Embedded Inductors with Laser Machined Gap

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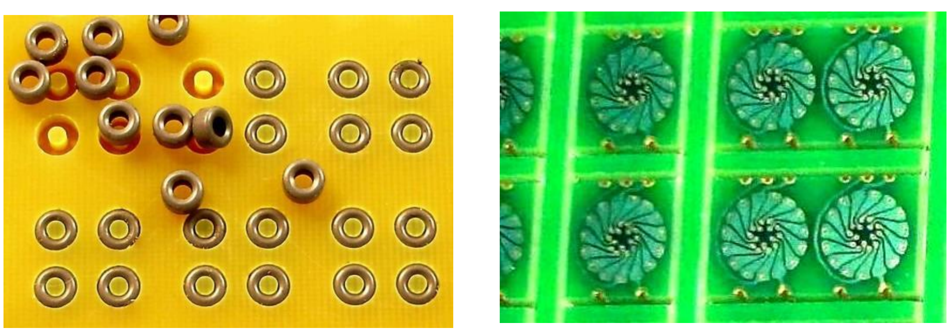
Abstract: This work presents the fabrication of embedded inductors and the experimental laser machining of gaps in the underlying ferrite structure. Design calculations are presented for a test coupon of power inductors. These devices are designed for use in DC/DC converters operating in the 500kHz to 5 MHz range and having inductance values between 1 to 10 uH. The power inductors are constructed by embedding on a ring-shaped ferrite cores(toroids) into an FR-4 substrate, laminating copper foil to the top and bottom surfaces, imaging and etching conductive windings on the top and bottom surfaces. The windings are interconnected with plated-through-hole (PTH) vias. Gapping can be achieved with different laser systems, each having specific benefits and trade-offs. For this experiment, a YAG laser system was used to produce a 0.2 mm gap into a 6.35 mm OD core. Inductance values are presented for before and after the gapping procedure.

Energy efficiency is a major driver in the evolution of electronics and electronics packaging. To manage power consumption, portable appliances (smartphones, tablets, e-readers etc.) often use multiple supply voltages and DC/DC converters. Most are based on switch mode power conversion (SMPC). In a power converter, inductors and transformers are used to temporarily store energy during switching cycles. They also have the function of filtering noise. The power magnetics are often the largest and most expensive devices in the circuit. Integrating the magnetics into either a power converter module or system board can significantly reduce size and cost of the power converter function.

Embedded magnetics offers a means for integrating the magnetic functions into a PCB substrate. Ferromagnetic cores are embedded into a PCB substrate, and the inductive windings are implemented using photolithography and standard PCB processes. Rather than building one-at-a-time, devices are arrayed on a PCB panel and fabricated using automated and batch process. In most instances, the embedded core will be a ring shaped (toroid), since this is the most efficient shape in terms of delivering high inductance per turn and containing the induced magnetic flux. Additionally, toroids are a relatively easy shape to manufacture and generally inexpensive compared to other core shapes. Common materials are pressed ceramic ferrites and tape-wound amorphous metals.



1a. Core Insertion 1b. Etched Transformers

Figure 1. Embedded Magnetic Construction

As indicated above, inductors and transformers are used in power converters to temporarily store energy during a switching event. A key metric of magnetic materials is their ability to store magnetic flux energy. When current is driven through a conductor wound around a magnetic core material, it produces a **magnetic field** (H) which induces a **magnetic flux** (B) in the underlying core material. The current energy is temporarily converted tomagnetic flux and stored within the magnetic core. The flux, B,is essentially the field density within the core.B has units of Tesla (or Gauss[1]) and H is the measure of

[1] 10000 Gauss = 1 Tesla

magnetizing field strength and has the units of Oerstads[2]. B and H are closely related to Voltage and Current, where the flux density is proportional to the applied voltage and the magnetizing force, H, is proportional to current.The relationship between the field and flux is tied by the materials **permeability**, μ.

$B = \mu H$(1)

Flux density may also be expressed in terms of inductance and drive current, as characterized through the relationship:

$B = L\,I / N\,Ac$ (2)

Where L is the inductance, I is the drive current, N is the number of windings and A_c is the cross section area of the core.

Designers often use the B-H curve to analyze the relationship between the drive voltage and drive current. Figure 2 identifies that magnetic materials have a flux saturation level, B_{SAT}, which is the state where the magnetic core has reached peak flux density. At that point, the core cannot store more energy, regardless of the amplitude of drive voltage. For ferrite materials, saturation occurs in the range of 0.350 to 0.550 Teslas[3], depending on the composition. Cores with high permeability will saturate with modest currents. To allow higher drive currents, a gap is often introduced into the magnetic flux path. This effectively reduces the permeability of the core material and results in a reduction of the inductance of the windings. As depicted in figure 2, gapping the core flattens out the B-H curve. Reducing the inductance allows the core to store energy from higher drive currents.

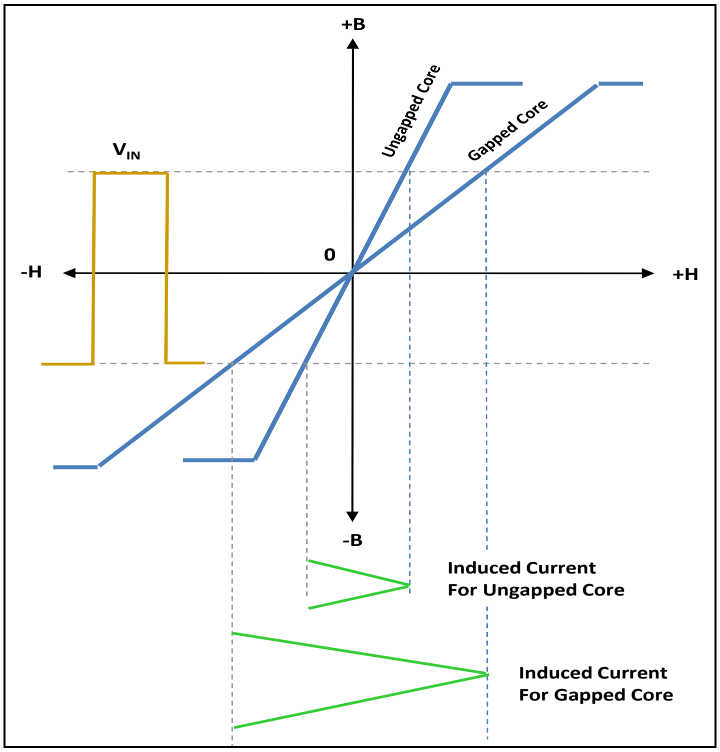


Figure 2, Typical B-H graph for an ungapped and gapped ferrite core

A gap is produced by placing a small cut through the core. Gapping is a common method for reducing the inductance and enabling the core to be driven at higher currents before reaching saturation. It also serves to stabilize the performance of a core over different operating temperatures and drive currents. Basically, gapping the core reduces the effective permeability. The relative permeability for a gapped core can be calculated by the equation:

$\mu_r' = \mu_r / (1 + (g \times \mu_r / l_e))$ (3)

where g is the gap distance and l_e is the path length of the flux around the circumference of the core . In many instances, the reduction in permeability by gapping will exceed 10x. It may seem counter-productive to create materials and core structures with high permeability and then diminish them with a gap. However, this is necessary to add stability and allow higher drive currents. There is always the option of using powdered iron core materials, which are often described as having a distributed

[2]One Amper/meter = 4 x 10^{-3}Oersted

[3]Tesla is a unit of magnetic flux density, which can also be characterized in gauss. 1Tesla= 10,000 Gauss,

gap. These materials generally have permeability's less than 100 and are generally more expensive due to the precious metals used in their construction and limited number of suppliers. With conventional ferrites, we can apply a gap to achieve permeability's between 100 and 1000, which reduces the number of windings required to achieve a specific inductance. Reducing the number of windings is beneficial in reducing resistance loss in the windings. Also powdered iron materials generally exhibit higher core loss[4] which can also impact the power converters efficiency.

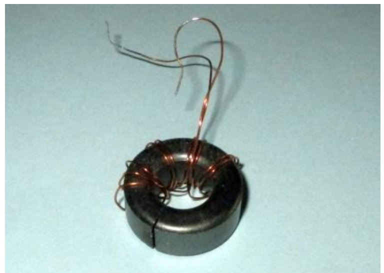


Figure 3, Example of a Gapped Toroid

Figure 4 shows a typical graph of permeability vs temperature for a 2000 permeability manganese zinc (MnZn) material, which is typically used for power applications. Here we see wide variations over temperature. Gapping the core reduces the permeability to about 350 and flattens-out the characteristics over the full temperature range. This is important for applications that need to perform to at temperatures below 0° C.

