P • A • R • T 2

COMPONENTS

On the CD-ROM

Properties of Materials

SECTION 5

ELECTRONIC AND FIBER OPTIC COMPONENTS

This section reviews the basic components in their discrete form that make up electronic circuits and systems. The first two chapters cover fundamental passive and active discrete components, respectively. Another chapter is devoted to batteries and fuel cells. While batteries convert chemical energy into electric energy via an oxidation-reduction electrochemical reaction, the reactants are contained within the cell, whereas in a fuel cell, one or both of the reactants are not embedded, but fed from an external supply when power is needed. A chapter on relays and switches compares the characteristics of solid-state and electromechanical versions. Another on connectors describes various types of connectors along with design, application, and reliability issues. Finally, a completely new chapter explores the characteristics and applications of optical fiber components, ranging from the optical fiber itself to connectors, couplers, fiber gratings, circulators, switches, and amplifiers.

Since the selection of materials to fabricate electronic components is fundamental to their operational characteristics and expected lifetimes, valuable background information covering a broad range of electronic materials is provided on the accompanying CD-ROM.

The treatment of specialized components is covered in separate sections of the handbook: Section 6, Integrated Circuits and Microprocessors; Section 7, UHF and Microwave Devices; Section 8, Transducers and Sensors; and Section 9, Radiant Energy Sources and Sensors. D.C.

In This Section:

On the CD-ROM:

Blech, I. A., "Properties of Materials," reproduced from the 4th edition of this handbook, is a comprehensive review of conductive and resistive materials, dielectric and insulating materials, magnetic materials, semiconductors, electron-emitting materials, and radiation-emitting materials.

CHAPTER 5.1
PASSIVE COMPONENTS

Carrington H. Greenidge, Thomas S. Gore, Jr., Emanuel Gikow, Joseph M. Giannotti, John R. Vig, Sam Di Vita

RESISTORS

Carrington H. Greenidge

Introduction

The resistive function is a fundamental element of electronics. It results from the characteristic of a material to impede the flow of electrons through that material in a measured or calibrated manner. Resistors are devices that exhibit this primary characteristic along with secondary characteristics. The primary characteristic, which is measured in ohms, is derived from the resistivity (rho) of the material and the geometry of the resistance element. The basic relationships between resistance, voltage (volts), current (amps), and power (watts) are defined by Ohm's law relationships: $I = E/R$ and $P = I * E$.

In general, resistive devices have an equivalent circuit as shown in Fig. 5.1.1, where series inductance (L) and shunt capacitance (C) are secondary (reactance) characteristics that affect device response at high frequencies. The use of different materials and geometries results in a wide range of secondary characteristics and capabilities that provides an expanding portfolio of resistor products to meet new application requirements.

Resistor Terminology

Resistance value. The primary characteristic of the device measured in ohms (Ω).

Nominal resistance value. The ohmic value attributed to a resistor and identified by color coding or some other identification technique.

Resistance tolerance. The allowed variation of resistance value from the nominal value; it is marked on the resistor or identified by some other technique.

Resistance stability. The estimate of the variation of resistance value over time when operated within ratings.

Power rating. The maximum value of steady-state power that can be dissipated by a resistor, over long periods of time without significant change in resistance value.

Voltage rating. The maximum voltage that may be applied across the element without significant change in resistance value.

Temperature rating. The temperature at which the resistor will operate at full rated power. Operation of the resistor at temperatures above the established rating is possible at reduced power levels up to a temperature called the zero power level or zero derating. This temperature usually reflects the hot-spot temperature of the resistor.

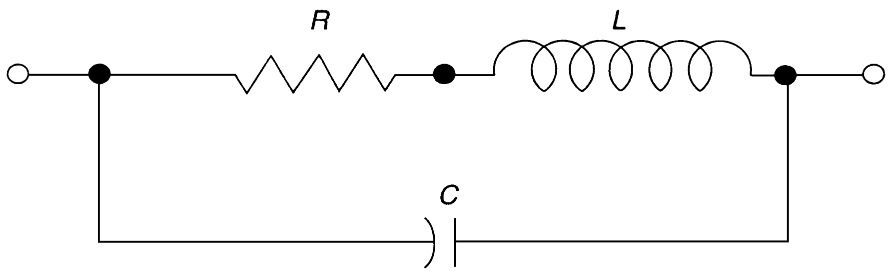

FIGURE 5.1.1 Equivalent circuit of a resistor.

Temperature coefficient of resistance (TCR). The variation of resistance value as a function of temperature expressed in parts per million/degree Celsius or as a percentage per degree Celsius. TCR is usually retraceable.

Voltage coefficient of resistance (VCR). The variation of resistance value as a function of applied voltage expressed in parts per million (PPM) or percent per volt. VCR is usually retraceable.

Noise. The instantaneous voltage instability that occurs in a resistor owing to thermal excitation of the structure (Johnson noise) or current effects (current noise). Most resistors have basal noise index and third harmonic (THI) levels. Significant deviation from these indices suggests the presence of structural abnormalities.

High-frequency effects (see Fig. 5.1.1). The application of ac voltages produces inductive and capacitance reactance in many resistors. Series inductance increases the overall impedance of the resistor while parallel capacitance decreases the impedance.

Fixed resistors. Resistors that in the completed state cannot be adjusted.

Adjustable resistors. Resistors that in the completed state can have the resistance value changed by some external technique that is nonreversible.

Variable resistors. Resistors that in the completed state can be changed by some technique (usually mechanical) that is reversible.

Precision resistors. Precision resistors are used in applications requiring tight tolerance (less than ±1 percent), tight TCR (less than ±100 PPM), long-term resistance stability (less than ±1 percent drift), and low noise.

Semiprecision resistors. Semiprecision resistors are used in applications in which long-term stability (up to ±5 percent) is important but initial tolerance (±1 percent) and TCR (±100 PPM) requirements are not as critical.

General-purpose resistors. These devices are used in applications where wide resistance tolerances and resistance shifts (±5, 10, and 20 percent) are acceptable.

Fixed Resistors for Thru-Hole Applications

Fixed wirewound resistors are constructed using an appropriate length and diameter of resistance wire that is wound around a mandrel or core to achieve a specific resistance. Leads, lugs, or other terminals (including solderable terminations for surface mount applications) are provided at each end of the resistance wire, mechanically secured and protected in an appropriate package. Wirewound resistors provide very tight tolerance, excellent long stability, high temperature capability, and very low noise. They have poor high-frequency response because of inductive properties and high-resistance value limitations because of thin wire fragility. Wirewound resistors are used in precision and power applications.

Fixed carbon composition resistors consist of a slug of inert binder mixed with measured amounts carbon particles to give the desired nominal resistance. Axial lead terminations are embedded in each end of the slug during a formation process. The entire assembly is molded into a plastic housing that provides mechanical stability. Alternatively, a carbon particle/binder slurry is established on the outside wall of a glass tube, terminal leads are mounted at each end using a conductive cement and the assembly is molded into a protective case.

Carbon composition resistors are in the general purpose category and provide a wide resistance range. The slug construction provides exceptional transient overload protection and these devices have exceptional reliability. The high-frequency response of these resistors is diminished because of capacitive reactance.

Fixed film resistors (carbon film, cermet, and metal films) are constructed by establishing the appropriate film on an insulating substrate. Terminations, usually cap and lead assemblies, are provided at each end. The film resistance element is adjusted to value using a mechanical or a laser spiraling technique that cuts a helix path into the film or by the mechanical removal of film from the surface (unlike the unadjusted glass tube carbon comp device described previously). A protective coating is usually established over the entire structure to provide mechanical and environmental protection.

Carbon film resistors are available primarily as general-purpose resistors but can fit into semiprecision applications where ± 1 percent tolerances are needed but looser TCRs are acceptable.

They are available over a wide resistance value range (in some specialty areas going into the teraohm range) and they have a good high-frequency response. Their environmental performance, however, is not equal to the metal film and cermet devices described as follows.

Metal film (thin film, thin metal film, or metal oxide) resistors are used in precision (< ±1 percent) and semiprecision (±1 percent) applications. They are the most stable film devices with TCRs ±25 and ±50 PPM/°C generally available at reasonable cost. Tighter tolerances and TCRs are available at higher cost. Metal films are selected over precision wirewound devices because of lower cost, better high-frequency response and wider resistance range.

Cermet films are used primarily in semiprecision applications, but are also available for some precision (< ±1 percent) and general purpose (> ±1 percent) use. The element structure (different ratios of insulating CERamic and conductive METal particles, fused together on a substrate) provides a wider resistance range than metal film or wirewound resistors. The long-term stability is not as good and tighter tolerances and TCRs are not available.

Resistor networks are structures with multiple fixed elements established on one substrate. The elements are usually Cermet films but precision devices are available in thin film technologies. There are two basic packages, the single in-line package (SIP) and the dual in-line package (DIP) with three standard circuits or interconnections (isolated element, pull-up, and terminator) as shown in Fig. 5.1.2.

Custom circuits, both simple and complex, can be designed for special applications. The termination (pin) count for SIPs ranges from 2 to 20 or more while DIPs are usually 14 or 16 pins. Pin spacing is usually 0.100 in.

Resistor networks in general have a higher per element cost than discrete devices. However, savings in assembly cost, improved circuit board real estate usage and more uniform electrical characteristics (stability, TCR, and high-frequency response) drive the selection of resistor networks.

