25: Stabilized Single Frequency HeNe Lasers

The common red (633 nm) HeNe laser, while highly monochromatic, generally does not produce just a single frequency (or equivalently, wavelength) of light. As noted in the section: Longitudinal Modes of Operation, several closely spaced frequencies will generally be active at the same time and their precise values and intensities will change over time. For many applications, this doesn't matter. However, for others, it makes such a laser useless.

If you have, say, $5,000 to spend, you can buy a red (633 nm) HeNe laser that actually produces a single frequency with specifications guaranteed stable for days and that don't change over a wide temperature range. While the operation of such a HeNe laser is basically the same as the one in a barcode scanner (and in fact may use the identical model HeNe laser tube!), several additional enhancements are needed to eliminate mode sweep and select a single output frequency. Simply constructing the laser cavity of low thermal expansion materials isn't enough when dealing with distances on the order of a fraction of a wavelength of light! Active feedback is needed. The most common implementation of these lasers starts with a short red (632.8 nm) tube that can only oscillate on at most 3 longitudinal modes. (For technical reasons, stabilized lasers at the other common visible and IR HeNe wavelengths are more difficult to implement and are much less common. More on this below.) It then adds optical feedback to keep them in a fixed location on the HeNe gain curve by precisely adjusting the distance between the mirrors over a range of about 1/2 the lasing wavelength. This is most often done with a heating coil (inside or outside the tube), but a PieZo Transducer (PZT, an expensive version of the beeper element in a digital watch) may also be used. The PZT reduces the time for the system to stabilize to a few seconds, compared to up to 30 minutes for the heater. But, for a laser that will be left on continuously, this probably doesn't matter. Some lasers use a means of cooling in addition to the heater like a piezo fan, probably to allow the laser to run stably over a wider temperature range. And a few including the Melles Griot 05-STP-909/910/911/912 (originally based on the Aerotech Syncrolase 100) use a miniature RF induction heater surrounding the HR mirror mount to control only its length, not that of the entire tube. With direct heating of such a small mass, the response is quite fast. This also makes for a more compact package than a full tube heater.

Many schemes work well and it's amazing how dirt simple these really are considering their hefty price tags! It's easy to build perfectly usable systems from a common surplus HeNe laser tube and a few common junk parts.

The common ones are listed below:

Type of Stabilization Technique	Variation	Precision
Normal (multimode) HeNe laser	---	---
Single mode without stabilization	1.5 GHz	$3x10^{-6}$
Single mode amplitude stabilization	10 MHz	$2x10^{-8}$
Lamb dip stabilization	5 MHz	$1x10^{-8}$
Gain peak stabilization	5 MHz	$1x10^{-8}$

Dual mode polarization stabilization	1 MHz	$2x10^{-9}$
Second order beat stabilization	200 kHz	$4x10^{-10}$
Zeeman beat frequency stabilization	100 kHz	$2x10^{-10}$
External reference (iodine) cell stabilization	<5 kHz	$1x10^{-11}$
External reference (F-P resonator) stabilization	<1 Hz	$1x10^{-14}$

Note that an etalon inside the laser cavity could also be used to select out a single longitudinal mode. For high power lasers which would require long tubes supporting many modes, this would be needed with both the overall mirror spacing and etalon being feedback controlled. But for low power lasers (e.g. 1 to 3 mW), the use of a short tube to limit the number of modes in conjunction with basic feedback control is a much less complex lower cost approach.

Stabilized lasers (or anything that needs to be regulated to some precision) can be classified as two types. The technique is "intrinsic" - basically derived from an internal reference - if what is used to regulate the device is a fundamental property of its construction - the laser physics in this case. It is "extrinsic" if some external reference is used. Most commercial stabilized HeNe lasers are of the first type since they exploit the known and essentially fixed frequency/wavelength and shape of the neon gain curve in the E/M spectrum. Additional techniques may be used to further reduce the uncertainty.

Most common commercial stabilized HeNe lasers are red at 633 nm, partially because of all the available HeNe wavelengths with a single frequency output power of less than 2 mW. Systems like this are both relatively easy to implement and generally useful for a wide range of applications. The approaches usually fall into one of two subclasses:

1. **One or Two Mode stabilized systems:** These use random polarized HeNe laser tubes that are short enough that only a few modes will oscillate at the same time. Adjacent modes of a random polarized HeNe laser tube are almost always orthogonally polarized. So, where two modes are oscillating, separate signals corresponding to the amplitude of each mode can be easily obtained by feeding a pair of photodiodes from a polarizing beamsplitter. (If a tube has modes that aren't orthogonally polarized or that behave strangely, it gets recycled into another application or the dumpster.) The signals may be obtained from the waste beam out of the HR mirror of the laser or by sampling a portion of the output beam. Either one or both of the photodiode signals can then be used for the feedback loop depending on whether intensity or frequency stability is most important. Note that under some conditions, up to 3 or even 4 modes may be permissible in a tube that is to be used for these purposes. More below.
    - Where the best frequency stability is desired, the ratio of the mode signals (usually made 1:1) is used in the feedback loop. This results in better absolute frequency stability since this ratio is independent of the actual output power, which may change as the tube warms up and ages due to use. With a ratio of 1:1, the two modes are parked equally spaced on either side of the gain curve. Even if the tube oscillates on 3 modes if one is near the center of the gain curve (1 strong one and 2 weak ones), there will only be 2 modes when stabilized. The overall approach is shown in [Dual-Mode Single-Frequency Stabilized HeNe]

