Bringing Rapid Prototyping In-House

A White Paper for RF/Microwave Executives

INTRODUCTION

Productivity. Innovation. Time to market. Day to day, year over year, businesses are forced to make critical R.O.I.—related decisions that impact the future and the bottom line—some of them reactionary, some forecasted. For a growing number of electronics manufacturers, many of those decisions revolve around whether a function should be performed by an outside contractor or kept in-house. But for many companies in the RF/microwave industry, this decision is often concerned with continuing to employ an outside printed-circuit-board (PCB) fabricator for prototype PCBs, or to make a $10,000 to $100,000 investment in an in-house, rapid PCB prototyping machine that may represent a key competitive advantage.

A company manager or executive faced with such a decision must weigh the benefits of having an in-house PCB prototype milling machine, which can boost design prototyping with its fast turnaround time, and even encourage engineering experimentation due to the fast and easy access to prototype PCBs, versus the cost of the investment and its effect on the bottom line. Using outside PCB prototype fabrication services may be quite less than the cost of an in-house PCB milling machine, but how do those costs compare over time? And what other factors must be considered when weighing a decision between using outside PCB fabricators and buying a PCB prototype milling machine? A recent online poll by *Microwave Journal* showed that over 80% of the engineering readers surveyed named a PCB prototype milling machine as the most important tool in their design arsenal.

Prototyping, of course, is essential to the growth of any company involved in manufacturing their branded products, and a key step in the process of creating new products. Whether it is creating new automobiles or new package designs, companies in a wide range of industries have turned to the practice of rapid prototyping to speed their time to market. Rapid prototyping includes such techniques as three-dimensional (3D) printing to transform early product concepts into real examples. Whenever time to market is critical, rapid prototyping can produce a “first draft” of a new product that allows testing, evaluation, and further refinement of the product idea, which helps a company more quickly and cost-effectively transform early concepts into marketable products. At the same time, for concepts that may not make practical products, rapid prototyping can spare a company further investment time and expenses by revealing the product’s flaws at an early stage of the development process.

What follows is a review of two different ways to build prototype RF/microwave PCBs: through an outside PCB fabrication company and by investing in an in-house PCB milling machine. Hundreds of RF/microwave companies have invested in in-house rapid prototyping machines through a leap of faith in what they might mean to their companies, and have reaped the benefits. More fiscally conservative companies balk at such an investment, until they fully understand how it will impact the bottom line and help the company. The cost of a rapid prototyping machine can be considerable compared to the perceived low overhead cost of an outside PCB fabrication facility, but often overlooked are its advantages in terms of market-readiness, product performance, design flexibility, timing, and innovation.

THE NUANCES OF RF/MICROWAVE PROTOTYPING

A prototype PCB is the first tangible representation of a design from an engineer’s imagination, perhaps with some help from a computer layout program. It is the opportunity to turn a concept into a reality, and to evaluate that reality through testing to see if it is ready for production. Ideally, a prototype reflects in large part a final product, in terms of choices of circuit elements, integrated circuits (ICs), circuit-board material, and the dimensions of the circuit traces.

Computer-aided-design (CAD) and simulation programs can predict the performance of a prototype circuit and its various component parts, but cannot always account for the prototype's behavior under all operating conditions. By building a first circuit or prototype of a design (Figure 1), it can be characterized with different signals and under different operating temperatures and conditions. Typically, a prototype PCB may undergo testing and return to engineering for modifications several times before that prototype PCB is ready to be mass-produced as a final product.

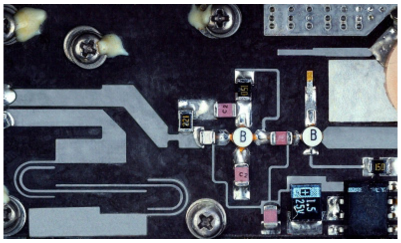


Figure 1. A prototype PCB provides real-world insight into a circuit design, and can be tested to check performance over a wide range of operating conditions.

