Characteristics of materials for microwave devices

V R K MURTHY*, K C JAMES RAJU* and B VISWANATHAN+

*Department of Physics, +Department of Chemistry, Indian Institute of Technology, Madras 600 036, India

Abstract. The characteristics of materials like ferrites, garnets, ferroelectrics, temperature-compensated dielectrics and copper-coated PTFE-based composites, extensively used in microwave devices are discussed.

1. Introduction

The transmission lines for the guided propagation of electromagnetic waves in the microwave frequency range (1 to 100 GHz) are waveguides and microwave integrated circuits (MICs). The waveguide components/devices are bulky and expensive but can carry high power whereas MICs show their versatility in low power, light weight and miniaturized microwave systems. The development of these waveguide-based components and MICs depends upon the availability of materials with specific characteristics. Hence the physicochemical properties of such materials have an impact on microwave technology. In this paper, we describe a few sets of such microwave materials and their characteristics which make them suitable for microwave devices.

2. Microwave materials and characteristics

The primary requirements of a microwave material are low d.c. conductivity, low dielectric and magnetic losses, and temperature-independent dielectric or magnetic properties. Some of the materials that satisfy these requirements are ferrites, garnets, ferroelectrics and temperature-compensated dielectrics which are ceramic materials and copper clad composites based on PTFE which are used as substrates for MICs.

2.1 Ferrites and garnets

Spinel ferrites are a class of magnetic materials with a general formula MFe_2O_4 (M = a divalent metal). M can be replaced with two divalent metals with the chemical formula $M_{1-x}M'_xFe_2O_4$. The parameter x varies from 0 to 1, thus changing the physical parameters according to device requirements. M can also be replaced with monovalent and trivalent metals and lithium and lithium zinc ferrites belong to such a family (Baba et al 1971). Garnets are another class of materials with the cations being rare earths and iron. An example of such a family of compounds is yttrium iron garnet ($Y_3Fe_5O_{12}$). One can prepare garnets and ferrite powder materials using conventional ceramic method and this is most widely used by industrial organizations.

A comparison of ferrite and garnet compounds is given in table 1. Various techniques

Table 1. Comparison of the characteristics of ferrites and garnets.

Ferrites	Garnets
Variable resistivity	Very high resistivity
Saturation magnetization variable	Low
Curie temperature variable	High
Coercivity low	Low
Stable compounds	Stable compounds
Can be prepared at low temperatures also	Very high temperatures only
Structure cubic	Cubic
Partially filled structure	Completely filled structure
Line-width high	Low
Microwave losses medium	Low
Dielectric constant high	High
Low cost	High cost

Table 2. Typical specification of a microwave material (ferrite) for use as isolator/attenuator.

Saturation magnetization	200–2000 Gauss
Microwave loss tangent	1×10^{-4}
Coercivity	1 Oe
Line-width	1–10 Oe
BH squareness ratio	0·75
Dielectric constant	15

Table 3. Typical characteristics of lithium ferrite.

Resistivity	8×10^{5} ohm-cm
Saturation magnetization	3745 Gauss
Resonance line-width	30 Oe
Squareness ratio	0·95
Curie temperature	890 K
Microwave loss	1×10^{-4}
Dielectric constant	10

are currently employed in characterizing these materials at microwave frequency. However, the most reliable method 'cavity perturbation technique' has been used for the microwave characterization of these materials and the details were given by Murthy and Raman (1989). The specifications of a ferrite material for isolator/attenuator applications are given in table 2 and some characteristics of lithium ferrite for such devices are given in table 3.

