Tlam OptoTEC™ Series Miniature Thermoelectric Modules
by the Laird global thermoelectric R&D team

Executive Summary:
Laird's OptoTEC™ series of miniature thermoelectric modules (TEMs) is being expanded in 2013 to include modules made using Laird Tlam circuit boards instead of traditional ceramic-based circuit boards. All TEMs consist of pellets of semiconductor material soldered between two circuit board substrates. Tlam is a laminated circuit board product capable of transporting heat to and from the semiconductor pellets while providing excellent heat spreading, improved reliability and low cost in high volume. Laird is the only company in the world that makes both TEMs and thermally conductive circuit boards. We are uniquely positioned to offer innovations based on this combination of thermal technologies to our customers. This white paper discusses the performance, reliability, advantages and limitations of OptoTEC TEMs made using Tlam in addition to describing other new products using Tlam that are currently in development.

Introduction
Thermoelectric cooling is an active thermal management technique, using electrical power to transport heat and refrigerate objects to below ambient temperatures, but without the moving parts required in compressor-based refrigerators. Thermoelectric cooling utilizes the Peltier effect, a property of certain semiconductor materials, where passing an electrical current through the material causes heat to be picked up at one electrical contact and deposited at the other. In practice, TEMs consist of many pieces of semiconductor material connected electrically in series and thermally in parallel to combine their heat pumping capacity. This arrangement requires two circuit boards to form the electrical circuit: one on the "hot side" of the TEM where heat is deposited, and the other on the "controlled side" or "cold side" where the Peltier effect absorbs heat and achieves refrigeration.

Tlam is a family of thermally conductive printed circuit board products made by a lamination process. Each Tlam panel consists of a layer of standard copper foil which can be etched to form circuit traces, a thin layer of thermally conductive dielectric material to electrically isolate the circuit traces from the environment, and a thick metal backing plate to provide structural strength and heat spreading. Tlam is used in applications where the components in the circuit produce a lot of heat, such as high powered LEDs, power supplies or motor drives. Traditional circuit board materials such as FR-4 have very poor thermal conductivity, so any heat produced by the circuit must radiate off the top of the circuit board. With Tlam, the heat can also be transported off the bottom of the circuit board. Furthermore, the metal backing plate quickly carries heat laterally away from hot components, reducing their temperature and extending their lifetime. The Tlam product line offers several choices of metal backing plate such as aluminum or copper, and several types and thicknesses of dielectric material for different temperature ranges and levels of electrical isolation.

Ceramic-based circuit boards are used in most TEMs because they have low thermal resistance in transporting heat through their thickness. That thermal resistance creates a parasitic temperature difference between the semiconductor and the outside of the module:

$$\Delta T = \left(\frac{Q}{A}\right)\frac{t}{\kappa} \qquad (1)$$

where (*Q/A*) is the heat transported per unit area, *t* is the thickness of the circuit board material, and κ is its thermal conductivity. For a TEM with 10 W/cm^2 dissipating out of its hot side and circuit boards made of Al_2O_3 (κ = 24 W/mK) of thickness 0.6 mm, the ΔT comes out to about 2.5°C. This parasitic temperature difference must be overcome by the TEM in order for it to maintain its controlled side at the desired temperature. As a result, the through-thickness thermal resistance of a TEM's circuit boards must be carefully controlled. The thermal resistance of Tlam substrates is determined primarily by the type and thickness of the dielectric layer. We chose the 1KA dielectric material, whose thermal conductivity is 3 W/mK. This is significantly lower than the thermal conductivity of aluminum oxide, but it is also much thinner. The smallest standard thickness of 1KA is 0.004" (0.1 mm) but the Laird Thermal Materials R&D group developed 1KA that is only 0.003" thick. This reduced the parasitic temperature difference to the same level as an equivalent ceramic circuit board.

