Frequency Sweep Calibration

In order to make quantitative measurements of the hyperfine splittings and compare these measurements to the handbook data, it is essential to calibrate the frequency sweep of the laser. This is accomplished with an unamplified Michelson interferometer shown as part of Figure 3.

Density of the gas is extremely small, the effect is greatly enhanced by the 8-9 resonance where these measurements are made.

The experimental setup is shown in Figure 10. The Mach-Zehnder interferometer is used to measure the refractive index. Here, the input laser light is first split by a beamsplitter, and the beams travel down different paths through the interferometer. They are then recombined at a second beamsplitter. The intensity at the photodiode is sensitive to the relative phase of the two beams as they interfere in the second split.

The interferometric data and the calculated theoretical curves are shown in Figure 11.

Resonant Faraday Rotation

These students familiar with the small magnitudes of the Faraday rotation in bulk condensed matter might assume it would be impossible to detect the effect in a much more dilute gas sample. The following experiments with magnetic field in gas might even amaze them.

The reason for this large effect is the presence of a magnetic field in the rubidium absorption and dispersion responses that occur near the atomic resonances D3 line at 889.95 GHz.

Professor David Van Baak, another of TeachSpin’s collaborating scientists, has published (AJP 64) a detailed theoretical explanation of this phenomenon. The magnetic field is used to resolve the Zeeman splitting of one of the Doppler-free transitions with the same setup (Figure 5), but using circularly polarized pump and probe light. The splitting is observed via the sum of the splitting in the excited and ground states. The inset in Figure 14 shows the D-F splitting of one of the Doppler-free transitions with the same setup (Figure 5), but using circularly polarized pump and probe light. The splitting is observed via the sum of the splitting in the excited and ground states.

The experimental setup (Figure 10) is the same, but the magnetic field is used to resolve the Zeeman splitting of one of the Doppler-free transitions with the same setup (Figure 5), but using circularly polarized pump and probe light. The splitting is observed via the sum of the splitting in the excited and ground states.

The Zeeman splitting is greatly enhanced by the S parameter.

The experimental setup is shown in Figure 10. The Mach-Zehnder interferometer is used to measure the refractive index. Here, the input laser light is first split by a beamsplitter, and the beams travel down different paths through the interferometer. They are then recombined at a second beamsplitter. The intensity at the photodiode is sensitive to the relative phase of the two beams as they interfere in the second split.

The interferometric data and the calculated theoretical curves are shown in Figure 11.

Below, Figure 13 shows the experimental data as well as the theoretical predictions using Van Baak’s model.

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DIODE LASER SPECTROSCOPY

INTRODUCTION

Spectroscopy can be broadly defined as the study of the interaction of electromagnetic radiation with matter. Since its discovery, it has become a fundamental tool in experimental and theoretical physics. Originally, spectroscopy was confined to examining the interaction of visible light with gases. With the development of new atomic, molecular, and solid-state techniques, spectroscopy took center stage in verifying the predictions of this radical theory.

Fig. 1: Rubidium Atomic Energy Level Diagrams

Fig. 2: The Diode Laser Head

However, there appeared to be an intrinsic limit to the precision of a spectroscopic measurement of gases. This arises from the motion of the atoms in any gas which Doppler broadens both the absorption and emission lines of the spectrum. For a typical gas at room temperature, this broadening is 

\[ \Delta \nu = \frac{V}{c} \frac{\lambda}{\lambda_0} \]

where \( \Delta \nu \) is the lifetime-limited linewidth of the Doppler D line in air, \( V \) is the velocity of the gas, \( c \) is the speed of light, and \( \lambda_0 \) is the transition wavelength.

The centerpieces of the apparatus is the grating-stabilized diode laser. Herein to research quality by our unique feedback system, the laser is temperature and current regulated. Optical feedback from a grating, retroreflects laser light to create an external cavity that stabilizes the laser to run at a controlled wavelength. A piezo-motor, moveable in the feedback loop, allows the grating position to be changed by an applied voltage. Using the internal ramp generator to modulate both the laser current and piezo-stack, students readily achieve laser sweeps of 10-GHz.

Fig. 3: Block Diagram for Transmission Spectroscopy

The frequency-sweep laser light is passed through a cell containing a rubidium vapor and the transmitted light is detected. Data for natural rubidium is shown in Figure 4.

Fig. 4: Transmitted Light vs. Laser Frequency

The breadth absorption peaks observed by this method are observed as the ground state F = 2 transition of 85Rb and the excited 5P 3/2 state of both isotopes. The 85Rb and 87Rb states are designated as a and b, and the energy level diagram in Figure 3.

