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Alternate Intensity Modulation of a Dual-Wavelength He-Ne Laser for Differential Absorption Measurements

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Abstract. A simple method is demonstrated for internal intensity modulation of the 3.391 and 3.392-μm emissions of a He-Ne laser with equal amplitudes and 180° out of phase to each other. A modulation amplitude of 0.7 mW peak-to-peak at 1kHz for the individual emissions has been obtained from a laser plasma tube 50 cm long while maintaining the total-intensity modulation as low as 0.25 μW for a signal averaging time of 1 s. This laser source can greatly simplify the setup and improve the sensitivity of differential absorption measurements for the methane remote sensing.

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It is known that the $\lambda_0 = 3.392$-μm emission (Ne $3s_2 - 3p_4$) from a He-Ne laser is strongly absorbed by methane because its center frequency is only 90 MHz lower than that of one component line of the ν_3 $P(7)$ line of methane [1, 2]. The emission at a nearby wavelength, $\lambda_1 = 3.391$ μm (Ne $3s_2 - 3p_2$), can be obtained by introducing into the laser cavity an absorption cell filled with methane [3–6]. The latter line is 9 GHz, at least, apart from all strong lines in the methane absorption spectrum. As a result, the absorption coefficients of methane in the air at λ_0 and λ_1 still have a high contrast of 13:1 [6]. The differential absorption at these two wavelengths, therefore, provides a sensitive method of detecting the presence or measuring the concentration of methane in the air [3]. The methane monitoring is important in mines and industrial plants. Also, it is useful for the detection of leaks from natural gas pipelines because methane constitutes more than 90% of natural gas.

A straightforward way of the methane remote sensing is to point two lasers, one emitting the λ_0 line and the other the λ_1 line, to the area being probed and to monitor the intensity of the reflected or transmitted radiation at the two wavelengths with separate detectors. The methane absorption is identified by the difference of the relative attenuation between the two wavelengths. This method needs, however, not only large volumes for both the transmitter and the receiver but also a complex electronic circuit for signal derivation unless the laser output power is highly stabilized. Furthermore, when the radiation reflected from some topographic targets is to be monitored, the two laser beams must be aligned so precisely collinear as to hit on the same target. One method for simplification of the whole system is to modulate the two laser beams 180° out of phase to each other by a chopper and to detect the reflected/transmitted radiation by a single detector. However, the laser power stabilization and precise optical alignment still remain essential.

In the present paper a simple method to internally modulate the output power of the 3.391 and 3.392 μm lines of a He-Ne laser with equal amplitudes and 180° out of phase to each other is demonstrated. The alternate intensity modulation is accomplished by placing a low-pressure methane cell inside the laser cavity and by vibrating one of the cavity mirrors. The residual modulation in the total output power is kept at a very low level by a simple servo control. This laser source can be used not only to make the design of methane remote sensing systems very compact and straightforward but also to improve the detection sensitivity.

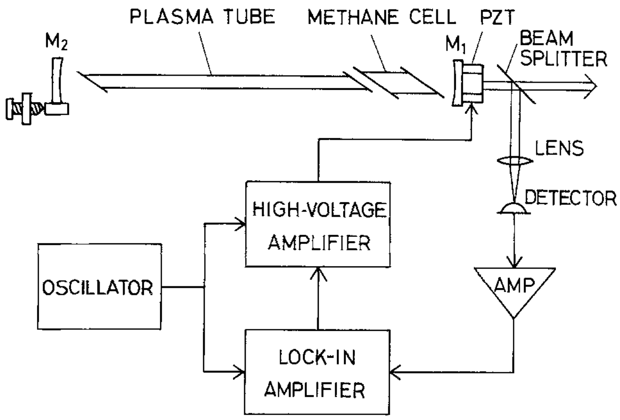

Fig. 1. Schematic diagram of the intensity-modulated dual-wavelength He-Ne laser

1. Experimental Setup

The structure of the intensity modulated dual-wavelength He-Ne laser is shown in Fig. 1. In essence, it consists of a He-Ne laser with an intracavity absorption cell filled with low-pressure methane and a feedback loop which tunes the cavity so as to give null modulation in the total output power. The cavity length is about 68 cm, but it is manually adjustable by ± 3 mm. The dc discharge tube with Brewster's angle windows is 2.5 mm in bore diameter and 50 cm in effective discharge length. The absorption cell, again with Brester's angle windows, is 4.2 cm long. Concave mirrors, M_1 and M_2, of 3 m radius of curvature have a 90% and $\approx$100% reflectivity, respectively. The mirror M_1 is mounted on a piezoelectric translator and vibrated at the frequency ω near 1 kHz with a peak-to-peak amplitude of $\approx$0.6 μm. The output beam is partially reflected by a beam splitter and monitored by an InAs detector. The error signal to control the cavity tuning is provided by phase sensitive detection of the resulting amplitude modulation at ω in the total output. An appropriate choice both in the cavity length (within the ± 3 mm range of the manual adjustment) and in the methane pressure is essential for large modulation amplitude of the individual emissions at 3.391 and 3.392 μm, as shown below.

