Technical Bulletin

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Designing with Planar Ferrite Cores

This review of planar ferrites discusses issues relevant to the magnetics designer. These include standard sizes and shapes; conductor types; material selection; power handling; gapping; assembly; design hazards; prototypes and development; core manufacturing; and special applications.

The primary appeal of planar magnetics is obvious: in many applications there is a great benefit to having power transformers and inductors that are not tall. Printed circuit boards are only as compact as the tallest component on them, and that is often a magnetic. But low height is not the only reason for the growing use of planar ferrites in power magnetics. Planar designs offer advantages that include low leakage inductance; excellent repeatability of performance; economical assembly; mechanical integrity; and superior thermal characteristics.

Briefly described, a planar transformer or inductor consists of a pair of wide, long cores having short legs assembled around a set of flat windings. This arrangement is in contrast with the conventional approach, which uses narrow cores having long legs assembled around a thick cylinder of windings. The planar magnetic covers a large square area in very low profile, whereas the traditional magnetic has a roughly cubical volume. The planar windings are usually flat copper traces, either stamped or in a printed circuit board, in place of the traditional coils of magnet wire.

With the arrival of industry standard core sizes and geometries, offered by multiple ferrite vendors in state-of-the-art power ferrite materials, planar magnetics are being used in a growing proportion of new power supply designs.

Background

Faraday's Law continues to have the final word in magnetic design.

Faraday's Law: $V = 4.44\, N\, A_e\, f\, B\, 10^{-8}$

Where: V is the applied potential (volts rms)
4.44 is the form factor for a sine wave
N is the number of turns
A_e is the core cross-sectional area (cm^2)
f is the frequency (hertz)
B is the peak flux density (gauss)

Since no practical materials have been discovered which allow extremely high current density without loss, or extremely high flux density without saturation, the only variable in Faraday's equation that can be adjusted to significantly shrink the size of a magnetic is frequency. The great benefit of ferrites, of course, is that they permit operation at frequencies into the hundreds of kilohertz, even to several megahertz. With the frequency very high, Ae and N may be set to small values, and the resulting magnetic is miniature in comparison with a low frequency device.

But there are limitations to how high the switching frequency may realistically be set. Losses in the switches, increased core loss that requires the flux density to be derated, and parasitic elements together have the effect of setting an upper bound on the frequency that a designer can use. And with all of the variables in Faraday's Law limited, the volume of the magnetic is more or less fixed. The designer may then begin to think about spreading that fixed volume out on the board (and through the board), instead of standing it up tall on a smaller footprint.

Thus the recent trend in power magnetics is a slowing in the increase of typical switching frequencies, along with a growing interest in planar devices.

Core Geomietries

The most frequently discussed planar ferrites are the E-cores. *Figure 1* illustrates the contrast between a planar E and a traditional E-core. It is plain to see how the planar geometry spreads out the volume of ferrite over a large area, resulting in low height. The part in *Figure 1(a)* exhibits rounded corners on the legs, and it can be made at intermediate heights, all the way down to an I-core, as in *Figure 1(c).*

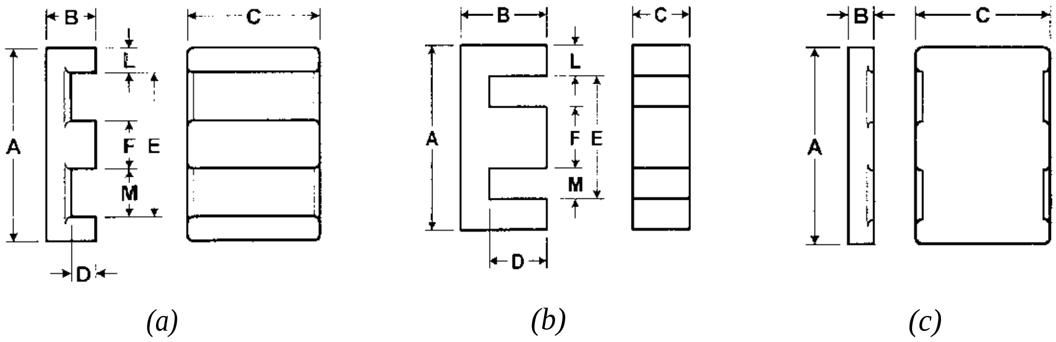

Figure 1. *(a) Planar E-core. (b)Traditional E-core. (c) Planar I-core, made with the same tooling as the planar E-core.*

