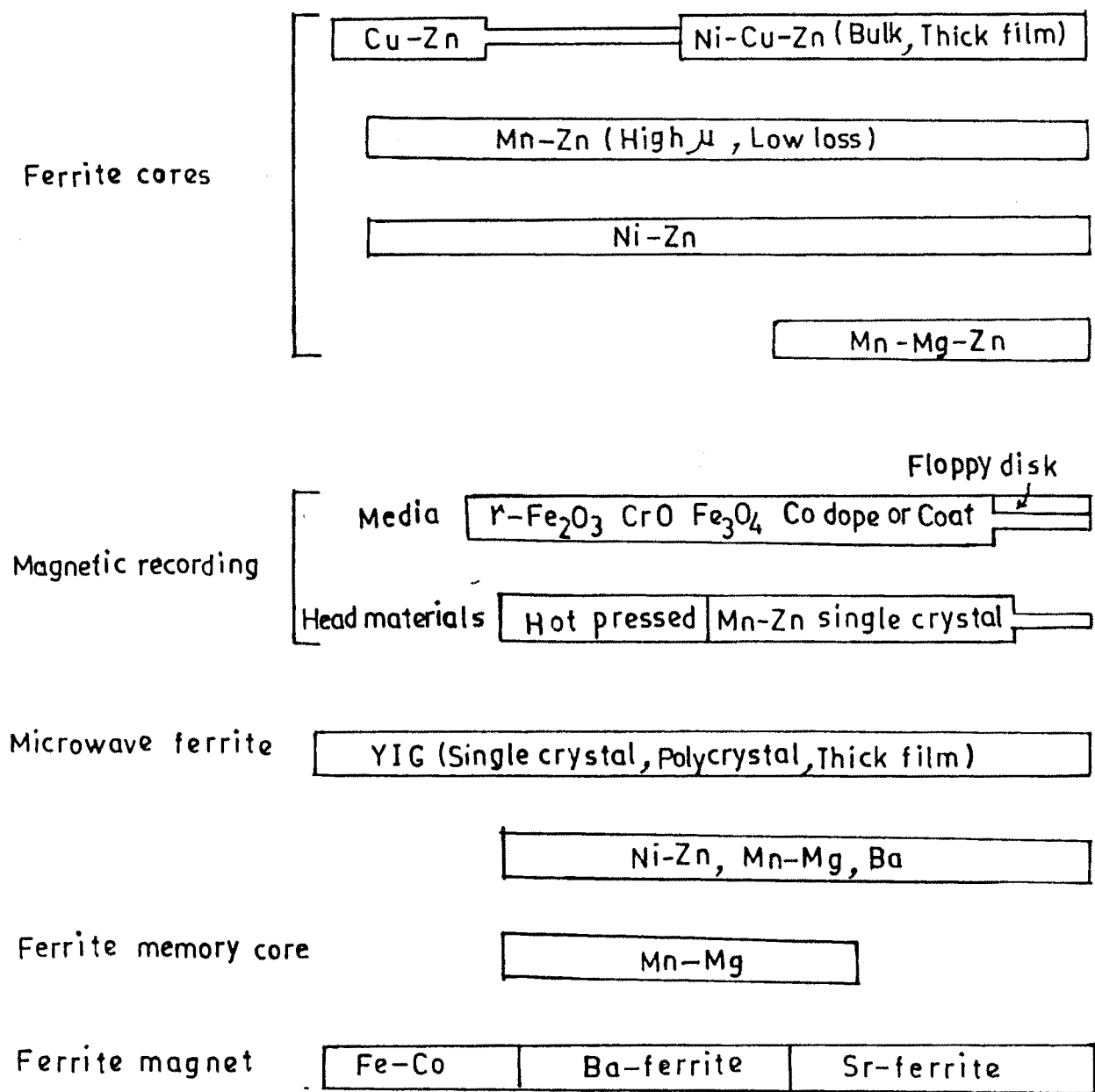