From a design standpoint, Tlam is a drop-in replacement for ceramic circuit boards. Products using a new material must also be manufacturable and it turns out that Tlam is actually easier to work with in this regard. Before forming a solder joint, a carefully controlled amount of solder is placed on the circuit board. This is done by placing the circuit boards in a fixture and stenciling solder paste onto the desired areas. Ceramic circuit boards are typically delivered individually because expensive equipment is required to separate them. Tlam circuit boards, in contrast, are delivered as a scored panel ready to snap apart. A single panel can be placed in the stenciling fixture with fewer parts to handle and align, resulting in better manufacturing accuracy with higher throughput.

Performance

The performance of a TEM is measured as the maximum temperature difference ΔT_{max} that it can create and its heat pumping capacity Q_{cmax}. These are primarily determined by the figure-of-merit zT of the semiconductor pellets. For further information, download the Thermoelectric Handbook .

Performance will be degraded slightly by resistive heating in excess electrical resistances (for example, circuit traces that are too thin) and by paths for heat conduction (for example, sealant applied around the perimeter of the TEM allows some heat to leak to the cold side). The semiconductor pellets used in Tlam OptoTEC TEMs are the same as those used in ceramic-based OptoTEC TEMs. Further, the copper foil used to form the circuit traces is the same thickness as the copper pads on ceramic circuit boards. Therefore, the performance of Tlam OptoTEC TEMs meets the same specifications as ceramic-based OptoTEC TEMs. Thousands of TEMs have been manufactured using Tlam and ceramic circuit boards, and their performance measurements have verified that the two types are equivalent.

Reliability

The Tlam OptoTEC series of TEMs are expected to pass Telcordia GR-468-CORE Issue 2 reliability testing. Contact a Laird sales representative to obtain a copy of the detailed report. Telcordia Technologies publishes and maintains a set of test specifications for optoelectronics components used in telecommunications devices, including thermoelectric modules. The test specifications include protocols for high temperature storage, temperature cycling (thermal shock), mechanical shock, vibration and on/off power cycling. All five test protocols were carried out on Tlam OptoTEC TEMs. The tests performed differed from those specified in Telcordia GR-468-CORE Issue 2 in the following ways:

1. High temperature storage stress testing was performed at 100°C, which is a more severe condition than required. The TEMs passed despite the higher severity.
2. Temperature cycling was performed with more cycles, and a higher time rate of change of temperature, than required. The TEMs passed despite the higher severity condition.
3. An insufficient number of modules were tested in power cycling. The tested modules exhibited only a small amount of performance degradation (see, for example, the power cycling data in Figure 1 below), so we expect that additional modules currently under test will pass.

The tested TEM designs used Tlam with a copper backing plate 0.025" thick. This allows the use of any copper backing plate thickness up to 0.025". Thicker plates will be more massive and therefore more susceptible to failure in mechanical shock and vibration testing (though thicker plates will have no effect in the other stress tests). Additional TEMs are currently under test with weights attached to them to simulate thicker copper plates. Tlam with aluminum backing plates was not stress tested, though many TEMs have been built using aluminum. The thermal expansion coefficient of aluminum is sufficiently different from copper that all stress tests would need to be repeated in order to qualify it. The largest TEM tested measured 11.2 x 12.2 mm, so that is the maximum size that will qualify under Telcordia.