In recent years, industry standard planar E-core sizes have become established. Although each ferrite vendor offers some unique parts, and many designers have developed special cores for particular applications, a group of generally accepted sizes has evolved. An IEC standard, 61860, "Dimensions of Low Profile Cores made of Magnetic Oxides," is nearing final approval. Table 1 lists the standard planar E-cores. For each E/E set, there is a corresponding E/I set, called the E/PLT (for plate). For the E/I set, the inside height is only D, instead of 2D, and the height of the set is 2B-D.

Core	A mm	B mm	C mm	D mm	E mm	F mm	A_e cm^2	l_e cm
E/E14	14.00	3.50	5.00	2.00	11.00	3.00	0.147	2.07
E/E18	18.00	3.98	10.00	1.98	14.00	3.98	0.401	2.42
E/E22	21.60	5.72	15.90	3.18	16.50	5.08	0.806	3.21
E/E32	31.75	6.35	20.32	3.28	25.40	6.35	1.29	4.17
E/E38	38.10	8.26	25.40	4.45	30.48	7.62	1.92	5.28
E/E43	43.18	9.53	27.90	5.46	35.05	8.13	2.27	5.75
E/E58	58.40	10.55	38.10	6.50	51.10	8.10	3.10	8.07
E/E64	64.00	10.20	50.80	5.10	53.60	10.20	5.19	6.97
E/E102	102.00	20.30	37.50	13.13	86.00	14.10	5.40	14.8

Table 1. *Industry standard planar E cores. Dimensions reference Figure 1(a).*

The E shape is not the only planar geometry. Other conventional shapes are produced in low profile versions. These include PQ, RM, and pot cores *(Figures 2 and 3).* There are several advantages to these styles. One is that the centerposts and skirt IDs are round, resulting in a more efficient use of copper. The ER series is a planar E-core style that uses a round center leg *(Figure 4).* Another advantage can be the efficient use of board real estate, especially with the RM geometry, which can be designed for a square footprint.

A significant appeal of the low profile versions of standard shapes is the relative ease of making preliminary samples. Standard stock cores are machined down to planar height. After the best height is established, production quantities of cores are usually manufactured by setting up the standard tools to press shorter parts.

The IEC standard 6 1860 will include standard specifications for low profile RM cores and ER cores, in addition to the planar E/Es and E/Is.

