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# External cavity wavelength tunable semiconductor lasers – a review

INVITED PAPER

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*External cavity tunable lasers have been around for many years and now constitute a large group of semiconductor lasers featuring very unique properties. The present review has been restricted to the systems based on the edge emitting diode lasers set-up in a hybrid configuration. The aim was to make the paper as concise as possible without sacrificing, however, most important details. We start with short description of the fundamentals essential for operation of the external cavity lasers to set the stage for explanation of their properties and some typical designs. Then, semiconductor optical amplifiers used in the external cavity lasers are highlighted more in detail as well as diffraction gratings and other types of wavelength-selective reflectors used to provide optical feedback in these lasers. This is followed by a survey of designs and properties of various external cavity lasers both with mobile bulk gratings and with fixed wavelength selective mirrors. The paper closes with description of some recent developments in the field to show prospects for further progress directed towards miniaturization and integration of the external cavity laser components used so far to set-up hybrid systems.*

**Keywords:** tunable lasers, external cavity, optical amplifiers, wavelength selective mirrors.

## 1. Introduction

Numerous applications of semiconductor lasers, including high resolution spectroscopy and wide bandwidth communication network systems, require means to tune their output to one or more specific wavelengths with a variety of spectral and temporal characteristics. In particular, narrow spectral line-width, high frequency modulation, and widely tunable wavelengths that cover the spectral range from visible to far-infrared are demanded. Radiation sources of high power, near-infrared diffraction limited and single frequency are also required for a myriad of scientific applications such as materials characterization or laser and amplifier pumping and frequency doubling. Pairs of such diode lasers with appropriately selected frequency were used to generate terahertz waves [1,2] which have already become an important tool for penetrating solid objects in the quest to improve imaging technology. One of the key current trends in optical networking is redirecting of a time – division multiplexed (TDM) trend towards wavelength – division multiplexed (WDM) systems [3]. To provide an access to laser sources with the precise emission wavelengths required by the system becomes thus a great challenge in setting up any WDM network.

Unfortunately, in ordinary solitary diode lasers, because of the semiconductor's inherent broad gain spectrum, usually more than one mode will operate simultaneously resulting in multiple output wavelengths and broad spectral line-width. Such a laser is amenable to control only by externally induced variation of the energy gap and refractive index through changes in temperature or pressure as well as by variation of the injection current. The latter causes, however, simultaneous and inseparable shifts in the frequency, the output power and for a multimode laser the allocation of power among the various modes. Furthermore, a solitary diode laser is usually sensitive to optical feedback. It was observed long time ago that return beam may induce oscillations that appear in the laser output intensity and their frequency varies with the cavity length, laser design and operating conditions [4].

To achieve single frequency operation, a special wavelength selection mechanism has to be built into the diode. Such mechanism may be either based on exploiting a wavelength selective loss which would be lowest for the selected wavelength or some kind of dispersers can be used to serve that purpose. Distributed feedback (DFB) lasers, distributed Bragg reflector (DBR) lasers and their more advanced versions like sampled-grating DBRs (SG DBR) [5] and superstructure grating DBRs (SSG DBR) [6], as well as vertical cavity surface emitting lasers (VCSEL), can represent this group of devices. Such lasers can be tuned, alas, over only a limited spectral range by changing temperature or the current of the diode. The tuning range may also have gaps in it. In particular, tuning range of the VCSELs is limited by built-in wavelength resonant structures and therefore they will be excluded altogether from considerations in this review. The easiest way to obtain a really widely-tunable laser is perhaps to make a DFB array [7] but due to the increasing losses in the coupler, as a number of DBR lasers is increased, there is a trade-off between the tuning range and output power. Other monolithic solutions like a grating assisted co-directional coupler with rear sampled

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grating reflector (GCSR) have been demonstrated and implemented [8] yet they suffer from complicated tuning mechanism requiring the control of three or more currents.

However, the laser system can also be forced to operate in a single longitudinal mode by placing the diode laser in an external resonant cavity comprising a wavelength selector. Through insertion of the wavelength selective elements in the system, the external cavity configuration permits operation in a single mode with a line-width which is considerably less than that of a solitary laser diode. Moreover, selection and tunability of the emission wavelength by external control can be executed without the complications associated with variation of the temperature or pumping level. At the same time, such system retains the high efficiency which is characteristic of the injection laser while providing an output mode that can be spatially and spectrally superior to that of the solitary diode laser.

It is the purpose of this paper to review some topics related to the semiconductor lasers that use a waveguide resonant cavity extended beyond the solitary edge emitting laser. Such lasers are called "external cavity lasers" (ECL) or sometimes "extended cavity lasers" depending on subtle differences in the structure and operation [9]. They have been known since long time ago at least from the year 1964 [10]. However, their numerous virtues they now owe, mainly developments in the field of diode lasers or strictly speaking semiconductor optical amplifiers (SOA) are promising. This is why they still are the subject of interest and research and their properties are continuously being improved at pace with general progress in semiconductor technology and optoelectronics. Wavelength tunability is one of the main important features of these lasers and special attention will be paid to this particular property. To emphasize this intention, lasers will be termed "external cavity tunable lasers" (ECTL).

## 2. External cavity lasers – the basics

### 2.1. Classification and definitions

Schematic diagrams of different presently known configurations of the ECTLs are given in Fig. 1. An elementary ECL is displayed in Fig 1(a). It consists of a semiconductor optical amplifier (SOA) with the mirror like rear facet,

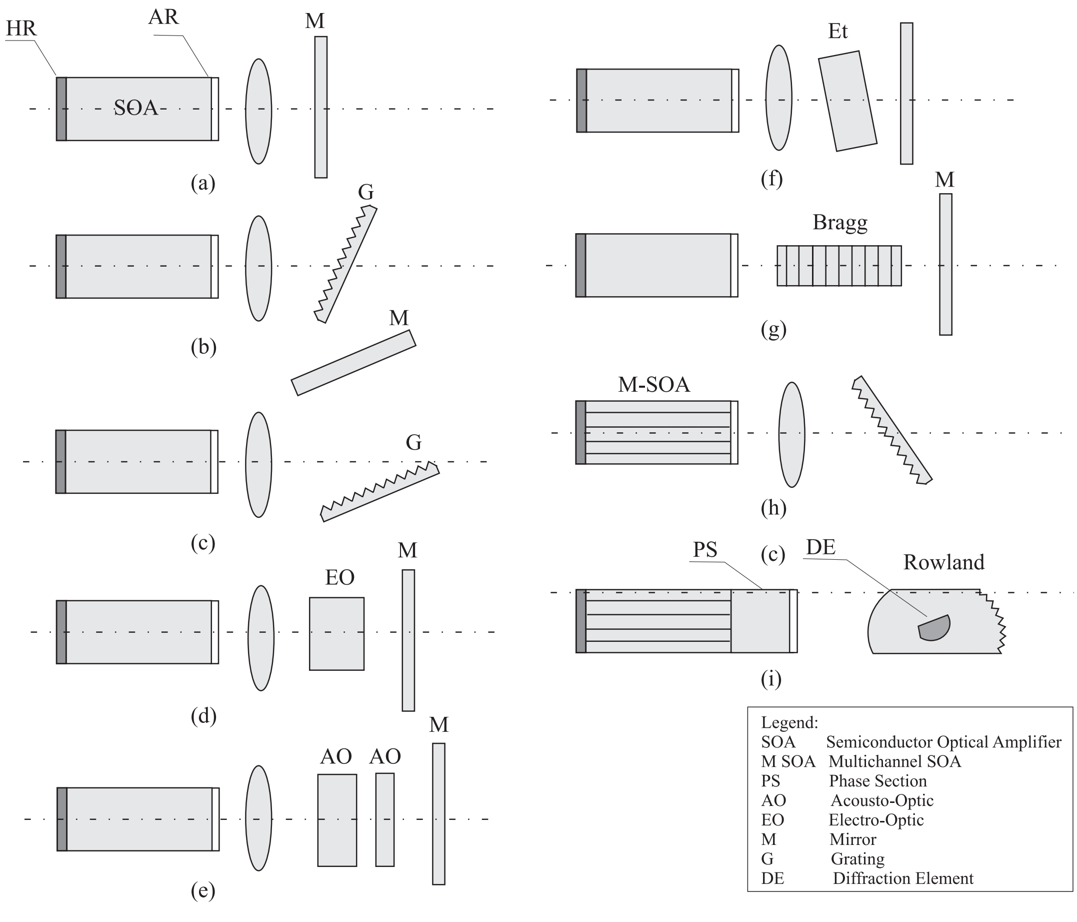



Fig. 1. Schematic diagrams of the ECTLs based on the papers indicated in the cited references. Consecutive drawings display configurations that comprise: (a) elementary ECL consisting of a gain medium (SOA), collimating optics, and two mirrors – one of which formed by a high reflectivity coating (HR) on the SOA's rear facet, (b) Littrow (after Ref. 11), (c) Littman (after Ref. 12), (d) electro-optic filter (after Refs. 13 and 14), (e) acousto-optic filters (AO) (after Refs. 15 and 16), (f) etalon plus wavelength selective mirror (after Ref. 17), (g) Bragg waveguide (after Refs. 18 and 19), (h) multichannel SOA (after Refs. 20 and 21), and (i) multichannel SOA with phase shift section (PS), and Rowland grating (after Refs. 22 and 23).

a lens, and a reflector. The output from the SOA is collimated and redirected backwards. Function of the SOA usually performs a diode laser chip in which the rear and front facet have been coated with the high and very low reflectivity films, respectively. The intra-cavity lens is a critical element in the cavity design. Among various features, it is required that it should have a large aperture ratio in order to collect most of the divergent light emitted from the SOA. The reflector should provide optical feedback to excite lasing in the cavity.

Changing position of the reflector will perturb frequency and spectrum of the emission. In general, reflectivity of the reflector must be wavelength dependent to enforce single frequency operation of the system. It may be then termed "a wavelength selector". Schemes of the ECLTs with various wavelength selectors are shown on consecutive drawings of Fig. 1. In the text, to follow we shall discuss some more important features of the respective designs.

This paper refers to numerous papers published since the time the ECL lasers were invented and *ipso facto* containing a variety of notations. To make the text legible, we shall be describing laser performance using notations defined below.