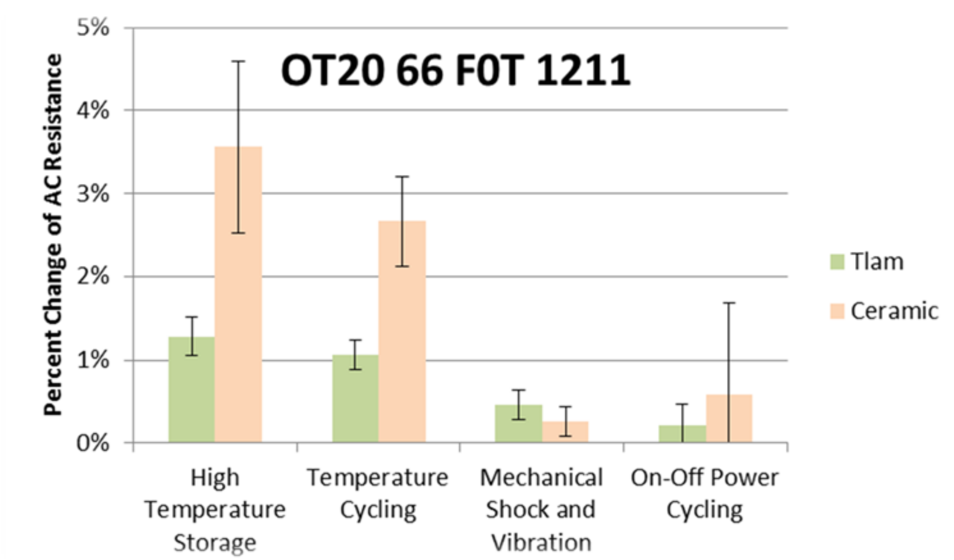

Figure 1. Change of resistance of Tlam-based and ceramic-based TEMs caused by stress testing.

Typical results of stress testing are shown in Figure 1. The degradation of the TEMs is measured by changes in their resistance. Note that the two stress tests that caused the largest resistance changes were the tests that were performed more aggressively than required by the standard.

Advantages

Advantage 1: Better efficiency when cooling concentrated heat loads

Laird has demonstrated that when the component being cooled is smaller than the TEM, a Tlam-based TEM uses less power to maintain the desired temperature difference than a ceramic-based TEM. For complete details, download the application note "OptoTEC Thermoelectric Coolers for Optoelectronic Applications" from

http://www.lairdtech.com/Products/Thermal-Management-Solutions/Thermoelectric-Modules/

or read our SPIE conference proceedings paper

The efficiency improvement is due to improved heat spreading in the Tlam as compared to the ceramic circuit boards. In ceramics, the through-thickness thermal resistance (which should be as low as possible, see above) is improved by using thinner ceramics; however, the in-plane heat spreading within the ceramic circuit board is only improved by using thicker ceramic. Therefore, the use of ceramic circuit boards to cool concentrated heat loads forces a compromise. By contrast, in Tlam the through-thickness thermal resistance is determined by the dielectric layer whereas the in-plane heat spreading is determined by the metal backing plate. As a result, the use of Tlam circuit boards allows simultaneous optimization of both in-plane and through-thickness thermal properties.

