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Refractive index measurements by probe-beam deflection

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Abstract. Two deflection techniques for the measurement of the dispersive properties of an optical medium have been implemented. Prismatic deflection is used to measure the dispersion of a medium exhibiting Electromagnetically Induced Transparency (EIT) with the $5S_{1/2} - 5P_{3/2} - 5D$ cascade system in ^{85}Rb and ^{87}Rb. In addition, the dispersion associated with a saturated absorption and hyperfine pumping spectrum is measured by deflection due to a spatial inhomogeneity of the refractive index induced by an expanded Gaussian-profile pump beam.

PACS. 39.30.+w Spectroscopic techniques – 33.55.Ad Optical activity, optical rotation; circular dichroism

1 Introduction

Direct measurement of optical dispersion is both of fundamental interest, for example relating to the phenomena of "slow" [1] and "trapped" [2] light in media exhibiting Electromagnetically Induced Transparency (EIT) [3,4], and in application providing a reference for active stabilization of a laser frequency [5]. In the case of laser locking, an advantage of measuring the dispersion directly is that the laser frequency does not have to be "dithered" [6] to obtain an error signal. Other dither-free techniques include polarization spectroscopy [7,8]; the dichroic atomic vapour laser lock (DAVLL) [9]; a combination of saturated absorption and DAVLL [10,11]; and Sagnac interferometry [12,13]. However, direct measurement of optical dispersion typically requires an actively stabilised interferometer [14], therefore simpler alternatives would be extremely useful. Dispersive signals typically have higher signal to noise ratios which can be important in sensor-type application where sensitivity is an issue.

In this paper, we develop two simple techniques to measure the dispersion of a medium, both based on deflection of a probe beam. First, we apply prismatic deflection [15], to study the dispersion of a medium exhibiting EIT. Second, we measure the deflection of a probe beam due to a spatial inhomogeneity in the refractive index induced by a Gaussian-profile pump beam. This technique is applied to measuring the dispersion associated with a saturated absorption/hyperfine pumping spectrum, however, both techniques are generally applicable to the measurement of any dispersive spectrum.

The paper is organised as follows: Section 2 outlines the theory of the rapid variation with frequency of the refractive index in pump-probe spectroscopy; in Section 3 we discuss the experimental details, present the results and discuss their significance; finally, Section 4 concludes our findings and presents possible extensions to this work.

2 Non-linear spectroscopy

In this section we discuss two types of Doppler-reduced non-linear spectroscopy; first EIT, and then saturation/hyperfine pumping spectroscopy. EIT is an interference phenomenon whereby the absorption of a medium as measured by a weak probe is reduced drastically by the presence of a pump beam coupled to one of the probed states. Typically there is a rapid change of absorption (sub-Doppler features, even sub-natural linewidth features are possible) within a wide Doppler-broadened background. There is a concomitant rapid variation in the refractive index of the medium. The group velocity of light can be written as [16] $v_{\rm gp} = c/(n + \omega dn/d\omega)$, where c is the speed of light, n the refractive index and ω the angular frequency of the light. Our work is conducted with room temperature Rb vapour, for which the refractive index is $n - 1 \approx 10^{-6}$. Strong modification of the absorption of the medium (EIT) in the cascade system is only observed if the two laser frequencies maintain the two-photon resonance condition. The EIT resonance is only observed over a narrow frequency width as the probe laser frequency is scanned with the pump laser's frequency fixed. The medium can be modelled as having a complex dielectric constant, dependent on the strength of the pump beam. As the refractive index of a vapour is close to unity, the Kramers-Kronig formulae [17] can be used to relate the absorption coefficient (proportional to the imaginary part of the dielectric constant) to the refractive index (proportional to the real part of the dielectric constant). Therefore

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the rapid variation of the absorption of an EIT resonance is associated with a rapid spectral variation of the refractive index. This rapid variation of the refractive index can yield substantial reductions in the group velocity of the medium. It is this frequency dependence of the refractive index that we wish to investigate in this work.

We study the dispersion features associated with the EIT cascade system, $5S_{1/2} - 5P_{3/2} - 5D_{3/2,5/2}$, in ^{85}Rb and ^{87}Rb. This example is known to display a complex dispersion feature due to the hyperfine structure of the 5D state [18,19], and is expected to display a rich dispersive spectrum.