2. Principle of Operation

Because the 3.391 and 3.392 μm transitions in Ne share the $3s_2$ state as their upper levels, there is a competition between the oscillations at these two wavelengths in a He-Ne laser. Under usual conditions the 3.391 μm oscillation is completely suppressed by the 3.392 μm oscillation which has a much lower threshold. However, the former oscillation can be obtained by introducing a methane absorption cell inside the cavity and thus raising the threshold for the latter. At the methane pressures giving a medium loss to the 3.392 μm line the simultaneous oscillation at these two wavelengths occurs. When both emissions coexist, increasing loss (or decreasing gain) to the λ_0 line decreases the λ_0 emission and increases the λ_1 emission, and vice versa.

In the present method the change of the loss and/or gain for both lines is caused by the cavity tuning, i.e., the minute change of the cavity length. This is possible because the gain of each line is frequency-dependent and the absorption of methane for the λ_0 line is so, too, when low pressure methane is used.

The maximum variation of the output power of each line against cavity tuning is expected if the cavity length is such that the frequency of the λ_0 emission coincides with the center frequency of the methane absorption (more exactly, the frequency giving the minimum net gain) when the λ_1 emission is at its gain peak, i.e., the line center. This places a condition on the cavity length L that

$$\nu_1 - \nu_m = N/2L\,, \tag{1}$$

where ν_1 and ν_m are the line centers, expressed in wave number, of the 3.391 μm transition and the methane absorption, respectively, and N is an integer. Substituting $\nu_1 = 2948.787\ \mathrm{cm}^{-1}$ and $\nu_m = 2947.912\ \mathrm{cm}^{-1}$, (1) gives

$$L = 5.7\,N\ \mathrm{mm}\,. \tag{2}$$

Equation (2) means that the maximum variation in the output power of each line vs. cavity tuning is obtained repeatedly at every 5.7 mm change of the cavity length. This is the reason why the manual cavity length adjustment of ± 3 mm is required in the present system.

This cavity-length dependency was experimentally verified. Figure 2 shows the observed variation of the output power of the individual lines and the sum of both vs. cavity tuning at various cavity lengths. The power of the λ_1 line and the total power were monitored simultaneously by two detectors. An external methane cell was used to select the λ_1 line. The power of the λ_0 line was obtained from the difference of the output of the two detectors. The cavity length was decreased manually from (a) to (e) by 1.43 mm steps. It is seen by comparing (a) and (e) that a change of cavity length by 5.7 mm gives similar power curves as expected.

From these curves the optimum cavity length is chosen to obtain the maximum power change of the individual emissions with little change in the total power. Figure 2a (or, equivalently, Fig. 2e) is found to be nearly the best. In Fig. 2a, as the cavity is tuned from A to B,