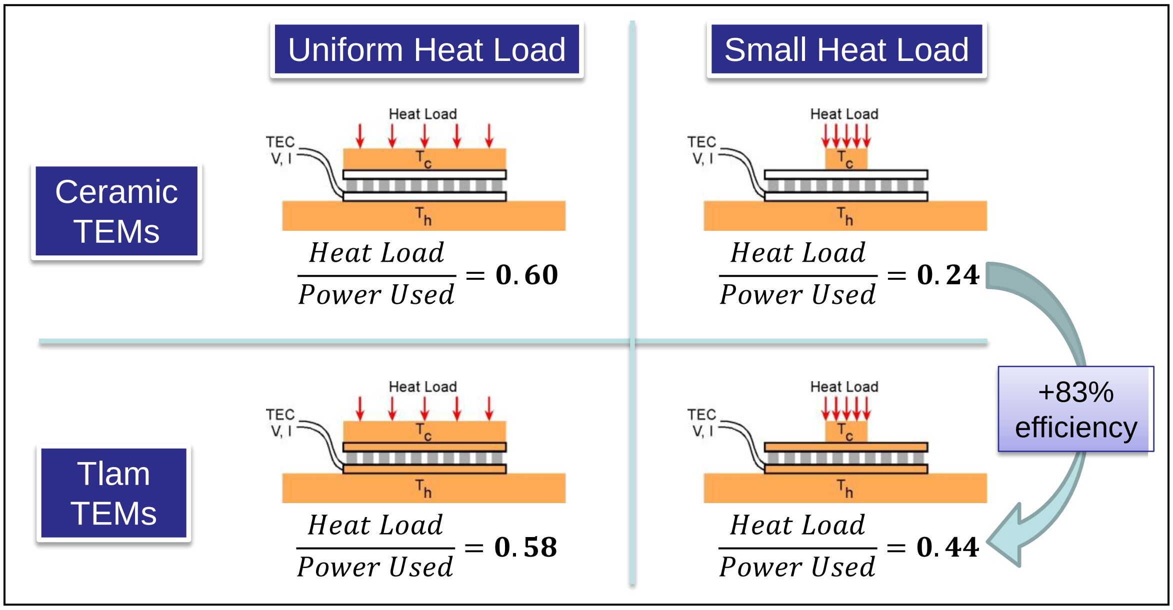

Figure 2. Efficiencies of Tlam-based and ceramic-based TEMs used to cool uniform and concentrated heat loads.

Figure 2 illustrates the experiments and provides the measured efficiencies (heat load on the TEM divided by the electrical power required to maintain the desired temperature). In these experiments, the same heat load was used for all modules, and the TEM drive voltage and current were adjusted to enforce the same temperature differential for all modules. As expected, uniform heat loads allowed the TEMs to run at the highest efficiencies, and the efficiencies of Tlam and ceramic-based TEMs were equal within the experimental error. Under non-uniform heat loading, efficiencies fell, but that of the ceramic-based TEMs fell much more. The Tlam

OptoTEC TEMs provided an 83% greater efficiency than the ceramic-based TEMs when cooling a heat load smaller than the TEM.

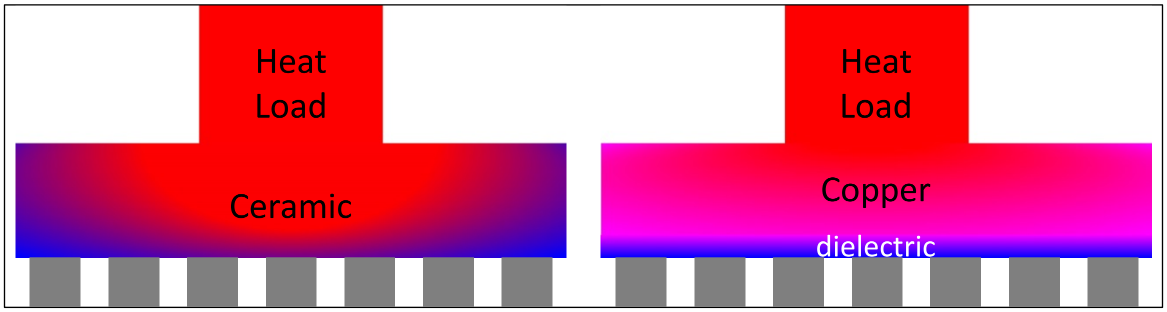

Figure 3. Schematic of heat spreading in ceramic (left) vs. Tlam substrates.

Figure 3 illustrates the temperature distribution in the top circuit board for the ceramic case (left) and the Tlam case (right). Red areas are at higher temperatures, transitioning to blue for cooler temperatures. The heat load is the small red block on top, and the gray squares at the bottom represent the semiconductor pellets. In the ceramic case, the temperature spreads out uniformly in every direction from the heat load, causing the center of the ceramic to be warmer than the outer edges at the bottom. In Tlam, the copper layer spreads the temperature uniformly across the whole substrate, and below the copper, almost all the parasitic temperature difference appears in the thin dielectric layer where the heat is uniformly delivered to the semiconductor pellets.

Advantage 2: Cost

Ceramic circuit boards make up a significant fraction of the raw material costs of a traditional TEM. When used in high volume, Tlam circuit boards can be much less expensive. Tlam panels are 18" x 24", and usable circuit boards can be made out of most of that area via the same printing, etching, and plating processes that are used for FR-4. Most board shops are capable of handling copper-backed Tlam. For a TEM such as OT20,66,F0T,1211 up to 2,000 circuit boards can be produced from a single panel of Tlam, resulting in low per unit substrate costs (see Figure 4 below).

