

DESIGN AND FABRICATION OF PLANAR INDUCTORS FOR INDUCTIVE PROXIMITY SENSORS

by

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(ABSTRACT)

Position sensing is one of the most important tasks in the industrial manufacturing of goods and materials. Position sensing can take on a variety of forms and is used in the measurement of a wide range of variables such as distance, speed, the number of revolutions per minute, orientation, identification, and in collision protection. Proximity sensors play a significant role and are used in a plethora of industries including agriculture, consumer goods, transportation, industrial processes, electrical services, medical, military and avionics.

This research is aimed at improving the performance and manufacturability of inductive proximity sensors through the design and fabrication of coils using multilayer ceramic technologies common in the manufacturing of hybrid microelectronics components and circuits. As another alternative, multilayer structures utilizing polymer materials and fabrication techniques common to the printed circuit board (PCB) industry were also investigated.

Manufacture of the coils utilizing ceramic and polymer materials and hybrid and PCB fabrication techniques would eliminate the problems of repeatability, and the placement and potting of the coil. The fabrication techniques also lend well to the mass production of the coils using techniques that are well established in the electronics industry. The overall result would be a planar inductor with high yield that is suitable for mass production.

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Chapter 1

Introduction

1.0 Introduction

Position sensing is one of the most important tasks in the industrial manufacturing of goods and materials. Position sensing can take on a variety of forms and is used in the measurement of a wide range of variables such as distance, speed, the number of revolutions per minute, orientation, identification, and in collision protection. Proximity sensors play a critical role and are used in a wide assortment of industries including agriculture, consumer goods, transportation, industrial processes, electrical services, medical, military and avionics.

Position sensing can be accomplished through a variety of means such as, inductive, Hall effect, electrodynamic, capacitive, and photoelectric proximity sensors. Each method of sensing operates on a different principle, therefore some work better in certain environments and are limited to use with specific materials. The purpose of this work was to enhance the performance of one type of position sensor; the inductive proximity sensor.

Inductive proximity sensors are used in a wide range of industrial applications and environmental conditions. Inductive proximity sensors are assembled with four major components; the core, coil, electronics and the housing that contains those components. The current coil design consists of wire, hand wound on a plastic bobbin, which is inserted into the ferrite core. The associated electronics are fabricated using

thick film or printed circuit board technology. The core and coil assembly is soldered to the electronics and the whole assembly is potted. This method of manufacturing introduces coils that sense differently due to variations in the way the coil is wound, number of turns on the bobbin, placement, and effects of potting. As a result each coil must be tested and in many cases tuned to achieve a performance that is within the manufacturer's specified tolerances. This method of manufacturing is labor intensive, not only in the production of the coil, but in the testing and quality control due to variations in each individual coil.

This research is aimed at improving the performance and manufacturability of inductive proximity sensors through the design and fabrication of coils using multilayer ceramic technologies common in the manufacturing of hybrid microelectronics components and circuits. As another alternative, multilayer structures utilizing polymer materials and fabrication techniques common to the printed circuit board (PCB) industry were investigated.

Manufacture of the coils utilizing ceramic and polymer materials and hybrid and PCB fabrication techniques would eliminate the problems of repeatability, and the placement and potting of the coil. The fabrication techniques are suitable to the mass production of the coils using techniques that are well established in the electronics industry. The overall result would be a planar inductor with high yield that is suitable for mass production.

This work describes the design, fabrication, and measurement of solid state low profile planar multilayer inductors and is described in the following chapters: Chapter 1

briefly describes the problem and the proposed method to improve the sensor coil; Chapter 2 describes an inductive proximity sensor, applications, operation and past work performed in the fabrication of planar inductors for various applications over the past century; Chapter 3 describes the design and simulation of the planar inductors; Chapter 4 explains the fabrication methods used to fabricate the coils; Chapter 5 describes the measurement of the fabricated coils; and Chapter 6 discusses the conclusions that can be made from the study with suggestions for future work to enhance the performance of these sensors.

1.1 Summary

This chapter provides an introduction to the problem of fabricating inductive proximity sensor coils in a reliable method that is compatible with techniques for mass production using multilayer technologies and materials. This chapter also presents the manner in which the thesis is arranged.

Chapter 2

Literature Search and Background

2.0 Proximity Sensors

The proximity sensor is a non-contact alternative to physically actuated switches, which can provide either a 'go/no go' single output that indicates the presence or absence of a target object, or in some cases a linear device that provides an output that is proportional to the distance between the target and the sensor. The various sensing types; inductive, hall effect, electrodynamic, capacitive, and photoelectric use different forms of sensing technology but each provides generally the same type of output.

2.1 Inductive Proximity Sensors

Inductive proximity sensing, often referred to as Eddy Current Killed Oscillator (ECKO) sensing, has been widely used in industry for over thirty years. Inductive proximity sensors are used in a wide range of industry and commercial applications to detect the presence of various ferrous, nonferrous materials, and other materials, which are good electrical conductors. The inductive proximity sensor has a number of characteristics that are not found in some of the other sensing technologies; detection of objects without contact, the ability to sense moving objects, detection of small and low mass objects, detection of objects through barriers such as metal foil and paper, solid-state circuitry which eliminates contact bounce, the ability to sense quickly at high switching frequencies that allow up to 10,000 detections/s, low power requirements,

analog, digital, and proportional outputs, the ability to withstand hostile environments, and they can be installed in any position. Following are a few examples of proximity sensors' applications:

- Detection of speed, direction, and motion can be accomplished by an inductive sensor and toothed gear for use in conveyor and transportation systems.
- Processing of foodstuffs and beverages including, can and bottle manufacturing, transporting, filling, capping, packaging and warehousing.
- Processing and manufacture of consumer goods and products.
- Positioning of parts for automatic welding in the manufacture of automotive and machinery products in the aircraft and shipbuilding industry.
- Counting of small parts.
- Inspection of metal parts.
- Detection of metal in packaging.
- Motor control.
- Use in remote and hazardous conditions.

2.1.1 Inductive Proximity Sensor Components

The sensor as shown in Figure 2.1 is usually comprised of a core, winding, associated electronics, and housing. The sensor may be housed in different housing materials such as, nickel plated brass, stainless steel, or plastic with connection for input power and sensor output. The sensor head itself may be in the form of a shielded or

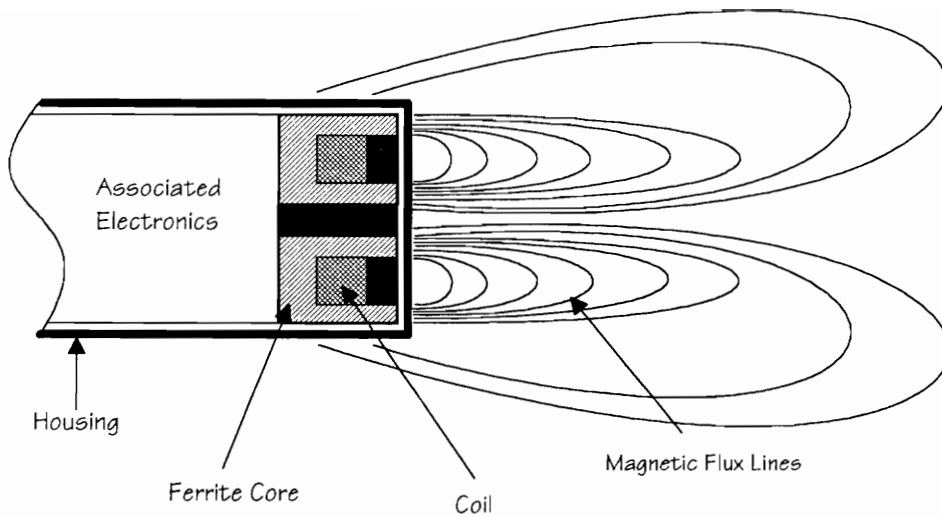


Figure 2.1 Typical Inductive Proximity Sensor

unshielded sensor in which the sensor is mounted flush or above the housing respectively. It is also available in a variety of terminations and may be powered by ac or dc with the most common being 2-wire dc analog, 2-wire dc digital, 3-4 wire dc digital, 2-wire ac, and 3-wire ac linear sensors. The main portion of the sensor electronics are comprised of an oscillator circuit, but it may also contain short circuit and incorrect wiring protection.

2.1.2 Sensor Operating and Environmental Conditions

The conventional sensor is designed to operate over a wide temperature range from -4°F to 158°F (-25°C to 70°C) and a relative humidity of 10% to 90%

noncondensing. Some specially designed sensors are made to operate under much wider temperature ranges including wash down and immersion in liquids. This is particularly common in the process and manufacture of goods used in the food and beverage industries and with use involving chemicals. Whereas plastic and metal housings are commonly used in the manufacture of the sensors, under prolonged chemical exposure, metals can corrode under harsh conditions and plastics may soften, which can cause embrittlement. For this reason, corrosion resistant stainless-steel and polytetrafluorethylene (Teflon) are commonly used in severe and corrosive environmental conditions. Proximity sensors are subject not only to variations in temperature and humidity, but they must be able to withstand shock, vibration and dirty environments. Since proximity switches contain no moving parts and are filled with a potting compound, they as a rule of thumb can withstand an acceleration of up to 30 g's and an amplitude of 1 mm up to a frequency of 55 Hz. Their method of manufacture also prevents foreign bodies and dust from entering the sensor and impairing performance, while providing additional support to the mechanical housing.

2.1.3 Sensor Operating Principle

The sensor electronics consist of an oscillator circuit similar to that of Figure 2.2, formed from a LC tank circuit. The capacitance and inductance of the circuit determine the oscillator frequency which can range from 20 kHz up to several megahertz. The inductance of the tank circuit is formed by an air cored coil or ferrite cored and coil. The oscillator generates a current that flows through the coil and produces a alternating

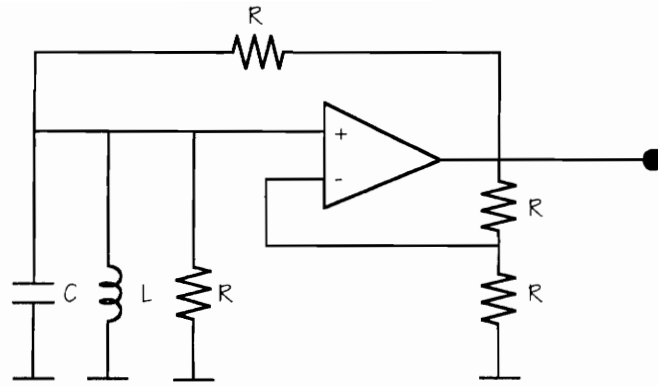


Figure 2.2 Conceptual Oscillator Circuit

magnetic field which emerges from the sensor. The oscillator circuit itself has just enough positive feedback to sustain oscillation. When the target, a piece of conducting material, is placed in front of the sensor, the magnetic fields emanated from the sensor induce eddy currents on the surface of the target material. The induced eddy currents consume energy due to the resistance of the material and radiate opposing magnetic fields which are absorbed by the sensor. This results in a loading of the oscillating circuit which then provides information of target presence through the different types of outputs.

Inductive sensors provide a high frequency oscillation with a high amplitude as an output. In the case of the analog output or the digital output through a Schmitt trigger, the oscillation is killed by the target loading the circuit, resulting in a output that

is usually on or off (go-no go). If the object is at the switching point of the circuit, the output can switch between the two states. This is known as "chatter" and can be overcome by hysteresis. In the case of a linear sensor the output has a direct linear relationship with the distance between the sensor and the target. This is provided by a linearizer between the amplifier and its output. Figure 2.3 shows the basic operation of the inductive proximity sensor and its output.

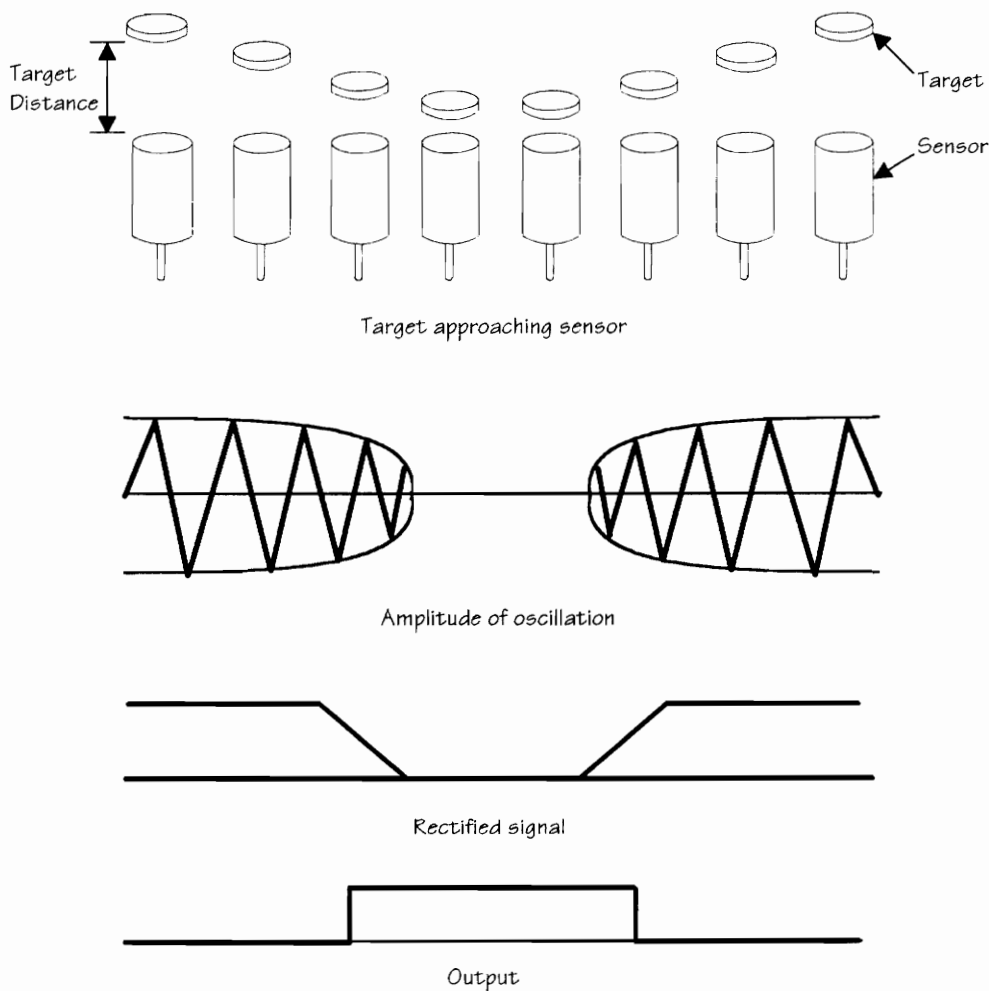


Figure 2.3 Operating Principle

Other factors need to be considered when using inductive proximity sensors such as the frequency of operation, target material and size, and sensor type (shielded or unshielded). At higher operating frequencies, current flows nearer the surface of the target, this phenomenon is known as "skin effect". The skin depth is different for different frequencies and materials. For this reason sensing ranges defined by CENELEC and NEMA (European and U.S. standards) are defined for a target of mild steel 1 mm thick three times the nominal sensing range of the sensor, or equal to diameter of the sensor whichever is greater. If a material other than mild steel is used, the sensing range should be adjusted (multiplied by a correction factor) according to the following table:

Table 2.1 Sensor Factor Adjustment for Various Target Materials

Material	Factor
400 Series Stainless Steel	1.15
Cast Iron	1.10
Mild Steel	1.00
Aluminum Foil	0.90
300 Series Stainless Steel	0.70
Brass	0.40
Aluminum	0.35
Copper	0.30

The thickness of the target material will also affect the sensing range of the sensor. If the material is less than the skin depth, some of the electric field will emerge behind the

target and the effective conductivity will be less, further reducing the sensing distance. The operating frequency will also affect how many samples the sensor will see per second which will affect the response of the sensor.