### 2.1.1. Solitary diode laser

Emitted wavelength

$$\lambda = \frac{2nl}{m}, \tag{1}$$

where $l$ is the length of the diode laser cavity, $m$ is the longitudinal mode number, and $n$ is refractive index of the diode material.
Mode frequency

$$v_m = \frac{c}{\lambda}. \tag{2}$$

Spectral line-width [24]

$$\Delta v = \frac{\upsilon_g h v \Gamma g R_m n_{sp}}{\pi P}(1+\alpha^2), \tag{3}$$

while

$$a = \left(\frac{4\pi}{\lambda}\right)\left[\frac{(dn/dN)}{dg/dN}\right]$$

where $R_m, \upsilon_g, hv, \Gamma, g, n_{sp}$ and $P, N$ are the mirror loss, the group velocity of light, the photon energy, the optical confinement factor, the bulk gain at threshold, the spontaneous emission factor, and the laser output power and electron concentration, respectively. Parameter $\alpha$ reflects the strong amplitude – phase coupling of the lasing field in a semiconductor laser resulting from the highly detuned optical gain spectrum.
Cavity mode spacing

$$\Delta\lambda_m = \lambda_m - \lambda_{m+1} = \frac{\lambda^2}{2nl\left(1 - \frac{\lambda}{n}\frac{\partial n}{\partial \lambda}\right)} \cong \frac{\lambda^2}{2nl}, \tag{4a}$$

or

$$\Delta v_m = \frac{c}{\lambda^2}\Delta\lambda_m = \frac{c}{2nl}. \tag{4b}$$

### 2.1.2. External cavity laser

On the assumption that the mirror is nonselective and the photon lifetime is significantly longer due to loss-free propagation over a distance $L > nl$, the cavity mode spacing is

$$\Delta\lambda_{mE} = \lambda_{mE} - \lambda_{mE+1}, \tag{5a}$$

or

$$\Delta v_{mE} = c/[2(nl+L)]. \tag{5b}$$

The effects of external feedback on behaviour of an ECL are expected to differ characteristically depending on the distance from the SOA to the reflector and on the reflectivity of the SOA front facet. When this distance is smaller than the output coherence length and the reflectivity is high, the combined SOA and the external reflector system will behave as a laser with a compound cavity [25]. Some of the properties of semiconductor lasers make then the appearance of the external feedback effects somewhat complex.
In particular, two following features become essential:

- broad gain spectrum half-width, which permits different longitudinal modes of the diode cavity to be excited with a slight change in the external feedback conditions,
- very sensitive dependence of the SOA's active region refractive index on the temperature and the excited carrier density.

In effect, numerous changes in the dynamic behaviours of the ECL lasers appear explainable only in terms of the compound laser cavity interference effects [25]. Concomitant with reduction of the spontaneous phase fluctuations, the external cavity decouples the resonant laser frequency from the strong dependence on the semiconductor refractive index.

While refractive index fluctuations contribute significantly to the observed bandwidth of a solitary diode laser, for an external cavity laser, they are negligible due to extended cavity filled with air. In result, the ECL system can be made immune to dynamic instabilities and one can expect a stable laser action in a single mode. Since the line-width of such a mode in a solitary laser is on the order of 5 MHz/mW [24], it is more appropriate to describe the ECL output signal in a category of the single-frequency. What is very essential, however, most ECL designs provide facility for changing this frequency within very wide range of wavelengths and this is why we decided to term them ECTL.

Design of the ECTLs and trade-off associated with the choice of cavity configuration, characteristics of the SOA and wavelength selector performance, must be considered simultaneously. In addition, these features must be integrated into a single opto-mechanical package. Six distinctively different types of wavelength selectors have been used to build ECTLs as has been shown in Fig. 1. At the very beginning also prisms were tried as the wavelength selector [11] but they did not turned out to be very promising for practical applications. Currently, the main effort is directed towards development of the designs suitable for building optical integrated systems. Nevertheless, the best practical results have been obtained so far with the systems that use bulk mobile gratings in the cavity [26–28].

## 2.2. Components essential to operation of ECTLs

### 2.2.1. Semiconductor optical amplifiers

Operation mechanism and therefore the structure of semiconductor optical amplifiers (SOA) is based on the same principles as those we deal with in technology of the edge emitting diode lasers [29,30]. Ideally, a tunable external cavity laser should have minimal threshold current and low output power variation across a possibly broad wavelength range of operation. Quantum well (QW) structures are very useful in this respect since they offer low threshold currents, broad laser tuning range, and the ability to tailor the optical gain to a specific wavelength range demanded by a particular laser application. In QW structures, the discrete onset of subbands in joint density of transitions allows for more than one local maximum in the gain spectrum. Specifically, in a single quantum well (SQW) structure, the pumping strength can be adjusted so that, equally high-gain peaks arise from the first and second quantized state transitions, resulting in a wide spectral region of near equal gain [31]. Quantum wells with various profiles of the potential distribution can be applied but most often graded index separatly confined (GRINSCH) structure is employed to benefit low temperature sensitivity of the threshold current observed for such structures [32]. A theoretical model for the gain of QW lasers with such a well profile has been proposed showing that a nearly constant gain can be achieved over an extended spectral range [31]. Experimentally this was shown for a single well AlGaAs graded-index separate-confinement heterostructure [32]. One of the key issues in the quest for more broadband operation is the band-filling range. Incorporating pseudomorphic $In_xGa_{1-x}As$ quantum wells in an $Al_yGa_{1-y}As$-GaAs material system has resulted in a structure which allows for an increased band filling and tuning range extending to 130 nm [30] (845.4 nm < $\lambda$ < 975.6 nm). However, broadly tunable QW laser diodes have been mainly focused on materials which contain multiple identical wells (MQW) [33,26] including QWs with strained layers [34]. In addition, gain calculations and experiments have shown that a wider and flatter gain profile than that of a material which consists of say three identical QWs can be obtained when we use non-identical QWs [35] with different QW width or barrier height. In particular, so-called staggered MQW [36] and step-graded index MQW structures [32] provided a wide gain spectral range. Using the feedback of an external cavity grating which induces carrier redistribution to a specific well through mode competition and spectral variations in carrier lifetime leads to tailoring of the wavelength range. Emphasis put on particular bands of the gain spectrum through preferential population of the wells becomes feasible in such structures [35]. In the wavelength region of 950 nm staggered MQW structures enabled tuning range of 80 nm [36], while structures with step-graded index MQW operated at the wavelengths from 1440 to 1640 nm demonstrated particularly wide tuning range of 200 nm [32]. Lasers used in the latter experiment were grown on an InP substrate. They comprised an undoped active layer that consisted of four InGaAs quantum wells having thickness of 9 nm and spaced by 22.5-nm-thick barriers. The graded index layer was composed of a series of four step-like lattice-matched InGaAsP layers with successively increasing band gaps represented by $\lambda$ = 1.04,1.12, 1.21, and 1.25 µm. A similar laser with regard to the active region structure demonstrated operation in the wavelength region extending from 1320 nm to 1562 nm that translates to 242 nm of continuous tuning [26].

A great number of various III–V material systems have been used to make the SOAs. Most often they were just the same as those that serve as material for fabrication of diode lasers and their choice depended on the required wavelength range of laser operation. Geometry of the SOA waveguide may be different and in practice varies from a narrow-stripe-burried heterostructure [29] to a broad-stripe ridge-wave guide diode laser chip with configuration typical for high power diode lasers [37]. In quest to increase output power of the ECTLs, a tapered amplifier gain-guided design has been tested and shown to be a very effective one [38]. High output continuous wave (CW) powers (> 1 W) in a single-lobed diffraction limited beam have been achieved from a variety of material systems. In particular, broad tuning ranges at around 1 W power levels have been demonstrated at the wavelengths near 860 nm with the use of the ECTLs based on the GaAs/AlGaAs heterostructures [38]. Other demonstrations of about 0.5 W power levels at various wavelength ranges followed soon [39,40]. By way of example, in Ref. 41, it has been described a high power (> 1 W CW, and 3 W quasi CW) ECTL that exhibited near-diffraction limited, broadly tunable (~20 nm) single longitudinal mode performance at the wavelength near 970 nm. The ECTL comprised the SOA made from the InGaAs/AlGaAs material system.

Apart from the gain, the most important difference between a diode laser and the SOA is that the latter should be deprived of the ability of lasing. This can be achieved by removing the optical feedback through diminishing reflectivity of the facets that otherwise would form a F-P cavity. It is known that tunable range of the ECTL's with an external grating may be limited less by the gain spectral width of the SOA than by reflectance of the SOA's front facet and coupling efficiency between this facet and the grating. To make the facet in question possibly transparent it is coated with an AR (antireflective) film that secures reflectivity on the order of $10^{-3}$–$10^{-4}$. Most often this is just a $\lambda/4$

thin layer of $SiN_x$, $Al_2O_3$, or $SiO_2$. Optimum tuning results are obtained when the wavelength of the minimum reflectivity of the AR coating is aligned to the peak in the spontaneous emission excited in the structure. However, as the lasing wavelength shifts from the original gain peak of the solitary diode laser, the carrier density must increase to compensate for the decrease in the gain. Thus, the gain peak of the ECL necessarily shifts toward the shorter wavelength. This suggests that it would be advantageous to set the optimum wavelength of the AR coating to a wavelength shorter than the gain peak of the original SOA. It is almost impossible, unfortunately, to completely suppress the influence of the internal mode of the diode laser over the entire tunable range of the broad-band ECTL. This is because the AR coating technique optimizes the anti-reflectivity within a finite wavelength range. Outside that range, the internal mode seriously affects the tunability of the ECTL and some other method must be found of effectively controlling the internal mode. Such controlling is possible either by changing the injection current or the temperature. However, changing the injection current changes the output power, and changing the temperature takes a fairly long response time. These methods are thus not suitable for good control of the internal mode. To cope with this problem, a two--section SOA was proposed [42] which employed a phase control (PC) section for controlling the internal mode. By injecting current into this section, the refractive index of the PC section changes in a way analogous to that already utilized for a multi-section DBR diode lasers [7]. Using this approach, a 1.5 μm tunable laser with a wide wavelength tuning range of 154 nm has been fabricated [42].

SOA chips composed of the gain and phase sections fabricated from the InGaAsP/InP material system have been also reported in Ref. 43. In this case, in order to cover the desired wavelength range, the structure of the gain section comprised three different types of quantum wells with appropriately shifted band-gap wavelengths ($\Delta\lambda_g = 10$ nm). The heterostructure layer sequence were that of double channel planar buried diode lasers while the phase region was bulk type and consisted of quaternary material with a band gap wavelength of 1.4 μm. Both sections have been integrated monolithically using butt joint technology.

In conclusion, standard diode laser chips can serve as the SOA in various ECTL systems if only their front facet can be made antireflective. Yet better performance can be expected if the gain region comprises multi-quantum structures designed to enlarge the gain spectral range.

Choice of the reflectivity of the SOA's rear facet depends on the way the output beam is collected from the particular ECTL set-up. It may be close to 100% when the beam reflected from the grating is used as the output [30] or as low as 0.2% when the SOA is fiber pigtailed [41].

### 2.2.2. Diffraction gratings

Standard reflective diffraction gratings holographic or blazed [44] can be used successfully in the systems described above, providing that they have been selected with proper care to satisfy conditions specified in Sect. 2.3. It is also essential to use gratings with high enough efficiency to diminish optical losses in the ECTL system. Gratings have in general a high reflectivity of about 85% for the S-plane (i.e., when the wave electric vector is perpendicular to the grating grooves) and a low reflectivity on the order of about 15% for the P-plane (electric vector parallel to the grating grooves), both figures depending on the kind of the particular grating [45]. However, considering optimum orientation of the grating with respect to the SOA, if the latter has geometry of a broad contact ridge waveguide which is most common, the following aspects must be taken into account:

- output beam emitted by semiconductor ridge waveguide quantum well lasers is mainly TE polarized in the plane of the p-n junction,
- quantum well diode lasers with active region stripes wider than about 10 μm tend to operate in a fundamental transverse mode; on the other hand it is difficult to avoid excitation of multimode action in the lateral plane,
- due to asymmetry in dimensions of the active region the output beam is elliptical in cross-section with divergence of 60° and 10° in the plane perpendicular and parallel to the p-n junction, respectively.