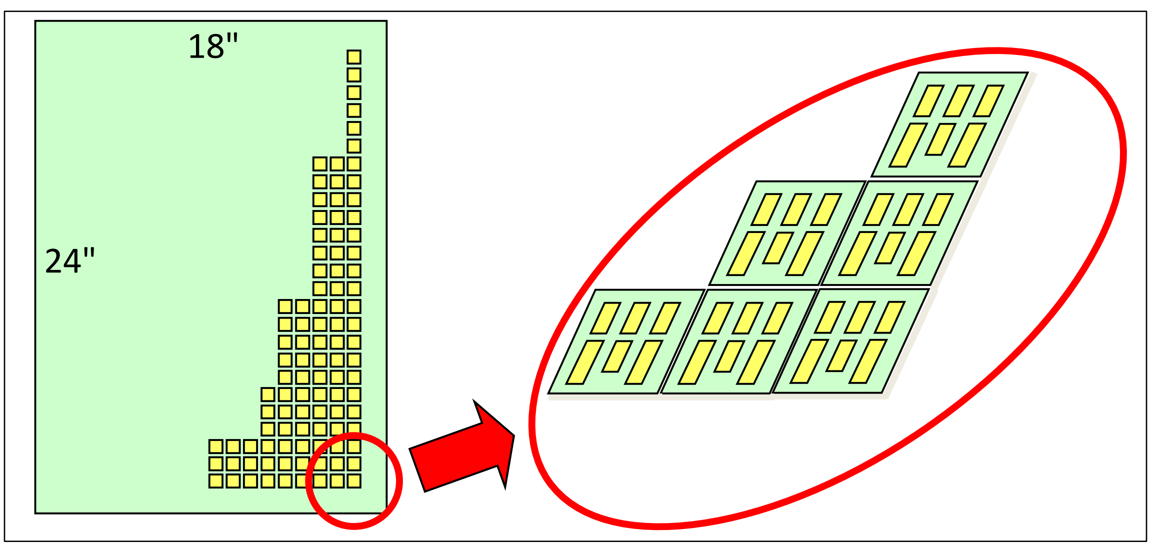

Figure 4. Illustration of the layout of many TEM substrates on a single Tlam panel

As an added bonus, the backside of the Tlam (the thick copper plate which becomes the exterior faces of the TEM) is automatically plated with nickel/gold during processing at the board shop. This nickel/gold plating makes it easier for end users to solder the TEM to a heat exchanger, or solder components to the controlled side of the TEM.

Advantage 3: Reliability

The primary root causes of TEM field failure are high-temperature diffusion of impurities and mechanical stresses. Large mechanical stresses are induced when a TEM is under a temperature differential: thermal contraction causes the cold side to shrink to a smaller size, while thermal expansion causes the hot side to expand. The semiconductor pellets are mechanically attached to both sides by solder, so they experience a shear strain and large shear stresses at their solder joints. Tlam reduces these shear stresses by allowing some strain to occur in the relatively softer dielectric layer instead of the semiconductors.

The size difference between the circuit boards of a TEM with a ΔT is not very large:

$$\delta = \alpha(\Delta T)\frac{w}{2} \tag{2}$$

where α is the thermal expansion coefficient and w is the width of the module. For a 12-mm-wide Al_2O_3-based TEM such as OT20,66,F0,1211 under a ΔT of 60°C, the outer edges of the two circuit boards are displaced by only 2.5 micrometers. However, the ceramic circuit boards are extremely stiff. The most mechanically compliant parts in a ceramic-based TEM are the semiconductor pellets themselves. Repeated power cycling will fatigue the materials, eventually creating micro-cracks in the semiconductor couples or the solder joints and degrade performance. On the other hand, the polymer-based dielectric layers in a Tlam-based TEM are mechanically much more compliant than the semiconductor pellets. The small displacements can easily be accommodated by movement of the dielectric layer. As a result, the stress on the semiconductor pellets and solder joints is drastically reduced. This effect is illustrated in Figure 5 below; note that the semiconductor pellets (gray blocks) are strained into a trapezoidal shape in a ceramic-based TEM, whereas they remain almost rectangular in a Tlam-based TEM. The strains have been exaggerated to enhance visualization.

