PACIFIC LASERTEC™

215 Bingham Drive
San Marcos, California
92069-1403 USA

www.pacificlasertec.com

APPLICATION NOTE

Center Wavelength, Spectral Linewidth, and Coherence Length of Helium-Neon (HeNe) Lasers

We frequently receive questions about HeNe laser center frequency (or wavelength), spectral linewidth, and coherence length – all of which are inter-related. The primary challenge in responding to these questions, is that "it depends".

Frequency and wavelength parameters (and the resulting coherence length) depend on manufacturing parameters, environmental factors, and the time over which measurements are taken. For instance, are you concerned about instantaneous coherence length over some milliseconds, or coherence length over the course of days, months or even years? To understand the issues surrounding this, we first need to consider the general frequency parameters of the laser.

Center Frequency of a HeNe Laser without Active Frequency Stabilization

The center frequency of a HeNe laser is determined by several factors, the most significant being the mix ratio of Neon isotopes used during manufacture (the "gas fill").

Neon possesses three stable isotopes, Ne_{20}, Ne_{21} and Ne_{22}. Naturally abundant Neon consists of approximately 90.48% Ne_{20}, 0.27% Ne_{21} and 9.25% Ne_{22}. Some HeNe lasers simply use ultra-pure Neon in its naturally abundant ratio, but others use ultra-pure Neon with special proportions of each isotope.

Why use special mixtures? The doppler broadened gain curve for each isotope of Neon is slightly shifted in frequency. If we therefore mix the Neon isotope with the shortest center frequency, and the Neon isotope with the longest center frequency, the overall gain curve is broader than for either isotope by itself. This results in increased output power and reduced power fluctuations. That shift, in terms of both frequency and wavelength, is as follows:

Gas Mixture	Vacuum Center Wavelength (nm)	Center Frequency (THz)	Frequency Shift vs Standard
Pure Ne_{20}	632.991420	473.612198	- 500 MHz
Naturally Abundant Ne	632.991293	473.612293	- 405 MHz
Pacific Lasertec Standard	632.990752	473.612698	0
Pure Ne_{22}	632.990084	473.613198	+ 500 MHz

Table 1

What happened to 632.8 nm, as is most commonly associated with Helium Neon lasers? Table 1 shows the *vacuum* wavelength, versus the wavelength in air. Conversion to wavelength in air is available through multiple online sources, though various formulae for the conversion are sometimes used which deliver slightly different results. With that uncertainly in mind, we therefore cite the vacuum wavelength.

Pacific Lasertec stocks a few specific gas mixtures as part of our standard offering, though we only disclose gas mix details for a particular model on a 'need to know' basis. You might wonder if you can specify a *custom* Neon isotope mixture to attain a specific center frequency. The answer is yes . . . and no. A laser with a custom gas mixture must be documented and tested. This is to ensure that if the laser is ever returned to us, we can replicate it with a like unit. We also must test / verify the performance parameters of the laser to ensure it performs as expected. Additionally, gases with the required purity levels and certified mix ratios cost many thousands of dollars per liter. All said, for custom gas mixes, there must be a reasonable business case to do it, whether it is price, volume or strategic value.

We are often asked whether the center frequency can change after the laser is built, and if so, by how much. First one must agree on what "center frequency" actually means. For the typical HeNe laser, it's not actually a single lasing "line" but the center of the region within the Doppler broadened gain curve, which is approximately 1.6 GHz at the full-width, half-maximum points. This means that the cavity modes can oscillate ±800 MHz from the center frequency as specified in the above table under normal operating parameters. However, this can be significantly reduced via active frequency stabilization, as will be covered later.

There are other factors that cause frequency shifts in HeNe lasers, including manufacturing tolerances in physical structure, Helium to Neon ratio, gas temperature & pressure, and others. Overall, manufacturing tolerances and use conditions result in an additional uncertainly of roughly ± 50 MHz, which translates to ± 0.0001 nm in terms of center frequency or wavelength.

Taking worst-case values over time and temperature, and accounting for manufacturing and usage variability, it is safe to assume that our standard products will have a center (vacuum) frequency of 473.612698 THz ± 1,350 MHz. Or, in terms of wavelength, 632.990752 ± 0.001796 nm -- over their operating lifetime. Again, for instantaneous times, or time durations of some seconds or minutes, the variability is much, much lower.

Spectral Line-width of a HeNe Laser without Active Frequency Stabilization

The popular notion of any laser producing a single frequency or wavelength of coherent light is not based on reality. Most HeNe lasers operate with multiple longitudinal modes (or lasing lines) simultaneously oscillating in the cavity. *This is not to be confused with multiple transverse modes* which are related to the structure of the beam profile! A laser can have multiple longitudinal modes and still be single transverse mode (also known as TEMoo). These designations are *frequently* misused, so when someone refers to a "single mode" laser, it must be clarified as to whether this refers to a single longitudinal mode, or a single transverse mode.

