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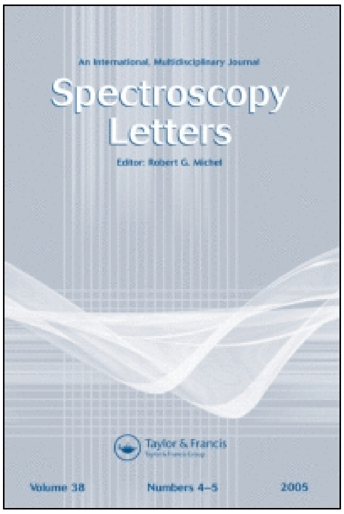

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CONTINUOUSLY TUNABLE EXTENDED CAVITY DIODE LASER AT 780 nm FOR HIGH RESOLUTION SPECTROSCOPY

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CONTINUOUSLY TUNABLE EXTENDED CAVITY DIODE LASER AT 780 nm FOR HIGH RESOLUTION SPECTROSCOPY

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ABSTRACT

In this communication we have investigated and compared the tuning abilities of an ECDL system, using a grating in Littrow configuration, depending on the laser diode (LD) used. We have achieved experimentally a wide continuous frequency tuning range by applying translation-rotational movement of the grating together with appropriate injection current correction. The fluorescence spectrum of Rb in the vicinity of 780 nm has been recorded in an external absorption cell. The wide mode-hop free frequency tuning gave us the possibility to reach exactly the maximum of each fine component of the Rb D_2 line. By scanning the applied magnetic field strength, sub-natural width resonance (SNWR), with FWHM in the kHz range, have been observed in the fluorescence signal and in the transmitted output power. Such resonance is very appropriate for measuring weak magnetic fields.

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Key Words: Continuously tunable lasers; High resolution spectroscopy; Coherent population trapping.

INTRODUCTION

Highly coherent, small size, easy to operate laser sources with wide continuous frequency tuning range are required in many spectroscopic applications. Recently, unique and wide-spread laser sources became the LDs with some modifications. To tune the solitary LD wavelength to a specific transition is usually difficult, ambiguous and sometimes even impossible. To improve the characteristics of the LD itself an extended cavity diode laser (ECDL) configuration is commonly used, which allows easy manipulation and high coherence of the wavelength emitted [1]. Many configurations have been used for realization of the optical feedback. However, one of the most frequently used - the Littrow configuration, has the advantage of realization of a compact and easy-to-operate system.

The main purpose of this investigation is to achieve continuous mode hope free frequency tuning of a 780 nm diode laser in an extended cavity configuration and to apply it for high resolution spectroscopy in Rb. Theoretical considerations will be made about the influence of the optical feedback parameters on the tuning abilities of an ECDL system when different kinds of LDs are used.

THEORETICAL MODEL

In the following section we will discuss the theoretical model which has been used to investigate the tuning abilities of an ECDL system, depending on the diode laser used. Basically, the ECDL system can be presented as a three-element resonator, the rear diode laser facet amplitude reflectivity being r_1, the internal coupling facet amplitude reflectivity-r_2, and r_3 is considered as a frequency dependent amplitude reflectivity of the external grating. The oscillation condition for the coupled-cavity laser system is given by [2]:

$$r_1 e^{(g-\alpha_m)l_d} e^{i\omega\tau} r_{eff} = 1 \qquad (1)$$

where l_d is the LD chip length, $\tau = 2nl_d/c$ is the LD round trip transit time, α_m is the loss and n is the LD chip index of refraction. r_{eff} is the effective reflectivity of the composite mirror formed by the LD coupling facet and the grating and it is

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given by the expression:

$$r_{eff} = \frac{r_2 + r_3 e^{i\omega\tau_{ext}}}{1 + r_2 r_3 e^{i\omega\tau_{ext}}} \tag{2}$$

where $\tau_{ext} = 2L_{ext}/c$ is the round trip transit time of the external cavity.