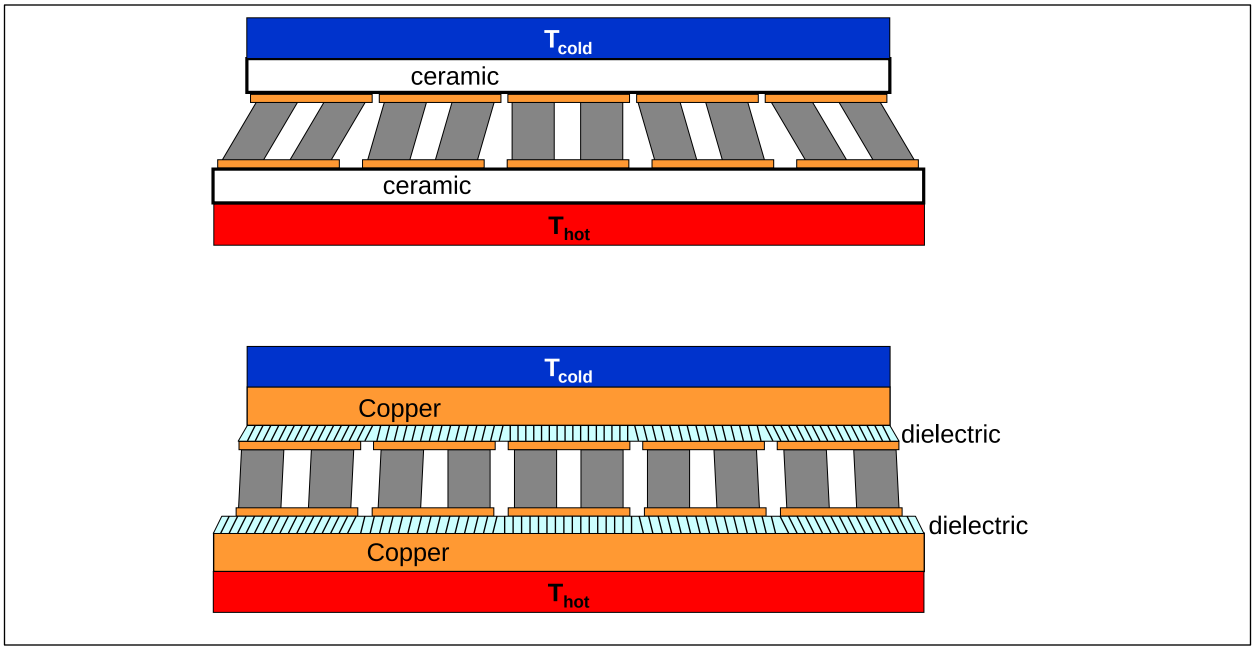

Figure 5. Schematic of the relative strain in semiconductor pellets under exaggerated thermal expansion strain in a ceramic-based TEM (top) and a Tlam-based TEM with compliant dielectric layers (bottom).

The reliability testing Laird performed to qualify Tlam OptoTEC TEMs under Telcordia requirements might have shown a difference between Tlam and ceramic-based TEMs of the same design. However, neither type of module suffered much performance degradation at all in the relevant tests. More severe mechanical shock and vibration tests are underway to quantify this advantage. Further, high temperature storage and long-term power cycling tests are planned in order to estimate MTBF (mean time between failures).