Taking all this into account, in practical applications as a rule the SOA is oriented with the plane of its active region parallel to the grating grooves. In some designs though, the SOA's was positioned perpendicular to the grating grooves with satisfactory results, may be because the system was built in the Littman configuration [28].

Bulky glass gratings determine the size of the ECL system and therefore some attempts have been made to substitute them by gratings made of silicon. The additional advantage such gratings present is that this could be useful for the ECLs developed in MOEM (micro-opto-electro-mechanical) technology [46]. Silicon gratings can be made in many ways, i.e., using holography [47], by lithography [44], or direct electron beam (E-beam) writing and etching [48]. Each method brings good results and economical reasons may decide which one of them will be chosen. Profile of the grating grooves depends on the particular method used for their fabrication. The E-beam writing process combined with reactive ion eching (RIE) delivers gratings with rectangular grooves which have been found quite satisfactory for ECTL operation [49]. In addition, this method is particularly compatible with other processing operations involved in the MOEM technology since it enables pattern generation without any primary mask.

A problem of the optimum groove profile has been not yet solved neither theoretically nor experimentally. Efficiency diagrams of the gratings made holographically and by E-beam writing followed by RIE are shown in Fig. 2. The diagrams display grating efficiency versus wavelength and the Littrow angle of incidence for as measured for two polarizations, with electric vector E parallel and perpendicular to the grating grooves.

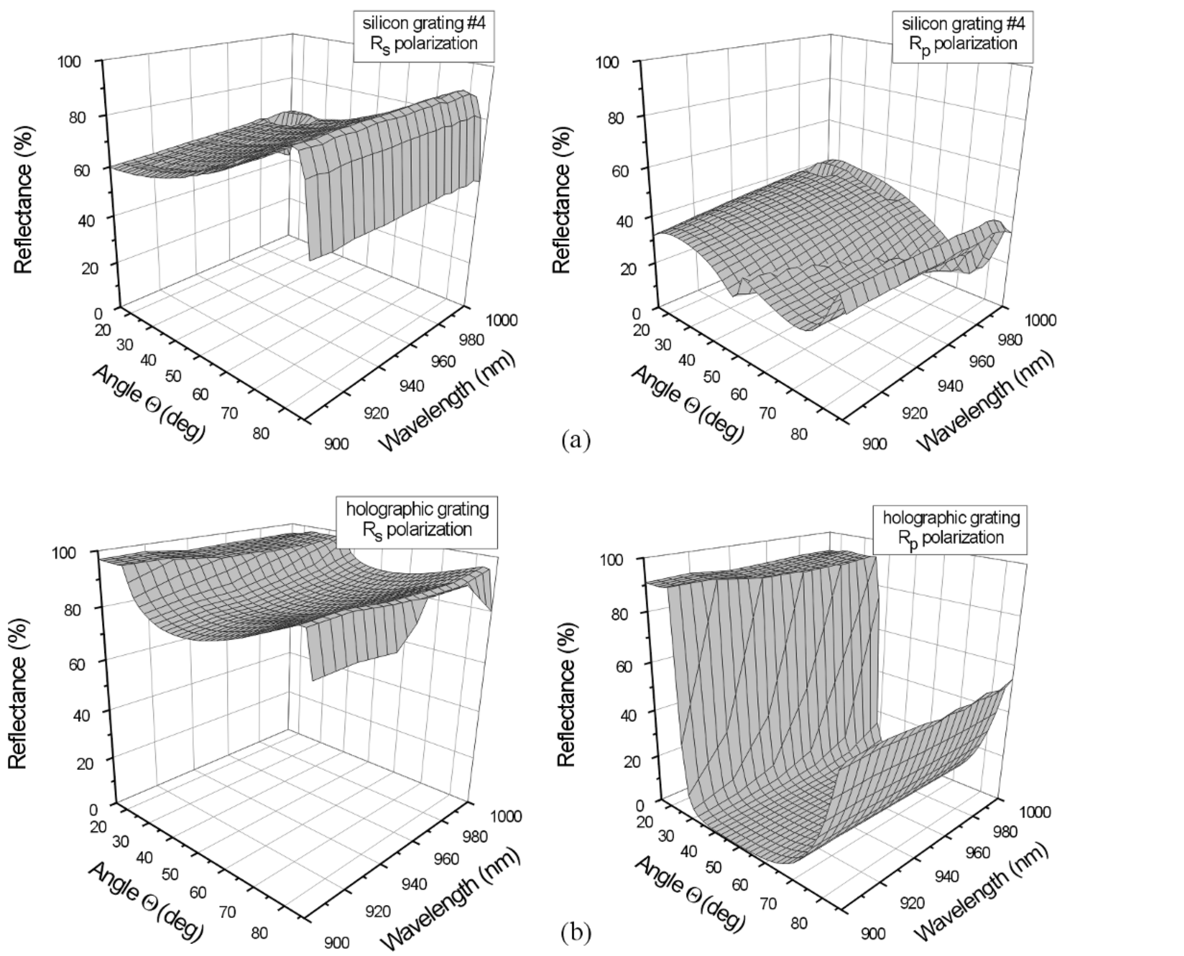



Fig. 2. 2-D diagrams showing variation of the grating reflectivity versus the Littrow incident angle $\theta$ and the wavelength $\lambda$ for the $P$ and $S$ polarization planes denoted as $R_P$ and $R_s$, respectively: (a) holographic glass grating (1200 l/mm) and (b) E-beam written silicon grating (1000 l/mm) (after Ref. 49).

### 2.2.3. Wavelength selective mirrors

An effort put to eliminate bulk pivoting gratings from the ECTL designs has led to the idea that they could be substituted by a tunable wavelength selective grating structures operating at normal incidence. This should be feasible if parameters of the grating and the waveguide were designed to enforce lateral confinement of the light within the set-up and to control the spectral bandwidth and angular width of the beam. The structures have been materialized and termed "grating waveguide structures" (GWS) [50], "sub-wavelength resonant gratings" (SRG) [51] or "resonant grating mirror" [52]. A ray picture model applicable to high finesse structures of this type is displayed in Fig. 3.

In the simplest form, the resonant GWS is comprised of a substrate, a waveguide layer, and a grating layer. When a plane wave is incident normally on the GWS and the grating is symmetric about the axis along the waveguide, the coupling processes are also symmetric about this axis. As a result, two identical modes propagating in opposite direction will be excited. The grating simultaneously serves then as an element for coupling the incident plane wave to waveguide modes and also as a Bragg reflector for the modes. Bragg reflection creates a standing wave pattern between the modes laterally so we can describe the structure as being in both transverse and lateral resonance. The key feature is the relative phase shift between the incident and the diffracted waves, which results in destructive interference. Experiments that support theoretical modelling have been reported in detail in Ref. 50. A passive dielectric GWS structures achieved by metalorganic chemical vapour

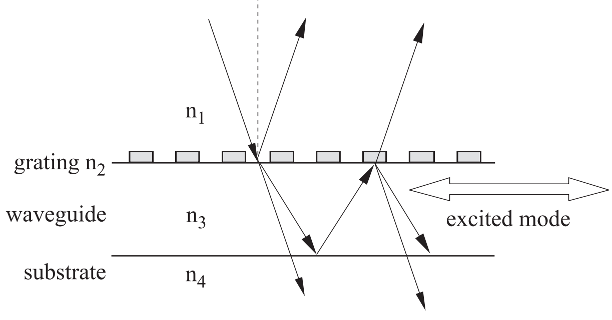



Fig. 3. Ray picture model of a grating waveguide structure (GWS) showing operation mechanism of a wavelength selective mirror (after Ref. 52).

deposition (MO CVD) and selective RIE processing on InGaAs/InP substrate have shown spectral characteristics typical for a resonance. The spectral bandwidth was down to the subnanometer range and significant transmission and reflection change, as well as high contrast ratio were achieved. The semiconductor structures could modulate laser light at relatively high rates by applying an external varying electric field. In particular, modulation of the reflected intensity at the frequencies up to 10 MHz was demonstrated with these active GWS at the wavelength of 1.55-μm. It is expected that GWS with smaller active areas could be modulated at even higher frequencies. A tunable laser with a thermally tuned SRG as an external mirror was demonstrated in Ref. 51. A liquid-crystal sub-wavelength resonant grating (LC-SRG), as an electrically tuned wavelength-selective mirror in the external cavity, was employed in this experiment. This kind of filter is attractive because of its inherently simple and compact structure, narrow and sharp reflection peak, and normal incidence operation without any higher order diffraction loss. It was shown that the laser output light can be controlled by an external cavity incorporating sub-wavelength optical elements [53] and the concept of using fixed-wavelength resonant gratings in a laser cavity to force single-wavelength lasing was previously demonstrated for large-area semiconductor lasers [54].

In addition, it has been found that the peak reflection wavelength of an SRG is sensitive to the refractive index of the cladding material on top of the grating structure [55]. If means are provided to vary the effective index of the waveguide mode, the wavelength at which resonant reflection takes place at normal incidence is changed and the laser emits at a different wavelength. One of the ways to obtain a tunable SRG is to place a cladding layer of nematic liquid crystal (LC) on top of a sub-wavelength grating to tune the resonant frequency of the SRG. Schematic cross-section of this device is displayed in Fig. 4. Two indium tin oxide (ITO) layers, seen on the drawing, play the role of transparent electric contacts. Voltage applied to these contacts produces in the LC layer an electric field.

For a normal incident light with a wavelength at the resonance of the device, it excites a leaky waveguide mode in a homogeneous silicon nitride ($SiN_x$) layer that is underneath the sub-wavelength gratings due to grating coupling. This leaky mode interacts with the zeroth-order waves and in theory results in complete reflection and zero transmission for plane incident wave and infinite gratings [50]. In practice, there will be a certain amount of transmission at resonance depending on the coupling strength of the gratings. The gratings can thus also serve as the laser output facet. For all other wavelengths, no waveguide mode is excited and, therefore, they pass straight through except for the Fresnel interfacial reflections. The resonant wavelength can be tuned electrically through voltage applied to the liquid-crystal cell.

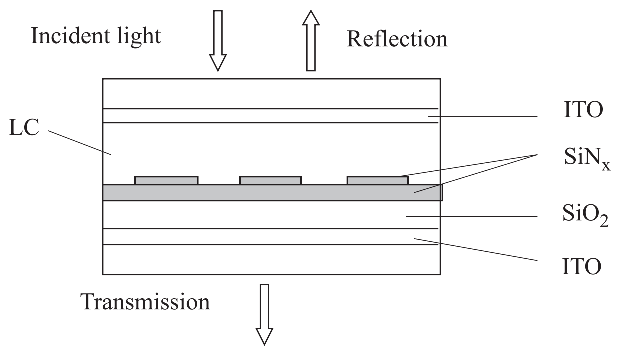



Fig. 4. Schematic cross-section of a tunable LC-SRG filter (after Ref. 51).

An electric field tunes orientation of the bi-refringent nematic liquid-crystal molecules, leading to a change in refractive index of the liquid-crystal layer for a linearly polarized, normal incident light and hence, a shift in the resonant peak wavelength of the SRG. Using such a tunable reflective filter as a mirror in the laser allows the tuning of the laser wavelength.

