CO₂ laser frequency stabilization using the radio-frequency optogalvanic Lamb dip

Chin-Chun Tsai, Tyson Lin, Cherng-Yn Shieh, Tsu-Chiang Yen, and Jow-Tsong Shy

The Lamb dip of the CO₂ saturation signal in an extracavity low-pressure CO₂–N₂ rf glow discharge is detected optogalvanically and used to stabilize the frequency of a CO₂ laser. The frequency stability is estimated to be better than 100 kHz.

Key words: CO₂ laser, frequency stabilization, rf optogalvanic Lamb dip.

Recently Shy and Yen1,2 stabilized a CO₂ laser at the line center, using the optogalvanic Lamb dip in an intracavity direct current (dc) glow discharge of a low-pressure N₂–CO₂ gas mixture. This method can be applied to the regular, sequence, and hot band laser transitions, and the frequency stability is better than $1 \times 10^{-9}$ under proper operational conditions. Recently the same method has been applied to a CO laser.3 However, this method has several difficulties, e.g., it is not easy to have stable discharge at low pressure (e.g., <500 mTorr), and the signal-to-noise ratio (SNR) of the optogalvanic signal is strongly dependent on the conditions of the discharge cathode. In this paper we present our preliminary results on the optogalvanic Lamb-dip stabilization of a CO₂ laser using a radio frequency (rf) discharge.

The optogalvanic effect is a change in the electric impedance of a discharge caused by illuminating the discharge with radiation having a frequency corresponding to an atomic or molecular transition in the discharge. The optogalvanic detection technique has been widely applied in the field of atomic and molecular spectroscopy4–6 and also to the stabilization of laser frequencies.6 The applications of the optogalvanic effect in the stabilization of CO₂ lasers can be found in Refs. 1 and 2. Both dc and rf discharges have been used in optogalvanic spectroscopy, and the rf discharge has the following advantages over dc discharge: (1) It can maintain discharge at low gas pressure and thus minimize the pressure broadening, (2) there is no noise from the sputtering of electrodes, and (3) it is suitable for the spectroscopy of scarce or corrosive gas. Recently Kim and Jones7 observed the optogalvanic signal of a low-pressure (0.5-Torr) rf discharge of CO₂. They suggested that the optogalvanic effects can be used as an infrared detector, which is an inexpensive and fast response. Therefore it is worthwhile to study the possibility of frequency stabilization of a CO₂ laser using the rf optogalvanic Lamb dip.

Our experimental arrangement for rf optogalvanic signal measurement is shown in Fig. 1. The CO₂ laser is an Edinburgh waveguide CO₂ laser (Model WL-8), which has a grating for line selection and a piezoelectric transducer (PZT) for frequency tuning. The laser has output power of >1 W for most lasing transitions. The frequency stabilizer (Edinburgh Model 209) consists of a phase-sensitive detector, an oscillator (at 220 Hz), a comparator, an integrator, and a high-voltage amplifier. For rf optogalvanic signal measurement, the stabilizer is used to scan the frequency across the gain profile. Lenses L₁ and L₂ are used to adjust the beam size in the discharge tube. The reflected laser beam is nearly collinear with the incoming beam to optimize the overlap between them and also to avoid the optical feedback effect, which would introduce serious fluctuations in the laser frequency and output power.

The discharge tube is a Pyrex tube with a 10- or 15-mm inner diameter. The tube is sealed at both ends by ZnSe windows. A pure CO₂ gas or a CO₂–N₂ gas mixture ([CO₂]:[N₂] = 1:1 or 1:2) is flowing through the discharge tube. The pressure of the gas mixture inside the tube is measured by an MKS manometer. The rf discharge is maintained by a Colpitts-type oscillator similar to that reported by Lyons et al.8 Our oscillator circuit is shown in Fig. 2, in which a 6AQ5A tube is used.

The authors are with the Department of Physics, National Tsing Hua University, Hsinchu, Taiwan 30043, China.

Received 6 July 1990.
0003-6935/91/272842-04$05.00/0.
© 1991 Optical Society of America.
to maintain higher ac voltage across the tube. The discharge tube is placed inside induction coil, L. A wide range of inductances for the coil is used, and the oscillator frequency is 25–35 MHz. On illumination of the discharge, the change in the tank impedance causes a change in the plate voltage. Hence the modulation of the discharge impedance because of the chopper is detected as a drop in voltage across resistor $R_p$. This signal is passed to the lock-in amplifier through capacitor $C_0$.