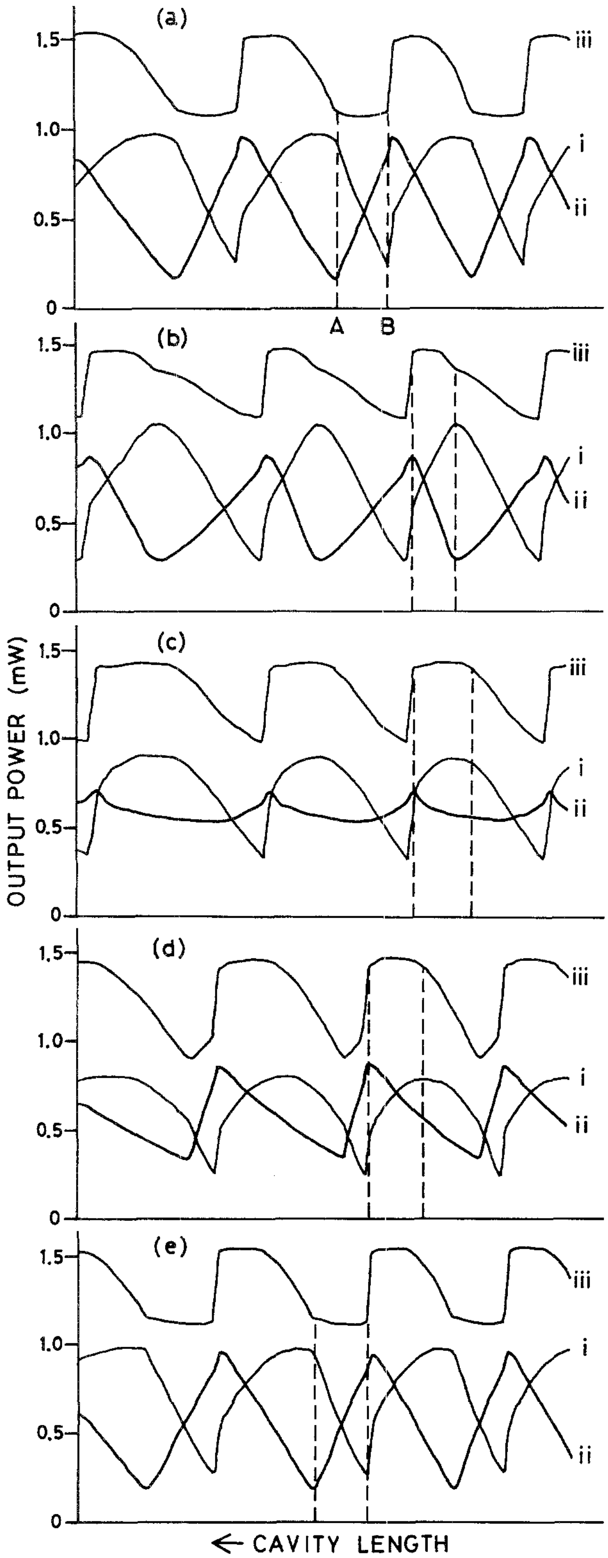

Fig. 2a–e. Observed output power of the 3.392 μm (i) and 3.391 μm (ii) lines and the sum of both (iii) vs. the cavity length. The cavity length was decreased manually from (a) to (e) by 1.43 mm steps. In each curve one cycle of the power variation corresponds to a $\lambda/2$ change in the cavity length. The dashed lines denote a pair of points which give the maximum power change of the individual lines and no change in the total power. Ne pressure: 0.4 Torr; He pressure: 2.4 Torr; discharge current: 6 mA; methane pressure: 2.0 Torr

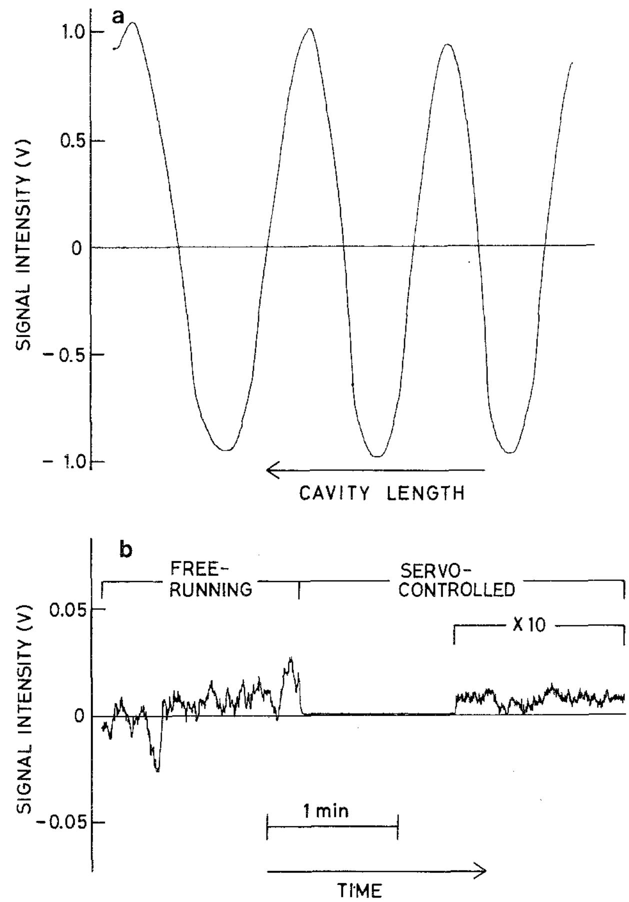

Fig. 3. (a) Amplitude of the intensity modulation at the fundamental frequency in the total output as a function of the cavity length. One cycle of the signal variation corresponds to a $\lambda/2$ change in the cavity length. (b) Time variation of the error signals both in the free-running and servo-controlled modes. The signal averaging time is 1 s

for example, the power of the λ_0 line decreases by 0.7 mW while the power of the λ_1 line increases by the same amount. If the cavity is tuned back and forth between A and B by a square wave the null intensity modulation in the total output will be achieved. It is trivial that even if a sinusoidal modulation of a frequency ω is used there are some tuning points which give null intensity modulation in the total output at the fundamental frequency ω.