Building a prototype PCB starts with a design concept. At one time, it was sketched on paper, with a schematic diagram showing interconnections and components, and then translated into a PCB. But with a growing reliance on computers and design software, "paper" designs have all but vanished, and circuit designs now reside within software files and digital code. Design programs include automatic rule-checking routines to alert a designer when circuit traces may cross or be placed too close together, or when additional grounding is needed, or when an IC or circuit component is not properly connected. Computer-based layout programs can also save files in industry-standard formats, such as Gerber files, to facilitate communication of a circuit between its designer and a PCB prototyping facility and later the board manufacturing plant.

BOARD MATERIAL CHOICES AND THEIR IMPACT ON DECISION MAKING

Fabricating a prototype circuit requires a choice of PCB material, a dielectric sheet typically laminated on one or both sides with a conductive metal, such as copper. Circuits are formed by removing the unwanted metal and leaving the desired circuit traces. One of the more popular circuit-board materials is FR-4, a low-cost, epoxy-based substrate that is well suited for a variety of analog and digital applications (Figure 2). Many different types of PCB materials are available but it is important to fabricate a prototype with the same material intended for final production, to best track performance as well as cost.

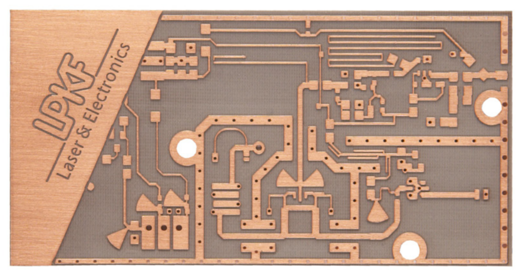


Figure 2. This photograph shows a bare FR-4 board laminated with a conductive metal, such as copper. This is an epoxy-based PCB material used for a wide range of analog and digital circuits (and prototypes). It can be laminated with conductive metal on one or both sides, for creating single-sided or double-sided circuit boards, respectively.

When selecting circuit material for a prototype, two of the more important material parameters to consider are relative dielectric constant (XR) and loss tangent. The relative dielectric constant, also known as permittivity, indicates the impact that a dielectric circuit material will have on the capacitance of a conductor fabricated on or within the material. Commercial circuit materials can be specified over a wide range of permittivity values. At higher values, an EM wave will travel at slower speeds along a conductive trace, and the trace will exhibit lower impedance and larger stray capacitance than circuit materials with lower permittivity values. For high-frequency analog circuits and high-speed digital circuits, PCB materials with lower values of relative dielectric constant will typically support higher performance levels than materials with higher values of permittivity. To allow designers to benefit from the reduction in circuit dimensions that occurs at higher relative dielectric constants, numerous suppliers of high-frequency circuit materials have developed low-loss materials with high values of relative dielectric constant capable of excellent performance.

Additional material parameters to consider for a prototype PCB material also depend on such factors as the bandwidth or maximum digital speed of the prototype design and its expected power-handling capabilities. For example, variations in PCB material dielectric constant across a panel of the material can result in inconsistent performance from multiple circuits fabricated from that same base-board material. The consistence of the relative dielectric constant with frequency and temperature can also result in variations in the impedance of transmission lines, and variations in the amplitude and phase responses of analog circuits, or timing errors in digital circuits. For circuits that must handle higher power levels, such as in a power amplifier, the thermal conductivity of the prototype PCB material is a concern and should be specified for the maximum expected power level of the circuit. In all cases, the PCB material that is used for a prototype should reflect the same choice that would be used for production circuits, in order to create a prototype circuit that is truly representative of the final production circuit.

The right choice of substrate material is very important for the overall performance of a circuit, especially for RF/microwave or high-speed digital designs. As material suppliers refine their products for improved performance or lower cost, it is even possible that a chosen substrate may change over generations of prototypes.

Why is this important to understand? Whether a chosen prototyping process is based on in-house equipment or an outside PCB service, it should provide the flexibility to process all of the possible material choices that an engineer might ultimately wish to experiment with and ultimately employ, to ensure the best chance of prototyping success.