2.2 Ferroelectrics

Ferroelectrics are electrical analogues of ferromagnets displaying Curie-Weiss law in their dielectric constant variation with temperature (Lines and Glass 1977). For

microwave applications they are used above the Curie temperature (T_c), i.e. in the paraelectric region because these materials do not exhibit their characteristic hysteresis, piezoelectric and pyroelectric effects in the paraelectric state but still exhibit large dielectric constant which depends on voltage and temperature with a lower dielectric loss. Majority of the applications utilizing ferroelectrics depend on their large nonlinearity in dielectric constant at a particular temperature above T_c either under a dc bias or under varying field strength of the microwave power (Horton and Donaldson 1967). A ferroelectric whose T_c is below room temperature, having low dielectric loss at room temperature, exhibiting large nonlinearity in dielectric constant above T_c but dependent on temperature only sluggishly is ideal for microwave applications. Materials like $BaTiO_3$, $SrTiO_3$, $(Pb_xSr_{1-x})TiO_3$ with $x = 0.315$, 0.35 and 0.45. $(Ba_{0.75}Sr_{0.25})TiO_3$ are used widely in microwave applications. All of them crystallize in perovskite structure with T_c below 393 K. They are used in the ceramic form and have resistivities of the order of 10^{11} to $10^{13}\,\Omega\text{m}$.

When a dc bias voltage is applied both the dielectric constant and the loss of a ferroelectric will decrease. The nonlinear dielectric properties enable them to be used in microwave filters, limiters, phase shifters, switches, mixers and modulators and as the active element for microwave parametric amplifiers/oscillators, harmonic generators and electromagnetic shock wave generators.

The advent of ferroelectric thin films will help as it decreases the amount of dc voltage required to bring in sufficient change in the dielectric constant (Das 1967). Ferroelectrics generally have relaxation in or around the microwave region. They can be used only at frequencies far away from the relaxation region. Ferroelectrics are characterized using coaxial cavities at smaller microwave frequencies and by a transmission technique at higher frequencies. However, data on the large signal microwave dielectric properties of ferroelectrics are scarce. Table 4 contains the data of a few ferroelectrics used in microwave applications. Unless otherwise specified, the materials given in this table were employed in ceramic form (Das 1964).

Table 4. Characteristics of some ferroelectrics used in microwave devices.

Material	ε	$\tan\delta$	frequency (GHz)	temp. (°C)	Curie temp. (°C)
Single crystal $BaTiO_3$	2000	~0.15	24.0	20	130
Ceramic $BaTiO_3$	600	~0.3	3.0	25	130
Hot-pressed $Cd_2Nb_2O_7$	435	0.069	4.0	26	−88
$(Ba_{0.73}Sr_{0.27})TiO_3$	3350	~0.16 (22 GHz)	12.4	21	20
Single crystal $SrTiO_3$	~1000	0.0013	7.65	−150	−163
$(Pb_{0.315}Sr_{0.685})TiO_3$	5475	0.05	1		23
$(Pb_{0.35}Sr_{0.65})TiO_3$	5750	0.055	0.2	20.5	
$(Pb_{0.45}Sr_{0.55})TiO_3$	4800	0.008	0.218	120	116

(Column header above table: "Measured at" spanning frequency (GHz), temp. (°C))

2.3 Materials for dielectric resonators

Dielectric resonators are used in MICs for frequency control. They are just a ceramic pellet in the form of a parallelopiped or cylindrical disc (Fiedziszko 1986). When a continuous band of microwave is passed through a dielectric resonator, it will resonate at a few discrete frequencies determined by the geometry and dimensions of the pellet. Since the electromagnetic field can satisfy the boundary conditions in more than one mode, one will get a series of modes each having different field pattern. The most widely used mode is the TE_{011} mode. The material used for making dielectric resonators should satisfy the conditions given below (Subba Rao et al 1990):

(a) The dielectric constant should be high (generally 10 to 100), (b) the dielectric loss should be low (tan $\delta = 0.0003$) and (c) the temperature coefficient of resonant frequency τ_f must be very small (τ_f must be less than ± 50 ppm).

A large ε will aid miniaturization while a low dielectric loss will result in a high Q value. But the value of τ_f depends on both the temperature coefficient of dielectric constant (τ_ε) and the coefficient of thermal expansion (α) since $\tau_f = \frac{1}{2}\tau_\varepsilon + \alpha$. Materials with compensating τ_ε and α give low value of τ_f. τ_ε depends only on the lattice dynamics of the material while α can be controlled through heat treatments. The materials should not have any relaxation near the frequency range of interest. The materials which are widely used as DR have perovskite or perovskite-related structures. But the role of secondary phases in DR materials is considerable. They help in sintering as well as in enhancing the desirable properties.