## 2.3. Optical configurations of the ECTLs

### 2.3.1. Littrow and Littman configurations

The two principal designs of the external cavity laser systems with bulk diffraction gratings as dispersive wavelength selectors are shown more in detail in Fig. 5. They are named Littrow (due to the Littrow retro-diffraction geometry) and Littman or grazing-incidence configurations (sometimes referred to as Littman/Metcalf's [56,57]). The lasing wavelength in each of these designs is determined by the centre of the grating dispersion curve, which is given by the well-known grating equation

$$m\lambda = d(\sin\varphi_i + \sin\varphi_d). \tag{6}$$

Here $m$ denotes any integer (called the diffraction order), $\lambda$ is the centre wavelength, $d$ is the grating groove spacing, $\varphi_i$ is the incident angle (measured with respect to grating normal), and $\varphi_d$ is the diffracted angle.

In the Littrow cavity, the grating is positioned at the Littrow angle under which the incident and diffracted angles are equal, i.e., $\varphi_i = \varphi_d = \theta$. Equation (6) reduces then to the following

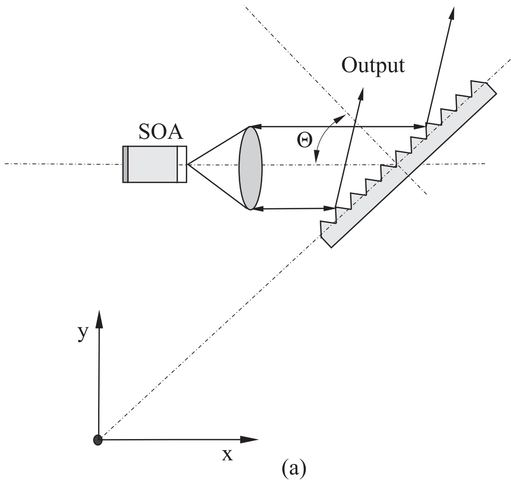
$$m\lambda = 2d(\sin\theta). \tag{7}$$

Most frequently the 1st order diffracted beam ($m = -1$) is reflected collinear with the incident beam and re-imaged on the AR coated SOA facet, although higher diffraction orders are also used in some designs [44].

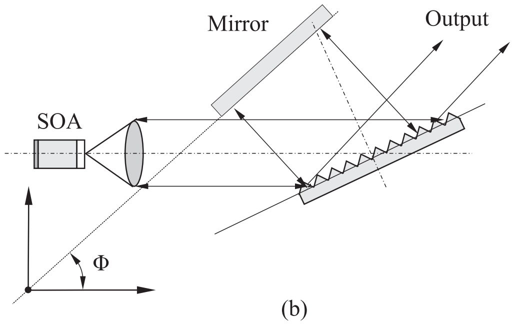
Adequately to the Rayleigh criterion, the resolving power of the grating in the Littrow configuration is expressed by [47]

$$\frac{\lambda}{\Delta\lambda} = \frac{2W}{\lambda}\sin\theta, \tag{8}$$

where $W$ is the distance covered by the beam on the grating when measured in a direction perpendicular to the grooves.



(a)



(b)

Fig. 5. Two principal designs of the external cavity tunable systems with bulk diffraction gratings: (a) Littrow configuration and (b) Littman (grazing-incidence) configuration.

We can derive from Eq. (8) that the retro-reflected laser frequency $v_g$ imposed by the grating is given by

$$v_g = \frac{c}{2d\sin\theta}. \tag{9}$$

This is the centre frequency of a feedback band-pass filter whose width $\Delta v_g$ can be calculated from Eq. (9) and is inversely proportional to the number of grating lines $N$ illuminated. That is,

$$\Delta v_g / v_g = 1/N. \tag{10}$$

Typically, a several cavity-longitudinal modes lie within the grating pass-band in dispersion-less vacuum--filled cavity of the length $L$. The cavity mode spacing $\Delta v_m$ termed also free spectral range (FSR) is given by

$$\Delta v_m = \frac{1}{T_g}, \tag{11}$$

where $T_g$, is the group delay and may be assumed equal to $T_g = 2L/c$. This yields the more familiar expression for longitudinal-mode spacing in the ECL systems

$$\Delta v_{mE} = \frac{c}{2(nl + L)} \approx \frac{c}{2L}. \tag{12}$$

To enhance cavity dispersion (and thus, enhance wavelength sensitivity) by narrowing the cavity pass-band in some Littrow designs, an etalon can be inserted into the cavity between the lens and the grating [11]. Its free spectral range must be greater than the full-width half-maximum (FWHM) of the Littrow grating bandwidth, and its finesse must be high enough to increase the wavelength selectivity by roughly a factor 10. This technique will force the cavity to operate single mode but it greatly complicates the tuning. The etalon must be tuned synchronously with the grating and cavity length.

Considering Eqs. (8) and (9), the angle of incidence $\theta$ should be as high as possible since this results in increase of the total path difference $W$ on the grating and allows for using a grating with the reasonably small period $d$. This would also increase the spectral angular dispersion $d\theta/d\lambda$ of the grating that may be derived from Eq. (7) in the form

$$\frac{d\theta}{d\lambda} = \frac{\tan\theta}{\lambda} = \frac{m_L}{2d\cos\theta} = \left[\left(\frac{2d}{m}\right)^2 - \lambda^2\right]^{-\frac{1}{2}}. \tag{13}$$

It comes out from Eq. (13) that the dispersion in the Littrow first order can be made as large as one wishes by making $d$ approach $\lambda/2$.

Tuning of the external cavity lasers in Littrow configuration is accomplished via wavelength selective properties of the grating feedback. According to Eq. (9), change of the angle $\theta$ by rotating the grating about the axis parallel to the grooves tunes the laser to a unique diffracted wavelength while nearby wavelengths are returned from the grating at differing angles and thus are suffering greater losses. We should understand, however, that the laser wavelength is determined by a combination of the standing-wave condition, or cavity length and the centre wavelength of the grating feedback, i.e., a grating angle. As the grating rotates the laser tunes by hopping from one longitudinal mode to the next. To tune between the cavity longitudinal modes, the cavity length must be adjusted in such a way that the cavity longitudinal mode wavelength matches the wavelength of the grating in the retro-reflection conditions. A mode hop occurs when the difference between the modal and grating frequencies ($v_m$ and $v_g$, respectively) exceeds half of the FSR, i.e., when

$$\left|v_m - v_g\right| \geq \frac{1}{2}\frac{c}{2L}. \tag{14}$$

Proper tuning involves therefore changing the diffraction angle as well as the external cavity length so that, the mode structure of the external cavity and the diffraction peak of the grating remain superimposed. This is equivalent to maintaining the same number of waves in the cavity at all wavelengths and places strict requirements on the mechanical tolerances and relative motions associated with the laser/grating/mirror combination. Continuous tuning becomes therefore a cumbersome two-step procedure. Nevertheless such tuning by simultaneous cavity-length changing and grating rotation has been demonstrated by several authors [58–61] using mechanical devices to synchronize the two motions.

Fortunately, a continuous tuning range, greater than half of the FSR, can be accomplished by rotating the grating about a carefully chosen pivot. This problem has been considered by a number of authors [62–65] and it was shown that the optimum pivot is located at the intersection between the grating plane and the line parallel to the rear facet of the diode.

Analysis of the relevant equations leads to the conclusion that the optimum pivot location for continuous tuning is situated along the line

$$y = \frac{L_0}{\tan\theta_o}, \qquad (15)$$

which is in the distance of $x_o = -L_o$ from the rear mirror of the SOA [64]. The $L_o$ and $\theta_o$ are defined in Fig. 6.

In Ref. 65, a Doppler-shift model was used to obtain a value for the tuning range and position of the ideal grating pivot was calculated for laser cavities containing any number of dispersive elements, which introduce not only group delay dispersion, but also frequency-dependent offset and tilt of the resonator optical axis. In addition, the continuous tuning range as a function of the pivot location error has been analyzed in order to find out tolerances for laser mechanical design.

It should be remembered, however, that according to detailed calculations given in Refs. 64 and 65, although the tuning range in the vicinity of the optimum pivot becomes extremely large, the tolerance to pivot location error in the *y* direction remains very restrictive depending on the particular ECL's cavity configuration and dimensions.

A second mirror of the ECL cavity is formed by the rear facet of the SOA (see Fig. 1). If this mirror is to serve as the output of the laser, its reflectivity must be appropriately adjusted so that to obtain highest possible output. The other way that can be chosen is to use as the output the reflected zero-th order beam. In that case the rear facet reflectivity should be made close to 100%. Such design takes the advantage of the fact that no matter how well the grating has been matched, some laser radiation will be diffracted into the zero-th order. Since this loss is unavoidable it can be put to use to extract radiation from the laser. However, when the grating is rotated in the Littrow configuration the zero-th order output also rotates, by the law of specular reflection. This inconvenience can be avoided by using special optical configurations with appropriately located optical elements [66]. But perhaps the simplest solution is to use additional mirrors rotated together with the grating by mechanical means [67].

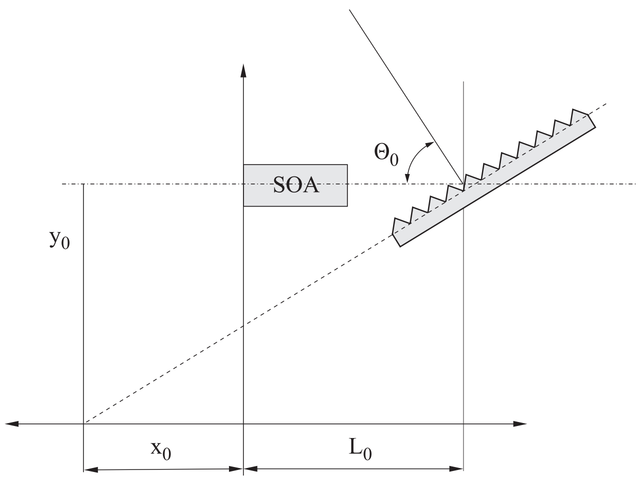


Fig. 6. Geometry of the ECTL system that satisfies condition of continuous tuning by proper positioning of the grating pivot.

The disadvantage of the Littrow geometry caused by deflection of the output as the wavelength is tuned can be eliminated by using a grazing-incidence configuration [Fig. 5(b)] commonly called "Littman". In this configuration cavity design uses a double pass through the grating and the incidence angle is much steeper than in the Littrow case (nominally 85° against around 30° in the Littrow case). The first-order diffracted beam is retro-reflected using an additional mirror. The double-pass scheme, coupled with grazing incidence on the grating, for which dispersion is extremely large, results in producing at least twice the dispersion present in the Littrow cavity and therefore excellent wavelength sensitivity without additional use of an etalon. The dispersion in the grazing incidence configuration cavity is further enhanced, relative to the dispersion of the Littrow cavity, because the diffraction grating is used at grazing incidence where the dispersion is extremely high due to large number of grooves (N) encountered by the incident beam. The zeroth grating order forms the output, and the laser is tuned by rotating the mirror.