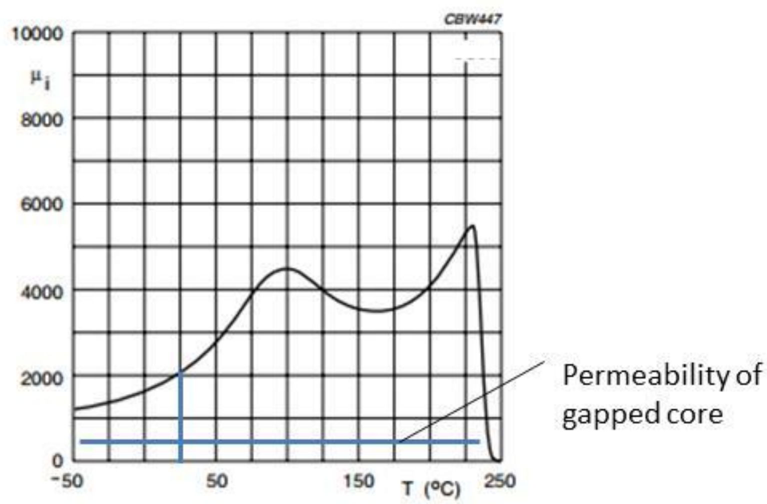


Figure 4, Ferrite permeability versus temperature (1500 permeability @ 25C)

This brings us to a design methodology. Once the designer determines the inductance required for an application, it is then a matter of over designing for much higher inductance, in anticipation that the inductance will be diminished after the core has been gapped.

For power converters, embedded magnetics are useful in applications ranging up to 60W.The power capability is primarily dictated by core sizes that are suitable for embedding into a PCB substrate. The PCB construction is limited by the PCB thickness and height (thickness) of the core. Practical applications include power to a microprocessor, battery chargers and LED lighting. There are many semiconductor SMPC controllers on the market tailored specifically for these applications. Most of these devices operate with switching speeds ranging from 500 kHz to 2MHz. At these switching speeds, inductors in the range of 1 uH to 10 uH are commonly used. For this investigation, a test coupon was designed with indictors ranging from 2.2uH to 10uH. The 10 uH configuration is the focus of this paper. Generally, for power applications, it is best to select MnZn ferrite materials with permeability in the range of 2K to 3K, due to their core loss properties. In this gapping experiment, however, cores with 5K permeability were selected simply because this value was available in the author's

[4]Core losses are a result of an alternating magnetic field in a core material. The core losses are due to hysteresis, eddy current and residual losses in the core material and is dissipated as heat.

inventory. This difference in permeability is not significant in this particular experiment. Once the gap is applied, the core's inductance per turn is dominated by the gap with the differences in the initial permeability only accounts for minor difference in the final inductance.

The 5K permeability core hasthe following mechanical dimensions; 6.35mm OD x 3.81 mm ID and x 2.54 mm height. To calculate the inductance, one first needs to know the cores inductance factor, A_L. The A_L value is generally provided by the ferrite manufactures, yet can also be calculated by the relation:

$$A_L = \mu_0\mu_r A_c / l_e \quad (4)$$

From equation 4, the inductance factor is directly proportional to the relative permeability, μ_r. In the case of the 5K permeability 6.35 mm OD core, the A_L value is 1.6 uH / N^2, where N is the number of windings[5] applier to the core. From the manufacturer specifications, the core has a cross section area A_c of 3.2 mm^2 and a path length l_e of 15.9 mm. To calculate the A_L value for the gapped core, we need to return to equation 3. We have all the details to calculate the gapped A_L value, except the gap width, g. Selecting the gap size requires trial and error. Inductors with larger gaps will have more stability, yet A_L values decrease with wider gaps. Cores with larger gaps require more windings to achieve a specific inductance.

For this experiment the objective is to cut a 0.15 mm gap into the 6.35 mm OD cores. Large cores are often gapped using diamond wheel cutters and other milling techniques. A typical gap from a diamond wheel is ≥ 0.25 mm. For small diameter cores (< 10mm OD) the handling and required fixtures for diamond wheel cutting can be challenging. With the embedded magnetic structure, we have the advantage of the cores being embedded and arrayed in an FR-4 substrate. This greatly facilitates the handling during the gapping procedure. Rather than holding each core individually, panel arrays can be placed on and X-Y stepping table and each core can be laser machined with a high degree of precision and efficiency. Gap widths can be narrower than what is practical with diamond wheel cutting. Also, the laser gapping process time is in the range of 3 to 10 seconds per core, which is much faster than what can be achieved with mechanical gapping, where one has to fixture and handle each core. For the core machined with a 0.15 mm slit, the new A_L' value is calculated as follows:

μ_r' = 5000 / (1 + (0.15mm x 5000/15.9mm))= 103

A_L =(12.57)(119)(3.2mm^2)/(15.9mm) = 260nH/N^2

Inductance can now be calculated by multiply the A_L valueby the square of the turns:

$$L = A_L N^2 \quad (5)$$

With desired inductance of 10 uH, the required number of windings are calculated to be 6 turns. To test the gapping of the embedded cores, a test panel was designed with different winding configurations. Embedded magnetic inductors were designed with 8, 10 and 12 windings. A 3mm thick panel of FR-4 sheet stock was milled with cavities to accommodate the cores. The cavities were milled to 2.8 mm depth and the ferrite cores were inserted and encapsulated with low shrink epoxy. 1 oz. Cu foil was applied to the top and bottom surfaces using 2 layers of 1080 pre-preg. Vias were drilled and plated to interconnect the top and bottom layers. Inductive windings were then applied through photolithography. Figure 5 shows the layer stack-up for the PCB.

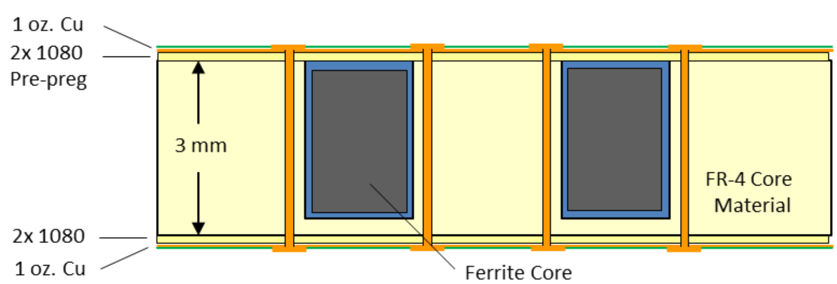


Figure 5, Test CouponCross Section

For laser cutting, there are 2 basic systems that are commonly used in industrial machining;CO2, and YAG. The CO2 has the larger beam width of 10um while the YAG beam width is 1.06um. Either system can be used for gapping the embedded cores. CO2 is good for cutting organics while YAG is often preferred for cutting metals and ceramics. In the cutting region, the bulk of the PCB cross section is filled with the ceramic ferrite material. So for this experiment, the narrow beam YAG laser was selected with the objective of producing a 0.13 mm (130 um) gap. To optimize the laser cutting, the key parameters

[5]Number of windings, N. Also commonly referred to as turns, T

include: beam power, beam aperture, feed rate, pulse rate, and focus depth. Experimental cuts were made using different power settings, focus levels. Additionally, different focus depths and multiple passes were investigated. After some experimentation, we settled on one pass focused 1 mm below the top surface of the panel and a feed rate of 1.3 mm/s. The cutting distance is 1.78 mm, so the actual cutting time was within 3 seconds. Forced argon gas was used to cool the cutting surface and blow out slag.

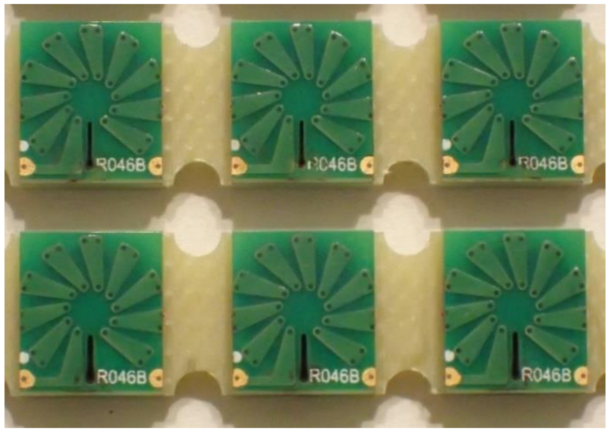


Figure 6, Laser gapped embedded inductors, 10 Winding Configuration

Two test panels were fabricated with 3 different windings configurations; 8, 10 and 12 windings. For each configuration, two rows of 10 units were implemented for each winding implementation. Here, the results are reported for the 10 turn configuration. The 1st panel was use to experiment with laser settings. Once the settings were established, they were used to run the second panel. Figure 6 shows some of the 10 winding devices. While the objective was to cut a 0.15 mm gap, during the experimentation phase, the gaps were inspected under a microscope and it was noticed that some debris and particulate remained in the gap after laser cutting. Also, inductance was measured after each test cut. Better consistency was achieved by widening the gap to about 0.2mm. This allowed much of the debris to be blown out of the gap by the laser and forces argon gas. With the wider gap, it was still possible to achieve 10 uH of inductance when using the 10 winding configuration. Table 2 summarizes the laser parameters that were used to cut gaps in the second panel. The inductance data for 20 units of the 10 winding configuration is summarized for each row in Table 3. Before gapping, the cores exhibited an A_L value of 1.6 uH/N^2. After laser gapping, the A_L value diminished to 0.10 uH/N^2. This is much lower than the calculated value and is attributed to the wider gap width. For the top row, the average inductance was 11.4 uH, 14% above the design target of 10 uH. For the second row, the nominal value was within 4% of 10 uH. The data in row 2 is partly skewed due to the low inductance value of the 10th unit in that row. The laser settings were by no means optimized and further refinement of the gapping process can narrow the data distribution and tolerance.