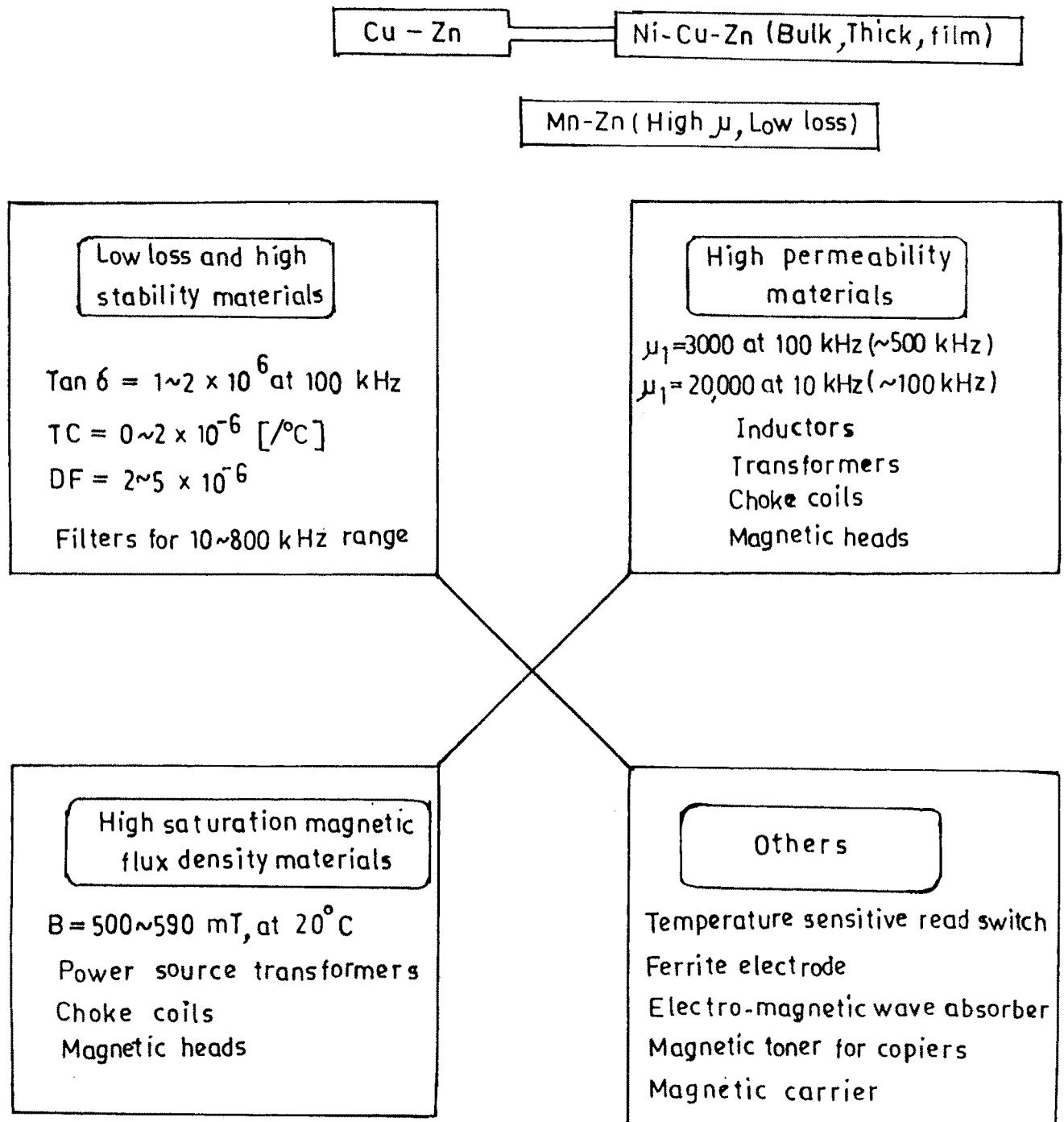Magnetic carrier