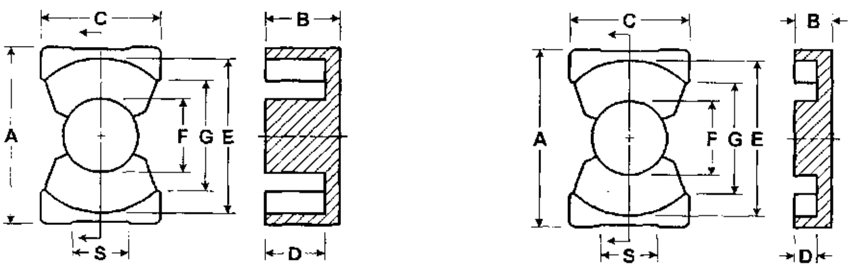

Figure 2. *PQ geometry – standard and planar.*

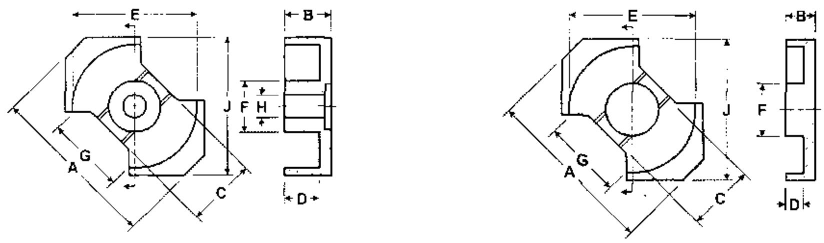

Figure 3. *RM geometry – standard and planar.*

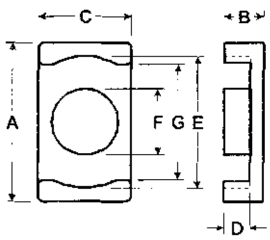

Figure 4. *ER Geometry*

Planar Winding Design

Four basic options are available for winding the planar transformer or inductor. (1) Stacked printed circuit boards; (2) stand-alone multilayer board; (3) integrated through-board; and (4) wire.

Stacked printed circuit boards. Individual boards fabricated to fit the shape of the core and terminations can be stacked, then electrically connected. Stamped copper traces are sometimes used, separated from each other with a dielectric film.

Stand-alone multilayer board. A separate printed circuit board consisting only of the planar windings may be fabricated to fit the core and terminations being used. The magnetic is assembled and then placed on the main board, or in a cutout on the main board to conserve height.

Integrated through-board. This approach has the potential for the best use of space. The windings are built into the main multilayer board being designed. Cutouts for the core centerleg and outside legs are made in the board. The core set assembles around the board, splitting the height between top and bottom. Termination difficulties that arise with the other approaches may be circumvented. If there are not enough layers in the main board, a hybrid approach may be tried in which some of the windings are separate from the main board. The risk with integrated windings is the initial commitment to fabricating a board that is unproven.

Wire. It is not unheard of for designers to take advantage of the planar geometry without making the commitment to printed circuit traces for the conductors. The consistency of performance and the low leakage of a printed circuit winding may be lost, and there may be higher assembly costs, but the height and thermal advantages still apply. A magnet wire winding may be cheaper to start up in production, be more adjustable, and exhibit lower fringing losses.

When using printed circuit windings, there are several benefits. Because the winding layout is fixed, and cannot vary in the way that conventional windings do, the repeatability of performance from one unit to the next is very good. Leakage inductance and proximity effects are quite low. By interleaving windings (P-S-P), typical leakages are less than 1% of primary inductance, down to 0.1%. There are drawbacks to interleaving, namely capacitance and assembly complexity. Each of these can be planned for, since they are consistent. The capacitance may even be exploited in some resonant designs.

A planar design normally has cost advantages when produced in volume. Manufacture of printed circuit windings is more automated than traditional coils. An operation is reduced or eliminated, because the magnetics assembly is integrated with the board assembly. Also, some soldering and hardware costs may be eliminated.

It would be problematic to implement coils with hundreds of turns using printed circuit windings. Fortunately, because the typical application is power, the turns counts are generally low. Depending on the topology of the circuit being used, there may be a need for the added complexity of sense windings or reset windings. The more practical problem that is encountered is making sure that the true copper cross sections are large enough to conduct full load currents.

Material Selection and Power Handling

For power transformers and inductors, the criteria used to select a ferrite material are the same whether the geometry is planar or conventional. There are excellent power materials available from several manufacturers. Each is designed for optimum performance in particular frequency and temperature ranges, and the material behavior is independent of the core geometry (although the thermal response is not.)

Planar designers have an incentive to push flux density higher than they would in similar, traditional designs. Any magnetics design involves a tradeoff between copper losses and core losses. In other words, using more turns of copper results in lower flux density and lower core loss; but using fewer turns of copper allows a lower current density and lower copper loss. In the typical planar device, the minimum total losses are achieved by favoring the current density, and letting the flux density run higher than traditional designs might allow.

Planar geometries by their nature have smaller windows relative to the total device volume, so space for windings is at a premium. With printed circuit windings the largest practical percentage of window actually filled by copper is typically lower than with magnet wire. For these reasons, there is much to be gained by keeping the turns count to a minimum.

At the same time, planar geometries have a higher ratio of surface area to volume. They are literally spread out over a greater area, which is a favorable thermal situation. On average, the core and conductor material that is generating heat is closer to the surface; and there is much greater surface per unit of volume to radiate heat. Finally, there is a natural opportunity to attach heat sinks or blow air against the large flat ferrite surfaces.