Figure 3a shows the amplitude of the resulting intensity modulation at ω in the total output measured by a lock-in amplifier as a function of the cavity tuning. The cavity length was same as that in Fig. 2a and a sinusoidal modulation voltage of 80 V peak-to-peak (which corresponds to the A to B displacement, ≈ 0.6 μm) of 1 kHz was applied to the piezoelectric translator. There are two null modulation points in every $\lambda/2$ range of the cavity tuning. This output of the lock-in amplifier is used as an error signal for the servo control of the cavity onto one of the null modulation points.

3. Results and Discussions

Figure 4 shows the waveforms of the 3.391 and 3.392 μm lines and the total output emitted from the present dual-wavelength He-Ne laser when it is controlled with the servo loop. The individual emissions are modulated alternately at 1 kHz with a 0.7 mW peak-to-peak amplitude while the total intensity is modulated primarily at 2 kHz. The amplitude of the residual fundamental-frequency component in the total intensity was evaluated from the error signal provided by the lock-in amplifier as follows: In Fig. 3b the time variation of the error signals both in the free-running and servo-controlled modes is shown. By comparing with the biggest signal in Fig. 3a which corresponds to a 0.5 mW peak-to-peak modulation, the residual fundamental modulation in Fig. 3b when the servo control is on is calculated to be 0.25 μW peak-to-peak. This is about 1/3000 of the modulation amplitude, 0.7 mW peak-to-peak, of the individual lines.

Using this dual-wavelength He-Ne laser as a transmitter the method for the methane remote sensing becomes very simple. When methane is present in the atmosphere the λ_0 component in the radiation attenuates more strongly than the λ_1 component giving rise to an ac signal at ω in the output of the detector which monitors the total intensity of the reflected/transmitted radiation. This ac signal is detected by a lock-in amplifier tuned to the frequency ω. In the ideal situation where the residual fundamental modulation in the total intensity of the laser is the dominant noise source, the minimum detectable methane density is estimated to be 0.4 ppm for a signal averaging time of 1 s and a 1 m optical pathlength using the known absorption coefficients, 9.9 ± 0.1 and 0.79 ± 0.01 cm^{-1} atm^{-1}, of methane in the air at the wavelengths λ_0 and λ_1, respectively [6].

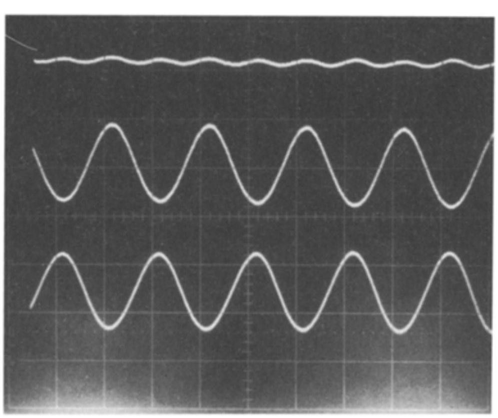

Fig. 4. Waveforms of the intensity of the total output (upper trace), the 3.392 μm line (middle trace), and the 3.391 μm line (lower trace). The modulation frequency is 1 kHz. Note that the total output is modulated primarily at 2 kHz

When the received laser power is weak other noise factors such as detector noise and background thermal radiation must be considered. It is favorable, then, to use a modulation frequency as high as possible to reduce the noise. With the piezoelectric translator and a driving circuit employed here the 0.6 μm movement of the mirror for the maximum modulation is limited to the frequencies lower than 1 kHz. However, the modulation frequency is extendable to a higher frequency by, for example, making use of mechanical and electrical resonances in the translator and the driving unit.

The methane pressure to maximize the modulation amplitude of the individual lines is about 2 Torr in the absorption cell 4.2 cm long. When the methane pressure is changed to 1 or 3 Torr the amplitude decreases to 70% or 65%, respectively, of the value obtained at 2 Torr. If the methane-air mixture is used instead of pure methane the modulation amplitude available becomes very small because the loss is almost frequency-independent owing to pressure broadening.

In the optimum condition shown in Fig. 2a the modulation depth is about 60% for the individual lines. Even a 100% modulation depth can be obtained by reducing the discharge current at a little sacrifice of the modulation amplitude. However, the sensitivity of differential absorption measurements is dependent on the modulation amplitude rather than the modulation depth.

The present dual-wavelength He-Ne laser can be scaled up in order to obtain a larger modulation amplitude by employing a longer plasma tube or a higher discharge current.

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