For the grating reflectivity the following expression has been used [3]:

$$r_3 = \frac{r_3^{max}}{N}\left|\frac{\sin\left(\frac{N\pi\omega}{\omega_o}\right)}{\sin\left(\frac{\pi\omega}{\omega_o}\right)}\right| \tag{3}$$

where N is the total estimated number of the grating grooves illuminated by the laser beam, ω_o is the frequency of the maximum of the reflection profile, r_3^{max} is the grating reflectivity there, and ω is the oscillation frequency.

By separating the real and the imaginary parts of Eq. (1), the equations for the threshold gain and the oscillation frequency have been obtained:

$$g_{th} = \alpha_m - \frac{\ln(r_1|r_{eff}|)}{l_d} \tag{4a}$$

$$\omega - \omega_q = -\frac{Arg(r_{eff})}{\tau} \tag{4b}$$

where $\omega_q = 2\pi q/\tau$ is the q-th LD chip longitudinal mode. The following expression has been used to take into account the dependence of the oscillation frequency on the threshold gain via the index of refraction [2]:

$$n - n_o = \frac{\alpha c}{2\omega}\left(g_{th} - g_{th}^{o}\right) \tag{4c}$$

where $g_{th}{}^{o} = \alpha_m - \ln(r_1 r_2)/l_d$ is the LD threshold gain without optical feedback, n_o and n are the indices of refraction of the LD chip without and with optical feedback respectively, α is the ratio of the real to the imaginary part change in the refractive index.

By combining Eqs. (4a,b,c), the following result has been obtained for the threshold gain:

$$g_{th} = \frac{1}{\alpha \cdot l_d}\left[\frac{2n_o l_d}{c}\left(\omega_q^{o} - \omega\right) - Arg(r_{eff})\right] + \alpha_m - \frac{\ln(r_1 r_2)}{l_d} \tag{5}$$

where $\omega_q{}^{o} = q\pi c/n_o l_d$ is the resonant frequency of the LD without optical feedback.

By simultaneous solving of Eq. (5) and Eq. (4a) the possible operation frequencies with their respective threshold gains for the ECDL system are obtained.

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THEORETICAL AND EXPERIMENTAL CONSIDERATIONS

To achieve long continuous mode hop free frequency tuning it is necessary to keep the oscillation frequency at the lowest threshold gain with respect to the other potential modes of the composite resonator. In order to achieve the maximum tuning range for a given ECDL system one should take into account all the parameters influencing the threshold gain and choose their most appropriate values. In our previous communication [3] we have investigated the tuning behaviour of different commercially available LDs. There we have shown that in order to achieve long continuous frequency tuning one needs rotation-translational movement of the grating together with appropriate injection current change to ensure matching between the external cavity mode and the LD mode change in the frequency domain. A way to facilitate this is to make the external cavity length an integer multiple of the optical path length of the LD chip. Then, if the current change rate does not provide matching, a new mode with a small intensity appears. Adjusting the injection current so that this so called “forerunner” disappears, synchronous movement of the solitary LD mode and the external cavity mode is ensured.

Here we have investigated theoretically and experimentally the tuning behaviour of an ECDL system using a LD with modest antireflection (AR) coating and compared it with our previous investigations and with a system with a good quality AR coated LD. The residual reflectivity of the coupling facet of the LD used in our experiment is $r_2 = 5.6 \times 10^{-3}$. The theoretical calculations for the threshold gain dependence on the reflectivity r_2 by tuning the ECDL length over a frequency interval equal to the external cavity FSR are shown in Fig. 1. It can be seen that for a frequency change of 10 GHz we have a significant change in the threshold gain for a commercially available LD chip (i.e. without any AR coating). A small change in the threshold gain can be seen for a LD chip with modest AR coating and almost no change in the case of good quality AR coating. Therefore the use of an AR coated laser diode is more appropriate for spectroscopy, because of the smallest output powerchanges.

