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Development of tuneable, narrow-band, and frequency stabilised laser heads in Observatoire Cantonal de Neuchâtel

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DEVELOPMENT OF TUNEABLE, NARROW-BAND, AND FREQUENCY STABILISED LASER HEADS IN OBSERVATOIRE CANTONAL DE NEUCHÂTEL

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ABSTRACT

We describe our investigations on tuneable, narrow-band and frequency stabilised laser heads. The work is motivated by the potentials of highly stable and narrowband laser light sources for a variety of technical and scientific applications and in particular for atomic clocks and high resolution space instruments.

1. INTRODUCTION

The past years have shown tremendous advancements in the field of compact and spectrally well-controlled diode laser sources, concerning both spectral narrowing of the laser emission and frequency control. These developments make it interesting to exploit the availability of such compact laser sources for, e.g., secondary wavelength references [1, 2], or for performance improvements of precision instruments like, e.g., compact atomic frequency standards [3, 4] or atomic magnetometers [5, 6]. This paper presents the realizations and studies of compact single-mode laser sources emitting between 780 and 940 nm, and application examples such as secondary wavelength standards, laser-pumped rubidium gas-cell atomic clocks and high spectral resolution LIDARs.

2. FREQUENCY-STABILISED LASER SOURCES

Many applications not only require well-controlled laser emission spectra, but also small size and low power consumption. Here semiconductor diode lasers are an excellent choice, being available in a huge variety of types spanning large ranges of emission wavelengths, output powers, and spectral characteristics.

Promising advances have been made towards intrinsically single-mode and narrowband diode lasers like, e.g., distributed feed-back (DFB), distributed Bragg reflector (DBR) or vertical-cavity (VCSEL) lasers, but still these devices are not always commercially available at the desired wavelength or are compromised by spectral line-widths of a few MHz or more, too large for applications aiming for ultimate performance in optical instrumentation and spectroscopy. Here we therefore focus on the realisation of compact external-cavity grating stabilisation of standard Fabry-Perot type laser diodes [7], whose

linewidth is spectrally narrowed by the optical feedback [8] and where there is usually a large choice of diodes commercially available.

3. THE OBSERVATOIRE COMPACT DIODE LASER MODULES

We have built two types of extended-cavity diode lasers (ECDL) using the Littrow configuration [9], which can be realized very compact [10, 11] and still offer the good frequency tuning behaviour and spectral linewidths around 300 kHz required for subsequent stabilisation to atomic or molecular resonances: Figure 1 shows the CAD design and the final realisation of an ECDL for laboratory use. With this design, ECDLs emitting at 780 and 795 nm (Rb); 852 and 894 nm (Cs); 935 - 945 nm (H₂O) have been realised so far.

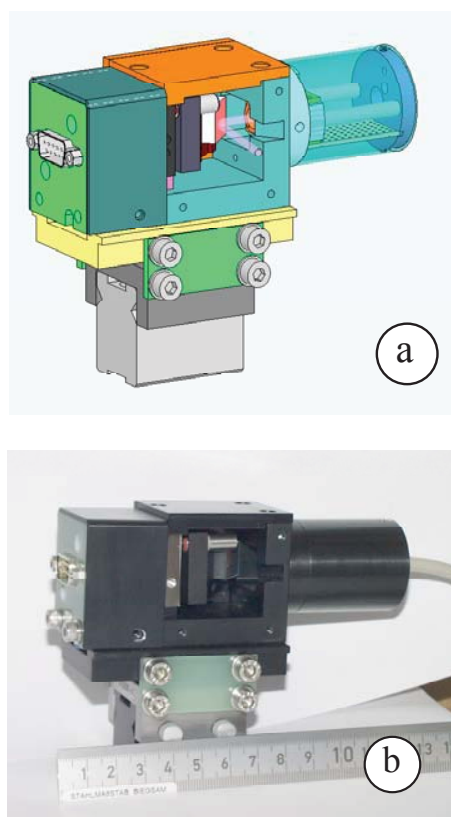


Fig. 1 Compact extended-cavity diode laser for laboratory use. a) CAD design. b) Realised device.

In a separate paper presented during this conference [12], we describe a more compact laser head module which in addition to an ECDL also includes frequency stabilisation to a Rb vapour reference cell and that has been developed for a gas-cell atomic clock.