BUILDING PROTOTYPES OUTSIDE

Once a prototype circuit design had been committed to a Gerber or other standard layout file, the traditional means of having a prototype PCB built meant choosing a "board shop" or PCB fabricator. With the widespread adoption of Internet-based websites and services, the search for a PCB fabricator has become greatly simplified. Most PCB fabricators show full listings of their capabilities on their websites. Some even offer free downloadable layout software to simplify the process of transferring circuit layout files to them. Many even suggest sending Gerber or other layout files to them in advance to help them determine prices for the job.

Those free software programs offered by many PCB shops may appear to have cost benefits, but they also have limitations. Many of these software tools are proprietary to one company, and don't provide industry-standard Gerber file exports. So, a circuit designer working with that software is "stuck" with that one PCB shop and cannot transfer layout files to other vendors. This can lead to problems and delays, especially if a chosen PCB shop is not able to process all of the substrates that a designer might choose. This is particularly true of circuit substrates for RF/microwave designs, since they often require specialized manufacturing equipment. A solution often requires a completely new design in a different software package that supports industry-standard file exports, such as Gerber or DXF, so that files can be sent to a different vendor.

Working with an outside board shop brings with it the benefits of that shop's expertise and experience. Based on a customer's performance requirements for a prototype circuit, that shop may recommend a particular type of high-frequency circuit-board material, or several materials that are capable of meeting a customer's performance requirements, but at different price points. Of course, a customer not familiar with those materials must trust in the expertise of the board shop that those materials will yield the performance expected of a prototype circuit under all operating conditions, including across frequency and temperature.

Some other considerations when selecting an outside PCB fabricator are facilities' capabilities in terms of inspection and environmental testing, if needed. For example, does the facility provide an ISO-9002 compliant quality system? Is it UL registered? Can it build PCBs to IPC-A-600 class 2 or class 3 standards as required? Essentially, the quality control that would be exercised over the creation of an in-house prototype PCB is being trusted to an outside facility, and some of these qualifications can provide some assurance of a facility's capabilities to meet high standards. ITAR registration is another important consideration when choosing an outside PCB vendor. Many PCB prototype vendors offer services through websites, where the actual manufacturing of the prototype often will be performed overseas, even when the "storefront" of the board house is located domestically.

Many PCB fabricators offer special 24-hour turnaround times for time-sensitive prototypes, but these fast-turnaround conditions, when available, are also much more costly than standard turnaround times of one to two weeks. Some PCB fabricators will also differentiate between prototype PCBs fabricated in the United States versus those built overseas, with lower prices quoted to customers willing to accept the much longer turnaround times associated with overseas PCB fabrication.

Although each PCB prototype fabrication quote has a relatively low cost associated with it, many PCB fabricators require a minimum order of 10 to 20 circuit boards so that, even for a prototype that has yet to be tested for performance, duplicate boards must be produced when perhaps only one or two are needed to verify the performance of the prototype PCB. The general problems associated with outside PCB fabricators are not with the quality of the fabrication, but in the often long and unpredictable lead times to receive a circuit board after a layout file has been transmitted and other requirements have been agreed upon.

Most design engineers will admit that it is rare when only one iteration of a prototype is needed as part of a product development cycle. More typically, when a prototype is first built, it goes through a series of modification cycles to correct design or fabrication mistakes. For this reason, the delay times from an outside PCB fabricator can be costly more in terms of product development than in the cost of the fabricator's fees. Those delays can translate into delays in product development and in time to market, which can be extremely costly in competitive areas of electronic sales. In addition, delays between prototype engineering versions can make it difficult to compile and keep track of engineering modifications, and can result in overlooked production-based problems plaguing the PCB prototype during times that are too long between design iterations.