Table 2, Summary of Laser Parameters used in Experiment

Parameters Used in Experiment		
Parameter	Setting	Units
Number of passes	1	-
Laser Power	9.8	W
Pulse Frequency	25	Hz
Pulse Width	0.5	mS
Pulse Forming Network (PFN)	500	-
Feed Rate	2	mm/s
Focus Depth	1.01 (40)	mm (mils)

In addition to inductance, the winding resistance is another key performance parameter. For power conversion, the winding resistance contributes to power loss and impacts the system efficiency. Table 4 summarizes the winding resistance for the 10 uH inductors. Average resistance is 0.065Ω, which is acceptable for most power converter applications. However, resistance can be reduced further by using heavier Cu foils on the top and bottom layers, and by plating the vias thicker. The vias in this experiment were plated to IPC standard 25um. Further resistance reductions can be achieved by plating the vias to 35-50um and capping the via barrels with copper.

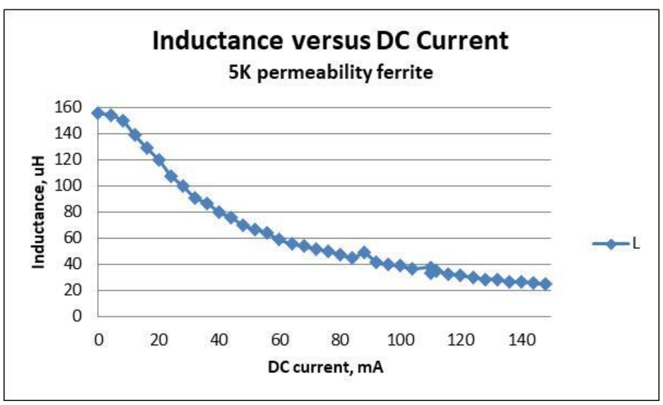
Table 3: Inductance Data

			100 kHz, 1 Vrms, Inductance, uH, before laser gappng													
Core Size	Winding		1	2	3	4	5	6	7	8	9	10	Min	Max	Ave	Std. Dev.	Ave uH/T2
6.35x3.81x2.54	10 turns	025046B	174	165	158	159	171	159	155	169	164	159	155	174	163.3	6.3	1.6
6.35x3.81x2.54	10 turns	025046B	162	143	148	164	145	161	150	154	154	169	143	169	155.0	8.7	1.6
			100 kHz, 1 Vrms, Inductance, uH, after laser gappng													
Core Size	Winding		1	2	3	4	5	6	7	8	9	10	Min	Max	Ave	Std. Dev.	Ave UH/T2
6.35x3.81x2.54	10 turns	025046B	12.7	16.5	12.9	9.7	9.8	10.1	9.4	10.7	10.4	11.8	9.4	16.5	11.4	2.2	0.11
6.35x3.81x2.54	10 turns	025046B	11.9	8.6	11.6	7.9	10.0	10.2	10.0	14.6	12.6	3.1	3.1	14.6	10.1	3.1	0.10

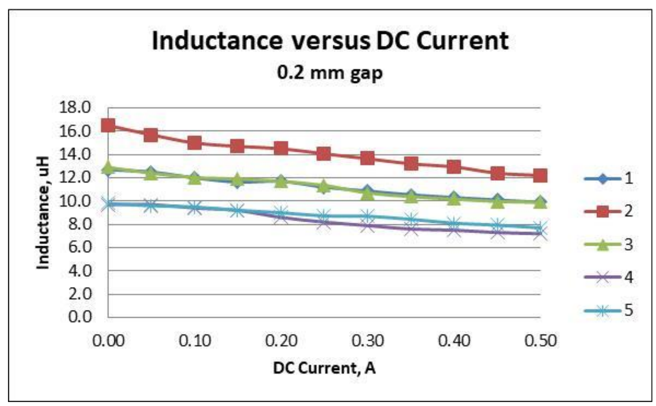
Table 4 Winding Resistance

	Winding Resistance, mΩ													
Unit #	1	2	3	4	5	6	7	8	9	10	Min	Max	Ave	Std. Dev.	Ave mΩ/T
10 Turns	64	62	63	68	61	69	68	71	67	61	61	71	65.4	3.6	6.5
10 turns	59	63	62	64	65	62	62	62	63	62	59	65	62.4	1.6	6.2

As described earlier, gapping reduces the cores sensitivity to DC currents. Figure 7 shows the inductance versus DC current for a typical 5K permeability core and the gapped samples. Prior to gapping, the embedded 10 turn inductors exhibited inductances in the range of 140 to 170 uH. To demonstrate the response of the un-gapped core a 10 turns inductor with 158 uH at 0 DC bias current was tested. As DC current is applied, the inductance diminished quickly. At 40 mA of DC current, the inductance of the un-gapped core diminishes to half of the starting value. In comparison, the second plot shows the performance for 5 gapped inductors when a DC bias current is applied. Degradation over the range of 0 to 0.5A is about 20% to 25%.



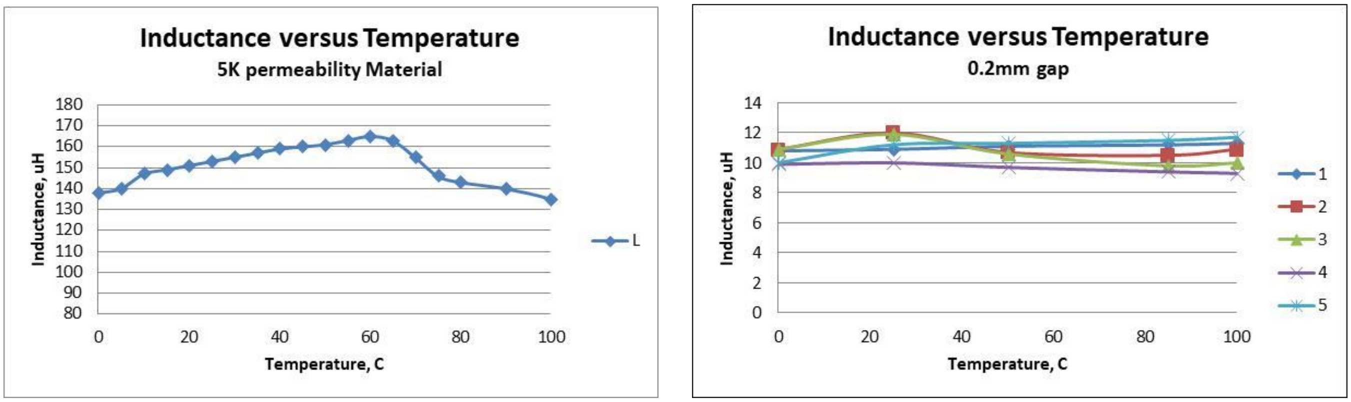
Typical profile
Core Size: 6.35x3.81x2.5 mm, 5 K permeability, 10 Turns



Embedded Magnetics sample units
Core Size: 6.35x3.81x2.5 mm, 5K permeability, 10 Turns

Figure 7, Inductance versus DC Current for Un-gapped and Gapped Ferrite Cores

Additionally, devices were tested over temperature. Figure 8 shows the characteristics for the un-gapped and gapped core from 0°C to 100°C. The ungapped core exhibits variation exceeding 20% over the temperature range while the gapped devices exhibit very little variation over the temperature range and remain within 10% of their value at ambient temperature.



Typical profile
Core Size: 6.35x3.81x2.5 mm, 5K permeability, 10 Turns

Embedded Magnetics sample units
Core Size: 6.35x3.81x2.5 mm, 5K permeability, 10 Turns

Figure 8 Inductance versus Temperature for Un-gapped and Gapped Ferrite Cores

Finally, a few of the inductors were cross sectioned to inspect the laser cut. Figure 9 shows a photo of a cross sectioned part. The direction of the laser cut was from top to bottom. The laser cut has a width in the 0.20 mm to 0.25 mm range,

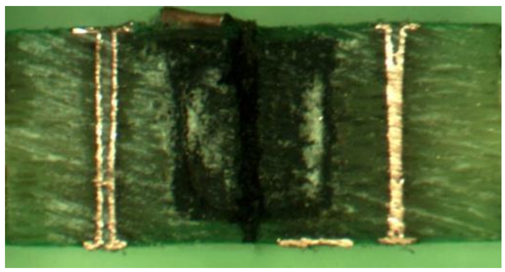


Figure 9, Cross section view

Summary

This paper demonstrates the viability for laser gapping embedded transformers and inductors. The PCB structure of the embedded magnetics brings efficiency to the gapping process. A design example was presented for a 10 uH inductor. After gapping, the device exhibited good stability under varying temperatures and DC bias current. Such device would be suitable for SMPC power converters operating in the 500 kHz to 2 MHz range. The embedded toroid structure is useful for reducing the circuit footprint and cost and is suitable for implementation in either a power conversion module or directly in the system board.

The original objective was to produce a 10 uH inductor using a 6 winding configuration and 0.15 mm wide gap. After experimentation, a 0.2 mm gap was implemented. The larger gap allowed debris to be blown out of the gap during the laser process and provided more consistency between inductance of the gapped devices. The caveat is that the larger gap requires designing the inductor to have a higher initial value. A 10 uH inductor was realized using a 10 turn configuration that had a pre-gapped inductance in the range of 140 uH to 170 uH. Design equations and methodology were presented as a guide for designers who want to pursue this technology.

References

1. Ferroxcube Product Selection Guide 2009.
2. Sanjaya ManikTala, *Switching Power Supplies A to Z*, 2006 Elsevier Inc., Burlington, MA.