A smaller target will effect the nominal sensing range, but a target larger than the of the standard will not necessarily increase the range of the sensor. The affect of sensing range to target size is shown in the following table:

Table 2.2 Affect of Sensing Range to Target Size

Target area as compared to Standard	Shielded	Unshielded
25%	56%	50%
50%	82%	73%
75%	92%	90%
100%	100%	100%

As noted before the type of sensor, shielded and unshielded will effect the operation of the sensor in different ways. Shielded sensors are constructed with a metal material surrounding the ferrite core. This directs the electromagnetic field towards the front of the sensor face. Nonshielded sensors differ from shielded sensors in that they do not have any metal material surrounding the ferrite core, thus they can also side sense targets. The nonshielded sensors use ferrite cores which have been modified. This can be achieved by removing the outer wall of the ferrite pot core, so that it is flush with the base of the ferrite. A shielded and unshielded inductive proximity sensor is shown in Figure 2.4

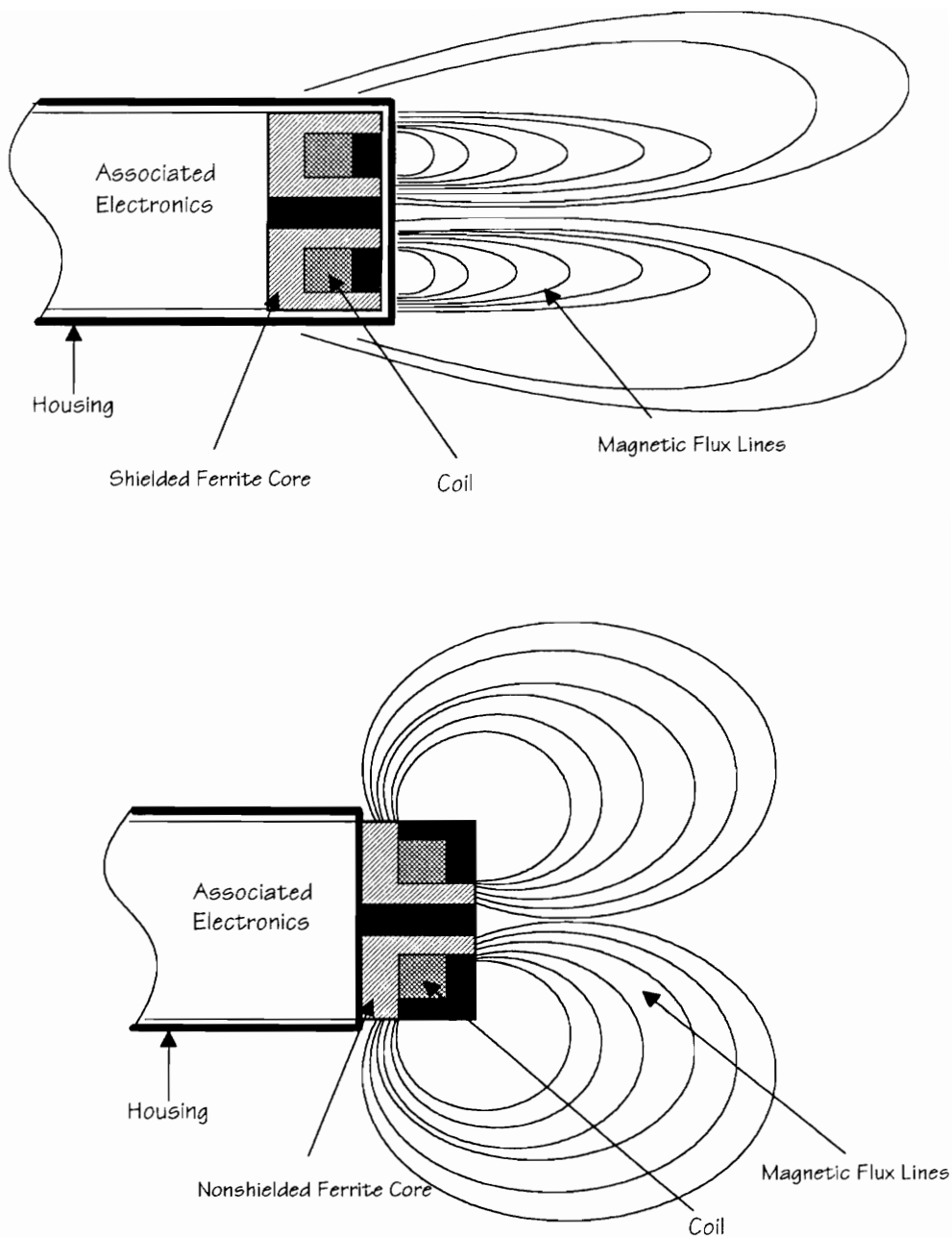


Figure 2.4 Shielded and Nonshielded Inductive Proximity Sensors

The shielded sensors will not sense as far as unshielded sensors due to the loading from the side lobes emanated from the coil/core. Although the magnetic field flux lines will mainly emanate perpendicular to the sensor surface there will be some flux linkage with the sensor housing particularly if the housing is metallic. This will result in an additional loading of the oscillator which will result in a decrease in the sensing distance.

2.1.4 Inductive Proximity Sensor Construction

Traditionally the coil is wound using clad wire or stranded wire on a plastic bobbin, which is then inserted into a cylindrical pot core. The leads come from cutouts in the bobbin and the core, and connect to the sensor electronics. In order to provide additional features while minimizing package dimensions, manufacturers use thick film and PCB technologies to package their sensor electronics. Some manufacturers even refer to this as a solid state proximity sensor[1]. The sensor electronics are manufactured using thick film materials on alumina substrates or PCB materials, and they can be mounted adjacent to the core or attached at a remote location. The electronics are attached to the core, they are then placed into a hybrid guide or epoxied and attached to the core and coil assembly. The coil wires are then soldered to the oscillator/sensor circuit, an end cap is placed on the core and the assembly is tested. In some cases, the circuit is actively tuned, and then potted and placed in the assembly housing. As stated before, problems may occur due to variations in the number of turns for the coil, the manner the bobbin is wound, or the placement of the electronics in the assembly. Sensor

design must also take into consideration variations due to ambient environmental conditions such as temperature and voltage drift.

By using thick film or PCB technologies for the coil windings many of these problems may be overcome. The windings fabricated using this technology have a high degree of repeatability, the substrate material can serve as a replacement for the plastic bobbin, the coils can be manufactured in a multi-up fashion for cost-effectiveness, the fabrication process can be automated, and reworking of the circuits can be alleviated. Thick film and PCB materials are mature technologies, therefore some of the earlier research performed with these technologies can be used as a basis for this work. In the case of thick film technology, an extensive amount of work has been done with thick film inductors in the past, including multilayer spirals using dielectric and ferrite paste materials. Until recently, PCB materials have predominantly been used as an interconnection method and therefore there is not as much literature available on the fabrication of magnetics using PCB materials. With recent advances in materials both technologies lend themselves to the production of inductive coils.

2.2 Thick Film Inductors

Thick film technology has been around since the 1950's and there has been extensive work performed on the fabrication of inductors using thick film technology. Most of the design and calculations of thick film inductors have their foundation based on work performed at the turn of the century with inductors and coils of various types and sizes by Perry[2], Jones[3], Maxwell[4], Nagoaka[5], Olenhausen[6], Rosa and

Cohen[7], Rosa[8], Cohen [9], Brooks and Turner[10], Lyle[11], and Grover[12], Dwight[13], Hazeltine[14] and Wheeler[14]. The early works were performed for inductors formed in single and multilayers with both circular and rectangular wires used for the various shapes and sizes. The inductance calculation formulae and models developed by various authors are base on both analytical and experimental work. Over the years a number of researchers have made changes or improvements on the formulae developed at the turn of the century in order to suit a particular application, method of processing, or in order to calculate inductance and quality factor taking into consideration certain approximations and limitations[16-50]. The various authors' work covers both thick film and thin film inductors over a wide range of frequencies. The majority of the work was performed for inductors in the 50 MHz - 10 GHz region using both thick and thin films and the models and fabrication techniques for their realization.

2.3 PCB Inductors

Printed wiring board (PWB) or printed circuit board (PCB) materials have been around since the 1930's. PCBs' have primarily been used as a method of interconnection but with the advancement of rigid, rigi-flex, and flexible PCB materials, they are currently used in a wide range of applications. Inductors fabricated using PCB materials have mainly been used for power supplies due to the current handling capability of the materials used. With the push for increased circuit densities, higher power and frequency operation, the PCB composites offer low-profile magnetics with increased manufacturabilty and performance. Design of the inductors using polyimide materials

follows that of thick film materials, with the designer needing only to take into consideration processing changes due to material properties.

2.4 Summary

This chapter provides an introduction into the operating principle of inductive proximity sensors including their application, construction, operating environment and performance. Also covered in this chapter is the fabrication of inductive coil using thick film and printed circuit board materials and technologies.

Chapter 3

Coil Design

3.0 Coil Fabrication Technologies

Multilayer structures can be fabricated from a variety of available ceramic and organic materials. In fabricating the multilayer coils, the materials were chosen for their design flexibility, performance, ruggedness and the suitability for large-scale production.

3.1 Coil Technology Using Ceramics

Recent advances have been made by both U.S. and Japanese firms in the development of low-temperature co-fireable multilayer ceramic (LTCC) systems. In the early 1980's Hughes invented a glass based low-temperature co-fired ceramic, which had the benefits of firing at traditional thick film temperatures of 850°C - 950°C. In the mid 1980's DuPont and other companies licensed the technology from Hughes for production of a family of low-temperature co-fired ceramics (LTCC). Over the past few years a number of companies have also developed LTCC materials including dimensionally stable transfer tapes compatible with both alumina and aluminum nitride. The LTCCs' have the advantage of being fired at a lower temperature thus, paste formed with noble metals can be used in the multilayer ceramics. The ceramic systems are based on the addition of glass to the ceramic oxides in the forming slurry for the formation of the LTCC tape. These new multilayer ceramics can be fired at lower temperatures (600-850°C) than the conventional multilayer technology (1400-1600°C). With the lower firing temperatures, use of high temperature refractory metals is no longer needed.

The currently available LTCC's demonstrate a dielectric constant ranging from 4 to 100 with various available tape thicknesses. With a thermal expansion matched to silicon and alumina, the availability of compatible low resistivity gold, gold platinum, silver, silver palladium thick film pastes, and the ability to apply thin film metallizations and dielectrics to the surface, these ceramic materials should lead to higher performance components and packages. For the ceramic multilayer coil DuPonts' 851 Green Tape™ LTCC system was chosen.

3.2 Coil Technology Using Polyimides

For this project, many PCB materials, such as polymers, plastics, glass, ceramic, and metals had to be considered. Due to the nature of the application, it was determined that a thin material needed to be chosen in order to have a multilayer structure that would fit the constraints of the optimized core, while at the same time meeting the desired electrical performance. For this reason, a flexible composite material was chosen to be the best alternative. Most composite materials come with a metal adhered to the surface which is then imaged or patterned in some manner to make the required circuit interconnections. A common metal used for multilayer technologies is copper. The copper can be electrically deposited or rolled and then adhered with an adhesive to the dielectric layer. In choosing the multilayer material it was advantageous to pick a material that is available in a variety of dielectric and metallization thicknesses. For the coil fabrication the DuPont Pyralux® family of flexible composites was chosen.

3.3 Design and Measurement of Coils

The first step in the design of the solid state inductive coil was the optimization of the ferrite core. Simulations were executed comparing various core geometries with those of the current coil and core configurations. The new coils were to be designed after the optimized core configurations were established. It was expected at the initiation of the research that the core simulation and optimization would take some time to complete. During this time work was begun on the coils in order to establish feasibility and to refine fabrication techniques.

The following sections describe the formulae currently used for spiral inductance and quality factor calculations and the designs for the Green Tape™ and Pyralux® samples. The Green Tape™ and Pyralux® designs have been listed in chronological order of their fabrication. Included in section(5.4) is a summary of all the designs included with their associated measurements.

3.4 Prediction of Inductance and Quality Factor

Before the new coils were fabricated, a literature search, as described in Chapter 2, was undertaken in order to investigate past coil designs including analytical and empirical models as well as the physical data that correspond to those models. The various researchers have developed a multitude of different equations and formulae which can be used to describe inductors and transformers. Since the fabrication of the inductors was performed in parallel with the literature search and development of the inductance and quality factor the inductors were designed using preliminary models,

these forms did not accurately describe the inductance and quality factor of the inductive coils. The models later developed were used to compare to the experimental data.

The first step in developing a model for the planar inductors is to derive an accurate model for the calculation of the inductance (L). The next step in producing an accurate model is to determine the resistance (R) over the desired frequency range of operation. The quality factor (Q) can then be calculated from the inductance and the total resistance over the specified frequency range. The spiral inductor can be modeled as a lumped parameter equivalent circuit as shown in Figure 3.1, where the resistance R_T is the total resistance, L is the inductance of the coil and C is the capacitance of the coil. The total resistance is due to the copper losses including; R_{DC} , the DC resistance of the coil, R_{PE} , the resistance due to proximity effects of the conductors and R_{SE} , the resistance due to the skin effect of the coil. R_{EQ} and L_{EQ} represent the equivalent resistance and inductance that would be measured at the coil terminals, respectively.

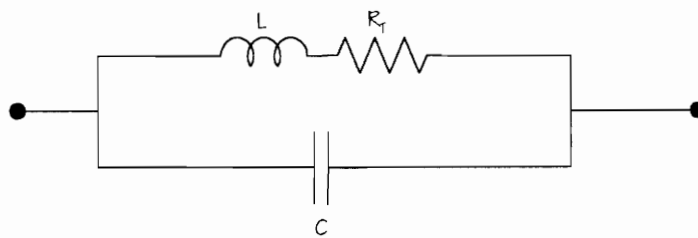


Figure 3.1 Equivalent Circuit Model for Spiral Inductor

3.4.1 Calculation of Inductance

Calculation of inductance has taken on many forms over the past century. This is in part due to the importance of magnetics in electronic and electrical circuits, but it is also due to the many physical forms the inductor can take. These actual inductances can be calculated using three basic methods; the first approach produces an exact expression for inductance using elliptic integrals; the second type, as in Grover[46], uses tabulated factors and the third type, a series expansion for the elliptic integrals as described by Cohen and Rosa[7]. Spiral inductors using thick film or PCB materials are a special case of the traditional inductor addressed in much of the research. Although many authors have addressed the case of the thick film spiral inductor, the majority of developed models were originally intended for inductors made of solid or stranded wire formed as an air coil or on a bobbin for insertion into a ferrite core. The forms considered include straight wires, circular coils of round and rectangular cross section including single and multilayer coils, helices of rectangular strip, flat spirals of strip, toroidal cores, polygonal inductors, and multilayer spirals of many turns. The following are equations that have been used to provide the basis for the calculation of inductance in thick film and PCB planar inductors. Some of the formulae and techniques are tedious and involve the use of empirical data while others are straightforward and lend themselves well to calculations using a computer

3.4.1.1 Perry, Hazeltine and Wheeler's Inductance Formulae

Many researchers have based their inductance calculations on the empirical formula proposed by Wheeler[14-15] in 1928 shown as:

$$L = \frac{a^2 n^2}{9a + 10b} \mu H$$

where:

- a = average radius in inches
- b = axial length in inches
- d_o = outside diameter in inches
- d_i = inside diameter in inches
- n = number of turns

Wheeler became interested in the subject after he was shown a simple formula derived by Professor Hazeltine[14] in 1923. The equation is shown below:

$$L = \frac{0.8a^2 n^2}{8a + 9b + 10c} \mu H$$

where:

- a = average radius in inches
- b = axial length in inches
- c = radial thickness in inches
- d_o = outside diameter in inches
- d_i = inside diameter in inches
- n = number of turns

Hazeltine developed his formula based on the coil shape that would give the most inductance for a given length and size of wire. The shape of the wire was given in Circular 74 of the Bureau of Standards[14] and is shown below for the single and multilayer air cored inductor. Circular 74 gave the values for a single-layer helical coil but it was based on tabulated values. Wheeler noted that the inductance has a parabolic variation with length and therefore analyzed the $1/L$ for intercept in terms of the shape (b/a) . The asymptotic straight line gives an approximation with less than 1% error if the ratio $b/2a > 0.4$. Perry[2] derived a formula similar to Hazeltine's, with the coefficients in

the denominator 5:9:10. Wheeler later found out that his formula was a second approximation for a series expansion of a long coil, as given by Rosa and Grover[12]. His ratio of 9/10 was very close to their theoretical value of $8/3\pi$ or 0.85[14]. Figure 3.2 shows a single-layer coil that has been formed along in the axial direction.

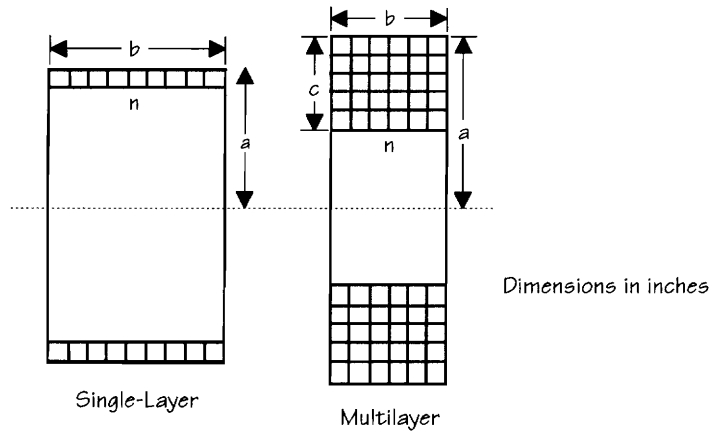


Figure 3.2 Single and Multilayer Air-Cored Inductors

For spiral inductors the turns are usually first formed perpendicular to the axis as shown in Figure 3.3. Wheeler modified his formula to better represent this form as:

$$L = \frac{a^2 n^2}{9a + 11c} \mu H$$

Where:

- a = average radius in inches
- b = axial length in inches
- c = radial thickness in inches
- d_o = outside diameter in inches
- d_i = inside diameter in inches
- n = number of turns

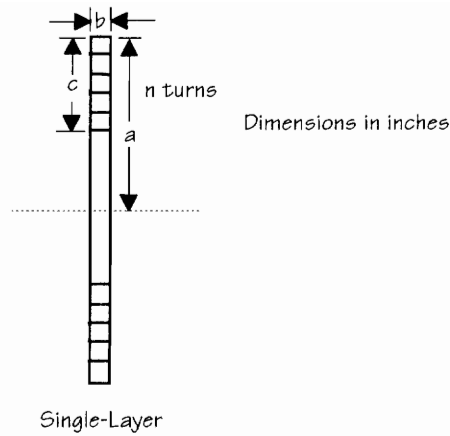


Figure 3.3 Single-Layer Air-Cored Inductor

Hazeltine and Wheeler's formulae are both limited in that they hold only for a certain response over a certain range and may not be accurate outside the parameters described below. Hazeltine's equation is accurate to within 1 percent when the coil has the approximate shape of Figure 3.1 and when the terms in the denominator are roughly equal. The calculations may not hold for too few turns (i.e. the length of the coil should be greater than $> 0.8a$, when the spacing between turns is too great, when a wire with a rectangular cross-section is used or when the skin effect or distributed capacitance has a significant effect[15]. As applied to thick film and PCB design care must be given to two factors. One part or all of the restrictions may be violated and second, some of the formulae were empirical relations developed to fit a certain response over a specified range. Outside of this range the relations may introduce some error.