PROTOTYPING IN-HOUSE

A growing number of electronics manufacturing companies, ranging from analog audio to high-speed digital and high-frequency RF/microwave circuit manufacturers, have come to appreciate the benefits of bringing prototype circuit fabrication capabilities in-house in place of using an outside PCB fabricator. One of the most obvious benefits is the tremendous increase in turnaround time, in some cases from days or weeks at an outside PCB fabricator to as little as hours or even minutes with an in-house circuit-milling machine or laser system. Of course, having the in-house capability versus placing an order with an outside firm also expands the range of possibilities on which circuits can be fabricated as prototypes, so that possible "alternative designs" can be fabricated as prototypes to experiment with different weights of copper on a dielectric board or other changes in key design parameters that might be too expensive to try at an outside PCB fabricator.

In-house prototyping helps save time when a design requires multiple prototype generations. Many first prototypes uncover shortcomings in a design, triggering a second-generation prototype. These shortcomings may be electrical or mechanical in nature, such as those from unexpected coupling or radiation effects. Addressing different design problems can lead to two, three, or even more design iterations. Saving time on each prototype generation can amount to a significant reduction in the overall design cycle, making a strong case for the use of in-house PCB prototyping equipment.

Having the in-house capability can bring hidden benefits, as Robert Kobak, Senior Technician at Shure, Inc. (www.shure.com), explains: "One of the more valuable applications for these milling machines is for fixing existing designs." In more than one instance, he notes that an in-house LPKF circuit-milling machine was used to fix work supplied by an outside PCB fabricator: "We've had cases where a board spin coming from one of our outside suppliers was missing some critical mounting hole, for example, for mounting a PCB to a chassis. We had one case where we had to drill a precision mounting hole across 100 boards, and do it repeatedly. We were able to do it with the LPKF milling machines." In one extreme case, Kobak was able to fix a multilayer circuit design that was missing via holes. "Some people thought it couldn't be fixed," said

Kobak, “but I reworked the Gerber files for that design to add via holes where we could place them.” Through a series of steps, and with the aid of the in-house circuit-milling machines, he was able to create new via hole connections through the multilayer circuit design, saving the design. “There was no way to do that without these machines,” he said, “and no economically feasible way to do it by going to an outside board shop.”

Of course, the largest single hurdle to switching from using an outside prototype PCB supplier in an in-house circuit-milling machine is the cost of the milling machine, which is a function of the machine’s features and capabilities. While the cost of any circuit-board milling system represents a significant investment for any company, it may not be that much more than the cost of just a few prototype PCB runs, especially when those runs involve multilayer prototype circuits. Multilayer circuits, with their embedded circuit layers and components, can be somewhat more complex to fabricate than single-layer circuits, but they also offer designers the opportunity to save an enormous amount of space that would be occupied by a single-layer PCB—by stacking circuit layers in a multilayer PCB. However having multilayer prototype PCBs fabricated at an outside board shop can result in costs that are a significant percentage of the total cost of an in-house circuit milling machine.

Kobak points out that the initial cost of investing in an in-house circuit-milling system seems less significant once the system’s contributions become apparent: “We ordered one LPKF milling machine, and then a second machine when we saw how well the first one worked. We bought the first one in 2007, a ProtoMat S62. We were going outside for prototype PCBs at the time, which can be expensive.” Shure, a world leader in professional audio electronic products, has fully embraced the use of wireless technology in its designs to free its customers from the need for long runs of connecting cables. The use of multilayer circuit boards to implement wireless transceivers and other circuits can save space, but can also lead to increased costs at an outside prototype PCB fabricator. Kobak explains that “an outside board shop will often charge for a minimum number of boards, such as 150, whether you need that many or not. The cost of a four-layer, 150-board run may be $10,000, while the cost of the S62 was under $30,000, including accessories and consumables.” For this example, with this single outside prototype PCB run at almost one-third the cost of an in-house PCB milling machine, it is easy to see the benefits of investing in an in-house circuit-milling solution after only a handful of outside board runs.