Laser Gapped Embedded Magnetics

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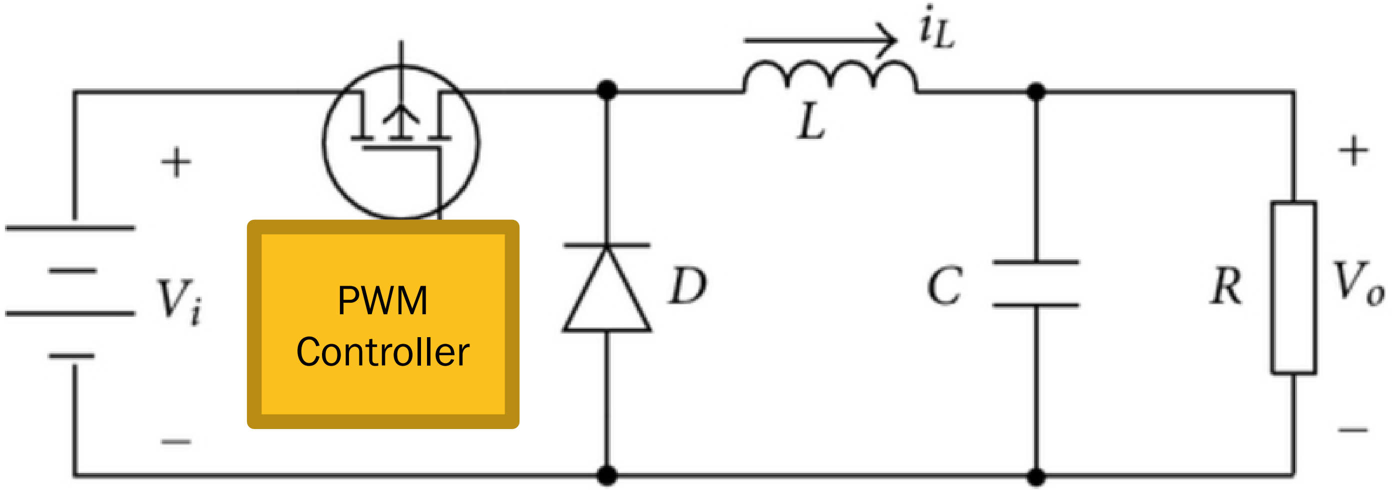
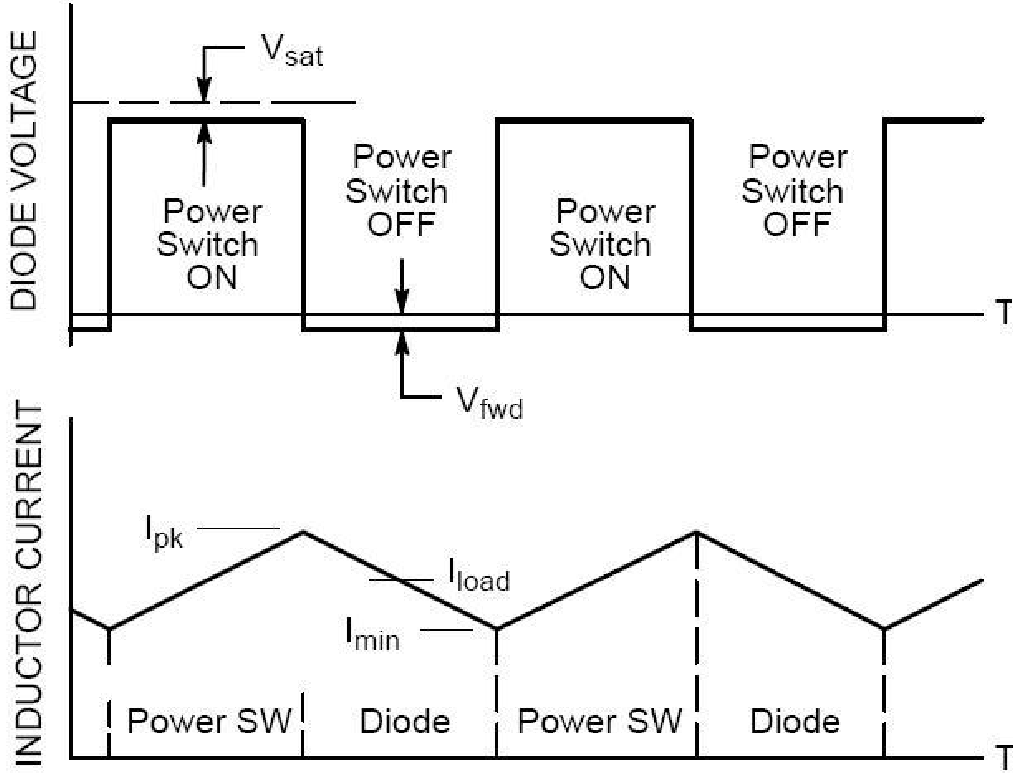
Radial Electronics

Switching Power Converter

For switching frequencies in the range of 500 kHz to 3 MHz, Inductor values in the range of 1uH to 20 μH are used

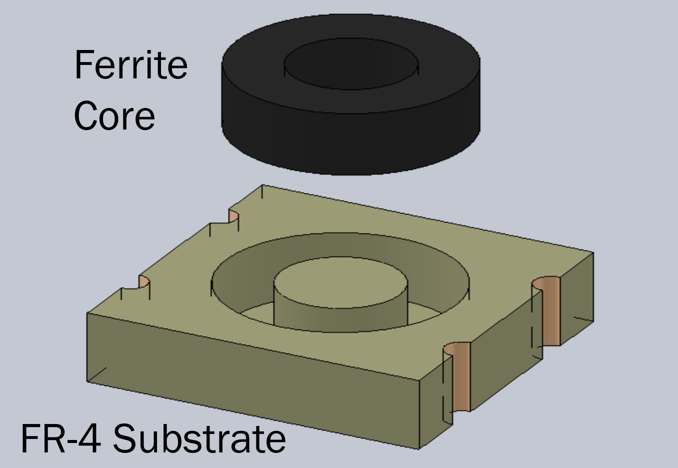


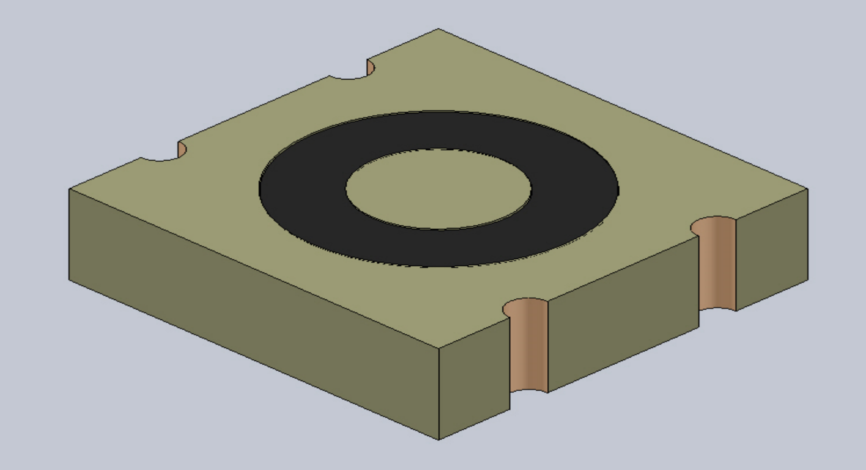


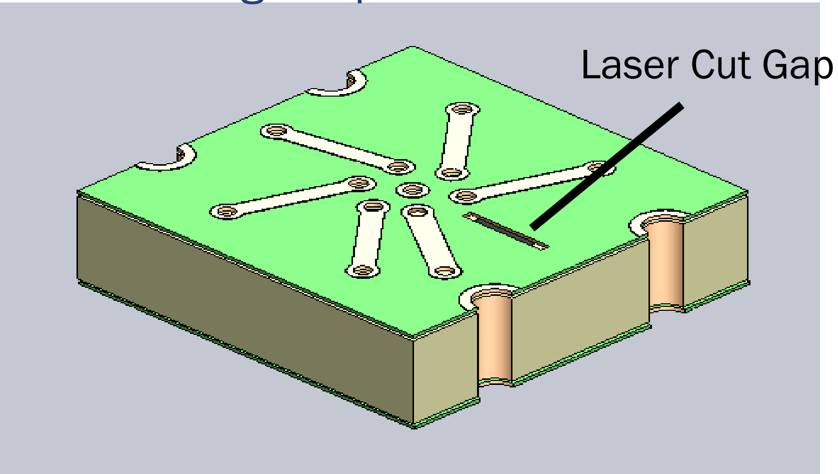
- The pulse width is used to control the output voltage
- The inductor temporarily stores energy in the form of magnetic flux (B)
- The inductor delivers both DC and AC currents to the loads

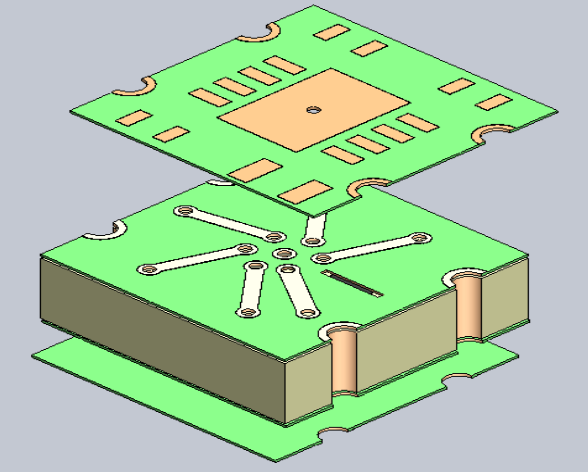
Why Embedded Magnetics?