Now we should take into account how the threshold gain changes for the other possible oscillation frequencies in the vicinity of the maximum of the grating profile. Fig. 2a shows the possible oscillation frequencies and their thresholds when the external cavity length is not an integer multiple of the optical pathlength of the LD. In this case, if we assume that the oscillating mode is the one with the lowest gain, the closely situated modes have higher enough threshold. However, it can be seen that a jump to other, quite distant, LD modes is possible. The difference between the threshold gain for the oscillating mode and the neighbouring one can be increased by making the ratio $L_{ext}/n_o l_d$ integer (see Fig. 2b).

Depending on the linewidth enhancement factor α and the ratio r_2/r_3 the span of the threshold gain variation for the possible solutions of the steady-state

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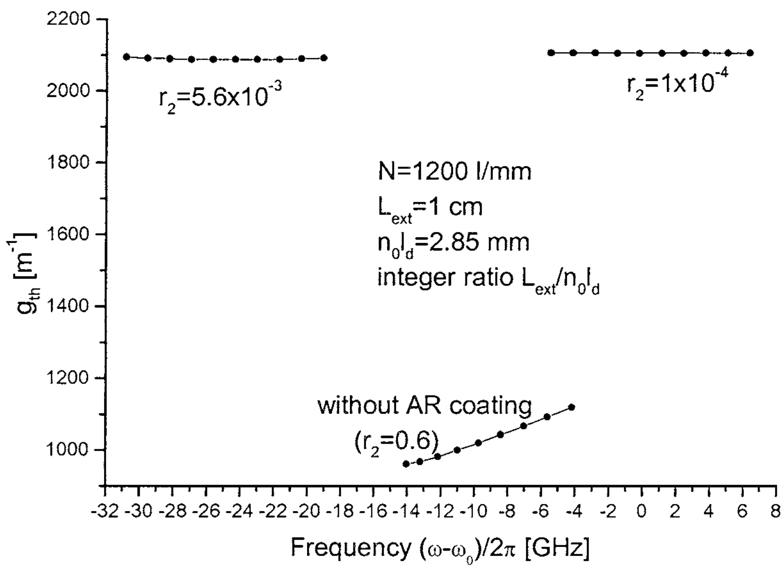

Figure 1. Calculated oscillation frequency thresholds when the ECDL length is changed by $\lambda/2$ for different kinds of LDs. The following values have been used in the calculations: $\alpha = -7; r_3^{max} = 0.3; \alpha_m = 0, r_1 = 0.6$.

equation changes. Thus, we distinguish two regimes of operation - monostable and bistable (frequency zones with multiple thresholds). For the bistable regime (Fig. 2) it is characteristic that a small change in the refractive index leads to a big output power change due to the change of the threshold gain. In [2] the values of the different parameters for both regimes have been calculated. It can be seen that one possible way to avoid bistable operation is to decrease the ratio r_2/r_3 by using AR coated LDs.

With decreasing the reflectivity of the coupling LD facet r_2 we decrease the quality factor of the LD resonator and thus - of the composite cavity. This leads to decreasing the difference in the threshold gain between the possible neighbouring solutions of the steady-state equation, which can be seen from Fig. 3a. Here only closely situated jumps of the oscillation frequency, i.e. between the longitudinal modes of the external cavity, are observed. If the detuning of the maximum of the grating from one of the LD modes equals $c/4n_o l_d$, a jump to the neighbouring LD mode is possible (Fig. 3b). This is a big disadvantage when an exact oscillation wavelength is required, which is to be tuned over a given interval. Here we should also point out that considerable improvement cannot be made by adjusting the ratio $L_{ext}/n_o l_d$ to be integer.

