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Rapid communication

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High repetition-rate wavelength tuning of an extended cavity diode laser for gas phase sensing

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ABSTRACT A method for rapid wavelength tuning of an extended cavity diode laser (ECDL) is presented providing for high resolution, narrow bandwidth output over limited spectral regions. The method permits tuning over isolated spectroscopic features at repetition rates of tens of kHz, greatly exceeding conventional ECDL tuning speeds. In this paper we present high repetition rate laser induced fluorescence (LIF) spectroscopy of the $5^2P_{1/2}$ to $6^2S_{1/2}$ transition in indium at 410 nm, to demonstrate the technique. The presented ECDL design is very easy to implement, cheap and robust, as it employs no moving parts and can be used over all wavelength regions where FP diode lasers are available. This extends the usefulness of standard FP diode lasers to high speed sensing applications. Advantages and disadvantages of the technique are discussed.

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1 Introduction

Rapidly tuneable laser sources which are compact and inexpensive are desirable for many practical spectroscopic applications, e.g., for industrial and environmental sensing [1]. To unambiguously determine species concentration or temperature, the wavelength tuning range of such lasers must cover a substantial part of the spectroscopic feature to be investigated. This then permits one to estimate the integrated signal line strength, which is important in situations where pressure, temperature and composition changes affect lineshapes. At atmospheric pressure the width of such identifying features are typically in the order of a few tens of GHz for transitions in the visible spectral region. For many practical applications (e.g., industrial sensing) very high spectral resolution is not required whereas rapid tuning over selected features is much more important. Laser tuning rates must match the dynamic timescales of the process to be studied. For example, the study of a turbulent combustion processes may require scanning rates exceeding 10 kHz.

Diode lasers represent an attractive light source for industrial sensing as they are compact, reliable, robust and inexpensive. Fabry–Pèrot (FP) diode lasers represent the simplest type of laser in this class, and they are available over a wide range of wavelengths, ranging from the near-infrared to the near-UV spectral regions. However, FP lasers generally exhibit unstable multi-mode emission limiting their usefulness for spectroscopy. By implementation of an FP diode laser in an extended cavity providing optical feedback from a grating, stable narrow linewidth single-mode emission can be achieved [2]. Such extended cavity diode lasers (ECDL) are widely tuneable, but normally rely on a mechanical movement of a grating or mirror. This limits tuning speeds to a few hundred Hz or below, if tuning ranges exceeding 10 GHz are desired [3]. Many sensing applications require much faster tuning rates than this. Fast electro-optical tuning of an ECDL, has been used to overcome this problem [4]; however, at greatly increased complexity and cost. For applications requiring a wide tuning range but only a limited spectral resolution, a mode-less ECDL has recently been demonstrated [5]. Competitive technologies in this area are therefore mostly based on alternative laser architectures such as current tuned distributed feed-back (DFB) lasers [1, 6, 7], thermally cycled DFB lasers [8], vertical cavity surface emitting lasers (VCSEL) [9], and pulsed quantum cascade (QC) lasers [10]. All of these laser types are available over limited wavelength regions only, and thus the present method provides opportunities for applications where these technologies are not applicable, e.g., in the visible spectral region.

In this paper we present a technique for rapid current tuning of ECDL lasers, capable of scanning over 30 GHz frequency ranges at a rate of 10 kHz. The principle of this technique is illustrated in Fig. 1. The diode injection current is continuously varied whilst keeping the extended cavity length and the grating angle fixed. This results in an effective change in the FP cavity length with an associated shift of the diode mode spectrum (indicated in Fig. 1b at times t_0 to t_3). At t_0 one of the diode modes (shown as a dashed line) overlaps with one of the modes imposed by the extended cavity structure, and thus the ECDL emits single-mode radiation at this wavelength. At t_1, however, one of the neighboring diode modes over-

