Internally coupled Fabry-Perot interferometer for high precision wavelength control of tunable diode lasers

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An internally coupled confocal Fabry-Perot interferometer (FPI) has been developed for both high precision wavelength calibration and stabilization of tunable diode lasers (TDL). Our FPI is tunable and thermally stable and works over a large wavelength range (0.6–30 μm)—characteristics that cannot be simultaneously realized with conventional etalons. As part of a versatile wavelength control system the instrument has already considerably improved the quality of our diode laser spectra and will facilitate the use of TDLs in sub-Doppler spectroscopy and as local oscillators in heterodyne radiometers.

I. Introduction

Tunable diode lasers (TDL) are used in both Doppler-limited and sub-Doppler infrared spectroscopy. Until now, however, the full potential of TDLs has not been realized experimentally due to two essential problems:

(1) A precise wavelength calibration is notoriously difficult to achieve. One of the better methods is to use highly stable air-spaced Fabry-Perot interferometers (FPI),[1,2] which produce fringes with a separation of a few hundred megahertz; these are sufficient for the calibration of Doppler-limited spectra. However, in sub-Doppler spectroscopy where linewidths are of the order of a few megahertz, closer calibration fringes are desirable.

(2) The frequency jitter of the diode, which is typically 10 MHz,[2–4] becomes important for the application of diode lasers to sub-Doppler spectroscopy (e.g., saturation absorption,[5] two-photon absorption,[6] double resonance[7]) and as local oscillators in heterodyne radiometers (see Sec. III). This jitter may be reduced by operating the TDL in a liquid helium Dewar[8–9] thus avoiding temperature and pressure fluctuations associated with closed cycle refrigerators usually employed, but this technique is not convenient. A better idea is to stabilize the TDL to a FPI[2,10–11]—a technique widely used in dye laser spectroscopy. Until now, however, no such frequency stabilization system of practical importance has been reported for diode lasers.

In this paper we report a new technique for both high precision wavelength calibration and stabilization of tunable diode lasers. Our procedure is fairly straightforward and can be applied to all the spectroscopic techniques mentioned above. The crucial element is a novel broadband scanning Fabry-Perot interferometer, which should also be of considerable interest in other fields (e.g., dye laser spectroscopy). The concept and design of this instrument are discussed in Sec. II, while Sec. III contains a description of its applications including the wavelength control procedure together with preliminary results.

II. Internally Coupled FPI

A. Basic Idea

Diode laser spectra are usually calibrated with germanium etalons or with air-spaced Fabry-Perot interferometers. Germanium-etalons are simple to handle but somewhat problematic due to their high thermal instability. In addition, their performance is limited to wavelengths shorter than ~15 μm. Air-spaced FPIs, on the other hand, are more stable by 2 orders of magnitude[1] and can be constructed for any desired wavelength by choosing mirrors with appropriate dielectric coatings. However, several pairs of mirrors are required for operation over the entire wavelength range (3–30 μm) of diode lasers because of the small spectral range (a few microns) covered by each dielectric coating; this problem is also encountered in the visible region. A larger spectral range may be covered by mirrors consisting of very thin metal films[12] but such mirrors are difficult to manufacture, thus restricting their wider use.

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These problems are overcome with what we call an internally coupled Fabry-Perot interferometer (icFPI). The basic idea of this instrument is schematically illustrated in Fig. 1.

In conventional etalons radiation is coupled into the cavity through partially transmitting mirrors. Instead, our basic confocal icFPI consists of two ordinary gold-coated spherical mirrors (M_1,M_2) and a beam splitter S which is inserted between them for the purpose of coupling the beams into and out of the interferometer. By choosing a suitable beam-splitter material (e.g., CsI) a very large range of operation (0.6–30 μm) can be achieved.