Fig. 1·5(b) — RELATION BETWEEN THE CHARACTERISTICS OF SOFT FERRITIES AND THEIR APPLICATIONS .

microwave components such as circulators, insulators, gyrators; phase shifters, YIG-tuned filters, switches and substrate for microwave integrated circuits etc.

The microwave ferrites are widely used in radar systems for air traffic control, communication network and microwave heating. Hexaferrites find wide applications in motors, generators, loudspeakers, telephones, motor switches, magnetic latches and magnetic separators.

The spinel ferrites are extensively used for miniaturization. Some ferrites exhibit a typical rectangular hystersis loop. Due to this square loop characterization they are suitable for flip-flops in computer and memory devices. The square loop ferrites typically utilize hysteresis information.[21] Other applications are loading MW antenna in radio receivers, broad band transformers, mechanical filters, directional couplers etc.

A wide variety of ferrite cores are available now-a-days which find extensive applications in TV, audio, tape recorders, telephone exchanges, computers, control equipments, transmission equipment etc. The paints containing ferrites when applied over tall buildings are effective in suppressing the ghost images.[22] Some ferrites are finding use as catalysts in chemical reactions and environmental protection.

Power ferrites for high frequency applications have been developed in order to suppress gyromagnetic and dielectric losses by high a.c. resistivity, low magnetic flux density and small core sizes. The piezomagnetic ferrites have been developed for use in ultrasonics and radio frequency electronics.

Ferrites have entered new areas like atmospheric pollution control[23], hydrogen production[24] sensors, bioceramics and cancer treatment.[25] Applications of ferrite as humidity sensors[26] and thermojunctions[27] are being developed.

Research on the application of ferrites for protecting the natural environment is being currently investigated. These include -

i.   Washer disposal method for factory drains[28]

ii.   Heat decomposition of Co_2 using a mixture of carbon and ferrite powders heated at 300^0C - 700^0C.[29]

iii.   Transformation of solar energy to hydrogen energy using ferrites as catalysts.[30]

iv.   Heat decomposition of No_x gas using spinel ferrite.[31]

1.9   REVIEW OF LITERATURE

The polycrystalline Ni-Zn ferrites are suitable for magnetic heads, radio frequency coils, transformer cores and rod antennas. Ni-Zn ferrite is the most suitable material for device applications in the supermicrowave and lower millimeter wave range.[32,33] The Ni-

Zn ferrites possess a very high electrical resistivity, excellent magnetic properties and low eddy current losses than Mn-Zn and Mg-Zn ferrites.

Many workers have studied the electrical[34] and magnetic properties[35] of non-stoichiometric Ni ferrites and the mixed stoichiometric Ni ferrites.[36-42] Bagdanovich[43] has reported the influence of porosity on the initial permeability, Q factor and parameters of hysteresis loop of Ni-Zn ferrite. Developments in the preparation of Mn-Zn and Ni-Zn ferrites, with reference to technically important properties such as Ms, Hc, μi, loss factor, dependence of μi on temperature, time and applied magnetic field etc. are reported by Das.[44] The magnetic phase transition for Fe_3O_4 and structurally disordered $Zn_x Ni_{1-x} Fe_2O_4$ are reported by Hang et.al.[45] Mossbauer and magnetization studies of Ti^{4+} substituted Ni-Zn ferrite are carried out by Srivastav et.al.[46]

Rezlescu et.al.[47] have studied the effect of addition of CaO, Na_2O, ZrO_2, Sb_2O_3 and K_2O on the densification of Li-Zn and Ni-Zn ferrites. They have observed that such additives affect the porosity. Das et.al.[48] have studied the microstructure of Ni-Zn ferrites obtained from hydrothermal process. Patil et.al. have studied the lattice parameter of Mn Ti and Mn Sn substituted Ni-Zn ferrite and it is found to increase with Mn addition.[49] Seeback coefficient and

electrical conductivity of mixes Ni-Zn ferrites at room temperature are measured by Ravinder et.al.[50] The effect of substitution of a Jahn Teller ion like Cu^{2+} on the properties of Ni-Zn ferrites has shown some interesting results.[51] Ni-Cu-Zn ferrite give high initial permeability and have tremendous potential for applications as SMO, MICI, incomputer memory devices and in logic devices. Joshi et.al.[52] have reported their results on magnetization, Curie temperature and Y-K angles of Cu substituted Ni-Zn ferrites. They have observed that on addition of copper the Curie temperature and magnetisation are lowered. This is attributed to lower magnetic moments of Cu^{2+}.