The narrow pass-band of the external cavity determines the number of the cavity modes that can be supported, given that the intrinsic diode gain is essentially flat over the entire dispersion width. In typical technical solutions the bandwidth corresponding to this dispersion is on the order of 2.7 GHz and 35 GHz for the Littman and Littrow configurations, respectively. From this perspective, it is clear why the grazing-incidence cavity has also the potential for higher mode stability. The grating bandwidth in the latter can be configured to support a single external cavity mode, whereas the Littrow configuration may in some cases support a finite number of modes.

The advantages of the grazing-incidence configuration can be further enhanced by substitution of the tilted mirror in the system shown in Fig. 5(b) by a grating [68]. The system comprises then two gratings and tuning of the laser is accomplished by rotation of the Littrow grating. Dispersion of the grazing-incidence grating and that of the Littrow one must add for improved operation. It has been shown that the double-grating configuration has the advantages of less-steep tuning curve and provides a single-pass line-width that is almost a factor of 2 narrower than that of the single-grating design [12]. However, for single mode operation of a double-grating laser, several parameters must be carefully determined. First, it is necessary to shrink the cavity length as much as possible so that the FSR between adjacent cavity modes is large enough. Secondly, the rotation mount must be carefully designed. Otherwise the scan is subject to mode hops, in which one mode fades out while another fades in as the Littrow grating is rotated.

### 2.3.2. Electronically tunable ECLs

Mechanical tuning of the ECTLs performed by moving the grating either by motor or a piezo-electric actuator, although rather simple, has unfortunately couple of disadvantages. It is difficult to achieve high repetition rates, high frequency tuning speeds, and a good reproducibility. To address these problems we can incorporate into the cavity a fixed electro-optical crystal. When a voltage is applied across such a crystal, a change of refraction index that is proportional to the electric field takes place. That changes the optical length in the crystal, which obviously in turn tunes the laser. The tuning action obviously can be carried out very rapidly due to the character of the electro-optic (EO) phenomenon. The maximum mode-hop-free tuning range unfortunately still remains restricted by the mode spacing of the cavity, nevertheless such mode-hop-free tuning operation across 10 GHz bandwidth has been demonstrated in practice using an EO crystal cut as a prism that due to its shape was matching elongation and deflection effects [13]. Yet another concept presented in Ref. 14 yielded a five times higher frequency-change-voltage ratio and a frequency-tuning interval more than three times higher than those obtained with the prism approach. The increased sensitivity was achieved mainly due to optimization of the shape and thickness of the EO crystal that was used in this design. Maximum tuning speed achieved was 1.5 GHz/µs.

A new approach to laser tuning has been based on the notion that function of the wavelength selective element in the ECL can be fulfilled by a pair of acousto-optic (AO) devices accommodated inside the cavity with an etalon and a fixed mirror [16]. Fast and accurate selection of the lasing wavelength should be possible then to perform through varying the drive frequency of the AO devices. The notion has proved practical although turned out quite complicated. The ECLT described in Ref. 15 comprised an AO tunable filter and an AO Bragg cell modulator. The filter had the property that for an incident plane-polarized signal, a narrow region of the optical spectrum was diffracted into the orthogonal polarization and the peak wavelength of the filtered spectrum was a function of the acoustic wave frequency. An unavoidable consequence of the filtering operation was that the optical wave was frequency shifted. To restore polarization and compensate this frequency shift, a second AO device with the frequency shift equal and opposite to that of the AO tunable filter was placed inside the cavity. An AO Bragg cell modulator was used for that purpose but a second AO tunable filter could be used as well. With the second device in place, the optical signal returned to its initial frequency upon making a round trip through the laser cavity, hence single-mode operation was possible. The second AO device also provided additional flexibility since the relative phase of the electric driving signals applied to the AO devices could be varied to interpolate between the Fabry-Pérot modes of the external cavity. None continuous tuning was achieved in the cited work but the method is believed to be capable to deliver such tuning. In any case, the lasing wavelength in the experiment could be changed electronically within 10 µs or faster.

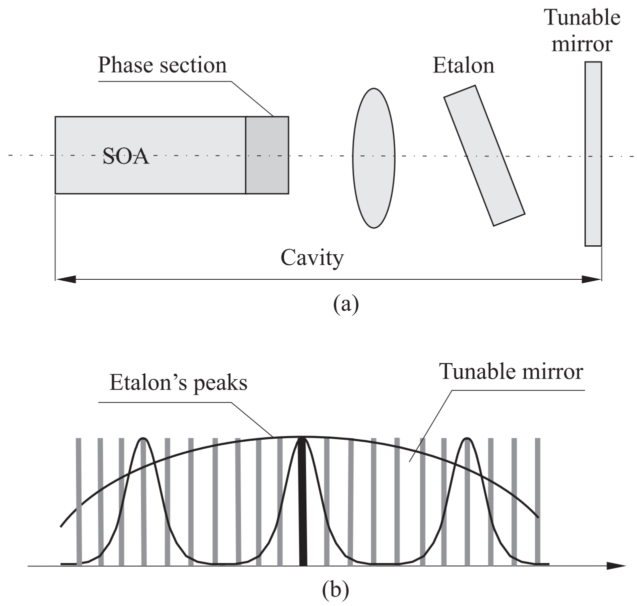



Fig. 7. Diagram of an ECTL with a tunable filter functioning as the fixed wavelength mirror: (a) schematic of the configuration and (b) filtering executed by superposition of the spectral characteristics of the etalon and the LC-SRG (after Refs. 17 and 43).

Interesting results have been obtained through integration of an etalon in combination with a tunable filter to select a specific channel as shown in Fig. 7 [17,43]. The SOA chip contained a gain and a phase section, the mirror was a liquid crystal-based tunable filter. The etalon acted as a periodic filter or grid generator of which the transmission peaks were fixed and aligned to the required frequency channels. It thus assisted in suppression of the cavity modes neighbouring the SOA cavity mode. The liquid crystal-based tunable mirror worked in the reflection mode and served as a wavelength selector owing to its wavelength dependent reflectivity. It exhibited one reflection peak over a very wide wavelength range by adjusting the amplitude of the ac voltage signal [Fig. 7(b)]. In result, the device required only two parameters to tune the wavelength, namely the phase section current and the voltage applied to the tunable mirror. The integration of the phase control on the chip made possible to avoid the need for mechanical tuning of the cavity length. In an ideal situation, as shown in Fig. 7(b), a maximum feedback from the external cavity that results in a local maximum of the forward output power at the wavelength selected by the phase current and position of the LC mirror's reflection peak due to the voltage polarizing the mirror. For a solid state etalon, dispersion of its material induces a wavelength-dependent

FSR that results in an intrinsic limitation of the maximum achievable wavelength accuracy at a fixed temperature setting of the thermo-electric cooler.

### 2.3.3. External cavity lasers with waveguide Bragg gratings (WBG)

The tunable solitary diode lasers with Bragg gratings (DFB) belong now to a well established signal sources in the WDM fibre network. However, low production costs become very essential along with rapid growth of demand for broad-band high speed and low cost the Internet services, so-called, WDM-passive optical network (WDM-PON) [69]. It has been widely recognized that success of the WDM-PON in entering the broad-band network market depends on the development of low-cost optical components, especially WDM light sources which should be completely flexible in the wavelength allocation to subscribers. One of the proposed solutions is an ECTL configuration with Bragg gratings as external reflectors [69]. In favour of that choice is high thermal stability of this configuration. In particular, hybrid integrated ECTLs composed of Bragg grating written in planar lightwave circuits have attracted a lot of interest because they are suitable for mass production at relatively low cost and offer long-term stability [19]. To bring nearer the idea of an ECTL with the planar waveguide and Bragg grating (WBG), such a laser system is presented on a schematic drawing of Fig. 8. Apart of the SOA, it consists of a $LiNbO_3$ substrate showing a high EO tuning slope at 1.5 μm. A 13 mm-long Bragg grating was engraved via photoreactive effect in a Fe-doped section of the waveguide by a holographic setup with an argon laser. The built-in EO phase section makes the laser tunable. Similar idea has been exploited also in other works [70]. Intrinsic stability of the device has been here enhanced by integrating the phase section and the grating in a single device. Another advantage of this design is the drastic reduction of the voltage needed for frequency scans.

This type of the ECTL structure can also be based on a waveguide platform made from a polymer to decrease the cost [69]. In this approach, a 2-mm long WBG was written by the E-beam lithography process. The obtained peak reflectivity and the FWHM bandwidth of the WBG were around 30%, and about 0.45–0.6 nm, respectively. It was therefore suspected that 3–4 longitudinal modes existed within the WBG reflection bandwidth. The laser was tuned by changing temperature of the waveguide. A Cr-Au metal heater was used for that purpose. Since the $dn/dT$ of the polymer waveguide is negative, the lasing wavelength was almost linearly proportional to the generated heating power.

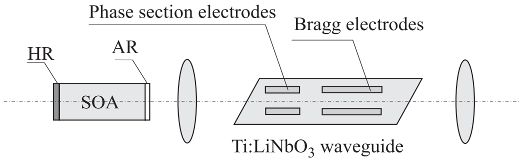



Fig. 8. Schematic of an ECTL with a planar waveguide and Bragg grating (WBG) (after Ref. 19).

## 3. A survey of selected practical ECTL systems and their parameters

A plethora of ECTLs constructions have been tried but not all of them proved to be practical. The obtained parameters show nevertheless the range one can expect and they have been listed in Table 1. So far, designs with mobile bulk grating performing in the Littrow configuration are most widely used [27,61,71,72]. Their characteristics depend obviously on the particular design, but in general they show typical features displayed in diagrams of Fig. 9 [49]. Characteristics plotted in these diagrams were measured for a simple Littrow configuration [Fig. 5(a)] with the SOA comprising an InGaAs/AlGaAs single quantum well (SQW) structure. The grating was rotated and translated mechanically. The SOA chip was oriented in such a way that the chip was coaxial with the optical axis of the system and the p-n junction plane was parallel to the grating grooves to comply with the results of discussion in Sect. 2.2. Moreover, we have found that configuration in which the QW plane was perpendicular to the grooves was totally ineffective. The grating did not select any particular mode and no tuning of the ECTL was observed for this configuration. The most probable reason for this result was that the grating was playing the role of a relatively broadband feedback due to multimode operation of our broad contact diode lasers that usually takes place along the lateral direction in the cavity. Such observation was also confirmed by the results published elsewhere [73].

Line-width of the operating ECTL mode and the wavelength tuning range are among the most important parameters of the lasers in question. Obtained results published in the literature differ significantly depending on many factors. Measurements of the line width are heavily related to the method and instruments used in their course. Nevertheless an external cavity with a grating in Littrow mount produced a line-width of 10 kHz [74]. This line-width was later considerably narrowed to as low as 300 Hz by appropriate detuning of the external cavity feedback phase from the resonance with the field reflected from the AR-coated facet of the SOA [75]. Magnitude of the optimal detuning depended on the facet reflectivity. However, not all levels of detuning were always possible, the combined reflectivity of the SOA facet and grating had to exceed that of the facet alone if the external cavity is to maintain control of the laser.