3.4.1.2 Nagaoka, Rosa and Grover's Inductance Formulae

In Terman[47] and Grover[46] an equation is given for a long solenoidal multilayer coil as shown in Figure 3.4.

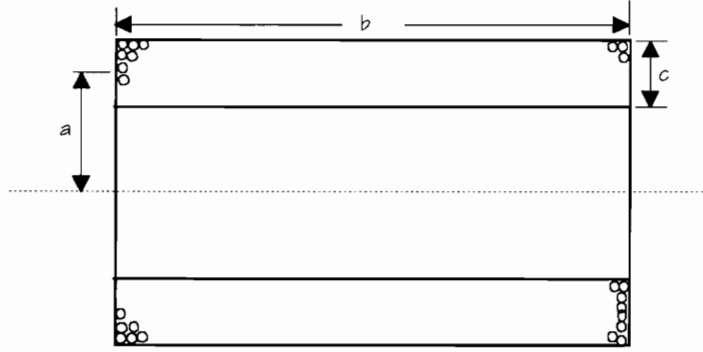


Figure 3.4 Long Multilayer Solenoidal Coil

This formula has its basis from the Nagaoka formula which is written as:

$$L_0 = \frac{2.54 \times 0.03948 \left(\frac{d}{2}\right)^2 n^2}{L} K$$

Rosa and Grover rearranged the equation to be:

$$L_0 = F n^2 d \text{ microhenries}$$

Where:

$$F = 2.54 \times 0.03948 \left(\frac{d}{4l}\right) K$$

It can be recognized that this is the equation for the inductance of a single layer solenoid and F can be determined from Table 12 in Terman[47] or Table 40 and 41 in Grover[46]. In order to correct for the thickness of the winding a second term was added to the above equation:

$$L_0 = Fn^2d - \frac{0.03193n^2ac}{b}(0.693 + B_s)\mu H$$

Where the quantity B_s is given in Table 13 except that b/c is substituted for l/c in the table. If the insulation is a large fraction of the wire size a correction factor can be added for the inductance value. This correction factor is shown below:

$$\Delta L = 0.3193an(2.303 \log_{10} \frac{D}{d} - 0.155)\mu H$$

where D is the distance between wires and d is the diameter of the bare wire.

Terman[47] also describes formula for a multilayer coil of short solenoidal form as shown in Figure 3.5.

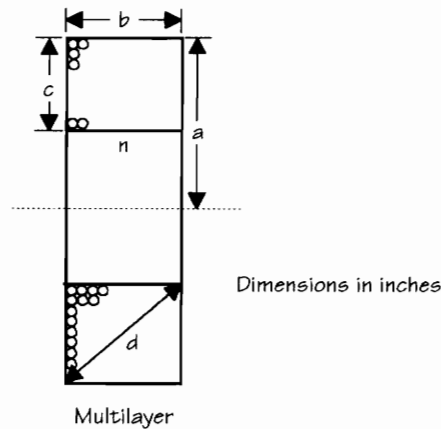


Figure 3.5 Short Multilayer Solenoidal Coil

The inductance of the coil shown in Figure 3.4 can be expressed in several ways, where a is the mean radius, b the axial thickness, c the radial thickness, d the diagonal winding width and n the number of turns. A simple formula is given as shown below:

$$L_0 = \frac{l^{5/3}}{D^{2/3}} I \mu H$$

or

$$L_0 = an^2 J \mu H$$

where I and J are the factors given in Figures 28 and 29 of 27 and 28 of Terman[47].

Where greater accuracy is desired from the curves of 28 and 29 the following equations (Stefan's Formula[47]) can be used along with Table 16 of Terman[47] to calculate y_1 , y_2 , and y_3 :

for $b > c$

$$L_0 = 0.3193an^2 \left[2.303 \left(1 + \frac{b^2}{32a^2} + \frac{c^2}{96a^2} \right) \log_{10} \frac{8a}{d} - y_1 + \frac{c^2}{16a^2} y_3 \right] \mu H$$

for $b < c$

$$L_0 = 0.3193an^2 \left[2.303 \left(1 + \frac{b^2}{32a^2} + \frac{d^2}{96a^2} \right) \log_{10} \frac{8a}{d} - y_1 + \frac{b^2}{16a^2} y_2 \right] \mu H$$

The terms y_1 , y_2 , and y_3 are constants that depend on b , c and the n the total number of turns. The accuracy of the equation is improved when the cross section of the coil is square and the insulating space between the conductors is small. Here again the inductance calculation can be adjusted for when the wire insulation is an appreciable portion of the wire thickness with the following factor:

$$\Delta L = 0.3193an(2.303 \log_{10} \frac{D}{d} - 0.155) \mu H$$

Hazeltine's formula given in Section 3.1.1.1 is an approximation to the above formulas.

3.4.1.3 Burkett's Inductance Formula

Burkett[22] modified Hazeltine's formula to take into account that for thick and thin film inductors the height of the coil will be negligible. Thus the b term in the denominator is set equal to zero and the equation becomes:

$$L = \frac{0.8a^2n^2}{8a+10c} \mu H$$

Where:

a = average radius in inches

c = radial thickness in inches

d_o = outside diameter in inches

d_i = inside diameter in inches

n = number of turns

It is unclear how accurate Burkett's formula is since, unlike the measurements of Hazeltine, all of his measurements were performed over a 15 mil ground plane. Burkett assumed that a ground plane would not have an effect on the inductance, but measurements have shown that the ground plane can have a significant effect on the inductance values.[33]

3.4.1.4 Inductance Calculation by Olivei

The disadvantage of the above equations is that are based on empirical experiments that hold true only for certain equations. Olivei[16] has done analytical work based on modeling the Archimede's spiral as concentric circles and by considering the magnetic flux at the center of the spiral by using the Biot-Savart law determined that

the total inductance was due to the self inductance of all of the loops. Olevei failed to take into consideration the mutual inductance between the coils and he also assumed that the magnetic flux density at the center of the spiral was the average flux density of the spiral. These assumptions led to a calculated inductance less than the actual measured values.

3.4.1.5 Inductance Calculations by Remke

Remke[29] picked up where Olevei left by replacing each turn of the spiral by a concentric circle therefore greatly simplifying the geometry of the problem. Remke went on to calculate the mutual, internal self, and external self inductance and the effects due to a ground plane.

3.4.1.6 Inductance Calculations by Rodriguez, Dickens, Whelan and Carpenter

Similar two-dimensional work has been performed by Rodriguez[33] and Carpenter[43] who have written a program to calculate the mutual and self inductance of multilayer spirals. Rodriguez, like Remke, modeled a two dimensional spiral as a set of concentric loops.

3.4.1.7 Inductance Calculations by Murgatroyd, El-Missiry and Evans

Murgatroyd[48] considered the single-turn foil inductor, using a coupled-circuit approach to calculate the current distribution, and therefore the effective resistance and effective inductance. El-Missiry also used the coupled-circuit approach for the

multilayer case. To make the problem manageable both authors made the simplifying assumption that the current distribution across the width of the conductor was constant for any given turn, but allowed to change from one turn to the next. The assumption that the current is constant for each turn is met by subdividing each turn into a notional set of coaxial parallel filament coils. If the filaments are made small enough the current can be assumed to be uniform across the cross-section of the coil. The solution set of the electrical equations will then provide the filament currents for the mutually coupled coils and give a close approximation to the current distribution across the foil. This technique was extended to the multilayer case with the turns assumed to be terminated in equipotentials, so that redistribution of current is allowed between the turns.

This type of approach produces two types of problems, the formation and solution of a large set of simultaneous solutions and the calculation of the self and mutual inductance of the coils which are all coaxial, but have small differences in diameter. The accuracy of the results will depend directly on the calculation of the self and mutual inductances for the filament coils. Evans investigated other methods to calculate the self and mutual inductances choosing to calculate them using Grover's formulae.

3.4.1.7 Inductance Calculations by Dodd

Dodd[49] has developed a model for the analysis of the coil used in eddy current testing used in nondestructive testing. Dodd assumes that space is divided into regions of linear, isotropic, and homogeneous media, one of which contains an infinitely thin coil carrying

current I. Dodd assumes axial symmetry and a sinusoidal current flowing through the coil. The differential equation set up by spatial part of the vector is shown below:

$$\frac{\delta A}{\delta r^2} + \frac{1}{r} \frac{\delta A}{\delta r} + \frac{\delta^2 A}{\delta z^2} - \frac{A}{r^2} + \omega^2 \mu \epsilon A - j\omega u \sigma A + u I \delta(r - r_0) \delta(z - z_0) = 0$$

Once the differential equation is solved for a particular conductor configuration, any number of delta function coils can then be superimposed to achieve the desired shape. The current is assumed to be uniform across the cross-section of the conductor. Dodd uses Green's Method to determine the magnetic vector potential for the particular coil and conductor configuration. After the vector potential has been determined the induced voltage is obtained by summing the vector potential for n coils. This can be approximated by integrating over a turn density of n turns for the unit cross-sectional area. The impedance of the coil is determined by the forced current I. The coil impedance in air was determined by using the case of a coil over a two-conductor plane and setting the parameters of the semi-infinite planes to that of air. Shown below is the impedance of the coil:

$$\begin{aligned} Z &= \frac{j\omega\pi u n^2}{(l_2 - l_1)^2 (r_2 - r_1)^2} \int_0^\infty \frac{1}{\alpha_0^3 \alpha^3} J^2(r_2, r_1) \{ 2\alpha(l_2 - l_1) + 2e^{-\alpha_0(l_2 - l_1)} - 2 \\ &\quad + (e^{-2\alpha_0 l_2} + e^{-2\alpha_0 l_1} - 2e^{-\alpha_0(l_2 - l_1)}) \} \\ &\quad \times \left[\frac{(\alpha_0 + \beta_1)(\beta_1 - \beta_2) + (\alpha_0 - \beta_1)(\beta_1 + \beta_2)e^{2\alpha_1 c}}{(\alpha_0 - \beta_1)(\beta_1 - \beta_2) + (\alpha_0 + \beta_1)(\beta_1 + \beta_2)e^{2\alpha_1 c}} \right] d\alpha \\ J(r_2, r_1) &= \alpha^2 \int_{r_1}^{r_2} r_0 J_1(\alpha r_0) dr_0 \\ \alpha_i &= \sqrt{\alpha^2 - \omega^2 \mu_i \epsilon_i + j\omega \mu_i \sigma_i} \\ \beta_i &= \left(\frac{\mu_0}{\mu_i} \right) \alpha_i \end{aligned}$$

Where:

- r_1 = outside coil radius in meters
- r_2 = inside coil radius in meters
- c = thickness of semi-infinite region III i.e. the target in meters
- l_1 = distance from bottom of coil to target in meters
- l_2 = distance from top of coil to target in meters
- $J_1(x)$ is a Bessel function of order $m=1$
- And $\mu_i, \sigma_i, \alpha_i$ are the media parameters

3.4.1.9 Inductance Formulae Chosen for Calculations

Wheeler's and Dodd's formulas were used to calculate the inductance for the Green Tape™ and Pyralux® inductors. Whereas many of the other formulae require the user to input values from an empirically generated table these formulae calculate the inductance based on the physical dimensions of the inductors themselves.

3.4.2 Resistance Calculations

The principal causes of energy loss in the air-core inductors are the copper loss, due to the dc resistance and skin effect, the proximity loss due to the interaction between nearby turns, dielectric losses associated with the distributed capacitance of the coil, eddy current losses due to nearby metal objects, and core losses. For the case of the air-cored spiral thick film and PCB inductors, the only losses that need to be considered are the losses due copper losses, proximity effect and dielectric losses. Typically the resistive losses are divided into the dc resistance and the ac resistance or losses due to frequency effects such as the skin and proximity effects. The calculation of the skin and proximity effects is dependent on the manner the formulae were developed; in some cases the

losses are calculated separately and in others they are lumped together. The following sections describe the formulae used to calculate the different resistive components.

3.4.2.1 DC Resistance Calculation

The dc resistance of the winding is based on the geometrical configuration of the winding and the conductivity of the material used for a conductor. Shown below is an equation for the dc resistance for the spiral inductor:

$$R_{dc} = \frac{\rho l}{A} = \frac{\rho l}{Wt} = \frac{\rho(2n\pi a)}{Wt} = \frac{2n\pi\rho a}{Wt} \Omega$$

Where:

- ρ = The Resistance of the conductor in ohm-meter
- a = The mean radius of the coil in meters
- n = The number of turns for the spiral
- W = The width of the conductor in meters
- t = The thickness of the conductor in meters

3.4.2.2 Skin Effect Resistance Calculation

At low frequencies the current is uniform across the cross-section of the spiral conductor. As the frequency of operation increases the current density becomes non-uniform. When the current is flowing through the conductor the magnetic flux lines form concentric circles around the conductor. Some of the flux lines exist inside the conductor encircling the center of the inductor, while not encircling the current flowing nearer the surface of the conductor. This results in the inductance at the center portion of the conductor being greater than the inductance towards the surface of the inductor. This increased reactance forces the current flow towards the surface of the conductor where the impedance is lower. The current will be redistributed so as to flow where the

least number of flux lines will encircle it. This effectively reduces the cross-section of the conductor and is known as the "skin effect"[47]. For the spiral conductor of rectangular cross-section the current will flow primarily along the edge of the conductor and the resistance will be high since only a small portion of the conductor carries any current. The skin effect resistance has been calculated Bureau of Standards Circular 74 and repeated in Butterworth[47], Grover[46] and Terman[47]. In these cases the skin effect has been calculated separately from the proximity effect and is shown in a tabular form for various geometries. It was desirable to utilize a formula for the skin effect resistance which could analytically calculated based on the geometry of the inductor under consideration. For this work two formulas were considered that of Dowell[49] and that of Ferreira[50]. Both Dowell and Ferreira's work are based on the effects of eddy currents in inductor and transformer windings. Although Ferreira calculations were based on those of Dowell, the calculations are presented in a slightly different manner. Ferreira separates his skin effect and proximity effect terms whereas Dowells terms are lumped together as one impedance. Dowells equation was chosen to calculate the ac resistance including the skin and proximity effect. The equation is shown in the following section describing the proximity effect resistance calculation.

3.4.2.3 Proximity Effect Calculations

When two or more currents are carrying current in close proximity with each other the current distribution in one conductor is affected by the magnetic flux produced by the other conductors as well as the magnetic flux produced in the conductor

itself[47,51]. This affect is termed the proximity effect and it can cause the ac to dc resistance ratio to be larger depending on the physical construction of the coil. The field of a current-carrying winding will normally cut the conductors of that winding perpendicular to the conductor axis. The calculations by Dowell assume a magnetic field parallel to the conductor surface as he recognized that the leakage flux lines run parallel to the surface of the windings.

Shown below is the ac to dc resistance ratio F_R as taken from Dowell. This ratio term includes the resistance due to both the skin and proximity effect. The ac resistance of the coil can be found by multiplying the dc resistance by the ac to dc resistance ratio.

$$F_R = M' + \frac{(m^2-1)D'}{3}$$

$$M = \alpha h \coth \alpha h$$

$$D = 2\alpha h \tanh \frac{\alpha h}{2}$$

$$\alpha = \sqrt{\frac{j\omega\mu_0\eta}{\rho}}$$

$$\eta = \frac{N_l a}{b}$$

Where for the spiral inductor some terms of the original equation have been modified to match the figure given by Dowell so that:

a = print height (m)

b = winding height (m)

h = winding width (m)

m = number of turns per layer

N_l = number of layers

M' and D' = real parts of M and D

3.4.2.3 Distributed Capacitance

The distributed capacitance for the spiral inductor can be modeled to include the capacitance between the turns and the capacitance between layers. The interturn capacitance was modeled by Smythe[33] as the capacitance between parallel cylinders C_p for each of the parallel-cylinder equivalent capacitors which are added in series to give C_{Cal} , which in turn is added to C_x the ground plane capacitance to calculate the overall capacitance C_T :

$$C_p = \frac{2\pi\epsilon l}{\cosh^{-1}\left[\frac{D^2}{2a^2} - 1\right]} pF$$

$$C_{Cav} = \frac{C_p}{n}$$

$$C_T = \frac{C_x}{3} + C_{Cal}$$

Where:
 D = The outside diameter of the wire in mm
 a = Radius of inner conductor in mm
 l = Length of coil in mm
 ϵ = Permittivity of dielectric material
 n = Number of turns
 C_x = Ground plane Capacitance

Grossner[51] has modeled the capacitance between layers to be:

$$C_L = \frac{4}{3} K_c \frac{N_L}{N_L^2 - 1} \epsilon_i \epsilon_0 \frac{2\pi r h}{D_L}$$

Where:
 K_c = Constant that depends on geometry
 N_L = Number of turns per layer
 ϵ_i = Relative permittivity of the insulation
 r = Average radius of turns in m
 h = Axial length of coils in m
 D_L = Distance between coil layers in m

3.4.3 Q Calculations

The quality factor can be calculated once the equivalent resistance and inductance is known from the model shown in Figure 3.1, where the quality factor is given as:

and L_{eq} and R_{eq} are shown as:

$$Q = \frac{\omega L_{eq}}{R_{eq}}$$

$$R_{eq} = \frac{R}{(1-\omega^2 LC)^2 + \omega^2 C^2 R^2} \Omega$$

$$L_{eq} = \frac{L(1-\omega^2 LC) - CR^2}{(1-\omega^2 LC)^2 + \omega^2 C^2 R^2} H$$

$$\text{Where: } R = R_{dc} + R_{se} + R_{pe} \quad \text{and} \quad C = C_T + C_L$$

3.5 Green Tape™ and Pyralux Designs

There are two types of inductors, square and spiral. Although the square inductor exhibits a larger inductance, the spiral inductor exhibits a better quality factor. The spiral inductor is based on Archimedes spiral. A generic spiral inductor is shown in Figure 3.6[41]. The spiral inductor is defined by the outside radius, inside radius, conductor width, spacing between the conductors and number of turns. Each of the Green Tape™ and Pyralux® coils were made by connecting the spiral in each layer in series.