Fixed Resistors for Surface Mount Applications

Film chip resistors are constructed by establishing a resistive element on the top surface of a rectangular ceramic chip. Solderable terminations are created at each end and short extensions of the terminations are also created on the underside of the chip to enhance the bond strength after solder attachment. A glassy or plastic passivation layer is usually formed over the resistive element for environmental protection. Resistance value is established using laser trim techniques. Film chip resistors have excellent power handling capability because of the thermally efficient mounting technique. This allows for improved board component density compared to axial devices. As new, more accurate placement equipment is developed, the physical size of the parts is shrinking. The size, XXYY, in millimeters, is defined by XX the approximate length and YY the approximate width. The size trend, from 1206 to 0805 to 0603 to 0402, is clear. Larger sizes, 1210, 2012, and 2520 are used when higher power levels are required.

Cermet and metal film chips have similar electrical and performance characteristics as the axial designs from which they were derived. Because of size standardization, the electrical performance is more uniform and assembly operations are simplified. Film chip resistors are now the workhorse resistive component.

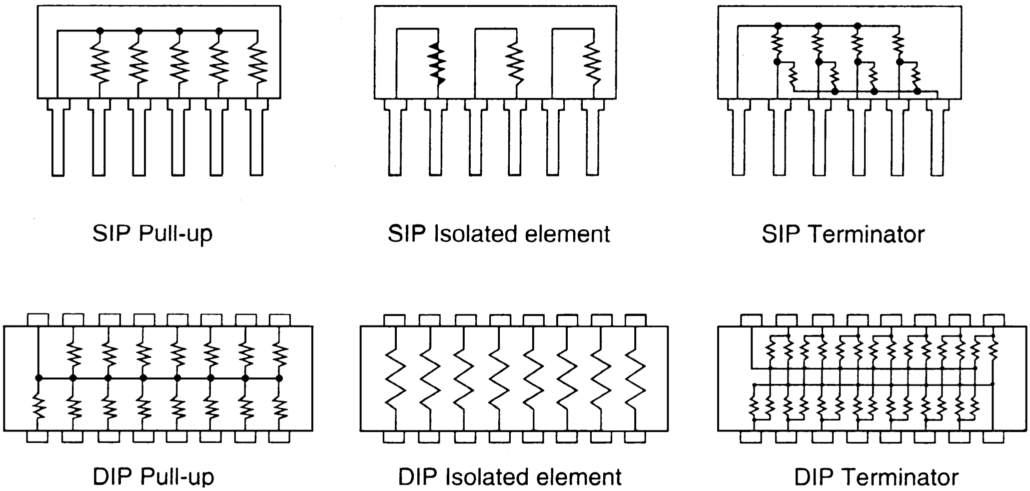

FIGURE 5.1.2 Standard SIP and DIP circuits.

The metal electrode face-bonding (MELF) resistor is the surface mount technology (SMT) equivalent of the axial designs described previously. Modifications to the protective coating process leave the endcap backwalls exposed, which provides the solderable surfaces required for surface mounting. MELFs are not as popular as the rectangular chip because of more difficult assembly routines but are used because they are the lowest cost tight tolerance, tight TCR SMT device.

Wirewound chips have been developed to satisfy the needs for precision wirewound performance in the 100 percent SMT assembly environment (as opposed to the mixed through-hole and SMT environment). The performance characteristics of wirewound chips and fixed wirewound resistors are similar.

Surface mount networks are multiple element devices derived from the DIP concept with either standard or custom internal circuitry. "Gull"-shaped or "J"-shaped terminations (which sit on the solder pads of an SMT board) are molded into the completed device body. Lead spacing can be 0.100 to 0.50 in. and can be placed on opposing or on all four sides.

Chip arrays are the true SMT derivatives or resistor networks and are essentially sets of chip resistors integrated into a monolithic structure (although internal circuitry can be much more complex, including film capacitors, than just isolated elements). Chip arrays use termination constructions similar to chip resistors with pitch down to 0.025 in.

Variable Resistors

Potentiometers are precision devices designed with either film, wirewound, or conductive plastic elements and are available in single or multiturn and single multisection units. The electrical output in terms of voltage applied across the element is linear or follows a predetermined curve (taper) with respect to the angular position contact arm. *Precision potentiometers* can provide superior resolution (tracking of the actual resistance to the theoretical resistance defined by the taper) where precise electrical and mechanical output and quality performance are required. *General purpose potentiometers* are used as gain or volume controls, voltage dividers or current controls in lower precision circuits. These devices can be ganged together and/or provided with rear-mounted switches. *Trimmer potentiometers* are lead-screw actuated, multiturn devices principally used as "set and forget" devices to control low current or bias voltages or to balance circuit variables.

Rheostats are larger, variable resistors, usually wirewound, for power applications. They are used for controls for motor speed, ovens, heaters, and other applications where higher current levels are present.

CAPACITORS

Thomas S. Gore, Jr.

Introduction

A capacitor consists basically of two conductors separated by a dielectric or vacuum so as to store a large electric charge in a small volume. The capacitance is expressed as a ratio of electric charge to the voltage applied $C = Q/V$, where Q = charge (C), V = voltage (V), C = capacitance (F). A capacitor has a capacitance of one farad when it receives a charge of 1C at a potential of 1V. The electrostatic energy in watt-seconds or joules stored in the capacitor is given by

$$J = {}^1\!/\!_2 CV^2$$

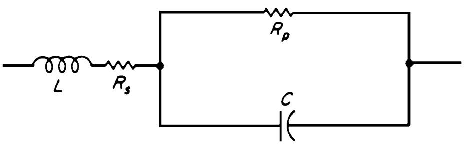

FIGURE 5.1.3 Equivalent circuit of a capacitor; R_s = series resistance owing to wire leads, contact terminations, and electrodes; R_P = shunt resistance owing to resistivity of dielectric and case material, and to dielectric losses; and L = stray inductance owing to leads and electrodes.

Dielectric. Depending on the application, the capacitor dielectric may be air, gas, paper (impregnated), organic film, mica, glass, or ceramic, each having a different dielectric constant, temperature range, and thickness.

Equivalent Circuit. In addition to capacitance, a practical capacitor has an inductance and resistance. An equivalent circuit useful in determining the performance characteristics of the capacitor is shown in Fig. 5.1.3.

Equivalent Series Resistance (ESR). The ESR is the ac resistance of a capacitor reflecting both the series resistance R_s and the parallel resistance R_p at a given frequency so that the loss of these elements can be expressed as a loss in a single resistor R in the equivalent circuit.

Capacitive Reactance. The reactance of a capacitor is given by

$$X_c = 1/2\pi fC = 1/\omega C \quad (\Omega)$$

where $f = \omega/2\pi$ is the frequency in hertz.

Impedance (Z). In practical capacitors operating at high frequency, the inductance of the leads must be considered in calculating in impedance. Specifically,

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

where R is the ESR, and X_L reflects the inductive reactance.

The effects illustrated in Fig. 5.1.3 are particularly important at radio frequencies where a capacitor may exhibit spurious behavior because of these equivalent elements. For example, in many high-frequency tuned circuits the inductance of the leads may be sufficient to detune the circuit.

Power Factor (PF). The term PF defines the electrical losses in a capacitor operating under an ac voltage. In an ideal device the current will lead the applied voltage by 90°. A practical capacitor, owing to its dielectric, electrode, and contact termination losses, exhibits a phase angle of less than 90°. The PF is defined as the ratio of the effective series resistance R to the impedance Z of the capacitor and is usually expressed as a percentage.

Dissipation Factor (DF). The DF is the ratio of effective series resistance R to capacitive reactance X_C and is normally expressed as a percentage. The DF and PF are essentially equal when the PF is 10 percent or less.

Quality Factor Q. The Q is a figure of merit and is the reciprocal of the dissipation factor. It usually applies to capacitors used in tuned circuits.

Leakage Current, DC. Leakage current is the current flowing through the capacitor when a dc voltage is applied.

Insulation Resistance. The insulation resistance is the ratio of the applied voltage to the leakage current and is normally expressed in megohms. For electrolytic capacitors, the maximum leakage current is normally specified.

Ripple Current or Voltage. The ripple current or voltage is the rms value of the maximum allowable alternating current or voltage (superimposed on any dc level) at a specified frequency at which the capacitor may be operated continuously at a specified temperature.

Surge Voltage. The surge voltage applicable to electrolytic capacitors is a voltage in excess of the rated voltage, which the capacitor will withstand for a specified limited period at any temperature.

Fixed Capacitors

Precision Capacitors. Capacitors falling into the precision category are generally those having exceptional capacitance stability with respect to temperature, voltage, frequency, and life. They are available in close capacitance tolerances and have low-loss (high-Q) dielectric properties. These capacitors are generally used at radio frequencies in tuner, rf filter, coupling, bypass, and temperature-compensation applications. Typical capacitor types in this category are mica, ceramic, glass, and polystyrene. The polystyrene capacitor has exceptionally high insulation resistance, low losses, low dielectric absorption, and a controlled temperature coefficient for film capacitors.

Semiprecision Units. Paper- and plastic-film capacitors with foil or metallized dielectric are nonpolar and generally fall between the low-capacitance precision types, such as mica and ceramic, and the high-capacitance electrolytics.