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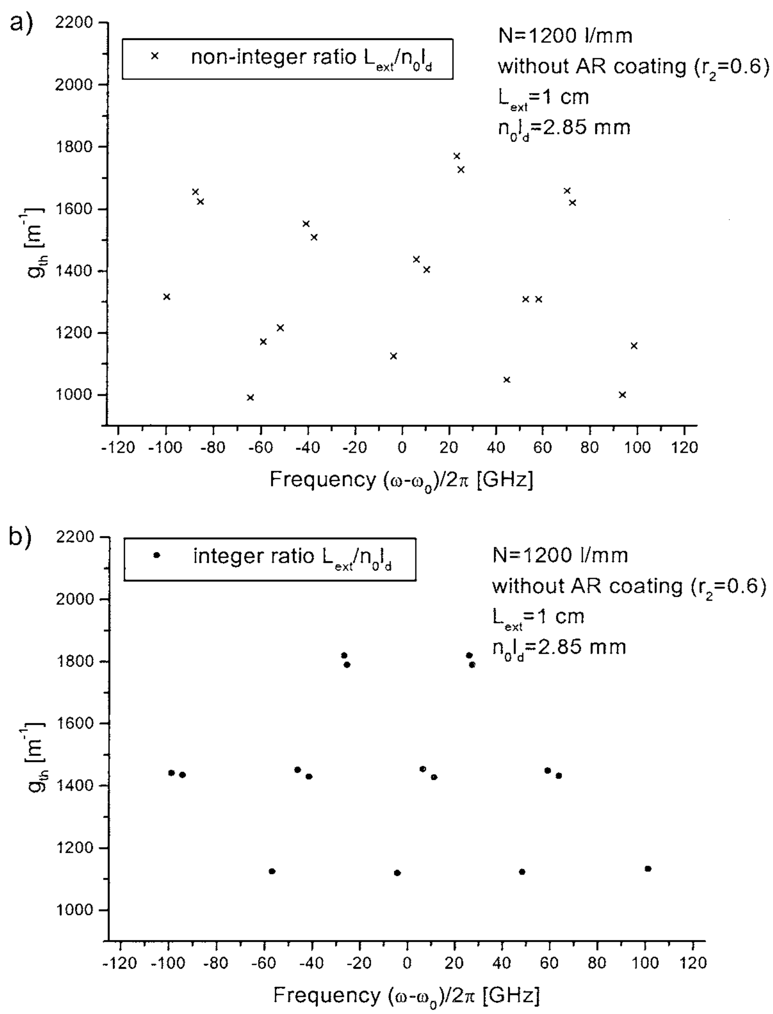

Figure 2. Possible solutions of the steady-state equation for LD without AR coating ($r_2 = 0.6$), *a* and *b*.

One other consideration which should be made is about the influence of the optical feedback width on the threshold difference between neighbouring modes. We have calculated the possible oscillation frequency threshold gains depending on the grating used at a constant beam size (Fig. 4). It can be seen that a dramatic change in the threshold for two adjacent modes is not present. However,

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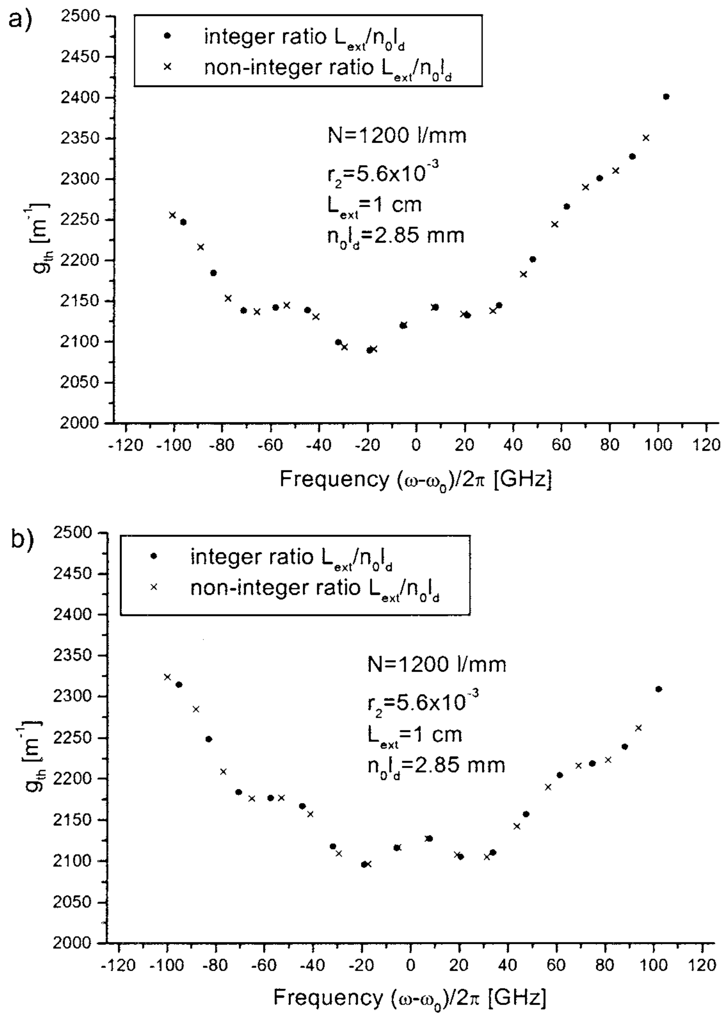