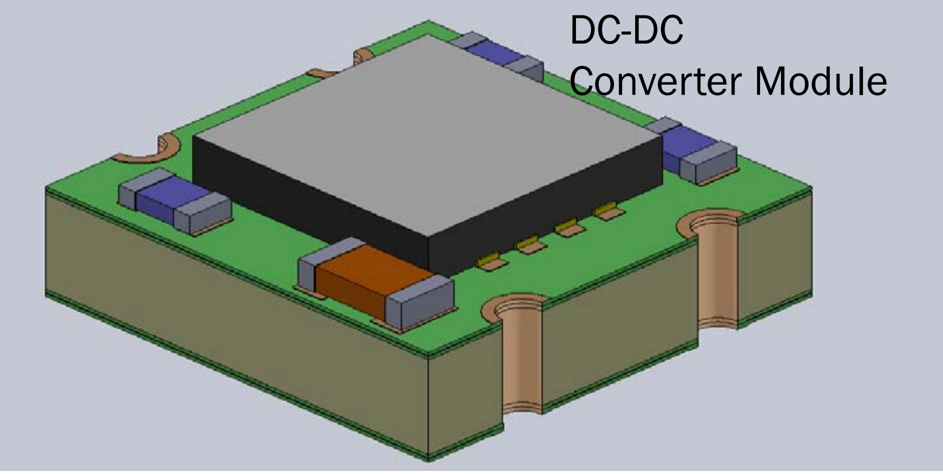
- Reduce Size
- Reduce Cost
- Improve Efficiency
  - Reduce Core Loss
  - Reduce Winding Resistance
- Reduce Noise
  - Ring Shape Core



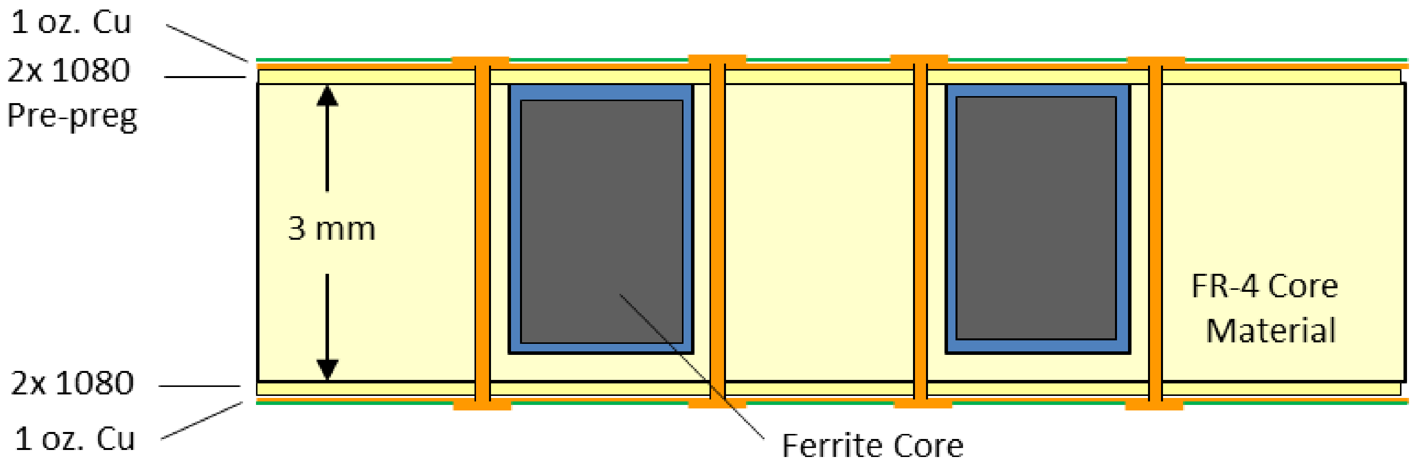


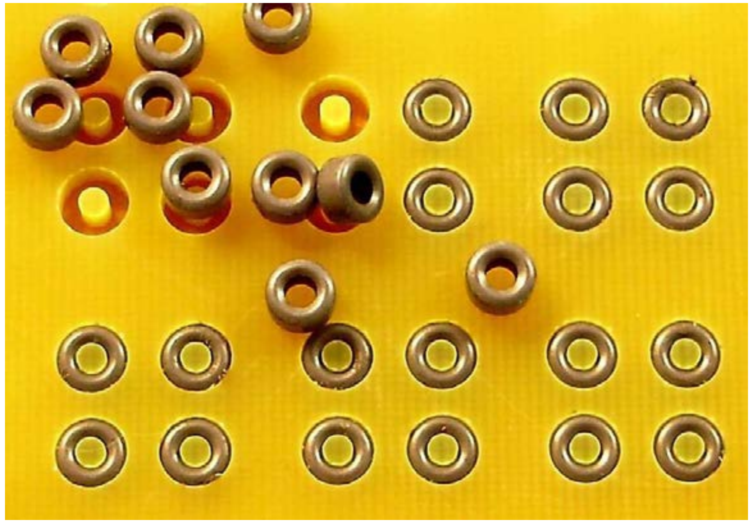


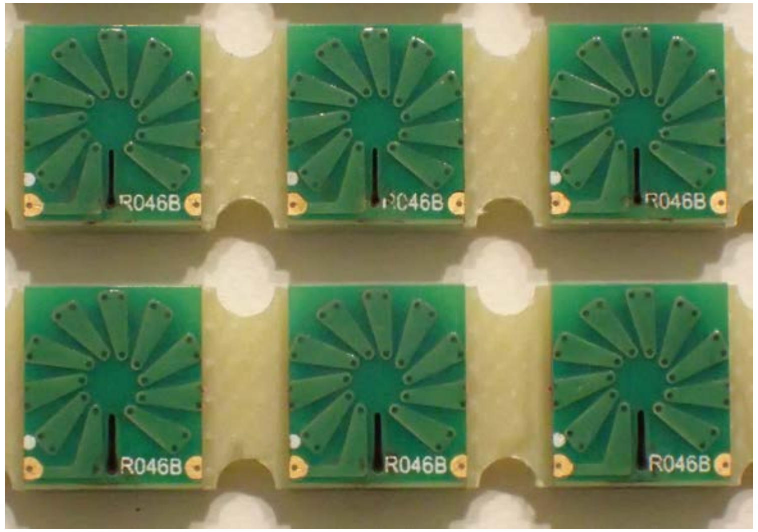




Layer Stack







Device Size: 8.5mm L x 7.6mm W x 3 mm ht
Core Size 6.35mm OD, 3.81mm ID x 2.54mm ht

Voltage Isolation

Guidelines from IPC-2221, Table 6

Dielectric Properties

Material	Dielectric Strength	Comments
Poly-para-xylene	> 5000 V/mil	Ferrite Coating
Encapsulation Epoxy	> 1000 V/mil	
FR-4	> 500 V/mil	
Solder Mask	> 500 V/mil	Recommend 2 or more layers
Polyimide Cover-lay	> 6000 V/mil	

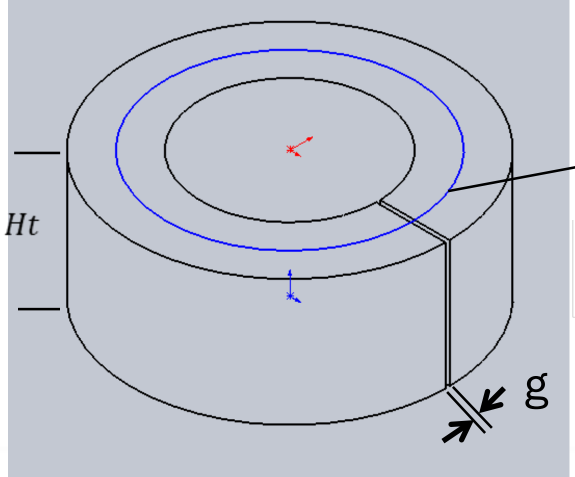
Working Voltages & Recommended Conductor Separation

Working Voltage, Vpk	Internal Conductors		External Conductors Coated	
	mm	inch	mm	inch
30	0.05	0.002	0.05	0.002
50	0.6	0.024	0.13	0.006
100	0.1	0.004	0.13	0.006
150	0.2	0.008	0.40	0.016
250	0.2	0.008	0.40	0.016
300	0.2	0.008	0.40	0.016
500	0.25	0.010	0.80	0.032
1000	1.5	0.060	2.33	0.092
2000	4.0	0.158	5.38	0.220