General Purpose. Electrolytic aluminum and tantalum capacitors and the large-usage general-purpose (high-K) ceramic capacitors both have broad capacitance tolerances, are temperature-sensitive, and have high volumetric efficiencies (capacitance-volume ratio). They are primarily used as bypass and filter capacitors where high capacitance is needed in small volumes, and with guaranteed minimum values. These applications do not require low dissipation factors, stability, or high insulation resistance found in precision and semiprecision capacitors. On a performance versus cost basis, the general-purpose capacitors are the least expensive of the groups. High-capacitance aluminum electrolytic capacitors have been designed for computer applications featuring low equivalent series resistance and long life.

Suppression Capacitors. The feed-through capacitors are three-terminal devices designed to minimize effective inductance and to suppress rf interference over a wide frequency range. For heavy feed-through currents, applications in 60- and 400-Hz power supplies, paper or film dielectrics are normally used. For small low-capacitance, low-current units, the ceramic and button-mica feed-through high-frequency styles are used.

Capacitors for Microelectronic Circuits. Table 5.1.1 lists representative styles of discrete miniature capacitors electrically and physically suitable for microelectronic circuit use (filtering, coupling, tuning, bypass, and so forth). The chip capacitor, widely used in hybrid circuits, is available in single-wafer or multilayer (monolithic) ceramic, or in tantalum constructions, both offering reliable performance, very high volumetric efficiency, and a wide variety of capacitance ranges at moderate cost. Temperature-compensating ceramic chips are used where maximum capacitance stability or predictable changes in capacitance with temperature are required.

General-purpose ceramic and solid electrolytic tantalum chips are used for coupling and bypass applications where very high capacitance and small size are necessary. The ceramic chips are unencapsulated and leadless, with suitable electrodes for soldering in microcircuits. The beam-leaded tantalum chips are attached by pressure bonding. The tantalum chip is also available in a multiple-unit assembly in the dual-in-line package for use on printed-circuit boards.

Transmitter Capacitors. The principal requirements for transmitter capacitors are high rf power-handling capability, high rf current and voltage rating, high Q, low internal inductance, and very low effective series resistance. Mica, glass, ceramic, and vacuum- or gas-filled capacitors are used primarily for transmitter applications. Glass dielectric transmitter capacitors have a higher self-resonating frequency and current rating than comparable mica styles. The ceramic capacitors offer moderately high rf current ratings, operating temperatures to

TABLE 5.1.1 Characteristics of Typical Capacitors for Microelectronic Circuits

Type of capacitor	Typical capacitance range	Typical working voltage range, V, dc	Temperature range, °C	Dissipation factor, %	Minimum insulation resistance, MΩ at 25°C	Temp. coeff., ppm/°C	Max. capacitance change over temp. range, %	Termination
Chip:								
Ceramic, temperature-compensating	1 pF to 0.027 mF	50–200	–55 to +125	0.1 at 1 MHz	50,000	0 to –750	. . .	Metallized
Ceramic, general-purpose	390 pF to 0.47 μF	25–200	–55 to +125	3.0 at 1 kHz	10,000	. . .	±15	Metallized
Tantalum oxide (beam-lead), dry	100–3000 pF	12–50	–55 to +85	0.6 at 1kHz	10,000	+200	. . .	Beam lead
Tantalum oxide Polar, solid electrolyte	0.1–47 μF	3–35	–55 to +85	4.0 at 120 Hz	. . .	. . .	±10	Metallized
Metallized, film (metal case)	0.1–10 μF	50–100	–55 to +85	2.5 at 1 kHz	5,000	. . .	±10	Axial
Variable ceramic trimmer	Min. 1–3 pF, max. 5–25 pF	25	–55 to +125	0.2 at 1 MHz	10,000	. . .	±5–±15	Printed circuit

105°C, and high self-resonant frequencies. The gas or vacuum capacitor is available in a wide range of capacitance and power ratings and is used where very-high-power, high-voltage, and high-frequency circuit conditions exist. These units are also smaller than other transmitting types for comparable ratings. The circuit performance of the transmitter capacitor is highly dependent on the method of mounting, lead connections, operating temperatures, air circulation, and cooling, which must be considered for specific applications.

Variable Capacitors

Variable capacitors are used for tuning and for trimming or adjusting circuit capacitance to a desired value.

Tuning Capacitor (Air-, Vacuum-, or Gas-Filled). The parallel plate (single or multisection style) is used for tuning receivers and transmitters. In receiver applications, one section of a multisection capacitor is normally used as the oscillator section, which must be temperature-stable and follow prescribed capacitance-rotation characteristics. The remaining capacitor sections are mechanically coupled and must track to the oscillator section. The three most commonly used plate shapes are semi-circular (straight-line capacitance with rotation), midline (between straight-line capacity and straight-line frequency), and straight-line frequency (which are logarithmically shaped). For transmitter applications, variable vacuum- or gas-filled capacitors of cylindrical construction are used. These capacitors are available in assorted sizes and mounting methods.

Special Capacitors

High-Energy Storage Capacitors. Oil-impregnated paper and/or film dielectric capacitors have been designed for voltages of 1000 V or higher of pulse-forming networks. For lower voltages, special electrolytic capacitors can be used which have a low inductance and equivalent-series resistance.

Commutation Capacitors. The widespread use of SCR devices has led to the development of a family of oil-impregnated paper and film dielectric capacitors for use in triggering circuits. The capacitor is subjected to a very fast rise time (0.1 ms) and high current transients and peak voltages associated with the switching.

Reference Specifications. Established reliability (ER) specifications are a series of military (MIL) specifications that define the failure-rate levels for selected styles of capacitors. The predicted failure rate is based on qualification-approval life testing and continuous-production life testing by the capacitor manufacturer.

INDUCTORS AND TRANSFORMERS

Emanuel Gikow

Introduction

Inductive components are generally unique in that they must be designed for a specific application. Whereas resistors, capacitors, meters, switches, and so forth, are available as standard or stock items, inductors and transformers have not usually been available as off-the-shelf items with established characteristics. With recent emphasis on miniaturization, however, wide varieties of chokes have become available as stock items. Low inductance values are wound on a nonmagnetic form, powdered iron cores are used for the intermediate values of inductance, and ferrites are used for the higher-inductance chokes. High-value inductors use both a ferrite core and sleeve of the same magnetic material. Wide varieties of inductors are made in tubular, disk, and rectangular shapes. Direct-current ratings are limited by the wire size or magnetic saturation of the core material.

Distributed Capacitance

The distributed capacitance between turns and windings has an important effect on the characteristics of the coil at high frequencies. At a frequency determined by the inductance and distributed capacitance, the coil becomes a parallel resonant circuit. At frequencies above self-resonance, the coil is predominantly capacitive. For large-valued inductors the distributed capacitance can be reduced by winding the coil in several sections so that the distributed capacitances of the several sections are in series.

Toroids

The toroidal inductor using magnetic-core material has a number of advantages. Using ungapped core material, the maximum inductance per unit volume can be obtained with the toroid. It has the additional advantages that leakage flux tends to be minimized and shielding requirements are reduced. The inductance of the toroid and its temperature stability are directly related to the average incremental permeability of the core material. For a single-layer toroid of rectangular cross section without air gap,

$$L = 0.0020N^2 b\mu_d \ln (r_2/r_1)$$

where L = inductance (μH)
b = core width (cm)
μ_d = average incremental permeability
r_1 = inside radius (cm)
r_2 = outside radius (cm)
N = total number of turns

Incremental permeability is the apparent ac permeability of a magnetic core in the presence of a dc magnetizing field. As the dc magnetization is increased to the point of saturating the magnetic core, the effective permeability decreases. This effect is commonly used to control inductance in electronically variable inductors.

Inductors with magnetic cores are often gapped to control certain characteristics. In magnetic-cored coils the gap can reduce nonlinearity, prevent saturation, lower the temperature coefficient, and increase the Q.

Adjustable Inductors

The variable inductor is used in a number of circuits: timing, tuning, calibration, and so forth. The most common form of adjustment involves the variation of the effective permeability of the magnetic path. In a circuit comprising an inductor and capacitor, the slug-tuned coil may be preferred over capacitive tuning in an environment with high humidity. Whereas the conventional variable capacitor is difficult and expensive to seal against the entry of humidity, the inductor lends itself to sealing without seriously inhibiting its adjustability. For example, a slug-tuned solenoid can be encapsulated, with a cavity left in the center to permit adjustment of the inductance with a magnetic core. Moisture will have little or no effect on the electrical performance of the core. The solenoid inductor using a variable magnetic core is the most common form of adjustable inductor. The closer the magnetic material is to the coil (the thinner the coil form), the greater the adjustment range will be. Simultaneous adjustment of both a magnetic core and magnetic sleeve will increase the tuning range and provide magnetic shielding. In another form, the air gap at the center post of a cup core can be varied to control inductance. Not only is the result a variable inductor, but also the introduction of the air gap provides a means for improving the temperature coefficient of the magnetic core by reducing its effective permeability.

Power Transformers

Electronic power transformers normally operate at a fixed frequency. Popular frequencies are 50, 60, and 400 Hz. Characteristics and designs are usually determined by the voltampere (VA) rating and the load. For example, when used with a rectifier, the peak inverse voltage across the rectifier will dictate the insulation requirements. With capacitor input filters, the secondary must be capable of carrying higher currents than with choke input filters. There are a number of ways by which the size and weight of power transformers can be reduced, as follows:

Operating frequency. For a given voltampere rating, size and weight can be reduced as some inverse function of the operating frequency.