Tuning characteristics may not necessarily reveal continuous tuning since quite often mode hoping is hidden in the recorded spectrum. True continuous tuning over a wide band has been reported in rather small number of cases. A classic solution that used a motorized translation stage to simultaneously vary the cavity length and rotate a grating is described in Ref. 61. In another approach continuous tuning range equal to 50 GHz in the region of 1510–1560 nm was achieved by combined rotation-translation of the grating using three independent piezoelectric transducers (PZT) that controlled the grating rotation and cavity length

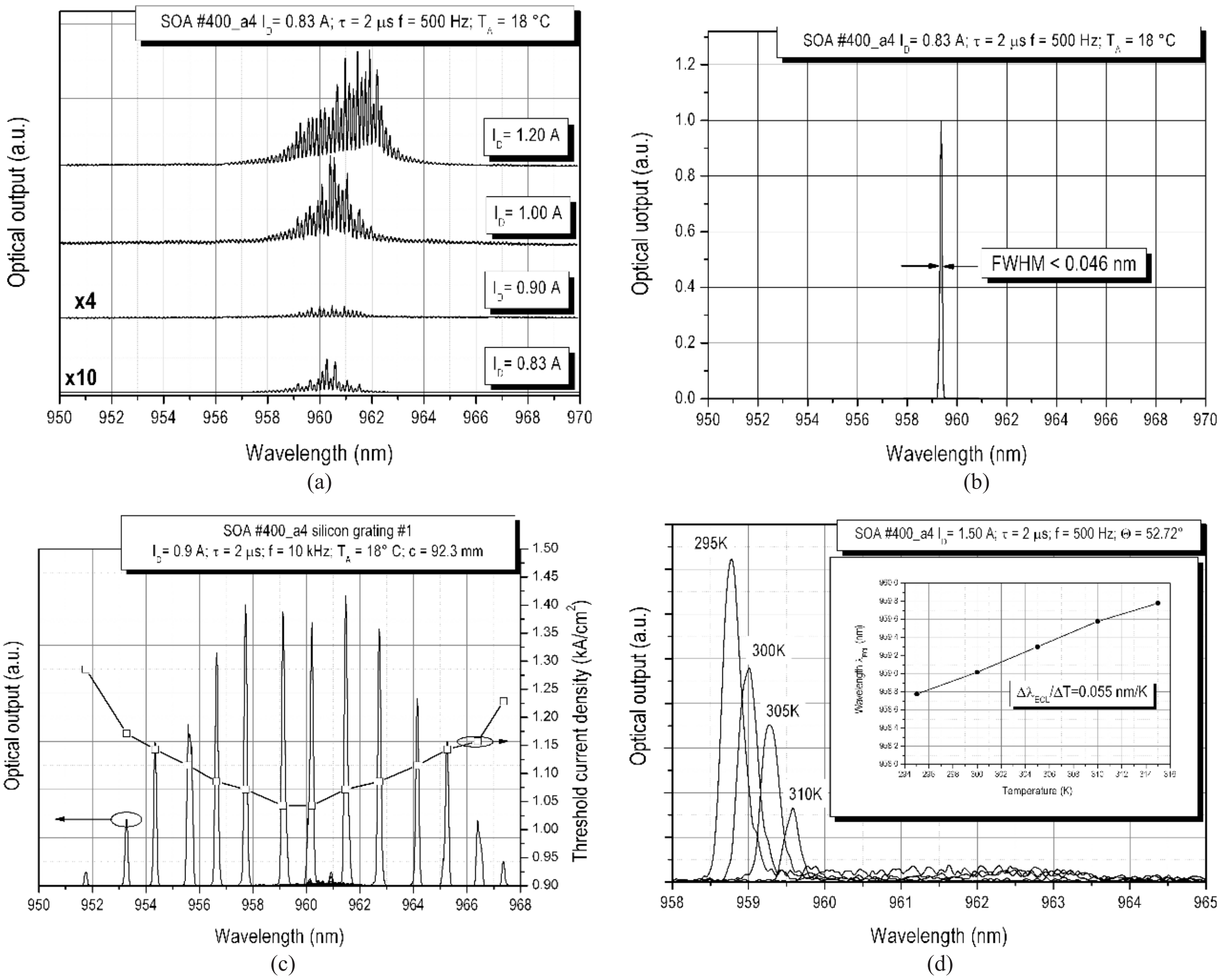



Fig. 9. Typical characteristics of ECTLs; a) spectrum of a solitary diode laser: (a) and a single frequency mode of the ECTL (b): (c) tuning characteristics, and (d) temperature dependence of the lasing mode (after Refs. 48 and 49).

[76]. Such make up has allowed in addition for housing the laser in an extremely small package. In Ref. 77, there is described an ECTL system that enabled a continuous tuning within the range of 1020 GHz (approximately 2.3 nm at 830 nm) using a single PZT that simultaneously rotated the grating and varied the cavity length. In that case, modulation was more straightforward than for tuning scheme employed in Ref. 76 since there was no need to synchronize the control of multiple transducers. In general, the tuning spectral range depends on the SOA gain spectrum, AR coating and configuration of the ECTL. The record number so far reached was 242 nm for the laser operating in the 1.5 µm band. Relevant numbers characterizing other lasers described in the literature are given in Table 1.

Despite the great effort put to improve the lasers with mobile bulk diffraction grating their major disadvantages still wait to be eliminated. The main problem is to ensure thermal and mechanical stability of the laser, high wavelength selectivity and wide- range mode hope-free tuning. Any lateral translations of the SOA chip can result in variations in the optical gain in the cavity and induce rather complicated changes in the laser output power while axial translations of the SOA can perturb the resonant frequencies of the compound cavity of the laser. Stabilized fixed position of the grating and remaining optical components is required for the same reasons. Equally important are any changes in the SOA chip temperature that might give rise to variation in the gain spectrum and optical path length within the solitary diode itself.

The external cavity mode structure is essentially a comb function and numerous possible modes exist under the relatively broad gain curve of the SOA. The loss curve of the grating ideally would allow selection of only a single one of these modes. Therefore the width of the grating dispersion must be narrow enough to support as few modes as possible in order to maintain single mode operation although it was determined that such operation did not depend critically on the grating dispersion. Nevertheless, any instability in the cavity invokes mode hoping which is also encouraged by the residual cavity of the SOA that still functions inside the longer external cavity formed by the grating. Moreover, in the case of broad contact SOAs the gain may be no uniformly distributed in the plane of the active area due to the material nonhomogeneities and temperature gradient. To diminish finesse of the residual cavity, reflectivity of the SOA's AR-coated facet must be made low enough so that the modulation of the SOA's gain curve was insignificant. For maximum grating dispersion, the gain chip should be mounted in the ECL cavity with its junction plane parallel to the grating grooves as discussed in Sect. 2.2.

As it was already mentioned, to ensure that the same mode is always selected by the grating when tuning the laser, the cavity length must be properly adjusted. Rotation of the grating combined with its linear translation have been very often used for that purpose [58,67]. The combined effect of simultaneous translation and rotation can also be achieved in a single motion by rotating the grating about a remote point located in precisely chosen place (see Sect. 2.3).

Quite often speed with which the laser can be tuned is also essential. Mechanical arrangements are in this respect beyond consideration but piezoelectric translators may offer a satisfactory solution [77].

Despite all the difficulties, investigations of various hybrid grating external-cavity semiconductor lasers continue to be pursued mainly due to their outstanding spectral performance. Although a great emphasis usually is being put on the quality of the components used to construct ECLs, some designs show that even low cost commercial components can be used to make these lasers with satisfactory parameters. By way of example the laser described in Ref. 27 featured a very rigid construction and good parameters. Its cavity was constructed on a mirror mount, eliminating the need for the milled base plate with separate diode, collimating lens and grating assemblies of other designs. The total length of the extended cavity was about 20 mm, which was long enough to reduce the line-width below 1 MHz, while at the same time the corresponding mode spacing of 8 GHz was large enough to provide a useful continuous scan range and robust single frequency operation before making a much larger hop corresponding to the 50 GHz free spectral range of the solitary laser diode cavity. The continuous frequency scans of 8 GHz could be achieved using a PZT alone and larger continuous scans were expected with appropriate synchronous translation and rotation of the grating. The laser could also be tuned discontinuously over a range of about 20 nm around the free- running wavelength of the solitary laser diode by rotating the grating (see also Table 1).

Many applications in nonlinear optics, e.g., photo-mixing or spatially resolved spectroscopic measurements taken by using distributed optical fiber networks, require output powers of more than 100 mW but with the same excellent spectral properties like single frequency operation and broad continuous tuning ranges. Wavelength tunable emission with output powers of up to 1 W has been obtained in different wavelength ranges by using tapered amplifiers operating in external grating cavities [38]. However, substantial drawback of those laser systems was the missing capability of continuous wavelength tuning in a stable single frequency mode. This difficulty has been overcome by using a wavelength tunable low power single frequency oscillator in combination with a semiconductor optical amplifier [39]. Function of the oscillator played an ECTL in Littman configuration, whose emission was tunable without mode hops across the entire 20 nm gain spectral profile. The amplifier was a GaAs/GaAlAs quantum well tapered geometry structure with a peak gain at 782 nm and a spectral bandwidth of 20 nm. The input width of the active area increased from nearly 5 μm up to 150 μm at the output facet. Both facets have been AR-coated with a residual reflectivity of approximately 1% at the small end of the taper and 0.1% at the large end [39]. Using appropriate optics and a 60-dB Faraday isolator, at the input power of 2.4 mW emitted by the ECTL, the system was capable to deliver the output power up to 500 mW limited by gain saturation.

Advantages gained by using ECLs have turned out to be a sufficient argument to implement these devices to series production. Designs of those available on the market, in general, follow classic technical solutions based on using mobile bulk gratings with the external cavity in Littrow or Littman configurations. Some additional optical elements are usually included into these designs to improve optical parameters of the lasers. Special effort is made to attain highly stabilized operation and continuous tuning. Taking advantages offered by different semiconductor structures employed as SOAs, we now can make ECTLs suitable for operation at any wavelength in the range extending from UV up to far-infrared. Particularly interesting are developments focused on increasing the laser output power without sacrificing ability to their single frequency operation and tunability. By way of example, an ECTL of a compact design has been described in Ref. 40 that was capable to emit optical beam of an excellent quality ($M^2 < 1.2$) with the output power reaching 1 W at the wavelength range from 775 to 785 nm. The line width of this emission was in the region of a few megahertz and side mode suppression was better than 55 dB. The laser output signal could be modulated up to 100 MHz and tuned mode-hop-free across 15 GHz at the rate of 1 kHz when using a piezoelectric actuator.

