22: Inhomogeneous Broadening in Neon and Mode Sweep

The shape of the neon gain curve is by now familiar, but what does it really mean? The popular notion of it being the result of some magical process is fine as a first step, but doesn't help in attempting to understand how it is affected by wavelength, or for explaining phenomena like the Lamb Dip.

What is really being depicted in the gain curve is a combination of a curve derived from what's called the "natural line width of neon" which is homogeneously broadened, and the distribution of atomic velocities of excited neon atoms as they translate into a distribution of Doppler shifts in optical frequency.

Ignoring Special Relativity (which is acceptable for the velocities involved), the Doppler shift in optical frequency is equal to the relative velocity of the excited atom divided by the speed of light multiplied by the optical frequency or:

$$\Delta f = -f_0 * \frac{v_a}{c}$$

Where:

- Δf is the optical frequency shift.
- f_0 is the original optical frequency.
- v_a is the velocity of an atom in the upper lasing energy state relative to a photon traveling along the axis of the laser tube.
- c is the speed of light.

At any temperature above absolute zero, all atoms are in motion and have a probabilistic distribution of velocities (speed and direction), which all contribute to the Doppler broadening. For a Fabry-Perot (linear) cavity, the photons traveling in either direction "experience" the relative speed of the excited atoms. Stimulated emission will only occur when the Doppler-shifted energy of the photon matches a possible lasing transition of an excited atom. The width of the Doppler broadening is directly proportional to optical frequency, but it is also affected by other factors including temperature and pressure, since these impact the distribution of atomic velocities. The shape of the Doppler broadening curve is then the result of the aggregate of the motion of all the atoms available for stimulated emission. And the width of the inhomogeneously broadened neon gain curve is the width due to homogeneous line-width of neon plus the inhomogeneous Doppler broadening. Since they are added like independent noise souces using the square-root of the sum of the squares, the increase in neon gain bandwidth due to the homogeneous line-width is quite small (just over 5 percent even at 3,391 nm). Thus, the change is close to 1/5th even if the homogeneous part is ignored.

Assuming the FWHM value of 1.6 GHz for the entire inhomogeneously Doppler-broadened gain bandwidth of the common red wavelength of 632.8 nm, at the mid-IR wavelength of 3,391 nm it is only 315 MHz. And at the green wavelength of 543.5 nm it is about 1.86 GHz. The optical frequency difference between cavity modes (c/2L) is only dependent on cavity length and the speed of light. Thus, the number of lasing modes possible for a given cavity length decreases as the gain bandwidth becomes narrower at longer wavelengths.

Note that the lasing modes themselves will have a very narrow bandwidth – possibly as small as 5 kHz or even lower for a laser operating with a single mode. At that point, physical vibrations, laser power supply noise, and other external effects are the limiting factors, not the theoretical minimum bandwidth for the HeNe laser which is under 1 Hz! (Schawlow–Townes linewidth). I originally thought that finding values for the bandwidth of commercial HeNe lasers would be straightforward, but it seems to be near impossible. The only specifications I am aware of from a laser manufacturer are in Laboratory for Science brochures. The best is for their model 220 Ultra Stable HeNe laser, which lists 5 kHz over a period of 1 second. But the value for the type of HeNe laser tube that used to be found in barcode scanners may not be all that much greater if it is mounted to minimize vibrations and driven with a well filtered HeNe laser power supply.

One would expect that with the much smaller gain bandwidth at 3,391 nm of 315 MHz, there would be fewer longitudinal modes oscillating compared to 632.8 nm. Or equivalently, a laser tube would need to be much longer for the same number of modes to fit within the FWHM of 315 MHz. But because of the very high gain at 3,391 nm, the lasing threshold will be lower and thus the effective gain bandwidth of the neon gain curve is going to be wider. I do not know by how much, but with a potential gain over 40 times that of the 632.8 nm transition, it could be very significant. There might even be more modes than at 632.8 nm.

Due to the longer wavelength, mode sweep for a laser tube at 3,391 nm will have a complete cycle that is over 5 times as long as one at 632.8 nm. These same numbers would apply to mode competition at 3,391 nm interfering and stealing power from a 632.8 nm laser.