DETERMINATION OF OFFSET BETWEEN A FIXED WAVELENGTH LASER AND AN ABSORPTION LINE USING FREQUENCY MODULATION SPECTROSCOPY

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Frequency modulation spectroscopy is used as a new method to determine the detuning or optical frequency offset between a fixed laser line and the center of an adjacent absorption line. Because the offset is measured directly using high precision RF techniques, the accuracy is limited only by the laser linewidth. The method was demonstrated using (a) a dye laser set at a fixed frequency and an etalon resonance and (b) an infrared He-Ne laser and a methane absorption line.

1. Introduction

Determination of the offset between a given fixed laser wavelength and an absorption line is one of the fundamental aims of spectroscopy. In those cases where an auxiliary tunable laser is not available, these offsets are conventionally measured using a spectrometer to directly measure the respective wavelengths. This indirect method shows large errors because it requires precise measurements of the wavelengths of the light. Another method to measure the offset between a given laser line and an absorption line of a gas is to measure the pressure dependence of the absorption cross section at the given wavelength. A least square fit gives the offset from these data. This has been done with several gases, for example, with methane and a He-Ne laser at 3.39 μm [1] or with sulfur dioxide and a deuterium fluoride laser at 3.98 μm [2]. For the application of this method other data about the absorbing gas are required such as the line strength of the adjacent line or the pressure broadening coefficient. To overcome these problems we have applied a new method for direct measurements of line offsets using frequency modulation (FM) spectroscopy.

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2. FM spectroscopy

Frequency modulation (FM) spectroscopy, described in detail in ref. [3] has been proven to be a versatile tool for the detection of small optical absorptions or gains with high spectral [4–7] and temporal [7–9] resolution. Previous applications of FM spectroscopy have utilized a tunable dye laser, externally modulated at fixed radio frequencies (RF). Spectroscopic information was obtained by sweeping the laser frequency. For the offset measurements described in this paper, however, the laser frequency was fixed and spectroscopic information was obtained by sweeping the RF frequency.

Fig. 1 shows the experimental setup for FM spectroscopy. The vertically polarized laser beam is sent into a phase modulator consisting of a single $LiTaO_3$ crystal. The modulator was driven by a RF sweep generator (Hewlett Packard Model 8690B) whose output power was leveled in such a way that the RF power going into the modulator was stable and independent of the RF frequency, ν_{RF}. The leveling loop consisted of a 30 dB amplifier (Mini Circuits Model ZHL 2-8), an output coupler (Mini Circuits Model ZFDC 20-5), a crystal detector (Hewlett Packard 8472A), and the internal leveling circuitry of the 8690B unit. The RF power was monitored at the modulator using a power sensor (Hewlett Packard 8481A) and a power meter (Hewlett Packard 435B).

