

Embedded Magnetics Technology Overview

Jim Quilici
Radial Electronics
El Dorado Hills, Ca.

Abstract — Inductors and transformers are basic building blocks in electronic systems. Their functions include energy storage, signal filtering, voltage isolation, and impedance matching. Applications range from power conversion, communications, and electronic sensors. Embedded magnetics provides a new approach for fabricating transformers and inductors. Ferrite elements are embedded into an FR4 substrate and the device windings are realized using printed circuits techniques. In comparison, the vast majority of small transformers and inductors, used today in communications and power conversion, wound manually one at a time or by using semi-automatic equipment. Manual soldering and assembly is often employed to install these devices into their respective packages. The advantage of the embedded approach is that it uses a batch assembly process that is highly automated. With automation comes improved consistency and reliability. This paper describes the device composition and fabrication on a printed circuit line.

Background

Magnetic components are used in all types of communication and RF systems. Transformers provide voltage isolation and impedance matching while inductors are used for energy storage and in filter circuits. In many cases, these components are wound on small cores made of ferrite or other magnetic materials. The toroid shape is the most efficient for establishing a magnetic reluctance path through the core material and transferring electromagnetic energy between the windings. The small size of many RF transformers and inductors has defied automation and generally these devices are hand wound. Figure 1, show a typical transformer used for LAN communications. The Ethernet application use 8 of these small transformers to interface the transceiver silicon to the transmission cable. Typically these devices are integrated into the Ethernet RJ45 connector or packaged in a discrete module that is sits on the system board between the connector and the transceiver. The transformers provide the functions of voltage isolation, impedance matching and filtering. To date, these small transformers have defied automation. While they can be made cheaply with off shore labor, the performance and reliability can vary greatly due to manual assembly.



Figure 1, Wound toroid transformer

In most applications, the magnetic components are used in conjunction with an Integrated Circuits (IC). Over the years, the silicon industry has worked to bring failure rates below the range of 50 parts per million (ppm). In comparison, a manually wound component typically has failure rates in the range of 1000 ppm. The high failure rate is primarily attributed to nicks and kinks in the wire that occur during winding. The

fine gauge wires can also become brittle and stressed when the wound component is installed and soldered into its respective package. Consistency is another issue. Wound transformers and inductors have secondary circuit elements; such as inter-winding capacitance, leakage inductance and winding resistance. These secondary “parasitic” elements often determine key performance parameters, such as bandwidth, insertion loss and return loss of a device. With manual construction, the wires are manually dressed around the magnetic core. It is difficult to control the parasitic elements in a consistent manner. Performance variations can be significant, depending on the person who wound the device or even the time during a work-shift, in which the device was fabricated.

Construction

Embedded magnetics can provide consistency and reliability unmatched by manual construction. Rather than hand winding each device, RF transformers and inductors are fabricated using printed circuit technology. This allows devices to be manufactured using a high degree of automation and in batch processes. The windings are defined by photolithography, making them highly repeatable.

There are actually a couple of alternatives for producing the embedded magnetic device, each having varying degrees of complexity and cost. The differences are primarily in the fabrication of the windings and the vias used to connect the top and bottom winding layers. The most basic classification is associated with the vias. Either plated-through-hole (PTH) or blind-vias (BV) may be employed. Figures 2 and 3 depict cross sections of the two construction techniques.