We have also investigated another type of non-linear pump-probe spectroscopy which yields rapid variation of the absorption with the laser frequency. Saturated absorption and hyperfine pumping features are generated on the D_2 lines of alkali metal atoms if two laser beams of the same frequency overlap and counter-propagate through a cell [20]. Conventionally the weaker beam, the probe, is detected on a photodetector, and its transmission measured as the laser frequency is swept across a resonance. For an alkali metal atom with nuclear spin, I, there are two hyperfine ground states: $F = I + 1/2$ and $F = I - 1/2$. For Rb, the atom used in the work presented here, there are two stable isotopes (^{85}Rb, $I = 5/2$; ^{87}Rb, $I = 3/2$) with the hyperfine splitting of the ground-states (3.0 GHz for ^{85}Rb, 6.8 GHz for ^{87}Rb) exceeding the room temperature Doppler width (500 MHz), whereas the excited state hyperfine splitting is less than the Doppler width. So the absorption spectrum consists of four isolated Doppler broadened absorption lines. The counter-propagating pump beam introduces sub-Doppler absorption features. There are three excited state resonances coupled to the ground state via electric dipole transitions, namely $S_{1/2}(F) \rightarrow P_{3/2}(F' = F + 1, F, F - 1)$. In addition, one observes three cross-over resonances, appearing halfway in frequency between each pair of conventional resonances [21]. Consequently, based on the Kramers-Kronig relations between absorption and refractive index, we expect the refractive index spectrum to exhibit six sub-Doppler peaks on top of a broad background, arising from hyperfine pumping, for each of the four lines.

3 Experimental details and results

The prismatic deflection measurements were performed using the apparatus shown schematically in Figure 1. The set-up comprised a pump and a probe beam nearly counter-propagating through a vapour cell with a square cross-section. The probe laser with wavelength 780 nm was attenuated such that less than 1 mW was incident on the cell at angle of 45°. The pump laser had a power of 35 mW at a wavelength of 776 nm. Both beams had a spot size of approximately 1 mm, and crossed in the cell at an angle of 10 mrad. For small variations in refractive index of the vapour induced by the coupling beam, Δn, the angular deflection of the probe beam is given by $\Delta\theta = 2\Delta n$. This angular displacement is mapped into a

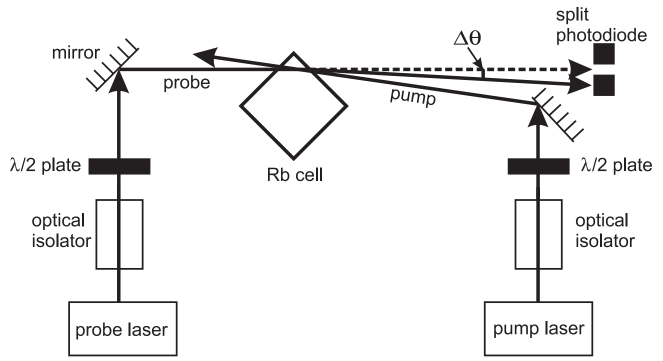

Fig. 1. The experimental set-up used to measure the beam deflection associated with an EIT resonance in a Rb vapour cell. The pump beam, resonant with the $5P_{3/2} \rightarrow 5D_{3/2,5/2}$ transition, induces a refractive index change which is detected by deflection of a probe beam resonant with the $5S_{1/2} \rightarrow 5P_{3/2}$ transition. The deflection is measured as a displacement on a split photodiode.

translation by allowing the probe beam to propagate a length, L, and measuring the difference between two segments of a split-photodiode (Hamamatsu S6058 Si PIN quadrant photodiode with a spacing between segments of 10 μm). Summing the signals from the two sides yields the absorption spectrum of the probe. Schlesser and Weis have demonstrated that beam displacements of the order of a nm are detectable with a split photodiode [22]. For a length, L, of the order of 1 m, with our setup this would correspond to an ultimate sensitivity of refractive index variation of 1 part in 10^9.