Laser. Commercial examples include the Coherent 200, Spectra-Physics 117/A/B/C (and identical Melles Griot 05-STP-901), REO SHL. Axsys/Teletrac 150, and many others.

Some inexpensive (this is relative!) stabilized HeNe lasers only use a single mode for frequency locking. When on the slope, this will be reasonably stable after warmup once the output power has reached equilibrium.

- When the best intensity stability with a polarized output is desired, the signal from a single mode (one photodiode channel) is compared to a reference voltage and this becomes the error signal in a feedback loop to put its mode near the center of the gain curve. Even if the tube oscillates on up to 4 modes if there are two on either side of the gain curve, with one near the center of the gain curve when stabilized, there will be at most 2 weaker modes on the tails of the gain curve. Since these will be orthogonally polarized to the dominant center mode, they can be blocked by the output polarizer. The overall approach is shown in Single-Mode Single-Frequency Stabilized HeNe Laser. Commercial examples include the Spectra-Physics 117A (and identical Melles Griot 05-STP-901), and REO SHL.
- When the best intensity stability of the total output (without regard to polarization) is desired, a non-polarizing beam sampler is used or the signals from the two photodiode channels are summed and compared to the reference. I am not aware of any commercial lasers using this approach.

2. **Zeeman split systems:** A magnetic field is used to create a pair of lasing modes that differ from each other by a relatively small frequency. The stable optical frequency along with the Zeeman difference frequency are used for a variety of metrology applications. These may be classified as either axial or transverse based on the orientation of the magnetic field:
   - **Axial:** Like the single mode systems described above, the tube length is such that only a single longitudinal mode will oscillate. However, a powerful axial magnetic field splits this single mode into two sub-modes with counterrotating circular polarization states. When passed through a polarizer at the output, this results in a beat frequency in the 100s of kHz to several MHz range (depending on the magnetic field strength and other factors) which may be used to derive the stabilization feedback signal and is also key to the measurement technique for which these are designed. The overall approach is shown in Dual-Mode Stabilized Axial Zeeman-Split Dual-Frequency HeNe Laser. Commercial examples include the HP/Agilent 5501B, 5517, 5518A, and 5519A/B (though the heater is actually *inside* the tube for these); Excel 1001; Zygo 7705; and others.
   - **Transverse:** Like the two mode systems described above, the tube length is such that a pair of modes can oscillate when straddling the gain curve but only a single mode when at the peak. A moderate transverse magnetic field in conjunction with the natural birefringence of the mirror system results in a beam frequency in the 10s to 100s of kHz range. Since the beat frequency varies slightly with the mode position, it may be used in a PLL feedback loop for frequency stabilization. One example is the Laboratory for Science model 220.

Most commercial stabilized HeNe lasers for general laboratory applications are of type (1) and operate with 2 orthogonal modes for frequency stabilization, though some use 1 mode for intensity stabilization (or can select between them with a switch). (Regardless, only a single longitudinal mode - thus a single optical frequency - may be allowed to exit the laser, the other being blocked with a polarizer.) These include the Coherent 200, Spectra-Physics 117 and 117A (and the identical Melles Griot 05-STP-901), many from Zygo, and various models from REO, Thorlabs, and others. For example, in the Melles Griot 05-STP-901 frequency and intensity stabilized HeNe lasers (no longer in production), the laser cavity permits a pair of orthogonal polarized longitudinal modes to be active and can provide very precise control by straddling these on either side of the gain curve (frequency stabilized mode) or a single longitudinal mode that is also used for the output on one side of the gain curve (intensity stabilized mode). Those from other companies are generally similar.

All the interferometry lasers manufactured by Agilent (formerly Hewlett Packard), Excel, and one model from Zygo (the 7705) are of type (2). While lasers from Teletrac/Axsys, Optodyne, Renishaw, and others are type (1).

And there are hybrid approaches. For example, the Zygo 7701/2/12/14 lasers generate and lock a single frequency via dual mode stabilization, But it is split into two using an Acoutso-Optic Modulator (AOM) rather than the Zeeman effect.

For some photos of the (quite simple) Zeeman split stabilized HeNe tube used in the Hewlett-Packard 5517 laser head, see the Laser Equipment Gallery (Version 1.86 or higher) under "Assorted Helium-Neon Lasers". And for more information on these lasers, see the sections starting with: Hewlett-Packard/Agilent Stabilized HeNe Lasers.