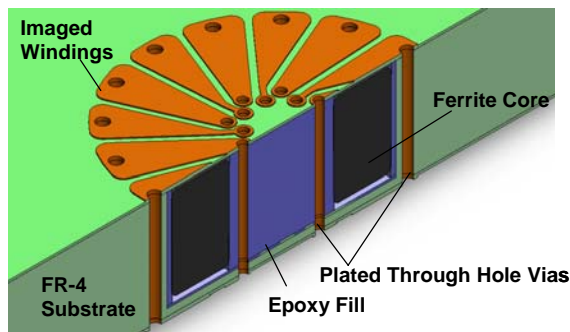


Figure 2 Cross Section View, Plated Through Hole (PTH) Construction

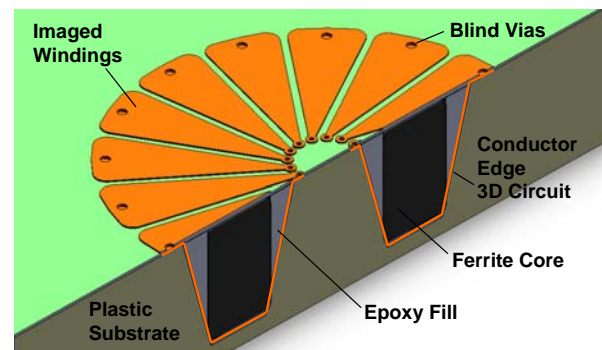


Figure 3, Cross Section View, Blind Via (BV) Construction

Of the two, PTH is the more straight forward approach. Winding layers are disposed on the top and bottom surface of the substrate and vias are mechanically drilled to interconnect the layers. Given a required inductance, the designer begins by selecting the ferrite core material and geometry. Ferrite cores come in many shapes and sizes, yet the toroid is the most efficient shape and is available in a variety of diameters, from multiple manufacturers. To begin the design, the designer must consider the window area of the core and the number of vias that can be fit within that area. Another consideration is the height of the core and the aspect ratio of the interconnecting vias. Most PCB subcontractors can produce vias with 1:12 aspect ratios. If the designer plans to use a 0.25mm (0.010”) via, the height of the inserted core will be limited to about 3.05mm (0.120”) in order to keep the aspect ratio of the via within a practical limit. Often the designer is trying to achieve a specific inductance, which is a function of the core size and number of windings. So some analysis is required to determine the optimum core size and via design.

Once the windings have been designed and artwork created, substrates may be prepared. For PTH, this can be achieved by simply routing cavities into FR4 sheet stock. The ferrite cores are inserted into the cavities and encapsulated with epoxy. Ferrite materials are sensitive to the shrinkage forces imposed by the epoxy,



which will reduce their permeability¹. Ferrite materials with higher permeability (>5,000) are more sensitive to epoxy stress and exhibit greater degradation. Low perm materials, which are commonly used for filters and power applications, are less affected by epoxy shrinkage. The point is that the designer must account for the reduction in permeability when selecting the core size. This may require winding some samples and characterizing their reduction in inductance with different epoxy encapsulates. There are a wide variety of epoxy encapsulates that are suitable for the application. A low shrink epoxy should be selected. The designer should also consider the material's thermal expansion coefficient and the devices process and operation temperatures. Generally, the more stable materials are loaded with silica or another filler material. This reduces the shrinkage and expansion coefficient, making the construction more stable under thermal gradients. In the case of the PTH construction, the material should also have hardness sufficient for drilling the center via array. After the cores have been inserted and the epoxy encapsulation is cured, the panel should be planarized, cleaned and prepped for lamination.

For transformers, voltage isolation is often a key requirement. FR4 has a withstanding voltage >13kV/mm (500 V/mil). For telecommunications, a transformer usually needs to withstand over 1500Vrms of voltage stress. A laminate thickness of 0.10 mm (0.004") is generally sufficient to provide the required isolation. FR4 pre-preg and foil are applied to both the top and bottom surface. Vias are then drilled, plated and the panels are then imaged and etched with the winding array. The benefit of this method is that it readily fits within the capabilities of most PCB shops. The primary limitation is the aspect ratio of the vias. This dictates the via diameter and number of windings that may be applied within the core window, for a specific core thickness. Also, with high density designs, the drilling time and cost may be significant. If a transformer design has 24 windings (48 vias) and is arrayed across a 609mm (24") square panel, there can easily be over 100,000 vias. The drill time is significant and is the dominant factor for determining the product cost.