The probe beam frequency was scanned through the $5S_{1/2}(F = 2) \rightarrow 5P_{3/2}(F' = 3)$ transition for ^{87}Rb, and the $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 4)$ transition for ^{85}Rb. The pump beam frequency was tuned to resonance between the upper F state of the $5P_{3/2}$ level and both the $5D_{3/2}$ and $5D_{5/2}$ levels. Typical results are shown in Figure 2. The traces show the difference signal which measures the refractive index, the rapid variation with respect to the Doppler profile being a consequence of the enhanced transmission on the $5S_{1/2} \rightarrow 5P_{3/2}$ transition when the coupling beam is resonant with $5P_{3/2} \rightarrow 5D$ transition. The width of the features in these spectra are governed by many factors [18], including: the linewidths of the 5P and 5D states, which are $\Gamma_2 = 2\pi \times (5.9\text{ MHz})$ and $\Gamma_3 = 2\pi \times (0.5\text{ MHz})$, respectively; additional contributions to the linewidths arise from the finite laser beam crossing angle, the laser linewidths and power broadening. Note also that even for perfectly counter-propagating beams the transition is severely Doppler-reduced, but not Doppler-free, on account of the wave-vector mismatch between the coupling and probe beams. The sum signal corresponding to the EIT modified absorption signal is identical to the spectra obtained in our previous work [18]. The difference signal was calibrated by translating the split photodiode using a translation stage, such that the output signal for a given beam displacement is known. This is converted to a refractive index change using Snell's law. For the data shown, the maximum refractive index variation

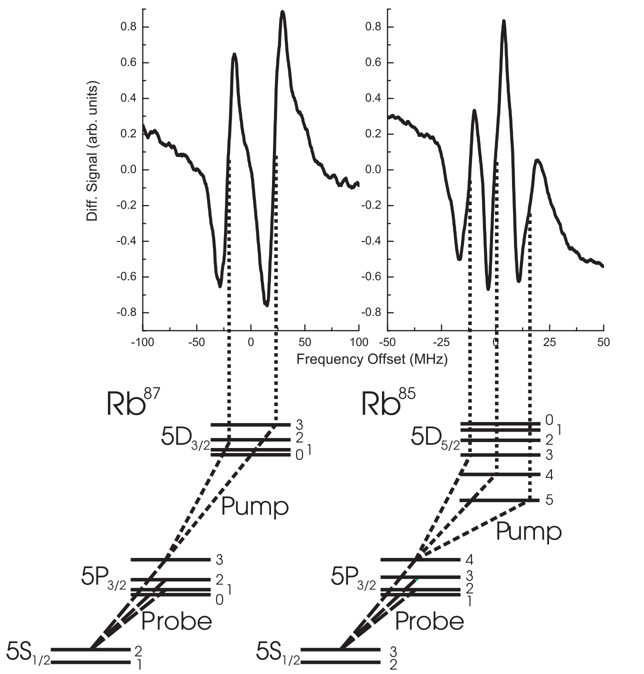

Fig. 2. The difference signal obtained from the split-photodiode for (left) the $5S_{1/2} - 5P_{3/2} - 5D_{3/2}$ cascade system in ^{87}Rb and (right) the $5S_{1/2} - 5P_{3/2} - 5D_{5/2}$ cascade system in ^{85}Rb. The difference signal measures the refractive index change. The energy level diagrams (not to scale) show the relevant transitions.

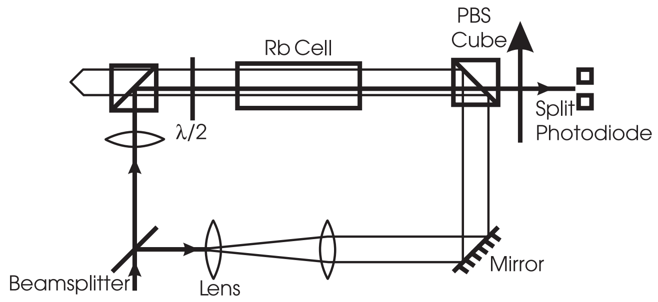

Fig. 3. The experimental set-up used to measure the beam deflection associated with a spatial inhomogeneity of the refractive index. The axes of the pump and probe beam are displaced by translating the second polarising beamsplitter cube (PBS) as indicated.

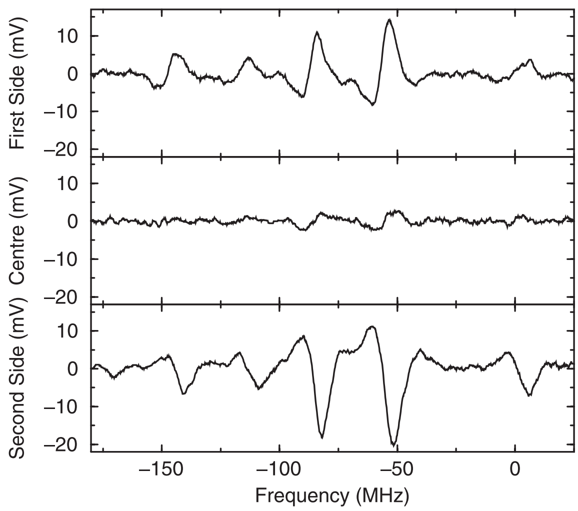

Fig. 4. The deflection signal for the offset saturated spectroscopy set-up illustrated in Figure 3. The pump and probe beam axes are offset by approximately +1 mm (top), 0 mm (middle) and −1 mm (bottom). The asymmetry in the signal size between the two sides is the result of beam imperfections. The slowly varying background due to differential hyperfine pumping has been removed.

was 1 part in 10^6. It is worth noting that the effect of the hyperfine splitting in the 5D state creates regions of sub- and super-luminal group velocity in close proximity. Such an effect could create new possibilities in the control of light pulses [16].

