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Laser Cooling for TO Packages using Embedded Thin-Film Thermoelectric Coolers

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Background

Laser diodes employed for telecommunications have traditionally used thermoelectric coolers (TECs) for precision temperature control; to improve diode output levels and maintain wavelength integrity. A major trend for photonics in telecommunications has been the move to more integrated packaging that is smaller and simpler in structure in order to reduce costs. This in turn has opened the door for higher volume manufacturing. In the course of this transition, conventional TEC solutions have become increasingly difficult to implement as this technology has not kept pace with the size and power density requirements for next generation devices.

Bulk thermoelectric Coolers (TEC's) are routinely used with laser diodes (LD) for both source and pump lasers. Traditional TEC's have a maximum heat pumping capacity (Qmax) of 10W/cm2 or less. Furthermore, in order to achieve an acceptable efficiency the TEC must be operated at a small percentage (~30% or less) of its maximum power (Qmax). Cooling power sources greater than 10W with a conventional TEC becomes impractical because of the size of the TEC needed to pump the heat generated by the laser.

In addition to smaller packaging and higher heat densities, the junction temperature of laser diodes can directly affect the performance and lifetime of devices. As the junction temperature rises, a significant loss of power output (luminosity) will occur. The forward voltage of the diode is also dependent on the junction temperature. As the temperature rises, the forward voltage decreases causing excessive current drain on other diodes in the array.

An example of the continuing reduction in device size is shown below in Figure 1: from right to left, the butterfly package, a TOSA style package and finally a TO-56 package.

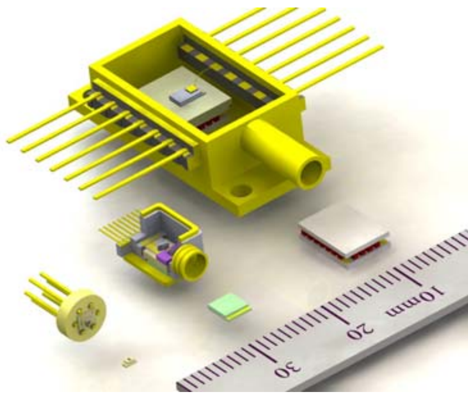

Figure 1: Size comparisons of optoelectronic packages and thermoelectric coolers

In some instances, designers choose to place the cooling device outside the package if it is too large to be placed inside. Of course this means you are now cooling the entire package. Cooling the device by cooling the entire package is at best an inefficient method for thermal management.

If it is our desire to continue to shrink the overall size of our devices while maintaining an efficient thermal management system, we must shrink the size of the TEC. Thin film thermoelectric devices have demonstrated heat pumping capacities up to 150 W/cm^2 and can be embedded within the package itself. Embedded Thermoelectric Coolers (eTEC's) actively cool the diode to reduce the diode's junction temperature, improving performance and increasing reliability.

Thin-Film Thermoelectrics

Thermoelectric cooling makes use of the Peltier effect to create a heat flux between two surfaces. A Peltier thermoelectric cooler is a solid-state active heat pump that transfers heat from one side of the device to the other against the temperature gradient (from cold to hot) with the consumption of electrical energy.

Thin-film thermoelectric coolers (eTECs) are smaller and thinner than conventional TECs and show promise for direct integration using industry standard manufacturing methods. Thin films are material layers ranging from fractions of a nanometer to several microns in thickness. Thin-film thermoelectric materials are grown using a Metalorganic Chemical Vapor Deposition (MOCVD) reactor and devices are then fabricated using conventional semiconductor fabrication processes.

The benefit of thin-films over thick, bulk materials for thermoelectric devices is illustrated in equation 1. Here the Qmax (maximum heat pumped by a module) is shown to be inversely proportional to the thickness of the thermoelectric material, L.

$$Q_{\max} = \frac{S^2 T^2}{2 \cdot R_{Total}} = \frac{S^2 T^2 A}{2 \rho_c L} \qquad \text{Eq. 1}$$

As such, TE coolers manufactured with thin-films can easily have 10x – 20x higher Qmax values for a given active area, A. This makes thin-film TECs ideally suited for applications with high heat flux densities.

In addition, thin-film TECs have a low mass and therefore have little self heating or cooling. By placing the eTEC in the package, the cooling is closer to the heat source while also providing for a more rapid thermal response. All integration is done inside the package to get the cooling as close to the junction as possible and to minimize the cooling of extraneous material.

Thermoelectric Performance

The most basic representation of the operational space for a thermoelectric cooling device is a load line shown in Figure 3.