4. APPLICATION EXAMPLES

In the following we discuss some applications of narrow-band frequency stabilized lasers that can benefit from the realisation of compact devices. While ultimate state-of-the-art performance of much larger laboratory devices will in most cases be superior to the stability and precision of the laser modules discussed here, a compact device offers the potential for, e. g., mobile applications with volume restrictions or applications requiring large unit numbers but moderate price. Depending on the specific application the implemented atomic or molecular reference line will differ and also the laser type used might change.

4.1 SECONDARY WAVELENGTH REFERENCES

A laser module stabilized to a suitable reference line can serve as a secondary wavelength reference and find applications in fields like telecommunication or the experimental realisation of the meter unit [1]. Using diode lasers stabilized to the D₂ line of ⁸⁷Rb, frequency stabilities of $4 \cdot 10^{-12} \cdot \tau^{-1/2}$ were previously demonstrated using laboratory setups [13], validating the feasibility of this approach. Our compact stabilized laser module reaches similar stabilities [12] and can be easily adopted to meet wavelength stabilisation to other alkali atomic resonance lines at 795, 852, or 894 nm. We also envisage a modification of the module to meet the Rb 2-photon transition at 778 nm, which is recommended as a metrology reference wavelength [1].

The implementation of frequency doubling techniques allows to extend the wavelength range met by the laser module to 1556 or 1560 nm, and thus into one of the standard wavelength ranges used in telecommunications. A simple system for frequency doubling in this wavelength range was recently demonstrated using compact and standard commercial components only [14].

4.2 ATOMIC FREQUENCY STANDARDS

In addition to the application in gas-cell clocks discussed in [12], narrow-band and tuneable laser diodes are used in most of the other new atomic frequency standards, and in particular in the laser optically pumped Cs/Rb beams, in the laser cooled atoms and ions clocks and in the new generation of "optical" frequency standards. In Observatoire Cantonal

de Neuchâtel, the laser sources described in section 3 have been used for developing the ON-METAS primary Cs continuous fountain [15] and will serve as laboratory tool in the realisation and optimisation of a space laser-pumped atomic beam standard [16].

4.3 BASIC RESEARCH AND PRECISION LASER SPECTROSCOPY

ECDLs are one of the most commonly used instruments for fundamental research in atomic and molecular physics. In Observatoire Cantonal de Neuchâtel, the laser heads shown on figure 1 are employed for studying the basic interaction between atoms and photons, and in particular the effects of AC Stark shift [17], laser recoil induced resonances [18], Sisyphus, adiabatic and degenerate Raman sideband transverse laser cooling of cold atomic beams [19], etc.

4.4 HIGH SPECTRAL RESOLUTION LIDARS

Atmospheric measurements by advanced LIDAR (Light Detection and Ranging) techniques can profit from stabilised laser sources used to seed their high-power transmitter lasers. For example, narrow-band Faraday Anomalous Dispersion Optical Filters (FADOF) [20] based on alkali atom vapours offer improved background light reduction in the LIDAR receiver units compared to simple interference filters and thus allow daylight-operation even of compact PRN-cw (pseudo-random noise) instruments [21-22], but they also require the transmitter laser to operate within the narrow transmission windows of the filters (cf. Fig. 2). Thus the transmitter lasers have to be stabilized to the alkali resonance exploited in the FADOF filter, where stabilisation based on Doppler-broadened absorption can be sufficient.

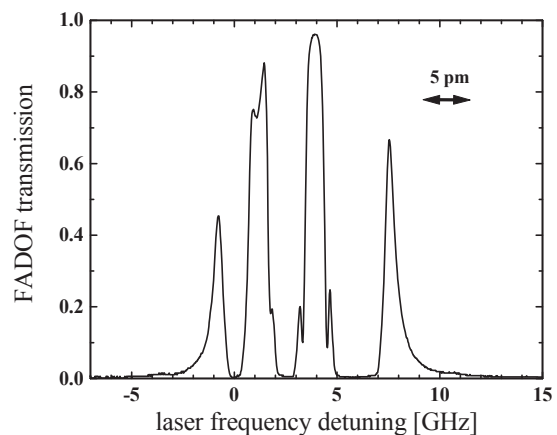


Fig. 2 Transmission curve of a Rb FADOF filter for daylight PRN LIDAR measurement ([22]).