B-H Curve

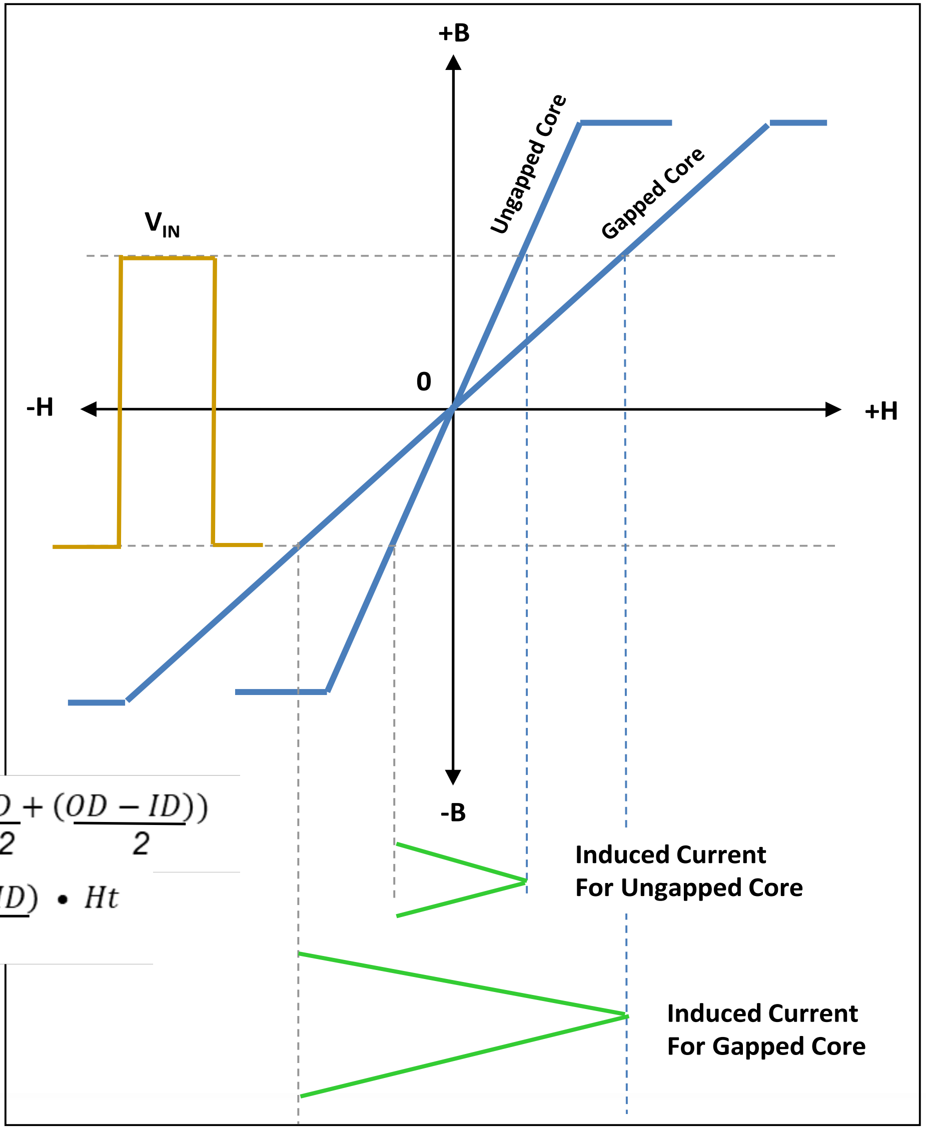
$B = \mu_0 \mu_r H = \mu_0 \mu_r (N I / Le)$

Where B = Magnetic Flux Density
H = Magnetic Field
μ_0 = Permeability of free space
μ_r = Permeability of the Ferromagnetic Material
N = Number of Windings
I = Current
Le = path length for magnetic flux



$$Le = 2\pi \cdot \left(\frac{ID}{2} + \frac{(OD - ID)}{2}\right)$$

$$A_c = \frac{(OD - ID)}{2} \bullet Ht$$



$$L = \frac{BNA_c}{I} = \frac{\mu_0 \mu_r H A_c}{I}$$

$$\text{Inductance Factor } A_L = \frac{\mu_0 \mu_r A_c}{Le}$$

Where A_c = Cross Section Area of the Core

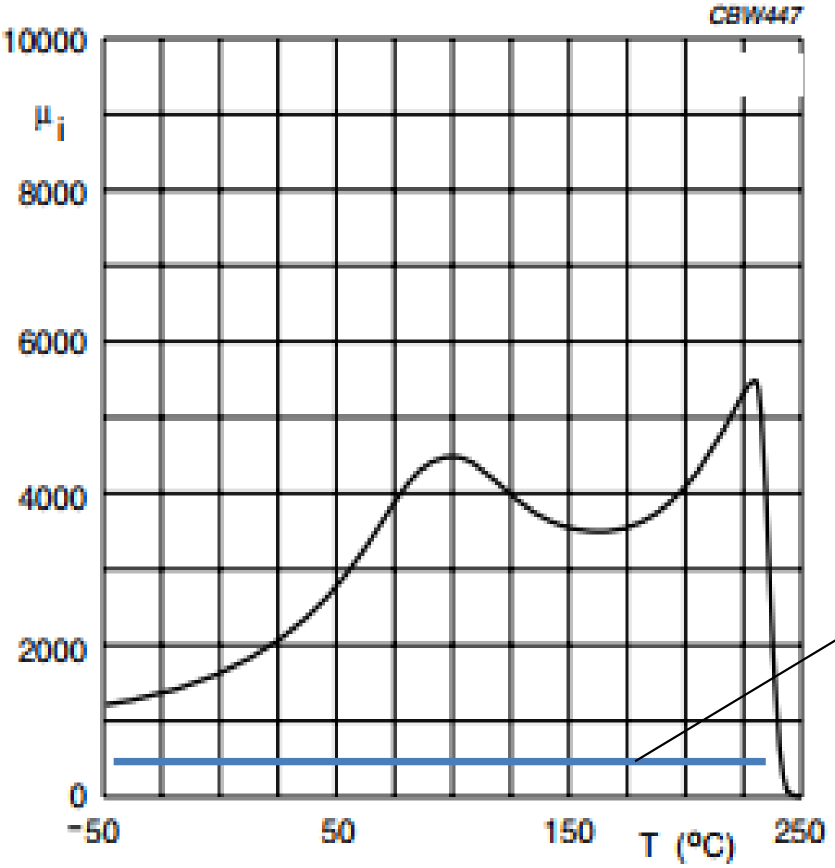
$$L = A_L \bullet N^2$$

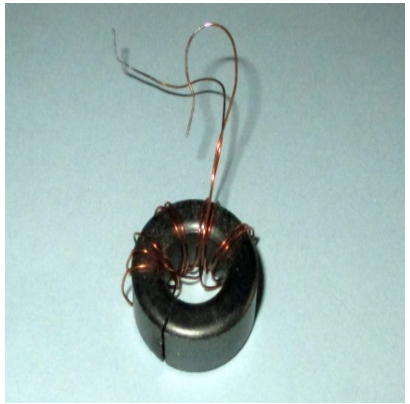
Relative permeability of gapped core

$$\mu_r' = \frac{\mu_r}{(1 + (g \bullet \mu_r / L_e))}$$

Why Gap?

- Gapping will typically reduce the permeability of the ferrite core ≈ 10x
- Gapping allows the core to be driven with higher voltages and currents
- Gapping stabilizes performance over temperature gradients
- Gapping stabilizes the performance when DC currents develop in the windings.





Design Example

Relative permeability of gapped core

Ferrite Core Characteristics

Core OD = 6.35 mm, ID = 3.81 mm, ht = 2.54 mm

Permeability = 5000

Path Length, $Le = 2\pi \bullet \left(\frac{3.81}{2} + \frac{(6.35 - 3.81)}{4} \right) = 15.9\text{mm}$

Core Cross Section Area, $Ac = \frac{(6.35 - 3.81)}{2} \bullet 2.54\text{mm} = 3.2\ \text{mm}^2$

With a 0.13 mm gap;

$\mu_r' = 5000 / (1 + (0.13\text{mm} \times 5000 / 15.9\text{mm})) = 119$

$A_L = (12.57)(119)(3.2\text{mm}^2) / (15.9\text{mm}) = 301\ \text{nH/N}^2$

With 10 windings, the inductance; $L = 10^2 \bullet 301\ \text{nH/N}^2 = 30\ \mu\text{H}$

Laser Options

- Laser Options
  - CO_2, Wavelengths range from 9400 nm to 10600 nm
    - Larger beam width, good for cutting organics and polymers like FR-4
  - Nd:YAG. Wavelength range from 946 to1440 nm
    - Preferred for cutting metals and ceramics

Parameters Used in Experiment		
Parameter	Setting	Units
Number of passes	1	-
Laser Power	9.8	W
Pulse Frequency	25	Hz
Pulse Width	0.5	mS
Pulse Forming Network (PFN)	500	-
Feed Rate	2	mm/s
Focus Depth	1.01 (40)	mm (mils)

- For the 3mm thick test coupons, a YAG laser was used with a beam power of ≈ 10W
- Multiple variables can be used to control the power and cutting speed and quality of the cut
  - beam power; beam aperture, feed rate, pulse rate, and focus depth, number of passes
  - forced argon gas was used to cool the cutting surface and blow out slag
  - Each cut was about 1.8 mm long and was done in under 3 seconds
    - After some experimentation, we settled on one pass focused 1 mm below the top surface of the panel and a feed rate of 2 mm/s.

