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Frequency Chain Towards the Ca Intercombination Line Based on Laser Diodes: First Step

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Abstract. Stable, narrow linewidth operation of red and 1.3 μm free-running laser diodes with external gratings in non-Littrow geometry is demonstrated. The resonance of the saturated fluorescence of an atomic beam with a contrast of 25% and a linewidth of 400 ± 50 kHz of the Ca intercombination line 4^1S_0–4^3P_1 ($\lambda = 657$ nm) is shown. A high-power (110 mW) single-mode external cavity laser diode at 1.3 μm is used for second-harmonic generation in a KTP crystal. The beat signal (signal to noise ratio about 25 dB) of 10 nW second-harmonic radiation at 1.3 μm and the radiation of a laser diode in the visible spectrum, as a step to realize a frequency chain, is observed.

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The intercombination line of laser cooled Ca vapor sample is one of the promising candidates for a frequency standard in the optical region [1]. However, even though the recoil splitting of the ^{40}Ca intercombination line was resolved many years ago and several experiments of dye-laser frequency stabilization to the ^{40}Ca line were reported [2, 3], as far as we know, accurate measurements of frequency stability using two independent laser systems have not been carried out to date. In order to estimate the stability, accuracy and reproducibility of an optical standard, the comparison with an independent laser and direct measurements of the optical frequency are required. The frequency chain from the ^{40}Ca reference at 657 nm to a Cs atomic clock is being developed in several laboratories [4] and a new scheme of the frequency chain from the Ca line to the microwave region based on Laser Diodes (LDs) only has been proposed recently [5].

A number of experiments on nonlinear spectroscopy of the intercombination transitions of Ca, Ba and Sr [6–10] have been carried out by using highly coherent LDs. It is clear now that LDs can be used to develop a portable frequency/wavelength standard in optics.

The elaboration of highly coherent LDs in the visible and at 1.3 μm suitable for a frequency chain is the main purpose of this work. We present here also the results of preliminary experiments on nonlinear spectroscopy of the Ca line at 657 nm using a LD in the visible and the observation of the beat signal between this laser and the second harmonic of a 1314 nm LD as a step to realize a frequency chain towards the Ca intercombination line.

1 Laser Diode with External Cavity

High spectral resolution demands narrow laser linewidth, precise frequency tunability and good long-term stability. There are a lot of techniques to improve the spectral characteristics of LDs. Their advantages and peculiarities have been discussed elsewhere [6]. A method of the weak optical feedback from an external high-Q Fabry-Perot cavity is not very effective for LDs in the visible because frequency-noise reduction is limited by strong enhancement of relaxation oscillations [10]. Therefore, the extended-cavity technique using an AntiReflection (AR) coated LD and a dispersive element in the extended cavity was applied.

For LD linewidth narrowing by this technique both high efficiency and high resolution of the dispersive element are desirable. A holographic grating of total internal reflection with high diffraction efficiency (≈70%) and selectivity (3200 lines/mm) is convenient for the External Cavity Laser Diode (ECLD), especially in the case of two-facet-emitting LDs [7]. However, with a commercial LD emitting light in one direction we have to utilize the zeroth order of the grating as the output beam which is rather weak due to the high efficiency of the holographic grating. Beside of that, the direction of the output zeroth-order reflection from a grating in Littrow configuration depends on the laser wavelength, which complicates the alignment of the experimental setup. That is why we prefer another optical scheme of an external cavity with a conventional grating [11].

The scheme of the ECLD is shown in Fig. 1. The external dispersive cavity consisted of the LD, a coupling objective lens (NA = 0.65), a PZT-driven 100% dielectric mirror, an

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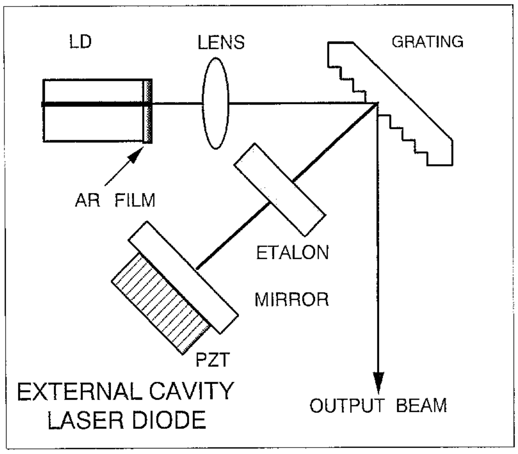

Fig. 1. Optical scheme of the external cavity laser diode. The zeroth-order reflection from the grating is used as output

