Technical Note
Tunable Laser Diode Absorption Spectroscopy (TDLAS)

Spectral Features
Absorption spectroscopy is a widely used technique for sensitive trace-species detection. The amount of light absorbed by a target gas at a specific wavelength is proportional to the amount of the gas in the path of the light. The target gas is the gas being measured; for example the amount of water vapor in a sample of air can be measured. As shown above, a beam light is passed through a sample and the amount of light transmitted is measured by a detector. The target gas does not absorb all light, but a predictable amount of very specific wavelengths of light. If the light’s wavelength is adjusted, the amount of light detected on the output will vary accordingly.

An absorption spectrum diagram shows the amount of light absorbed by a material through a range of wavelengths. The graph above is a diagram for water vapor with the wavelength on the x-axis and the transmittance on the y-axis. Transmittance is similar to absorbance except it shows how much light gets through the gas (the amount of light detected) rather than the amount absorbed. A value of 1.0 on the y-axis means all of the light is transmitted through at that wavelength. You can see three regions (absorption bands) on the water spectrum graph where light is absorbed. A traditional absorption spectroscopy technique would be to measure the absorption of one of these regions. This is a good technique as long as there are no other gases in the sample that absorb at the same wavelength. The graph on the lower left shows methane transmittance in the same wavelength range as the diagram for water. For measuring moisture in methane, traditional techniques do not work because methane has a much stronger absorbance in the same regions on the graph and completely drowns out the measurement. The solution to this setback is to measure the individual peaks at a sharper resolution of the spectrum and find a location along the x-axis where the peaks do not interfere very much (or not at all). The graph below shows the same spectrums as above except it is expanded around a particular target wavelength. The moisture peak can be measured and discriminated from the methane absorption peaks. As long as these isolated or semi-isolated peaks can be found and the spectrometer used to measure the peaks has adequate resolution, these features can be analyzed to measure target gas concentrations down to part-per-million (ppm) or part-per-billion (ppb) levels.

Beer’s Law
The fundamental theoretical principle of absorption spectroscopy is the Beer-Lambert Law. Beer’s law describes the relationship between transmitted and incident spectral intensities when the laser beam passes through a uniform gaseous medium. The equation of Beer-Lambert law is simple and straightforward:

\[ A = -\ln \left( \frac{I}{I_0} \right) = X \cdot \phi \cdot S \cdot L, \]

where \( A \) is the absorbance; \( I \) and \( I_0 \) are the transmitted and incident laser intensities; \( X \) is the mole fraction of species; \( P \) is the total pressure; \( S \) and \( \phi \) are the linestrength and lineshape of a particular transition of the species. In essence, the target gas concentration can be determined by measuring \( I_0 \) and \( I \) with the spectrometer.
Tunable Diode Lasers

The SpectraSensors TDLAS sensor utilizes a tunable diode laser as the light source. Diode lasers are compact, rugged and affordable.

Figure 1 shows a comparison between laser linewidth and a typical absorption transition linewidth. Tunable diode lasers have very narrow linewidth (in the order of MHz), which is several orders of magnitude smaller than any spectral feature being measured (in the order of GHz). The laser frequency is tuned by laser injection current over the selected absorption transition and as it passes through the sample gas and the absorption is measured across that scan.

Measurement Technique

If we tune the lasers in frequency across an absorption transition, then the transmitted laser intensities will have characteristic lineshapes which is a function of the number of absorbing molecules. The top graph in Figure 2 shows typical transmitted laser intensity along with an estimate for the reference laser intensity $I_0$. The small dip in the transmitted laser intensity corresponds to an absorption feature. Thus, we can use the measured lineshape (e.g. area under the lineshape) to extract the species concentration. This technique is usually called direct absorption spectroscopy. Direct absorption technique has two major disadvantages which significantly limited its application in practical gas sensing fields: First, the baseline fit become difficult and often impossible when the line is broadened and/or blended with neighbors. Second, direct absorption has relatively low sensitivity because of the direct addition of noises. This shortcoming limits its applications in trace gas detection when the measured spectra is interfered by neighboring lines (due to pressure broadening) or other background gases.

To overcome the corresponding weakness and limitations discussed above, SpectraSensors employed a more sensitive technique called wavelength modulation spectroscopy with second harmonic (2f) detection for sensitive trace-species detection. A fast kHz sine wave modulation is added to drive the laser, and a lock-in amplifier is employed to detect the harmonic component at twice the modulation frequency (2f). By using wavelength modulation with 2f detection, the measurement sensitivity is improved by shifting the detection to higher frequencies where laser excess noise and detector thermal noise are both much smaller; in addition flow-generated noise outside the detection bandwidth is suppressed using phase-sensitive detection. The bottom graph in Figure 2 shows the normalized second harmonic (2f) signal. The concentration of the absorbing species can be determined from the measured 2f peak height.

Since the scan range is much wider than the absorption feature, it is assured that the center of the absorption peak will be found in the scan. This and the fact that diode lasers are very stable explain how the system compensates for slight drifts in the x-axis automatically over long periods of time (years).

Compensating for possible contamination of the mirror must also be considered. The DC signal will decrease (as shown in the top graph in Figure 2) if the mirror became partially obstructed over time (assuming everything else was the same). By normalizing 2f signal by the laser intensity, any changes and fluctuations in laser power are automatically compensated. In other words, if only 10% or 50% of the light were getting through, the normalized 2f signal would not be different and the measurement would not be affected. If the mirror becomes very dirty, not enough light will get to the detector and the power cannot be measured at all. The system checks during every scan for a minimum amount of light. If that test fails, the system will show a “power fail” error indicating that the mirror must be cleaned or something else is wrong.