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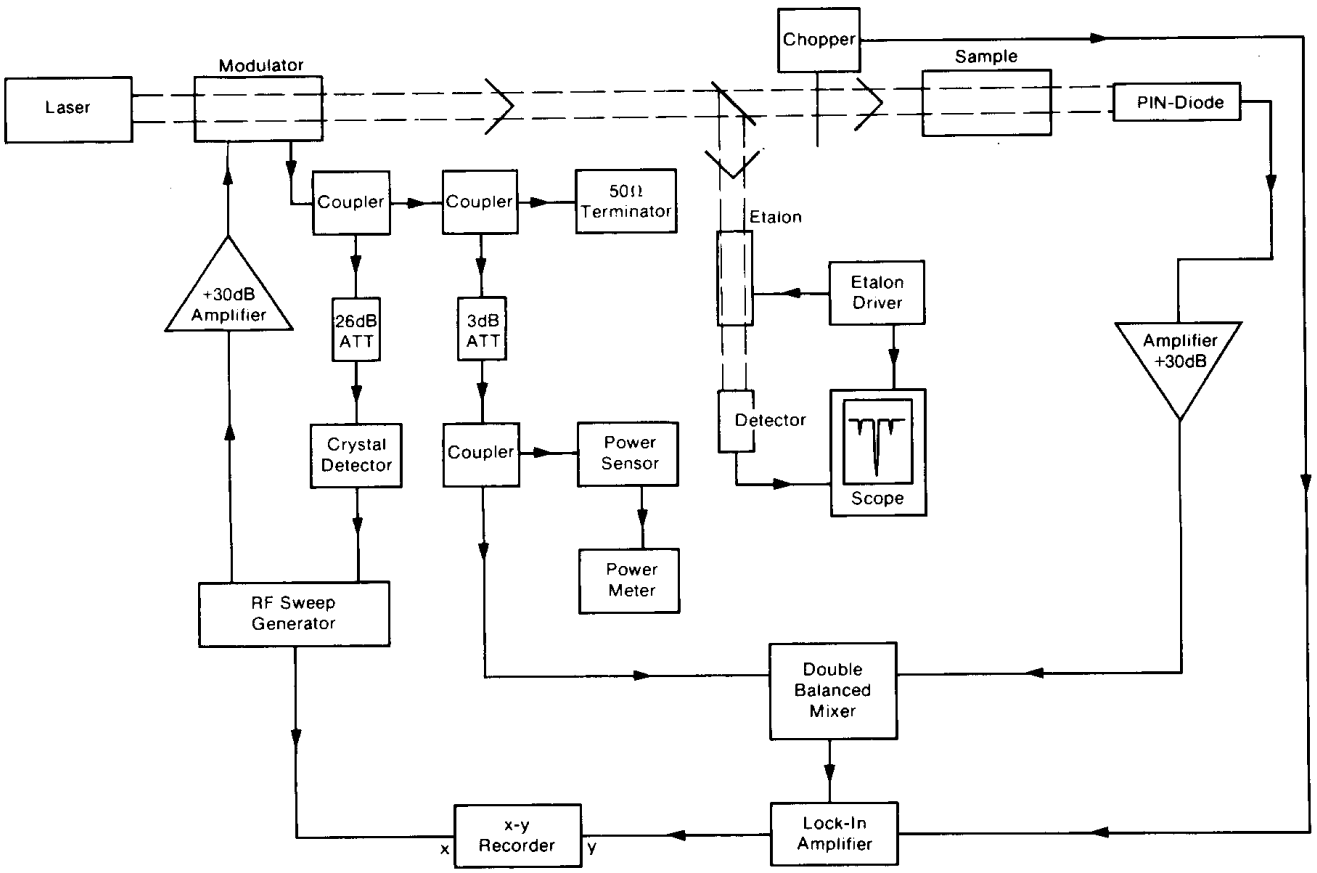

Fig. 1. Experimental setup for FM spectroscopy.

RF power at the modulator was (30 ± 1) dBm, producing a frequency modulated beam consisting of a carrier and two sidebands at frequencies $\nu_0 \pm \nu_{RF}$. The sideband intensity was of about 15% of that of the carrier. A fraction of the beam was detected through a scanning confocal etalon (free spectral range 2 GHz and finesse of 150) for mode and modulation monitoring. The main part of the beam was chopped and passed through a sample containing narrow absorption lines. The light was detected by a fast photodiode (Motorola MRD 510).

The photodiode output was amplified and mixed with a small fraction (7 dBm) of the leveled RF power in a double balanced mixer (Mini Circuits Model ZFM-4). The DC signal from the double balanced mixer is amplified and detected through a low pass filter using a lock-in amplifier and an x–y plotter. The output of the double balanced mixer is a DC signal whose amplitude depends on both the amplitude of the photodiode output and the phase difference between this output and the local oscillator. We have deliberately made the path length difference seen by the two signals large enough that the phase difference oscillates rapidly compared with the variation in photodiode output as the RF frequency is swept. In the limit of small modulation index and weak absorption the FM signal is given by

$$S = S_0[(\delta_- - \delta_+)\cos\varphi_R + (\phi_- + \phi_+ - 2\phi_0)\sin\varphi_R], \quad (1)$$

where $\delta_\pm$ and $\phi_\pm$ are the absorption and phase shifts, respectively, of the laser sidebands at $\nu_0 \pm \nu_{RF}$, ϕ_0 is the phase shift of the carrier, φ_R is the RF phase difference, and S_0 is a constant. An example of such a signal is shown in fig. 2. A simple calculation shows that the envelope of this signal, in the rapid RF phase variation limit, is given by

$$\bar{S} = \bar{S}_0[(\delta_- - \delta_+)^2 + (\phi_- + \phi_+ - 2\phi_0)^2]^{1/2}. \quad (2)$$

For the remainder of the data shown in this paper we have plotted only the envelope.