For some design teams, having an in-house circuit-board milling machine not only represents increased speed and flexibility in creating prototype circuits, it is also a means of building circuits that help evaluate new components for those circuits. Most companies try to know as much as they can about a new component from an outside supplier, be it a discrete transistor or an IC, before committing that component to a PCB design. Having an in-house circuit-board milling machine makes it possible to create small runs of evaluation circuits—circuit boards which emulate how a particular component will be used in an actual application, so that component can be evaluated under realistic working conditions.

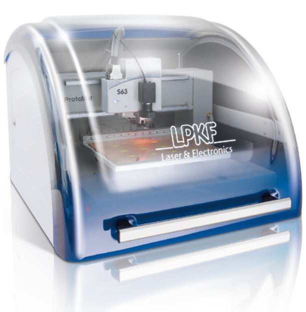
Garry Ingram, Technical Support Engineer for Raytheon Indiana (www.raytheon.com), comments that his company has used an LPKF milling machine for 14 years for its initial intended purpose, of fabricating prototype circuit boards, but has also used it as part of the process of evaluating new RF and microwave components: “With any new components, you have to see how they perform in the environment in which they will be used, including the PCB dielectric material on which they will be mounted. The LPKF equipment allows us to make those PCBs for evaluating the performance of new RF/microwave components.”

An investment in an in-house circuit-milling machine can equate to a relatively short period of time and activity at an outside PCB fabricator, depending on the number of prototype PCBs being fabricated. If a company or engineering department requires three or four prototype PCB runs in a short period, it may equal the cost of an in-house circuit-milling machine. But what type of circuit-milling machine? What types of features and capabilities are needed to reliably replace an outside prototype PCB supplier?

Commercial circuit-milling machines are available as mechanical or laser-based systems, typically with high-performance stepper motors used to achieve precise positioning on a circuit board. Both types of PCB fabrication machines are designed to work with copper-coated circuit-board materials. They form circuits by means of milling, a subtractive process that removes unneeded copper from the board, rather than the chemical-etching processes of many outside PCB fabricators and in-house “wet-etch” departments. A number of parameters can be used to compare different circuit-milling machines, such as the dimensions of the largest board it can process, the circuit feature resolution it can achieve, the milling speed, etc. These parameters will be determined by a company’s anticipated requirements of present and future prototype PCBs. A system capable of handling a large circuit board size, for example, can fabricate a large number of different circuits or a number of versions of one circuit at the same time. A circuit-milling machine’s spindle speed will determine how many holes can be drilled in a given time, such as 100 holes per minute, and how fine a trace can be milled reliably. Comparing the parameters of different circuit-milling systems will provide insight into the quality and quantity of prototype circuits that each system can produce in a certain time.

For example, circuit feature resolution of 2 μm or better will usually exceed the capabilities of most outside PCB fabricators. It will also typically exceed the fabrication needs of most prototype and experimental circuits. Repeatability of ±2 μm will ensure that circuit features remain consistent from circuit to circuit and board to board. These dimensional tolerances can support high-speed digital circuits at speeds beyond 40 Gb/s and analog microwave circuits at frequencies well into the millimeter-wave range, beyond 40 GHz. Such tolerances may exceed current needs, but provide room for future growth and experimentation.

Any circuit-milling machine under consideration for in-house PCB prototyping (Figure 3 shows an example of such a machine) should handle a wide range of dielectric materials, from low-cost FR-4 materials through low-loss PTFE soft boards and harder ceramic-filled circuit materials. It should be able to read standard CAD and computer-aided-manufacturing (CAM) files from industry-standard software suppliers (or at least the set of software tools being used by the company considering the circuit-milling machine) as well as standard layout file formats, including Gerber, HP-GL, and DXF files.