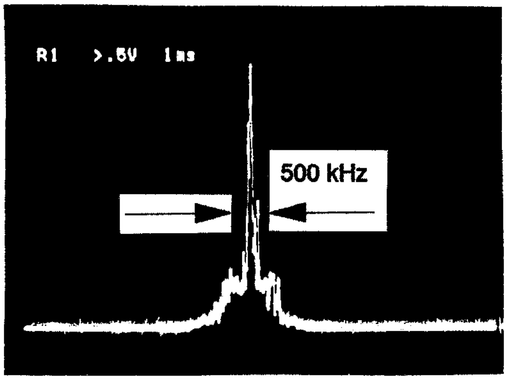

Fig. 3. Transmission resonance of the high-Q Fabry-Perot cavity. The side bands are due to the frequency modulation of the ECLD at 250 kHz

etalon (10 mm thick, 30% reflectivity) and a grating (1300 lines/mm, blazed for 700 nm). All the elements of the laser cavity were mounted on an invar base plate isolated from the optical table with a damping spacer. The $p-n$ junction of the LD was parallel to the grooves of the grating. The angle of incidence on the grating was 55°. Under these conditions the efficiency of the first order of the grating was measured to be 30%. A servo system was used to stabilize the temperature of the LD close to 14° C.

The external cavity was constructed with a commercial InGaAlP laser diode (TOLD 9220). It is well-known that an AR coating of the LD facet is necessary for efficient linewidth narrowing of LDs in the visible. It is difficult to provide strong coupling with an external cavity without AR coating and, therefore, the typical laser linewidth is a few MHz in this case [8, 10]. It is insufficient for high-resolution spectroscopy. So, the LD output facet was coated with a HfO_2 AR film. The laser threshold currents before and after AR coating were 48 mA and 58 mA, respectively. The AR-coated LD operated in the multi-longitudinal mode regime (Fig. 2, curve a). Under selective optical feedback the threshold current was reduced to 45 mA. The ECLD spectrum was single mode from the threshold up to 62 mA. The maximum power of the zeroth-order output beam was 2.5 mW. The suppression of the nondominant modes was greater than 30 dB (Fig. 2, curve b). As compared with a Littrow configuration, the folded scheme of the external cavity has the following advantages.

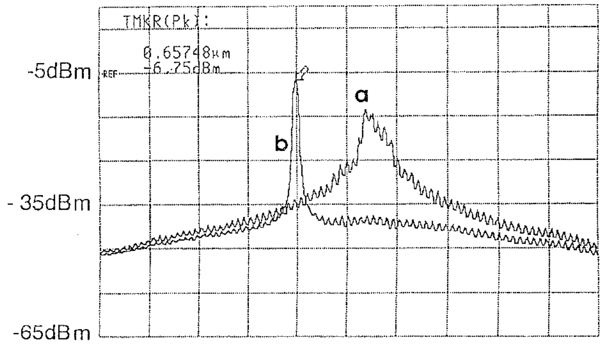

Fig. 2. Longitudinal mode spectra of the antireflection-coated LD. (*a*) with no optical feedback; (*b*) with selective optical feedback

– The direction of the output beam is kept stable while the frequency tuning is accomplished by rotation of the output mirror.
– It is possible to find a proper relationship between the diffraction efficiency of the grating and its selectivity by variation of the angle of incidence.
– The spectral selectivity is higher due to double reflection from the grating.

Frequency fine tuning in the range of approximately 1 GHz was provided by changing the voltage applied to the PZT on which the output mirror was mounted. Stable single-mode operation was easily obtained for cavity lengths within 5 cm to 20 cm. A Fabry-Perot supercavity was used to monitor the spectrum. It was a PZT-tunable planospherical (1 m curvature radius) cavity with high reflection ($R \approx 0.9999$) mirrors and an invar spacer ($L = 10$ cm). The cavity linewidth was estimated to be 100 kHz. The Fabry-Perot cavity was placed inside a chamber to reduce the disturbances produced by vibration and acoustic noise.

To reduce the influence of acoustic noise the ECLD was placed inside an acoustically insulated box. The random frequency drift was reduced from 15 MHz/min to 1–2 MHz/min in this way. The linewidth of the free-running ECLD was estimated to be less than 100 kHz by using the supercavity (Fig. 3). The frequency-noise measurement made with a low finesse cavity as a discriminator showed approximately the same value of the laser linewidth (35 kHz). Further linewidth reduction can be obtained by frequency stabilization to a resonance of a stable optical cavity using an electrical feedback method [12].