With modern low loss ferrites, optimized for high operating temperatures, designers have an opportunity to be aggressive with flux density, resulting in smaller packages, or higher throughput power, than would otherwise be possible.

For example, Table 2 compares two cores that are similar in size, one planar (E/E32), and one a conventional square leg E-core (Lamination size E2627). [Side note: a common point of confusion concerns the term "lamination size." These ferrites have nothing to do with laminations, except that there is an established family of widely available bobbins for steel laminations. The ferrites are sized to take advantage of the bobbins, so the lamination dimensions persist.]

Core	E/E32	E2627
Style	Planar	Traditional
Total Window Area	0.605 cm^2	1.127 cm^2
Core Cross Sectional Area	1.29 cm^2	0.836 cm^2
Area Product	0.78 cm^4	0.94 cm^4
Ratio of Window Area to Core Area	**47%**	**135%**
Exposed Surface Area	**23 cm^2**	**19 cm^2**
Volume with Full Windings	**11.3 cm^3**	**12.6 cm^3**
Minimum Height	**1.3 cm**	**2.5 cm**
Core Dimension */Ref. Figure 1(a) and 1(b)]*	A = 31.8 mm B = 6.4 mm C = 20.3 mm D = 3.2 mm E = 25.4 mm F = 6.4 mm M = 9.5 mm	A = 30.5 mm B = 13.4 mm C = 9.4 mm D = 9.0 mm E = 21.9 mm F = 9.4 mm M = 6.2 mm

Table 2. *Comparison between a planar E-core and a conventional E-core of similar size.*

Examining Table 2, is it plain that the window area is much smaller for the planar core. The window is less than half the core cross section, whereas for the conventional core the window is much larger than the core cross section. The relatively small window makes achieving efficient use of the conductors a high priority, even at the expense of higher flux density. The good news is that the exposed surface area is much greater for the planar core, so it is able to radiate heat more effectively. Even though the planar core is a little smaller in area product and total volume than the conventional core, it may be designed for similar performance, and at a much lower height.

Another potential advantage of the planar magnetic is mechanical integrity. In applications that will be exposed to vibration or shock, the tall, heavy mass of a traditional ferrite magnetic is vulnerable to becoming dislodged due to high angular forces. In contrast, the planar magnetic has a center of mass located close to – or even within – the board it is attached to. There is a trade-off, however. Planar cores themselves are more susceptible to breaking under mechanical or thermal stress. Traditional cores are more compact; planar cores present thinner cross sections for the same mass.

In cores operating at typical modern switching frequencies, the flux density is loss limited, rather than saturation limited. The planar designer is able to push the flux density higher, for the reasons described above, but she or he must still pick a core loss limit that results in acceptable overall efficiency and temperature rise. One fact that may not be obvious is that for a given voltage, core and winding, an *increase* in frequency results in a *decrease* in core loss.

This is significant when thinking about planar magnetics, because there is not much winding flexibility. If the conventional designer discovers that the flux density is too high, adding a few turns may resolve the problem. Adding turns to a tooled printed circuit winding is not so easy. Faraday’s law allows another way to cut the flux density: boosting the frequency. In ferrites at typical switching frequencies, the loss exponent for B is greater than the loss exponent for f:

Power Loss = $a(f^c)(B^d)$, where $d > c$; and $(f \times B)$ = Constant, for a given structure.

Therefore, the net result of an increase in frequency is some amount of decrease in the core loss.

Gapping

Power inductors use gapped cores in order to maintain a predictable inductance, and to prevent core saturation over the design range of currents and temperatures. Planar cores are quite suitable for inductors, provided some precautions are taken.

The designer sets the gap shallow enough so that there is enough inductance to hold the ripple current to an acceptable level, but deep enough so that the core will not saturate under maximum load. Finding the optimum gap is an iterative process, since the number of turns is a variable as well. The ferrite manufacturer’s curves for DC bias performance are used to determine whether saturation levels are reached at maximum current for a given gap. It is important to remember to derate the bias curves with temperature, because ferrite saturation decreases with increasing temperature, and planar inductors often see significant temperature rise.