External cavity lasers in the grazing-incidence configuration are reported in the literature rather rarely. This might be caused by relatively more complicated make up and higher optical requirements involved with double dispersing by the grating. It is also believed that AR coating of the SOA front facet must provide lower reflectivity than it is necessary in the Littrow configuration. However, in Ref. 28, an ECTL in grazing-incidence configuration has been described that used a standard optical components and a commercial GaAlAs diode laser. Geometry of the laser cavity was like the one shown in Fig. 5(b). It was simple three-mirror cavity that consisted of a high-reflection-coated rear facet of the diode laser, SOA gain medium, collimating lens, a 1800-line/ mm holographic diffraction grating at grazing incidence and an external mobile mirror. One end of the laser cavity was the rear facet of the diode laser with HR coating and about 97% reflectivity. The other end was the external mirror. The front facet of the SOA had an AR coat-

Table 1. A survey displaying developments in the field of the ECTLs.

| Laser set-up | Center wave -length (nm) | Line-width (MHz) | Tuning range | | SMRS (dB) | Cavity mode spacing (GHz) | Output power (mW) | Ref. No | Year |
|---|---|---|---|---|---|---|---|---|---|
| | | | (nm) | (GHz) | | | | | |
| Littrow (M) | 1500 | 0.010 | 55 | 7 300* | 50 | | 3 | 74 | 1983 |
| Littrow (M+PZT) | 1260 | 0.010 | 15 | 3 000 | 30 | | | 58 | 1986 |
| Littrow (M) | 1555 | | 240 | 30 000* | | | 5 | 54 | 1990 |
| Littrow (M) | 1500 | | 242 | 32 300* | 42 | | 45 | 26 | 1990 |
| Littrow (M) | 1540 | < 0.100 | 82 | 10 300* | | | 0.8 | 59 | 1991 |
| Littrow (M) | 1300 | | 160 | 28 400* | 40 | | 40 | 33 | 1991 |
| Littrow (M) | 852 | < 50.00 | 35 | 12 400* | 20 | | 1000 | 38 | 1993 |
| Littrow (M+PZT) | 1310 | | 17 | 2 880 | | 1.99 | | 65 | 1993 |
| Littrow (M) | 970 | < 0.300 | 20 | 6 400* | | 1.5 | 1000 | 41 | 1995 |
| Littman (M) | 825 | | 40 | 17 700* | | 1.5 | 6.5 | 61 | 1996 |
| Littrow (M+PZT) | 780 | 0.350 | 20 | 9 800* | | 8.0 | 80 | 27 | 1998 |
| Littrow (M+PZT) | 814 | < 1.000 | 14 | 80 (fine) | | | 75 | 80 | 2001 |
| MOEMS (E) | 1536 | 0.1 nm | 16 | 2 000* | 60 | | 0.016 | 81 | 2001 |
| Littman (M+PZT) | 780 | 0.010 | 20 | 9 800* | | 1.2 | 18 | 28 | 2003 |
| Littrow (M) | 412 | 0.800 | 4 | 6 900* | 35 | | 30 | 72 | 2003 |
| Littrow (M+PZT) | 2130 | 3.800 | 60 | 46.4 | 25 | 0.37 | 15 | 82 | 2004 |
| Acousto-optic tunable filter | 1550 | 0.120 | 132 | 16 500* | 50 | 2.0 | | 16 | 2004 |
| Littman (MEMS) | 1544 | 0.030 | 40 | 5 300* | | | 12 dBm | 79 | 2005 |
| Fixed LC tunable mirror | 1550 | 2.300 | | 200 | 45 | 11 | 50 | 17.83 | 2006 |
| Waveguide external cavity | 1553 | 0.018 | | 6.6 | 40 | 2.1 | 7 | 19 | 2006 |

Legend: M- moved by motors; PZT – piezoelectric actuators; E – moved by applied voltage due to an electrostatic force; SMRS – side mode suppression ratio; * – calculated.

ing that had a reflectivity estimated to be between 2% and 10%. Unlike in majority lasers described in the literature, the junction plane of the SOA in this ECTL system was oriented perpendicularly to the grooves of the diffraction grating. The diffraction angle and diffraction efficiency into the first order were measured to be approximately 85° and 40%, respectively. The diffraction grating at grazing incidence served for wavelength selection and output coupling. The first-order reflection from the grating was reflected back into the laser by the external mirror. Neglecting coupling losses, about 15% of the power was returned to the SOA and the internal cavity modes of the solitary diode laser were therefore strongly coupled to the external cavity. The zeroth-order reflection from the grating was the output of the laser. The laser frequency was tuned by rotating and translating the external mirror.

The average length of the laser cavity was roughly 12 cm which corresponded to an axial mode spacing of 1.2 GHz. The laser emitted beam of single frequency, had a narrow linewidth of 10 kHz, and was continuously tunable over the range of 20 nm (see Table 1).

## 4. Prospects for further progress

### 4.1. New semiconductor materials

A major advantage of the ECTL configuration is that it may be employed regardless of the material from which we make the SOA. This feature enables to build lasers emitting in very wide wavelength range that is limited only by the availability of the gain chips. So far, a great number of

ECTLs emitting within the near-infrared wavelength range across 0.8 to 1.6 µm have been described as indicated in the preceding sections but there is still an effort being put into development of new materials and structures that would expand the spectral limits towards both ultraviolet (UV) and far-infrared. The UV emitting ECTLs have immediately appeared after the InGaN/GaN diode laser chips with suitable AR coating had become available [72,73]. They were soon followed by mid-infrared ECLTs based on the development of GaInAsSb quantum well lasers with AlGaAsSb barriers lattice matched to the GaSb substrates [81]. In the latter, edge-emitting index-guided ridge-waveguide lasers with 6-µm ridge width were used. They operated CW at 2.3 µm and could be tuned within 177 nm [82].

Totally new opportunities have been opened up when the technology of quantum cascade (QCL) lasers matured enough to make possible fabrication of the SOAs. These lasers can operate in the 3–20 µm wavelength range and it turned out to be a straightforward way to use them as SOAs in the ECTL configuration. Spectral characteristics of the gain in QCLs are of the same shape as those for inter-band lasers [83] and typical QCL structures can be used to make the SOAs. In the particular case described in Ref. 84, a structure composed of 25 periods of alternating active regions and injectors embodied between lattice-matched GaInAs separate confinement layers was used. The active regions included 4 quantum wells and they were grown on InP substrates by MBE. This process was followed by low-pressure MOCVD growth of the InP layers performing as upper cladding and contact layers. The wafers were processed into F-P mesa waveguide laser chips by chemically assisted ion beam etching. Their back and front facets were subsequently coated with a $Si_3N_4$ passivation layer. Then index-coupled DFB structure was imprinted on the ridge. The lasers were pulse operated (100 ns, 1 kHz repetition rate) at room and above the room temperature (390 K), and generated the 5.34-µm wavelength. To form an external cavity the emitted light was collected by a mirror collimator and the feedback was provided by a highly reflecting gold mirror. Introduction of the optical feedback has caused a strong increase in the laser output power, however, the QCLs were as sensitive to optical feedback as the solitary inter-band diode lasers. It turned out that in order to achieve stable laser operation optical feedback should or spectrally controlled by an optical grating. Grating-tuned external-cavity system with a QC laser has been reported in Ref. 85. An intra-band InGaAs/InAlAs QC structure grown by MBE and fabricated into 10–12-µm-wide ridge waveguide laser was employed. It operated in the 4.5–5.1 µm wavelength range at 80 K temperature. A 4-µm echelle blazed grating was used and mounted in the Littrow configuration with zeroth-order output.

## 4.2. New perspective ECTL systems

So far this paper has been devoted mainly to the macro-scale tunable laser diodes. It is obvious, however, that the micro-scale embodiments have been as well attracting the research interests in recent years. In Ref. 86, there has been described a micro-fabricated tunable laser diode of 5 × 5 mm size and obtained about 20-nm range wavelength tuning. However, the micro-mirror for this laser diode and its actuator were fabricated using nickel plating and that was incompatible with the integrated circuit (IC). The use of a surface-micro-machined poly-silicon mirror to form an external cavity for the laser diode was reported in Ref. 87.

Another integrated tunable laser device of 2 × 1.5 mm size was fabricated and studied for potential applications in WDM systems [88]. This device uses a polysilicon three-dimensional (3-D) micromirror integrated with a FP laser diode and a self-contained optical filter. The 3-D micromirror was positioned near (10 µm) to the exit window of the laser diode to form the external cavity. The optical fibre was fixed very close (15 µm) to the rear output window of the laser diode with the intention of directly collecting the output laser beam without the need for optical lenses. To maximize the transmittance and to prevent unnecessary feedback to the laser diode, the end facet of the optical fibre was AR coated. Change of the voltage applied to the comb-drive, caused displacement of the 3-D micromirror and executed change of the external cavity length thus tuning the wavelength of' the laser diode.

The movable 3-D micromirror formed by a 1.5-µm-thick polysilicon layer had the size of 300 × 300 µm and was coated with a 0.5-µm thick gold layer to increase its reflectivity to over 90%. The difference in residual stresses between the polysilicon layer and the gold layer makes slightly deformed the 3-D mirror to a shape of a concave reflector, which was helpful for coupling the reflected beam with the laser diode. Compared with its macroscale and microscale counterparts, this devise had the advantages of compactness, low driving voltage, and better compatibility with IC processes.

Combination of a mocro-electro-mechanical system (MEMS) laser diode with an external cavity mirror may be considered as a classic arrangement for the ECTL in the MOEM technology. Two end facets of the laser diode and an additional reflective mirror formed the internal and external rasonant cavities, respectively. The laser operated at the wavelength of 1540 nm and exhibited 0.1-nm linewidth which was yet too large for WDM applications. By changing the length *L*, the laser could be tuned within a wavelength range of 16 nm but it was observed that the wavelength does not change smoothly all over the tunable range and mode-hoping phenomenon was observed.

Although the approach described above looks in general promising, there is still room for exploitation of dispersive characteristics featured by diffraction gratings integrated with SOAs and modulators in MOEM configurations. An example of the design that uses such an opportunity has been presented in Ref. 79. The device was operating in the Littman configuration in which the beam emitted by the AR-coated intra-cavity facet of the SOA was collimated by a lens, diffracted by a grating, and frequency-selected by the requirement that the beam be retro-reflected to the SOA along the path selected by the out-of-plane mirror tilt and lens position. Varying the virtual pivot MEMS actuator voltage changed the cavity length and in-plane mirror angle, giving substantial mode-hop-free tuning ranges. The latter could be extended by cavity length adjustment through change of the grating piezoelectric (PZT) actuator voltage. Excellent long-term stability resulted when the MEMS and PZT voltages, as well as the SOA chip current, were controlled by servos with regard to the relative intensity of the zeroth-order etalon-sampled outputs. Best results with respect to jitter were obtained, however, by eliminating the servos and driving the gain chip and actuators directly by low-noise dc sources. The laser operated in the wavelength range of 1527–1567 nm and the obtainable line width was $\Delta v$ = 15 kHz.

Other options offered by MEMS technology have been presented more in detail in Ref. 46. The proposed ECTL had the Littrow configuration with the external cavity formed by a grating that retro-reflected $12^{th}$ order diffracted beam. The grating was mounted on the elastic cantilever tip with the loads applied by two comb electrostatic actuators. One was used to rotate the grating about the pivot point, while the other provided a linear translation to adjust the cavity length. Geometry of the suspension was designed to simulate the operation of an ideal pivot (see Sect. 2.3). The SOA was a stripe ridge-waveguide InGaAsP device. Emission from the HR coated facet was coupled into a lensed single mode fibre. The external cavity and the tuning elements consisting of a blazed grating, elastic elements and comb drives that were all fabricated by deep reactive ion etching (DRIE) of "bonded on silicon-on-insulator" (BOSOI) material. Integration of these gratings with the suspension and the drive had lead to a low cost tuning element. The laser operated at $\lambda$ = 1508 nm and could be tuned to the longer wavelengths over a spectral range of $\Delta\lambda$ = 20 nm. The spectral selectivity of the grating was sufficient to obtain single mode operation with a side mode suppression ratio of –20 dB.