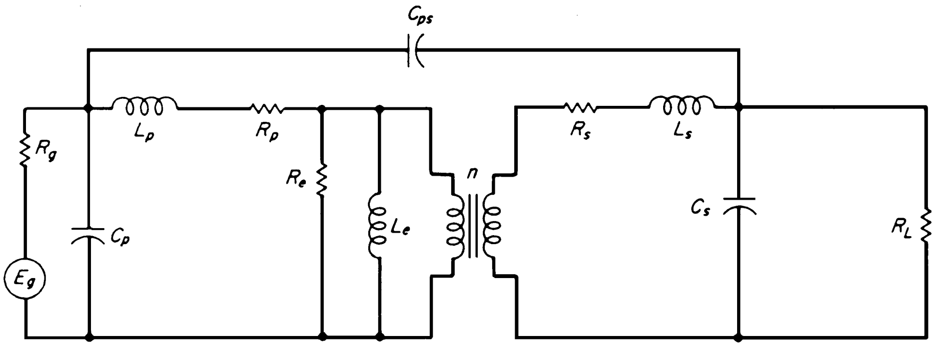

FIGURE 5.1.4 Equivalent circuit of a broadband transformer; E_g = generator voltage, R_g = generator impedance, C_p = primary shunt and distributed capacitance, L_p = primary leakage inductance, L_s = secondary leakage inductance, C_s = secondary shunt and distributed capacitance, R_p = primary winding resistance, R_e = equivalent resistance corresponding to core losses, L_e = equivalent magnetizing (open-circuit) inductance of primary, n = ideal transformer primary-to-secondary turns ratio, C_{ps} = primary-to-secondary capacitance (interwinding capacitance), R_s = secondary winding resistance, R_L = load impedance.

Maximum operating temperature. By the use of high-temperature materials and at a given VA rating and ambient temperature, considerable size reduction can be realized by designing for an increased temperature rise.

Ambient temperature. With a given temperature rise and for a fixed VA rating, transformer size can be reduced if the ambient temperature is lowered.

Regulation. If the regulation requirements are made less stringent, the wire size of the windings can be reduced, with a consequent reduction in the size of the transformer.

Audio Transformers

These transformers are used for voltage, current, and impedance transformation over a nominal frequency range of 20 to 20,000 Hz. The equivalent circuit (Fig. 5.1.4) is the starting point for the basic analysis of the transformer frequency response.

A prime consideration in the design, size, and cost of audio transformers is the span of the frequency response. In wide-band audio transformers the frequency coverage can be separated into three nearly independent ranges for the purpose of analysis. Thus, in the high-frequency range leakage inductance and distributed capacitance are most significant. In the low-frequency region the open-circuit inductance is important. At the medium-frequency range, approximately 1000 Hz, the effect of the transformer on the frequency response can be neglected. In the above discussion, the transformation is assumed to be that of an ideal transformer.

Miniaturized Audio Transformers

Frequency Response. The high-frequency response is dependent on the magnitude of the leakage inductance and distributed capacitance of the windings. These parameters decrease as the transformer size decreases. Consequently, miniaturized audio transformers generally have an excellent high-frequency response. On the other hand, the small size of these transformers results in increased loss and in a degradation of the low-frequency response, which is dependent on the primary open-circuit inductance.

Air Gap. The primary open-circuit inductance is proportional to the product of the square of the turns and the core area, and inversely proportional to the width of the gap. As the transformer size is reduced, both the core area and number of turns must be reduced. Consequently, if the open-circuit inductance is to be maintained, the air gap must be reduced. A butt joint has of necessity a finite air gap; as a result the full ungapped inductance is not realized. An interlaced structure of the core, where the butt joints for each lamination are staggered, most closely approximates an ungapped core. A substantially higher inductance, 120 H, is possible.

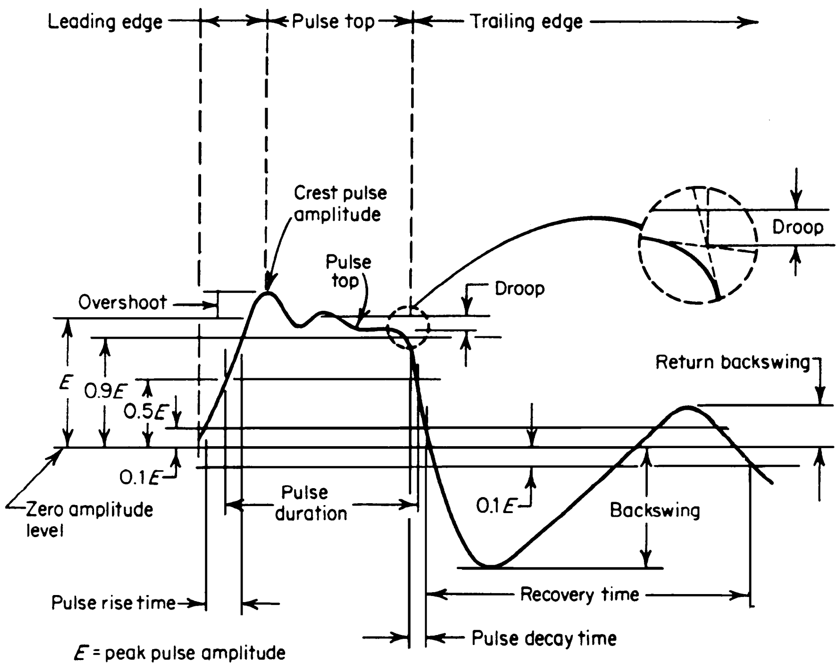

FIGURE 5.1.5 Pulse waveform.

The problem with taking advantage of this effect is that as the air gap is reduced, the allowable amount of unbalanced direct current flowing in the transformer winding must be lowered to prevent core saturation.

Pulse Transformers

Pulse transformers for high-voltage or high-power applications, above 300 W peak, are used in modulators for radar sets. Their function is to provide impedance matching between the pulse-forming network and the magnetron. Prime concern is transformation of the pulse with a minimum of distortion. Lower-power pulse transformers fall into two categories: those used for coupling or impedance matching similar to the high-power pulse transformers, and blocking oscillator transformers used in pulse-generating circuits. Pulse widths for such transformers most commonly range from about 0.1 to 20 μs.

Assuming the pulse transformer is properly matched and the source is delivering an ideal rectangular pulse, a well-designed transformer should have small values of leakage inductance and distributed capacitance. Within limits dictated by pulse decay time the open-circuit inductance should be high. Figure 5.1.5 shows the pulse waveform with the various types of distortions that may be introduced by the transformer.

Broadband RF Transformers

At the higher frequencies, transformers provide a simple, low-cost, and compact means for impedance transformation. Bifilar windings and powdered-iron or ferrite cores provide optimum coupling. The use of cores with high permeabilities at the lower frequencies reduces the number of turns and distributed capacitance. At the upper frequencies the reactance increases, even though the permeability of the core may fall off.

Inductive Coupling

There are a variety of ways to use inductive elements for impedance-matching or coupling one circuit to another. Autotransformers and multiwinding transformers that have no common metallic connections are a common method of inductive coupling. In a unity-coupled transformer, N_1 = number of primary turns, N_2 = number of

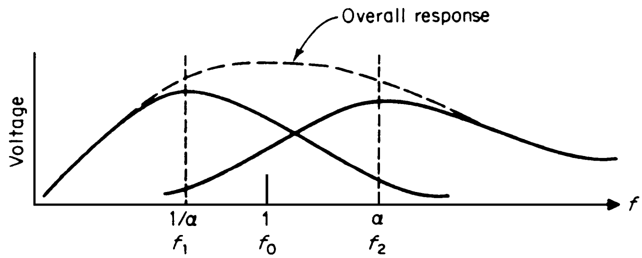

FIGURE 5.1.6 Response of a staggered pair, geometric symmetry.

secondary turns, k = coefficient of coupling, M = mutual inductance, n = turns ratio, L_1 = primary open-circuit inductance, L_2 = secondary open-circuit inductance, I_1 = primary current, I_2 = secondary current, E_1 = primary voltage, E_2 = secondary voltage, Z_1 = primary impedance with matched secondary, Z_2 = secondary impedance with matched primary. Transformer relationships for unity-coupled transformer, $k = 1$, assuming losses are negligible:

$$n = N_2/N_1 = E_2/E_1 = I_2/I_1 = Z_2/Z_1 \qquad M = \sqrt{L_1 L_2}$$

Single-Tuned Circuits

Single-tuned circuits are most commonly used in both wide-band and narrow-band amplifiers. Multiple stages that are cascaded and tuned to the same frequency are synchronously tuned. The result is that the overall bandwidth of the cascaded amplifiers is always narrower than the single-stage bandwidth. The shrinkage of bandwidth can be avoided by stagger tuning. A stagger-tuned system is a grouping of single-tuned circuits where each circuit is tuned to a different frequency. For a flat-topped response the individual stages are geometrically balanced from the center frequency. In Fig. 5.1.6, which illustrates the response of a staggered pair, f_0 = center frequency of overall response, and f_1, f_2 = resonant frequency of each stage. The frequencies are related as follows:

$$f_0/f_1 = f_2/f_0 = \alpha$$

Double-Tuned Transformers

One of the most widely used circuit configurations for i.f. systems in the frequency range of 250 kHz to 50 MHz is the double-tuned transformer. It consists of a primary and secondary tuned to the same frequency and coupled inductively to a degree dependent on the desired shape of the selectivity curve. Figure 5.1.7 shows the variation of secondary current versus frequency.