Fringing losses can be severe in any gapped ferrite inductor, and they are potentially the worst with a planar geometry. Flux that is crossing through the gap region in the center of the core set has a tendency to fringe, or bow out, into the winding space. When the flux intersects the copper windings, eddy currents are generated, and energy is wasted. If the winding is not a round magnet wire, but rather a flat copper trace, lying normal to the direction of the fringing flux, then the eddy currents are given extra degrees of freedom. The resulting losses can be disastrous. The remedies include keeping the gap depth small; keeping the conductor out of the area closest to the gap; and considering an E/I core set, so that the gap is not centered in the winding stack. All the solutions have drawbacks (saturation, size, leakage), so the tradeoffs must be weighed.

In most cases, the best repeatability for an inductor will result when the gap is specified as an inductance (A_L), rather than a depth of grind. The manufacturer centers the gapping process by measuring inductance, rather than by physically measuring the gap depth. Not only is the electrical measurement inherently more precise than the dimensional measurement, but the electrical measurement bucks out any effects due to material permeability variation or effective parameter variation.

It is critical during development to correlate the manufacturer's A_L measurement with the inductance actually recorded using the printed circuit winding. The vendor's test bobbin will be different from the low turns coil the inductor sees in operation, and there can be a discrepancy between the inductance calculated from the A_L and the inductance measured in the circuit. The good news is that the variability in planar bobbins is low, so that once a correlation is established, it remains valid.

For gaps less than about .020", and depending on the size of the planar core, the ferrite manufacturer may require a wider tolerance than the industry standard ±3%. This is due to the challenge of maintaining a uniformly flat, parallel grind along a wide centerleg.

Assembly

There are several alternatives available for holding core sets together around the windings.

Some planar cores are offered with recessed slots and clips that fit into them without increasing the overall height. This is an attractive arrangement for prototyping, and can be suitable in some production settings. The disadvantages are cost of the clips, increased core cost due to manufacturing complexity, labor-intensive assembly, and difficulty assembling in an integrated board.

Planar cores may be assembled with tape, the same as conventional ferrites. This is particularly useful in development work, where it is desirable to be able to disassemble the core set without damaging it.

The most common production method of assembly is to use high temperature, thin adhesive. For power ferrites, the mating surfaces can be face bonded without significant effect on the electrical performance. If the adhesive is appropriately selected, the result is a very strong assembly that is usually the least expensive to assemble in production volumes.

Some designers construct custom fixtures to hold planar cores in place. These are used to solve special mechanical or heat sinking problems.

Design Hazards

In addition to the precautions cited above for gapped cores, there are some typical pitfalls that designers should be aware of for any planar construction:

- **Skin and proximity effects.** The opportunity to use flat copper traces and to interleave windings actually helps to address skin effect and proximity effect limitations. But the typical planar application involves large currents and high frequencies, so care must be taken. AC copper losses may become significant.
- **True copper cross section.** Over-estimating the copper fill in the window could easily result in much higher current density than anticipated. Board material, insulation, and mechanical tolerances all represent window space that is not filled with conductor.
- **Winding termination.** Connecting from planar windings to the input and output terminals can be tricky. This spot can be a source of parasitics and high winding resistance. It is possible to find that termination resistance makes up the majority of a transformer's high frequency winding resistance.
- **Mechanical integrity.** Especially because large temperature excursions are normal in planar magnetics, care should be taken to account for the coefficients of thermal expansion among the cores, heat sinks, clamps, glues, and boards. CTE for ferrite is quite low, 10-11 ppm/°C. Also, ferrite is brittle – it is a ceramic, after all – and the planar cores are flat, thin sections that cannot absorb as much strain as more compact geometries can.