3.5.1 Green Tape™ Design Summary

A summary of the physical coil dimensions is shown for the coils fabricated using Green Tape™ material is shown in Table 3.1.

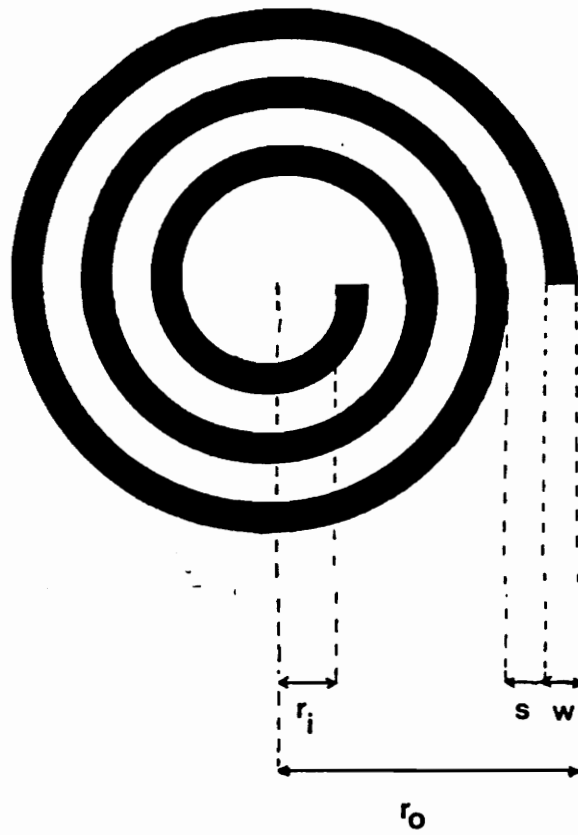


Figure 3.6 Generic Spiral Inductor

Table 3.1 Green Tape™ Coil Design Summary

Sample	D _i (mils)	D _o (mils)	Layers	Turns/ Layers	Conductor Width (mils)	Conductor Spacing (mils)	Average Turn radius a (mils)	Axial Thickness b (mils)	Radial Thickness c (mils)
GT1	389	558	3	3	17.6	4.4	236.75	11.1	84.5
GT2	250	826	15	5	53	8	271.5	55.5	293
GT3	391	604	15	5	14	4.4	248.5	55.5	106
GT4	391	723	15	5	23.8	4.4	278.5	55.5	166
GT5	422	642	32(16)	3	23.8	4.4	266	118.4	110
GT6	422	642	32(16)	3	23.8	4.4	266	118.4	110

Shown in Table 3.2 are the inductance and quality factors calculations based on the physical dimensions of the designed Green Tape™ coils at an operating frequency of 200 KHz, which is a typical operating frequency of inductive proximity sensors.

Table 3.2 Inductance and Quality Factor Calculations for the Green Tape™ Coils

Sample	L μ H Wheeler's Formula	L μ H Dodd's Formula	Q Wheeler's Formula	Q Dodd's Formula
GT1	1.48	1.52	0.44	0.45
GT2	46.83	43.41	0.48	0.04
GT3	102.08	90.38	2.71	2.4
GT4	100.7	91.65	2.27	2.07
GT5	45.23	40.45	5.17	4.62
GT6	45.23	40.45	4.2	3.75

3.5.2 Pyralux® Design Summary

A summary of the physical coil dimensions for the coils fabricated using Pyralux® materials is shown in Table 3.3.

Table 3.3 Pyralux® Coil Design Summary

Sample	D _i (mils)	D _o (mils)	Layers	Turns/ Layers	Conductor Width (mils)	Conductor Spacing (mils)	Average Turn radius a (mils)	Axial Thickness b (mils)	Radial Thickness c (mils)
P1	250	484	1	4	53	7	183.5	43.74	117
P2	248	716	10	7	24	6	241	43.74	234
P3	398	614	15	5	14	5	253	58.61	106
P4	398	734	15	5	24	5	283	58.61	168
P5	418	648	15	5	15	5	266.5	103.61	115
P6	418	648	15	5	15	5	266.5	43.61	115
P7	418	648	15	5	15	5	266.5	88.61	115
P8	418	648	12	5	11	24	266.5	50.86	115

Shown in Table 3.4 are the inductance and quality factors calculations based on the physical dimensions of the designed Pyralux® spiral inductor coils at an operating frequency of 200 KHz, which is a typical operating frequency of inductive proximity sensors.

Table 3.4 Inductance and Quality Factor Calculations for the Pylalux™

Sample	L μ H Wheeler's Formula	L μ H Dodd's Formula	Q Wheeler's Formula	Q Dodd's Formula
P1	0.1	0.19	0.04	0.09
P2	27.75	56.34	0.22	0.44
P3	60.61	91.43	1.66	2.51
P4	53.94	92.8	0.59	1.02
P5	62.69	85.72	3.43	4.69
P6	62.69	101.38	0.92	1.49
P7	62.69	89.11	2.69	3.82
P8	16.95	26.81	2.96	4.68

The inductance, resistance and quality factor can be calculated for any frequency desired. The resistance and quality factor for Green Tape coil 5 versus frequency is shown in Figure 3.7 and 3. 8 respectively.

3.6 Summary

This chapter describes the formulae used to calculate the inductance, resistance, capacitance and quality factor for the inductive coil designs. The various equations were used to design and simulate the performance of the inductive coils in the frequency range of interest. The simulated data is compared with the actual coil measurements in Chapter 5. The quality factor and resistance are provided for one sample over a frequency range

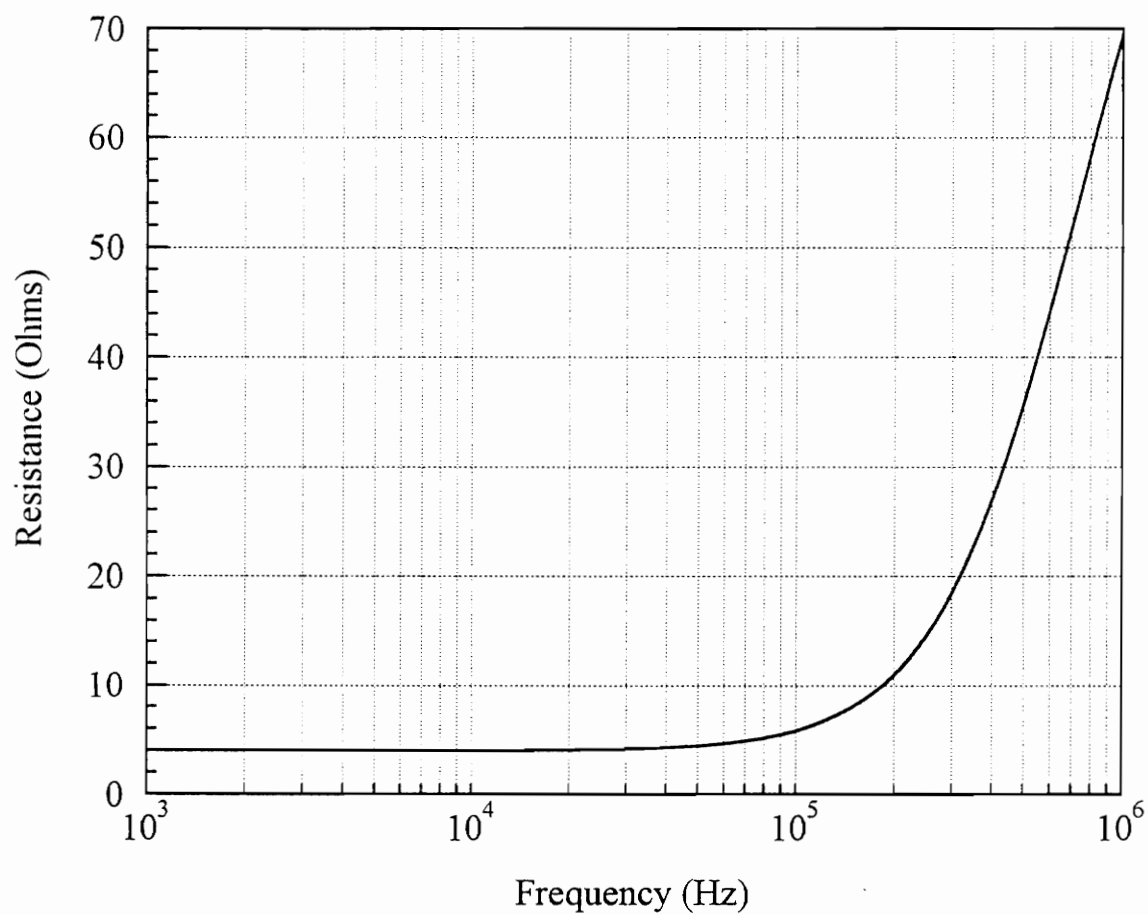


Figure 3.7 Resistance versus Frequency for Green Tape Sample 5

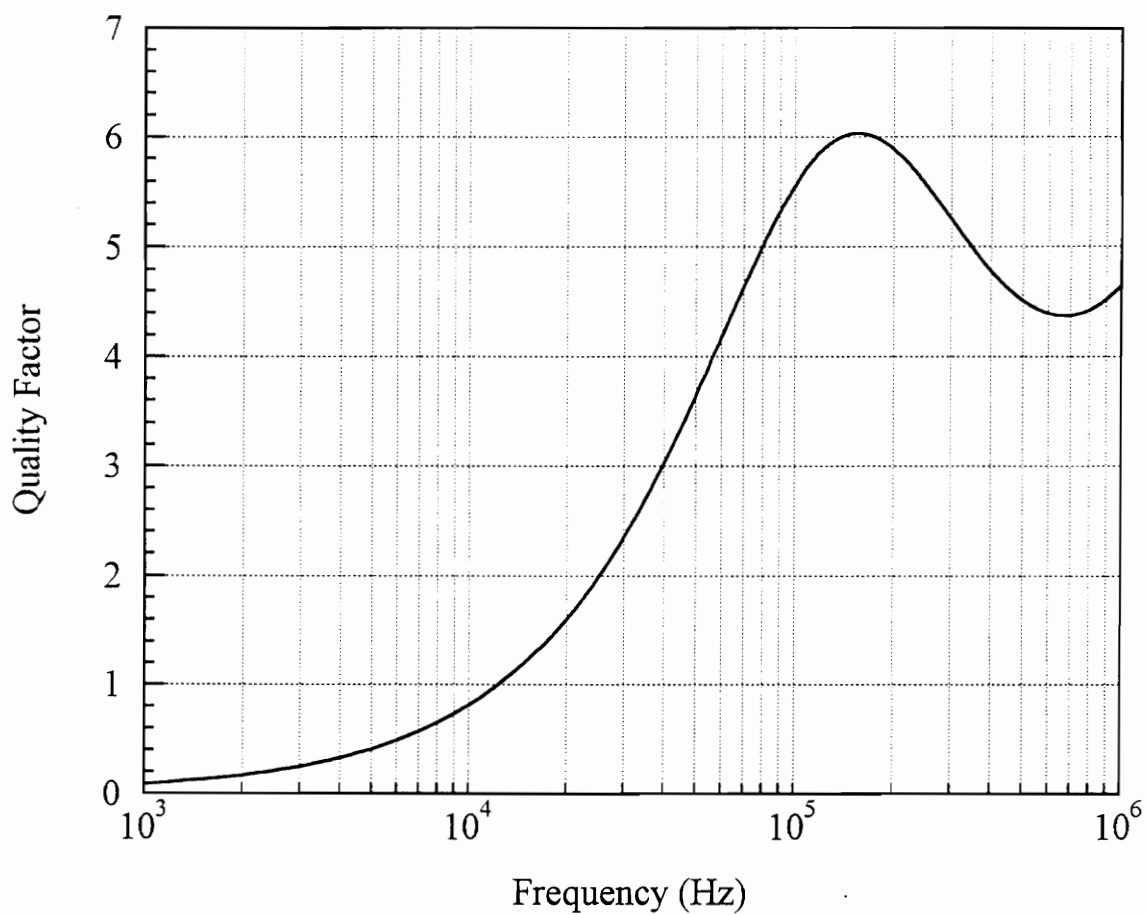


Figure 3.8 Quality Factor versus Frequency for Green Tape Sample 5

Chapter 4

Coil Fabrication Techniques

4.0 Coil Fabrication Techniques

The following two sections describe the coil fabrication using Green Tape™ and Pyralux® technologies.

4.1 Low Temperature Co-fired Ceramic Coil Fabrication

The Green Tape™ system is a family of tape dielectrics that can be processed like traditional thick film materials, but has the advantages of co-firing like that of a traditional high temperature multilayer ceramic. The tape system is a system in which the interconnections and vias can be printed, and the multilayer structure can be fired at one time (co-fired). It offers advantages over high temperature co-fired alumina of high conductivity metals, low k dielectric, low processing temperature, and low capital investment. It offers advantages over multilayer thick film circuits by offering high print resolution, low surface roughness, single firing, good dielectric thickness control, and an unlimited number of layers. Green Tape™ is available in the green (hence the name) unfired form of the ceramic. The tape is available in three thicknesses 4.5, 6.5 and 12.5 mils (unfired). Gold, silver, silver palladium, and birox resistor paste have been formulated to be compatible with the Green Tape™ system. The Green Tape™ system is processed using normal thick film equipment and processes. The tape is blanked, vias filled, the pattern or circuitry printed, collated, laminated, burnt out and fired to make a hermetic multilayer ceramic structure. The advantage of Green Tape™ is that it can be

formed into almost any shape or form. This is important when trying to fabricate a ceramic coil to fit various core shapes and sizes.

Before fabricating the Green Tape™ samples, the designer must take into consideration material properties that are unique to Green Tape™. During firing, the Green Tape™ samples shrink 12% in the x and y direction and 17% in the z direction, thus the designer must take this shrinkage into effect during the design process. At this point, a system of thick film inks compatible with the Green Tape™ were chosen. A silver system of thick film inks was chosen for the coil fabrication, due to the low cost and resistance per square as compared to the gold and palladium systems.

4.1.1 Plotting and Master Artwork Generation

Once the layout is complete, the circuit design is transferred to a masking film with the trade name Rubylith®, a red gelatin substance on a supportive five mil Mylar® backing.

The rubylith is placed in an E size drafting plotter in which the pen has been replaced by a diamond scribe. The plotter used is a HP 7576 unit with a removable Micrasem rubyscribe. Through a linking program, an output file is produced which enlarges the circuit layout and plots it using the scribe on the rubylith. The circuits are typically magnified 10 times in order to provide better resolution for the positive used in screen preparation. Once the rubyliths are scribed, they are "peeled" by pulling up the masking material in those regions where ink is to be deposited.

4.1.2 Reduction of Master Artwork

The master artwork, or "rubylith", that has been produced earlier is now placed on a fixed camera system. For our process, the 10X reduction lens is placed on the camera and, using Kodak orthofilm, a 1X positive of the layout is produced using a f stop of 32 and an exposure of 25 seconds. Photographic methodology is a somewhat subjective science, so the above values are typical of those used in the laboratory. Some users will adjust the time and f stops in order to produce a more accurate positive.

The positive is then placed in Kodak developer, a two part 1:1 volume noncritical mixture, for approximately 3 minutes or until the image is clear. One must take some care not to develop the positive too long in order to avoid overdeveloping the emulsion. Once the positive is removed from the developer, it is rinsed with water at a temperature of 25°C and placed in Kodak stop bath for approximately 30 seconds in order to stop the positive from developing any further. Upon removing the positive from the stop bath, it should be rinsed with water at a temperature of 25°C and placed in a solution of Kodak fixer which will react with the emulsion and form a protective coating for the positive. After sitting in the fixer for three minutes, the positive should be placed in a water bath for four minutes. Following the water rinse, the positive should be hung on clips, or by some other means, in order to dry.

4.1.3 Screen Preparation and Emulsion Application

The next step is to produce the stencil or pattern. This is accomplished by producing a pattern on a screen of stainless steel mesh. These come in a variety of wire

sizes and mesh size. Typically, the mesh size varies from 80-400 wires per inch with the most popular being 80, 165, 200, 230, 250, 280 and 325. The 80-200 mesh is used for solder masks, 200-230 for resistor prints, 250-280 for dielectric prints and 200-325 for conductor prints. The pattern is produced by adhering a water soluble photosensitive film onto the screen and then exposing it to ultraviolet light. The ultraviolet light hardens the film where it is exposed, leaving the unexposed pattern to be washed out with warm water.

The first step in preparing the screen is the removal of any oils and abrading the screen. Oils from handling can affect the adhesion of the emulsion on the screen. The abrader provides a roughened surface for the emulsion to adhere to on the screen. The degreaser/abrader #78 is commercially available from Ulano, a major supplier of screen printing products.

