CERAMIC EMI FILTERS - A REVIEW

The discoidal feed-through capacitor, a unique configuration of a ceramic multilayer chip, is utilized as an EMI suppression device and as an element in EMI feed-through filter assemblies.

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Electromagnetic interference (EMI) can be defined as any electrical signal radiated or conducted into or out of electronic equipment, thus disrupting the normal operation of the equipment. It includes the frequency range of the entire electromagnetic spectrum, from direct current to the visible frequencies and can be either continuous or intermittent in nature.

Sources of continuous EMI can include, for example, automobile ignition systems, radio and TV transmitters, motors, computer clock oscillators, switching power supplies, ultrasonic equipment, and microwave devices. Intermittent EMI is produced by electrostatic discharges, lightning, switching on and off of inductive loads such as motors and welding machines, RF heating and soldering equipment and a category which has recently come under intense study, the detonation of nuclear weapons in the atmosphere.

The EMI propagation modes may be radiation, conduction, and any combination of the two. The various modes of propagation are illustrated in Figure 1. In the combination modes, the wires connecting various pieces of equipment act as receiving or transmitting antennas.

Electromagnetic interference can be suppressed and controlled by two basic techniques: shielding and filtering. In the shielding technique, the entire piece of equipment is enclosed in a tightly sealed metal or metallized plastic housing. This housing is then tied to ground by a solid, low resistance connection.

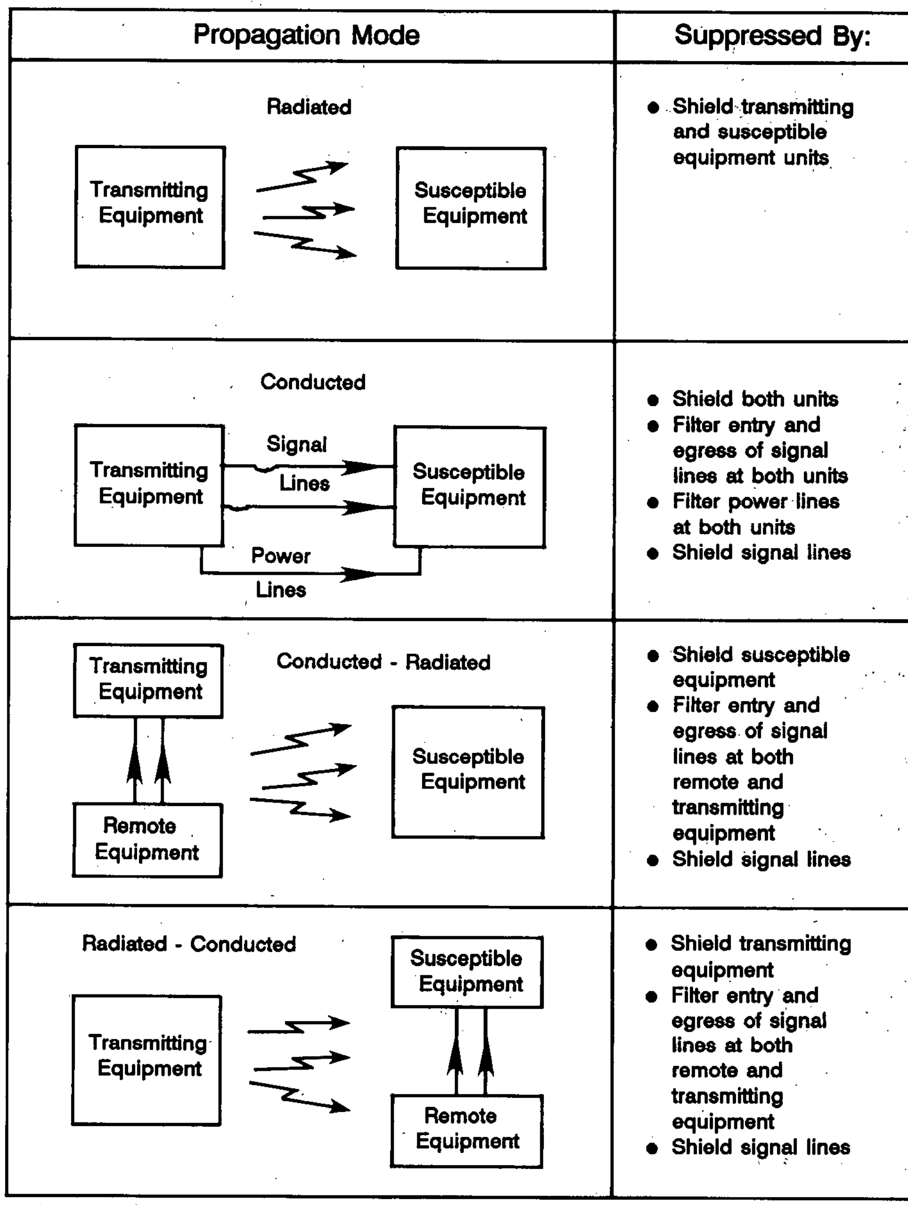

Figure 1. Propagation Modes For EMI.