Figure 3. Threshold gain variation as a function of the possible oscillation frequencies when *a*) the grating maximum exactly matches one LD longitudinal mode and *b*) is detuned from it by $l_d/4c$.

the suppression of all LD longitudinal modes but one when increasing the optical feedback resolution is significant

A well-known approach for a long continuous frequency tuning, when in an ECDL system a good quality AR coated LD and a grating in Littrow configuration

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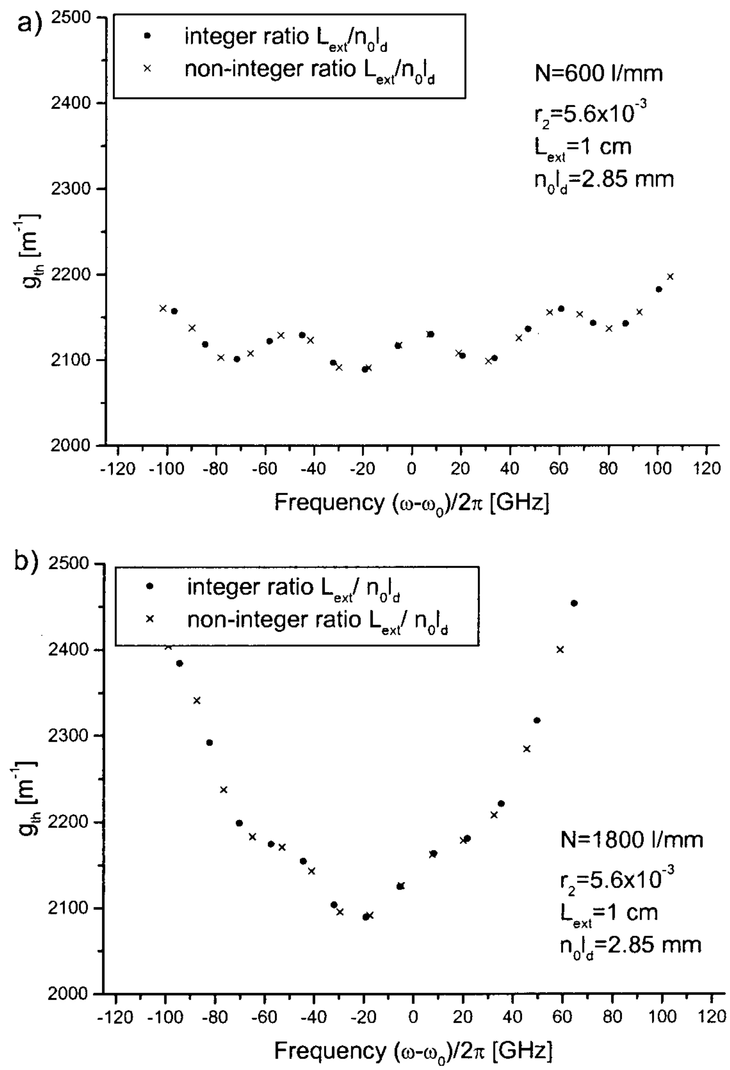

Figure 4. Potential oscillation frequencies threshold change depending on the grating used, *a* and *b*.

