AIP | Review of Scientific Instruments

Narrow linewidth tunable external cavity diode laser using wide bandwidth filter

Daniel J. Thompson and Robert E. Scholten

Citation: Review of Scientific Instruments **83**, 023107 (2012); doi: 10.1063/1.3687441
View online: http://dx.doi.org/10.1063/1.3687441
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/83/2?ver=pdfcov
Published by the AIP Publishing

Narrow linewidth tunable external cavity diode laser using wide bandwidth filter

Daniel J. Thompson and Robert E. Scholten[a)]
ARC Centre of Excellence for Coherent X-ray Science, School of Physics, The University of Melbourne, 3010, Australia

(Received 7 August 2011; accepted 2 February 2012; published online 24 February 2012)

We demonstrate single mode operation of an external cavity diode laser (ECDL) employing an interference filter with multimode bandwidth for mode selection. A cateye reflector maximizes feedback efficiency and reduces susceptibility to intra-cavity optical misalignment. Narrow linewidths of 26 kHz are observed, and the laser can be tuned over 14 nm using a single 785 nm filter, without alteration of the output beam direction. The cateye reflector and filter allow a mechanically rigid design free of significant mechanical resonances, illustrated by comparison of the frequency noise spectrum with that of a common Littrow ECDL design using a diffraction grating and kinematic mount.
 [http://dx.doi.org/10.1063/1.3687441]

I. INTRODUCTION

Common external cavity diode laser (ECDL) designs such as the Littrow and Littman-Metcalf configurations use diffraction gratings for wavelength selection. These lasers require precise alignment and are therefore sensitive to acoustic and mechanical disturbances, particularly when a spring-loaded kinematic mount is used to align the grating or feedback optic.

Narrow bandpass filters provide an alternative approach to wavelength selection, and with sufficiently narrow bandwidth, can ensure operation on a single external cavity mode.[1–4] An important advantage is the ability to use the cateye reflection geometry, which is self-aligning and thus inherently mechanically robust.[5] Single mode operation of cateye lasers has relied on extremely narrow filters, with bandwidths comparable to the intrinsic mode spacing of the laser diode, typically of order 125 GHz (0.25 nm for a 780 nm laser diode). Unfortunately, filters with the required narrow linewidth and high transmission are not readily available, limiting the widespread adoption of this approach.

Here we show that bandpass filters with much larger transmission bandwidths (3 nm), which are readily available at a broad range of wavelengths, can be used to achieve single mode operation of a tunable external cavity diode laser. We demonstrate the principles with a 780 nm diode laser and show that the wavelength can be tuned by more than 14 nm by rotation of the filter in conjunction with changing the diode temperature by 30 °C. We measure a narrow laser linewidth of 26 kHz, and in comparison to a common grating-based design, the frequency noise and sensitivity to vibration are substantially reduced due to the cateye reflector geometry and the insensitivity of the wavelength to filter rotation.

II. MODE SELECTION

The output frequency ν of an ECDL is dependent on a combination of frequency-dependent gain and loss factors and the product of these factors gives the total transmission function:[6]

$$T_{\text{total}} = G_{\text{D}} T_{\text{D}} T_{\text{cavity}} T_{\text{filter}}, \tag{1}$$

where G_{D} is the semiconductor gain profile of the laser diode, T_{D} and T_{cavity} represent the transmission functions for the cavities formed between the front and rear facets of the diode, and between the diode rear facet and the external cavity reflection element, in this case a cateye reflector. T_{filter} is the transmission function of an intra-cavity filter. The laser will oscillate at the frequency for which the product of these factors is greatest.

The relative dispersion factors are compared in Fig. 1. The intrinsic semiconductor gain profile G_{D}, which we approximate as a Gaussian of width 10 nm, is very broad in comparison to other dispersive mechanisms in an ECDL.[7] For the filter transmission function T_{filter} we use the measured spectrum provided by the filter manufacturer. The function is approximately rectangular, with peak transmission $T_{\text{peak}} = 90\%$ and width 3 nm. From the derivative of the transmission function (Fig. 1), the edge widths are 0.3 nm full width at half maximum (FWHM). The transmission window wavelength shifts with rotation according to[8]

$$\lambda(\theta) = \lambda_0 \sqrt{1 - \left(\frac{\sin(\theta)}{n_{\text{eff}}}\right)^2}, \tag{2}$$

where θ is the angle of incidence, λ_0 is the wavelength at normal incidence, and $n_{\text{eff}} = 2.13$ for p-polarization.[9]

The internal diode cavity modes are described by the Airy function,

$$T_{\text{D}} = \frac{1}{1 + F \sin^2 \delta(\nu)}, \tag{3}$$

where $F = 4r_1 r_2/(1 - r_1 r_2)^2$ is the coefficient of finesse for the diode cavity, $r_{1,2}$ are the amplitude reflection coefficients of the diode rear and front facets, $\delta(\nu) = 2\pi n L_{\text{D}} \nu/c$ is the phase shift for one traversal of the semiconductor gain medium,

a)Electronic mail: scholten@unimelb.edu.au.