As a second example, the Differential Absorption Lidar (DIAL) technique [23] for selective measurement of specific atmospheric constituents also requires stabilized seeding lasers. This technique relies on measurements performed with the transmitter laser tuned to the centre or out of the absorption lines of the molecules considered, and thus requires well-stabilised seeding signals. We are currently developing a seeding laser system for the ESA Water Vapour Absorption Lidar in Space (WALES), a satellite-borne DIAL instrument for measurement of atmospheric water vapour [24, 25]. In order to increase the dynamic range of the instrument, measurements will be made simultaneously on four wavelengths corresponding to water vapour resonances of different absorption strength, as well as one off-line wavelength which requires the fourth laser to be offset-locked with a detuning of several GHz relative to one of the three first lasers [25]. Here exploitation of compact laser modules will allow to realise a system of four narrow-band lasers stabilised to a reference water vapour cell, with a volume well below 27 litres. Figure 3 shows an example of water vapour spectrum obtained with our ECDLs.

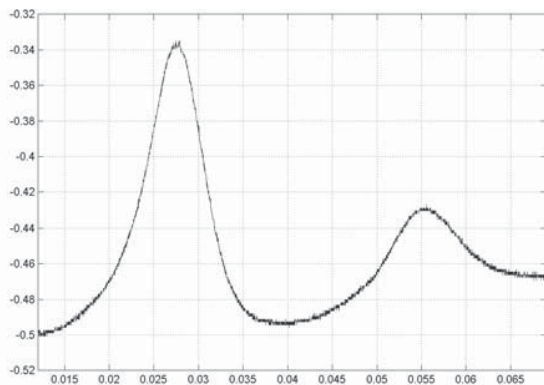


Fig. 3 Water vapour spectrum obtained the laboratory ECDLs of Observatoire Cantonal in a 1 m long cell. The horizontal scale shows a total frequency scan of approximately 6 GHz (around 935 nm) in 60 ms while the vertical scale corresponds to the voltage obtained with a photo-detector and a 50 k Ω resistor (the contrast of the strong absorption line is higher than 30%).

4.5 OTHER APPLICATIONS OF ECDLS

Due to their narrow line-width, ECDLs are very useful for the characterisation of other types of laser sources (DFB, DBR, VCSEL) and of high resolution optical instruments. In Observatoire Cantonal de Neuchâtel, a heterodyne laser test-bench has been assembled and is routinely used for (1) studying and comparing different

laser frequency stabilisation schemes (exploiting for example the Zeeman effect [26], or the Doppler and Sub-Doppler absorption [12]); (2) developing industrial and frequency stabilised interferometers; (3) measure the stability and accuracy of precision wave-meters; (4) characterize the spectrum of single-mode or frequency modulated laser diodes (figure 4).

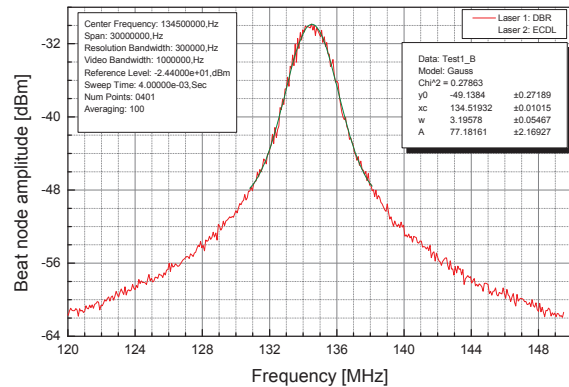


Fig. 4 Spectrum of the beat note between two laser diodes emitting around 780 nm, an ECDL and a DBR. The lasers are locked to adjacent lines of a Rubidium vapour.

5 CRITICAL ISSUES FOR SPACE & INDUSTRIAL APPLICATIONS

When considering industrial and space applications of tuneable or frequency stabilised narrowband laser sources, other issues than their spectral purity and stability are of major concern. The laser procurement must be secured and depending on the specific application a trade-off between price, volume, consumption, reliability, lifetime, performance, etc. must be found. In this respect, evaluating the available devices (type of laser, manufacturer, etc.), optimising their performances and determining the critical properties for a given application (spectral width, AM-FM noise, frequency stability, etc.) is of primary importance. In some cases, it may very well appear that the desired laser source is simply not available or is not satisfactory in terms of performances, reliability or price. As a result, industrialisation and/or space qualification are delayed or even stopped.

In Observatoire Cantonal de Neuchâtel, different issues are being addressed in view of the use of ECDLs (and of tuneable diode lasers in general) in industrial product and space equipment. Some examples are briefly described hereafter. They are all focused on the use of diode lasers in atomic clocks but the analysis may easily be extended to other applications.