With the blind via approach, one has the option of using either laser drilling or mechanical drilling. Lasers can drill blind vias order or magnitude faster than mechanical drills. Yet even with mechanical drilling the depth is only a few mills and drilling time is much lower than the PTH design. Blind vias can also be implemented at a smaller diameter and higher density than the PTH. The challenge with the BVA process, however, is in producing the bottom half windings. This requires implementation of a 3-dimensional (3D) circuit. There are a number of ways in which the 3D windings can be fabricated. One method utilizes molded plastic substrates. The substrate should be fabricated from a high temperature polymer, like Liquid Crystal Polymer (LCP) or Nylon 66. Substrates can also be milled from FR4 or G10 sheet stock. The substrates are plated with 1/2 oz copper and coated with an electro-deposited (ED) photo-resist. The cavity can then be imaged with either contact or projection photolithography. Depending on the depth of the cavity, there will be some diffraction as the light enters and images the cavity sidewalls and bottom surface. This requires that the artwork be compensated to correct for the diffraction and that the light source be highly collimated. In Radial's development work, we have found that the sidewalls of the cavity need to have a slope greater than 10° in order sufficiently expose the cavity sidewalls. Imaging has been successful down to a depth of 2mm (0.080").

Another method for fabricating the 3D circuit is to cover the plated substrate with an etch-resist material and image the 3D surface with laser ablation. For etch resist, Radial has successfully imaged the 3D cavity using $\approx 5 \mu\text{m}$ of tin flash plating, as the etch resist. The tin flash can then be selectively ablated (removed) with a diode pumped laser. A spray etching system is then used to remove the exposed copper, while copper underlying the tin flash remains intact. An alternative is to use a polymer etch resist and Co2 laser for the ablation. A simple spray enamel is sufficient as an etch resist. One has to be careful to use enamel that can withstand subsequent process temperatures and the devices operating temperatures. Otherwise, the etch resist will need to be stripped after etching the exposed copper. Again, a spray etching system is used to remove the exposed copper. Figure 4a and 4b show 3D circuit's fabricated using ED photo-resist and laser ablation.

¹ **permeability** is the measure of the ability of a material to support the formation of a magnetic within itself

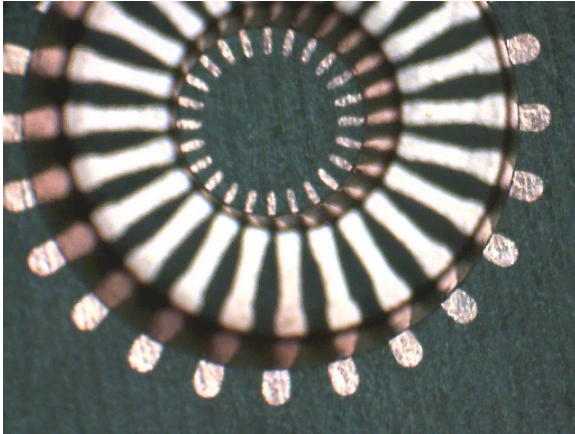


Figure 4a, Imaged 3D circuit

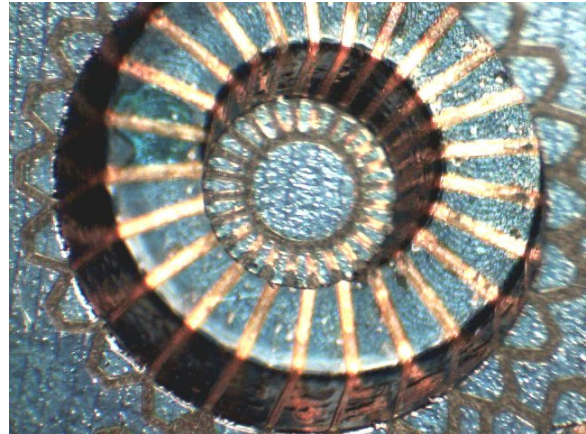


Figure 4b, Laser ablated 3D circuit

Once the 3D circuit is imaged, the ferrite core can be loaded into the cavity and encapsulated with a low shrink epoxy. As with the PHT design, the designer should select an epoxy with low expansion coefficient. An advantage of the BVA approach is that the ferrite cores are inserted around a center pedestal. This reduces the encapsulating material to just a thin film between the ferrite core and cavity walls. The epoxy volume is much lower, compared to the PTH design. Since vias are not being machined into the filler encapsulate, it is practical to use softer encapsulates. Softer materials apply less shrinkage stress and buffer the ferrite cores from stress forces caused by mismatches in thermal coefficients. In general, less encapsulate results in a more stable design under thermal transitions and less degradation of the ferrite permeability.

