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APPLICATION NOTE

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

We often receive questions about HeNe laser center frequency (or wavelength), spectral linewidth, and coherence length. 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 it is measured. For instance, are you concerned about instantaneous coherence length, over some milliseconds, or coherence length over the course of many days? To understand the issues surrounding this, we first need to consider the center frequency of the laser.

Please note that the effects of Mode-Pulling are ignored for the purposes of this discussion.

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	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
Newport Standard Products	632.990752	473.612698	0
Pure Ne_{22}	632.990084	473.613198	+ 500 MHz

* Vacuum wavelength

You might wonder if you can request a specific center frequency or the associated Neon mix ratio. The answer is yes, and no. A laser with a custom gas mixture must be documented and tested to ensure that if the laser is ever returned to us, we can replicate it. We also must test / verify the performance parameters of the laser to ensure it performs as expected. With these factors in mind, there must be a reasonable Business Case for manufacturing units with custom gas mixtures, whether it be volume, price, or perhaps some strategic value. All said, we can, and do provide custom gas mixes, but gases with the required purity levels and certifications can cost tens of thousands of dollars per liter, so it is not done without careful consideration.

In addition to the Neon mix ratio, there are other factors that affect the center frequency, including manufacturing tolerances in physical structure, Helium to Neon ratio, temperature, and pressure to name a few. Overall, this represents an uncertainly of roughly ± 50 MHz or ± 0.0001 nm.

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 really 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 one refers to a “single mode” laser, it must be clarified as to whether the intended meaning is 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. Typical Gaussian fit values are in the range of 95 to greater than 99%. 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 longitudinal modes oscillating while longer lasers will have 4, 5, or even more. The number of longitudinal modes present 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. For example, a laser with a cavity length of 20 cm will typically produce up to 3 longitudinal modes. Each mode generally has an instantaneous spectral line-width ≤ 500 kHz.

Specification documents for Newport models indicate the longitudinal mode spacing per model. For example, one of our more popular models specifies a mode spacing of 438 MHz. Manufacturing tolerances, specifically regarding mirror spacing, can contribute up ± 50 MHz variation from unit to unit. While the details of “Mode Pulling” are beyond the scope of this document, the phenomena also affects longitudinal mode spacing, albeit to a much lesser degree. For example, mode pulling is normally on the order of tens or hundreds of kHz, and certainly less than ± 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, temperature variations and pressure effects. This would equate to 473.612698 THz ± 1,350 MHz, or 632.990752 ± 0.001796 nm for our standard products.

Polarization States for Longitudinal Modes

The polarization state of the longitudinal modes is also important to understand. We specify "randomly polarized" and "linearly polarized" models, and each is particularly well suited in specific application areas.

For randomly polarized lasers, each adjacent longitudinal mode has orthogonal polarization. The orientation of the two planes remains fixed with respect to the laser package and orthogonal with respect to one another over the lifetime of the laser. However, the orientation of the planes with respect to the laser housing is not normally indicated.

For linearly polarized models, each adjacent longitudinal mode is forced to have the same polarization through proprietary construction techniques. The orientation of the polarization plane remains fixed with respect to the laser package and does not vary over time. The plane's orientation is normally indicated on the laser package.

There are several issues pertaining to model selection in terms of polarization and its impact on system performance. Please contact the factory for further assistance.

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/second, and Δf is the change in frequency (or the spectral width of the source) during the time of interest 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 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 for a specific laser under laboratory conditions and with typical test and measurement times, this value is normally understood to be about double that, or 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 x 10^{-6}.

Through special construction techniques, HeNe lasers are available operating on a single longitudinal mode with spectral line-widths of less than 500 kHz. 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 and spectrometers.

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. The 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 ± 2x 10^{-8}.

For even higher precision, a single longitudinal mode of a Newport 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 ± 1 x 10^{-10}.

For further discussion of these topics, please contact an Applications Engineer or your local Service Center.