Limitations and Unknowns

As noted in the Reliability section above, the designs that have been stress tested define the scope of what will qualify under Telcordia GR-468-CORE Issue 2. This is not to say that designs outside that scope are unreliable, only that they are not yet tested. For example, only TEMs built with BiSn solder (T_m=138°C) have been stress tested; results for higher melting point solders such as SnSb and BiSb are forthcoming.

One tangible limitation of Tlam as applied to TEMs is that the lead wire attachment traces must be large enough to anchor the lead wires during handling and installation. The polymer-based dielectric layer used in Tlam provides a good adhesive bond with a peel strength of 0.8 kg per cm of trace width, as measured by continuous steady-state peeling of a trace off of its circuit board at a 90° angle. [More information under the Datasheets tab on Laird's website.] Standard OptoTEC "porch style" designs (part numbers with F0 or F2 in their description) provide enough area between the copper trace and the dielectric to maintain a good bond under any foreseeable abuse. We verified this by testing Tlam OptoTEC TEMs to failure in a lap shear experiment; we found that the semiconductor pellets fractured but their copper circuit traces remained bonded to the dielectric. Nonetheless, we recommend against the use of Tlam in porchless style (F1) OptoTEC designs.

The outgassing behavior of Tlam-based TEMs in ultrahigh vacuum is not yet known. Outgassing can be an issue in some optics applications; for example, many engineers avoid the use of grease-based thermal interface materials in vacuum because short-chain polymers in grease are known to slowly volatilize and redeposit onto other surfaces in the vacuum system. This behavior causes long-term degradation of optical components. NASA maintains a searchable database of the outgassing characteristics of a large number of materials. Unlike grease, the dielectric layer in Tlam is a fully cured and cross-linked epoxy loaded with thermally conductive ceramic particles, and as such, it contains no un-bonded short-chain polymers. It is possible, however, that water vapor or other liquids may be absorbed by the epoxy during the time it spends in open atmosphere, and these volatile species may later outgas in ultrahigh vacuum. We look forward to testing the suitability of Tlam OptoTEC TEMs for use in ultrahigh vacuum, and we have several potential solutions for problems that may arise.

The thermal expansion and mechanical characteristics of Tlam are different from those of ceramics, and as such, the suitability of Tlam OptoTEC TEMs for micro-positioning applications has not yet been proven. Where submicrometer positioning precision is required, for example in the alignment between a cooled laser diode and a nearby optical fiber, the increased coefficient of thermal expansion of Tlam's copper backplate and dielectric layer may increase positioning tolerances. Potential solutions include the use of much thinner copper backplates (for an extreme example, see "future work" below). We do not foresee thermal expansion of the dielectric being an issue because its total thickness is only approximately 75 micrometers and therefore its thermal change in thickness will be on the order of tens of nanometers.

Future work

The Tlam OptoTEC series is Laird’s first introduction into the potential for Tlam in thermoelectric modules. As noted above, Tlam comes in many varieties: the backing plates can be different metals of various thicknesses, and different dielectric types and thicknesses are available. In addition, Tlam can be laminated in a "double-sided" configuration with etchable copper foil on both sides, or in multilayer stacks with several layers of foil circuit traces. Our next series of new products will use double-sided Tlam to create OptoTEC TEMs only one millimeter thick. This is possible because a double-sided Tlam circuit board is only 0.25mm thick or less, as compared to 0.5-1.0 mm thickness of ceramic circuit boards.

Summary

Laird has released a new series of OptoTEC miniature thermoelectric modules that use Laird's Tlam printed circuit boards in place of traditional ceramic-based circuit boards. These Tlam OptoTEC TEMs have the same performance as ceramic-based TEMs and are expected to pass Telcordia GR-468-CORE Issue 2 reliability qualification testing. Their advantages include improved efficiency when cooling heat loads that are smaller than the TEM, lower cost when manufactured in high volume, and improved MTBF in cycling applications. We believe that the use of Tlam is the most significant innovation in the design of thermoelectric modules since the invention of the thin film TEM.