B. Design

The performance characteristics of the icFPI can be derived with the aid of conventional multiple-beam interference theory. An accurate description requires consideration of reflections and losses (absorption, diffraction, etc.) from both beam splitter surfaces (reflectivity r; transmittivity t) and the resonator mirrors (reflectivity, $R < 1$). The intensities of the reflected I_R and transmitted I_T beams indicated in Fig. 1 are then given by

$$I_R = I_A/[I + f * \sin^2(\delta/2)], \tag{1}$$

$$I_T = I_C - I_B/[1 + f * \sin^2(\delta/2)], \tag{2}$$

with

$$I_A = I_0 * Rr^2/(1 - R^2t^4)^2,$$

$$I_B = I_0 * 2rt[1 - (1 + 2r/t) * (R^2t^4)^2]/(1 - R^2t^4)^2,$$

$$I_C = I_0 * (t^2 + 2rt), \qquad f = 4R^2t^4/(1 - R^2t^4)^2.$$

Here I_0 is the incident intensity, and δ is the phase difference between two successive beams. Equations (1) and (2) correspond to the well-known Airy formulas. However, the transmitted intensity of the icFPI corresponds to the reflected intensity of a conventional FPI and vice versa.

The values of the finesse F^* and the contrast K—here defined as the difference between maximum and minimum intensity divided by the incident intensity—are of some importance for the operation of the icFPI. Using Eqs. (1) and (2) we obtain

$$F^* = \pi/2 * 1/\arcsin[1/(2 + f)^{1/2}], \tag{3}$$

$$K_T = (I_A/I_0) * 1/(1 + 1/f), \tag{4}$$

$$K_R = (I_B/I_0) * 1/(1 + 1/f). \tag{5}$$

As in the previous equations, subscripts T and R denote the transmitted and reflected beam, respectively.

Figure 2 shows the finesse F^* as a function of the parameter R^2t^4, which describes that part of the intensity remaining inside the FPI after the beam has completed one full traversal of the cavity. We simplify the following discussion by neglecting losses at the beam splitter ($r = 1 - t$) and assuming $R = 0.95$, thus leaving the constrasts K_R and K_T as a function of t only. These functions (see Fig. 3) predict a maximum contrast (of nearly 0.6) for the transmitted beam with a

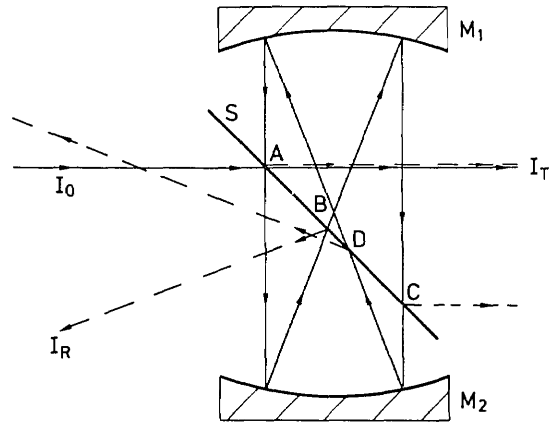

Fig. 1. Principle of a confocal internally coupled Fabry-Perot interferometer. By means of a beam splitter S part of the incident beam I_0 is coupled into the resonator (point A). Running the usual path of a confocal FPI this beam is partially reflected each time it passes points A, B, C, and D. Those partial beams reflected at the same point can be superimposed to obtain the desired interference fringes.

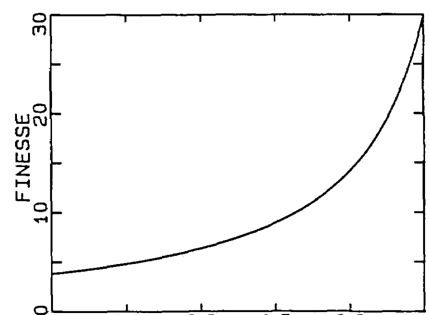

Fig. 2. Finesse F^* of the icFPI as a function of the parameter R^2t^4.

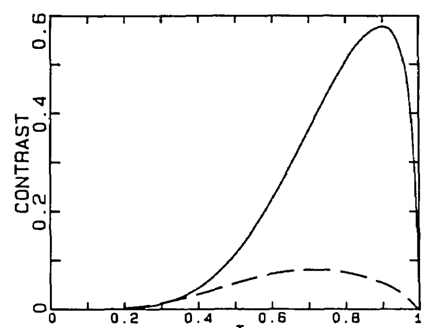

Fig. 3. Contrast of a transmitted (K_t) and a reflected (K_r) beam (compare Fig. 1) as a function of the beam splitter transmissivity t.

beam splitter transmissivity of $t \cong 0.9$, a result that has been confirmed by our experiments. The quoted transmissivity is achieved with the following arrangement of the beam splitter:

beam polarization perpendicular to the plane of incidence;

angle of incidence: 45°;

beam splitter material: NaCl.

