

# Actively controlled tuning of an external cavity diode laser by polarization spectroscopy

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**Abstract:** We report on an universal method to achieve and sustain a large mode-hop free tuning range of an external cavity diode laser. By locking one of the resonators using a closed loop control based on polarization spectroscopy while tuning the laser we achieved mode-hop free tuning of up to 130 GHz with a non AR-coated, off-the-shelf laser diode.

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**OCIS codes:** (140.2020) Diode lasers; (140.3425) Laser stabilization; (140.3570) Lasers, single-mode; (140.3600) Lasers, tunable; (140.4780) Optical resonators

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## 1. Introduction

Shortly after the invention of the semiconductor laser [1, 2, 3] it became evident that its properties could be significantly improved by coupling a fraction of the laser light back into the laser diode [4]. Usually this feedback is accomplished by a reflection grating in either Littrow [5] or Littman [6] configuration, thus forming an external cavity between the laser diode's end facet and the grating. By rotating and moving the grating with piezo actuators it is possible to scan the wavelength which makes the external cavity diode laser (ECDL) a versatile tool for many applications such as precision spectroscopy [7], cooling and trapping [8] as well as sensing [9, 10]. Most applications require that the wavelength scan is free of mode-hops, i. e. the wavelength must vary continuously over time. Setting up and maintaining a large mode-hop free tuning range is difficult, since the external and the internal cavity formed by the end facets of the semiconductor itself need to be tuned synchronously. This is usually achieved by moving and/or tilting the grating and simultaneously applying a ramp to the laser diode current. The varying current adjusts the internal cavity length and keeps the internal and external cavities synchronized [7]. Mainly, two problems occur. First, the components do not generally respond in a linear fashion. Second, vibrations and thermal fluctuations lead to mode-hops.

However, an active control of the laser diode current or the piezo actuators voltage ramps can overcome these problems. Two methods exist: One approach systematically adjusts the slope and shape of the voltage ramp until the scan is free of mode-hops [11]. This method compensates non-linearities and large mode-hop free tuning ranges have been demonstrated. However, it needs some time to find the optimal set of parameters and does not offer realtime control. Another approach employs the top-of-fringe locking scheme by modulating the laser diode current to generate an error signal which can be used to implement a closed loop control [12].

We present a novel method to achieve and sustain even larger mode-hop free tuning ranges by locking one of the ECDL's resonators while ramping the free spectral range (FSR) of the other using a closed loop control based on polarization spectroscopy. This method is straight forward in the implementation and does not require a rf-modulation of the current.

We have investigated two locking schemes: (1) locking of the laser diode current to the length of the external cavity and thus to the voltage of the piezo actuators (Piezo-Current-Locking, PCL). (2) locking of the piezo actuators voltages to the length of the internal resonator, which is altered by varying the temperature of the laser diode (Temperature-Piezo-Locking, TPL). The latter overcomes the limitation of the tuning range due to the laser diode's maximum current ratings, but is inherently slower. It is reasonable to always use the parameter with the higher bandwidth as the control variable. In the case of TPL for example, the external cavity length can be altered quickly using the piezo actuators, whereas the temperature of the laser diode allows a slow, but smooth variation of the internal FSR.

In either case, the Stokes-parameter  $S_1 = (I_p - I_s)$ , i.e. the intensity difference of the p- and s-polarization components, of the ECDL output is used as an error signal to control the FSR of the

locked cavity. Since our technique uses the state of polarization (SOP), it is independent of output power. Basically, our method is comparable to the Hänsch-Couillaud locking scheme [13] in the sense of probing a cavity's resonance using the SOP. However, the theoretical model of our technique reveals important differences as the entire system consists of coupled resonators. Furthermore, the probe laser and the sample cavity form one entity.

