Low Profile Embedded Magnetics for RF Communication Systems

Jim Quilici
Radial Electronics
El Dorado Hills, California

Abstract - Portable electronics demand that inductors and transformers to be implemented in low profile surface mount packages. In communication systems, magnetic components are used for impedance matching, voltage isolation, energy storage, noise filtering, and combining signals. Inductors can be implemented on ferrite bobbins with semi-automatic winding equipment. The inductance value and performance is constrained by the low inductance factor (A_L) of the bobbins and resistance of the fine gauge wires used to construct the windings. RF transformers are usually wound on either ring or binocular shaped core structures. Small size defies automated winding and the majority of devices are wound manually using low cost offshore labor. With manual construction there are issues with consistency and reliability. Embedded magnetics provides a new approach for fabricating the small transformers and inductors used in RF circuits. Ferrite elements are embedded into an FR-4 substrate and the device windings are realized using printed circuits techniques. This approach provides highly consistent performance and eliminates the need to dress fine wires and welding or soldering them to the package I/O pads. Additionally, the devices are fabricated in an automated and batch process. Rather than winding one at a time, devices are fabricated in an panel array format. With automation comes improved consistency and reliability. This paper describes the device composition and fabrication on a printed circuit line. A design example is presented to show the circuit layout and test results.

Inductors and transformers are basic building blocks of communication systems. For wireline transmission, transformers are used for; coupling signals to the transmission line, impedance mating and providing voltage isolation. In wireless communications, transformers are used to couple the antenna to differential transmitters and receivers. Additionally, common mode transformers and inductors are used for noise filtering.

Inductors and transformers come in many different shapes and sizes. Chip inductors and common mode transformers are widely used in RF systems. For inductors, a fine gauge wire is wound around a bobbin. The bobbin material can be plastic, ceramic or a ferrite[1] material. For a common mode filter, two wires are wound bifilar around the bobbin. The wires are fine gauge and can have significant winding resistance. Another common process for fabricating chip inductors is accomplished by printing spiral patterns on MLCC[2] substrates. The fine line conductive spirals are implemented by printing thick film conductive inks, which also result in relatively high winding resistance. Implementing these devices in small surface mount packages, places additional constraints. RF inductors implemented in common 0402, 0603, 0805 package sizes are limited to inductance values under 1 uH. For inductance values exceeding a few hundred nH, winding resistance often exceeds 1Ω and can exceed 5Ω for inductances approaching 1 uH. The winding resistance is a loss mechanism and degrades the circuit performance. Improvement comes through using larger core structures and increasing the conductivity of the windings.

Ferrite Toroid's (ring shaped) offer the most efficient core structure for magnetic components. Figure 1 depicts inductors wound on bobbin and toroid core structures. When a current is applied to the inductive windings, the electromagnetic field surrounding the wire induces a magnetic flux (B) in the core material. The flux temporarily stores energy and, in the case of a transformer, transfers energy between the primary and secondary windings. When the core material is ferromagnetic, like a ferrite, it will have a relative permeability much higher than nonferrous material or free space. Permeability can be thought of as the materials ability to temporarily store magnetic flux energy. For the bobbin structure, the magnetic flux path extends beyond the ends of the bobbin and travels through a low permeability path to the opposite end. Even if the bobbin is implemented in high permeability ferrite material, these cores offers relatively low inductance factors (inductance per turn, A_L) due to the discontinuity of the magnetic flux path. Also, the electromagnetic energy emanating from the core can stimulate nearby circuitry and cause noise problems. In comparison, the toroid offers a continuous high permeability path through the core structure. The magnetic flux is mostly contained in the core material and the toroid provides a more efficient and low noise alternative

---

[1] Ferrites are homogenous ceramics structures made by mixing Iron Oxide (Fe_2O_3) with oxides and one or more metals, such as manganese, zinc, nickel and magnesium. They are pressed and fired in a kiln.