Table 2: Inductance Data

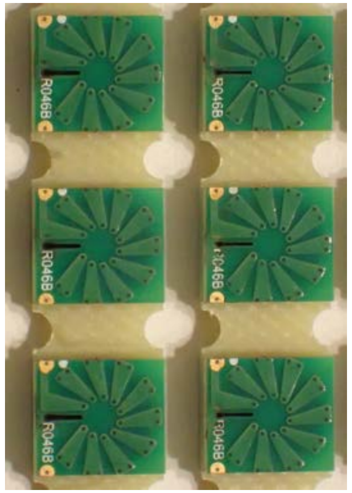
Test Coupon 1

100 kHz, 1 Vrms, Inductance, uH, before laser gappng

Core Size	Winding		1	2	3	4	5	6	7	8	9	10	Min	Max	Ave	Std. Dev.	Ave uH/T2
6.35x3.81x2.54	10 turns	025046B	174	165	158	159	171	159	155	169	164	159	155	174	163.3	6.3	1.6
6.35x3.81x2.54	10 turns	025046B	162	143	148	164	145	161	150	154	154	169	143	169	155.0	8.7	1.6

100 kHz, 1 Vrms, Inductance, uH, after laser gappng

Core Size	Winding		1	2	3	4	5	6	7	8	9	10	Min	Max	Ave	Std. Dev.	Ave UH/T2
6.35x3.81x2.54	10 turns	025046B	12.7	16.5	12.9	9.7	9.8	10.1	9.4	10.7	10.4	11.8	9.4	16.5	11.4	2.2	0.11
6.35x3.81x2.54	10 turns	025046B	11.9	8.6	11.6	7.9	10.0	10.2	10.0	14.6	12.6	3.1	3.1	14.6	10.1	3.1	0.10

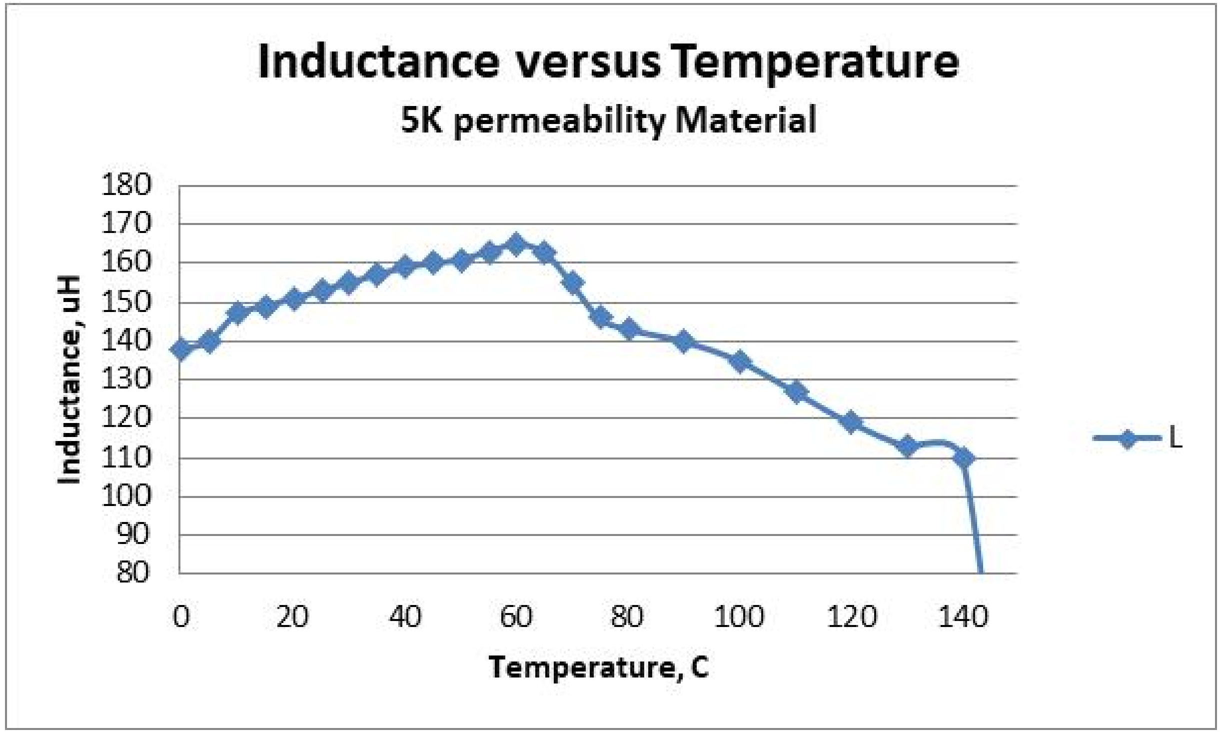


Core Size: 6.35mm OD, 3.81mm ID x 2.54mm height, 5K permeability
After laser gapping, the effective permeability of the core is about 350

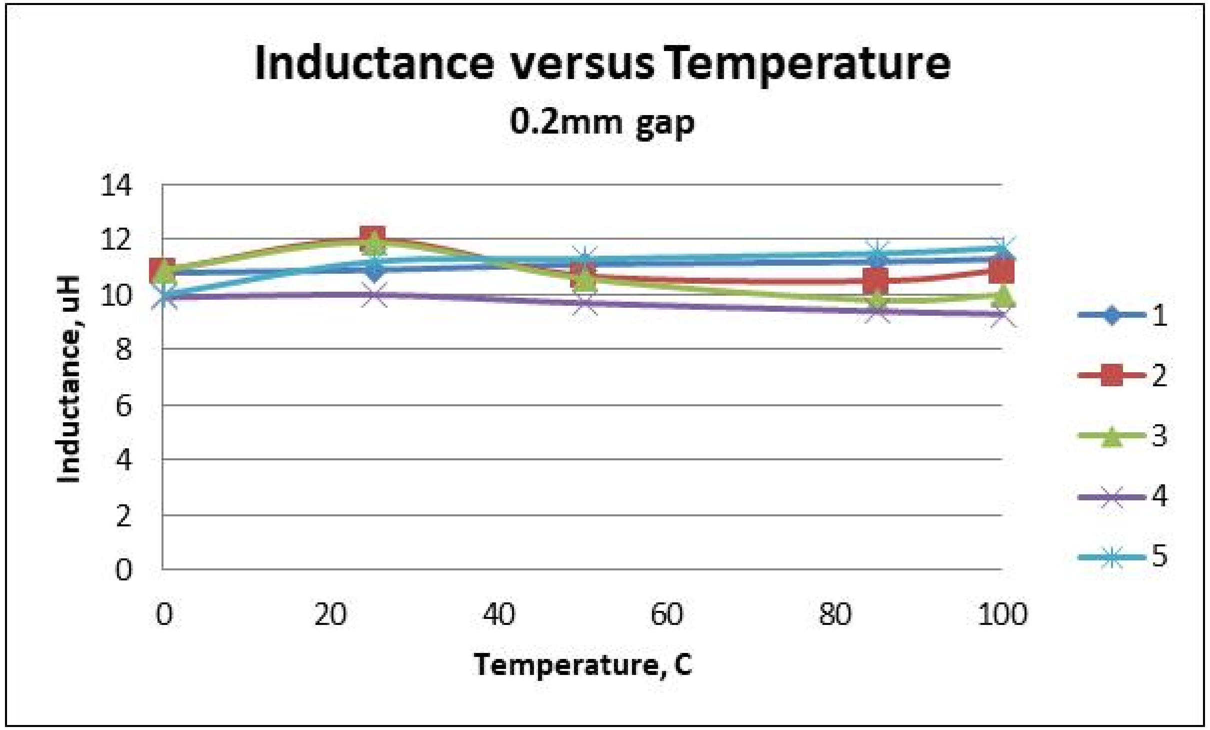
100 kHz, 1 Vrms, Winding Resistance, mΩ

Unit #	1	2	3	4	5	6	7	8	9	10	Min	Max	Ave	Std. Dev.	Ave mΩ/T
10 Turns	64	62	63	68	61	69	68	71	67	61	61	71	65.4	3.6	6.5
10 turns	59	63	62	64	65	62	62	62	63	62	59	65	62.4	1.6	6.2

