Spectroscopy of the 689 nm Intercombination Line of Strontium Using an Extended-Cavity InGaP/InGaAlP Diode Laser

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Abstract. A visible diode laser emitting at 690 nm at room temperature has been frequency-stabilized using a simple scheme based on optical feedback from a diffraction grating. The possibilities offered by these lasers for high-resolution spectroscopy are demonstrated by recording the sub-Doppler signal of the 689 nm intercombination line of strontium and resolving the hyperfine structure of the close P63 R70 (8, 4) transitions of iodine.

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In recent years, semiconductor diode lasers have increasingly attracted the interest of spectroscopists as new sources of coherent radiation in the visible and near-infrared region of the spectrum [1, 2]. Their spectral coverage and the available output power are steadily increasing, making them a real alternative to dye lasers for atomic and molecular spectroscopy experiments. In fact, because of their unique properties of compactness, efficiency, low amplitude noise and fast frequency tunability, they not only allow a drastic simplification of the experimental set-ups, but also lead to an improvement of their performances. On the other hand, the low spectral purity of this kind of lasers may represent a serious drawback for their use in high-resolution-spectroscopy experiments. This is particularly evident for the AlGaNP visible diode lasers which have been commercially available only for a few years now. The first visible diode lasers, operating at ~670 nm at room temperature, were gain-guided and emitted on several modes. With the development of index-guided lasers, single mode operation was achieved but still with a linewidth of several tens of megahertz.

Different techniques have been demonstrated for the frequency stabilization of diode lasers [3]. Two main approaches have been followed: one is fast electronic feedback for the stabilization of the laser frequency to a Fabry-Pérot resonance by changing the injection current to the diode. The other main approach to diode laser frequency control is to take advantage of the sensitivity of these lasers to optical feedback. In particular, it has been demonstrated the possibility of improving the spectral properties of visible diode lasers operating at 660 nm [4, 5] and 670 nm [6, 7] using different schemes of optical feedback. In [5, 7] the diodes were treated with an antireflection coating on the output facet in order to increase the coupling efficiency.

In this work, we demonstrate that diode lasers emitting at 690 nm at room temperature can be used in an extended-cavity configuration without any additional coating treatment with a reduction of the emission linewidth to less than one megahertz. The low amplitude noise of these lasers allowed us to use a simple apparatus to perform high resolution spectroscopy of the 5s11S0–5p13P0 intercombination transition of strontium at 689.448 nm. This transition is of metrological interest because of its narrow natural linewidth (8 kHz). Also, the hyperfine structure of the P63 R70 (8, 4) iodine transitions at 689.455 nm was resolved which can provide an accurate frequency marker close to the Sr line.

Experimental Set-Up

The basic elements of the experimental apparatus used in this work were the frequency-stabilized diode laser, the Sr and iodine cells, and the set-up for recording sub-Doppler spectra by saturation or polarization spectroscopy.

The laser diode was a Toshiba TOLD9140 InGaAlP laser diode. It emits ~20 mW cw at 690 nm at room temperature with an injection current of 65 mA. The emission bandwidth was found to be typically ~50 MHz. A low-noise current source was used as power supply for the diode; the laser’s temperature was actively stabilized to better than 1 mK.

For frequency stabilization and control, the diode was mounted in a pseudo-external cavity formed by an AR coated collimator (focal length = 8 mm), a 1200 lines/mm diffraction grating in the Littrow configuration, and a 30% reflection beam-splitter as output coupler. The length of the external cavity was 8 cm. The polarization of the beam was
chosen perpendicular to the grating rules in order to have optimal efficiency of the grating. With the cavity properly aligned, the laser operated in a single mode. By observing the transmission of a 1 m long confocal Fabry-Perot interferometer, the linewidth was measured to be less than 1 MHz in a 5 ms interval. On longer time scales the acoustic jitter of the cavity caused a larger linewidth. The Fabry-Perot interferometer was instrumented; it is essentially due to the low finesse (≈ 80) of the Fabry-Perot interferometer at this wavelength, and to its alignment which was not perfect in order to avoid unwanted optical feedback effects. In fact, a linewidth of the order of 1 MHz is typical for extended-cavity diode lasers. A more accurate determination would require heterodyning of two similar lasers. The narrow strontium transition investigated in this work can also provide a significant test for the actual linewidth of the laser, although this experiment the observed linewidth was not due to the laser but to different experimental factors, as discussed below.

The optical feedback from the grating also allowed a coarse selection of the wavelength in a range of about 7 nm at fixed temperature. In fact, by rotating the grating the emission wavelength showed discrete jumps of about 1 Å, corresponding to the spacing of the modes of the diode. The fine tuning to the frequency of interest was then achieved by slight adjustments of the temperature of the diode and of the injection current. Continuous frequency scans of about 6 GHz were possible by synchronously changing the current to the diode and the length of the external cavity using a piezoelectric transducer on the grating. The available output power in the two beams produced in opposite directions at the beam-splitter was about 4 mW and 2 mW. The weak zero-order reflection from the grating was sent to the Fabry-Perot interferometer for the calibration of the frequency scan. The wavelength of the laser was measured using a travelling Michelson interferometer with an accuracy of one part in $10^7$ (constructed by R. Droling of NIST, Boulder, Colorado).