[2] Multi-Layer Co-fired Ceramics

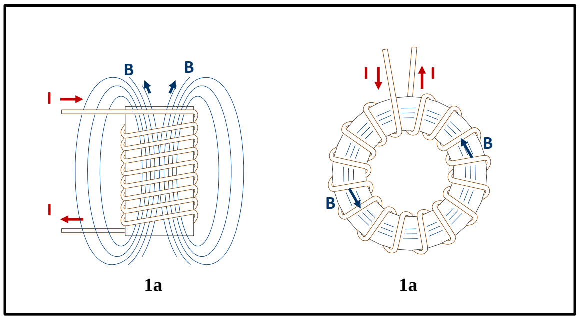


Figure 1, Inductors wound on bobbin and toroid core structures

The advantage of the bobbin construction is due to automation, which makes them more economical. In comparison, the toroid structure offers much higher inductance per winding. Consequently, it requires fewer turns to provide a specific inductance and provides much lower loss due to secondary effects; like winding resistance, leakage inductance and inter-winding capacitance. The drawback is that, historically, toroids have been difficult to wind. The small size cores used in RF applications have defied automation. Consequently, the devices implemented on these cores are fabricated one at a time using legions of manual off shore labor. With high manual content come issues with consistency, reliability and yield.

Embedded magnetics provides a means for producing these small RF inductors and transformers with an automated and batch process. Rather than fabricating devices one at a time, they are arrayed and produced on a PCB panel format using standard production processes. Fabrication is highly automated and can be accomplished with a mere fraction of the labor content used to produce wire-wound inductors and transformers. Device performance enters a new level of consistency and the reliability of a printed circuit board.[3]

Construction

Most RF transformers can be implemented in with 2 PCB layers. Figure 2 shows a cross section of an embedded magnetic transformer. A cavity is milled into an FR-4 substrate. Cores are inserted and encapsulated in place. For RF applications, we use ferrite materials with high permeability[4]. The performance of high permeability ferrite materials will diminish under mechanical stress and pressure. It is necessary to encapsulate with a low shrink epoxy to fill any voids ore caps around the core. The encapsulation protects the core during the lamination process.

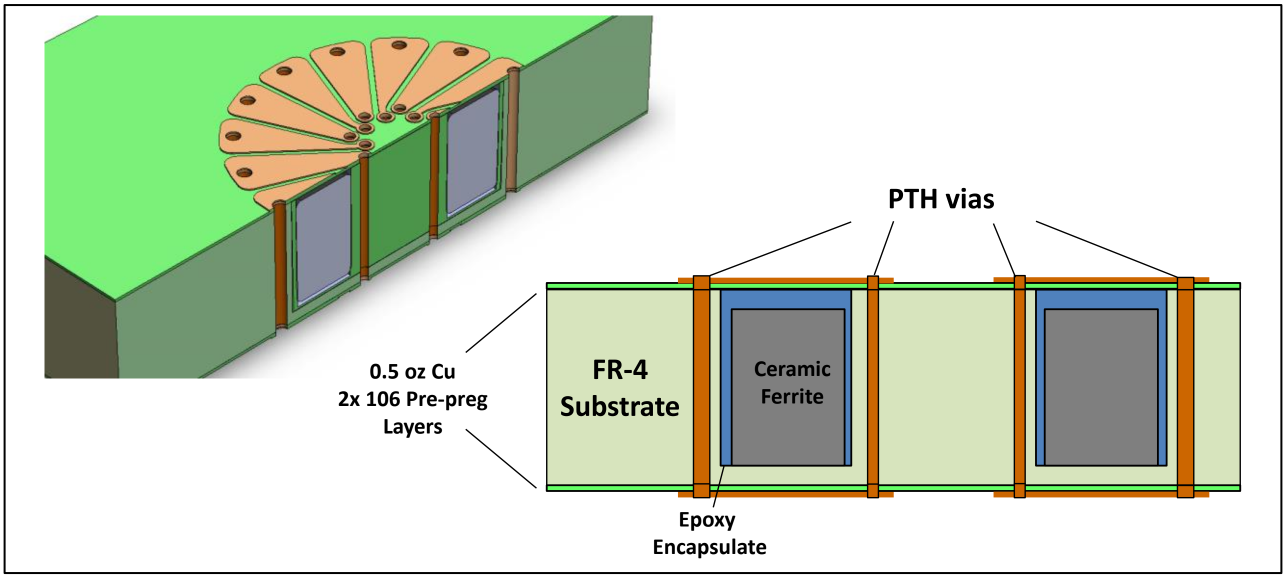


Figure 2, Cross section and layer stack

---

[3] Wire wound magnetic components typically have failure rates in the range of 1,000 ppm