The low loss Ni-Cu-Zn ferrites for deflection yoke used in display monitors with a high resolution have been developed earlier.[53] Narn et.al.[54] have studied the effect of Cu substitution on the electrical and magnetic properties on Ni-Zn ferrites. Miggue et.al.[55] and Nakamura et.al.[56] have studied the electromagnetic properties and microstructure of low temperature fired Ni-Cu-Zn ferrite. Deshmukh[57] has studied effect of Cu substitution on the properties of Ni-Zn ferrites prepared by chemical route. They have reported the change in magnetization on copper substitution.

Nakamura et.al.[58] have studied the low temperature sintering of Ni-Cu-Zn ferrite and clarified the relation between preparation

conditions (calcination temperature particle size of starting materials) and some properties of the sintered ferrite. They observed that the sintering density and the complex permeability of Ni-Cu-Zn ferrite ceramics can be controlled by particle size, starting oxide materials and calcination temperature.

Jau-Ho Jean et.al.[59] have studied the effect of PbO addition on the densification, microstructure and properties of low temperature Co-firable Ni-Cu-Zn ferrite. They have observed that the densification kinetics are greatly enhanced with a small amount of PbO which is present as a dopant in the NiCuZn ferrite. The grain size becomes larger when PbO is added.

Zhang et.al.[60] obtained the ultra-fine and highly reactive Ni-Cu-Zn ferrite powder by gel self propagating method. They observed that densification of ferrites and homogeneous grain growth were the main factors affecting high initial permeability. Lin et.al.[61] have applied microwave-sintering technique for densifying Ni-Cu-Zn ferrite materials and multilayer chip (MC) inductors. They have reported that high impedance multilayer chip inductors can be achieved by microwave sintering of the materials at $800\text{-}850^0C$ for 20 minutes.

1.10 ORIENTATION OF THE PROBLEM

The production of high quality ferrites will continue to increase every year. It will experience a steady growth with further advancement in science and technology. In the last few decades the soft ferrites have aroused considerable interest due to their electrical, magnetic, electronic, microwave and computer applications.

Snoek has explained that the Ni-Zn ferrites have quite excellent magnetic properties. Ni-Zn ferrites exhibit significantly low eddy current losses than Mn-Zn ferrites. Ni-Cu-Zn ferrite has many applications including rotary transformers, noise filters, multilayer ferrite chip components etc. The new power ferrites have two new attributes not previously needed in other applications. (i) They have to possess higher saturation. (ii) they require relatively low core losses at higher flux densities and at fairly high frequencies.

At present Ni-Cu-Zn ferrites have been used extensively for the production of the MLCI so develop Ni-Cu-Zn ferrites with excellent magnetic properties especially with high initial permeability is needed to be done. From the literature survey, it is observed that the nickel ferrites seen to be interesting.

In view of the above consideration, it was proposed to undertake work on preparation, characterization and measurement of

electrical magnetic properties of Ni-Cu-Zn ferrites. The work involved -

i. The preparation of $Ni_xCu_{0.2}Zn_{0.8-x}Fe_2O_4$ ferrites with $x = 0.2, 0.3, 0.4, 0.5, 0.6, 0.7$ and 0.8.

ii. X-ray diffraction studies for determination of crystal structure and lattice parameters.

iii. Determination of Curie temperatures.

iv. D.C. and A.C. electrical conductivity measurements to understand the conduction mechanism.

v. Magnetisation studies to observe the variations in the magnetic moments, magnetization and hysteresis with composition at room temperature and

vi. The variation of permeability with temperature to understand the role of substitution.