In filtering, at all points of conductor (input and output signal and power lines) entry to or egress from the shielded container, a filter is installed in the line at the point of penetration of the shield. Filtering and shielding are commonly used in combination to optimize circuit performance.

Feed-through filters can vary in

complexity from a simple single element (a capacitor or inductor) to multi-element configuration obtaining three or more capacitors and inductors, depending on both the sensitivity of protected circuits to EMI and the nature of the interference.

CAPACITORS AS EMI FILTERS

Reactance (the ac equivalent of resistance) of a capacitor can be expressed as:

$$X_c = 1/2\pi f C \qquad (1)$$

where X_c is capacitive reactance in ohms, f is the frequency of the ac signal in hertz, and C is the capacitance in farads. Consequently, as frequency and capacitance increase, X_c of the circuit decreases. In the circuit diagram of Figure 2, as the frequency increases with switch S1 closed, the capacitor will present a lower and lower impedance path; and, therefore more of the signal will be shunted to ground through the capacitor.

If one measures the signal voltage with switch S1 open and then again with S1 closed, the following relationship exists:

$$V1 > V2 \qquad (2)$$

where V1 is measured with the capacitor not in the circuit and where V2 is measured with the capacitor in the circuit.

The suppression of signal or insertion loss is defined as:

$$IL(dB) = 20 \log_{10} V2/V1 \qquad (3)$$

where the insertion loss, IL, is expressed in decibels (dB). Insertion loss (IL), although precisely defined for both manufacturers and users of EMI filters by MIL-STD-220, is probably the most often misinterpreted term in the EMI filter industry. This term is frequently confused (and used interchangeably, although incor-

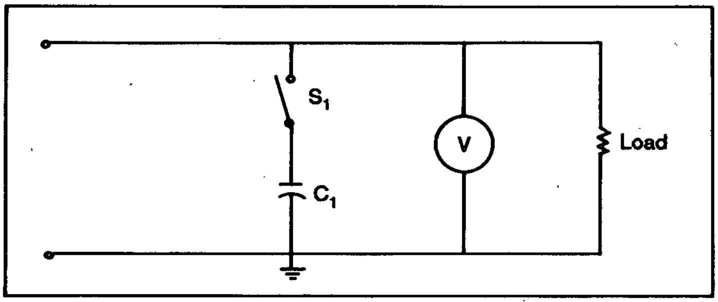

Figure 2. Capacitor as a Filter.

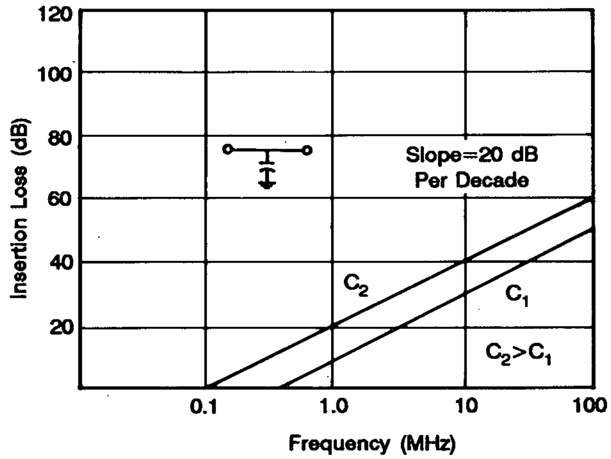

Figure 3. Attenuation of a Capacitor.

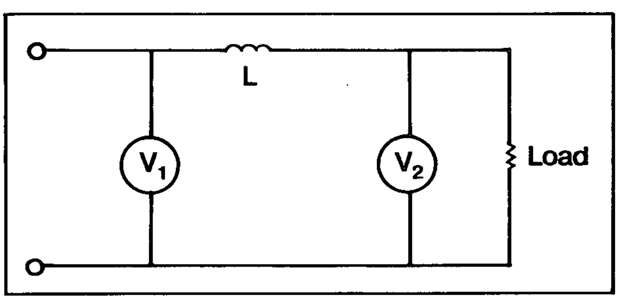

Figure 4. Inductor as a Filter.

rectly) with attenuation. A close comparison of the expressions for each term will make the difference quite obvious since it will produce different results. Insertion loss is measured in pure resistive 50Ω source and load impedance systems with filter out and in the place (Figure 2). On the other hand, attenuation is measured with the filter in place and the real world source and load impedances which are never 50Ω nor are they solely resistive (Figure 4).