Bandwidth

A comparison of the relative 3-dB bandwidth of multistage single- and double-tuned circuits is shown in Table 5.1.2. Most significant is the lower skirt ratio of the double-tuned circuit, i.e., relative value of the ratio of the bandwidth at 60 dB (BW_{60}) to the bandwidth at 6 dB (BW_6).

POLED FERROELECTRIC CERAMIC DEVICES

Joseph M. Giannotti

Introduction

The usefulness of ferroelectrics rests on two important characteristics, asymmetry and high dielectric constant. Poled ferroelectric devices are capable of doing electric work when driven mechanically or mechanical work

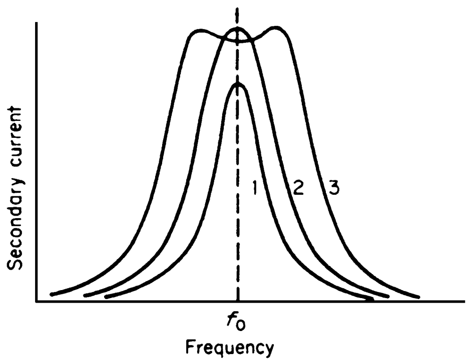

FIGURE 5.1.7 Variation of secondary current and gain with frequency and with degree of coupling: 1 = undercoupled; 2 = critically coupled; 3 = overcoupled.

when driven electrically. In poled ferroelectrics, the piezoelectric effect is particularly strong. From the design standpoint, they are especially versatile because they can be used in a variety of ceramic shapes. Piezoelectricity is the phenomenon of coupling between elastic and dielectric energy. Piezoelectric ceramics have gained wide use in the low-frequency range up to a few megahertz over the strongly piezoelectric nonferroelectric single crystals such as quartz, lithium sulfate, lithium niobate, lithium tantalate, and zinc oxide. High dielectric strength and low manufacturing cost are prime factors for their usefulness.

The magnitude and character of the piezoelectric effect in a ferroelectric material depend on orientation of applied force or electric field with respect to the axis of the material. With piezoelectric ceramics, the polar axis is parallel to the original dc polarizing field. In all cases the deformations are small when amplification by mechanical resonance is not involved. Maximum strains with the best piezoelectric ceramics are in the range of 10^{-3}. Figure 5.1.8 illustrates the basic deformations of piezoelectric ceramics and typical applications.

Transducers

The use of barium titanate as a piezoelectric transducer material has been increasingly replaced by lead titanate zirconate solid-solution ceramics since the latter offer higher piezoelectric coupling, wider operating temperature range, and a choice of useful variations in engineering parameters. Table 5.1.3 gives the characteristics of different compositions.

The high piezoelectric coupling and permittivity of PZT-5H have led to its use in acoustic devices where its high electric and dielectric losses can be tolerated. For hydrophones or instrument applications PZT-5A is a better choice, since its higher Curie point leads to better temperature stability. The low elastic and dielectric losses of PZT-8 composition at high drive level point to its use in high-power sonic or ultrasonic transducers. The very low mechanical *Q* of lead metaniobate has encouraged its use in ultrasonic flaw detection, where the low *Q* helps the suppression of ringing. The high acoustic velocity of sodium potassium niobate is of advantage in high-frequency thickness-extensional thickness-shear transducers, since this allows greater thickness and therefore lower capacitance.

Since ceramic materials can be fabricated in a wide range of sizes and shapes, they lend themselves to designs for applications that would be difficult to achieve with single crystals. Figure 5.1.9 illustrates the use

TABLE 5.1.2 Relative Values of 3-dB Bandwidth for Single- and Double-Tuned Circuits

	Relative values of 3-dB bandwidth		Relative values of BW_{60}/BW_6	
No. of stages	Single-tuned	Double-tuned*	Single-tuned	Double-tuned
1	1.00	1.00	577	23.9
2	0.64	0.80	33	5.65
3	0.51	0.71	13	3.59
4	0.44	0.66	8.6	2.94
6	0.35	0.59	5.9	2.43
8	0.30	0.55	5.0	
10	0.27	0.52	4.5	

*Based on identical primary and secondary circuits critically coupled.

of simple piezoelectric elements in a high-voltage source capable of generating an open-circuit voltage of approximately 40 kV. Piezoelectric accelerometers suitable for measuring vibrating accelerations over a wide frequency range are readily available in numerous shapes and sizes. Figure 5.1.10 shows a typical underwater transducer, which uses a hollow ceramic cylinder polarized through the wall thickness. Flexing-type piezoelectric elements can handle larger motions and smaller forces than single plates.

Resonators and Filters

The development of temperature-stable filter ceramics has spurred the development of ceramic resonators and filters. These devices include simple resonators, multielectrode resonators, and cascaded combinations thereof,

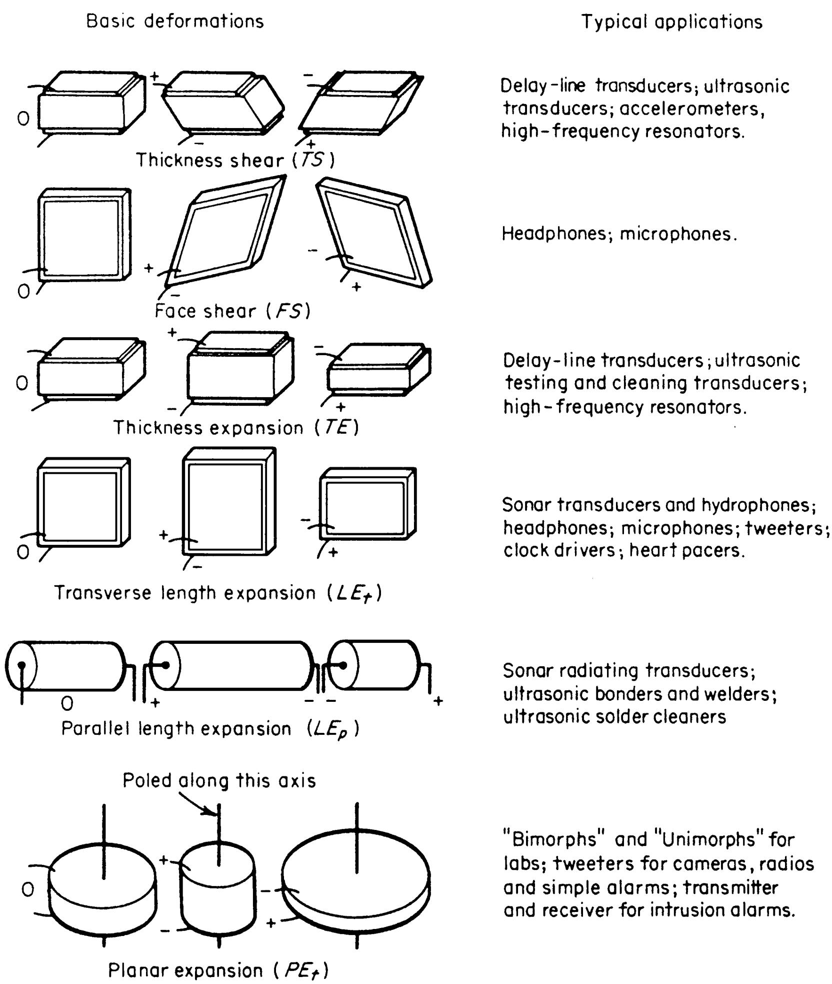

FIGURE 5.1.8 Basic piezoelectric action depends on the type of material used and the geometry. Generally, two or more of these actions are present simultaneously. TE and TS are high-frequency (greater than 1 MHz) modes and FS, LE_t, LE_p, and PE_t are low-frequency (less than 1 MHz) modes. The thickness controls the resonant frequency for the TE and TS modes, the diameter for PE_t, and the length for the LE_t and LE_p modes.

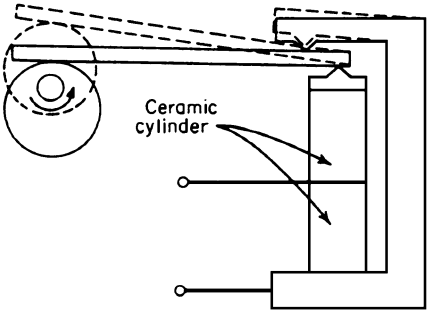

FIGURE 5.1.9 High-voltage generator.

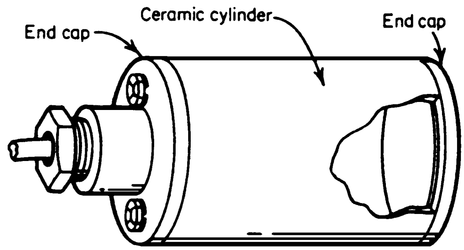

FIGURE 5.1.10 Underwater sound transducer.

mechanically coupled pairs of resonators, and ceramic ladder filters, covering a frequency range from 50 Hz to 10 MHz.