The second step in producing the pattern is the application of the emulsion. The emulsion comes in a variety of forms and thicknesses. The form we choose to use is the direct emulsion manufactured by Ulano; this can be directly applied to the screen. It is available in thicknesses ranging from 20 microns (CDF-2) to 70 microns (CDF-7). The screen is placed under a water spray so that a fine sheet of water covers the screen, thereby providing a means by which the emulsion can adhere to the wire mesh in the screen.

The emulsion comes in rolls, which can be cut to the proper size. Once the emulsion has been cut and the screen wetted, the emulsion can be applied. The emulsion comes with a supportive mylar backing which will later be removed. The emulsion is

rolled onto the screen (opposite to the cavity side of the screen) being careful not to let any air bubbles get trapped under the screen. Bubbles will cause the pattern in the area of the bubble not to adhere, resulting in a deformity in the printed pattern. Once the emulsion is applied it needs to dry for approximately 30 minutes under a fan, or for about four hours with no air movement. Afterwards, the mylar backing can be removed. If the backing is hard to remove, the emulsion needs to dry longer.

4.1.4 Screen Exposure

The next step in the pattern production is to align the positive onto the screen to be exposed. Screens come in a variety of mesh angles, the most commonly used being 22.5°, 45°, and 90°. The positive at this point will be 4" x 5"; the border of the positive is now removed and the positive is aligned on the screen. Alignment is more critical with 90° screens than for other mesh angles. Care must be taken in lining up the conductor parallel with the mesh for better printing resolution.

After lining up the conductors, the positive should be taped at the edges in order to hold it flat against the screen. This reduces the undercutting effect of the light which can lead to smaller conductor runs. It is also helpful in taping down the pattern to remember the orientation with which the pattern will be printed so that the pattern is not printed upside down. When taping the pattern down it is good practice to double the tape edges over to facilitate tape removal later on.

The screen is then exposed to ultraviolet light for a certain amount of time. This time is dependent on the type of ultraviolet source and the thickness of the emulsion. For

our Microcircuit UV source, screens with one layer of CDF-4 or CDF-5 were exposed for 5 minutes.

4.1.5 Pattern Generation

After exposure, the positive is removed and the screen is washed under slight pressure with water at approximately 100°C. Although it is beneficial to wet the cavity side of the screen every once in a while, one must be careful not to apply too much pressure since this could result in the emulsion pulling away from the screen.

After the pattern is washed out, it is advisable to inspect it under a microscope to ensure that all of the emulsion is removed. If the pattern is satisfactory, the screen can be placed under normal fluorescent lighting in order to firm up the emulsion.

4.1.6 Blanking

The next step in the fabrication is to prepare the slag cast Green Tape™ into a useable format. The Green Tape™ comes in rolls 50 feet long by 10 inches wide. The tape comes in two prefired thicknesses, 4.5 and 12.5 mils. For the inductor application we are using 4.5 851AT tape. The 851AT exhibits the following fired physical properties and electrical properties:

Thermal expansion(25-300°C)	7.9 ppm
Density, Theoretical	3.02g/cm ³
Actual	2.89g/cm ³
Camber	conforms to setter
Surface roughness	8-10 inches
Thermal conductivity	2.2 W/mK

Flexural strength	70 N/mm ²
Biaxial strength	35.2 3 Kpsi
Dielectric constant	7.9 @ 1MHz
Dissipation factor	0.3%
Insulation resistance	10 ¹² @ 100VDC
Breakdown Voltage	1000 VAC/25m
Thickness	4.5 mils

The Green Tape™ is taken from the roll and cut into 4" X 10" strips, removed from the Mylar support and blanked, using a blanking die, into to 3" X 3" squares. In order to hold and align the tape during screen printing and subsequent lamination, registration holes are punched during the blanking process. The registration also play another important purpose. On one corner of the Green Tape™ there is an additional registration hole to help the processor keep tack of the machine and transverse direction of the tape. During processing and lamination every other blank should be rotated 90°. This is due to prevent non-uniform shrinkage in the machine and transverse direction of the Green Tape™ In order to have reproducible lot shrinkages of 12% ± 0.2%, each layer must be placed as above. During the blanking process enough layers of the Green Tape™ are blanked out in order to process the package with extras for alignment purposes.

4.1.7 Via Formation

The vias for the interconnections between the coils were formed using a YAG laser. The blanks were placed on a hold down plate that was placed on the laser table for the cutting of the vias. At an earlier time the proper laser parameters had been

determined for the Green Tape™ samples. The via locations and diameter were entered into a computer program which interfaced to the ESI Model 25 laser then cut the vias. The Green Tape™ vias were cut 10 mils in diameter using 13 Watts at a Q-switch frequency of 1.87 KHz. The via cutting resulted in a hole with no visible burning of the material and a minimum amount of slag or melted glass. Vias of 7, 10, and 17 mils have also been formed using a high speed drill using speeds ranging from 30,000 RPM for 17 mil holes to 85,000 RPM for 7 mil holes.

In order to fill the vias with conductive thick film paste, copper stencils were laser imaged at the same time as the Green Tape™. Imaging the tape and the stencils at the same time eliminated problems due to misalignment from lasering at different times. The copper masks for each layer were cut using 18 Watts at a Q-switch frequency of 2 KHz, and three cutting passes.

4.1.8 Via Filling

Once the vias were lasered they were then filled using on-contact printing with the copper stencils and a porous printer plate. The porous stone helps to hold down the blank during printing. A piece of tissue paper is placed under the blank and the vacuum is turned on. The vacuum helps pull the via paste through the mask and blank and the tissue paper helps to prevent the paste from entering the porous plate and pulling out of the via. The vias were filled using DuPont 6141 silver via paste using a squeegee of durometer 60 and attack angle of 45°. The 6141 via paste has a viscosity of 1000-25000

Pa-S at 25°C. After filling the vias the blanks were then settled and dried as described in section 4.1.10 and 4.1.11.

4.1.9 Printing

The inductive coils were printed using a 5" x 5" screens of mesh 325 and 400 at an angle of 90°. The emulsion applied was Ulano CDF-4. The conductors were printed using a speed of 15mm/s with a snap-off of 30 mils. A 60 durometer squeegee was used with an attack angle of 45. The inner layer and top layer paste used was Dupont 6142 with a viscosity of 170-220 Pa-s. Printing of the coils uses the same printing stone as that of the vias.

4.1.10 Settling

The printed blanks were settled at room temperature for ten minutes under a laminar flow hood in order to remove the mesh impressions and to allow the paste to settle slightly.

4.1.11 Drying

Once the blanks had settled for ten minutes they were then dried at 120°C for fifteen minutes in order to remove the solvents from the printing inks. It is crucial not to dry the Green Tape™ at a higher temperature typical of normal thick film inks, doing so will drive off all of the solvents making the Green Tape™ brittle. This can cause alignment and delamination problems during the lamination phase of the processing.

4.1.12 Collation and Lamination

After the specific layers have been printed, they must then be collated and laminated. Each layer is placed on the laminating die, maintaining the original order. The lamination confining die is then placed into a uniaxial press, and heated at 70°C under 3000 psi of pressure for 10 minutes.

4.1.13 Machining

After lamination the green part must then be cut to remove the excess Green Tape™ from the desired structure. This can also be done using a CO₂ laser after firing. For the cylindrical cores, the Green Tape™ blanks were taken to a machine shop to be formed into a shape that would fit into the pot core. First, each sample was roughed out from the laminated 3" X 3" blank. Then the center of each coil sample was cut to the desired inside diameter using an end mill. The coil was then placed on a spindle and the outside diameter was turned down to the desired dimensions using a lathe.

4.1.14 Burnout

The next step in the fabrication of the package is to burn out the organics from the green laminate. This is accomplished placing the laminate on an alumina or quartz setter and then placing the part in a programmable box furnace. This is done using a burnout profile, with a peak temperature of 350°C for 60 minutes. The part is removed

from the box furnace, and once it has reached ambient temperature, is placed in a typical belt furnace. For the thicker samples the peak temperature was held for 120 minutes in order to remove all of the volatiles from the ceramic.

4.1.15 Firing

The Green Tape™ laminate is fired using an extended 850°C profile. This profile provides for a rise rate and a descent rate of 50°C/min with a peak firing temperature of at least 850°C for 15 minutes. The substrates were fired in a four and five zone convection conveyor furnaces.

4.2. Pyralux® Coil Fabrication

Pyralux® copper-clad laminated composites are constructed of DuPont Kapton® polyimide film with copper foil on one or both sides, bonded together with a proprietary c-staged modified acrylic adhesive. All copper-clad laminates are available with rolled, annealed or electro-deposited copper. In addition, both types are available with double-treated copper (nodules of electro-deposited copper on both sides of the copper foil). Double-treated copper; if used, eliminates surface preparation steps prior to resist or coverlay lamination. The Pyralux® system comes in a variety of single and double-sided copper composites with dielectric film thicknesses ranging from .5 to 5 mils, acrylic adhesive ranging from .5 to 2 mils and copper weights of 1/8 to 2 oz./ft². In some ways the Pyralux® coil fabrication follows the same processing steps as that of the

Green Tape™ The design steps are the same as the Green Tape™ but the shrinkage correction factor is not needed in the design of the coils.

Pyr lux® processing differs from that of the thick film in that it is a subtractive not additive process. The circuits can be fabricated using single or double sided composites which are connected to each other through plated-through holes (PTH) or silver-through holes (STH). The STH's are formed by filling the vias of the circuit with an conductive silver epoxy, whereas the PTH's are formed by plating the walls of the vias using electroless and electroplating followed by solder plating. The Pyralux® coil samples were fabricated using STH's and PTH's

4.2.1 Plotting and Master Artwork Generation

Same as Green Tape™

4.2.2 Reduction of Master Artwork

Same as Green Tape™

4.2.3 Blanking

The Pyralux® samples are blanked in the same manner as the Green Tape™ samples using a 3" X 3" blanking die. This helps in registration of the various layers of the sample.

4.2.4 Cleaning of the Pyralux®

After blanking the Pyralux®, the surface is then prepared for the imaging and etching process. The Pyralux® blanks are first cleaned using methyl alcohol in order to remove an anti-tarnish agent applied by the manufacturer. Next the surface is cleaned with a slightly abrasive cleaner in order to remove any oils or oxidation that might be on the surface. The abrasive cleaner also helps to prepare the surface for the photoresist application. After cleaning the samples are rinsed with deionized water and then heated or pre-baked before the photoresist application at 100°C.

4.2.5 Photoresist Application

The various structures can be imaged using screen-printed, spun liquid, or dry-film photoresist. In order to image the sample Shipley 1400-27 Micropositive photoresist was applied using a spin coater at 3000 RPM for 30 seconds. The photoresist was then post-baked at 100°C.

4.2.6 Imaging/Exposure

The coils were imaged on the Pyralux® using the photopositives as the mask. The photopositives were aligned on the Pyralux® samples using the registration markers to align the samples. Once the samples were aligned, a glass plate was then placed and secured over the sample. The sample was then exposed for seven seconds using a 1000 W UV exposure system to produce the image.

4.2.7 Developing

After exposure the samples were then developed in Shipley 353 developing solution to remove the exposed photoresist. After development the samples were then rinsed in deionized water.

4.2.8 Etching

The samples were etched in a copper sulfate solution using a spray etcher. Each sample was etched for 5-10 minutes depending on the amount of copper already absorbed by the sulfate the solution. The spray etcher has advantages over a solution with mechanical agitation in that it will provide a fresh solution over the Hxrface of the sample, providing a faster etch rate.

4.2.9 Via Formation

Vias were formed in the Pyralux® using a high speed programmable drill rotating at 30,000-40,000 RPM for a 17 and 10 mil drill bit respectively. In order to drill acceptable holes an entry material of Mylar® and an exit material of litho paper was used. The samples and corresponding adhesive layers with entry and exit materials were stacked onto the drill, hold down and the via holes were all drilled at one time.

4.2.10 Drying

Once the laminates were drilled they were then dried in an oven at 100°C for 60 minutes to remove any moisture before lamination. Pyralux® and the modified acrylic

adhesive are capable of absorbing water up to 33% of their weight which can lead to problems during lamination.

4.2.11 Epoxy Via Fill, Silver-Through-Holes(STH)

Some of the Pyralux® samples processed were interconnected using a conductive polyimide silver epoxy (STH's). After drying each layer of Pyralux® and modified epoxy were individually filled using Epo-Tek P10 polyimide epoxy. The epoxy cured during the lamination process making acceptable interconnections. One advantage to using the polyimide is that the coefficient of expansion is roughly the same as the Pyralux® samples.

4.2.12 Lamination

The samples were laminated using a soft-pad lamination system so that the samples would conform around the various coil windings during lamination. The soft pad system is a stack of materials comprised of a layer of 200 A FEP film on the bottom, the structure to be laminated, 200A FEP film, litho paper, clear vinyl (18 mils), litho paper, and 200 A FEP film. The samples and soft pad are collated and placed onto the lamination die. The samples were laminated on an uniaxial press at 350°F and 335 psi of pressure maintaining both heat and pressure for one hour. After one hour the platen heaters were turned off and the platens were allowed to cool to 212°F, at which time cooling water was applied to bring the samples to room temperature.

4.2.13 Plated-Through-Hole (PTH) Vias

PTH's are fabricated by depositing copper through electroless and later electroplating onto the walls of the vias. The process is described below in the following sections.

4.2.13.1 Imaging

Through holes are first plated using an electroless solution to plate a thin coating of copper onto the walls of the vias. The main problem with electroless copper is that it will plate any exposed area of the sample. In order to eliminate any unwanted plating, the samples must first be imaged using a photoresist. For this application the positive photoresist will not work. The positive photoresist is a basic will react with the acidic copper sulphate solution and not adhere to the sample. In order to image the sample a xylene negative photoresist solution was applied to the coils. Selectilux negative photoresist, was applied to the sample and the sample was imaged using a negative as described earlier in the report. Once the sample was imaged, the vias were drilled using the programmable drill.

4.2.13.2 Electroless Plating

After drilling the vias were plated using an electroless copper solution. The first step in this process was to sensitize the polyimide surface using a acidic sensitizing solution. The Transene sensitizer prepares the surface for better adhesion of the copper film. The sample is placed in the sensitizer for a period of two minutes. The next step

in the process is to place the sample in a Transene activator solution. The activator solution activates the surface of the sample in preparation for the electroless plating. The samples were placed in a two part electroless solution and plated for 2 hours at 40°C with moderate mechanical agitation of 250 RPM using a teflon coated magnetic stirring rod.

4.2.13.3 Electroplating

After electroless plating the samples were electroplated in a copper sulfate solution. A copper bar was used as the anode and a wire was soldered to the sample to serve as the cathode for the plating solution. The sample was plated for one hour at a temperature of 100°C, at a voltage of 3 volts and a current of 1 A under slight mechanical agitation of the solution.

4.2.13.4 Resist Stripping

After plating the negative photoresist was removed using Lansolin photoresist stripper. The sample was placed in the stripping solution for fifteen minutes and the copper was mechanically removed from the sample using a cotton swab. This was necessitated due to the copper deposition covering the photoresist and which made it harder to strip the photoresist.

4.2.14 Machining

After lamination, the Pyralux® must then be cut to remove the excess Pyralux® from the desired structure. This was done in the same manner the Green Tape™ coils were formed.

4.3 Summary

This chapter describes the fabrication of the Green Tape™ and Pyralux® coils. Each step of the process is described for both coil fabrication techniques. Six Green Tape™ and eight Pyralux® coil were fabricated.

Chapter 5

Coil Measurements

5.1 Design and Measurement of Coils

After the coils were fabricated they were then measured using a HP 4172 LCR meter, an HP 4192 impedance analyzer, and a HP 4194 Impedance analyzer. In the following two sections the sample designs are discussed and the inductance, resistance and quality factor measurements are shown graphically. Although the measurements were taken up to 2 MHz, the frequency of operation of a typical inductive proximity sensor is in the 100 to 300 KHz range.

5.2 Green Tape™ Coil Sample Measurements

5.2.1 Green Tape™ Sample 1

The first coil fabricated was a three layer inductor with three turns per layer. This coil was to show feasibility and to determine a "ball park figure" for the inductance and quality factors achievable with this technology. The first coil was designed approximately to the core dimensions. Subsequent designs were fabricated to the dimensions of the optimized core. The first design had three turns 17.6 mils wide, with a spacing of 4.4 mils and a shape coefficient(d_i/d_o) of 0.6760 after shrinkage. The interconnections between layers were made with 10 mil vias. The first Green Tape™ coil was measured and had the following measurements; 1.75 microhenries inductance, 2.53 ohms resistance at 200Khz. At this time the inductance measurements showed

promise, but the quality factor was lacking. The low quality factor was attributed to contact resistance during measurement. The inductance and Q versus frequency are shown in Figure 5.1.

5.2.2 Green Tape™ Sample 2

Based on the results of the first Green Tape™ sample a second Green Tape™ sample was designed to fit into a optimized core with a thinner center leg than the current pot core. The second design had conductor widths of 46.64 mils, spacing of 7.92 mils and a shape coefficient of 0.2989. It was decided not to fabricate the coil for the optimized core, since there was no way to reliably fabricate a core of the same properties as the current 30mm core that was being used.

5.2.3 Green Tape™ Sample 3

The third Green Tape™ sample was designed for the optimized shielded core. The sample had 5 turns, 15 layers(plus bottom connection layer), conductor widths of 14 mils, spacing of 4.4 mils and a shape coefficient of 0.647. The interconnections between layers were made with 10 mil vias. Since the shielded Green Tape™ coils were cut during machining, measurements were unobtainable.