The deflection in the experiment described above arises from a sequence of discrete refractive index variations (cell-vapour, vapour-cell). However, there may be situations where it is not convenient to confine the vapour within a prism geometry. For this reason, we have demonstrated that beam deflection also arises as a consequence of a continuous refractive index variation. The classic work of Wood (see, for example, [23]) demonstrated refraction of near-resonant light transmitted through inhomogeneous atomic vapours. In our experiment the atomic vapour is uniform but there is a variation of the refractive index induced by the spatial inhomogeneity of the pump beam. This experiment exploits the intensity dependence of the refractive index of the medium, and was performed using the set-up shown in Figure 3. Two counter-propagating beams, derived from a single laser are scanned across the D_2 line in Rb. The probe and pump beams have spot sizes of 1.5 mm and 3 mm, respectively. In addition, the probe beam is focussed using a 50 cm lens onto the split photodiode.

The position of the probe beam within the pump beam profile was adjusted by translating the polarizing beam splitter (PBS) cube as indicated. Typical spectra for a positive, zero and negative displacement between pump and probe beam axes are shown in Figure 4. As expected, if the probe beam is moved to the other side of the pump beam the signal changes sign. In addition the deflection is cancelled when the two beams are coaxial. The asymmetry in the signal size between the two sides is the result of beam imperfections. These results confirm that the difference signal arises from a deflection, and not some other mechanism (e.g. differential absorption of the two halves of the probe beam).

In Figure 5 we show deflection spectra for optimal axis offset for the two ground state hyperfine transitions in ^{85}Rb. Both spectra should contain six dispersion features corresponding to the Doppler resonance $S_{1/2}(F) \rightarrow P_{3/2}(F' = F+1, F, F-1)$; and three cross-over resonances. However, for the $S_{1/2}(F = 2) \rightarrow P_{3/2}(F')$ transition the relatively small hyperfine splitting means that not all the peaks are clearly resolved.

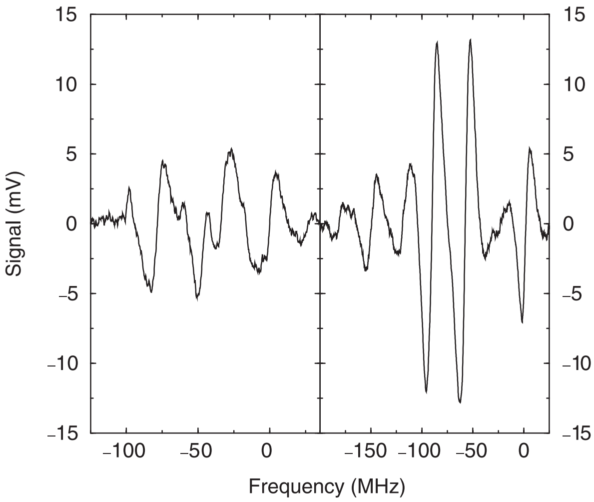

Fig. 5. The deflection signal for the offset saturated spectroscopy set-up illustrated in Figure 3. The left and right curves correspond to the $S_{1/2}(F=2) \rightarrow P_{3/2}(F')$ and $S_{1/2}(F=3) \rightarrow P_{3/2}(F')$ transitions in ^{85}Rb respectively. The pump and probe power are 140 μW and 12 μW, respectively. The zero of the frequency scale corresponds to the $F \rightarrow F' = F+1$ transition. The slowly varying background due to differential hyperfine pumping has been removed.

4 Conclusion

In summary, we have demonstrated two deflection techniques for mapping the refractive index of a medium in pump-probe experiments. The rapid variation of refractive index with respect to frequency was clearly demonstrated both in an EIT cascade experiment with two lasers, and in a saturated absorption/hyperfine pumping experiment with a single laser. In the prismatic deflection experiment we measured refraction at a discrete interface whereas for an inhomogeneous pump beam we measured continuous refraction due to the inhomogeneity.

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