A CCD camera connected to a TV monitor is used to observe the infrared fluorescence which occurs when the laser is properly tuned to these transitions. This is the most sensitive detection method in use today. The reflection at the second interface of beam 2, with the 87Rb rubidium cell is in resonance with the other transition.

Now the fun begins. The students rearrange the apparatus so that the single laser beam is split into two co-linear beams, a probe (weak), which are sent through the Doppler-Free Spectroscopy system specifically designed for the advanced teaching laboratory.

Fig. 5: Block Diagram of Doppler-Free Spectroscopy

The pump and probe beams interact with the atoms having longitudinal velocity. Because the much stronger pump beam "autotunes" during the sweep, students observe the laser, at reaching Doppler 1 increases, producing the natural fluorescence shown in Figure 6.

Fig. 6: Narrow Features Indicate 5P 3/2 Hyperfine Structure

Given the Doppler width of about 10 MHz, the resonant states of both isotopes, Doppler broadening becomes the far smaller hyperfine splitting of the excited state.

Doppler-Free Spectroscopy

Now the fun begins. The students rearrange the apparatus so that the single laser beam is split into two co-linear beams, a probe (weak) and a pump (strong), which are sent through the cells respectively containing the rubidium vapor and the probe. The two beams interact with the atoms moving with different velocities, so that the pump beam has no chance to overlap the probe beam in resonance with the other transition.

Fig. 7: Block Diagram of Doppler-Free Spectroscopy

As the laser sweeps through an actual transition frequency, both pump and probe beams interact with the atoms having longitudinal velocity. Because the much stronger pump beam "autotunes" during the sweep, students observe the laser, at reaching Doppler 1 increases, producing the natural fluorescence shown in Figure 6.
DIODE LASER SPECTROSCOPY

INTRODUCTION

Spectroscopy can be broadly defined as the study of the interaction of electromagnetic radiation with matter. Since its discovery, it has been a cornerstone of experimental and theoretical physics. Originally, spectroscopy was confined to examining the interaction of visible light with gases. With the development of high-speed, high-voltage, semiconductor diode lasers, this has opened up new avenues of research.

However, there appeared to be an intrinsic limit to the precision of a spectroscopic measurement of gases. This arises from the motion of the atoms in any gas, which Doppler-broadens both the absorption and emission lines of the spectrum. For a typical gas at room temperature, this broadening is about 10 GHz. This arises from the motion of the atoms in any gas, which Doppler-broadens both the absorption and emission lines of the spectrum. For a typical gas at room temperature, this broadening is about 10 GHz.

STUDENT EXPERIMENTS

Diode Laser Characteristics

The diode laser used for these experiments can be tuned over a range of about 10 GHz. It can be turned on and off with an applied voltage. The current to the laser must be regulated and controlled. A piezo stack, mounted in the laser, allows the laser to be tuned to different frequencies. The output of the laser is very intense, so the pump beam has no effect on the sample. Students can begin these labs by studying the laser itself. Without the grating feedback, they can examine the threshold current for lasing and the wavelength as a function of laser temperature. The wavelength can be measured with a holographic spectrometer or any commercial spectrometer already on hand. Students can also observe mode hopping in the laser.

Classic Laser Spectroscopy

The simplest form of optical spectroscopy, transmission spectroscopy, is shown in Figure 3. The laser output is sent to a room-temperature vapor cell, which contains the gas under study. The light is then split into two beams: the absorption beam and the reference beam. The absorption beam interacts with the gas, while the reference beam passes through an empty cell. The two beams are then recombined and detected. The transmission of the two beams is then measured, and the difference is used to determine the gas concentration.

Doppler-Free Spectroscopy

As the laser sweeps through an actual transition, the frequency difference between the upper and lower levels changes. This change is caused by the Doppler effect, which shifts the frequency of the light emitted by the atoms. This effect can be eliminated by using a technique called Doppler-free spectroscopy. In this technique, the laser is tuned to a transition that is not affected by the Doppler effect. The laser is then slowly swept through the transition, and the change in the absorption is measured. The absorption is then used to determine the concentration of the gas.

Figure 7 shows the module controller. The module can be used for both research and teaching. It is easy to operate, and has been used in a number of different laboratories. The module is configured to provide the laser light from the cell, and the reference beam from the sample. The two beams are then recombined and detected. The transmission of the two beams is then measured, and the difference is used to determine the gas concentration.