[4] MnZn ferrite materials with relative permeability's ranging from 5,000 to 15,000

Once the core is in place, FR-4 pre-preg and copper foil layers is laminated to the top and bottom surfaces. Via holes are drilled and plated to interconnect the top and bottom surfaces. Once the via array is established, top and bottom circuit patterns can be imaged and etched to create the conductive windings. Figure 3 shows examples of winding artwork for an inductor, transformer and common mode filter (choke). The two colors indicate separate layers. These devices can be combined, arrayed and stacked to realize complex circuit functions. Figure 4 shows and example of an Ethernet media filter, realized with embedded magnetics. This device has 4 PCB layers and 8 transformer elements.

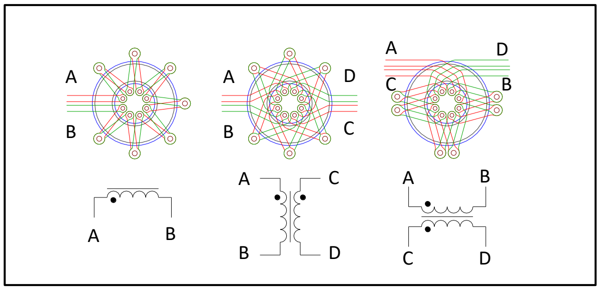


Figure 3, Winding artwork for common magnetic devices.

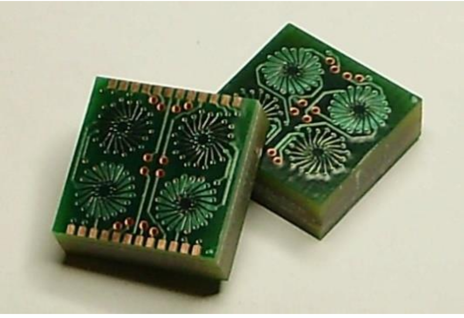


Figure 4, Ethernet Media Filter

Design Methodology

The starting point is to first determine how much inductance is required for the specific application. Inductors are primarily used in filter applications and the inductance values are determined through established design equations and network analysis. To determine the inductance required for a transformer, one needs to consider the communication signaling and transmission channel. Figure 4a shows and equivalent circuit for a transformer. In addition to the primary inductance, there are the secondary parameters of winding resistance, leakage inductance and inter winding capacitance and leakage inductance.

A transformer behaves much like a band pass filter, where it has a low end cut-off frequency[5] (fc1) and a high end cut off frequency (fc2). Similarly, the communication channel will behave as a low pass filter. Once we put the transformer in line with the signal, it becomes part of the communication channel. Generally, we don't want the transformer to constrain the bandwidth of the channel. Often the transformer's is designed to have a high end bandwidth exceeding the channel bandwidth so that it does not remove useful spectral content from the transmitted signal. As depicted in figure 4b, the low end cut off (fc1) is determined by the impedance of the channel and the primary inductance of the transformer. The high end cut off (fc2) is determined by leakage inductance and inter winding capacitance. Winding resistance primarily impacts the insertion loss in the passband and has some minor impact of the corner frequencies. These secondary parameters are all determined by the design of the conductive windings. The conductor widths, thickness and coverage over the underlying ferrite core impact winding resistance and leakage inductance. Inter winding capacitance is determined by the separation between the windings and the dielectric properties of the surrounding laminate material. Maximizing bandwidth requires balancing the primary inductance against the secondary parameters. Adding windings to increase the primary inductance will also reduce the device bandwidth by increasing the leakage inductance and inter winding capacitance. So to achieve a wide bandwidth, designers often use ferrites cores that have permeability of 5000 or greater. High permeability reduces the

---

[5] The corner frequency corresponds to half power point , where the attenuation is -3 dB.

number of windings required to achieve s a specific inductance. To minimize the secondary parameters, designers of wire wound transformers have limited techniques, like twisting the wires to try and balance the winding capacitance with the leakage inductors. Embedded magnetics provides a whole different approach to managing the secondary parameters and bandwidth. Designers can shape conductors and accurately control their spacing, much as one would design a transmission line. RF simulators can be employed to model the performance and signal integrity.