It isn't really possible to convert an inexpensive HeNe tube that operates on many longitudinal modes into a single frequency laser. Adding temperature control could reduce the tendency for mode hopping or polarization changes, and the addition of powerful magnets can force a polarized beam. But, selecting out a single longitudinal mode would be difficult without access to the inside of the tube. However, if the HeNe tube is short enough that the mode spacing exceeds about 1/2 the Doppler-broadened gain bandwidth for neon (about 1.5 GHz), it will oscillate on at most 2 longitudinal modes at any given time and these will each be linearly polarized and usually orthogonal to each-other. Then, stabilization is possible using very simple hardware. In fact, even if the mode spacing is a bit smaller - down to 500 or 600 MHz - then only 2 modes will be present most of the time but 3 may pop up if one is close to the center of the gain curve. This, too, is an acceptable situation since the tube can be stabilized with the modes straddling the gain curve and then only 2 modes will oscillate. For intensity stabilization, 4 modes may even be permitted. Note that while the modes of a random polarized and linearly polarized tube are similar (except for polarization), a random polarized tube is desirable to be able to use a tube that supports 2 modes with the benefits they provide, while being able to eliminate the second mode from the output. Also see the section: Inexpensive Home-Built Frequency or Intensity Stabilized HeNe Laser for details.

It may be possible with a combination of what can be done externally, as well as control of discharge current, to force a situation where gain is adequate for only 1 or 2 modes even for a longer tube. Whether this could ever be a reliable long term approach for a HeNe tube that normally oscillates in many longitudinal modes is questionable. What I don't think will have much success are optical approaches such as feeding light back in through the output mirror. Doing this would likely have the exact opposite of the desired effect but may work in special cases (it's called injection locking and is used with great success for other applications).

Coherent, Melles Griot, Spectra-Physics, and others will sell you a small stand-alone stabilized HeNe laser for $5,000 or so and Agilant (HP) and others have interferometers and other similar equipment which includes this type of laser (and are even more expensive!). Other manufacturers includ Zygo, Teletrac, Nikon, Micro-g Solutions, SIOS, NEOARK, and REO. The lab lasers that I've seen all use short HeNe tubes with thermal feedback control of the resonator length and all operate at the red HeNe wavelength (632.8xxxxxx nm to 8 or more significant figures). One typical system is described in the section: Coherent Model 200 Single Frequency HeNe Laser. The Spectra-Physics model 117A/118A laser actually uses a lowly SP088-2 tube similar to those in older grocery store barcode checkout scanners as its heart. A tube like this is visible in the Spectra-Physics Model 117 OEM Stabilized HeNe Laser Assembly. However, some do employ a custom tube with the heater inside to greatly speed up response and reduce heat dissipation to the outside. A stabilized HeNe laser for green or other color visible HeNe wavelength or one of the IR wavelengths is also possible using the same techniques.

As noted above, the actual stabilization mechanism for the general purpose stabilized lasers may be the ratio of amplitudes of two longitudinal modes (which is better for frequency stabilization) or the amplitude of one mode (which is better for intensity stabilization). These are usually stable to within a few parts in 10^9. However, the frequency drift when intensity stabilized is still not much - probably less than 1 part in 10^8. Output power variation may be 0.2 percent if intensity stabilized and 1 percent if frequency stabilized. Some allow either method to be selected via a switch, as well as providing for an external tuning input to vary the frequency over several hundred MHz. (However, due to the thermal control most often used, the response time is not exactly fast.)

The Zeeman split interferometer lasers may lock the difference frequency to a crystal clock, though most seem to use the basic polarized modes for stabilization, with the Zeeman beat used only as the reference for the interferometer. See the sections starting with: Hewlett-Packard/Agilent Stabilized HeNe Lasers. A few do lock the Zeeman frequency to a PLL. One of these was the Laboratory for Science Model 220. (Laboratory for Science is now out of business.) See the section Laboratory for Science Stabilized HeNe Lasers. Another example is the NEORK Model 262 Transverse Zeeman Laser.

More sophisticated schemes with even better precision and lower long term drift may lock to the "Lamb Dip" at the center of the neon gain curve or to one of the hyperfine absorption lines of an iodine vapor other type of gas cell, achieving stabilities on the order of 1 part in 10^{10} or even better. See, the section: Iodine Stabilized HeNe Lasers.

Due to the performance, simplicity, reliability, and relatively low cost of stabilized HeNe lasers, they are still often the preferred frequency reference for many applications. As noted, a typical system might go for $5,000. While this may seem high, it is small compared to many other technologies. The cost is not the result of expensive components or complex manufacturing, but more to the relatively limited number of units produced. If stabilized HeNe lasers were as popular as laser pointers, they would probably cost under $100.

Much additional information and specific details of actual systems may be found in the chapter: Commercial Stabilized HeNe Lasers.