5.1 DIODE LASER SPECTRAL PROPERTIES

In atomic clocks, the most important spectral properties - in addition to the wavelength and power - of the employed lasers are: (1) the spectral width; (2) the side modes rejection; (3) the AM noise spectrum; (4) the FM noise spectrum; (5) the spectral lifetime (that is the time during which it can be tuned to the desired wavelength). In some cases, the modulation bandwidth and the frequency and intensity sensitivity also play a major role. The requirements on all these parameters critically depend on the type of clock (ex.: gas-cell, atomic beam, cold atoms, etc.), on the application of the clock (ex.: ground or space) and on the desired performances (ex.: short-term stability or long-term stability.). In clocks using more than one laser, the requirements are not necessary the same for all the lasers (ex.: the cooling laser and the detection laser in an atomic fountain). There are cases where the laser requirements are still not known precisely and additional investigations are needed to determine the best trade-off (ex.: laser spectral width in clocks based on dark states created by a modulated laser). Finally, it must be noted that the laser spectral properties depend on its type (FP, DBR, DFB, fiber DBR, VCSEL, ECDL, etc.), on the manufacturer (material, process, etc.) and on the laser frequency stabilisation method.

To illustrate how one can improve the "spectral lifetime" of tuneable laser diodes, one can mention the optical CAD model of the Observatoire ECDL (figure 1). With this model, we could estimate how much light retro-reflected by the diffraction grating was coupled back into the emitting Fabry-Perot laser. By identifying the loss sources and by computing the sensitivity of this coupling towards various sources of misalignments (created for example by external temperature changes) it has been possible to improve the overall design and specify the mechanical and thermal stability. Once the "spectral lifetime" has reached the required value (for instance years), the analysis can be pursued so that the passive frequency (and intensity) stability of the ECDL is further enhanced [27].

5.2 LASER FREQUENCY MODE-HOP FREE TUNING RANGE

The laser frequency mode-hop free tuning range is of primary importance in atomic clocks, especially when considering industrial and space applications. The larger this tuning range, the larger also the "spectral lifetime", and therefore the lifetime of the clock. The absence of mode-hops may also facilitate automatic laser control systems [28].

In ECDLs (as well as in DBR / DFB-type lasers), the diffraction grating is used to reduce the spectral width

of the emitted light, but also to select the desired mode of the Fabry-Perot cavity, and therefore better control the unavoidable mode-hops. Coarse (but not continuous) tuning (typically $\Delta f \geq 10\text{-}100$ GHz) of the laser frequency is made by changing the grating angle (governed by the Bragg law) while fine (and mode-hop free) tuning (typically $\Delta f \leq 10\text{-}100$ GHz) is ensured by adjusting the external cavity length. Depending on the presence and quality of AR-coating on the front facet of the emitting laser diode, and if the coarse (grating angle) and fine (cavity length) tuning are properly matched, different methods exist in order to maintain in phase the resonant optical fields in the chip and out of the chip so that the mode-hop free tuning range is extended from typically 3-4 to several tens of GHz [29]. Note that this can be obtained even with a non-AR-coated laser diode, but with the disadvantage of a much larger intensity modulation during the frequency scan. Figure 5 shows one example of such enhanced continuous tuning range with the Observatoire ECDLs.

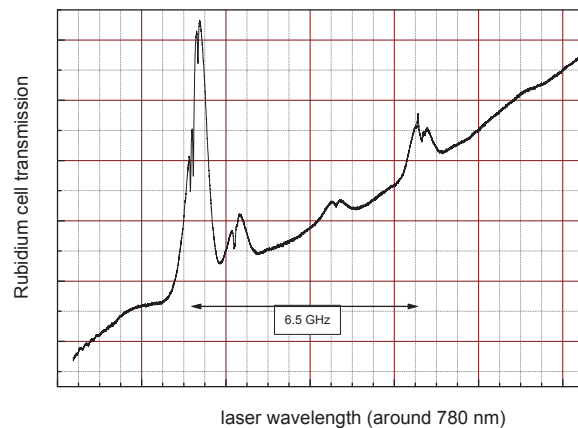


Fig. 5 Enhanced mode-hop free tuning range with an ECDL.

As it can be seen on figure 5, ECDLs may have a mode-hop free tuning range which even larger than DBRs and possibly of DFBs.

5.3 LASER VOLUME

Despite the miniaturisation efforts [30], DFBs and DBRs - when available - are often preferred to ECDLs due to their reduced volume. The use of Microelectromechanical and microoptoelectrical systems (MEMS and MOEMS) may very well change this situations if applied to the wavelengths useful for atomic frequency standards [31, 32, 33]. In fact, such tuneable laser sources may combine narrow linewidth, and large tuning range with reduced volume and weight.

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