  Thermal shock must be avoided. Ferrite should not be heated or cooled by more than 5° - 10° C per minute, or it may crack. Soldering and curing operations are places to be cautious of thermal shock difficulties.
- **Thermal runaway.** This caution serves to re-emphasize the importance of material selection. If the transformer or inductor is going to heat up, it is important to account for the worst-case core losses, and the core loss vs. temperature curve. If the core reaches a point at which increased temperature results in increased losses, a thermal runaway condition could occur.
- **Dimensional limits.** The biggest possible printed circuit windings must fit onto the smallest possible core. The ferrite vendors publish mechanical tolerances that are typically l-3% of the reference dimensions. The reason for these tolerances is that ferrites shrink during sintering, resulting in a spread of the finished dimensions that a normally controlled process will yield. The variation is not large within one production batch, but it is greater from batch to batch.

Prototypes and Development

The most direct route to a new planar transformer or inductor is to use a standard core set, of course. But designers need to make the best possible use of every bit of space, and this sometimes results in a special core. Most planar E-cores have rounded corners on the legs (see *Figure 1 (a)*). In addition to helping make the best use of printed circuit board space, since their cutouts have radiused corners, the rounded ferrite corners imply that the core height is adjustable by the manufacturer. The curvature is built into the tooling components for a part that is pressed with its legs down. Any core with a round centerpost is also pressed legs down and is usually adjustable in height (*Figures 2, 3, and 4.*) The alternative to pressing with legs down is pressing a core on its side. In that case, it is the width of the core that is adjustable, and not the height.

To develop a low-height variation of a standard core, the initial prototypes are ground down on the mating surface (and back, if needed) from standard parts. The grinding work may be done by the manufacturer, or by one of the many distributors and value-added shops that are experienced with the intricacies of machining ferrites. Once the design is settled and larger quantities are needed, the ferrite manufacturer produces production lots by pressing to the lower height. Obviously, it is wise to confirm any height or quantity limitations with the manufacturer early on.

In some instances, no existing core is right, and it is determined that a new application warrants the delay and expense of completely new ferrite tooling. Even then, there are strategies for making prototypes to try out designs before the tooling commitment is made. Parts can be machined from blocks, or from larger cores. *Figure 5* illustrates how a planar E-core could be cut out of a standard E-core, making only flat surface cuts.

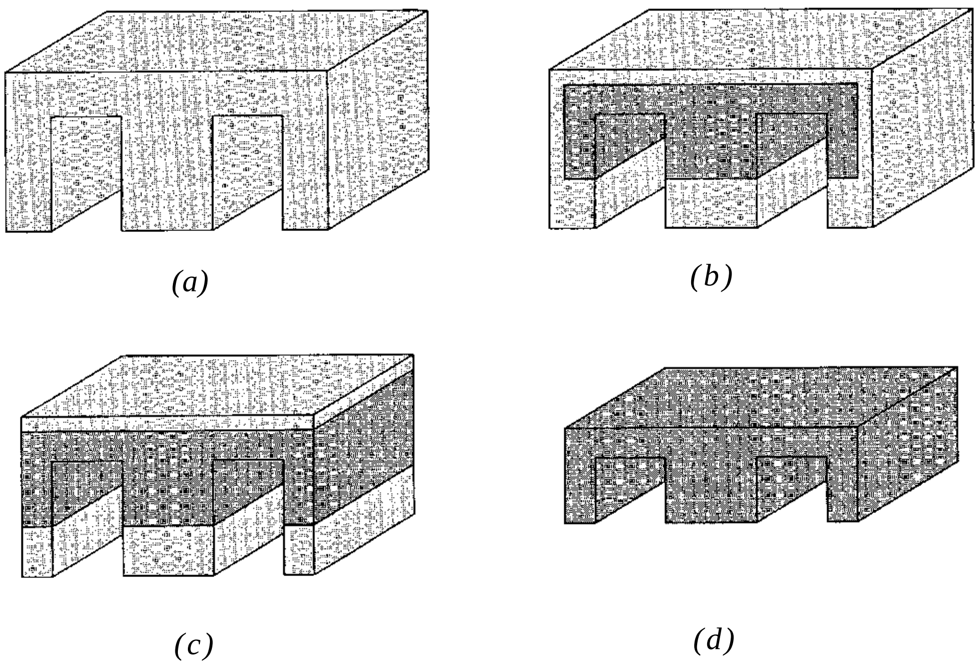

Figure 5. *(a) Standard (non-planar) E-core. (b) A planar core lurks inside the standard one. (c) The ends of the standard are removed by flat-grinding. (d) The mating surface and back are removed by flat-grinding, leaving the prototype planar core. Only outside, flat cuts were made; grinding on the inside surfaces or grinding cylinders is possible, but more costly. Adding material is not possible.*