The frequency-sweep laser light is passed through a cell containing a rubidium vapor and the transmitted light is detected. Data for natural rubidium is shown in Figure 4.

Doppler-Free spectroscopy can be used for both research and teaching. It is easy to operate, and has been used in a number of different laboratories. The module is configured to provide the laser light from the cell, and the reference beam from the sample. The two beams are then recombined and detected. The transmission of the two beams is then measured, and the difference is used to determine the gas concentration.

Figure 8 shows this result dramatically for the ground state D2 transition of 85Rb. Linewidths of about 10 MHz, these features represent a resolution (Δf) of about one part in forty million!
Diode Laser Spectroscopy

Introduction

Spectroscopy can be broadly defined as the study of the interaction of electromagnetic radiation with matter. Since its discovery, it has been an area of intense activity, both experimental and theoretical. Originally, spectroscopy was confined to examining the interaction of visible light with gases. With the development of new techniques, spectroscopy has taken center stage in verifying the predictions of this radical theory.

Figure 1 shows the modulation controller. The modulator can be interrogated independently, allowing exploration of the effects of changing a wide variety of parameters. Students turn dials to control the laser current and temperature, the laser’s rf output, the temperature, the piezo stack, and the ramp generator. Signals from two detectors are sent simultaneously to the controller, allowing the students to observe the effects of changing one parameter at a time. The six peaks seen in Figure 8 include three additional transitions, each corresponding to a separate ground state F = 0, ±1 selection rule. The energy level diagram of 85Rb (Fig. 5), implies that there are six peaks, not six, transitions from F = 2. Since the much stronger pump beam “saturates” any hyperfine splitting of both isotopes, Doppler broadening obscures the far smaller hyperfine splitting of the excited state.

Doppler-Free Spectroscopy

Now the fun begins. The students rearrange the apparatus so that the single laser beam is split into two co–linear beams, a probe (weak) and a pump (strong). These are directed at the rubidium cell in opposite directions. Figure 3 shows a block diagram of the apparatus. The optical configuration and the front cover is a photograph of this setup. The pump beam and a second reference probe beam are detected. For most frequencies within the Doppler range, the pump and probe do not interact with the atoms moving with different velocities, so the pump beam has no effect on the transmitted intensity of the probe.

Reflection at the second interface of beam splitter produces the reference laser which does not overlap the pump beam as it passes through the vapor on its way to Detector 2. The electronics of the controller allows us to subtract these beams from the probe beam, removing the Doppler background effect. Figure 3 shows this result dramatically for the ground state F = 2 transition of 85Rb. linewidths of about 10 MHz, these features represent “actual” transitions of about one part in forty million!

Figure 4 shows the transmitted light-voltage characteristic. If we take the rubidium fluorescence with the CCD camera. A separate power supply is used to provide a 10 mT magnetic field along the optical path with a Helmholz pair of coils surrounding the rubidium cell, provides the rubidium reservoir. The oven is heated, it produces no measurable ac or dc magnetic field at the sample. The heater is designed to keep the temperature of the oven constant within ± 0.01°C. The oven is connected to a temperature controller so that the single laser beam is split into two co–linear beams, a probe (weak) and a pump (strong). These are directed at the rubidium cell in opposite directions. Figure 3 shows a block diagram of the apparatus. The optical configuration and the front cover is a photograph of this setup. The pump beam and a second reference probe beam are detected. For most frequencies within the Doppler range, the pump and probe do not interact with the atoms moving with different velocities, so the pump beam has no effect on the transmitted intensity of the probe.

DIODE LASER SPECTROSCOPY

INTRODUCTION

The centerpiece of the apparatus is the grating–stabilized diode laser. Hereford to research quality by our optical physicists, the laser is both temperature and current regulated. Optical feedback from a diffraction grating, mounted on the laser’s external cavity, stabilizes the laser at a controlable wavelength. A piezo stack, mounted on the laser housing, allows the laser frequency to be swept from a grating, retroreflects laser light to create an interferometer in the laser. Without the grating feedback, the laser is temperature, the piezo stack, and the ramp generator. Signals from two detectors can be balanced, allowing the apparatus so that the single laser beam is split into two co–linear beams, a probe (weak) and a pump (strong). These are directed at the rubidium cell in opposite directions. Figure 3 shows a block diagram of the apparatus. The optical configuration and the front cover is a photograph of this setup. The pump beam and a second reference probe beam are detected. For most frequencies within the Doppler range, the pump and probe do not interact with the atoms moving with different velocities, so the pump beam has no effect on the transmitted intensity of the probe.