2 Nonlinear Spectroscopy of the Ca Intercombination Line

The experiment on nonlinear spectroscopy of the intercombination line 4^1S_0–4^3P_1 of ^{40}Ca ($\lambda = 657$ nm) using an ECLD was carried out with an atomic beam. The characteristics of the Ca atomic beam apparatus have been described else-

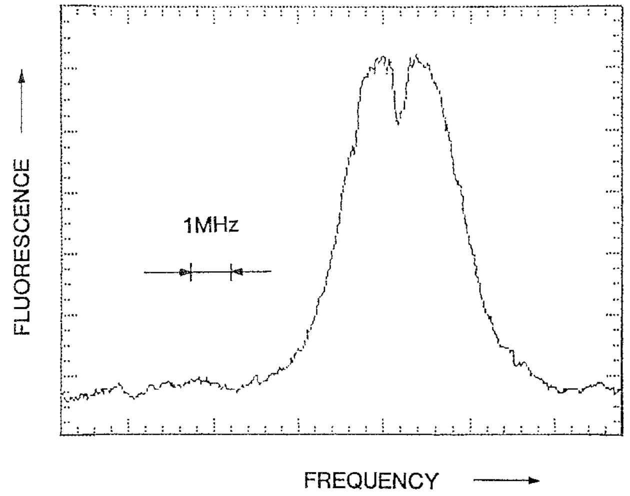

Fig. 4. Nonlinear fluorescence signal of the atomic beam on the intercombination line 4^1S_0–4^3P_1 of ^{40}Ca ($\lambda = 657$ nm) as a function of laser frequency

where [3]. Collimation of the atomic beam provided the residual Doppler broadening of about 4 MHz. The laser beam (1.5 mW) crossed the Ca atomic beam perpendicularly and was reflected with a cat's eye reflector. The cat's eye reflector was composed of a 250 mm focus lens and a flat mirror in the focal plane. The 1 cm spatial separation of the two counterpropagating beams excluded multiphoton processes [13] and parasitic optical feedback to the LD. The fluorescence from the excited Ca atoms was detected with a photomultiplier placed about 30 cm downstream from the excitation zone. To provide a frequency scale, the ECLD was FM modulated at 7 MHz, which gives two additional peaks of fluorescence corresponding to side bands. A transverse magnetic field was applied to the interaction region so that only the π-transition ($\Delta m = 0$) was excited by the linearly polarized laser light.

A saturation dip on the Doppler-broadened spectral profile of fluorescence is shown in Fig. 4. The dip contrast defined with respect to the Doppler-broadened line is about 25%. The laser beam cross section was 2 mm × 3 mm, so the maximum intensity of the exciting light was about 25 mW/cm^2. The nonlinear dip was observed even at a laser intensity of 5 mW/cm^2. The minimum width of the nonlinear dip (FWHM) is 400 ± 50 kHz. The spectral resolution was mainly limited by the frequency jitter of the free-running ECLD.

3 1.3 μm Laser Diode and Second-Harmonic Generation

According to the scheme of the proposed frequency chain from the microwave range to the Ca line [5] it is necessary to have a Second Harmonic (SH) of 1314 nm and sum-frequencies corresponding to 1314 nm and 657 nm simultaneously. It is difficult to accomplish this with a low-power LD and two independent build-up cavities for SH generation and sum-frequency mixing. Consequently, we have used for the nonlinear frequency conversions two single-pass schemes and a high-power LD.

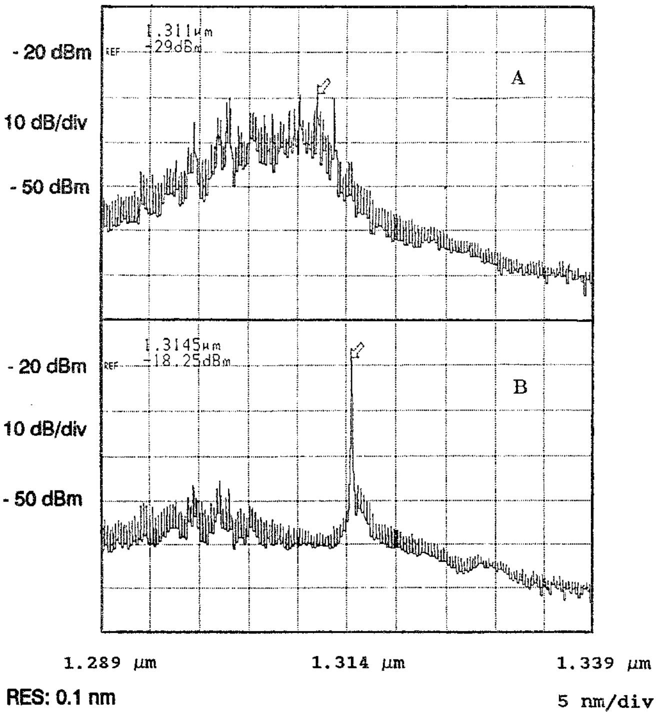

Fig. 5A, B. Longitudinal mode spectra of a high-power LD at $I = 450$ mA ($I_{\text{th}} = 50$ mA). **A** With no optical feedback; **B** with selective optical feedback (output power 110 mW)