Two lead titanate-zirconate compositions, PZT-6A and PZT-6B ceramics, are most widely used for resonator and filter applications. PZT-6A, having high electromechanical coupling coefficient (45 percent) and moderate mechanical Q (400), is used for medium to wide bandwidth applications, while PZT-6B, with moderate coupling (21 percent) and higher Q (1500), is used for narrow bandwidths. The compositions exhibit a frequency constant stable to within ± 0.1 percent over a temperature range from –40 to +85°C. The frequency characteristics increase slowly with time at less than 0.1 percent per decade of time.

Ceramic Resonators

A thin ceramic disk with fully electroded faces, polarized in its thickness direction, has its lowest excitable resonance in the fundamental radial mode. The impedance response of such a disk and its equivalent circuit are shown in Fig. 5.1.11.

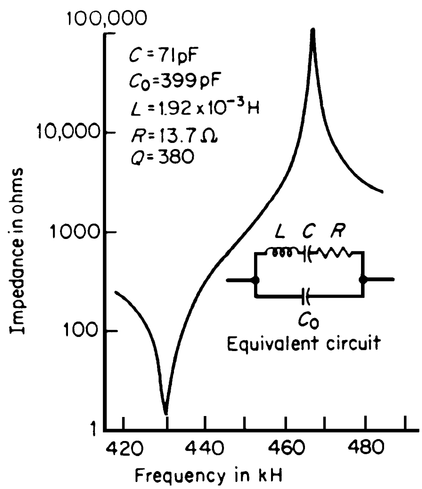

FIGURE 5.1.11 Impedance response of a fundamental radial resonator.

TABLE 5.1.3 Ceramic Compositions

	k_{33}	k_p	$\epsilon_{33}^T/\epsilon_0$	Change in N_1 –60 to +85°C, %	Change in N_1 per time decade, %
PZT-4	0.70	0.58	1,300	4.8	+1.5
PZT-5A	0.705	0.60	1,700	2.6	+0.2
PZT-5H	0.75	0.65	3,400	9.0	+0.25
PZT-6A	0.54	0.42	1,050	<0.2	<0.1
PZT-8	0.62	0.50	1,000	2.0	+1.0
$Na_{0.5}K_{0.5}NbO_3$	0.605	0.46	500	?	?
$PbNb_2O_6$	0.38	0.07	225	3.3	?

k_{33} = coupling constant for longitudinal mode.
k_p = coupling constant for radial mode.
ϵ_{33}^T = permittivity parallel to poling field, stress-free condition.
N_1 = frequency constant (resonance frequency × length).

Ceramic resonators can be used in various configurations for single-frequency applications or combined in basic L-sections to form complete bandpass filter networks.

QUARTZ CRYSTAL DEVICES

John R. Vig

Introduction

Piezoelectric crystal devices are used primarily for frequency control, timing, transducers, and delay lines. The piezoelectric material used for most applications is quartz. A quartz crystal acts as a stable mechanical resonator, which, by its piezoelectric behavior and high Q, determines the frequency generated in an oscillator circuit. Bulk-wave resonators are available in the frequency range from about 1 kHz to 300 MHz. Surface-acoustic-wave (SAW) and shallow-bulk-acoustic-wave devices can be made to operate at well above 1 GHz.

In the manufacture of the different types of quartz resonators, wafers are cut from the mother crystal along precisely controlled directions with respect to the crystallographic axes. The properties of the device depend strongly on the angles of cut. After shaping to required dimensions, metal electrodes are applied to the quartz wafer, which is mounted in a holder structure. The assembly, called a *crystal unit* (or *crystal* or *resonator*) is usually sealed hermetically in partial- to ultrahigh-vacuum.

To cover the wide range of frequencies, different cuts, vibrating in a variety of modes, are used. Above 1 MHz, the AT cut is commonly used. For high-precision applications, the SC cut has important advantages over the AT and the occasionally used BT cuts. AT-, BT-, and SC-cut crystals can be manufactured for fundamental-mode operation at frequencies up to about 100 MHz. Above 40 MHz, *overtone* crystals are generally used. Such crystals operate at a selected odd harmonic mode of vibration. AT-, BT-, and SC-cut crystals vibrate in the thickness shear mode. Below 1 MHz, tuning forks, X-Y and NT bars (flexure mode), +5° X cuts (extensional mode), or CT and DT cuts (face shear mode) can be used. Over 200 million 32.8-kHz tuning-fork crystals are produced annually for the world watch market.

Equivalent Circuit

The circuit designer treats the behavior of a quartz crystal unit by considering its equivalent circuit (Fig. 5.1.12). The mechanical resonance in the crystal is represented by L_1, C_1, and R_1. Because it is a dielectric with electrodes, the device also displays an electrical capacitance C_0. The parallel combination of C_0 and the motional arm, C_1-L_1-R_1, represents the equivalent circuit to a good approximation. As shown in Fig. 5.1.12*b*, the reactance of this circuit varies with frequency.

The Q values ($Q^{-1} = 2\pi f_s R_1 C_1$) of quartz-crystal units are much higher than those attainable with other circuit elements. In general-purpose units, the Q is usually in the range of 10^4 to 10^6. The intrinsic Q of quartz is limited by internal losses. For AT-cut crystals, the intrinsic Q has been experimentally determined to be 16×10^6 at 1 MHz; it is inversely proportional to frequency. At 5 MHz, for example, the intrinsic Q is 3.2×10^6.

Oscillators

The commonly used crystal oscillator circuits fall into two broad categories. In series-resonance oscillators, the crystal operates at series resonance, i.e., at f_s. In parallel-resonance or antiresonance oscillators, the crystal is used as a positive reactance; i.e., the frequency is between f_s and f_A. In this latter mode of operation the oscillator circuit provides a load capacity to the crystal unit. The oscillator then operates at the frequency where the crystal unit's reactance cancels the reactance of the load capacitor. When the load capacitance is changed, the oscillator frequency changes. An important parameter in this connection is the capacitance ratio $r = C_0/C_1$. Typically, the value of r is a few hundred for fundamental-mode crystals. It is larger by a factor of n^2 for nth-overtone crystals.

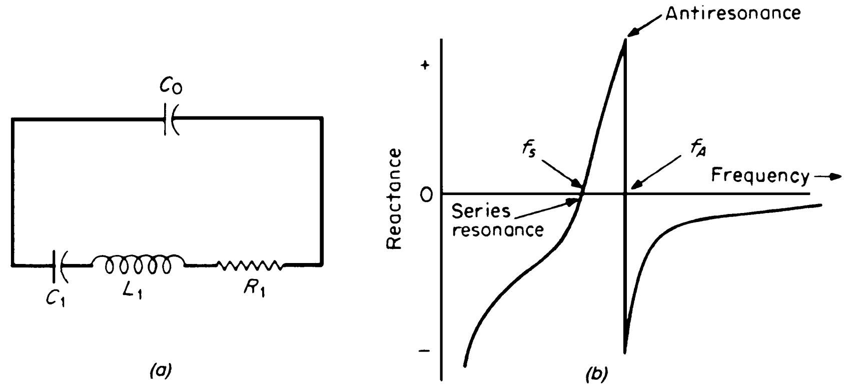

FIGURE 5.1.12 (*a*) Equivalent circuit and (*b*) frequency-reactance relationship.

When a load capacitor C_L is connected in series with a crystal, the series-resonance frequency of the combination is shifted from f_s by Δf, which is related to the other parameters by

$$\frac{\Delta f}{f_s} \approx \frac{C_0}{2r(C_0 + C_L)}$$

For a typical fundamental-mode AT-cut crystal unit with $r = 250$, $C_0 = 5$ pF, and $C_L = 30$ pF, the shift is 286 ppm. If such a crystal unit is to remain stable to, for example, 1×10^{-9}, the load reactance owing to C_L and the other circuit components must remain stable to within 1.2×10^{-4} pF. The frequency can also be "tuned" by intentionally changing C_L. For the above example, a change of 1 pF in C_L shifts the frequency by nearly 10 ppm.

Filters

Quartz crystals are used as selective components in crystal filters. With the constraint imposed by the equivalent circuit of Fig. 5.1.12*a*, filter design techniques can provide bandpass or bandstop filters with prescribed characteristics. Crystal filters exhibit low insertion loss, high selectivity, and excellent temperature stability.

Filter crystals are designed to have only one strong resonance in the region of operation, with all other responses (unwanted modes) attenuated as much as possible. The application of energy-trapping theory can provide such a response. If electrode size and thickness are selected in accordance with that theory, the energy of the main response is trapped between the electrodes, whereas the unwanted modes are untrapped and propagate toward the edge of the crystal resonator, where their energy is dissipated. It is possible to manufacture AT-cut filter crystals with greater than 40-dB attenuation of the unwanted modes relative to the main response.

Transducers

Whereas in frequency control and timing applications of quartz-crystal devices the devices are designed to be as insensitive to the environment as possible, quartz crystals can also be designed intentionally to be highly sensitive to environmental parameters such as temperature, mass changes, pressure, force, and acceleration. Quartz-crystal transducers can exhibit unsurpassed resolution and dynamic range. For example, one commercial "quartz pressure gage" exhibits a 1 ppm resolution, i.e., 60 Pa at 76 MPa (0.01 lb/in^2 at 11,000 lb/in^2), and a 0.025 percent full-scale accuracy. Quartz thermometers can provide millidegrees of absolute accuracy over wide temperature ranges. Quartz sorption detectors can detect a change in mass of 10^{-12} g. Quartz accelerometer/force sensors are capable of resolving 10^{-7} to 10^{-8} of full scale.