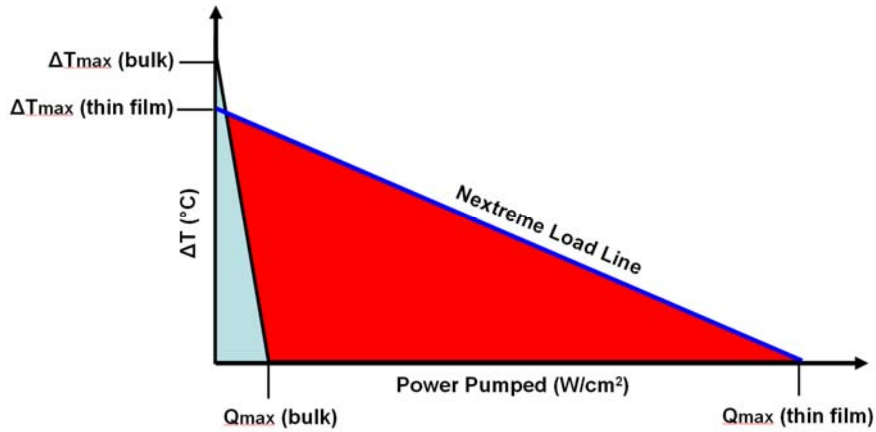

Figure 3: The load line - Nextreme's thin film devices are compared to a conventional TEC built with bulk thermoelectric pellets.

The load line represents the ΔT and Q_{pumped} conditions possible for a given TEC drive current. At the maximum drive current for the module, the load line is generated from two key parameters: 1) the maximum power the device can pump, Q_{max}; and, 2) the maximum temperature difference that the device can sustain between its top and bottom plates, ΔT_{max}.

A value for ΔT_{max} is obtained when no heat is flowing through the device (zero Q condition) and can be theoretically obtained from:

Equation 1 $$\Delta T_{\max} = \frac{\alpha^2 T_c^2}{2k\rho} = \frac{\alpha^2 T_c^2}{2KR}$$

Here α is the Seebeck coefficient; k is the thermal conductivity; ρ is the electrical resistivity; T_c is the cold junction temperature; K is the thermal conductance; and R is the resistance.

Q_{max} , shown on the x-axis, is obtained when there is no temperature difference between the top and bottom of the TEC.

Equation 2 $$Q_{\max} = \frac{A\alpha^2 T_c^2}{2\rho L} = \frac{\alpha^2 T_c^2}{2R}$$

Here A is the area of the device and L is the length (thickness) of the thermoelectric material.

The two parameters may be graphed on a chart (ΔT_{max} at Q = 0; Q_{max} at ΔT = 0) and the line connecting them is termed a load line. The resulting load line defines the operational space for TECs and is the best and usual way to illustrate TEC performance.

Cooling Demonstration

To illustrate the benefits for cooling a laser diode with an eTEC, a 1310 nm Fabry-Perot laser diode was mounted on the active side of an embedded thermoelectric module in a TO-8 package. Figure 2 shows the packaging scheme in which the eTEC was embedded inside the package. Figure 3 shows a side profile of the package. The eTEC is thermally coupled to the chip and TO base. A thermistor was installed to measure the temperature of the cold side of the TEC.

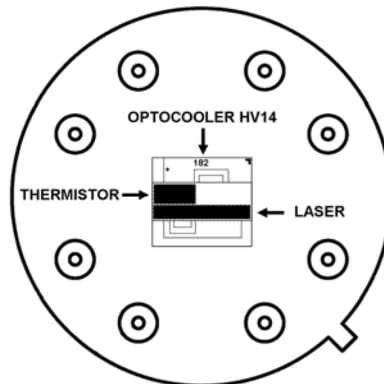

Figure 3. Illustration of a laser diode TO package with embedded OptoCooler HV14 TEC

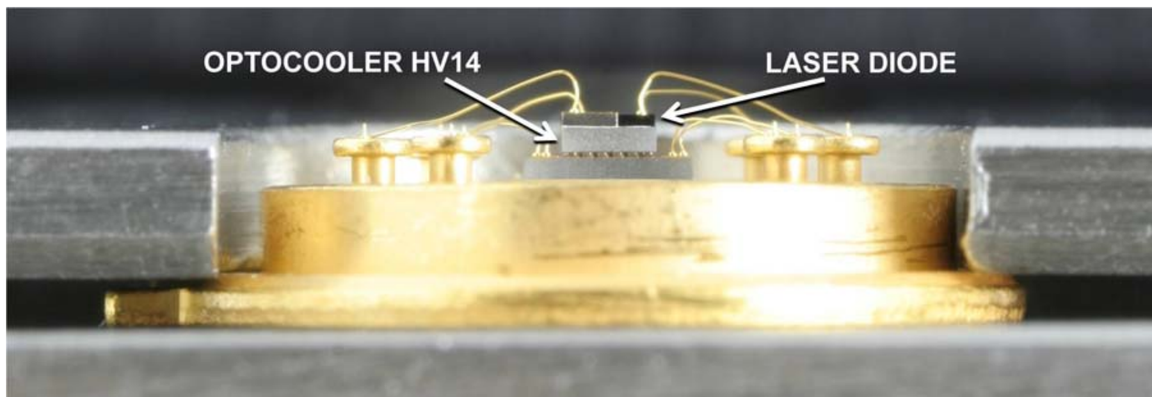

Figure 3. Side profile of a laser diode TO package (cap removed) with embedded OptoCooler HV14 TEC

At 85°C, the HV14 module operates at a maximum of 2.7V and can pump 1.7 watts of heat in a footprint of less than 3mm². The module can create a temperature differential (ΔT) of up to 50°C between its hot and cold sides.