A high-power multimode LD emitting up to 200 mW at 1.3 μm was used as an active element of an ECLD. The same folded scheme (see Fig. 1) of an external cavity was applied for longitudinal mode selection and linewidth narrowing. In order to rise the power of the output beam the angle of incidence on the grating (1200 lines/mm) was increased up to 85°. The LD junction plane was oriented to be parallel to the lines of the grating. The laser spectrum was analyzed with a confocal cavity having a free spectral range of 300 MHz and a finesse of 200. Under optical feedback a spectrum of the ECLD was completely single mode even if the threshold current was exceeded by a factor of up to 9 (Fig. 5). The maximum single-mode power of the output beam was 110 mW at $\lambda = 1314$ nm.

An effect of polarization switching by optical feedback [14] during alignment of the external cavity when the orientation of the LD junction was not exactly parallel to the grooves of the grating was observed. It happened because the dispersion efficiencies of the grating for two orthogonal polarization components of incident radiation are essentially different. The switching of the LD radiation from TE mode to TM mode led to stronger optical feedback and, consequently, to better side-mode suppression (more than 40 dB). However, also to an unwanted decreasing of the zeroth-order beam power by 3–4 times. The effect of polarization switching by external optical feedback in this scheme requires further investigation, because it may be useful for some applications.

A 5 mm long nonlinear KTP crystal with critical phase matching was used for SH generation. The angles of incidence of the laser beam were varied to optimize phase matching. About 100 mW of fundamental light yielded up to 11 nW of SH in a single-pass scheme.

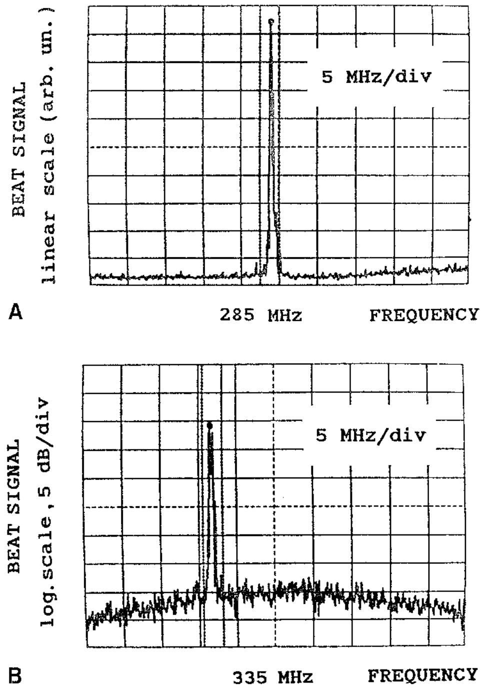

Fig. 6. Beat-note spectrum of an ECLD in the visible and SH radiation of the 1314 nm ECLD. Resolution bandwidth: 30 kHz; video bandwidth: 10 kHz; sweeping time: 500 ms

After separation of the fundamental light, the SH beam was mixed with radiation of the red ECLD (657 nm) on a Si avalanche photodetector. The beat note recorded on an rf spectrum analyzer is shown in Fig. 6a, b. The heterodyne spectrum shows that the linewidth of both LDs was less than 500 kHz for a sampling time of 500 ms. The signal to noise ratio is about 25 dB in a 30 kHz bandwidth. This ratio can be further improved by increasing the efficiency of SH generation.

4 Summary

The narrow-linewidth (less than 100 kHz) external-cavity laser diode operating at 657 nm with good long-term free-running stability was demonstrated. To obtain a sub-kHz linewidth level of the LD one has to use a fast electronic servo system to control the laser frequency to a stable high-Q reference cavity [12]. The laser was used for nonlinear spectroscopy of the Ca intercombination line. The resonance of saturated fluorescence with a contrast of 25% and a linewidth of 400 ± 50 kHz was shown.

The 110 mW single-mode external-cavity laser diode at 1.3 μm was used for second-harmonic generation in a KTP crystal. An effect of polarization switching by optical feedback during alignment of the external cavity was observed.

The 600 kHz beat signal (sampling time of 500 ms) between the 10 nW second-harmonic radiation of 1.3 μm and the fundamental radiation of the ECLD was observed. The signal to noise ratio was more than 25 dB which is high enough to use phase-locking.

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Note added in proof. When the manuscript was ready for publication we have learned that the recoil splitting of Ca was resolved by using an extended-cavity diode laser at the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany [15].