Once the cores are embedded in the 3D circuit and the top lamination is applied, the windings can be imaged, etched tied together with blind micro vias. Again, defining the windings with photolithography produces consistent and reliable performance. The conductor traces can be shaped, to minimize secondary parameters like winding resistance, leakage inductance and inter-winding capacitance. Figure 5 shows a completed PTH device. This device is an Ethernet media filter and contains 8 transformer elements stacked in two layers. For comparison, the internal construction of a conventional hand wound device is shown. Close inspection of the photo will show that the winding pattern on the embedded magnetic transformer is physically larger than the hand-wound counterparts. While automation provides much efficiency, it also has its constraints. Windings applied to the embedded magnetic core must adhere to conventional PCB design rules. There are specific limitations for line width and spacing, which must be followed for consistent photolithography and etching. Similarly, there are practical limitations associated with drilling and plating vias. Imaging a 3D circuit also has its own set of limitations. In the end, one can always cram more wire around ferrite core with manual assembly, compared the automated PCB process. Consequently, embedded magnetics generally requires the designer use larger cores to achieve a specific inductance value, compared to the hand-wound counterparts. Larger cores can have a slight cost premium, yet this is usually outweighed by the efficiencies of automation. The issue usually comes when displacing a hand wound component and fitting the design into an established footprint and package form-factor. When size is a constraint, the designer usually has the option to stack and array the embedded magnetic devices on multiple PCB layers.

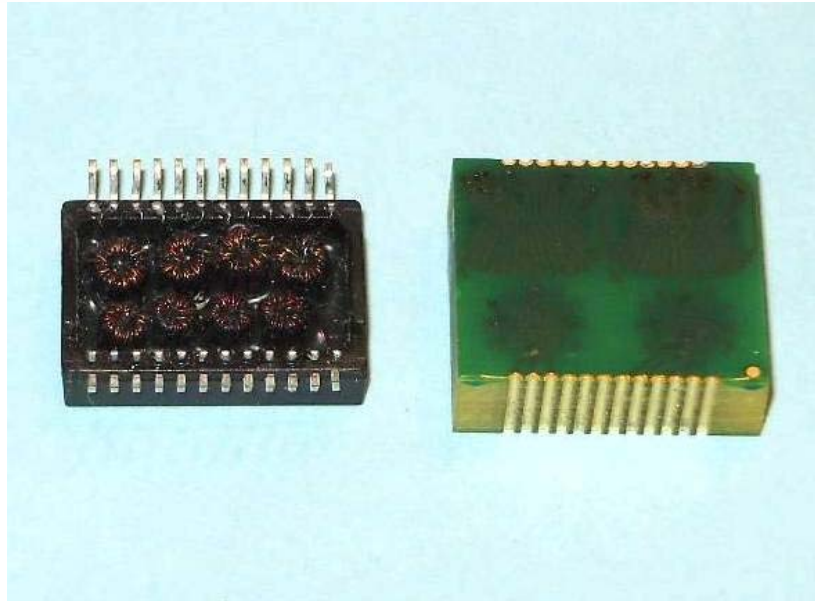


Figure 5, Gigabit Ethernet Media Filter. Bottom view of a conventional device and one realized with embedded magnetics