are used, is to choose an axis of rotation of the grating at the line of intersection of the plane of the grating and a plane parallel to the LD facet, at a distance from the beam spot on the grating equal to the optical path length of the composite resonator ($L_{ext} + n_o l_d$) [4]. In this case the round trip phase accrued is independent of the

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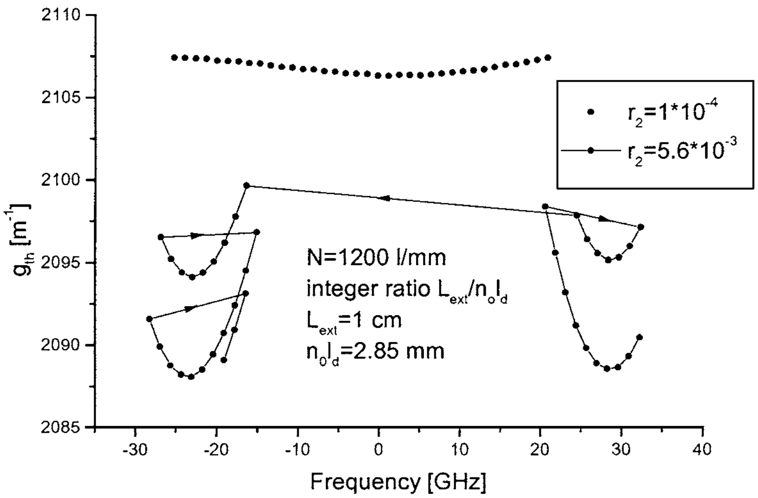

Figure 5. Synchronous continuous frequency tuning behaviour depending on the LD used.

Littrow angle, and hence of the feedback wavelength. Thus, when scanning the external cavity length, a synchronous optical feedback can be realized where the optical feedback wavelength matches a given longitudinal mode.

In our theoretical calculations we have introduced such kind of synchronous optical feedback, where at each iteration, changing L_{ext}, the solution with the lowest threshold gain is taken as the oscillation frequency. The results are presented in Fig. 5, where a smooth mode-hop free continuous tuning is present during the entire scanning interval when a good quality AR coated LD is used. However, with increasing the residual reflectivity of the coupling facet, mode hops appear. Our calculations show that to achieve continuous tuning in a large interval without injection current correction the highest possible value of r_2 is 2×10^{-4}.

With the experimental setup described in [3] long interval continuous frequency tuning of an AR coated ($r_2 = 5.6 \times 10^{-3}$) LD emitting at 780 nm has been realized. In a short external cavity ($L_{ext} \sim 2$ cm), scanning the external cavity length together with an appropriate injection current change, frequency tuning of the order of 80 GHz has been obtained and recorded using a 750 MHz FSR

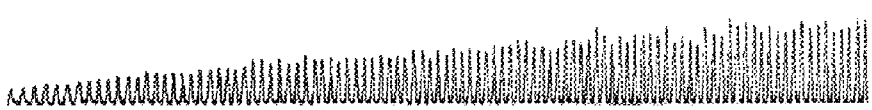

Figure 6. Continuous frequency tuning of the ECDL recorded with a 750 MHz FSR interferometer.

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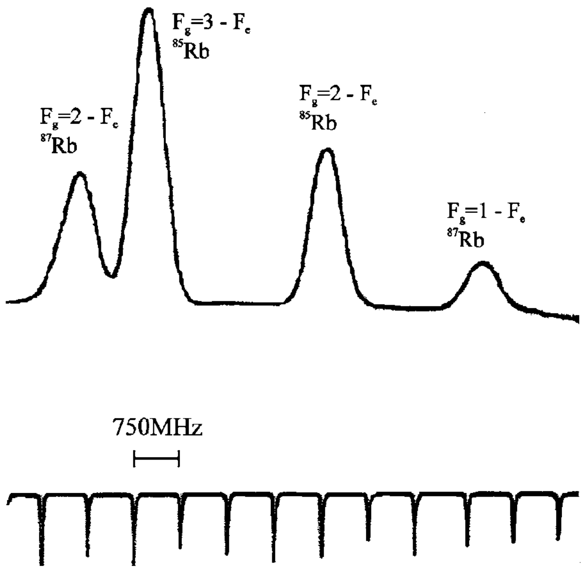

Figure 7. Rb natural mixture fluorescence spectrum around 780 nm.