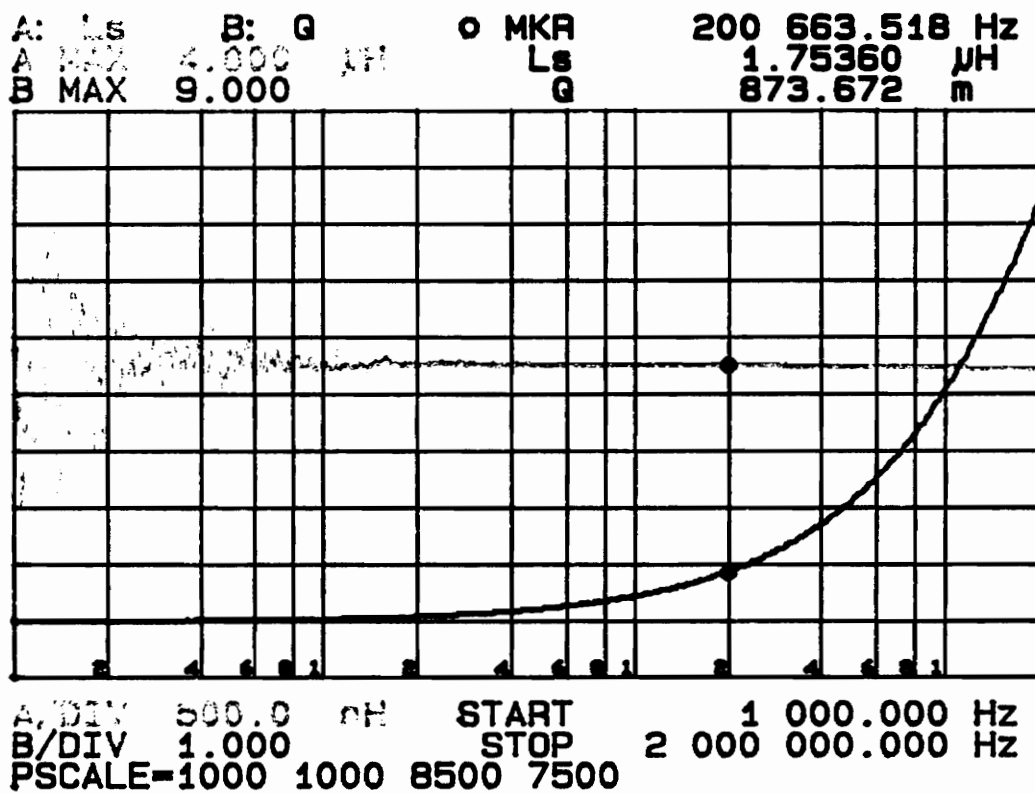


Figure 5.1 L and Q Versus Frequency for Green Tape™ Sample 1

5.2.4 Green Tape™ Sample 4

The fourth Green Tape™ sample was a designed for the optimized unshielded core. The sample had 5 turns, 15 layers (plus bottom connection layer), conductor widths of 27 mils, spacing of 4.4 mils and a shape coefficient of 0.54. The coil exhibited an inductance of 117 microhenries and a quality factor of 3.55 at 300 KHz. The inductance and Q versus frequency are shown in Figure 5. 2.

5.2.5 Green Tape™ Sample 5

The fifth Green Tape™ sample was a designed for the optimized shielded core. The sample had 3 turns, 32 layers, conductor widths of 29 mils, spacing of 4.4 mils and a shape coefficient of 0.644. The first Green Tape™ sample had a low quality factor that was thought to be attributable to the contact resistance during measurement. After the measurements in sample 4 also demonstrated a low quality factor, there was concern that the vias could be the cause of the additional resistance. Scanning Electron Microscope photos shown in Figure 5.3 displays a good interconnection between the adjacent layers, but in order to reduce any resistance due to the vias two 10 mil vias were placed in parallel in adjacent tape layers. Also of concern in the Green Tape™ layers was the fired print thickness of 6-9 microns for the silver conductors. In order to reduce the resistance due to the thickness of the printed conductor, each layer was printed twice, the conductors were widened and two layers were connected in parallel before the series connection was made. The resulting structure was a coil of 32 instead of 16 layers normally used in the

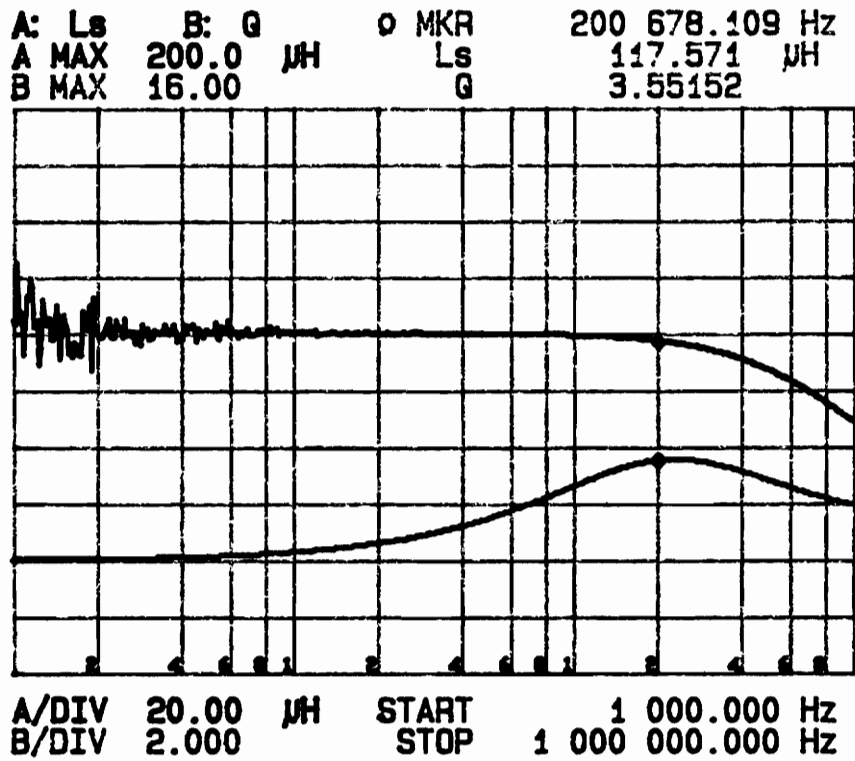


Figure 5.2 L and Q Versus Frequency for Green Tape™ Sample 4

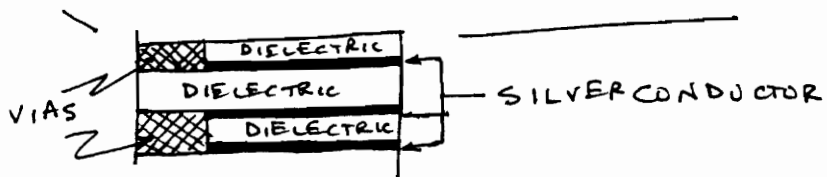


Figure 5.3 SEM Photographs of Vias

other designs. The coil resulted in an inductance of 38 microhenries, a quality factor of 5.8 and a resistance of 12.7 ohms at a frequency of 300 KHz. The L and Q versus and L and R versus frequency are shown in Figure 5.4 and 5.5 respectively.

5.2.6 Green Tape™ Sample 6

The sixth Green Tape™ sample was designed for the optimized shielded core. The sample had 3 turns, 32 layers, conductor widths of 23 mils, spacing of 13 mils and a shape coefficient of 0.54. Sample six was the same design as sample 5 with the addition of printing a coil on the bottom of the adjacent Green Tape™ layer. This would in effect be the same as four conductor prints for the parallel spiral layers. The top or spiral printed on the adjacent layer was not as thick and the spacing was increased between the layers so that the spiral would not be shorted. Although the spiral design works in theory, in practice some of the layers were shorted. This could be due in part to alignment or due to paste flow during the firing process. Although the coils were shorted the connection through the vias did not seem to contribute to the large values of resistance seen in sample four and five. The L and R versus frequency are shown in Figure 5.6

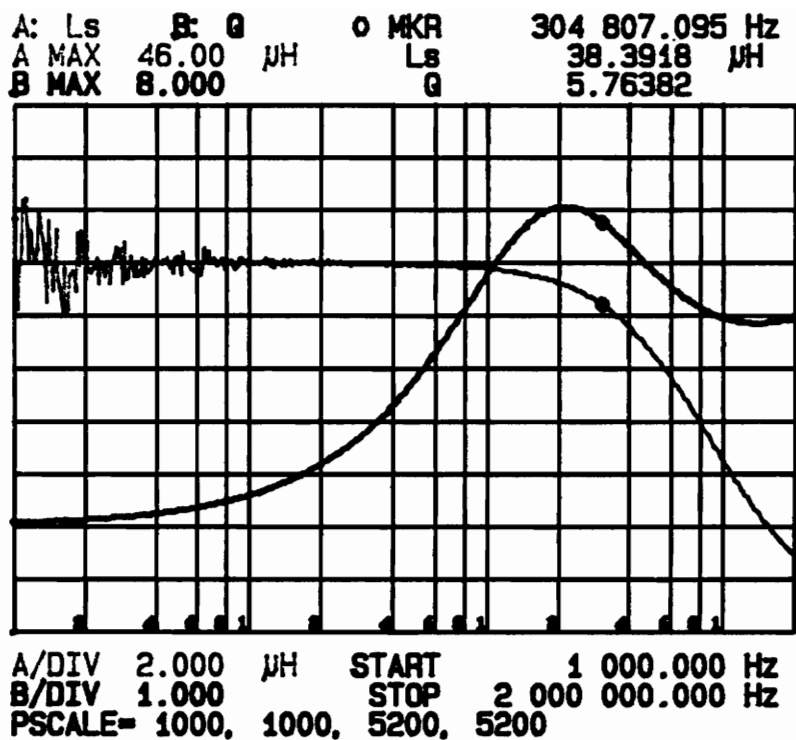


Figure 5.4 L and Q Versus Frequency for Green Tape™ Sample 5

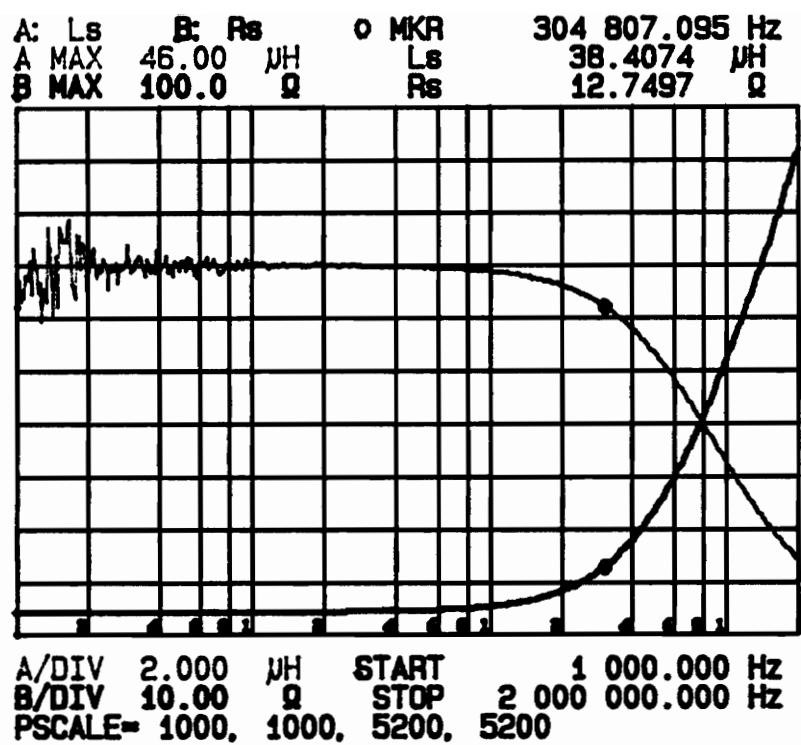


Figure 5.5 L and R_s Versus Frequency for Green Tape™ Sample 5

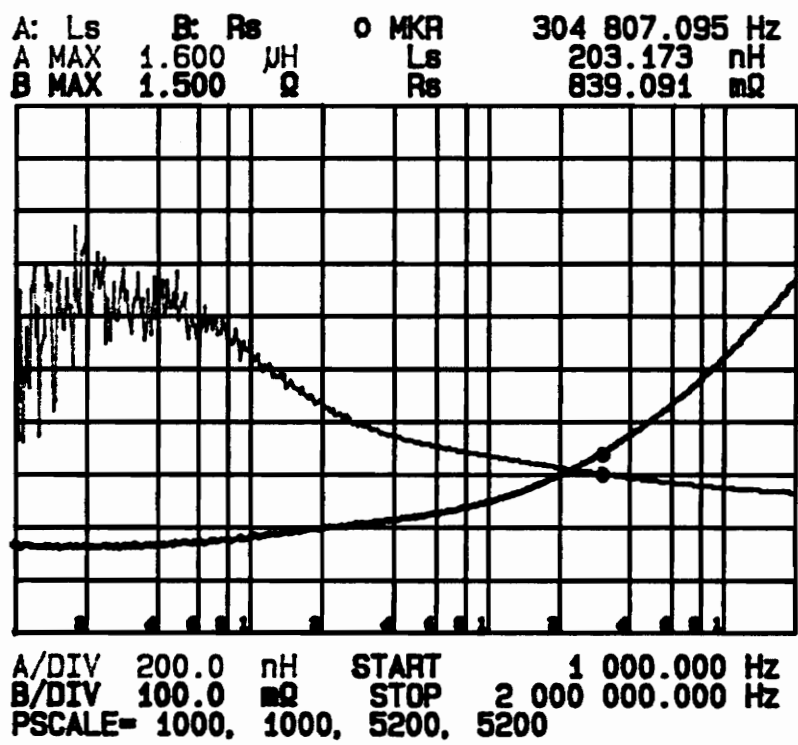


Figure 5.6 L and R_s Versus Frequency for GreenTape™ Sample 6

5.3. Measurement of Pyralux® Coils

The Pyralux® were fabricated in the same manner as the Green Tape™ coils using a series connection in order to connect the spirals on each tape layer. The samples were fabricated using single-sided copper-clad laminated composites. The laminates are made up of copper rolled or electrically bonded with a proprietary C-stage modified acrylic adhesive onto the KAPTON® dielectric. The various materials used were:

Table 5.1 Available Pyralux® Composites

Product Code	Copper (oz/ft ²)	Adhesive (mils)	Kapton® (mils)
LF9110	1	1	1
LF9120	1	1	2
LF9150	1	1	5
LF9220	2	1	2
LF0110		1	1
LF0120		1	2
LF0100		1	

5.3.1 Pyralux® Sample 1

The first Pyralux® sample was the same design as the Green Tape™ sample 2 for the optimized core with a thinner center leg. Although the Green Tape™ sample was not fabricated a few of the Pyralux® layers were etched and laminated together. The sample had 4 turns, conductor widths of 50 mils, spacing of 7 mils and a shape coefficient of 0.2948. The interconnections between layers were made using 10 mils via with conductive epoxy. The Pyralux® samples were fabricated using LF9120 and LF0100 resulting in an inductance of 330 nH and a Q of 3.2 for 1 layer at 200KHz. The L and Q versus frequency curve is shown in Figure 5.7.

5.3.2 Pyralux® Sample 2

The second Pyralux® sample was another design for the optimized core with a thin center leg. The sample had 7 turns, 10 layers, conductor widths of 24 mils, spacing of 6 mils and a shape coefficient of 0.2948. The interconnection were made between the layers using 10 mil vias with silver epoxy. The Pyralux® samples were fabricated using LF9120 and LF0100 resulting in an inductance of 39 microhenries and a Q of 10.7 for 1 layer at 200KHz. The L and Q versus frequency curve is shown in Figure 5.9.