Dielectric resonators are used in various types of filters and oscillators and as miniature radiating elements in microwave integrated circuits. Coupling to DR is easy and can replace bulky cavity resonators in many applications. These temperature-compensated dielectrics are characterized in the microwave frequency range using a method popularly known as Courtney's (1970) method.

Characteristics of some representative temperature compensated dielectrics are given in table 5 (Nomura 1983; Wakino et al 1984).

2.4 Copper-coated PTFE (polytetrafluoroethylene)

Metallized fluorocarbon polymers (PTFE) with woven or nonwoven glass fibre and with high dielectric constant ceramic fillers offer a combination of properties suitable

Table 5. Typical temperature-compensated dielectrics and their characteristics.

Materials	ε	Q	ppm/°C
$Ba_2Ti_9O_{20}$	39·4	3300(9·8 GHz)	5
$BaTi_4O_9$	37·8	2900(9·8 GHz)	
$Ca(Zr_{0.985}Ti_{0.015})O_3$	29·0	3300(4 GHz)	−23
$(Zr, Sn)TiO_4$	38·0	13000(3 GHz)	0
$BaO-PbO-Nd_2O_3-TiO_2$	88·0	2000(3GHz)	0
$Ba(Zn, Ta)O_3$	29·0	10000(7 GHz)	1
$Ba(Zn, Nb)O_3$	41·0	9150(9·5 GHz)	31

for applications like microwave antenna (Traut 1980) and microwave integrated circuits (Olyphant and Ball 1970). For these microwave applications, the microwave substrate chosen should meet certain exacting demands like uniform dielectric constant, controlled thickness and low loss (Woermbke 1979). The copper-coated PTFE substrate is most commonly used for this purpose. The substrate was conditioned in sodium hydroxide, acetone and water mixture. The preconditioned substrates were subsequently pre-treated with stannous chloride sensitizer and palladium chloride activator.

Copper coating was achieved by electroless method using a copper bath. Electroplating of copper should be resorted to for further increase in thickness if required. One can use electroless method to deposit copper for good adhesion, uniformity and smoothness. This approach is least expensive and reliable. The characteristics of copper-coated PTFE for microwave devices are that the dielectric constant is around 2·2 and the dissipation factor is 0·0001.

3. Conclusions

Considering the strategic role enjoyed by microwave technology in aerospace and communications, the demand for materials with more specific characteristics will increase, especially for miniaturized microwave systems. Ferroelectric thin films can also get a renewed interest. Temperature-compensated dielectrics can also be used as MIC substrates. Properties of high temperature superconductors are being exploited for various microwave applications. Materials with low loss and high ε are required for developing MICs in the lower microwave frequencies. Overcrowding of microwave frequencies and the special characteristics of millimeter waves force more and more systems to operate in the millimeter range, which requires materials with low dielectric constant and low loss at high frequencies.

References

Baba P D, Argentina G M, Courtney W E, Dionne G F and Temme D 1971 *IEEE Trans. Magnet.* 7 351
Courtney W E 1970 *IEEE Trans. Microwave Th. Tech.* MTT 18 476
Das R 1967 *Solid State Electron.* 10 857
Das S N 1964 *IEEE Trans. Microwave Th. Tech.* 12 440
Fiedziszko J S 1986 *Microwave J.* 189
Horton J B and Donaldson M R 1967 *IEEE Trans. Microwave Th. Tech.* 15 517
Lines and Glass 1977 *Principles and applications of ferroelectrics and related materials* (Oxford: Clarendon Press)
Murthy V R K and Raman R 1989 *Solid State Commun.* 70 847
Nomura S 1983 *Ferroelectrics* 49 61
Olyphant M and Ball J H 1970 *IEEE Trans. Elect. Insul.* EI-5 26
Subba Rao T, Murthy V R K and Viswanathan B 1990 *Ferroelectrics* 102 155
Traut R G 1980 *Microwave J.* 23 47
Wakino K, Minai K and Tamura H 1984 *J. Am. Ceram. Soc.* 67 278
Woermbke J D 1979 *Microwaves* 18 66