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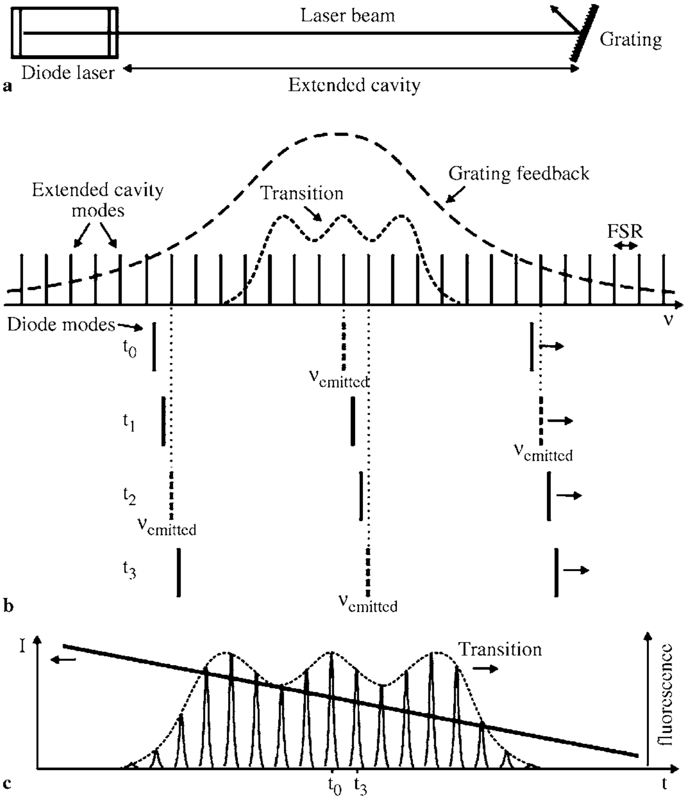

FIGURE 1 Schematic illustration of (**a**) ECDL system, (**b**) rapid current ECDL tuning, and (**c**) resulting spectrum

laps better with another extended cavity mode, and the ECDL starts emitting at this wavelength following a mode-hop. Similar modehops occur at t_2 and t_3, but at t_3 the original FP mode becomes active again at a frequency shifted by exactly one FSR of the extended cavity compared to t_0.

In the situation shown the spectroscopic feature of interest ("transition") covers less than one FSR of the FP laser (typically 50–100 GHz), and therefore a signal is only obtained at times t_0 and t_3 as the other laser modes (at t_1 and t_2) lie off resonance. The experimental spectrum is thus sampled at discrete wavelengths, with the resolution determined by the FSR of the extended cavity (see Fig. 1c). As current injection tuning can be performed very rapidly, such sampled spectral scans can be obtained very quickly (tens of kHz, limited by the thermal response of the active region in the FP laser). An advantage of the technique is that the background is continuously sampled in regions where the laser output is off resonance. This approach then offers rapid tuning capabilities in a very simple fashion, using off-the-shelf FP diode lasers and opto-mechanical components. In this paper we demonstrate the technique using a GaN diode laser operating in the blue spectral region. A related ECDL tuning scheme has previously been demonstrated in the near-IR spectral region, using a long cavity Littman–Metcalf design [11].

2 Experimental details

For these experiments a 410 nm Fabry–Pèrot (FP) diode laser (Nichia Corporation) was configured in an extended cavity. An 1800 lines/mm holographic grating was mounted in a Littrow configuration to serve as frequency-selective device and output coupler as shown in Fig. 1a. The length of the extended cavity was approximately 50 mm, resulting in a FSR of 2.9 GHz, whereas the FSR of the FP laser was of order 70 GHz [12]. The FP laser injection current was ramped at 10 kHz using a commercial current controller (Tektronix LDC8002). Higher scanning rates are in principle possible (up to 50 kHz for the present ECDL) but the present experiment was limited by the bandwidth of the available signal detection electronics. During a scan the injection current decreased linearly from 75 mA to just below lasing threshold at 45 mA. At maximum current the single mode output power from the laser was around 4 mW.

For LIF measurements the beam was focused to a 100 μm waist in a flame, to excite indium in the $5^2P_{1/2}-6^2S_{1/2}$ transition. LIF signals were collected near 451 nm ($6^2S_{1/2}-5^2P_{3/2}$) at right angles and imaged onto a 0.5 mm pinhole in front of a photomultiplier tube (PMT) equipped with a 451 nm interference filter. The flame was a laminar premixed CH_4/air Bunsen flame operated at a fuel/air equivalence ratio $\varphi = 1.06$, which was seeded at ~ 100 ppb levels of indium atoms (determined by absorption) using a nebulizer containing an aqueous solution of $InCl_3$. A photodiode was used to simultaneously monitor the laser power during the scans. The preamplified PMT and photodiode signals were acquired using a digital oscilloscope.

The recorded fluorescence signals were first normalized by the laser power, and the frequency scale of each scan was linearized, using the positions of the single-mode fluorescence peaks, which are separated by the FSR of the extended cavity.