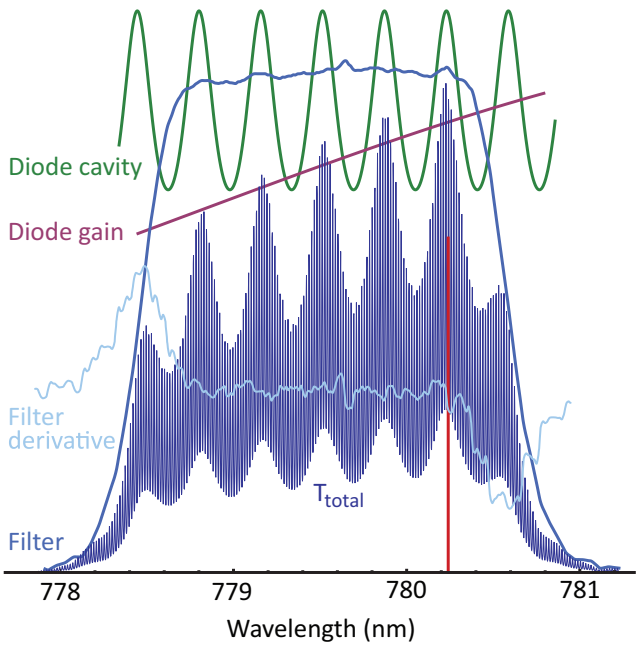

FIG. 1. (Color online) Schematic representation of the frequency-dependent factors that contribute to mode selection of an interference filter cateye ECDL, calculated for $\lambda_D = 783$ nm, rotated to 779.5 nm ($\theta = 14.5°$), $n = 3.5$, $L_D = 0.25$ mm, $L_{cavity} = 30$ mm, $r_1 = 0.85$, $r_2 = 0.15$, and $R_{cavity} = 1.0$. The diode gain curve is assumed to be Gaussian, with a FWHM of 10 nm. Numerous external cavity modes exist within the filter passband, yet the ECDL operates on a single mode because adjacent modes have reduced gain. At lower wavelength, the diode cavity transmission and the semiconductor gain are reduced, and at higher wavelength, the edge of the filter transmission reduces the overall gain. The measured transmission function for a 780 nm band pass filter[11] is shown with the numerical derivative, illustrating edge resolution of 0.3 nm (FWHM). The external cavity length and the diode mode have been chosen so that the overall gain peak occurs at $\lambda = 780.24$ nm, the $5S_{1/2} \rightarrow 5P_{3/2}$ transition in rubidium (vertical line).

ν is the laser oscillation frequency, L_D is the diode cavity length, and n is the semiconductor refractive index. A typical $\lambda = 780$ nm single mode semiconductor diode laser[10] has a physical cavity length of $L_D = 0.25$ mm and a refractive index of 3.5, giving a mode spacing of $\Delta\nu = c/2nL_D = 125$ GHz.

T_{cavity} is also described by Eq. (3) with appropriate changes to the reflection coefficient amplitudes and the cavity length, which becomes the external cavity length L_{cavity}. For a 30 mm external cavity in air the mode spacing is 5 GHz. In principle, the diode intrinsic mode function and the diode gain curve will select one or a few external cavity longitudinal modes. However, there is little control over which external mode is selected.

Grating feedback or a narrow bandwidth filter can select a single diode mode. We demonstrate here that the sharp edge of a broadband filter, combined with the wavelength dependence of the diode gain curve, can also select one diode mode (Fig. 1). The optimum wavelength is constrained on one side by the diode gain curve, and on the other by the edge of the filter function, such that one diode mode and one external cavity mode become dominant. The strongest lasing mode can be altered by rotation of the filter and adjustment of the diode mode frequency, either via the diode temperature or the diode injection current.