As with any piece of capital equipment, an in-house circuit-milling machine carries with it a learning curve but, if supported with suitable operating software, the training time can be minimized. The LPKF circuit-milling machines, for example, are supplied with CircuitPro, a multifunction software package that provides intuitive control and time-saving utility programs that enhance the efficiency of each system (Figure 4). The software allows operators to import data from any circuit-layout program. The LPKF software tools load and run on any standard Microsoft Windows®-based PC and provide control of each milling machine with clear, on-screen instructions. The software also includes a “what-you-see-is-what-you-get” (WYSIWYG) interface to show the manufacturing progress and manage all relevant parameters of the machine and its tools (Figure 5). The software orchestrates a variety of functions, including automatic tool changes, automatic tool calibrations, and management of tool life as well as feed rate and tool RPM.

Figure 3. A mechanical or laser prototyping system brings PCB fabrication capability inside a company, for improved precision and speed when creating prototypes.

LPKF Laser & Electronics

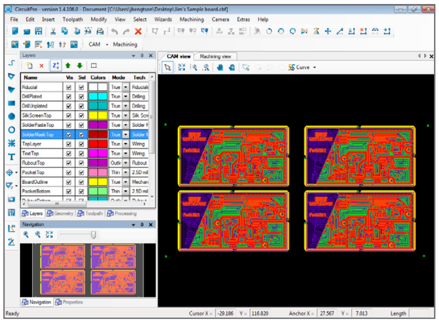


Figure 4. CircuitPro software imports and edits a wide range of circuit layout file formats for use in LPKF's manual and laser-based PCB milling systems. Depending upon the milling machine, the software supports fabrication of circuit features with better than1-µm resolution.

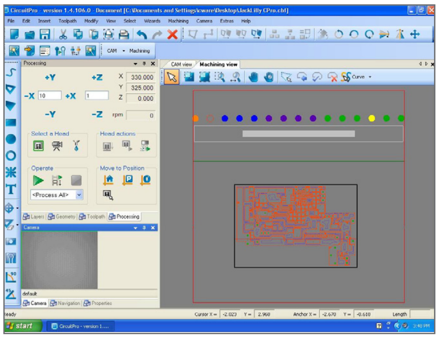


Figure 5. LPKF's CircuitPro software simplifies the use of the firm's PCB milling systems through a straightforward "WYSIWYG" operating interface

IN SUMMARY

The initial cost of an in-house circuit-milling system may seem prohibitive compared to the lower cost of having prototype PCBs fabricated by an outside board house. But in-house rapid prototyping capability brings with it fast turnaround speed, the flexibility to try different design variations, and even the capability to fix circuit designs considered "unfixable." In many cases, in-house circuit milling machines can top the precision and resolution of outside board shops, and do it faster.

Surveys of LPKF customers have revealed the impact of in-house savings by as much as two weeks for creating a prototype in house, compared to an outside facility (Figure 6). Better than 41% of surveyed customers reported a time savings of four to seven days on prototyping projects compared to using an outside board shop, while almost 23% attributed a savings of one to two weeks when using the LPKF systems compared to an outside shop. And, nearly 23% of surveyed customers credited the LPKF machines for a time savings of two weeks or more in their prototyping efforts, compared to using an outside service.

In addition to improved time to market, the LPKF customer surveys indicate that in-house PCB milling machines can bring a healthy increase in design productivity and creativity: engineers know they will see tangible results of their designs in a much quicker time. More than 70% of LPKF customers credited the rapid prototyping machines with fostering a more innovative design culture in their companies, while better than 57% of those customers linked the machines to increased productivity and another 59% with greater project momentum. A PCB milling machine represents an investment, but one that can bring healthy ROI in the near term and for many years to come.

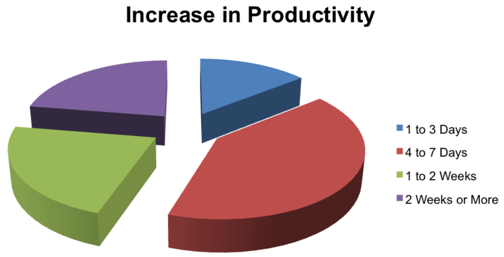


Figure 6. When surveyed, more than half of LPKF customers saved one week or more for their prototyping tasks compared to using an outside board shop.

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