3 Results and discussion

In Fig. 2 an example, single sweep, fluorescence spectrum recorded in 100 μs is shown. For comparison, a high resolution spectrum spanning 45 GHz is also shown, which was obtained using synchronous extended cavity and FP injection current tuning as described in previous publications [12, 13]. The spectra cover four hyperfine transitions which appear merged at atmospheric pressure [14]. In the rapid scan spectrum 12 distinct peaks appear, which correspond to the times when the laser output is in resonance with the indium transition. The peaks are separated by the extended cavity FSR. On resonance, the laser was verified to operate in single mode by performing slow scans over the indium transition whilst simultaneously analysing the laser output spectrum on a fast scanning FP etalon. Between these peaks regions of single mode operation at off-resonance diode modes, shifted by one or several FSR

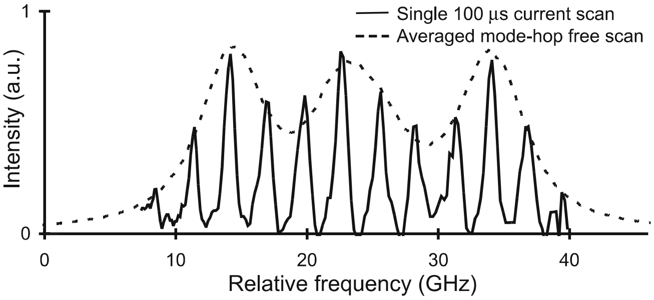

FIGURE 2 An indium fluorescence excitation spectrum ($5^2P_{1/2} - 6^2S_{1/2}$, at 410 nm) resulting from a 100 µs current scan. Individual peaks correspond to regions of single-mode excitation of the transition and are spaced by 2.9 GHz corresponding to the FSR of the extended cavity. A high resolution spectrum from a conventional slow single-mode scan is also shown for comparison

of the FP diode laser, was observed as well as narrow regions of multi-mode emission.

As seen there is good agreement between the rapid scan spectrum (acquired in 10^{-4} s) and the high resolution spectrum (single scans acquired in 10^{-1} s). Fluorescence was collected from a region near the flame front, and thus some of the deviations observed between the two spectra are due to rapid fluctuations in the local indium concentration and flame background emission, which also affect the off resonance signal levels in between the peaks.

The single-scan spectrum recorded at 10 kHz has a resolution of about 3 GHz, determined by the FSR of the extended cavity. One way of obtaining spectral information in the "gaps" seen in Fig. 2 is to decrease the extended cavity length from scan to scan. Here this was achieved by use of a piezo-actuator controlled grating mount. As a consequence the positions of the extended cavity modes gradually shift, permitting the sampling grid (mode spectrum) to be stepped across the lineshape. An example of this is shown in Fig. 3 where 25 individual spectra were acquired for each cavity length before the cavity was adjusted to shift the mode spectrum by 0.5 GHz. The data points show the mean of the peak positions from the individual scans ($n = 25$) and error bars denote standard deviations of individual peak values from the mean. Spectra were divided by the laser power which decreased approximately by a factor of three across the scan.

A non-linear least squares fit of a theoretical spectrum is shown as a solid line in Fig. 3. It consists of four Voigt profiles corresponding to the hyperfine transitions, whose positions and relative intensities are also indicated [14]. The data points are seen to agree well with both the theoretical spectrum and a conventionally obtained high resolution spectrum (dashed line), which is also shown.

It is observed that the scatter in the data increases towards larger frequencies, which is explained by the decreasing laser power at the end of the scan. As a result shot noise levels increase in the fluorescence signal (accounting for about half of the total observed fluctuations). The influence of background fluctuations from flame emission and electronic acquisition noise is also amplified for the same reason. Remarkably, the contribution due to laser noise is very small despite the dynamic character of the tuning method employed which relies on laser mode-hopping. An upper estimate from the simultaneously acquired laser output power traces, as well as from separate absorption measurements (data not shown), suggests that the laser power in each individual mode is repeatable to within 2% from scan to scan. The frequency stability from scan to scan is equally reproducible. As a comparison the intensity fluctuation of the ECDL when not scanned was around 0.1%.