Except for a few special models, HeNe lasers are designed to operate with a single transverse mode (TEMoo) resulting in a near-Gaussian beam profile. However, most will have multiple longitudinal modes oscillating in the cavity. The number of longitudinal modes is a function of the laser's mirror spacing, separated by c/2L in optical frequency. The shortest HeNe lasers will have 1 or 2 modes oscillating while longer lasers will have 4, 5, or even more. The number of longitudinal modes is determined again by the width of the Neon gain curve or Gain Bandwidth (GB) with a relationship of approximately:

$$n = \frac{GB\ x\ 2\ x\ L}{c} + 1 = \frac{1.6\ GHz\ x\ 2\ x\ L}{2.998\ x\ 10^{8}\ \mathrm{m/sec}} + 1$$

Where n is truncated to an integer and denotes the maximum number of longitudinal modes that can be oscillating at any given time. So for example, a HeNe laser with a cavity length of 20 cm will typically produce up to 3 longitudinal modes. In the case of "randomly polarized" lasers, each adjacent longitudinal mode generally has orthogonal polarization [there are some exceptions to this, but the topic is beyond the scope of this document]. In linearly polarized lasers, all longitudinal modes are forced to have the same polarization. Each mode generally has an instantaneous spectral line-width of approximately 1 MHz.

Worst case, the spectral line-width of the laser as a whole would be the width of the doppler broadened gain curve (GW) plus manufacturing tolerances and use conditions such as temperature. This is typically on the order of ± 0.002 nm. It is worth repeating that over time periods of seconds or minutes, the spectral line-width is much less.

Translating Spectral Linewidth to Coherence Length

Coherence length is a measure of the propagation distance over which the temporal coherence significantly decays. More simply put, it is the space over which a wave is relatively sinusoidal and predictable. It can also be stated as the maximum path length difference over which fringes can be produced in an interferometer, and is characterized as follows:

$$L = \frac{\mathrm{c}}{\Delta f}$$

Where L is the coherence length in meters, c = the speed of light in meters per second, and Δf is the change in frequency (or the spectral width of the source) during the time of interest, as measured in Hz.

Therefore, in the worst-case, long-term situation, a HeNe laser would have a Coherence length of:

$$L = \frac{2.998\ x\ 10^{8}\ \mathrm{m/sec}}{2.7\ x\ 10^{9}\ \mathrm{Hz}}$$

Or about 10 cm, worst-case, long-term. This is based on the aforementioned 2.7 GHz effective bandwidth over which lasing can occur taking into consideration the width of the Neon gain curve, manufacturing tolerances, temperature, etc. In common use in a typical laboratory environment, this value is normally understood to be on the order of 20 cm.

Actively stabilized HeNe Lasers

For common HeNe lasers, the longitudinal modes drift through the Neon gain curve as thermal effects cause the cavity length to change. So even if the laser is oscillating on a single longitudinal mode, there is no way to predict where within the Neon GB it may be at any given time, leading to an uncertainty in optical frequency of around ± 1.5×10^{-6}.

Through special construction techniques, HeNe lasers are available which operate in a single longitudinal mode with a spectral line-width of less than 0.5 MHz As a result, coherence lengths on the order of 500 meters can be attained over time periods of an hour or more, and over a few seconds, coherence lengths of several thousand meters are commonly observed. This represents an improvement of 100 to 1,000 or more compared to the un-stabilized laser. Lasers like these are widely used as optical frequency references in precision instruments such as wavemeters, spectrometers and interferometers.

The most common stabilized lasers are based on short, random polarized HeNe laser tubes that can oscillate on at most 2 longitudinal modes when they are straddling the Neon gain curve. A controller keeps the modes in a fixed location relative to the Neon gain curve indefinitely by sensing the amplitudes of one or both modes and electronically driving a heater to maintain the cavity length to a precision of a few nm. A polarizer blocks the mode that isn't wanted. Because they are locked to an intrinsic characteristic of the HeNe lasing process, these types of lasers are the gold standard for metrology applications with a typical long-term accuracy better than $\pm 2 \times 10^{-8}$.

And for even higher precision, a single longitudinal mode of a Pacific Lasertec HeNe laser tube can be locked to an absorption line of iodine vapor resulting in an optical frequency standard that has an absolute accuracy of better than $\pm 1 \times 10^{-10}$.

Should you require further information, or if you wish to discuss these matters in further detail, please visit https://pacificlasertec.com/contact for links to your nearest Distributor, Representative, or the Factory.

Sincerely,

Pacific Lasertec,
Technical Team