The absorption of NaCl beyond 15 μm now determines the long-wavelength limit of our icFPI. With the

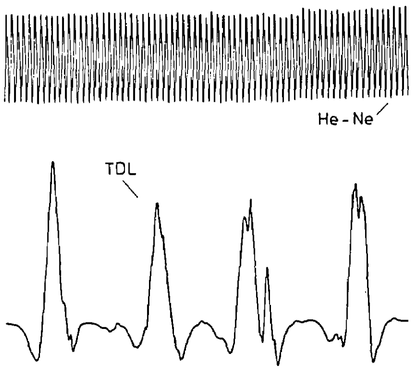

Fig. 4. Internally coupled FPI fringes of a free running diode laser (TDL) and an iodine stabilized He–Ne laser.

quoted specifications ($R = 0.95, t = 0.9$) the theoretical value of the finesse is only ~6, but for our applications (see Sec. III) a high finesse is not important.

To use this FPI as a TDL-frequency stabilizing device, its optical path length must be tunable. Because piezoelectric stacks do not permit mirror travels large enough for this purpose,[2] our icFPI is tuned by a 5-mm thick NaCl Brewster plate which may be precisely rotated by a commercially available scanner.[13] Due to polarization considerations the plane of incidence of the Brewster plate must be perpendicular to that of the beam splitter. The resulting arrangement partially compensates the astigmatism generated by both plates. Such an effect is highly desirable because the astigmatism of a resonator tends to reduce its finesse.

The resonator mirrors (diameters 2.5 cm) are separated by four quartz rods (length 25 cm), and the whole interferometer is operated inside a vacuum tank, resulting in minimal drifts of the optical resonator length l. Possible drifts Δl have been measured by long-time observations of the transmission of an iodine stabilized He–Ne laser to be as low as $\Delta l/l \cong 10^{-6}$/h.

Figure 4 shows the interference fringes of a diode laser ($\lambda = 10\ \mu$m) and a frequency stabilized He–Ne laser ($\lambda = 633$ nm), which have been measured simultaneously. These spectra were obtained by scanning the icFPI, and they demonstrate the broadband performance of our instrument. This figure also clearly shows the frequency jitter associated with a nonstabilized TDL.

III. Applications

A. Passive Calibration

As with conventional Ge etalons the new icFPI may be used for passive calibration of diode laser spectra. The considerably improved stability of the optical resonator length and the low sensitivity of the confocal mirror configuration to the angle of incidence of the beam permit a precise iterative determination of the fringe spacing.

If a starting value of the free spectral range (FSR) has been obtained by counting fringes between two well-known gas absorption lines covered by one laser mode, it can be used to predict the number of fringes between more distant reference lines of different modes to better than a half integer. Thus the fringe number between these lines can be unambigously measured—even in those cases where mode brakes are encountered— and a more precise value of the FSR is obtained. This procedure can be repeated until the systematic error caused by the dispersion of the NaCl plates exceeds the uncertainty of the measurement. Especially in those cases where no high precision reference lines are available, the quoted method is required for exploiting the full potential of a stable FPI. For example, we have recorded six NH_3 lines over four modes in the 900–919-cm^{-1} region. The wave numbers of these lines are given by Urban *et al.*[14] with a precision of $\sim 1 * 10^{-4}$cm^{-1}. A single value of the free spectral range, 0.00944813(22), was found to suffice for calibrating all these modes. The error is mainly due to the error of th NH_3 lines.