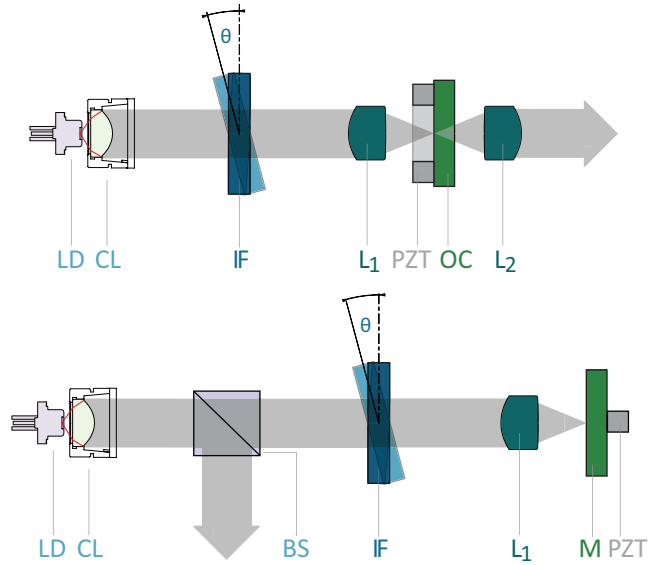

FIG. 2. (Color online) Upper: External cavity diode laser using broad bandpass interference filter (IF) and partially transmitting output coupler. LD laser diode; CL collimating lens; L1 cateye lens; L2 re-collimation lens; PZT multi-layer ring-shaped piezoelectric translator; OC partially transmitting output coupler. Lower: Using a beam splitter cube (BS) as an output coupler; M normal incidence mirror; PZT multi-layer square piezoelectric translator.

III. EXAMPLE CAVITY DESIGNS

Two configurations were constructed and evaluated (Fig. 2). The first is similar to previous cateye laser designs using ultranarrow filters,[2–5] where the cateye reflector also forms the laser output coupler. The output coupler must then be a partial reflector, and because the range of standard output couplers is limited, a second design was evaluated. The partially reflecting planar output coupler was replaced with a normal-incidence planar mirror, and an intra-cavity beam splitter cube used as output coupler. Both non-polarizing and polarizing beam splitter cubes were used. Here we discuss results with a 780 nm laser diode but successful operation has also been achieved at 670 nm wavelength.[12]

A. Output coupler design

The ECDL consists of a laser diode[10] and aspheric collimating lens ($f = 4.5$ mm 0.55 NA), a narrow passband interference filter in a rotating holder, and a cateye reflector. The cateye reflector was formed by an $f = 11$ mm 0.25 NA lens, mounted in a collimation tube machined to mount a 30% reflective output coupler. A multi-layer piezoelectric ring actuator was fixed to the rear facet of the output coupler, to allow cavity length tuning and fast frequency feedback control. An achromatic $f = 20$ mm lens was used to collimate the ECDL output beam. High transmission (greater than 90%) dielectric bandpass filters[9,11] were used, with nominal center wavelengths of $\lambda = 780$ and 785 nm and width $\Delta\lambda = 3$ nm. The laser diode, collimation tube and intra-cavity optics were mounted in an aluminum block. A 10 kΩ thermistor in the center of the block, and a Peltier thermoelectric cooler

between the block and a large aluminum baseplate, were used for temperature stabilization of the cavity.

B. Beam splitter cube designs

In the beam splitter version the output coupler was replaced with a plane dielectric mirror and $f = 4.5$ mm aspheric lens in a cateye configuration, and an 80/20 $10 \times 10 \times 10$ mm non-polarizing beam splitter cube was placed between the diode collimation lens ($f = 4.5$ mm) and interference filter. A piezoelectric transducer on the reflection mirror provided fine frequency tuning. A polarizing beam splitter cube ($5 \times 5 \times 5$ mm) was also used as an output coupler. With the polarizing beam splitter, rotation of the diode rotates the polarization of the intra-cavity beam and hence varies the ratio between out-coupled light and diode feedback. Increased feedback reduces the laser linewidth and in principle, the possible wavelength tuning range, at the expense of useful output power. The diode was rotated such that the feedback was approximately the same as that for the output coupler, 30%.