Performance

Consistency is one of the primary benefits of embedded magnetics. Once the circuit artwork is set, it can be step and repeated across the PCB panel. This level of repeatability cannot be matched with manual construction. The biggest variable will be the inductance per turn (A_L) of the ferrite core material. This value can vary as much as $\pm 20\%$ and will impact the device's open circuit inductance (OCL). If required, one can work with the ferrite supplier to get the cores graded to a tighter tolerance. The inductance primarily impacts low frequency performance. In most instances, the critical operation is at the higher frequency, at which the performance is primarily determined by the AC impedance of the windings and the circuit artwork. Figure 6 shows the schematic and frequency response of a typical transformer. If one thinks of a transformer as a band pass filter, the A_L ultimately defines the inductance and the low frequency cut-off point. High frequency performance is determined by all of the secondary characteristics of the transformer, such as winding resistance, leakage inductance, intertwining capacitance, etc. These secondary parameters are defined by how the conductors are wound around the core. Circuit windings can be carefully crafted to manage the capacitance and AC impedance of the windings. Leakage inductance can be controlled by assuring that the windings cover the core and minimize gaps, where electromagnetic energy may escape. Inter-winding capacitance can be controlled by the material selection and spacing of the conductors and vias. Similar to designing a high frequency PCB, All of these attributes can be modeled and optimized on an RF simulator. Before committing the PCB fabrication, performance can be evaluated at both the device and network level. Many applications require more than one transformer or inductor, in the circuit network. It is practical for the designer to model the interactions between different winding and other components in the device network. The model can also be used to evaluate the device's performance on the system board. This is a big advancement from the status quo. Historically, it has not been practical to accurately model wound components, due to the winding inconsistency.

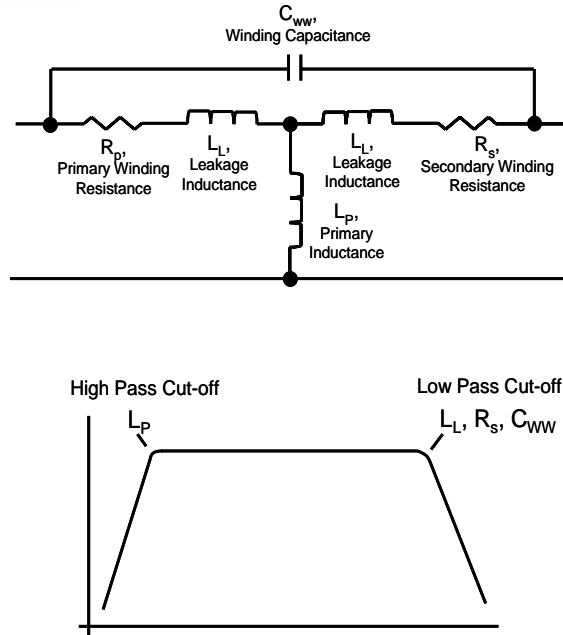


Figure 6, Transformer Equivalent Circuit and Typical Frequency Response

Stitching all of the windings together with vias may raise some concerns of discontinuities in the signal path. Test data shows that this is not an issue. Insertion loss and return loss data for the Gigabit Ethernet media filter is show in figure 7. The plots show 4 channels of data plotted against the industry spec limit. In the insertion loss plots, the pass band is smooth and doesn't exhibit the peaks and valleys that would indicate discontinuity or impedance mismatch. Return loss is a primary indication of the how well the device matches the circuit's characteristic impedance. In this case the Ethernet media filter, the transformer network should have a 100 Ω impedance. The test data shows a return loss is less than -20dB out to 125MHz, which is more than sufficient for the Ethernet application. The media filter is a 4 channel device, implemented with 2 channels on 2 layers. In the return loss plot, differences in the different curve shapes are attributed to differences in the circuit layout on the two different layers and the interconnection to the I/O pads. As one would expect, the two channels on the bottom layer have shorter interconnects and exhibit better return loss performance. The measured curves are consistent with results from the RF simulation.