5.3.3 Pyralux® Sample 3

The third Pyralux® sample was designed for the optimized shielded core. The sample had 5 turns, 15 layers, conductor widths of 14 mils, spacing of 5 mils and a shape

coefficient of 0.644. The interconnection were made between the layers using 10 mil vias with silver

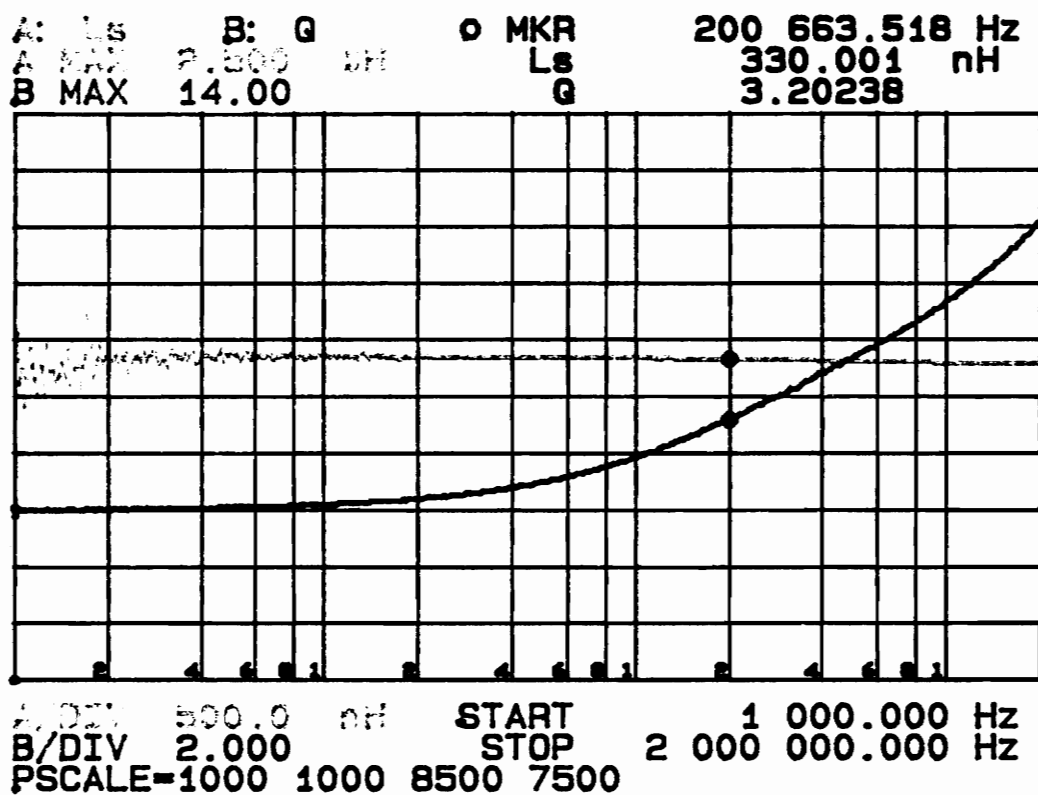


Figure 5.7 L and Q Versus Frequency for Pyralux® Sample 1

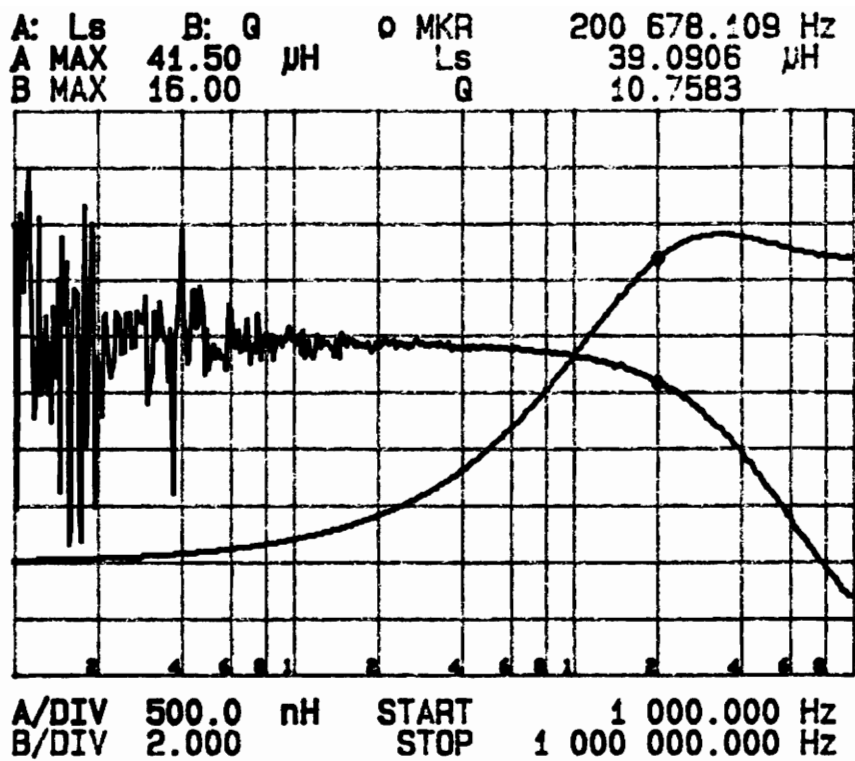


Figure 5.8 L and Q Versus Frequency for Pyralux® Sample 2

epoxy. The Pyralux® samples were fabricated using LF9120 and LF0100 resulting in a inductance of 26 microhenries and a Q of 1.15 at 200KHz. The L and Q versus frequency curve is shown in Figure 5.9.

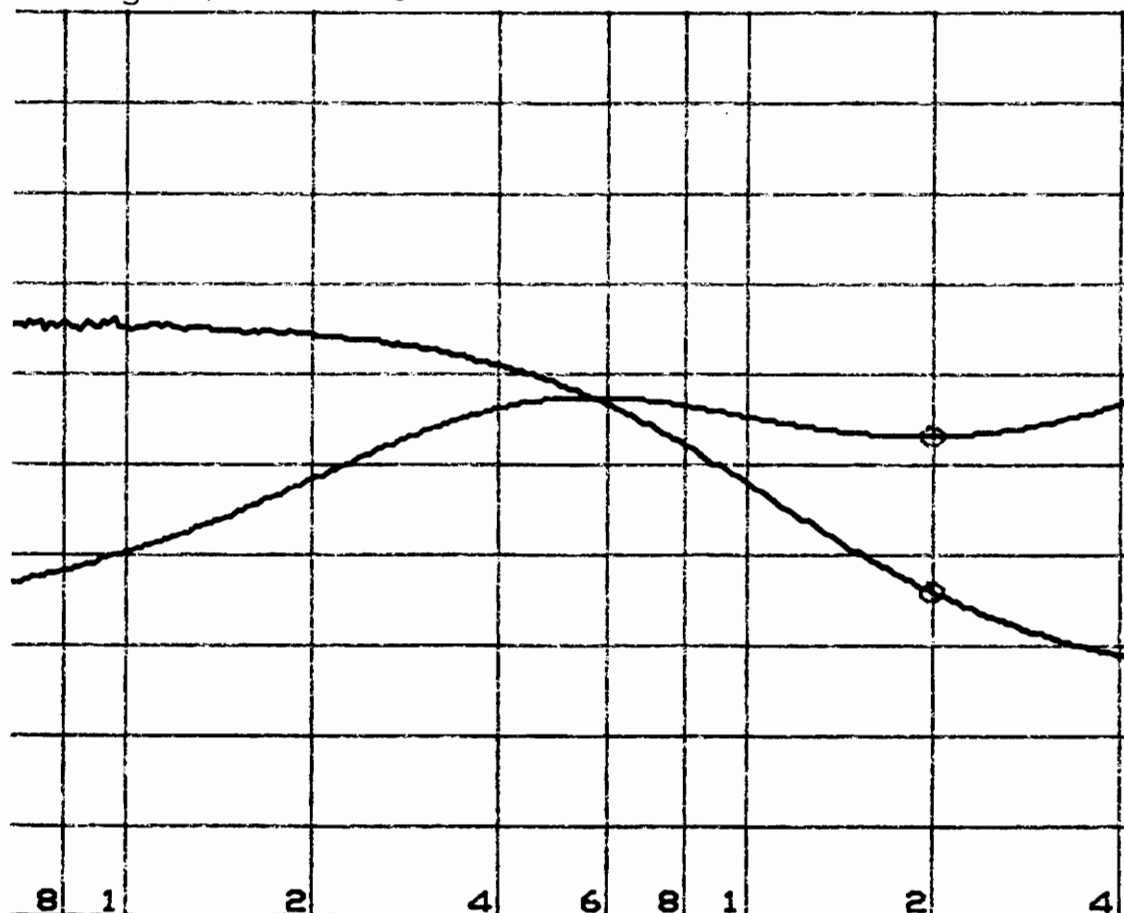
5.3.4 Pyralux® Sample 4

The third Pyralux® sample was designed for the optimized unshielded core. The sample had 5 turns, 15 layers, conductor widths of 24 mils, spacing of 5 mils and a shape coefficient of 0.54. The interconnection were made between the layers using 10 mil vias with silver epoxy. The Pyralux® samples were fabricated using LF9120 and LF0100 resulting in a inductance of 30 microhenries and a Q of 1.14 at 200KHz. The L and Q versus frequency curve is shown in Figure 5.10.

5.3.5 Pyralux® Sample 5

The fifth Pyralux® sample was the same as the fourth example, with the exception that the KAPTON® dielectric layer was 5 mils(LF9150) instead of 2 mils thick(LF9120). The sample resulted in a inductance of 9.6 microhenries and a Q of 1.04 at 200KHz. The L and Q versus frequency curve is shown in Figure 5.11.

Q O MKR 200 678.10
 μH A MAX 90.00 LS 25.8321
 B MAX 3.5 Q 1.15242



10 kHz 100 kHz
 μH START 1 000.00
 m STOP 1 000 000.00
 A/DIV 10.00 μH HZ
 B/DIV 500 m

Figure 5.9 L and Q Versus Frequency for Pyralux® Sample 3

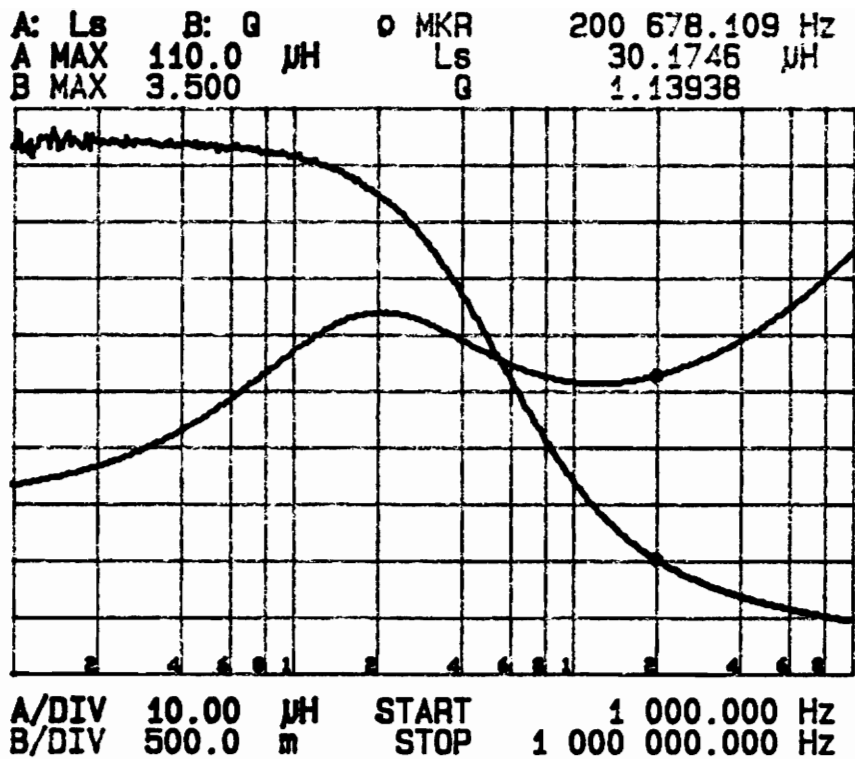


Figure 5.10 L and Q Versus Frequency for Pyralux® Sample 4

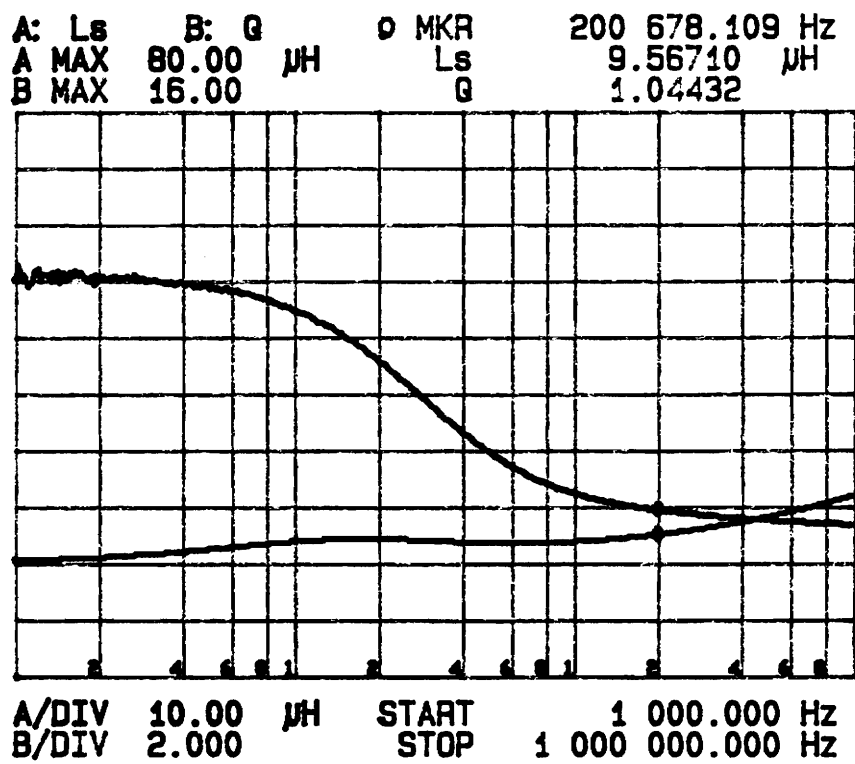


Figure 5.11 L and Q Versus Frequency for Pyralux® Sample 5

5.2.6 Pyralux® Sample 6

The Pyralux® samples also displayed a low quality factor from that which was expected from the various designs. As in the Green Tape™ the vias became suspect in the Pyralux® samples. Typically silver epoxies will display a higher resistance at high frequency and at high current. It was not known whether the vias were causing a high resistance/low quality factor, therefore it was decided to change the coil design to accommodate plated through holes(PTH). The design was made such that 17 mil PTH via connections for each subsequent layer were made at consecutive 45 angles on the inside and outside circumference of the coil. The sample had 5 turns, 15 layers, conductor widths of 15 mils, spacing of 5 mils and a shape coefficient of 0.645. The sample was fabricated using LF9110 and L0111 and the vias were plated using an electroless solution only. The coil had an inductance of 33 microhenries, a quality factor of 2.6 and a resistance of 25 ohms. The L, Q and L, R versus frequency before the coil was cut are shown in Figures 5.12 and 5.13 respectively. The coil was then cut and measurements were again taken of the coils performance. The results are shown in Figures 5.14, and 5.15. The resistance increased 5 ohms and the Q decreased proportionally. The increase in resistance can be attributed to some of the vias being partially cut during the machining process. In doing so, some of the copper forming the PTH for some of the vias was removed.