Compared to our Ge etalons the precision of the FSR value is improved by more than 2 orders of magnitude. It is, therefore, no longer problematic to use only one reference line for the calibration of several overlapping modes. As a first application we have measured the diode laser spectrum of the ν_6 band of methyl iodide.[15]

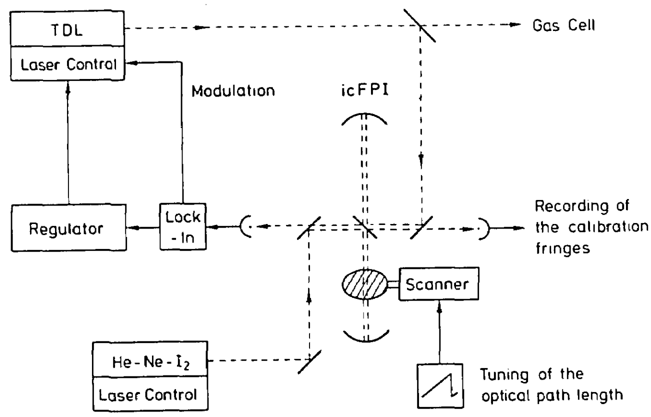

Fig. 5. Block diagram of our new wavelength control system. The diode laser is servo-locked (lock-in amplifier, regulator, laser control) to the tunable icFPI. The fringes of the iodine stabilized He–Ne laser are used for calibrating the TDL wavelength.

B. Frequency Stabilization

As we indicated in Sec. I, the main purpose of the design of our icFPI was the frequency stabilization of diode lasers. This has been performed with a newly constructed system, which is schematically shown in Fig. 5. In addition to the icFPI our system contains an iodine stabilzed He–Ne laser as a reference for very high precision wavelength calibration. As usual first a TDL mode is isolated by a monochromator (not shown in Fig. 5). Then a small portion of the beam is coupled into the interferometer and used for locking the laser to a peak of a fringe by means of a first derivative frequency lock procedure. Tuning of the laser is achieved by varying the optical path length of the icFPI. Simultaneously, a pattern of He–Ne laser fringes is generated, which is used for calibration. A gas absorption spectrum recorded and calibrated with this technique is shown in Fig. 6. $^{192}OsO_4$ was chosen

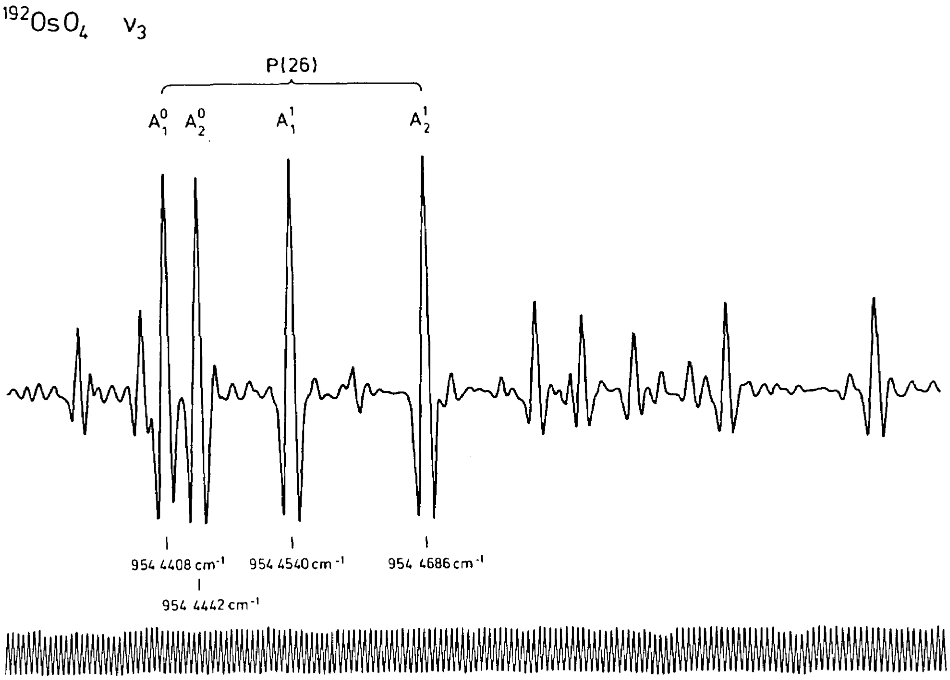

Fig. 6. Part of the ν_3 band of $^{192}OsO_4$ recorded and calibrated with our new technique. The upper trace shows the gas absorption spectrum in second derivative form; below is the fringe pattern of the He–Ne laser, which is used for calibration.

for this example because the transitions show narrow linewidths (~23 MHz for $\lambda = 10\ \mu m$).