A test bed consisting of a power meter, temperature controller, laser diode controller and optical spectrum analyzer was assembled to measure the effect of cooling on laser output and spectra.

For the test setup, a photo-detector was positioned in front of the infrared window in the package and connected to the power meter. The drive current for the laser diode was increased in 10mA steps up to 100mA with the TEC turned off and on. Figure 4 shows the resulting light current/voltage curves plotted in 10mA steps. With the TEC

turned on, the output level of the laser diode nearly doubled from 0.416 mW to 0.755 mW at 100 mA. What should also be noted though not shown here is the ability of the TEC to hold output levels steady at higher currents.

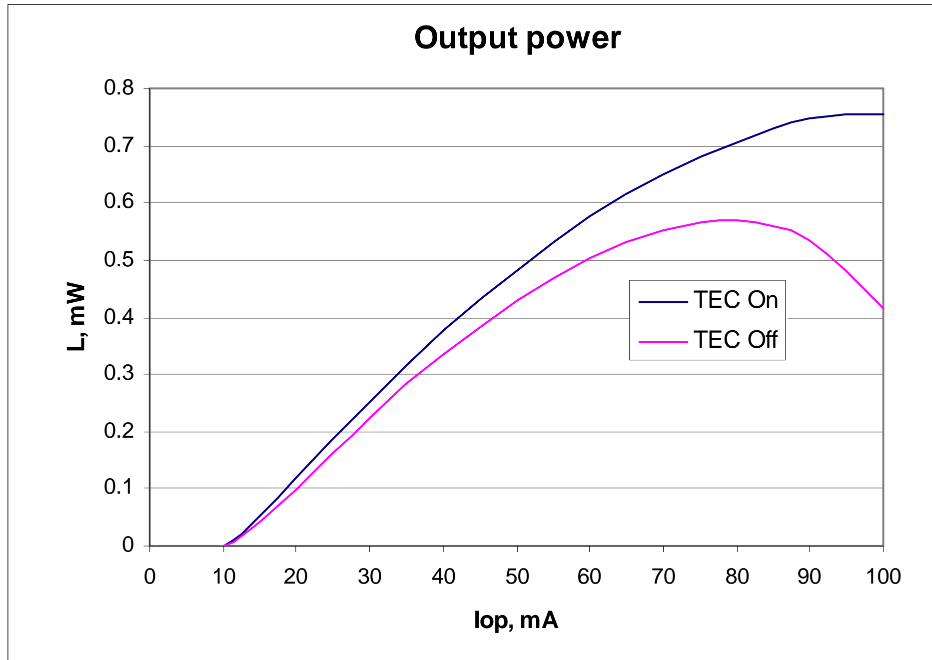

Figure 4. L-I-V Curves for laser diode power output

To illustrate the effect of cooling on wavelength, a fiber optic cable was positioned in front of the laser diode package to act as a light pipe into the optical spectrum analyzer (OSA). With the drive current set at 100mA and the temperature of the diode at 42°C, the OSA displays the spectral gain curve for the Fabry-Perot 1310 nm laser diode. When the TEC is turned on, the temperature of the diode quickly cools to ~21°C and the wavelength shifts to the left (blue) by approximately 13.6nm as illustrated in figure 5.