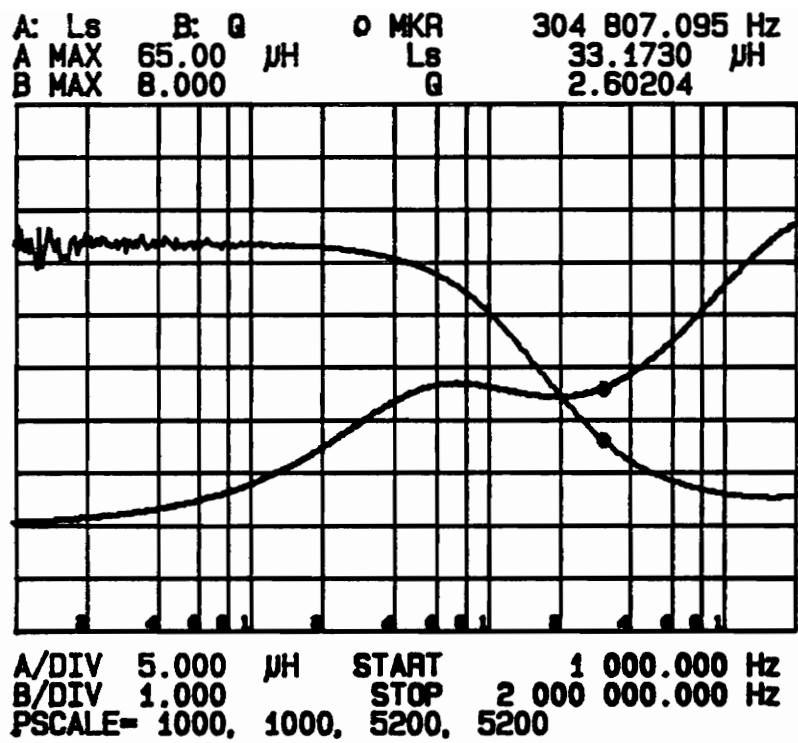


Figure 5.12 L and Q Versus Frequency for Pyralux® Sample 6 Before Machining

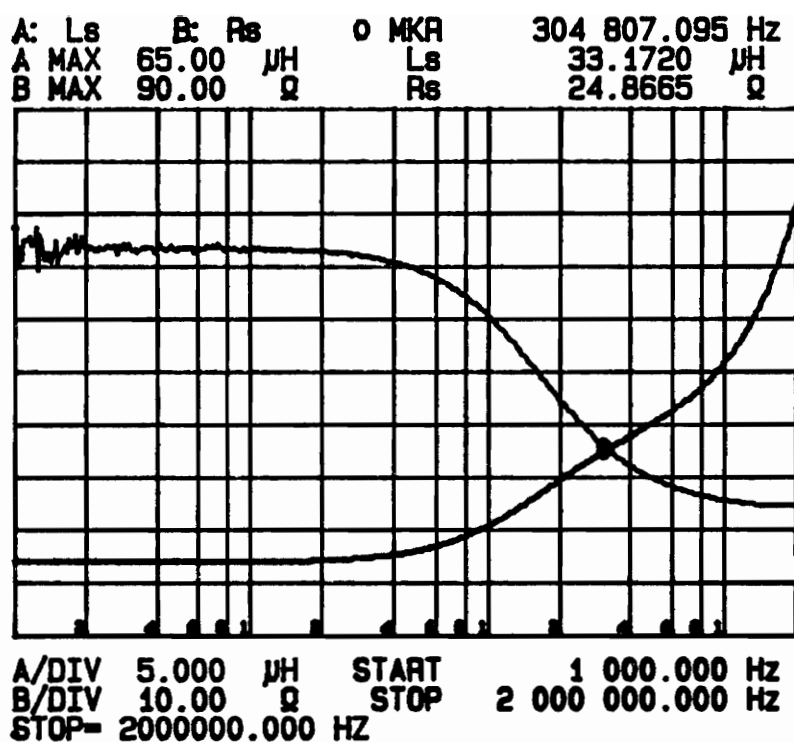


Figure 5.13 L and R_s Versus Frequency for Pyralux® Sample 6 Before Machining

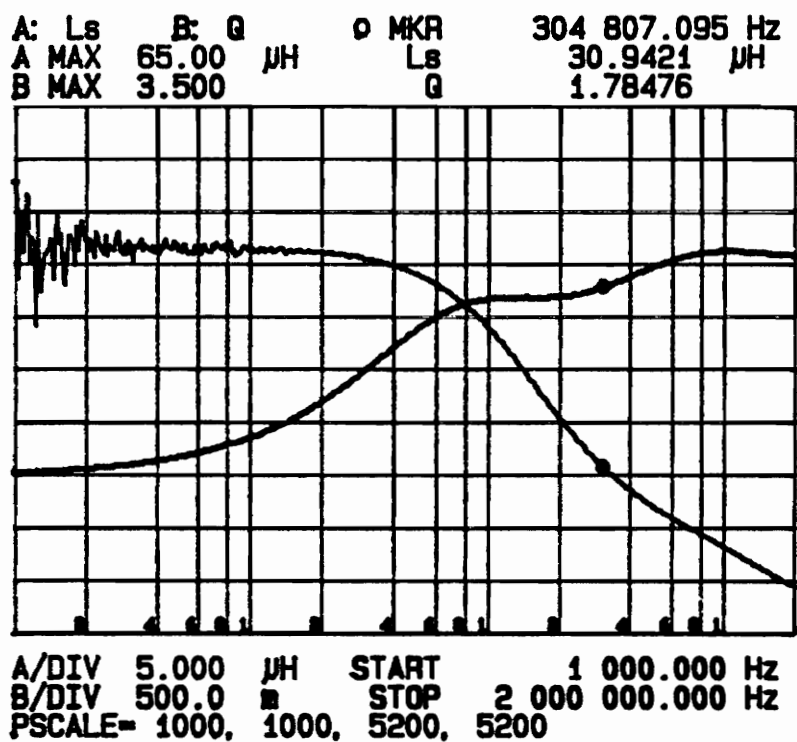


Figure 5.14 L and Q Versus Frequency for Pyralux® Sample 6 After Machining

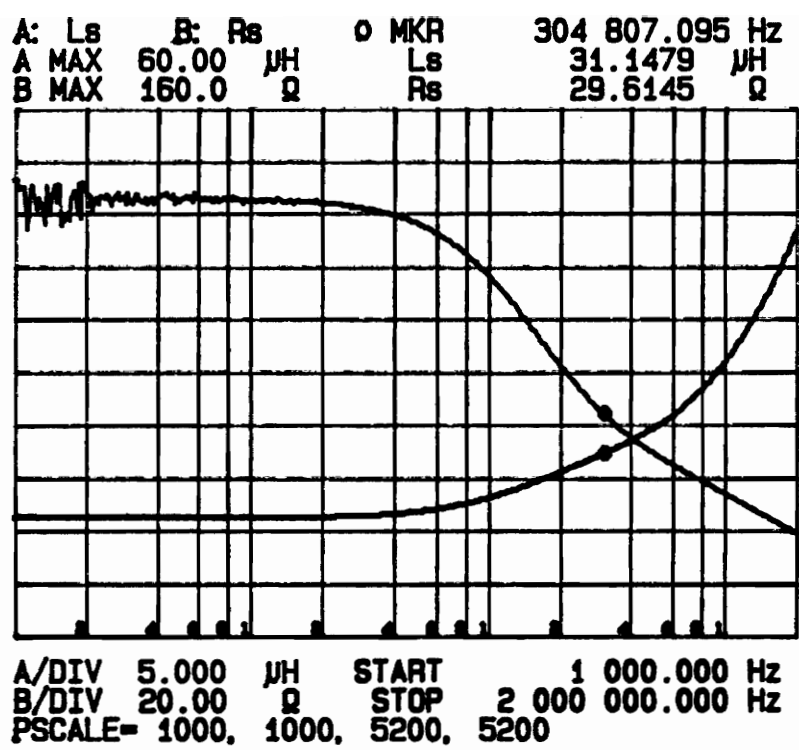


Figure 5.15 L and R_s Versus Frequency for Pyralux® Sample 6 After Machining

5.2.7 Pyralux® Sample 7

Sample seven was of the same design as that of sample six with the addition of 1 layer of LF0100 and LF0120 in order to see the effect of an increase in dielectric thickness. The results are shown in Figure 5.16 and 5.17. This experiment was to possibly determine to what degree proximity effects between the layers had to do with the increase in ac resistance. The experiment proved inconclusive due to the thin plating and increase of resistance in the vias.

5.3.8 Pyralux® Sample 8

The last Pyralux® sample was to determine if the proximity effects due to the parallel conductors had any effect on the increase in ac resistance. A 13 layer, 3 turn per layer coil of conductor width 11 mils and spacing of 24 mils with a shape coefficient of 0.645 was interconnected using STH's. The coils demonstrated an inductance of 18 microhenries, a quality factor of 3.5 and a resistance of 9.4 ohms at 300 KHz.

5.4 Summary

Shown following in Table 5.3 and 5.4 are the results comparing the various coil geometries and measurements. Also shown for comparison purposes are the calculated values of inductance and Q using Wheelers' and Dodd's formulae. Care should be taken in making direct comparison between the coils designs, due to the different number of turns, conductor thicknesses, measurement frequency etc.

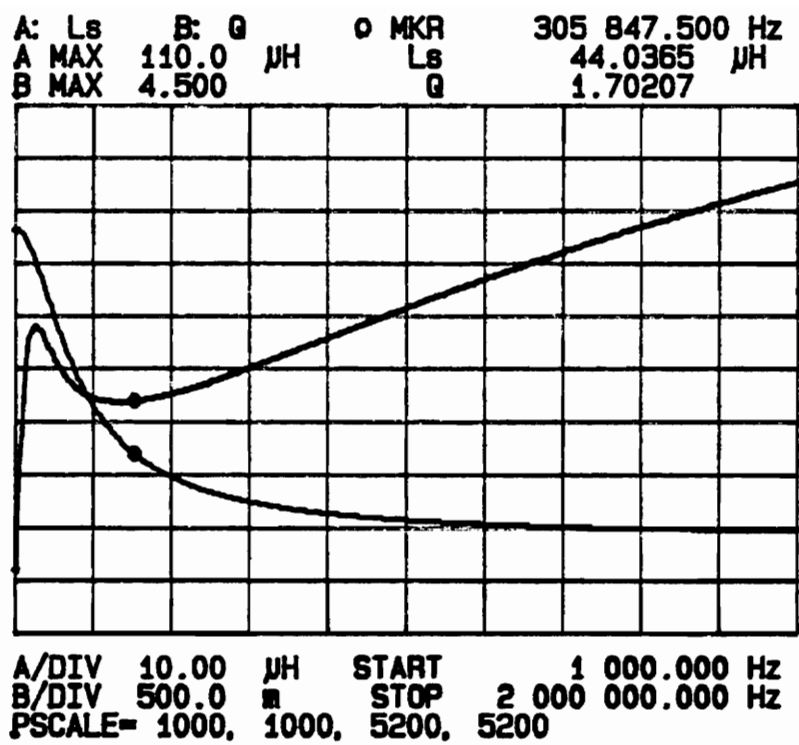


Figure 5.16 L and Q Versus Frequency for Pyralux® Sample 7

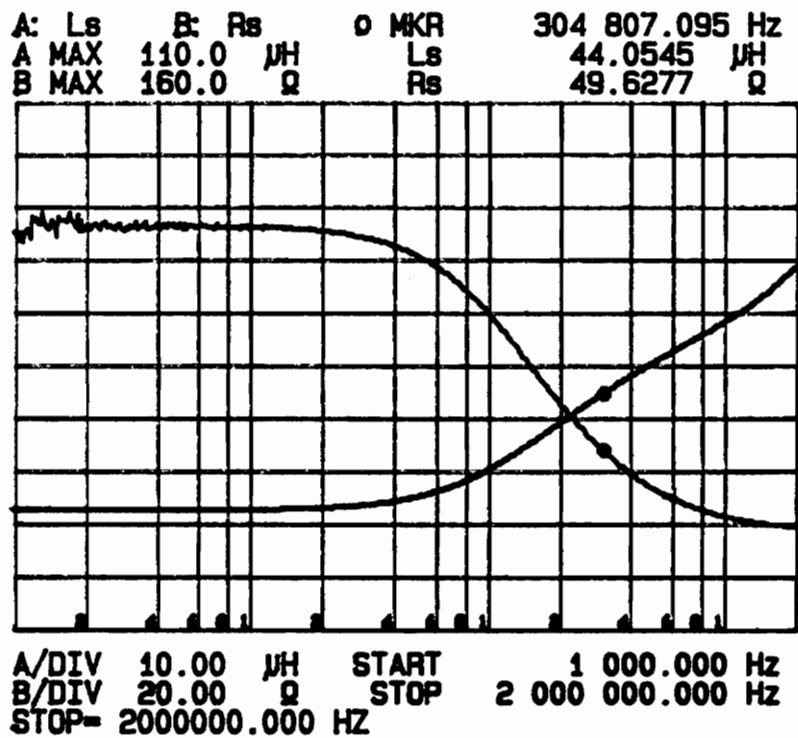


Figure 5.17 L and R_s Versus Frequency for Pyralux® Sample 7

Table 5.3. Green Tape™ Calculation/Measurement Summary

Sample	L μ H Wheeler's Formula	L μ H Dodd's Formula	Q Wheeler's Formula	Q Dodd's Formula	L μ H Measured	Q Measured
GT1	1.48	1.52	0.44	0.45	1.75	0.87
GT2	46.83	43.41	0.48	0.04	NA	NA
GT3	102.00	90.38	2.71	2.40	NA	NA
GT4	100.70	91.65	2.27	2.07	117.00	3.55
GT5	45.23	40.45	5.17	4.62	38.00	5.80
GT6	45.23	40.45	4.20	3.75	SHORT	SHORT

Table 5.4. Pyralux® Calculation/Measurement Summary

Sample	L μ H Wheeler's Formula	L μ H Dodd's Formula	Q Wheeler's Formula	Q Dodd's Formula	L μ H Measured	Q Measured
P1	0.10	0.19	0.04	0.09	0.33	3.20
P2	27.75	56.34	0.22	0.44	39.00	10.70
P3	60.61	91.43	1.66	2.51	26.00	1.15
P4	53.94	92.80	0.59	1.02	30.00	1.14
P5	62.69	85.72	3.43	4.69	9.60	5.80
P6	62.69	101.38	0.92	1.49	33.00	2.60
P7	62.69	89.11	2.69	3.82	44.00	1.70
P8	16.95	26.81	2.96	4.68	18.00	3.50

Shown in Figure 5.18 is a picture of a Green Tape™ and Pyralux®coil for the 30mm shielded coils.

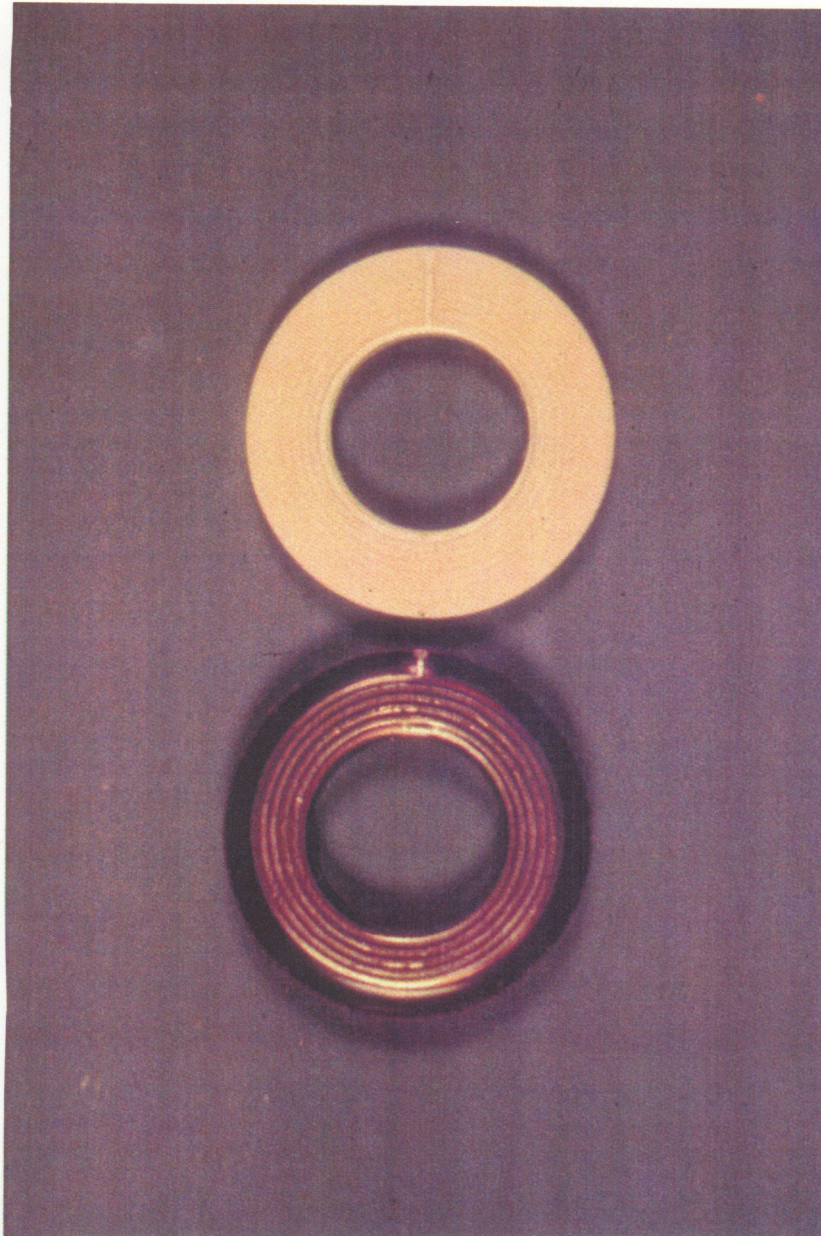


Figure 5.18 Green Tape™ and Pyralux® Coils

Chapter 6

Summary and Conclusion

Solid state inductors using Green Tape™ and Pyralux® materials were fabricated for the modified shielded and unshielded cores. The results indicate that the inductance values needed for either the shielded or unshielded sensor design are readily obtainable using LTCC's or flexible composite materials that utilize thick film and PCB material technologies. The fabrication methods show that the coils can be fabricated in a reliable, repeatable manner with promise for high yield.

The Green Tape™ coils were successfully produced exhibiting inductance of up to 120 microhenries and Q's of up to 6. In this work, various methods have successfully been employed in order to reduce the dc resistance of the coils; such as multiple vias, double printing of coils, and connection of layers in parallel. Overall, six designs were fabricated, some with up to 75 turns and 32 layers. Coils were printed with coil spacing as small as 4.4 mils.

The Pyralux® coils were successfully produced using STH and PTH technologies. Eight samples were fabricated, resulting in Q's of up to 11 and inductances of up to 105 microhenries. The composite were successfully fabricated with up to 75 turns and 16 conducting layers with etched line spacing of 5 mils.

Both Green Tape™ and Pyralux® represent materials that can be effectively utilized as an alternative to the current hand winding of coils. The only problem left to address, is the low Q factor exhibited by both the Green Tape™ and Pyralux® coils.

The fabricated coils did not exhibit a high Q factor, due to the a variety of causes. The coil resistance was due to the geometrical factors related to the size of the core (fixed inner and outer diameters), geometry of the windings and conductor layer thickness, and dielectric thickness all contribute to increase the distributed capacitance, skin resistance, and proximity resistance of the coils. For the specefic 30mm designs the quality factor at the frequencies of interest 100-300 KHz can be improved by designing the coils to limit the increase in resistance due to the proximity effect.

The proximity effect leads to main increase in resistance at the frequencies. It is suggested that in order to limit these effects that the conductors or printed windings be connected in paralelle to a litz winding but in a planar manner. This would lead to a decrease in the proximity effect and a proportional increase in the overall quality factor. This is obviously not the only means to increase the quality factor, the designer must also design the coils in a manner that will minimize capacitance and resistance. The coils under consideration give a large value of inductance which is promising for a number of applications including planar and integrated magnetics for applications such as power supplies. Coupled with a low resistance and interlayer capacitance this can lead to high quality factors.

As part of this work the models were developed for inductance, resistance, capacitance and quality factor. Although these values give an approximate value for the

various parameters, the accuracy of the results vary with design. Future work can also be applied to the models in order to increase their accuracy. The model developed for the quality factor was a lumped parameter model whereas for better results it would be advantageous model the capacitance as a distributed capacitance.

There are several areas of potential research that can follow this work. It is suggested that additional coils be simulated and fabricated in order to further verify the some of the models developed in this work. It is also suggested that the coils be optimized for the losses in order to provide for the highest possible quality factor. This may be possible by forming a number of parallel conductors on each layer of the multilayer material similar to the method employed in litz windings. The planar magnetics are also useful in a variety of other applications including power supplies, automotive electronic, avionics, etc. Further research and development of integrated magnetics in electronics will be needed in order to decrease the size of magnetics in order to keep pace with the decreasing size and increasing capabilities of other components in electronic circuitry. The main limitation in current electronics is the size of the magnetics, the complexity of the interconnections, the interface with the outside environment and the packaging of these electronics. Planar magnetics will play a major role in electronics far into the future.

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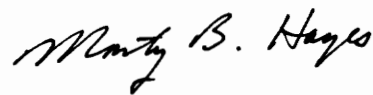
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Vita

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A handwritten signature in black ink that reads "Marty B. Hayes". The signature is written in a cursive, flowing style.