Standardization

Standardization exists concerning dimensions and performance characteristics of crystal units and oscillators. The principal documents are the U.S. military standards, the standards issued by the Electronics Industry Association (EIA) and by the International Electrotechnical Commission (IEC).

Temperature

The frequency versus temperature characteristics are determined primarily by the angles of cut of the crystal plates with respect to the crystallographic axes of quartz. Typical characteristics are shown in Figs. 5.1.13 and 5.1.14. The points of zero temperature coefficient, the *turnover points*, can be varied over a wide range by varying the angles of cut.

The frequency-temperature characteristic of AT- and SC-cut crystals follow a third-order law, as shown in Fig. 5.1.13 for the AT cut. A slight change in the orientation angle (7 min in the example shown in Fig. 5.1.13) greatly changes the frequency-temperature characteristic. Curve 1 is optimal for a wide temperature range (–55 to 105°C). Curve 2 gives minimum frequency deviation over a narrow range near the inflection temperature T_i. The frequency versus temperature characteristics of SC-cut crystals is similar to the curves shown in Fig. 5.1.13 except that T_i is shifted to about 95°C. The SC cut is a doubly rotated cut; i.e., two angles must be specified and precisely controlled during the manufacturing process. The SC cut is more difficult to manufacture with predictable frequency versus temperature characteristics than are the singly rotated cuts, such as AT and BT

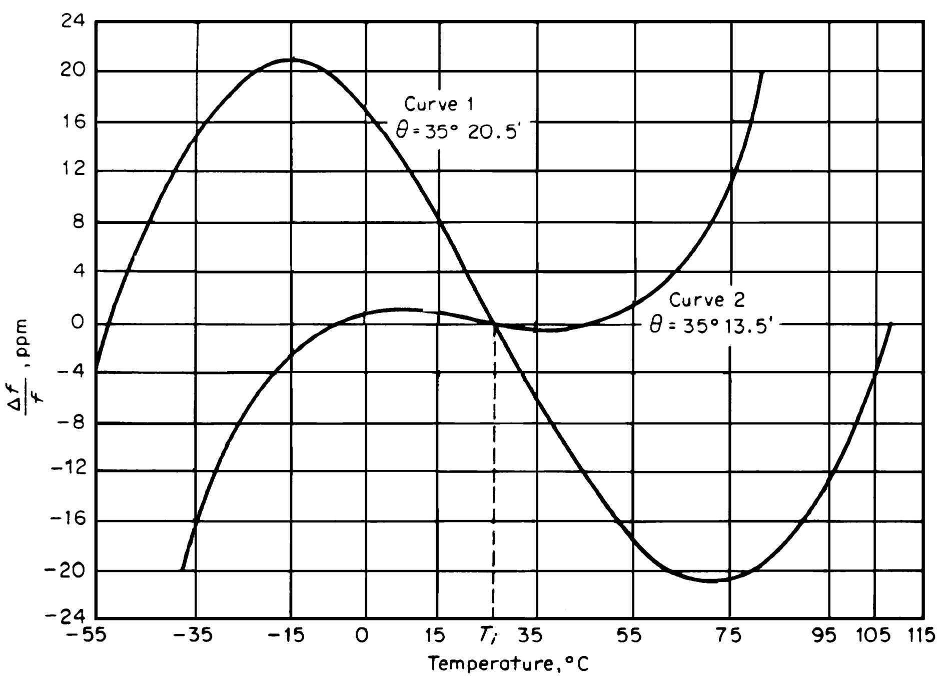

FIGURE 5.1.13 Frequency-temperature characteristics of AT-cut crystals.

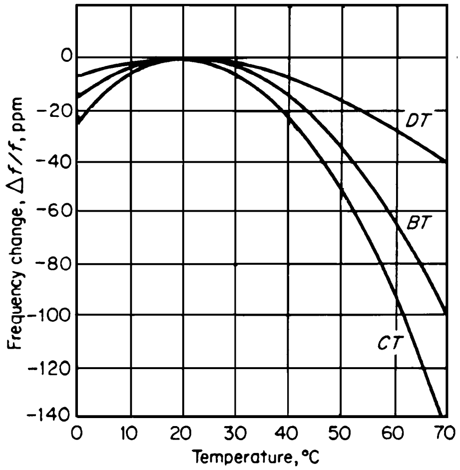

FIGURE 5.1.14 Parabolic frequency-temperature characteristic of some crystal cuts.

cuts. Many of the crystal cuts have a parabolic frequency versus temperature characteristic, as shown in Fig. 5.1.14 for the BT, CT, and DT cuts. The turnover temperatures of these cuts can also be shifted up or down by changing the angles of cut.

To achieve the highest stability, oven-controlled crystal oscillators (OCXO) are used. In such oscillators, the crystal unit and the temperature-sensitive components of the oscillator are placed in a stable oven the temperature of which is set to the crystal's turnover temperature. OCXOs are bulkier and consume more power than other types. In addition, when an oven-controlled oscillator is turned on, one must wait several minutes for the oscillator to stabilize. During warm-up, the thermal stresses in the crystal can produce significant frequency shifts. This thermal-transient effect causes the typical warm-up time of an oscillator to be several minutes longer than the time it takes for the oven to stabilize. The thermal-transient effect is absent in SC-cut crystals. In oscillators which use SC-cut crystals, the warm-up time can be much shorter.

In temperature-compensated crystal oscillators (TCXOs) the crystal's frequency versus temperature behavior is compensated by varying a load capacitor. The output signal from a temperature sensor, e.g., a thermistor network, is used to generate the correction voltage applied to a varactor. Digital techniques are capable of providing better than 1×10^{-7} frequency stability from –55 to +85°C. TCXOs are smaller, consume less power than OCXOs and require no lengthy warm-up times. A major limitation on the stabilities achievable with TCXOs is the thermal hysteresis exhibited by crystal units.

Aging

Aging, the gradual change in a crystal's frequency with time, can be a result of several causes. The main causes are mass transfer to or from the resonator surfaces (owing to adsorption and desorption of contamination) and stress relief within the mounting structure or at the interface between the quartz and the electrodes. The observed aging is the sum of the aging produced by the various mechanisms and may be positive or negative. Aging is also sometimes referred to as *drift* or *long-term stability*.

The aging rate of a crystal unit is highest when it is new. As time elapses, stabilization occurs within the unit and the aging rate decreases. The aging observed at constant temperature usually follows an approximately logarithmic dependance on time. When the temperature of a crystal is changed, a new aging cycle starts.

A major reason for the aging of low-frequency units (below 1 MHz) is that mechanical changes take place in the mounting structure. Properly made units may age several ppm/year, half that aging occurring within the first 30 days. Crystal units for frequencies of 1 MHz and above age primarily because of mass transfer. General-purpose crystal units are usually housed in solder-sealed or resistance-welded material enclosures of the HC-6 or HC-18 configuration that are filled with dry nitrogen. The aging rate of such units is typically specified as 5 ppm for the first month: over a year's time their aging may be from 10 to 60 ppm. Higher-quality general-purpose crystals may age as little as 1 ppm per year. If a lower aging rate is desired, overtone crystals in clean glass, metal, or ceramic enclosures should be used. Advanced surface-cleaning, packaging, and ultrahigh-vacuum fabrication techniques have resulted in units that age less than 5×10^{-11} per day after a few days of stabilization, or $<1 \times 10^{-8}$ per year.

Short-Term Stability

Short-term stability, or "noise," in the time domain $\sigma(\tau)$ is usually expressed as the 2-sample deviation of the fractional frequency fluctuations for a specified averaging time. The averaging times τ over which $\sigma(\tau)$ is specified generally range from 10^{-3} to 10^3 s. For a good oscillator, $\sigma(\tau)$ may range from 1×10^{-9} for $\tau = 10^{-3}$ s to 5×10^{-13} for $\tau = 1$ s to 1×10^{-12} for up to 10^3 s. For $\tau > 10^3$ s, the stability is usually referred to as *long-term stability* or aging. For $\tau < 1$ s, the short-term instabilities are generally attributed to noise in the oscillator circuitry although the crystal itself can also be a significant contributor.

When measured in the frequency domain, short-term stability is denoted by $S_\phi(f)$ or $S_y(f)$, the spectral density of phase fluctuations and frequency fluctuations, respectively, at a frequency separation f from the carrier frequency ν. £(f), the single-sideband phase noise, is also used in reporting the frequency-domain stability. The three quantities are related by $f^2 S_\phi(f) = \nu^2 S_y(f) = 2f^2$ £(f). For a low-noise 5-MHz oscillator, £(f) may be –115 dB(c) at 1 Hz from the carrier, and –160 dB(c) at 1 kHz from the carrier.

Thermal Hysteresis

When the temperature of a crystal unit is changed and then returned to its original value, the frequency will generally not return to its original value. This phenomenon, called *thermal hysteresis* or lack of *retrace*, can be caused by the same mechanisms as aging, i.e., mass transfer because of contamination and stress relief.