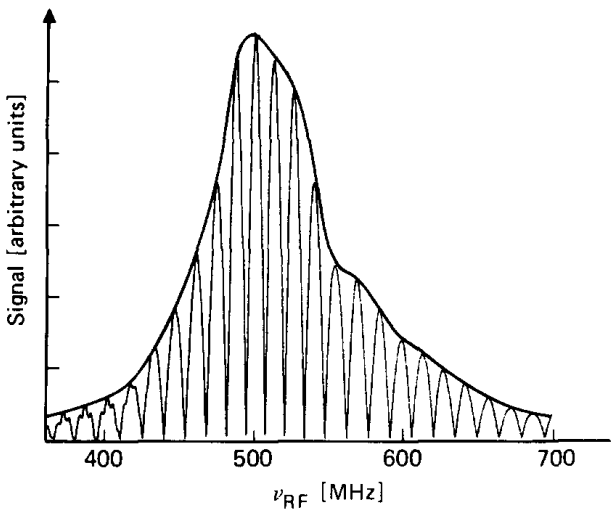

Fig. 2. FM signal of an etalon resonance with the laser tuned 500 MHz away from the resonance frequency. Also plotted is the envelope which would be obtained with phase independent detection of the FM signal.

For theoretical calculations eq. (2) has been used where for the absorption and phase shifts we have assumed a lorentzian form given by

$$\delta(\nu) = \delta_{\text{peak}} [R^2(\nu) + 1]^{-1} , \quad (3)$$

$$\phi(\nu) = \delta_{\text{peak}} R(\nu)[R^2(\nu) + 1]^{-1} , \quad (4)$$

where δ_{peak} is the peak absorption at ν_0 the center of the absorption line and $R(\nu)$ is determined by

$$R(\nu) = (\nu - \nu_0)/(\gamma/2) , \quad (5)$$

where γ is the full width of the line at half maximum.

3. Results

3.1. Etalon experiments

To study the method under controlled conditions an etalon in reflection was used to simulate absorption lines. An etalon in reflection normally acts as a mirror. On resonance the reflection is reduced by about 10%. A confocal etalon was used with a free spectral range of 1.5 GHz and a finesse of 20.

The wavelength of a cw single frequency rhodamine 6G dye laser tuned to 584 nm was set to a fixed offset $\Delta\nu$ from one etalon dip and the RF frequency was slowly swept from 100 to 1000 MHz.

Fig. 3 shows a comparison of the experimental results with theoretical curves which were calculated according to eq. (2) and assuming a lorentzian lineshape for the etalon. $\Delta\nu$ is varied in steps of 100 MHz from almost 0 to 700 MHz. Theoretical and experimental results show reasonable agreement. The decrease of the experimental signal at higher frequencies is due to the high frequency roll off of the photodiode and the signal amplifier.

3.2. Methane experiment

In a practical application, the offset between the He-Ne laser line at 3.39 μm and the nearest methane absorption line was measured using FM spectroscopy. For this experiment the photodiode was replaced by a fast InAs detector (Judson Infrared, Inc. Model J12LD, 0.25 mm i.d.) operating at room temperature. A cell of 25 cm length was filled with 2 Torr of methane. At this low pressure, pressure broadening of the line can be neglected compared to the Doppler broadening. Thus the absorption line has a full width at half maximum of 270 MHz at 293 K.

Fig. 4 shows an FM signal which was obtained from a He-Ne laser with a cavity length of 390 mm (Spectra Physics Model 120). Due to the short cavity the laser sometimes ran single mode and then one single peak was observed.

As the signal depends on the difference between the absorption of the two sidebands and on the different phase shifts it decreased at small RF frequencies and became zero at $\nu_{RF} = 0$. Obviously the laser line was situated within the methane absorption line and thus the offset could not easily be taken from the experimental curve. A least squares fit gave an offset of 56 MHz from the laser line to the center of the absorption line.