Finally, there is a shortcut past all of these development considerations. Some companies specialize in producing planar transformers and inductors. A standard or custom device purchased from one of these vendors may turn out to be the most efficient strategy in many situations.

Special Applications

This paper has focused on power magnetics and on the standard planar geometries. But there are other applications for planar cores, and other ways to achieve low profile.

- Planar magnetics are used in common mode chokes and broadband transformers. Instead of low loss power materials, high permeability ferrites are selected. Advantages are low leakage, repeatable performance, reduced assembly cost, and low height (naturally.) The main disadvantage in comparison with toroids is that there is always a mating surface, and even when the planar cores are lapped to a mirror polish, the mating surface gap degrades the inductance.

  There can also be an electrical advantage due to the geometry of the planar core compared with a standard shape. Inductance is proportional to the ratio of cross section to path length. Table 3 compares the A_L values for the same cores that were compared for power handling in Table 2. The difference is dramatic, but the planar core is severely limited because it has only half as much window area. That is a big disadvantage when the goal is high inductance, because inductance adds with the square of the turns.

Core	Style	A_e to l_e Ratio	Typical A_L (5000µ material)	Window Area
E/E32	Planar	31%	14,550	0.605 cm^2
E2627	Traditional	13%	5900	1.127 cm^2

Table 3. *The effect of geometry on inductance factor (A_L).*

- There is increasing interest in low profile toroids, especially in sizes under ½” OD for DC-DC converters. Just as the heights of planar E-cores may be adjusted at the press, toroid heights can be reduced without building new tooling. The limitations are ejecting very thin, unsintered parts from the tool without breaking them, and then sintering the parts without warping them.

- Other ferrite geometries have been introduced that are intended for low-profile design, without being specifically planar. EFDs are the most popular (*Figure 6.*) An offset centerleg pulls the coil down, using space that otherwise would be empty underneath the core.

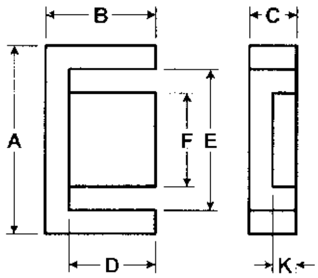

Figure 6. *EFD Geometry*

References

[1] Ferrite Cores, Data book, Magnetics Division of Spang & Company, Butler, PA, 1999.

[2] E.C. Snelling, Soft Ferrites; Properties and Applications, pp. 54-55, 256-261, London, Butterworth, 1988.

[3] Draft standard for 61860, "Dimensions of Low Profile Cores made of Magnetic Oxides," International Electrotechnical Commission, IEC, 1998, 51/528/CDV.

[4] Brown, E., "Planar Magnetics Simplifies Switchmode Power Supply Design and Production," PCIM, July 1992, pp. 46-52.

[5] Dai, Lofti, *et. al.*, "A Comparative Study of High-Frequency Low-Profile Planar Transformer Technologies," Applied Power Electronics Conference February 1994 Proceedings, pp. 226-237.

[6] Van der Linde, Boon, and Klaassens, "Design of a High-Frequency Planar Power Transformer in Multilayer Technology," IEEE Transactions on Industrial Electronics, Vol. 38, No. 2, April 1991, pp. 135-141.

[7] Carsten, B., "High Frequency Conductor Losses in Switchmode Magnetics," High Frequency Power Conversion Conference Proceedings, May 1986, pp. 155-176.

[8] Khai, Ngo, and Kuo, "Effects of Air Gaps on Winding Loss in High Frequency Planar Magnetics," PESC April 1988 Record, pp. 1112-l119.

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