If the insertion loss is measured as a function of frequency and is plotted on semilog paper, the slope of the curve will be 20 dB/decade of frequency (Figure 3). If the capacitance value in the circuit is changed from C1 to C2, the slope will remain the same; but the insertion loss at any frequency will decrease when C1 > C2. (See Figure 2.)

INDUCTORS AS EMI FILTERS

The reactance of an inductor can be expressed as:

$$X_L = 2\pi fL \qquad (4)$$

where X_L is the inductive reactance in ohms, f is the frequency in hertz, and L is the inductance in henries.

The inductive reactance is the ac analog of series resistance, and it can be seen that as the frequency and inductance increase, so does X_L.

In Figure 4, V1 > V2 and the suppression of the signal or insertion loss can be expressed as:

$$IL(dB) = 20 \log_{10} V2/V1 \qquad (5)$$

If a plot of insertion loss vs frequency is made on semilog paper, then, just as in the case for the capacitor, the slope will be ≈20 dB/decade of frequency (Figure 5). If the value of the inductor is changed, the insertion loss at any frequency will change; but the slope

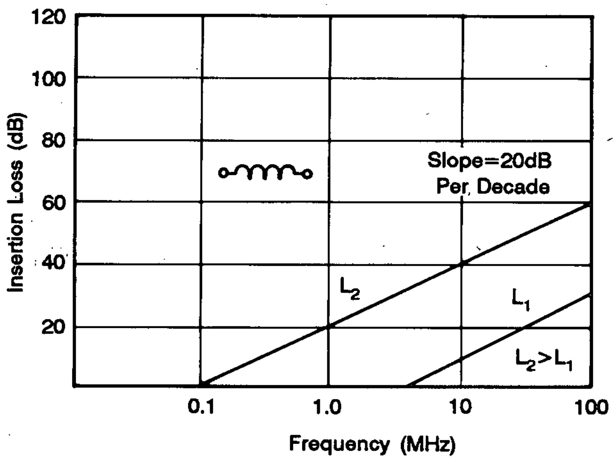

Figure 5. Attenuation of an Inductor.

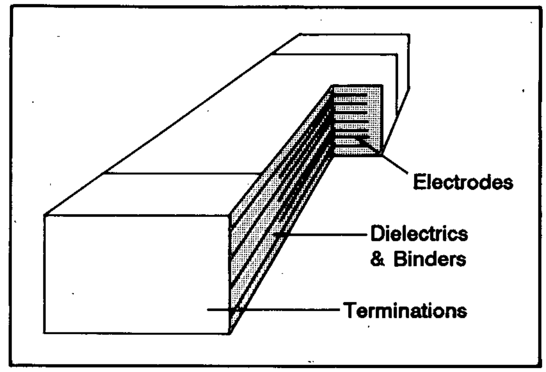

Figure 6. Cutaway View of a Chip Capacitor.

of the insertion loss vs frequency curve will remain constant at 20 dB/decade.

It can be seen that a single capacitor or inductor can be used to attenuate EMI by ≈20 dB/decade of frequency. Also capacitors and inductors can be used in combination to reduce EMI, and the suppression or insertion loss of combinations of these elements is additive, i.e., one capacitor and one inductor can be used to achieve 40 dB/decade of insertion loss. Three such components in the proper design can, therefore, result in 60 dB/decade suppression. These relationships will hold up to an upper value of insertion loss which occurs when the internal inductance and resistance of the capacitor and the series resistance and capacitance of the inductor produce a self-limiting effect. Depending on both the complexity of the filter and the component values, this ceiling will be between 70 and 120 dB for the EMI filters discussed.

DISCOIDAL MULTILAYER CERAMIC CAPACITORS

The multilayer ceramic capacitor has become the dominant capacitor in use by the electronics industry in the past decade. It is available as either a radially or axially leaded device. Unencapsulated and without leads, this passive component is known as a chip capacitor. Chip capacitors are monolithic, cofired sandwiches of alternating ceramic and metal layers (Figure 6). Each alternating conducting layer of metal is offset end-to-end, and layers of common polarity are connected with metallic terminations at each end of the capacitor (Figure 7). Since the capacitance of a dielectric is inversely proportional to thickness (Figure 8) and since capacitors sum in parallel (Figure 9), it can be concluded that multilayer ceramic capacitors have great volumetric efficiency (i.e., large capacitance in a small package). This characteristic, coupled with the reliability of ceramics and with the convenience of design for surface mounting applications, explains the popularity of the device.