Fig. 5 shows an FM signal which was obtained from a He-Ne laser with a 701 mm long resonator (Spectra Physics Model 124B). Laser gain was sufficiently high that at least two longitudinal modes separated by 217 MHz were lasing. The modulated laser spectrum contains sidebands on both modes and two FM peaks could be observed by sweeping the RF frequency. The asymmetric shape of the second peak is due to the roll off of the detector at high frequencies.

From the plotted curves a least squares fit gave offsets of 182 MHz and 427 MHz. The difference be-

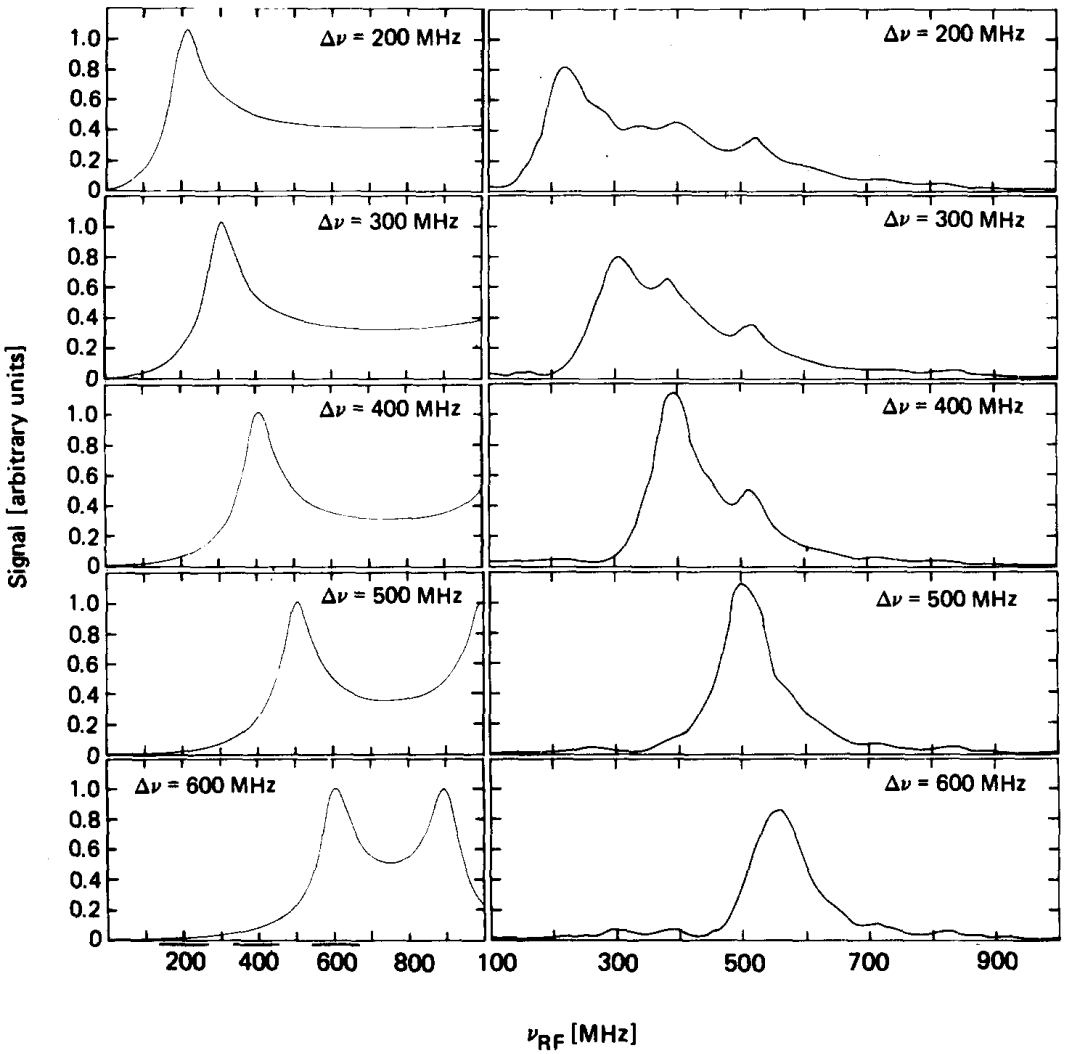

Fig. 3. FM signals from an etalon with FSR = 1.5 GHz and finesse of 20 in reflection with fixed laser wavelength and the RF frequency varied. Comparison of theoretically calculated values with experimental data. The wavelength difference $\Delta\nu$ between laser line and the center of the etalon dip is varied from 0 to 700 MHz in 100 MHz steps.

