⑥ Methods of Controlling Cavity Length

All stabilization schemes are based on the precise control of the HeNe laser's cavity length, either directly or indirectly:

- **Thin-film or wound heater:** This is by far the most common approach. Initially, the tube is heated to a temperature sufficiently above where it would reach thermal equilibrium from bore heating alone. How high this is set is a tradeoff betwen operation over an acceptable ambient temperature range and a laser that runs excessively hot. Then heater power can be used to balance convection cooling such that the tube temperature and actual cavity length are maintained constant based on mode feedback. The heater power at the operating point is typically 1/4 to 1/2 of the bore discharge power.

  Thin-film (Kapton) heaters are available from several manufacturers in a large variety of configurations, but may also be customized (at possibly significant expense) in terms of size, resistance, and temperature coefficient of resistance (which enables the actual resistance to be used to determine the tube temperature without a separate sensor). Thin-film heaters usually have an adhesive backing such that installation is very simple.

  Wound heaters may be implemented using an appropriate size and length of copper "magnet" wire wound "bifilar style" to minimize the magnetic field produced by the heater current. This is more labor-intensive but acceptable for prototype or small production runs.

- **Induction heater:** Since the mirror mount stems on modern HeNe laser tubes are made of metal, it is possible to couple energy into them via a small coil driven with a low power high frequency source, which can then be regulated to maintain the cavity length constant. This was pioneered by Aerotech in the Syncrolase S100, adapted by Melles Griot in the 05-STP-909/910/911/912. The thermal time constant of the mirror mount step is much smaller than that of the glass tube so response is better. However, with only a limited length available, it can be tricky to assure that lock will be maintained as other parts of the tube expand. One benefit of this approach is that *any* HeNe laser tube of suitable length where a coil can be fit can be stabilized.
- **Bore heat/fan:** This rather peculiar approach is to the best of our knowledge has only been used by Teletrac on some of the early stabilized HeNes. Some might call it a kludge, but it actually works remarkably well. Initial heating is provided by both the HeNe bore discharge and a couple of small light bulbs near the tube. Once a temperature set-point has been reached, the light bulbs are turned off (and not used while the tube is locked) and a low vibration PZT fan provides active cooling. The PZT fan is just a pair of blades that vibrate with variable amplitude based on the mode feedback - getting really excited when cooling will pull the desired mode into position. :) One advantage of this approach is that with active cooling (even if it is wimpy), the laser can run at a lower temperature closer to ambient than with heat-only. A disadvantage is

that even though designed to minimize vibration, the PZT fan is not perfect. And even miniscule vibration can be an issue for interferometer-based devices.

- **ThermoElectric Cooler (TEC):** In principle, a TEC (which can actually both cool and heat) could be used to control cavity length. However, since these are usually planar devices, adapting them to a cylindrical tube could prove challenging. This would require an adapter made of a high heat conductivity material. And even then, the thermal delay could make stabilization impossible. It might be possible to do this on one of the mirror mount stems though.
- **PieZo Transducer (PZT):** A PZT can provide movement over a small range which can be sufficient for cavity length control under the right conditions. Early Hewlett Packard (HP) metrology lasers (5500A/B/C and 5501A) used a PZT between the mirror spacing rod and the cathode-end mirror *inside* the tube envelope. So it would move the mirror directly by just enough displacement to cover a sufficient range to guarantee a suitable lock point. However, even though the mirror spacing rod (which along with the PZT determined the cavity length) was made of ZeroDur™, after awhile, the cavity length could still drift out of range and the lock-point might have to be reset. Later HP lasers (to the present) use a resistance heater, but it is still inside the tube.

  Where the tube structure that defines the cavity length is not made of a material like ZeroDur™, it would be difficult to use a PZT because the overall length would be changing by orders of magnitude more than a common PZT could accommodate. At the very least, the laser would have to use active temperature control and warm up for *hours* to reach thermal equilibrium before the feedback loop could be closed using the PZT. This is how the Spectra-Physics 119 laser was implemented.

  PZTs have orders of magnitude faster response than thermal solutions, but generally require high voltage drive, which is an added complication. High bandwidth is not really a requirement for stabilized lasers unless modulation is desired. However, PZTs can easily provide a small dither with only modest voltages and have been used for this purpose in several stabilized HeNe lasers including the Nikon NKL-85 and Spectra-Physics 119, as well as iodine stabiilized HeNe lasers built by NIST and Frazier, among others.

- **Electro-mechanical:** Finally, glass and metal are elastic on the micro-scale. So, in principle, an external electro-magnetic actuator like a common solenoid can push or pull on one of the mirror mount stems and actually squeeze or stretch the tube enough to control the cavity length. It's order of pounds to cover a few microns. We are not aware of any commercial stabilized HeNes using this approach for cavity length control, but at least one (Spindler and Hoyer) did use it for dithering.