A discoidal capacitor is a multilayer ceramic capacitor in the geometric configuration of a disk. Alternating conductor layers are offset and connected by the termination at the edge of the disk. The termination of the opposite polarity is made at a center hole. This configuration retains the volumetric efficiency and the reliability of the multilayer ceramic capacitor in a geometry which will be shown to be ideally suited to EMI filtering.

CHOICES OF MATERIALS

Multilayer ceramic capacitors are constructed of ceramic and metallic layers plus organic materials which are used solely to facilitate chip manufacture and which are eliminated during subsequent processing. Platinum, palladium, gold, silver, nickel, and copper are being or have been used to manufacture multilayer ceramic capacitors as part of the alternated conductive layers (electrodes) or the terminations. Capacitors suitable for the most common applications have been fabricated using these metals with adequate electronic performance. The choice of metallurgy of the electrode is generally determined by the chemistry of the cofired ceramic dielectric, but the choice of termination metals is determined primarily by the processes dictated by the user for installation of the capacitor in the circuit.

In specifying the electrical performance, then, the designer need only define the performance of the ceramic dielectric. In most cases, the user specifies both the expected capacitance of the device and the tolerance for change in capacitance from capacitor to capacitor over the operating temperature range of the circuit. Variance among capacitors is related primarily to the consistency of the manufacturing process.

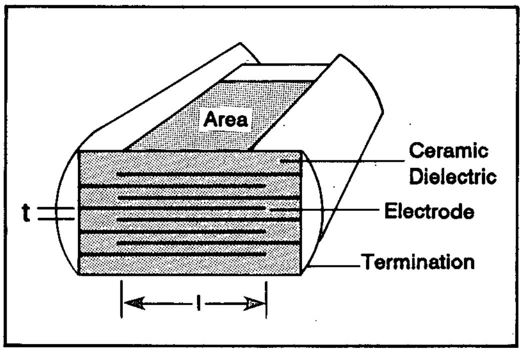

Figure 7. Cross-section of an MLC.

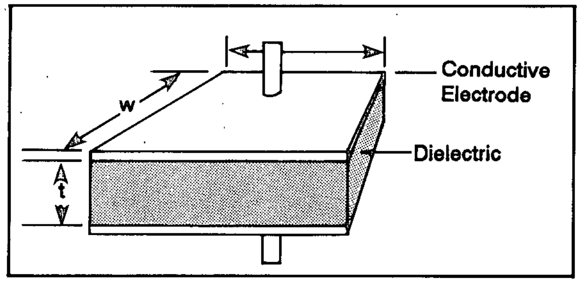

Figure 8. Definition of Capacitance.

Change in capacitance over the expected operating temperature range of the device is determined by the dielectric. Multilayer ceramic capacitors are generally available in three dielectrics: NPO (same as COG), X7R, and Z5U (sometimes Y5V). (These three-digit dielectric descriptions are specified by the Electronic Industries Association.)

Temperature stability of ceramic dielectrics is generally related to their dielectric constant (K). Some low K dielectrics are exceedingly stable, exhibiting <30 parts per million/°C change in capacitance over an operating temperature range from -55° to 125°C, i.e., maximum of $\approx$1% change over the entire temperature range. These dielectrics are specified as NPO ceramics and generally have a dielectric constant of $\leq$100.

X7R capacitors are designed for performance over the same temperature range as are those constructed of NPO dielectrics. However, this specification allows change in capacitance of $\pm$15% from nominal (a maximum of 30% change over the specified temperature range). The dielectric constant of X7R dielectrics can be as high as 3000.

Since the capacitance of a multilayer ceramic capacitor is directly proportional to the dielectric constant (Figure 8), it is apparent that the user can purchase $\approx$30 times as much capacitance in an X7R ceramic capacitor although 30 times the stability may be sacrificed.

The third dielectric, Z5U or sometimes Y5V, is designed solely for use at room temperature. Capacitance of these dielectrics can change as much as $\geq$50% as the operating temperature rises to 85°C. However, the dielectric constant of Z5U dielectrics can be $\geq$10,000 which allows the user to specify as much as 100 times the capacitance in Z5U as NPO in the same package. From the user's view, then, the choice of materials is based primarily on a tradeoff of capacitance volume efficiency and the variation in capacitance with the range of operating temperature of the device installed in a circuit.

SUMMARY

Ceramic EMI filters provide a superior solution to the problem of controlling EMI in advanced, high reliability, high performance electronic systems. The manufacturing technology for multilayer chip capacitors, which has evolved over the past 25 years, has been applied to the manufacture of discoidal multilayer ceramic capacitors. These unique capacitors provide the filter manufacturer with a spectrum of design capabilities and the ruggedness necessary to perform in a variety of hostile environments.

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