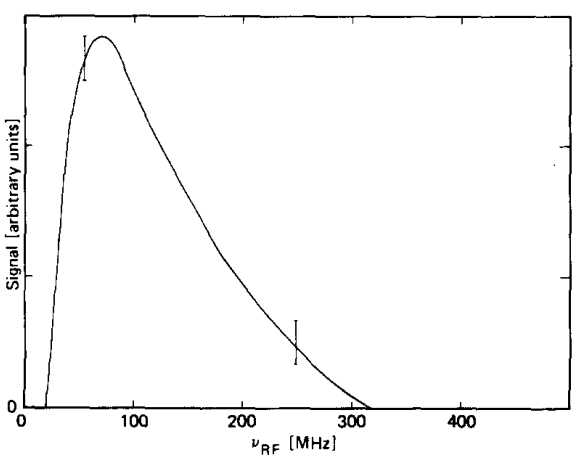

Fig. 4. FM signal from a methane absorption line at 3.39 μm obtained from a single mode He-Ne laser by sweeping the RF frequency. A least square fit gives a line offset of 56 MHz.

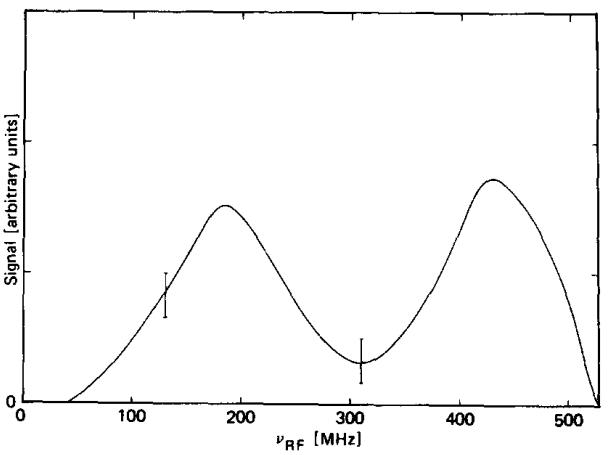

Fig. 5. FM signal from a methane absorption line at 3.39 μm obtained from a multimode He-Ne laser with 277 MHz mode distance by sweeping the RF frequency. A least square fit gives line offsets of 182 MHz and 427 MHz.

tween these two values is 245 MHz and a little bigger than the mode distance of 217 MHz which would be expected. This discrepancy may have been caused by laser frequency drift during the san.

Unfortunately the gain of the He-Ne discharge is very high at 3.39 μm and thus laser action can occur anywhere within the gain profile which has a width of 340 MHz. With the FM spectroscopy described above it is only possible to determine the offset between the actual laser emission line to the center of the absorption line without determining the sign of the offset. The experiment was repeated 10 times and offsets between 14 and 430 MHz were observed. A suitable averaging of these data yielded an offset of (150 ± 100) MHz between the center of the He-Ne gain profile at 3.39 μm and the center of the adjacent methane absorption line. This is in good agreement with previous work which gave (90 ± 60) MHz obtained by a least square fit of the pressure dependence of the absorption cross section [1].

4. Conclusion

A new technique to measure offsets between a narrow laser emission line and an adjacent absorption line using FM spectroscopy was demonstrated. The great advantage of this method is that the offset is measured directly. The precision of the measurements relies on the determination of the RF frequency and the stability of the laser wavelength. This can be better than 1 MHz.

On the other hand it is only possible to perform the measurements on very narrow lines with offsets limited by the RF equipment available. Our experiments were limited to offsets of less than 1 GHz. With the availability of phase modulators and fast detectors with bandwidths up to 30 GHz [10–12] the present technique can be readily extended to measure broad absorption profiles and pressure broadening coefficients.

Acknowledgement

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