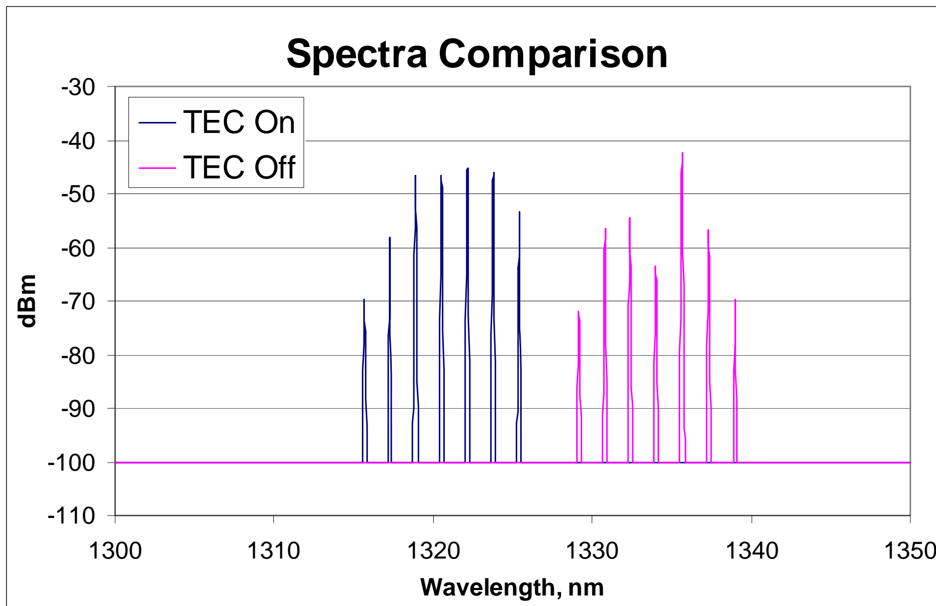

Figure 5. Spectra Comparison of Cooling Effect

The eTEC, being an active thermal device creates a thermal inversion that dramatically changes the thermal profile inside the package. Figure 6 shows a comparison of the thermal profile through the cross section of the module in two cases, a) with no eTEC, or in other words, a passive solution only, and b) with an eTEC actively cooling the junction. It can be clearly seen that the introduction of the eTEC provides a substantial benefit.

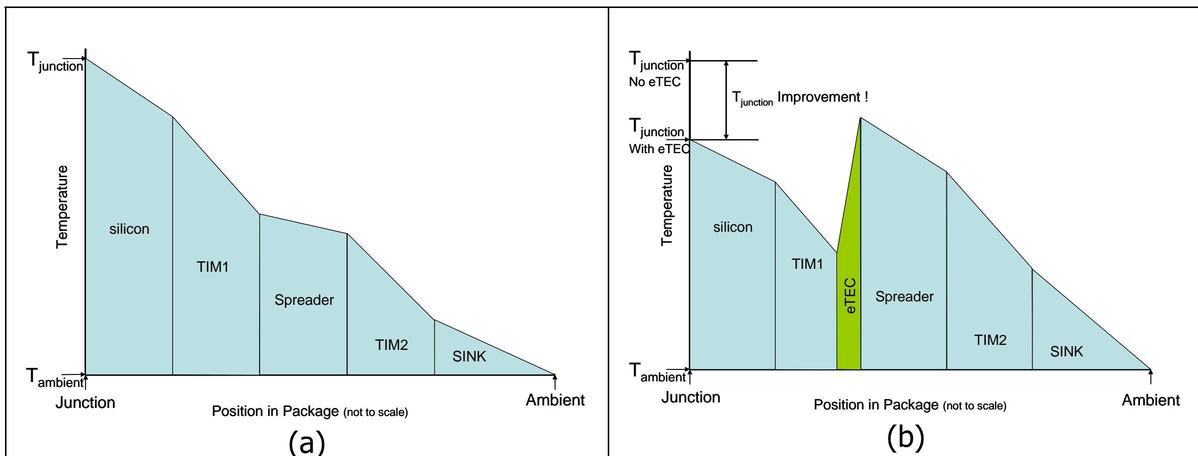

Figure 6: Temperature profiles through the cross section of a package included thermal interface materials (TIMs) without (a) and with (b) an eTEC. The temperature inversion created by the eTEC lowers the junction temperature relative to the no-eTEC case.

System Level Considerations

The heat that is pumped by the device and the additional heat created by the eTEC in the course of pumping that heat will need to be rejected into the system. Since the performance of the module can be improved by providing a good thermal path for the rejected heat, it is beneficial to provide high thermally conductive pathways. For small TO packages, this is typically accomplished through the electrical connections themselves, and depending on the operating characteristics, this level of thermal management might be sufficient. For packages with higher heat densities, a thermally-conductive feed-through or post needs to be employed to remove the heat.

Summary

Cooling laser diodes inside a package using embedded thermoelectric coolers provides several key benefits:

- Embedded thermoelectric coolers enable smaller, more cost-effective packages.
- Their small size allows placement of the cooler in intimate contact with the laser diode at the source of the heat while minimizing cooling of the package.
- Thin-film eTECs can be embedded in the smallest of packages.
- Fast response times enable precise temperature control.
- Higher output power enables longer transmission distances.
- Wavelength stability improves system reliability.
- Due to the reduced standoff height and mass, eTECs are more resistant to shock and vibration.

By taking advantage of the smaller; thinner form-factor of an eTEC, a new approach has been enabled for electronic thermal management that focuses on providing appropriate cooling when and where it is needed. This solution involves the integration of thin-film thermoelectric modules into the package and as close to the heat source as possible.