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interferometer (see Fig. 6). The small threshold difference between the neighbouring potential oscillation frequencies leads to a jump at a smaller mismatch between the solitary LD mode and the lasing one, than for LD without AR coating. However, more appropriate LDs when a certain wavelength is to be reached, are the AR coated ones.

The Rb fluorescence was recorded in an external absorption cell (Fig. 7). The cell (5 cm length, without buffer gas) was inserted in a mu-metal to prevent from earth and stray magnetic fields. The emitted ECDL frequency with linear polarization was tuned to each fine component of the D_2 line.

With the help of a Helmholz coil the magnetic field was scanned around zero value in both directions parallel to the beam propagation. In the fluorescence signal, recorded perpendicularly to the beam propagation, a sub-natural width dip was recorded when the ECDL was tuned to the $F_g = 2 \rightarrow F_e = 1, 2, 3$ transitions in ^{85}Rb (Fig. 8a) and the corresponding peak was observed in the transmitted optical power at zero magnetic field. The FWHM of the observed SNWRs was estimated to be of the order of 30 mG. However, when the ECDL emitted frequency reached the $F_g = 3 \rightarrow F_e = 2, 3, 4$ lines in ^{85}Rb, a peak was observed in the fluorescence signal together with a dip in the output power (Fig. 8b,c).

Such resonance has been observed by F.Renzoni et al. where an atomic medium was coherently excited and the Zeeman degeneracy removed [5]. There the dips were recorded in a Na atomic beam at the D_1 line by scanning the magnetic

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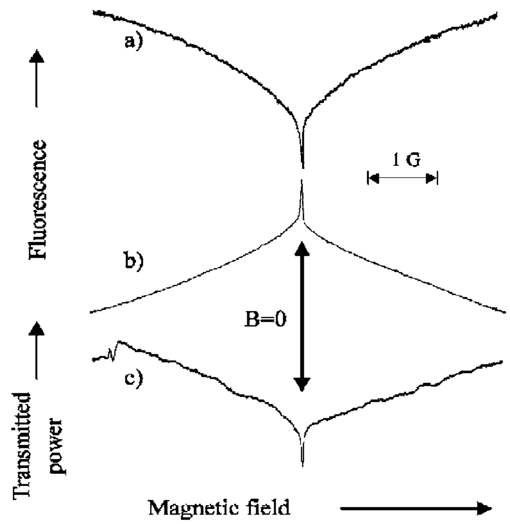

Figure 8. The total atomic fluorescence as a function of the applied magnetic filed. *a*) fluorescence signal and *b*) transmitted power when the ECDL frequency is tuned to the maximum of the $F_g = 2 \rightarrow F_e = 1, 2, 3$ transitions; *c*) fluorescence signal for the $F_g = 3 \rightarrow F_e = 2, 3, 4$.

field. In [6] a peak and a dip have been registered using two coherent laser beams which couple the Zeeman sublevels belonging to the same ground-state hyperfine level to an excited state from the Rb D_2 line. Details about the observed SNWR in Rb will be given elsewhere.

CONCLUSION

Our theoretical calculations show that when a commercially available LD or LD with modest AR coating is used, in order to achieve wide continuous frequency tuning range together with a translation-rotational movement of the grating, an appropriate change of the injection current is required. The highest value of the coupling facet reflectivity, which still requires current correction, according to our theoretical calculations is $r_2 = 2 \times 10^{-4}$. With decreasing the width of the optical feedback, oscillation frequency jumps to some other LD potential modes can be avoided.

Using an ECDL system having the ability of wide continuous frequency tuning, an external Rb cell was irradiated and sub-natural width resonance was observed by scanning the applied magnetic field. Such variations of the absorption or the refractive index of an atomic medium are appropriate for development of

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magnetometers, capable of measuring weak magnetic fields, based on coherent effects [7].

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