IV. ECDL PERFORMANCE

The output power for p-plane polarization was typically 50 mW at 780 nm using a 90 mW diode. Feedback efficiency was optimised by ensuring the laser diode transmission was focused exactly onto the reflective optical element (output coupler or mirror depending on the design), hence forming the cateye reflector. The focus of the combined diode collimation lens and cateye reflector also impacts the feedback efficiency of the external cavity[13] and the linewidth. Small and otherwise unnoticed changes to the lens focus can have quite a significant effect on the linewidth but are apparent only if the technical noise is small, comparable to the intrinsic cavity linewidth. With the cateye reflector, inherently good mode matching is ensured between the external cavity and the laser diode due to the robust alignment stability, leading to narrow linewidths. The linewidth can be reduced by increasing feedback from the external cavity,[13] and also by increasing the cavity length, though a short cavity is usually preferred to reduce the incidence of modehops to adjacent external cavity modes and thus to maximize the modehop-free tuning range.[7,13] The designs presented here exhibit modehop-free tuning ranges of at least 15 GHz with cavity lengths of 30 mm, with injection-current feed-forward to match the frequencies of the internal and external cavity modes.[6] Figure 3 shows a saturated absorption spectrum of the $\lambda = 780.24$ nm $5S_{1/2} \rightarrow 5P_{3/2}$ transition in rubidium (natural isotopic abundance).

The linewidths of the different configurations have been measured using the delayed self-heterodyne technique[14] with 2.2 km fiber delay (34 kHz resolution), independently with a commercial linewidth measuring instrument based on transmission through a high-finesse optical cavity,[10] and from the beatnote of two similar lasers. The lasers were in each case locked to a rubidium hyperfine transition using FM demodulation. The 250 kHz modulation was generated via the Zeeman effect using a coil around the atomic reference cell. The piezo actuator and the diode current were controlled with a combination of double-integrator, proportional and phase lead (differential) feedback.

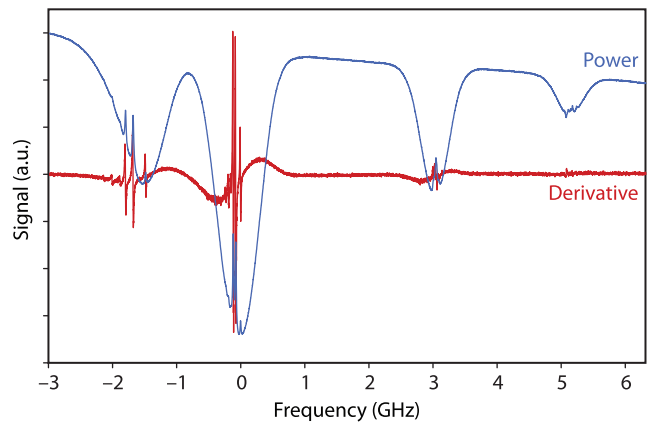

FIG. 3. (Color online) Saturated absorption spectrum and frequency modulation derivative for natural rubidium vapour, using the cateye laser with polarizing beam splitter cube.

Results from the self-heterodyne technique are shown in Fig. 4. Intrinsic full width at half maximum linewidths of the output coupler and polarizing beam splitter cube designs, determined from fits to a Lorentzian lineshape function, are $\Gamma = 42$ kHz and 39 kHz, respectively. Fits to a Gaussian function give full widths at half maximum of 73 kHz and 87 kHz, corresponding to rms laser linewidths of 31 kHz and 37 kHz. Using the commercial linewidth instrument, the measured linewidth of the bare laser diode was 2.5 MHz, and