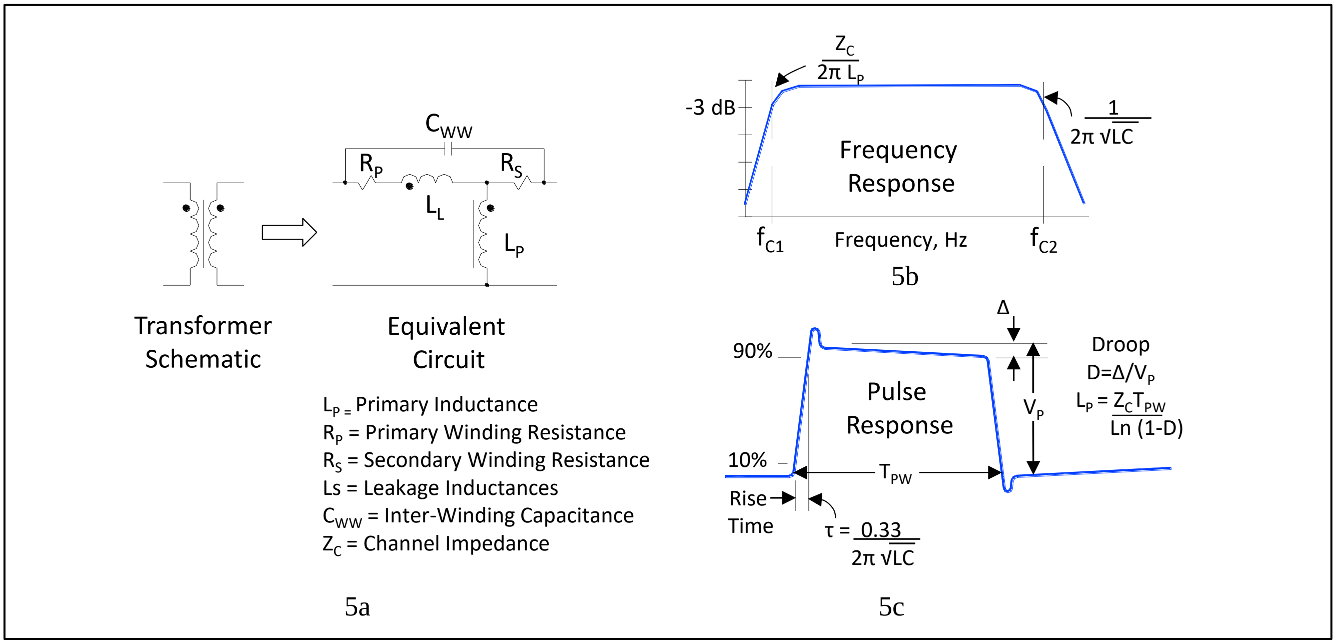


Figure 5, Transformer Equivalent Circuit and Associated Frequency and Pulse Response

The signal pulse response provides another means for determining the required inductance. Most digital communication is accomplished by transmitting single or multi-level pulses. As indicated in figure 4c, the pulse response can also be used to determine the required primary inductance. Here we consider the pulse width and the amount of voltage droop (Δ) that our system can allow. Droop must be managed to assure that the receiver at the far end of the channel has sufficient incoming signal levels so that a logic level can be determined. The primary inductance determines the droop that will occur after the pulse reaches its high level. Often it is acceptable to design for a 3% droop over the pulse width. Using that requirment we can use the following equation to calculate the required inductance.

$L_P = -(Z_C\ T_{PW}) / (\ln(1-D))$

So for instance, if we have a 100 MHz square wave with a 5 ns pulse width and we want to transmit it over a 100 Ω channel with less than 3% droop, the primary inductance should be as follows:

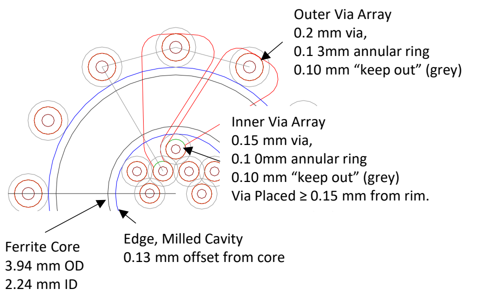
$L_P = -(100\Omega * 5\text{ ns}) / \ln(1-0.03) = 16.4\text{ uH}$

The inductance should be increased by 25% to 30%, to account for the tolerance of the ferrite material and its variation over temperature. So the primary inductance should be designed to ≥20 uH.