For a given crystal unit, the magnitude of the effect depends on the magnitude and direction of the temperature excursion, on the thermal history of the unit, and on the design and construction of both the crystal unit and the oscillator circuit. The effect tends to be smaller in OXCOs, where the operating temperature of the crystal is always approached from below, than in TCXOs, where the operating temperature can be approached from either direction. Thermal hysteresis can be minimized through the use of clean, ultrahigh-vacuum fabrication techniques (which minimize the mass-transfer contribution) and through the use of properly mounted SC-cut crystals (which minimize the stress-relief contributions). The magnitude of the effect typically ranges from several ppm in general-purpose crystals to less than 1×10^{-9} in high-stability crystals operated in OXCOs.

Drive Level

The amplitude of vibration is proportional to the current through a crystal. Because of the nonlinearities of quartz, the frequency of a crystal and the incidence of interfering modes are functions of the drive level. The drive level must be stated when a crystal's parameters are specified. The oscillator designer's ability to improve signal-to-noise ratios by using a higher drive level is limited. In SC-cut crystals, the drive level effects are significantly below those observed in AT- and BT-cut units. When the drive level is increased, the frequency of AT- and SC-cut crystals increases and the frequency of the BT-cut crystal decreases.

Acceleration, Vibration, and Shock

The frequency of a crystal unit is affected by stresses. Even the acceleration owing to gravity produces measurable effects. When an oscillator using an AT-cut crystal is turned upside down, the frequency typically shifts about 4×10^{-9} because the acceleration sensitivity of the crystal is typically $2 \times 10^{-9}\ g^{-1}$. The sensitivity is the same when the crystal is subjected to vibration; i.e., the time-varying acceleration owing to the vibration modulates the frequency at the vibration frequency with an amplitude of $2 \times 10^{-9}\ g^{-1}$. In the frequency domain, the vibration sensitivity manifests itself as vibration-induced sidebands that appear at plus and minus the vibration frequency away from the carrier frequency. The acceleration sensitivity of SC-cut crystals can be made to be less than that of comparably fabricated AT- or BT-cut crystals.

Shock places a sudden stress on the crystal. During shock, the crystal's frequency changes because of the crystal's acceleration sensitivity. If during shock the elastic limits in the crystal's support structure or in its electrodes are exceeded, the shock can produce a permanent frequency change. Crystal units made with chemically polished crystal plates can withstand shocks in excess of 20,000g (11 ms, 1/2 sine). Such crystals have been successfully fired from howitzers.

Radiation

The degree to which high levels of ionizing radiation affect the frequency of a crystal unit depends primarily on the quality of quartz used to fabricate the device and on the dose. When crystals made of natural quartz are subjected to steady-state ionizing radiation, their frequencies are changed permanently by approximately a few parts in 10^{11} per rad at a 1 Mrad dose. To minimize the effect of such radiation, high-purity cultured quartz should be used. The frequency change per rad is higher at lower doses. Pulse irradiation produces a transient frequency shift because of the thermal-transient effect. This effect can be minimized by using SC-cut crystals. Energetic neutrons change a crystal's frequency by about 6×10^{-21} per neutron per cm^2.

INSULATORS

Sam Di Vita

Introduction

Ceramics and plastics are the principal materials for electronics insulation and mounting parts. Ceramic materials are outstanding in their resistance to high temperature, mechanical deformation, abrasion, chemical attack, electrical arc, and fungus attack. Ceramics also possess excellent electrical insulating properties and good thermal conductivity and are impervious to moisture and gases. These properties of ceramics are retained throughout a wide temperature range and are of particular importance in high-power applications such as vacuum-tube envelopes and spacers, rotor and end-plate supports for variable air capacitors, rf coil forms, cores for wire-wound resistors, ceramic-to-metal seals, and feed-through bushings for transformers.

The properties of plastics differ rather markedly from ceramics over a broad range. In a number of properties, plastics are more desirable than ceramics. These include lighter weight; better resistance to impact, shock, and vibration; higher transparency; and easier fabrication with molded-metal inserts (however, glass-bonded-mica ceramic material may be comparable with plastic in this latter respect).

Ceramic Linear Dielectric Insulators

Ceramic insulators are linear dielectrics having low loss characteristics, that are used primarily for coil forms, tube envelopes and bases, and bushings, which all require loss factors less than 0.035 when measured at standard laboratory conditions. Dielectric loss factor is the product of power factor and dielectric constant of a given ceramic. Military Specification MIL-I-10B, Insulating Compound Electrical, Ceramic Class L, covers low-dielectric-constant (12 or under) ceramic electrical insulating materials, for use over the spectrum of radio frequencies used in electronic communications and in allied electronic equipments. In this specification the "grade designators" are identified by three numbers, the first representing dielectric loss factor at 1MHz, the second dielectric strength, and the third flexural strength (modulus of rupture).

Table 5.1.4 lists the various types of ceramics and their grade designators approved for use in the fabrication of military standard ceramic radio insulators specified in MIL-I-23264A, insulators—ceramic, electrical and electronic, general specification for. This specification covers only those insulators characterized by combining the specific designators required for the appropriate military standard insulators used as standoff, feed-through, bushing, bowl, strain, pin, spreader, and other types of insulators.

Currently, Grade L-242 is typical of porcelain, L-422 of steatite, L-523 of glass, L-746 of alumina, L-442 of glass-bonded mica, and L-834 of beryllia.

High-Thermal-Shock-Resistant Ceramics

Lithia porcelain is the best thermal-shock-resistant ceramic because of its low (close to zero) coefficient of thermal expansion. It is followed in order by fused quartz, cordierite, high-silica glass, porcelain, steatite beryllium oxide, alumina, and glass-bonded mica. Those materials find wide use for rf coil forms, cores for wire-wound resistors, stator supports for air dielectric capacitors, coaxial cable insulators, standoff insulators, capacitor trimmer bases, tube sockets, relay spacers, and base plates for printed radio circuits.

High Thermal Conductivity

High-purity beryllium oxide is unique among homogeneous materials in possessing high thermal conductivity comparable with metal, together with excellent electrical insulating properties.

TABLE 5.1.4 Property Chart of Insulating Ceramic Materials Qualified under MIL-I-10

Class L ceramics	Grade designators	Power factor, 1 MHz	Dielectric constant, 1 MHz	Dielectric loss factor, 1 MHz	Dielectric strength, V/mil
Steatite:					
Unglazed	L-523	0.00069–0.0010	6.42+	0.0041–0.0063	230
Glazed	L-543	0.0008–0.0014		0.005–0.008	330
Porcelain:					
Glazed	L-232	0.0076–0.0099	5.42–6.01	0.041–0.059	249
Zircon:					
Unglazed	L-433	0.0012–0.0014	8.14–8.22	0.010–0.012	259
Glazed	L-413	0.00119	8.92	0.011	191
Alumina:					
Unglazed	L-746	0.0001–0.0008	8.14+	0.0009	500
Glass:					
Borosilicate (Pyrex)	L-622	0.00074	4.19	0.0031	226
High silica (Vycor)	L-541	0.0017	3.78	0.0065	363
Glass-bonded mica:					
Unglazed	L-442	0.0017–0.0018	7.08–7.44	0.012–0.013	382
Forsterite:					
Glazed	L–723	0.0003	6.37	0.002	200
Cordierite:					
Unglazed	L-321	0.0049	4.57	0.022	245
Wallastonite:					
Unglazed	L-621	0.0004	6.49	0.003	293
Berylia	L-834	0.00015	6	0.0009	295

Care must be exercised in the use of beryllium oxide because its dust is highly toxic. Although it is completely safe in dense ceramic form, any operation that generates dust, fumes, or vapors is potentially very dangerous.

Some typical uses of beryllium oxide are:

1. Heat sinks for high-power rf amplifying tubes, transistors, and other semiconductors
2. Printed-circuit bases
3. Antenna windows and tube envelopes
4. Substrates for vapor deposition of metals
5. Heat sinks for electronic chassis or subassemblies

Polycrystalline sintered diamond powder is also an excellent dielectric. It has the advantage of a thermal conductivity twice as good as copper and three to four times that of beryllia. It provides a cost-effective solution for critical heat sinks for high-power diodes and similar solid-state devices.

Plastic Insulators

The term *plastics* usually refers to a class of synthetic organic materials (resins) that are sold in finished form but at some stage in their processing are fluid enough to be shaped by application of heat and pressure. The two basic types of plastics are *thermoplastic resins*, which, like wax or tar, can be softened and resoftened repeatedly without undergoing a change in chemical composition, and *thermosetting resins*, which undergo a chemical change with application of heat and pressure and cannot be resoftened.

Choice of Plastics

Some of the differences between plastics that should be considered when defining specific needs are degree of stiffness or flexibility; useful temperature range; tensile, flexural, and impact strength; intensity, frequency, and duration of loads; electrical strength and dielectric losses; color retention under environment; stress-crack resistance over time; wear and scratch resistance; moisture and chemical resistance at high temperature; gas permeability; weather and sunlight resistance over time; odor, taste, and toxicity; and long-term creep properties under critical loads.

Reinforced Plastics

These comprise a distinct family of plastic materials that consist of superimposed layers of synthetic resin-impregnated or resin-coated filler. Fillers such as paper, cotton fabric, glass fabric or fiber, glass mats, nylon fabric—either in the form of sheets or macerated—are impregnated with a thermosetting resin (phenolic, melamine, polyester, epoxy, silicone). Heat and pressure fuse these materials into a dense, insoluble solid and nearly homogeneous mass, which may be fabricated in the form of sheets or rods or in molded form.