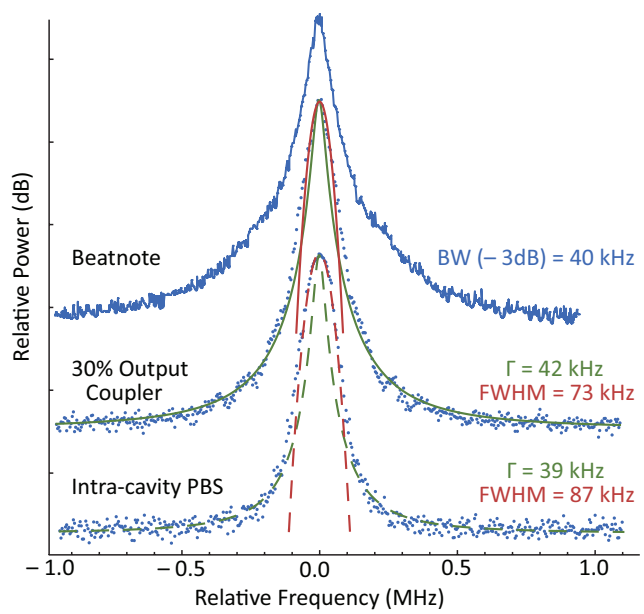

FIG. 4. (Color online) Spectrum of beatnote between two similar lasers, both of the partially reflecting output coupler design, locked to two distinct spectral features in the rubidium saturated absorption spectrum (top); delayed self-heterodyne laser linewidth measurement for individual laser of output coupler design (middle), and beam splitter cube design (bottom). In the self-heterodyne spectra, a central peak due to residual amplitude modulation on the first-order output of the acousto-optic modulator has been subtracted from each spectrum. The spectra were obtained with resolution bandwidth 3 kHz, sweeptime 225 ms, 50 sweep average. Lorentzian (Γ) fits exclude central 1 MHz; Gaussian (FWHM) fits include only central 1 MHz.

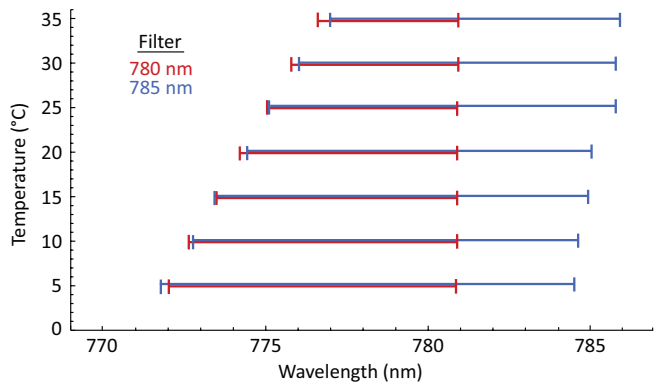

FIG. 5. (Color online) Wavelength tuning ranges at various laser diode operating temperatures for 780 nm and 785 nm interference filters in the output coupler ECDL configuration.

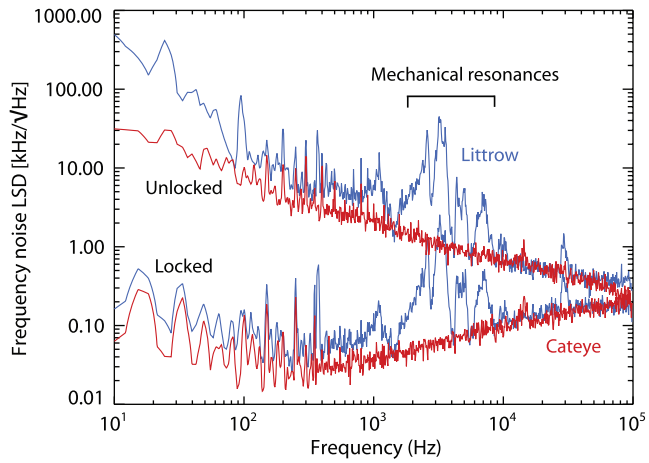

FIG. 6. (Color online) Frequency noise spectra for the output coupler cateye laser and a standard Littrow-configuration grating feedback design.[16]

the width for the output coupler (OC) design was 26 kHz (one-hour average) with a stipulated systematic uncertainty of ∼30%.[10] Figure 4 also shows the spectrum of the beatnote from interfering two similar OC lasers, with combined width of 40 kHz. The linewidth measurements are consistent given typical ECDL linewidth variations as discussed in Ref. 15.

Rotation of the filter (Eq. (2)) allows tuning from 772 nm to 781 nm using a broad 780 nm filter, and from 772 nm to 786 nm using a 785 nm filter (Fig. 5). The higher wavelength in the tuning range is limited due to the sharp edge of the filter transmission function; that is, the filter cannot be rotated to wavelengths greater than this cutoff. The laser can be tuned discontinuously over these ranges without alteration of the output beam direction.

The derivative of the transmission window wavelength (Eq. (2)) is

$$\frac{d\lambda(\theta)}{d\theta} = -\frac{\lambda_0^2}{2n_{\text{eff}}^2\lambda(\theta)}\sin(2\theta), \tag{4}$$

which is $-0.68\,\text{nm}/^\circ$ for a 785 nm filter rotated to 780.2 nm ($\theta = 13.8^\circ$). We require precision to within the internal diode mode spacing of 125 GHz, or 0.25 nm in 780 nm, corresponding to 0.38° in angle. By comparison, for a Littrow configuration ECDL with 1800 /mm grating, the sensitivity to rotation is $13.7\,\text{nm}/^\circ$, 20 times greater. The filter wavelength can be adjusted adequately without the need for a precision rotation mount.

