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Locking the Laser Frequency to an Atomic Transition

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Abstract. A simple method for stabilizing the laser frequency to an atomic transition is described. It makes use of the frequency shift caused by the Doppler effect. With this method the frequency of a dye laser can be kept tuned to an atomic resonance line within 10% of the linewidth for periods of several hours.

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Atomic and nuclear scattering experiments employing spin-polarized collision partners are gaining more and more interest. Several experimental techniques for the production of polarized beams are well known. Recent work has demonstrated that by applying optical pumping techniques, using an intense laser light source, an intense atomic beam with high polarization can be produced [1–3]. A crucial point for the laser-based experiments is the frequency stability of the dye laser; the frequency has to be constant within comparatively long periods of data accumulation typical for scattering experiments. Also spectroscopic studies, e.g. of two-step processes may require a stable laser frequency which is exactly tuned to an atomic transition.

The required stability may be illustrated for the Na D resonance line. This line has a natural width of 10.0 MHz FWHM or 4.2 MHz RMS; thus a laser stability of ± 1 MHz seems to be adequate. The typical frequency jitter of free-running single-frequency dye-lasers, however, amounts to ± 20 MHz. Recently, commercial laser systems employing active frequency stabilization to a Fabry-Perot etalon have become available which are specified with a linewidth < 1 MHz RMS and a frequency drift $< 50 \ldots 100$ MHz/h. Our experience with such a system shows that the specifications can be easily verified. Nevertheless, the observed long-term frequency drift of ca. 40 MHz/h and a considerable amount of smaller short-term fluctuations present a serious problem to optical pumping applications.

Sophisticated laser spectrometers [4, 5] exhibit excellent frequency stability, but they are unnecessarily complicated and difficult to operate for the present purpose. Alternatively, the laser frequency might be stabilized to an atomic transition employing lock-in techniques. A disadvantage of this method is the frequency modulation and the need for corresponding electronic equipment. Therefore, a different stabilization technique was tested.

1. Method

The stabilization method makes use of the Doppler shift; a typical set-up is shown in Fig. 1. The Na beam is intersected 500 mm downstream from the oven by the laser beam at right angle. The induced fluorescence light is monitored by two photodiodes (labeled A and B) which detect light originating from two zones each located at 1 mm distance from the axis. Due to the thermal velocity v of the Na atoms (ca. 900 m/s), the atomic resonance curves, as observed by the two diodes, appear frequency shifted by

$$\Delta\nu = \frac{v}{\lambda}\frac{\pm 1}{500} = \pm 3\,\text{MHz},$$

where λ denotes the resonance wavelength (589 nm). The calculated fluorescence intensity vs. laser frequency is shown in Fig. 2. The difference signal of the two photodiodes exhibits a zero-crossing with high slope at the center frequency. Thus it can be used as

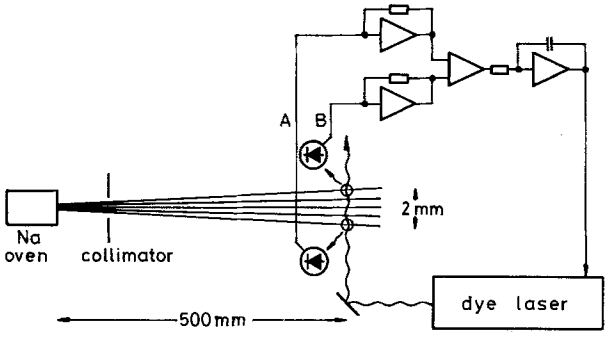

Fig. 1. Scheme of the optical pumping arrangement with components for frequency stabilization

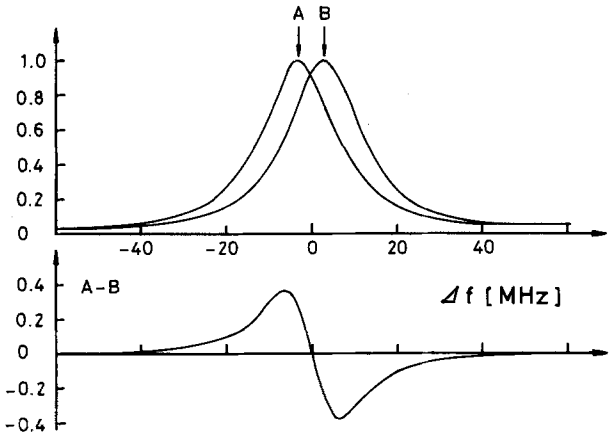

Fig. 2. Calculated light intensities vs. laser frequency as seen by the two photodiodes (upper part) and calculated difference signal (lower part). For the curves a Lorentzian shape has been assumed with linewidth 20 MHz FWHM, i.e. twice the natural width, in order to take line broadening by laser power and finite spatial acceptance of the photodiodes into account

error signal for the laser frequency stabilization. This shape also makes a corresponding servo loop insensitive to variations in atomic density and laser output power.

2. Experimental Details

For the detection of the fluorescence light photodiodes have been chosen instead of photomultipliers since they are smaller and offer constant gain. The beam area seen by the diodes is defined by small collimating tubes, no focussing optics have been installed. For typical atomic densities of 10^9 atoms/cm^3 and 10 mW laser power photodiode currents of 10 nA were obtained. This current is comparable to the leakage current if the diodes are operated with bias voltage, i.e. in conductive mode. Therefore the diodes were operated in the photoamperic mode by directly feeding the induced diode current into FET input operational amplifiers. The difference signal of the two diodes was send to an integrator circuit with 1 s cut-off time-constant in order to avoid oscillation of the servo loop. The integrator output was fed into the external scan input of the control box of the commercial laser system. Note that the dye laser used was already frequency stabilized to an etalon and that the described servo loop only has to correct for frequency drifts and not for short-term noise. The power supply for the electronic circuit was obtained from the laser control box; thus the servo loop could be built small and inexpensive.

Fine-tuning of the laser frequency can be accomplished either mechanically by moving the photodiode assembly or electrically by varying the gain of one of the FET amplifiers. The diode signals can additionally be used in the initial laser frequency setup procedure and as a monitor for the atomic beam density.

The servo loop provided frequency stability of better than ± 1 MHz. The loop was found to lock again after a laser mode jump since in case of large frequency detuning no error signal is produced. Under stable laboratory conditions locking of the laser frequency to an atomic transition for periods of several hours without any external control has been obtained.

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