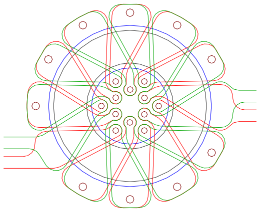
Once the inductance is determined, the next step it to select a core and design the windings. Ferrite manufacturers publish specifications for their cores. Key to our design is the toroid inner diameter and inductance factor (A_L), which is expressed as nH/T^2. Cores come in in a wide variety of sizes and it usually takes a few trial layouts before settling on the best size. For this design, a 3.94mm (0155”) OD core is selected. This core has an ID of 2.24 mm (0.088”). The height of the core is 1.27 mm (0.050”) and the core has an inductance factor of $A_{L=}$ 0.735 uH/T^2, when pressed in 5,000 permeability material. The required number of windings, (T) is calculated as follows:

$T = \text{SQRT}(L_P/A_L) = \text{SQRT}(20\text{ uH} / 0.735\text{ uH}) = 5.2$ turns.

This number is rounded up to 6 turns. Since there is a primary and secondary winding, the design requires that we fit 12 vias in the window area of the core. Figure 6 shows a preliminary layout for the circuit conductors. Via placement and the winding conductors must follow specific design rules to assure high yields in production. Conductors must have adequate separation to allow imaging plating and etching. The separation is also designed to control inter winding capacitance and provide sufficient voltage isolation. In this example, conductors are designed to be 0.1 mm apart. This brings to light, the limitation of embedded magnetics. With the wound devices, one can always cram more wires into the window area and the same inductance can often be achieved using a smaller core size. With embedded magnetics, we generally have to use larger core sizes to enable the vias to fit with adequate separation. The cost difference between the different core sizes is not really significant. The real tradeoff between the wire wound and embedded magnetics is size for automation. The embedded magnetic device may have a package footprint 20% to 50% larger than the wire wound component, yet is can be fabricated with a small fraction of the labor content. In applications that use more than one transformer, stacking in different PCB layers can often offset the footprint issue.



Preliminary Layout



Winding Design

Figure 6, Transformer winding construction and final artwork

To fabricate the devices, cavities are routed into a sheet of FR-4 core material that is 1.52 mm thick. Ferrites are inserted and encapsulated. As described earlier, 0.5 oz. Cu foil is laminated to the top and bottom surfaces. In the center of the device, the via aspect ratio is 10:1 whereas at the perimeter the via aspect ratio is 8:1. The via arrays were readily drilled and plated, then the panel was imaged and etched. Figure 7 shows the 20 uH transformers implemented in a PCB array. Half vias at the edge of the package provide lows cost I/O pads. After solder mask is applied, the total package height is < 1.8 mm, which is suitable for portable electronics. The panel is scored to easily separate the individual devices.