Frequency noise spectra were measured (Fig. 6) for the output coupler design presented in Fig. 2, and compared to similar spectra for a grating-feedback Littrow configuration ECDL in which the grating is aligned using a standard kinematic mount.[16] The laser was again locked to a rubidium hyperfine transition but using dc coupled feedback. The spectra clearly show substantially reduced susceptibility to mechanical resonances, in particular the absence of resonances associated with the springs in the kinematic grating mount.

V. CONCLUSION

ECDLs that use an interference filter for wavelength selection together with a cateye reflection mechanism have proven to exhibit narrow linewidths and greater frequency stability in comparison to diffraction grating-based ECDLs. A cateye reflector is self-aligning and insensitive to intra-cavity optical misalignment. We have shown that single mode operation is possible using a filter with bandwidth many times greater than both the external cavity mode spacing and the intrinsic laser diode mode spacing, making the cateye advantages more readily accessible.

Using only standard catalog optical components, our ECDL is mechanically less complex than common diffraction grating designs, and at a wavelength of 780 nm has demonstrated linewidth of 26 kHz, wavelength tunability over more than 14 nm, and reduced susceptibility to acoustic vibrations. Using saturated absorption frequency stabilization to an atomic reference,[16] the laser will remain locked even when bumped or knocked. The narrow linewidth and wavelength tunability, combined with the simple construction and stability, make these designs well suited to the cooling and trapping of alkali atoms.

ACKNOWLEDGMENTS

We thank E. Riis for helpful discussions and early results at 670 nm, and S. D. Saliba and D. V. Sheludko for advice and assistance. This work was supported by the Australian Research Council Discovery Project DP1096025. D.J.T. gratefully acknowledges the support of an Ernst and Grace Matthaei scholarship.

[1] P. Zorabedian and W. R. Trutna, Jr., Opt. Lett. **13**, 826 (1988).
[2] M. Gilowski, C. Schubert, M. Zaiser, W. Herr, T. Wübbena, T. Wendrich, T. Müller, E. M. Rasel, and W. Ertmer, Opt. Commun. **280**, 443 (2007).
[3] S. Perrin, F.-X. Esnault, D. Holleville, S. Guérandel, N. Dimarcq, and V. Ligeret, in *Proceedings of Joint IEEE International Frequency Control Symposium/21st European Frequency and Time Forum* (IEEE, 2007), Vol. 1–4, pp. 86–89.
[4] M. Scholl, "Interference filter stabilized external cavity diode laser," Technical Report (University of Toronto, 2010).
[5] X. Baillard, A. Gauguet, S. Bize, P. Lemonde, P. Laurent, A. Clairon, and P. Rosenbusch, Opt. Commun. **266**, 609 (2006).
[6] S. D. Saliba, M. Junker, L. D. Turner, and R. E. Scholten, Appl. Opt. **48**, 6692 (2009).

[7]P. Zorabedian, "*Tunable Lasers Handbook*," edited by F. J. Duarte (Academic, New York, 1995), pp. 349–442.
[8]P. H. Lissberger and W. L. Wilcock, J. Opt. Soc. Am. **49**, 126 (1959).
[9]Semrock LL01-780-12.5 780 nm laser line bandpass filter.
[10]We used a Rochester Precision Optics A230TM-B diode collimation lens in a Thorlabs LT230P collimation tube, a Lightpath Technologies C220TME-B for the cateye reflector, Noliac CMAR04 and CMAP04 multilayer piezoelectric actuators, Arima Lasers ADL-78901TX 780 nm laser diode, JouleOptik JOC-800-30-0537 30% reflective output coupler, Sirah Eagle-Eye optical spectrum analyzer and a MOGLabs DLC-202 ECDL controller. Note: certain commercial equipments, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement, nor does it imply that the materials or equipment are necessarily the best available for the purpose.
[11]Iridian Spectral Technologies ZX000039 785 nm laser line bandpass filter.
[12]E. Riis, private communication (29 January 2011).
[13]S. D. Saliba and R. E. Scholten, Appl. Opt. **48**, 6961 (2009).
[14]T. Okoshi, K. Kikuchi, and A. Nakayama, Electron. Lett. **16**, 630 (1980).
[15]G. Genty, M. Kaivola, and H. Ludvigsen, Opt. Commun. **203**, 295 (2002).
[16]C. J. Hawthorn, K. P. Weber, and R. E. Scholten, Rev. Sci. Instrum. **72**, 4477 (2001).