## 2. Experimental Setup

The whole setup consists of an ECDL in Littrow configuration, the SOP detection unit, a high finesse Fabry-Perot interferometer, and the control electronics (cf. Fig. 1). The basic setup of the ECDL is based on [14]. In contrast to the design presented in [5], this setup employs three piezo-actuators to allow an independent rotation and translation of the grating. The ECDL is equipped with an off-the-shelf laser diode (Sanyo DL7140-201S, 785 nm) without anti-reflection coating. By placing a quarter waveplate into the external cavity, it is possible to adjust the error signal for optimal locking and ECDL operation. Furthermore, the waveplate allows adjustment of the feedback amount into the laser diode by employing the polarization dependent efficiency of the grating.

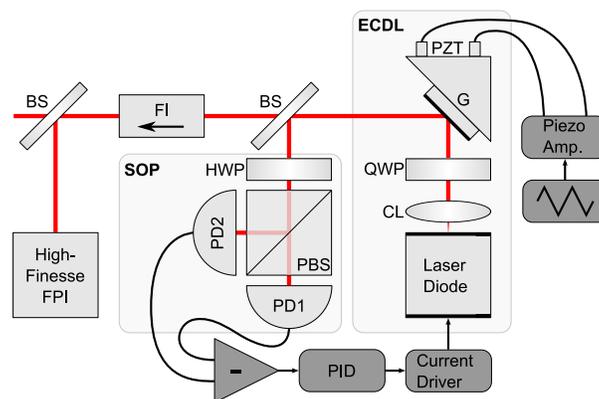


Fig. 1. Setup of the ECDL, spectral and polarization diagnostics, and electronics. CL-collimation lens, G-grating, BS-beam sampler, PD-photodiode, PBS-polarizing beam splitter, FI-Faraday isolator, QWP-quarter waveplate, HWP-half waveplate, FPI-Fabry-Perot interferometer, PZT-piezo-electric transducer

The SOP is measured by decomposing the laser light into its s- and p-basis states using a polarizing beam splitter. The respective intensities are measured with a photodiode (Philips BPW34). The difference of the photodiode signals yields  $S_1$ , which serves as the error signal for the closed loop control. A half waveplate in front of the beam splitter allows balancing the photodiode signals and moreover, it is possible to achieve sharp transitions of  $S_1$  at the resonances of the ECDL cavity (cf. Fig. 2). In addition, we have also employed a polarimeter (Thorlabs PAX5710IR1) to obtain an independent measurement of the SOP.

For spectral diagnostics, part of the ECDL's output is monitored by a high finesse interferometer (Toptica, FPI 100, FSR=1 GHz) with a finesse of at least 300. This interferometer allows a precise measurement of the tuning range, and furthermore the detection of mode-hops as well as multimode operation.

### 3. Principle

It is well known that the output power as well as the wavelength of an ECDL varies periodically while altering the internal or external cavity lengths [15]. These fluctuations, also referred to as self-mixing interference [16], are used for displacement measurements in sensing applications [17]. Thus, the intensity of the laser output carries the information about the resonance of the ECDL's compound cavity. But since the laser diode current needs to be altered during ECDL tuning for PCL, the intensity cannot serve as the error signal.

However, by placing a waveplate inside the external cavity, it is possible to transfer these intensity fluctuations to the SOP of the laser light (cf. Fig. 2). In the context of self-mixing interferometers, the SOP represents a measure of the length of the external cavity with respect to the internal cavity. Thus, the SOP carries the information about the resonance of the ECDL's compound cavity. In order to verify that the SOP offers the ability to be used as a locking signal and to get a better understanding of the SOP fluctuations, we have developed a theoretical model, which will be detailed in a future publication [18]. Briefly, we treat the ECDL as a three-mirror Fabry-Perot interferometer [19] and calculate the transmission profile using the Jones calculus [20] taking into account the polarization dependent efficiency of the grating. Thus, polarization elements, such as e. g. the intracavity quarter waveplate, as well as multiple reflections between any of the mirrors are automatically taken into account. There is an excellent agreement of our model and the dependence of the SOP as the cavities are tuned.