The separation $\Delta\nu$ of the calibration fringes is related to the wavelengths of the reference λ_r and the diode laser λ and to the free spectral range F of the icFPI by

$$\Delta\nu = F * \lambda_r/\lambda. \tag{6}$$

In comparison with the usual FPI calibration the fringe spacing is reduced by the wavelength ratio λ_r/λ, which is ~0.06 for the measurement shown in Fig. 6 ($\lambda_r = 633$ nm, $\lambda = 10.5\ \mu m$). This reduction is an additional merit of our system because such close fringes (distance only ~17 MHz in Fig. 6) permit a very precise calibration. A longer icFPI is now under construction to provide even closer fringes for application in sub-Doppler spectroscopy. This new idea of using a reference laser with a much shorter wavelength strictly requires a broadband scanning interferometer such as our icFPI; it cannot be achieved by conventional etalons.

Due to the effects of diffraction, refraction, and imperfect alignment of the two beams, Eq. (6) is not exact. The appropriate corrections are similar to those well known for wavemeters[16–18] and will, therefore, not be discussed in detail here. Also, the spacing $\Delta\nu$ of the He–Ne laser fringes changes when the interferometer is scanned [i.e., $\Delta\nu = \Delta\nu(\lambda)$]. This change is due to the dispersion of the Brewster plate and the variation of the free spectral range in the course of the scan. An exact calibration, therefore, requires an additional measurement: The TDL is stabilized to a gas reference line, and the icFPI is tuned. From the fringe patterns recorded for both lasers and the free spectral range of the icFPI $\Delta(\lambda)$ can be precisely determined for a complete TDL scan.

For the frequency lock procedure we modulate the TDL with 30 kHz. Thus our feed back loop (lock-in amplifier, regulator, laser control module) responds fast enough to suppress most of the diode FM noise including that generated by mechanical vibrations associated with our closed cycle refrigerator. To test the quality of the frequency stabilization, we have observed the slope of OsO_4 absorption lines. The remaining frequency jitter was found to be always considerably less than 1 MHz.

Another demonstration of the performance of our system is given in Fig. 7. Here the same OsO_4 lines as in Fig. 6 were recorded using an unstabilized TDL. Both spectra were obtained with the same diode mounted in an old two-legged style refrigerator and with a negligible lock-in time constant; the only integration was caused by the chart recorder. Besides, the frequency jitter of the diode chosen for this comparison was quite high. Thus the two figures illustrate that even under unfavorable conditions (poor quality diode, old generation cold head, and narrow linewidths) our system produces excellent spectra.

C. Local Oscillator

During the last decade an increasing number of studies[11,19–25] involving the use of diode lasers as local oscillators (LOs) in heterodyn radiometers have been published. A TDL heterodyne radiometer has the potential of high resolution spectroscopy of remote sources in the whole middle IR (3–30 μm), which is not possible with gas laser systems. The instrument may be used for the study of the earth's atmosphere, astronomical sources, etc. and may be operated either ground-based or from a balloon, spacecraft, etc. Although the quoted studies include some examples of

Fig. 7. Same spectrum as in Fig. 6 with the same but unstabilized TDL. For details of the experimental conditions refer to the text.

useful spectra obtained by TDL heterodyne radiometry, this technique is still far from being ready for wider applications. To achieve this goal, a number of improvements are required including a reduction of TDL noise and a supplementary wave number control procedure to fulfill the following specifications:

(1) The LO wave number should be known with a precision better than 10^{-4} cm^{-1}.

(2) Drifts of the LO wave number should be $< 10^{-4}$ cm^{-1}.

(3) Because of the limited mixer bandwidth, it is an advantage when the LO can be operated as close as possible to any desired wave number. This flexibility is essential when several spectral lines are to be observed simultaneously by one heterodyne measurement.