REFERENCES

1.   Hilpert S.
     Ber Deut. Chem. Ges. 42 (1909) 2248

2.   Sarnot S.I., Mathur, A., Govila R.K.,
     J. Phys. IV France 7 (1997)

3.   Neel L.
     Proc. Phys. Soc. (London) A-65 (1952) 869

4.   Anderson, P.W.
     Phys. Rev. 79 (1950) 350, 705

5.   Van Vleck J.H.
     Phys. Rev. 78 (1950) 266

6.   Yafet Y. and Kittel C.
     Phys. Rev. 87(1952) 290

7.   Gilleo M.A. and Geller S.
     Acta. Cryst. 10 (1957) 239

8.   Kato, Y. and Takai T.
     J. Inst. Electrical Engineers, Japan 53 (1953) 408

9.   Bragg, W.H.
     Phil. Mag 30 (176) (1915) 305

10. Nishikawa S.
     Proc. Math. Phys. Soc. Tokyo (1915) 199

11. Barth T.F.and Posnjak E.
     Z. Krist 82 (1932) 325

12. Van Uitert L.G.
     Proc. IRE 44 (1956) 1294

13. Kingeri W.D.
     'CERAMIC FABRICATION PROCESSES', M.I.T. Technical
     Press, John Wiley, NY (1958)

14. Komar A.P. and Klivshin V.V.
    Bull. Acad. Sci. (USSR) (1954) 403

15. Koops C.G.
    Phys. Rev. 83 (1951) 216

16. Kamiyoshi, K.
    Sci. Repts. Res. Inst. Tohoku Univ. Japan A3(1951) 100

17. Fair Weather A. and Frost E.J.
    Proc. Inst. Elect. Eng. 15 (1953) 100

18. Kramers H.A.
    Physica 1 (1934) 182

19. Gorter E.W.
    Philips Research Repts. 9 (1954) 295

20. Kulkarni R.G. and Patil V.U.
    J. Mater. Sci. 17 (1982) 843

21. Standley K.J. 'Oxide Magnetic Materials'
    IInd Edition, Clarendon Press, Oxford (1973) 139

22. Sohoo, R.F. 'Theory and applications of ferrites',
    Prentice Hall Inc. (1960) P.

23. Tamaura Y.
    J. Magn. Soc. Japan, 22 (1998) 396

24. Tamaura Y.
    'Solar Chemical Technology for Hybridization with Coat',
    'Gasification/ liquification/ Proc. 13th Conf. on energy system
    Economics, Tokyo, Jan. (1998)

25. Bahadur D.
    Abstract, DAE-BRNS National Symp. On 'Recent Trends in
    Electro and Magneto Ceramics', Shivaji University, Kolhapur
    (1999) 7

26. Waingankar A.S., Kulkarni S. G. and Sagare M.S.
J. Phys. IV (Paris) [Supl. III] (1997) 155

27. Know O.H., Fukushima Y., Sugimoto M. and Hirastsuka N.
J. Phys. IV (Paris) [Supl. 111] (1997) 165

28. J. Oh,
'New Ferrite Process and its Chemistry for removal of heavy metal ions from water'. Ref. 33, pp. 211-17

29. Miura S., Aoki A., Kitayama Y. and Kodama T.
J. Magn. Soc. Jan. 22 [Suppl.] S_1 (1998) 403

30. Tamaura Y., Kojima M., Hasegawa N., Tsuji M., Ehrensberger K. and Steinfeld A.
'Solar energy conversion into H_2 energy, using ferrites'. J. Phys. IV (Paris) [Suppl. 111] (1997) 673

31. Tabata M. and Chohji T.
'No Gas Removal with spinel ferrite at 200^0-400^0C'. J. Magn. Soc. Jpn 22 [Suppl. S_1] (1998) 406