However, there appeared to be an intrinsic limit to the precision of a spectroscopic measurement of gases. This arises from the motion of the atoms in any gas which Doppler-broadens both the absorption and emission lines of the spectrum. For a typical gas at room temperature, this broadening is $\Delta \nu = V/2C$ GHz where the lifetime-limited linewidth of the rubidium D line is about 6 MHz, a factor of 200 smaller. This problem can be remedied if the laser frequency can be controlled to within a few kilohertz of the atomic transition frequency. Precision of a spectroscopic measurement of gases.

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Frequency Sweep Calibration

In order to make quantitative measurements of the hypersensitive transitions and compare these measurements to the handbook data, it is essential to calibrate the frequency sweep of the laser. This is accomplished with an unstructured Michelson interferometer shown as part of Figure 5.

Straylight measurement of the pathlength difference, ΔL = L1 - L2, can be used to calibrate the frequency sweep in Hz/fringe. The optical frequency difference, Δf, between two successive maxima will be $f = 2\pi/\Delta L$. For our layout, where $\Delta L \approx 0.35\text{ m}$, the sweep calibration is 429 GHz/fringe. The difference between the marked features of Figure 9 is then 6.65 ± 0.2 GHz.

Below, Figure 13 shows the experimental data as well as the theoretical predictions using Van Bank’s model.

Resonant Faraday Rotation

These students familiar with the small magnitudes of the Faraday rotation in both condensed matter might assume it would be impossible to detect the effect in a much more dilute gas sample. The following experiments with microwave absorption of rubidium gas might even amaze them. The reason for this large effect is the magnetic field. The inhomogeneous magnetic field produces the absorption and dispersion response that occur near the atomic resonance D2 line at 780 nm. The magnetic field is used to resolve the Zeeman splitting.

Below, Figure 13 shows the experimental data as well as the theoretical predictions of the Zeeman splitting.

Spectroscopy, and much More, Using Modern Optics

• Observe Doppler-Free Spectroscopy of Rubidium Gas
• Michelson Interferometer Used to Calibrate Laser Sweep
• Observe Resonant Faraday Rotation in Rubidum Vapor
• Measure Temperature Dependence of Absorption and Dispersion Coefficients of Rubidum Vapor
• Lock Laser to Rubidum Hyperfine Transition
• Study Zeeman Splitting in Rubidum Spectrum at Two Wavelengths
• Study Stabilized Diode Laser Characteristics
Density of the gas is extremely small, the effect is greatly enhanced by the 5→6 resonance when these measurements are made.

The experimental setup is shown in Figure 10. The Mach-Zehnder interferometer is used to measure the refractive index. Here, the top laser light is first split by a beamsplitter, and the beams travel down different paths through the interferometer. They are then recombined at a second beamsplitter. The intensity of the interferogram is sensitive to the relative phase of the two beams as they interfere at the second splitter.

The interferometric data and the calculated theoretical curves are shown in Figure 11.

Resonant Absorption and Reflective Index

These students familiar with the small magnitude of the Faraday rotation in both condensed matter might assume it would be impossible to detect the effect in a much more dilute gas sample. The following experiments with microwave gas of low intensity may prove even more surprising. The reason for this large effect is the significant difference between the refractive index and absorption of the gas. The absorption and dispersion responses that occur near the atomic resonance are amplified by the Faraday rotation.

Professor David Van Baak, another of the Marquette University faculty that has had much to do with this collaboration since the student's research, has published [AP 844] a detailed theoretical explanation of this phenomenon. It turns out that the simple theoretical model of the atomic-light interaction is accessible to advanced undergraduate majors. The complete instrument includes all the essential components necessary to perform these measurements. Figure 12 is a block diagram of the apparatus.

Zeeman Splitting

The magnetic field is used to resolve the Zeeman splitting of one atomic line. Doppler broadening remains with the same setup (Figure 5), but circularly polarized pump and probe light. The splitting observed is the sum of the splitting in the excited and ground states. This is illustrated in Figure 13 shows the D1 spectrum from Rb D2 line at 795 nm. The spectrum of the "2P, F=2→0, mF=1" transition for different magnetic field values is also shown. This line was chosen because it is well separated from other absorptions, allowing for uncomplicated observation of the Zeeman splitting.

Below, Figure 14 shows the experimental data as well as the theoretical predictions using Van Baak's model.