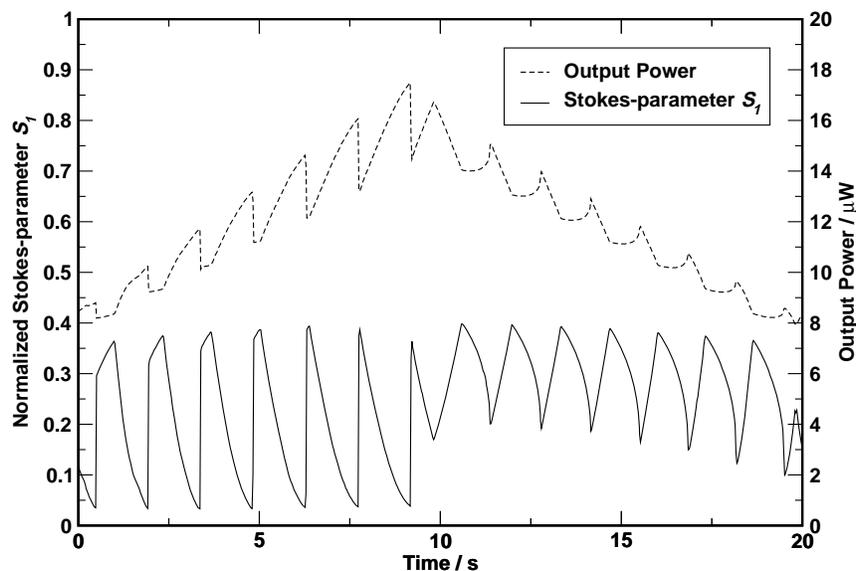


Fig. 2. Stokes parameter  $S_1$  and attenuated output power of the ECDL as measured with the polarimeter while the diode current was varied. The external cavity was held constant. The fast axis of the quarter waveplate was rotated about  $50^\circ$  relative to the original polarization of the laser diode.

### 4. Experimental results

We have investigated both locking schemes described above, i. e. PCL and TPL. For PCL, a signal generator was used to create a sawtooth pattern modulating the master control input of the piezo-controller (Thorlabs MDT693A). Gain and offset of each piezo actuator were optimized manually during locking. The current of the laser diode was controlled using a standard

analog PID controller driving the current modulation input. It incorporated an electronic limiter in order not to exceed the current limits of the laser diode. The setting of the half and quarter-waveplate was  $50^\circ$  and  $164^\circ$ , respectively. Especially the half-waveplate needs to be adjusted carefully in order to shift the setpoint on or as close as possible to the value of  $S_1$  under resonance condition. With locking engaged, changing the amplitude of the ramp-pattern of the piezo-voltage automatically adjusts the slope of the laser diode current ramp. By increasing this amplitude until the maximum current rating of the laser diode is reached, the maximum mode-hop free tuning range for a certain laser diode is achieved. Using PCL, we were able to scan 105 GHz mode-hop free at a central wavelength of 785 nm with a repetition rate of 11 Hz (cf. Fig. 3). Both, the positive and negative ramps are mode-hop free. The particular intensity dependence is due to the hysteresis and the nonlinear behaviour of the piezo actuators. Our locking scheme guarantees a synchronized adjustment of the diode laser current.