32. Ishino K. and Narumiya Y.
Am. Ceram. Soc. Bull. 66 (1987) 1469

33. Zhang Q., Itoh T., Abe M. and Tamaura Y.
In "ferrites" edited by Yamaguchi T. and Abe M. Proc. ICF-6, Tokyo (1992) 481

34. Orehotsky J. and Davidson C.R.
Magn. Lett (G.B.), 1,5,6 (1980) 117

35. Petrov V.V., Yu Chukolkin G. and Gashchitskii B.N.
Sov. Phys. Solid State, 22 (1980), P.

36. Satyanarayana R. Ramana S. Murthy, Seshigri T., Rao
J. Less Common metals, 90 (1983) 243

37. Whall T.E., Yeung K.K. and Prokova Y.G.
Phil. Mag. B (G.B.) 50, 6 (1984) 689, 53, 3 (1986) 167, 54, 6 (1986) 505

38. Sankpal A.M., Sawant S.R. and Vaingankar A.S.
Indian J. Pure and Appl. Phys. 26 (1988) 459

39. Srivastava C.M. and Patni M.J.
1, Proc. ICF 5 (1989)

40. Gajapthy, D.
Handbook of Ceramics and Compositions, Vol.1, Ed. Incholos
P. Cheremision, M. Dekkar Inc., New York (1990)

41. Hasab M.E.
J. Magn. and Magn. Mater. 98 (1991) 33

42. Chaudhari S.C.
M.Phil. Thesis, Shivaji University, Kolhapur (1998)

43. Bagdanovich M.P.
Sovt. Phys. Solid State 33 (12) 1952

44. Das B.K.
"Preparation and Characterization of Materials"
Academic Press, Inc. P. 75

45. Hang M., Fehnle M., Kron H. and Muller
J. Magn and Magn. Mater. 69 (1987) 163

46. Srivastav R.C., Khan D.C. and Das A.R.
Phys. Rev. B. 41, 18-125 (1990) 14

47. Rezlescu E., Rezlescu N., Pasnicu C. and Craus M.L.
J. Magn. and Magn. Mater. 157/158 (1996) 487

48. Dias A., Mohallem N.D.S. and Moreira R.L.
Mater. Res. Bull. Vol. 33, No. 3 (1998) 475

49. Patil S.A., Bhise B.V. and Ghatage A.K.
Mater. Chem. and Phys. 65 (2000) 38

50. Ravinder D.
Indian J. Phys 74A(3) (2000) 331

51. Srivastava C.M., Patni M.J., Srinivasan G. and Srinivasan T.T.
Bull. Mat. Sci., 3 (1981) 225

52. Joshi G.K., Khot A.Y. and Sawant S.R.
Solid State Commun. 65, 12 (1988) 1593

53. Kobayashi K.I., Moringa H., Araki T., Naka Y. and Oomura T.
J. Magn and Magn. Mater. 104-107 (1992) 413

54. Narn J.N., Jung H.H., Shin J.Y. and Oh J.H.
IEEE Transactions on Magnetics, Vol. 31, No. 6 (1995)

55. Miggue Lu,
Proc. of VIIth International Conference of Ferrites, Sept. 3-6 (1996)

56. Nakamura T.
Proc. of VIIth International Conference of Ferrites, Sept. 3-6 (1996)

57. Deshmukh U.B.
M.Phil. thesis, Shivaji University, Kolhapur (1998)

58. Nakamura T. and Okano Y.
J. Phys. IV (France) (1997)

59. Jau-Ho Jean and Cheng-Horng Lee
J. Amer. Ceram. Soc. 82(2) (1999) 343

60. Hongguo Zhang, Zhenwei Ma, Zhou Ji, Zhenxing Yue, Longtu Li and Zhilun Gui
J. Magn. and Magn. Mater. 213 (2000) 304

61. Tsay C.Y., Liu K.S., Lin T.F. and Lin I.N.
J. Magn. and Magn. Mater. 209 (2000) 189