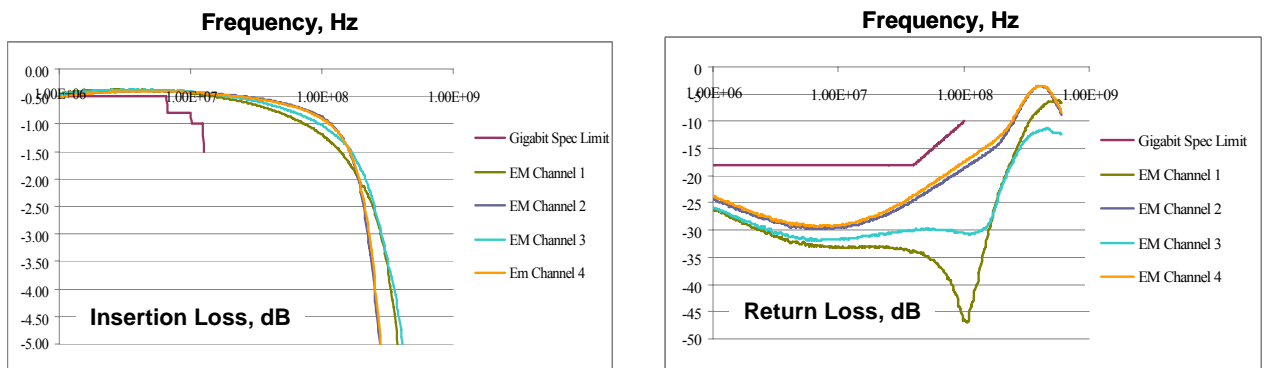


Figure 7, Insertion Loss & Return Loss Data for a Gigabit Ethernet module



Reliability

Reliability testing has only been completed on pre-production samples. Testing was done in accordance with standard requirements for computer and data communication equipment. Each Ethernet media filter has 4 channels. Prior to testing, the OCL of each channel on each sample was measured and recorded. After stresses testing, the OCL was tested again. Failures occur then there is a large drop in the OCL, an open or short circuit. All devices passed the stress testing, indicating that the embedded magnetic components have reliability consistent with standard PCB technology. Further testing is required to determine the stress parameters that cause failure.

Table 1 Embedded Magnetics Development Reliability Tests

Test Name	Method	Conditions	Duration / Frequency	Sample Size	Result
Thermal Cycling	Mil-Std-883, method 1010	-40°C to 100°C, 20 min dwell time	100 cycles	10	Pass
Highly Accelerated Stress Test (HAST)	JEDEC Spec 22-A110	85°C, 85% relative humidity (RH),	50 Hrs. 100 Hrs. 200 Hrs.	10	Pass
Autoclave, Pressure Cook + Humidity	JEDEC JESD22-A102	121°C, 15PSI for 96 hours then 85°C, 85% RH	500 hours	10	Pass
Low Temperature Storage	Mil-Std-810 method 502.4	Storage -55°C unbiased	100 Hrs.	10	Pass
High temperature Storage	Mil-Std-810 method 501.4	Storage 150°C unbiased	100 Hrs.	10	Pass
Solder Reflow	JEDEC-J-STD-20	Max. Temp. 255°C - 265°C, 20 second dwell time	3 passes	9	Pass
Hipot		1500 Vrms	60 sec.	6	Pass

Conclusion

Embedded magnetics provides an automated and batch process for fabricating small transformers and inductors. In the case of the Ethernet media filter, a 609mm (24”) square PCB panel format can easily accommodate over 800 devices. Rather than building one part at a time, they can be fabricated in batches. Automation and the PCB format allow manufacturers to reduce labor content, improve efficiency at test and assembly.

As demonstrated by the test data, embedded magnetic provide a practical method for implementing inductors and transformers. The fabrication uses standard process steps, is scalable and can be transferred between different manufacturing locations. While this paper demonstrates the Ethernet application, the technology can be employed in other data communication and power applications. The following is a summary of salient benefits:

1. Automated batch process that allows the devices to be fabricated on a PCB assembly line with a fraction of the labor content used to make conventional devices
2. Flexible design that can be tailored to a specific applications through circuit design and material selection.
3. Consistent performance that can be modeled and optimized
4. Reliability consistent with PCB technology
5. Relatively low lead times that are consistent with PCB technology

Finally, the product is essentially a PCB, which allows vertical integration of other passive and active components. Vertical integration can be used to actually reduce the overall system footprint. It also



provides short interconnects between devices, which is beneficial for high frequency performance and minimizing I^2R loss in power circuits. Whether building a device from hand wound components or embedded magnetics, the material cost is very similar. The main advantages of embedded magnetics come from reduced labor content, lower overhead, high yields and the consistent performance.

Contact: Jim Quilici, jquilici@radial-e.com