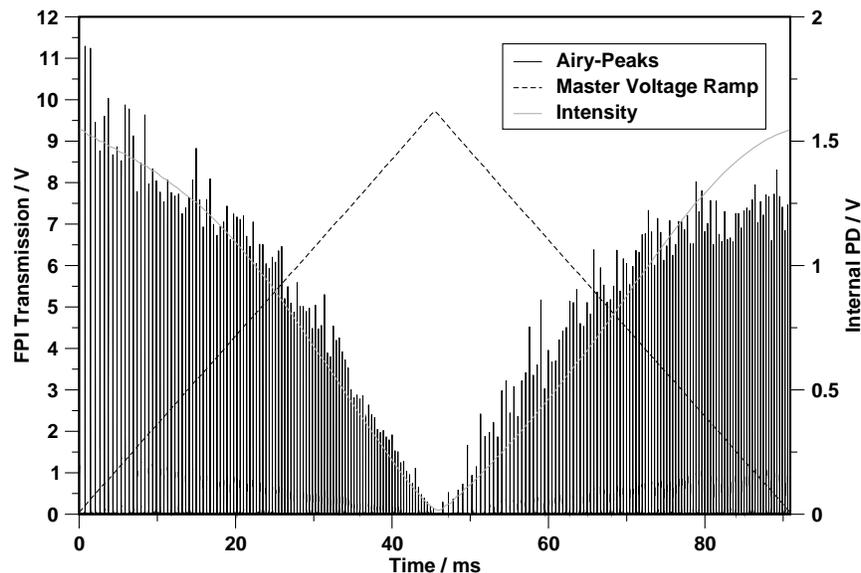


Fig. 3. Mode-hop free scan over 105 GHz at a scan rate of 11 Hz as measured with the Fabry-Perot etalon. The laser diode's internal photo diode was used to measure the intensity. In addition, the voltage ramp applied to the piezo controller is shown.

For TPL the setup is slightly modified. Instead of ramping the piezos, the temperature of the laser diode is changed using Peltier elements. A simple on-off controller based on a Schmitt-Trigger periodically swaps the polarity of the voltage source applied to the Peltier elements. The current of the laser diode was set to a fixed value whereas the piezo voltage was driven by the PID-controller. In 80 s, a 130 GHz mode-hop free scan (cf. Fig. 4) was possible. Then the maximum extension of the piezo transducers limited the tuning range. In principle, a faster scan rate should be possible, but this would have required a redesign of the temperature control mount of the laser diode in order to allow faster adjustments. For the 130 GHz tuning, a temperature change of the laser diode of  $3.6^\circ\text{C}$  from  $23.2^\circ\text{C}$  to  $26.8^\circ\text{C}$  was needed.

## 5. Conclusion

In conclusion, a novel locking scheme based on polarization spectroscopy for ECDLs has been developed. It can be implemented with comparably small means. Therefore, our method should easily incorporate into existing ECDL setups. Using our technique, we are able to scan up to

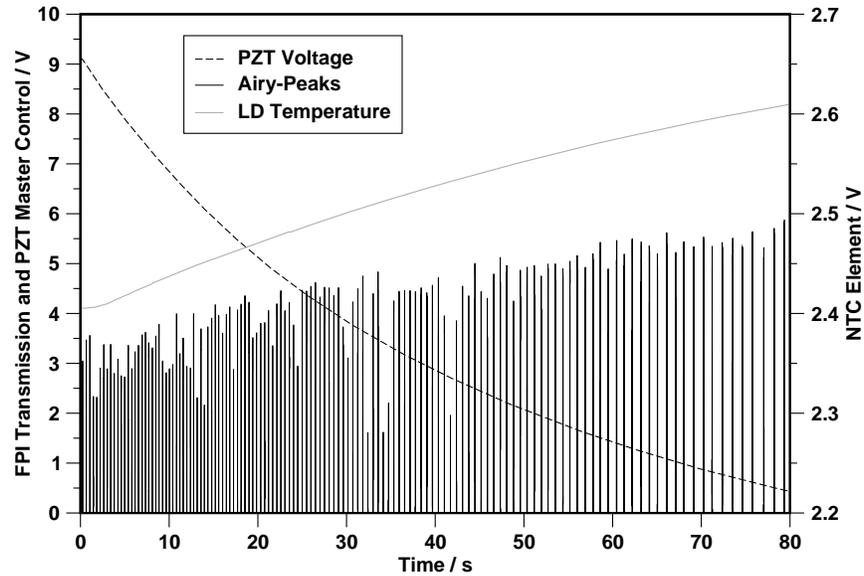


Fig. 4. Mode-hop free scan over 130 GHz as measured with the Fabry-Perot etalon. A NTC thermistor was used to measure the temperature of the laser diode. In addition, the locked voltage ramp of the piezo actuators is shown.

105 GHz mode-hop free at a scan rate of 11 Hz using PCL and 130 GHz in 80 s using the TPL method, respectively. In both cases, an non AR-coated, off-the-shelf diode laser operating at 785 nm has been used.

## 6. Acknowledgment

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