Locking Techniques for Stabilized HeNe Lasers

The purpose of locking in a stabilized HeNe laser is to assure that the desired output (single or two frequencies in most cases) has a controlled. optical frequency or frequencies. For use in metrology applications, this will mean that the single or dual lasing line is fixed at a known optical frequency (corresponding to a known wavelength related by c/f where c is the speed of light and f is the optical frequency). Therefore, the locking controller needs a reference, which can be *intrinsic* or *extrinsic*. An intrinsic reference uses the properties of the laser itself. An extrinsic reference requires some external device such as another laser (which itself has been locked to a known optical frequency), a gas cell having known spectral absorption with respect to optical frequency, or a physical device like a super high finesse Fabry-Perot etalon or interferometer. The chart below summaries the most popular locking techniques for red (~633 nm) HeNe lasers:

Locking Type	Maximum Output Power	Optical Frequency Variation	Optical Frequency Accuracy
Unstabilized multiple transverse mode	>200 mW	---	---
Unstabilized single transverse mode	>50 mW	1.5 GHz	$3x10^{-6}$
Thermal stabilization	2 mW	75 MHz	$1.5x10^{-7}$
Single mode Intensity stabilization	1.5 mW	10 MHz	$2x10^{-8}$
Gain peak stabilization	1.0 mW	5 Mhz+	$1x10^{-8}$
Lamb-Dip stabilization	0.5 mW	5 Mhz+	$1x10^{-8}$
Dual mode polarization stabilization	2.0 mW	1 MHz	$2x10^{-9}$
Three mode stabilization	3.5 mW	1 MHz*	$2x10^{-9}$
Secord order beat stabilization	3.5 mW	200 kHz*	$4x10^{-10}$
Transverse Zeeman beat stabilization	1.5 mW	100 kHz*	$2x10^{-10}$
External (Iodine Cell) stabilization	0.2 mW	<5 kHz+	$<1x10^{-11}$
External (Iodine Cell) offset locked	2.0 mW	<5 kHz	$<1x10^{-11}$
External reference stabilization	2.0 mW	<1 Hz	$<2x10^{-15}$

The useful output of these are NOT always absolutely pure single mode or single optical frequency limited by the laser dynamics:

* denote techniques where the output has either a pair of modes of similar amplitude close together in optical frequency, or a small "ghost mode" next to the main mode.

+ denotes techniques based on Pound-Drever-Hall locking or a similar implementation that adds some dither to the optical frequency.

The approaches listed in the first group are intrinsic and use the Neon Gain Curve (NGC) of the HeNe laser tube as the reference. The center of the NGC has an optical frequency which depends only on the neon isotope ratio, temperature, and pressure, all of which can be controlled fairly precisely. The gain bandwidth of the NGC is also relatively narrow (as these things go) at around 1.6 GHz which can both limit the number of longitudinal modes that are oscillating (more on this below) and make feedback using its profile be more precise. Thus the NGC can be used to accurately position the lasing line(s) at a known location. All but the most exotic (and expensive!) stabilized HeNe lasers use one of the intrinsic techniques based on the NGC listed above. The vast majority use single or two mode polarization stabilization.

Relatively simple approaches using an external F-P resonator or other type of interferometer are possible. For example, using a low finesse Scanning Fabry-Perot Interferometer (SFPI) to monitor the longitudinal modes with a digital control loop maintaining them in a specific location on the NGC can be used with three mode polarization stabilization to obtain higher power with one mode centered. Single and dual mode polarization stabilization are limited to a maximum of around 2 mW; three mode stabilization is capable of up to around 3.5 mW or a bit more. But this is still an intrinsic technique. (This could also be used for single or dual mode stabilization but would probably not provide much, if any, benefit.)

It should be noted that it is because the gain bandwidth of neon is relatively narrow at 1.6 GHz, that the NGC becomes so useful. Solid state (SS) lasers on the other hand have lasing medium gain bandwidths typically wider by a factor of 50 or more. While straightforward techniques can be used to force single mode in an SS laser, achieving precise control of optical frequency with such a wide gain bandwidth is more difficult. This is one of the primary reasons that SS lasers have for the most part as yet been unable to replace the lowly HeNe laser in applications requiring optical frequency accuracy and stability. Locking diode lasers at a specific optical frequency is even more complex.

Of the extrinsic technigues, a stabilized HeNe laser making use of an iodine cell is probably the most precise optical frequency reference available commercially (with an equally high price to match). Its absolute optical frequency accuracy may be two orders of magnitude better than the technique of two-mode polarization stabilization, used in most commercial stabilized HeNe lasers now and in the past.

Going beyond this level of precision to high finesse F-P resonators and such is generally the perview of advanced research. To get down to that< 1 Hz requires massive isolation chambers and active damping to minimize vibration and other external influences. Such a system is not likely to be portable! ;-)

The chart excludes any technques requiring use of intra-cavity devices like etalons to force single frequency operation. These are capable of both high power AND high stability but require special tubes and relatively complex control. Thus they are expensive and not at all common, though at least one company does claim to offer a 40 mW single frequency HeNe laser.

Having said all that, it's remarkably simple - almost trivial - to control the behavior of a common HeNe laser tube similar to those that used to be found in grocery store barcode scanners to provide a single frequency output with a stability of better than 1 part in 10,000,000. In fact, it can be done with a total of 4 parts costing only a couple dollars (besides the laser tube and power supplies). Nearly every possible technique imaginable has been explored at some time in the past. It's quite possible that trained pigeons have even been pressed into service for this purpose, and there's probably a patent on it. ;-) What are described here are only the most common (electronic) approaches.