It is also possible to obtain a higher spectral resolution by employing a longer extended cavity. This leads to a reduction of the spacing between the associated resonance peaks as the cavity FSR decreases. In Fig. 4 an indium fluorescence spectrum is shown, which was recorded using an ECDL cavity length of 100 mm (twice that used in Fig. 2). The peak values of the single mode regions are again seen to correspond well

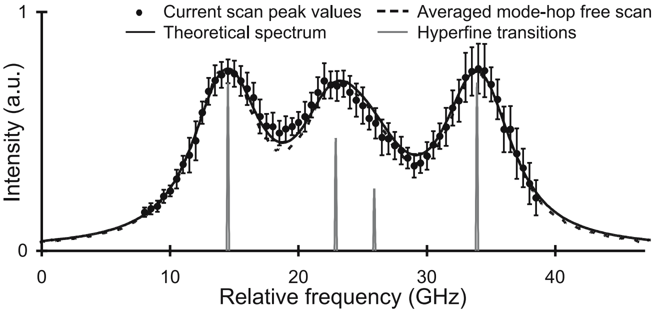

FIGURE 3 Indium fluoresecence spectrum obtained by the "mode stepping" technique described in the text. *Dots* represent averages of peak values extracted from indium fluorescence traces, like the one shown in Fig. 2, *error bars* indicate the standard deviation (25 individual spectra were used per data point). A theoretical fit to the data is shown as well as a conventional high resolution scan (*dotted line*). The position and relative intensities of the 4 hyperfine transitions are indicated

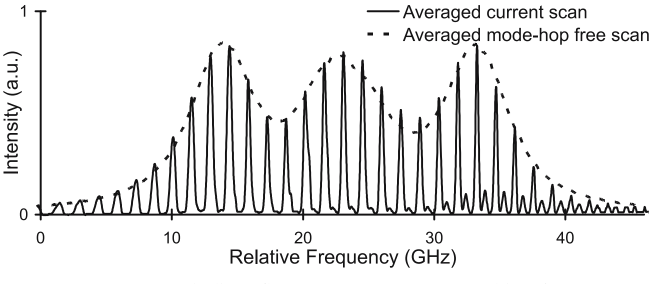

FIGURE 4 Average indium fluorescence spectrum resulting from current scans of an ECDL with a cavity length twice as large as that used for the scans shown in Fig. 2. Individual peaks correspond to regions of single-mode excitation of the transition and are spaced by 1.5 GHz corresponding to the FSR of the extended cavity. A high resolution spectrum from a conventional slow single-mode scan is also shown for comparison

with the previously acquired mode-hop free spectrum. For this longer cavity length a second set of weaker peaks, situated in between the single mode resonance peaks, appear in the low power part of the laser scan (between 30 and 45 GHz in Fig. 4). These peaks correspond to regions of multi-mode operation of the ECDL, where one of the active FP modes is the one which is on resonance with the indium transition. In addition to this, a much larger sensitivity to precise cavity alignment was observed for the longer cavity ECDL.

The maximum tuning range was found to be a function of the current modulation rate due to the finite thermal response of the FP laser to current injection; at modulation rates below 100 Hz the useful tuning range remained constant at around 70 GHz for the present laser which corresponds to the full FSR of the FP laser. Above 100 Hz it gradually decreases, to around 30 GHz at 10 kHz scanning rate, and to around 25 GHz at 50 kHz scanning rate, which was the highest scanning rate attempted here.

4 Conclusions

In this paper rapid wavelength tuning over the $5^2P_{1/2} - 6^2S_{1/2}$ transition at 410 nm in indium is reported with an ECDL system based on a blue GaN diode laser. Tuning rates exceeding 10 kHz were possible by employing injection current tuning in a FP diode laser mounted in a fixed length extended cavity. Rapid scanning is achieved over ranges spanning tens of GHz using a simple, compact and economical design requiring no moving parts. The method relies on a mode matching between FP laser and extended cavity longitudinal modes and as a result a standard FP diode laser could be employed. In contrast to some other extended cavity laser designs featuring single mode tuning, no expensive anti-reflection coatings are required on the FP laser. The availability of FP lasers over an extensive spectral range permits one to target a variety of species at good sensitivity with speed.

The probed transition consists of an isolated feature spanning less than one free spectral range of the FP diode laser, and thus there was no need for suppression of modes not overlapping with the transition. Probing of parts of more convoluted spectra would in principle be possible by suppressing side modes outside the region of interest (e.g., by an etalon or grating).

One direct application of the rapidly current tuned ECDL laser will be in a TLAF (two line atomic fluorescence) [15] flame temperature sensor where two such systems are required to probe two temperature sensitive states in indium [16]. This would permit accurate thermometry to be performed at tens of kHz with applications, e.g., in IC engine research.

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