Obviously the simplest procedure is to stabilize the TDL to an absorption line of a reference gas.[24,26] In many cases, however,—especially when the instrument is not operated in a laboratory—appropriate samples for all LO wave numbers desired are not available. A less restrictive method using a reference gas for absolute calibration, a nontunable FPI, high precision fringe interpolation, and a second diode laser locked to a gas absorption line, and measuring the FPI drift has been proposed by Poultney *et al.*,[11] but their procedure is rather complex.

A much simpler method is provided by our new diode laser control system: When the TDL is tuned to the desired wave number, the icFPI is locked to a He–Ne fringe by means of a second feedback loop (not shown in Fig. 5). The TDL is now stabilized to a fixed wave number and ready for use as LO. This method requires only moderate expense, but fulfills all the above specifications.

Because of the small separation of the He–Ne fringes (e.g., 17 MHz in Fig. 6), the TDL can always be stabilized within less than a half Doppler width to any desired wave number. Using a reference gas and the calibration procedure described before, the required precision of the LO wave number determination may

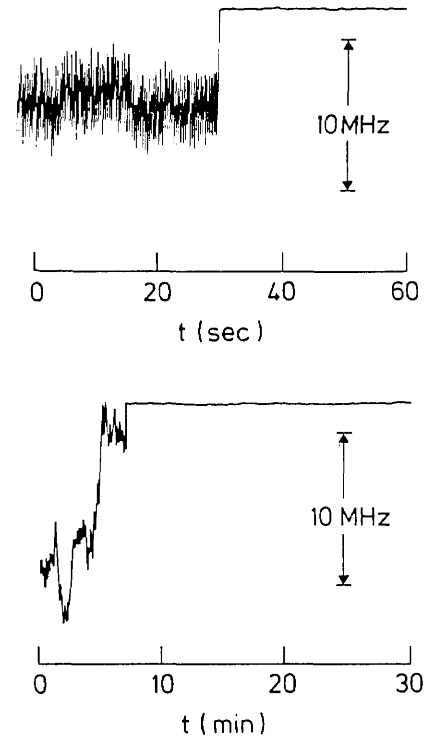

Fig. 8. Short-term and long-term drifts of the TDL stabilized to the He–Ne locked icFPI. The first part of each trace is TDL drift without stabilization. The short-term regularity in the FM period of the unstabilized TDL is caused by the closed-cycle refrigerator. The lock-in time constant was negligible for the short-term trace and 1 sec for the long-term trace.

easily be achieved. The long-term and short-term stability of our configuration has already proved to be excellent. In Fig. 8 typical drift measurements of the TDL with and without the stabilization to the He–Ne locked icFPI are displayed for two different time scales. The measurements were performed with a newest generation cold head and a better diode than those shown in Figs. 6 and 7. It can be seen that the remaining drifts of the stabilized TDL do not exceed a few hundred kilohertz. These drifts are mainly due to differences in the index of refraction of NaCl and its variation with temperature for the two laser wavelengths. In another experiment we have heated the interferometer; the resulting TDL drift was found to be as low as ~100 kHz/°C.

These results have encouraged us to start the development of a TDL heterodyne radiometer using the new stabilization technique.

IV. Conclusion

Our new wavelength control system is a versatile instrument, which we expect to lead to considerable progress in the application of diode lasers to high resolution IR spectroscopy. The achievable calibration accuracy is now determined by several test measurements which will be reported later; however, the accuracy ($\Delta\tilde{\nu}/\tilde{\nu}$) should not be much worse than 10^{-8}. Our technique combines wavelength calibration and stabilization and is thus superior to other high precision calibration procedures (e.g., measuring the heterodyne beat frequency between the TDL and a gas laser line,[27] wavemeters) leaving the TDL frequency jitter unaffected. In addition we feel that the price–performance ratio of our system is comparatively good. In this context it should be noted that the procedures described in Sec. III can also be performed with commercially available frequency stabilized He–Ne lasers[28] guaranteeing a fractional stability of the order of 10^{-8}. These devices have a more rigid mechanical design and are simpler to handle than the iodine stabilized He–Ne laser.

At the present time, we are applying our system to sub-Doppler spectroscopy. We have recently obtained a saturated absorption signal of an OsO_4 line. This signal was probed with the stabilized TDL, while, because of insufficient TDL power, a CO_2 laser had to be used to saturate the sample. Details and results of these experiments will be reported later.

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