Inductance versus Temperature

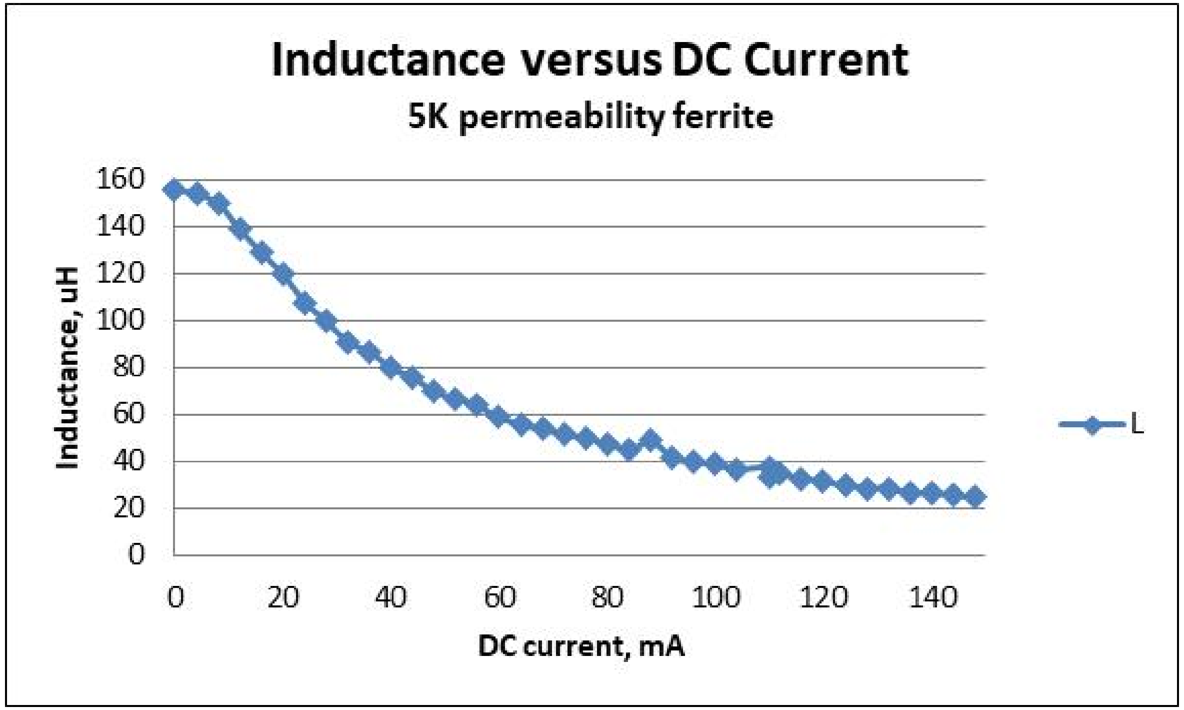


Typical profile
Core Size: 6.35x3.81x2.5 mm, 5K permeability, 10 Turns

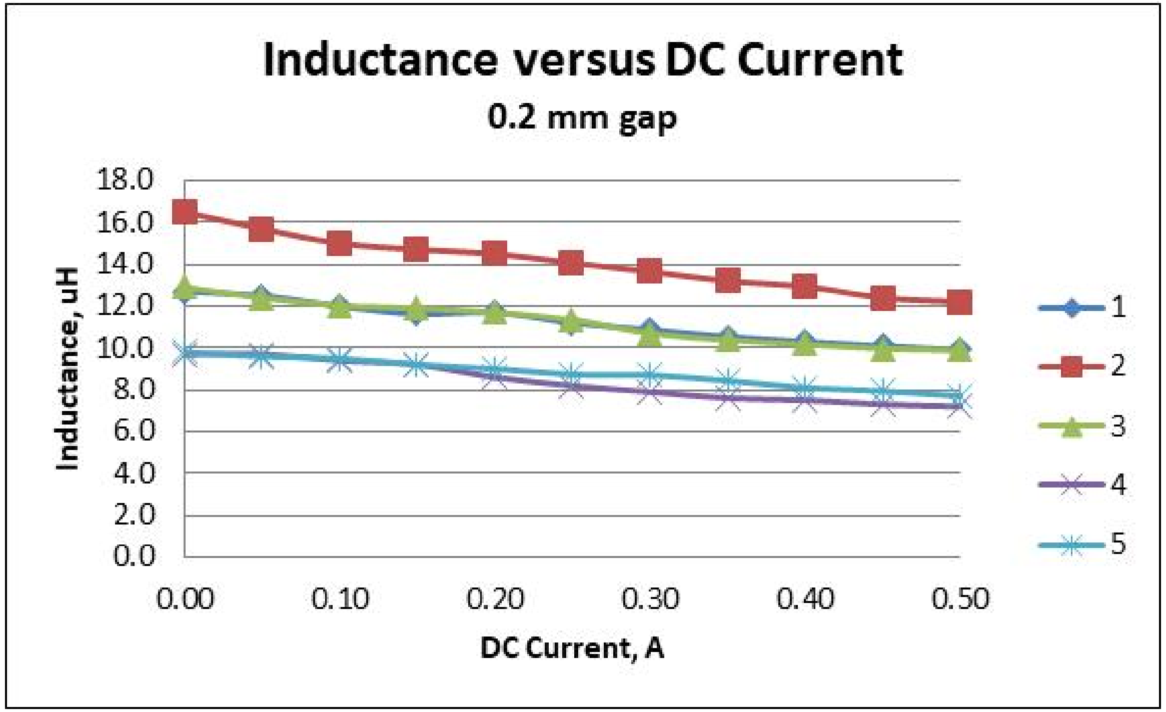


Embedded Magnetics sample units
Core Size: 6.35x3.81x2.5 mm, 5K permeability, 10 Turns

Inductance versus DC Current Data



Typical profile
Core Size: 6.35x3.81x2.5 mm, 5 K permeability, 10 Turns



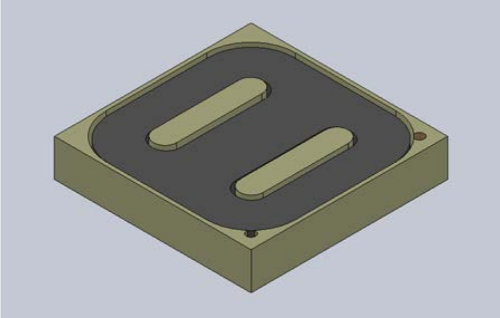
Embedded Magnetics sample units
Core Size: 6.35x3.81x2.5 mm, 5K permeability, 10 Turns

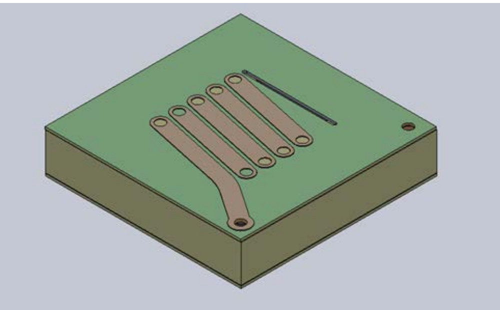
Test Coupon 2

	Inductance before gapping, uH							
Windings	4T	5T	6T	7T	8T	9T	10T	11T
Ave	31.9	54	81	117	156	207	260	327
Min	30	55	92	121	151	210	146	333
Max	37	64	96	138	192	245	332	356
STD Dev.	2.48	6.75	9.28	11.78	18.18	25.51	35.01	18.81

	Inductance after gapping, uH							
Windings	4T	5T	6T	7T	8T	9T	10T	11T
Ave	1.7	2.9	3.3	3.9	5.6	7.3	7.5	7.9
Min	1.5	2.2	2.9	3.6	4.6	5.8	6.4	7.8
Max	1.8	5.0	3.6	6.6	8.2	24.0	16.9	8.8
STD Dev.	0.11	0.70	0.21	0.70	0.86	3.63	2.02	0.46

	Winding Resistance, mΩ							
	4T	5T	6T	7T	8T	9T	10T	11T
Average	27	32	40	54	70	86	110	124
Min	24	28	34	45	40	80	98	100
Max	31	48	61	98	108	96	119	138
Std Dev	1.6	3.6	4.7	9.1	9.5	3.5	4.6	6.9

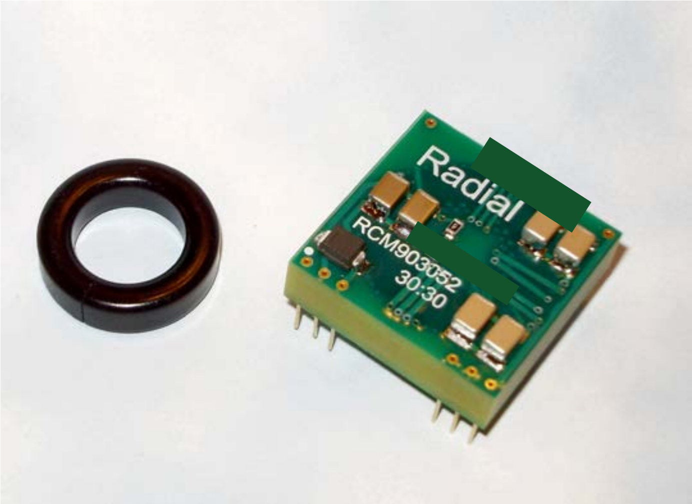




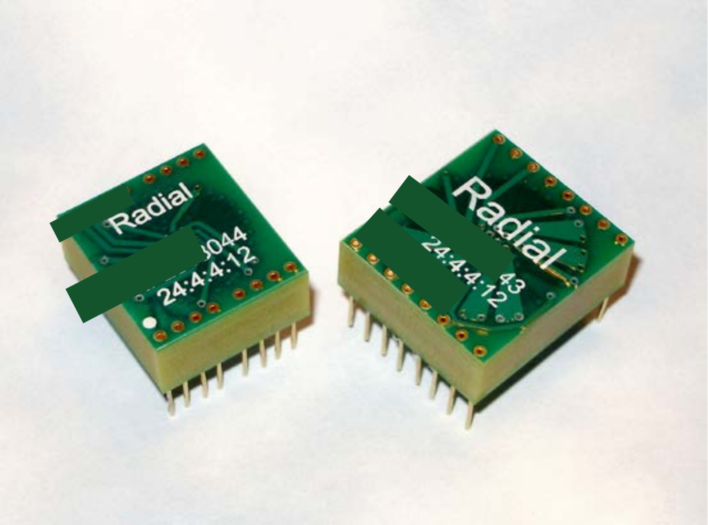
10.6 x10.6x 2 mm

Conclusions

- Automated and batch process
  - Transformers and inductors fabricated with just a small fraction of the labor used to manufacture similar wire wound devices
  - Process a can be implemented on most PCB manufacturing lines.
  - Panel format brings efficiency during manufacturing and test
  - Gapping process can be step-and-repeated
- Practical implementation of efficient low cost toroid shaped cores
  - Laser gapping provides stability over temperature and DC current
- Reliability consistent with PCB technology
- PCB format allows stacking and vertical integration of other passive and active components



Thank You



Any Questions?