Strontium was produced by sputtering in a hollow cathode discharge sustained by argon. Details on the construction of the cell have been given in [8]. The solid strontium cathode was 15 mm long with a 4 mm diameter hole drilled through it. With a discharge current of 100 mA and an argon pressure of 1 Torr we obtained densities of about $10^{13}$ atoms/cm$^3$ in the cathode bore, as estimated from the observed absorption signal. The minimum argon pressure at which the discharge operated in a stable regime was 0.2 Torr. We also used a sealed glass cell in which Sr vapors were produced by heating a bulb containing the metal. We observed a 5% absorption from the 689 nm line but the rapid degradation of the cell did not allow to use it for accurate measurements. For future experiments, we are considering the possibility of using a quartz cell, perhaps with some buffer gas to prevent strontium from coating the windows, or a heat-pipe. This would provide a cleaner environment and a reduction of the collisional broadening effects which affected the lineshapes observed in this work.

The 1 m long iodine cell was made from 1.5 cm inside diameter pyrex tubing. In order to observe transitions starting from excited vibrational levels with a good signal to noise ratio, it was necessary to heat the iodine cell to about 250$^\circ$ C. Iodine crystals were placed in a side arm of the cell and its temperature was maintained at 30$^\circ$ C, using a Peltier element in order to keep the $I_2$ vapor pressure low (0.6 Torr).

Doppler-free spectra were recorded using a polarization spectroscopy apparatus [9]. The pump beam was circularly polarized and gently focused in the cell. The weaker probe beam was linearly polarized and crossed the pump beam at a small angle (≈ 8 mrad) in the cell. The changes in the polarization of the probe beam were detected by a photomultiplier placed after a crossed polarizer. We used slightly different experimental schemes for Sr and for $I_2$. In the first case, the light transmitted through the crossed polarizer passed a grating monochromator in order to reduce the background due to the discharge. In the case of $I_2$, because of the small size of the signals, the polarization of the pump beam was alternatively modulated parallel to the probe beam and circular, at a frequency of 20 kHz using an electro-optic modulator; the output of the photomultiplier was sent to a lock-in amplifier for phase-sensitive detection. This scheme allowed a reduction of the noisy background due to the scattered pump light, with respect to the more common amplitude modulation.

Saturated absorption spectroscopy was not used for iodine because, for the investigated transitions, signals are extremely weak and difficult to detect. On the contrary, the saturation dip was easily detected for the intercombination line of Sr, as shown in the following.

Results and Discussion

As mentioned above, one of the features of semiconductor diode lasers is a very low amplitude noise in the low-frequency range in which most spectroscopy experiments are performed. This allowed us to observe also weak transitions in direct absorption. In Fig. 2 we show the absorption signal of the 689 nm intercombination line of Sr as observed by
passing the laser beam two times through the cathode bore in opposite directions and detecting the transmitted light by a photodiode. The fast sweep rate and low noise of the diode laser allowed us to detect the signals in real time on an oscilloscope (oscilloscope bandwidth ~50 kHz). The 1% Doppler absorption can be observed with a good signal to noise ratio, limited mostly by the light coming from the discharge. On the top of the Doppler profile a small saturation dip (~5%) can also be observed corresponding to the most abundant $^{88}$Sr isotope. A linewidth of 10 MHz was measured for the saturation signal, mostly due to collisions with the buffer gas.

In order to reduce the collisional broadening, we used a polarization spectroscopy scheme [9]. A Doppler-free spectrum recorded by this technique is shown in Fig. 3. A drastic improvement of the signal to noise ratio can be immediately observed, which allowed to detect the signals corresponding to the other two isotopes $^{86}$Sr and $^{88}$Sr, whose natural abundances are 9.9% and 7%, respectively. Also in this case, the output signal from the photomultiplier was directly recorded using the oscilloscope. The minimum linewidth we observed by this technique was 6 MHz FWHM. We performed a systematic investigation of the dependence of the observed linewidth on the pressure of the buffer gas. The results are shown in Fig. 4; they give a pressure broadening coefficient of $11(1)$ MHz/Torr. By extrapolation to zero pressure and to low laser intensity, we find a linewidth of $3(1)$ MHz, which is consistent with the residual Doppler broadening due to the finite angle between the pump and the probe beam. This result confirmed that the contribution of the laser linewidth to the observed width of the spectral lines was not more than 1 MHz.

The same apparatus allowed us to resolve the hyperfine structure of iodine transitions in this spectral region. In particular, Fig. 5 shows the spectra relative to the P(63) R70 (8,4) transitions at 689.455 nm. The line was identified from the molecular constants published in [10]. The upper trace in Fig. 5 shows the Doppler-broadened absorption profile while the lower trace represents the polarization spectrum in which the underlying hyperfine structure is resolved. As already mentioned, in this case it was necessary to use phase-sensitive detection with a modulation frequency of 20 kHz and a lock-in time constant of 10 ms. The frequency separation of the centre of this line from the Sr line is 4.5 GHz so that it can provide an interesting frequency marker at this wavelength. We also observed more intense I$_2$ transitions in this spectral region with a better signal to noise ratio. The investigation of this region of the spectrum of the I$_2$ molecule can allow a better understanding of the hyperfine structure of transitions involving low vibrational quantum numbers in the excited B state [11].
Conclusions

We have demonstrated the frequency stabilization of a semiconductor diode laser at 690 nm using optical feedback from a diffraction grating. A reduction of the emission linewidth by about two orders of magnitude was achieved with respect to the free-running operation. We used this laser to observe the sub-Doppler resonance of the intercombination line of Sr I and the hyperfine structure of iodine transitions by means of different high resolution spectroscopy techniques.

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References

3. See Ref. 2 and references therein