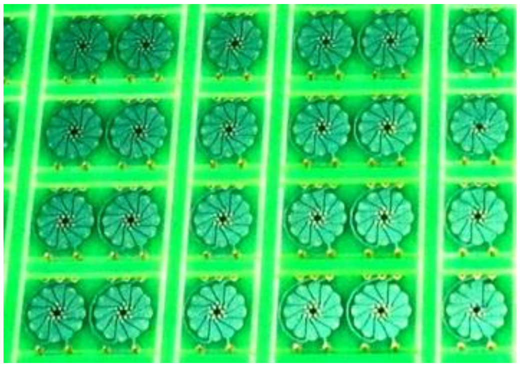
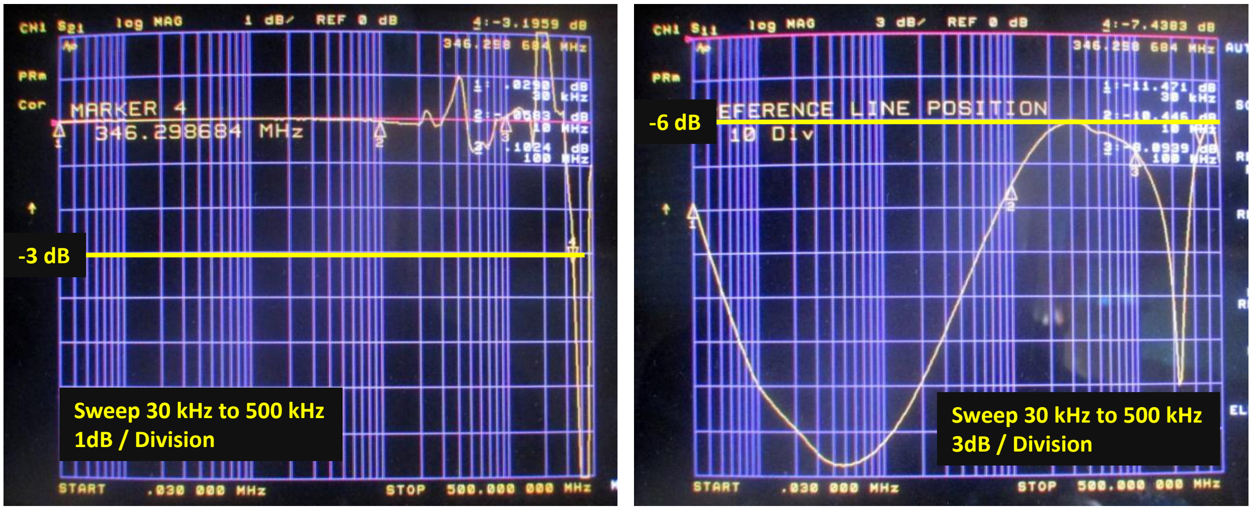


Figure 7, 20 uH transformers in a PCB panel format

Data collected on 20 devices exhibited an average inductance of 20.5 uH ± 0.7 uH. The winding resistance was measured at 92 mΩ ± 8 mΩ. Figure 8 shows plots of the insertion loss (S21) and return loss (S11) for one of these devices. The measurements were taken with a 2 port network analyzer that has a sweep range from 30 kHz to 3 GHz. For these measurements, the frequency was swept between 30 kHz and 500 kHz. The low end corner frequency, fc1, appears to be well below 30 kHz. At the high end of the spectrum there are some peaks and nodes associated with the leakage inductance, winding capacitance and their interaction with the test fixture. The high end cut off point, fc2, point occurs near 345 MHz. This is adequate to support 100 MHz transmission. Return loss, (S11) is a measure of how well the impedance of the device matches the channel. A mismatch in impedance can cause signal reflections and distortion. In this case, the device was tested with the 50 Ohm impedance of the network analyzer. The plot shows that the return loss is below -6 dB out to 300 MHz. Again, this is adequate to support 100 MHz transmission.



Insertion Loss. S21. 50 Ohm. 1dB/Division

Return Loss, S11, 50 Ohm, 3dB/Division

Conclusion

Embedded magnetics provides an automated and batch process for fabricating small transformers and inductors. They can be fabricated with just a small fraction of the labor used to manufacture similar wire wound devices. The process is portable and can be implemented on most PCB manufacturing lines. While there are some unique processes associated with loading and encapsulating the ferrite cores, after the cores are loaded the panel follows standard processes to image, drill and etch the circuit. In the case of the small RF transformer, over 3000 can be implemented on a 600 mm square panel format. LCR testing can be accomplished while in the panel format with flying probe or bed of nails test heads. This brings further efficiency. The PCB structure makes it practical to use FEA modeling tools to predict the performance before committing the artwork. Once realized, the devices exhibit consistency and reliability 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. 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 consistent performance

References:

1. Ferroxcube Product Selection Guide 2007
2. Magnetics Inc. Product Catalog, 2008
3. Nilsson, Riedel, *Electronic Circuits*, Pearson Education Inc. publishing as Prentice Hall, 2008

Authors Biography: Jim Quilici has over 30 years of experience developing microelectronics. He has designed and developed magnetic components for Pulse Electronics, Belfuse and Wurth Elektroniks. Additionally, he has worked for Level One, Intel and other silicon manufacturers, developing transceivers for data communications. Presently, Jim does design consulting and process development through Radial Electronics. He also is a part time lecturer in Network Analysis and Microelectronics at California State University Sacramento. He can be reached at jquilici@radial-e.com