The rf optogalvanic signal increases as the pressure in the discharge tube is increased, and one can easily see the Lamb dip of the CO$_2$ saturation signal at the power peak for gas pressure less than 0.7 Torr. One interesting phenomenon is that the optogalvanic signal is larger when the input voltage $V_{pp}$ of the oscillator is nearer the extinction voltage below which the discharge cannot be sustained. Figure 3 shows the optogalvanic signal versus pressure for a few different operating conditions. Pure CO$_2$ has a smaller signal than a gas mixture containing N$_2$, and the signal is higher when the diameter of the discharge tube is smaller and the rf is higher. Further study is needed for better understanding of the optogalvanic effect in the rf discharge.

To stabilize the CO$_2$ laser frequency, the optogalvanic signal from a rf oscillator is sent to a frequency stabilizer. The oscillator in the frequency stabilizer provides the reference signal (220 Hz) to the PSD, which is added to the high-voltage amplifier to modu-
late the PZT, which in turn modulates the cavity frequency. The signal output of the PSD corresponds to the first-derivative signal of the optogalvanic signal with respect to frequency. We have obtained a good SNR for a 1:1 CO$_2$-N$_2$ mixture at pressures between 200 and 700 mTorr and laser output power greater than 1 W. The SNR is an order of magnitude greater than the optogalvanic signal obtained from an extracavity dc discharge tube at the same laser power. Using this first-derivative signal of the Lamb dip as an error signal, we were able to stabilize the CO$_2$ laser at the center of most CO$_2$ laser transitions. A recorder trace of the error signal as we scan the frequency over a power peak with the fluctuation of the error signal after the laser is locked is shown in Fig. 4. Here, a 1:1 CO$_2$-N$_2$ mixture at 250-mTorr and a 15-mm-i.d. discharge tube are used. The laser line is 10P(20), and the peak power is 2.6 W, which corresponds to an intensity of 20 W/cm$^2$ inside the rf discharge tube. Because of the lack of another stable CO$_2$ laser, we were unable to measure the frequency stability by beating two stabilized lasers together and obtaining the Allan variance.$^{10}$ Instead, the frequency stability is estimated from the fluctuation of the error signal after the laser is locked. The frequency stability estimated in this way is better than 100 kHz. We believe that the frequency stability can be improved by optimizing discharge conditions and the gas mixture ratio.

From our results, we conclude that the rf optogalvanic Lamb dip has the following advantages over the dc optogalvanic Lamb dip: lower pressure and therefore smaller linewidth and smaller pressure shift, lower operation voltage, no need for water cooling, and a better SNR. One should note that the Stark$^2$ and Zeeman effects$^2$ of the CO$_2$ molecule are quite small, and the shift owing to these effects is well below 1 kHz in our case and so can be neglected with respect to the estimated frequency stability. The pressure shift is estimated to be <100 kHz,$^3$ which is also smaller than the estimated frequency stability. Although the rf optogalvanic Lamb dip is worse than for the saturated 4.3-μm fluorescence method$^4$ in terms of stability and the undisturbed center of molecular transition, it is cheaper and more convenient, since no optical detection is involved, and it is suitable for many spectroscopic applications. It also has the potential to stabilize the sequence-band CO$_2$ laser. Recently we observed the Lamb dip at the center of the sequence lines; however, the SNR is not high enough to provide good frequency stabilization for the sequence-band CO$_2$ laser since the signal is smaller than that of regular lines. Further investigation is currently under way.

In conclusion, we have stabilized a CO$_2$ laser at the center of the regular lines, using the rf optogalvanic Lamb dip. The frequency stability is estimated to be better than 100 kHz. The rf optogalvanic Lamb dip should be applicable to sequence-band CO$_2$ lasers and also other molecular lasers, e.g., CO and N$_2$O lasers.
J-T Shy thanks W. Richardson for sending us part of his dissertation. This research is supported by the National Science Council of China under contract NSC78-0417-M007-02 and by a research grant from the National Tsing Hua University.

References

9. W. Richardson, "Degenerate four-wave mixing and studies of the optogalvanic effect in a Hg–Ar discharge," Ph.D. dissertation (University of Southern California, Los Angeles, Calif., 1987).