In attempt to eliminate any mechanical movements of the components in the ECTL set-up, an entirely new approach has been proposed whose idea is shown in Fig. 10 [89]. Although this design is based on the concept of multichannel structures with active stripes [21], which are beyond the scope of the present review, we are discussing it here because the laser in question may be regarded as a monolithic two-dimensional realisation of an external grating laser by means of a fixed integrated grating and an array of active stripes. This combination replaces a single active element and a rotating grating when one of the stripes is injection pumped and is lasing at the wavelength determined by its position relative to that of the grating. As this geometry is accurately defined by a photolithographic mask, precise determination of the lasing wavelengths is possible at the design stage. A planar InP/InGaAsP/InP double heterostructure waveguide forms the body of the laser between the diffraction grating and the active wave-guiding stripes. The external facets of the active stripes together with the grating constitute the reflective boundaries of the resonant cavity. The grating is formed by a reflective wall vertically etched down through the waveguide core. It is curved in the plane of the device and focuses retro-diffracted light onto the internal ends of the active stripes. These stripes comprise a conventional InGaAs/InGaAsP multi-quantum well (MQW) active region that lies directly on the top of the wave-guiding core, the latter being continuous with the rest of the optical resonator body. This arrangement assures good coupling of the optical mode between the active stripe in the planar guide region. Semi-insulating InP provides current-blocking for electrically pumped stripes and also forms an upper cladding to the planar waveguide. The diffraction geometry employed was a standard 9-mm radius Rowland circle, the grating operated in the $16^{th}$ order and was blazed for retro-reflection. Lasing was observed from the active stripes, over a spectral range from about 1500 to 1535 nm. The emission beams were TE polarized and typical emission spectrum of a stripe exhibited single longitudinal mode with the line width below 0.1 nm. The measured wavelength of the laser emission from each stripe was in accordance with its geometric positioning with respect to the diffraction grating. This very high degree of wavelength linearity and spacing accuracy was a direct consequence of photo-lithographically determined geometric definition of the lasing cavity.

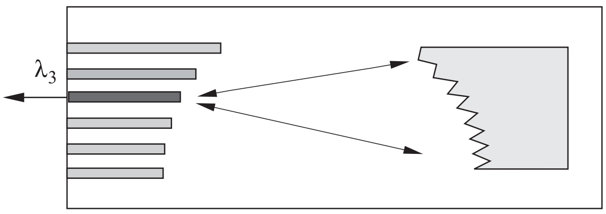



Fig. 10. Concept of a multi-stripe ECTL with a Rowland circle grating (after Ref. 89).

Similar concept, as discussed above, has been described by Kirkby in Ref. 90 and further developed by other authors [23,91–93]. The device described in Ref. 92 was made from InGaAsP/InP heterostructure and consisted of three sections, active, guide, and diffraction that comprised an optical amplifier (SOA), a phase-control section (PCS), a dispersive element (DE), and an etched diffraction grating (EDG), respectively. Schematic diagram of the device is given in Fig. 11. All components were monolithically integrated on an InP substrate. The diffraction grating had a shape of a 3-mm-radius Rowland circle echelle grating that worked in the $8^{th}$ order Littrow configuration. The design of the device could be easily modified to increase the number of channels and reduce the channel spacing by selection of a proper Rowland radius and grating order for a given grating period and waveguide separation. Wavelength tuning was achieved by current injection into DE and PCS elements and simply corresponded to the mechanical rotation and translation of the grating in a classic ECL. Its tuning mechanism was based on electrically controlled beam deflection exerted by DE pattern and provided by the PCS

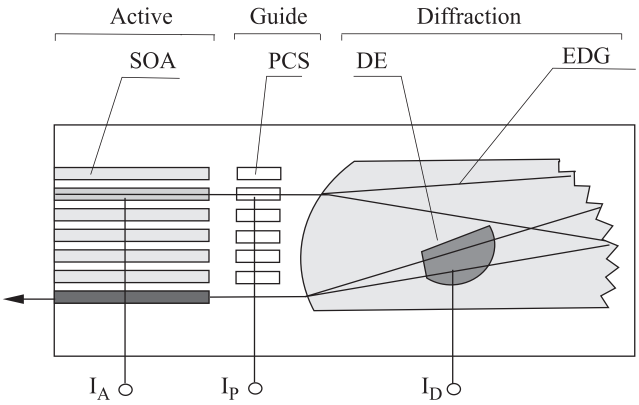


Fig. 11. Schematic of a multi-wavelength ECTL system with the Rowland circle grating (after Refs. 92 and 93).

phase matching between the active, guide and diffraction sections. The beam deflection was induced by refractive index change of the guide within the DE pattern. This was changing the incident angle of the beam at the grating pole and thus tuned the wavelength diffracted from the grating according to the Littrow condition. With its three p-type current electrodes, this device allowed for control of optical gain and optical power via $I_A$ current supplied to active section, control of the beam deflection via the current $I_D$ to DE pattern and the phase change via current $I_P$ to PCS. Therefore, the mutual adjustment of the beam deflection and the phase matching by $I_D$ and $I_P$, respectively, would yield continuous wavelength tuning.

The DE pattern deserves special attention. It had two interfaces along the optical path of the beam and at one side it was perpendicular to the waveguide. To determine the curves of the other interface, the light focused back to the waveguide after diffraction by the grating had to be considered. The phase difference between two adjacent grating elements had to be equal to a multiple of $2\pi$ for the lasing wavelength $\lambda$. To achieve the proper relationship more than one pattern could be employed in the laser system.

It should be noted that optical length of the external section and the incident angle on the grating were simultaneously changing with the increase in the DE current. Practically, this length change made selection of the external mode quite difficult and continuous tuning questionable. It was also difficult to obtain wide tuning range and high side-mode suppression ratio (SMSR). In order to overcome these problems, a modified device has been proposed and described in Ref. 93. It comprised additional reflective channels and was implemented in a Littman configuration based on the Rowland circle construction for a concave grating. The channel separations between the two waveguides on the Rowland circle were designed by the proper selection of the channel spacing for the given grating radius $R$ and the diffraction order $m$.

Lasing wavelength was selected (or tuned coarsely) by turning on the SOA and the appropriated channel element in the array. This was possible, since different channels lased at different wavelengths in accord with their diffraction and the incident angle of the beam at the grating pole. The lasing mode of each channel was also tuned finely by injecting the current to DE and PCS elements. In conclusion, the proposed device, although very complicated from the point of view of the operation, has been perceived as one of the cost-effective tunable or multi-wavelength sources that would be easy to fabricate by using standard patterning and etching processes. Summing up, perhaps most important is to note that integration of active devices with a fixed Rowland circle grating in Littman configuration may open new prospects for progress in fabrication of the tunable high quality laser sources.

## 5. Conclusions

A class of selected tunable semiconductor lasers has been overviewed with the purpose to summarize major developments in the field and to estimate potential for further progress. Characteristic feature of these lasers is that they have a compound resonant cavity called external or sometimes extended one. Such cavity provides new means to stabilize the laser line. This is because the active optical gain medium and its instabilities like those induced by change of temperature play much diminished role due to its minute length when compared with the whole cavity of the laser. The space between the mirrors in the ECTL compound cavity enables placing within it additional elements like etalon or phase controllers which help to tune the laser to required frequency and at least one of the mirrors in the compound cavity is usually frequency selective and acts as a tunable mode filter. In result, extremely narrow line-widths on the order of 10 kHz have been achieved from semiconductor lasers with the facility for tuning them in the wavelength range across of 242 nm. New materials and configurations appear that make these lasers still more attractive due to extension of the operation spectral range. Last but not least, the tunable ECTLs have the potential to be fabricated cheaply enough to promote their applications.

In summary, the advantages of the ECTLs over solitary diode lasers are so important that their future looks encouraging. This conclusion becomes still better supported if we consider multichannel external cavity lasers that are particularly interesting for high density (HD) WDM applications. This latter class of lasers has been omitted, however, in the present review to preserve its possibly concise form.

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## References

1. T. Kleine-Ostmann, P. Knobloch, M. Koch, S. Hoffmann, M. Breede, M. Hofmann, G. Hein, K. Pierz, M. Sperling,

and K. Donhuijsen, "Continuous-wave THz imaging", *Electron. Lett.* **37**, 1461–1463 (2001).
2. C.S. Friedrich, C. Brenner, S. Hoffmann, A. Schmitz, I.C. Mayorga, A. Klehr, G. Erbert, and M.R. Hofmann, "New two-colour laser concepts for THz generation", *IEEE J. Sel. Top. Quant.* **14**, 270–275 (2008).
3. L. Gasman, "Device development will tackle video traffic jam", *Fibre Systems Europe*, June, 2007.
4. T. Morikawa, Y. Mitsuhashi, and J. Shimada, "Return-beam induced oscillations in self-coupled semiconductor lasers", *Electron. Lett.* **12**, 435–436 (1976).
5. V. Jayaraman, Z.M Chuang, and L.A. Coldren, "Theory, design, and performance of extended tuning range semiconductor lasers with sampled gratings", *IEEE J. Quantum Elect.* **29**, 1824–1834 (1993).
6. Y. Tohmori, Y. Yoshikuni, H. Ishii, F. Kano, T. Tamamura, and Y. Kondo, "Over 100 nm wavelength tuning in superstructure grating (SSG) DBR lasers", *Electron. Lett.* **29**, 352–354 (1993).
7. J. Hong, H. Kim F. Shepard, C. Rogers, B. Baulcomb, and S. Clements, "Matrix-grating strongly gain-coupled (MG--SGC) DFB lasers with #4-nm continuous wavelength tuning range", *IEEE Photonic. Techn. L.* **11**, 515–517 (1999).
8. P.J. Rigole, S. Nilsson, L. Bäckbom, B. Stalnacke, E. Berglind, J.P. Weber, and B. Stoltz, "Quasi-continuous tuning range from 1560 to 1520 nm in a GCSR laser, with high power and low tuning currents", *Electron. Lett.* **32**, 2352–2354 (1996).
9. A. Wicht, M. Rudolf, P. Huke, R.H. Rinkleff, and K. Danzmann, "Grating enhanced external cavity laser", *Appl. Phys.* **B78**, 305–313 (2003).
10. A.D. White, "Reflecting prisms for dispersive optical maser cavities", *Appl. Optics* **3**, 431–432 (1964).
11. T.W. Hänsch, "Repetitively pulsed tunable dye laser for high resolution spectroscopy", *Appl. Optics* **11**, 895–898 (1972).
12. M.G. Littman, "Single-mode operation of grazing-incidence pulsed dye laser", *Opt. Lett.* **3**, 138–140 (1978).
13. L. Ménager, L. Cabaret, I. Lorgeré, and J.L. Le Gouët, "Diode laser extended cavity for broad-range fast ramping", *Opt. Lett.* **25**, 1246–1248 (2000).
14. L. Levin, "Mode-hop-free electro-optically tuned diode laser", *Opt. Lett.* **27**, 237–239 (2002).
15. G.A. Coquin and K.W. Cheung, "Electronically tunable external-cavity semiconductor laser", *Electron. Lett.* **24**, 599–600 (1988).
16. K. Takabayashi, K. Takada, N. Hashimoto, M. Doi, S. Tomabechi, T. Nakazawa, and K. Morito, "Widely (132 nm) wavelength tunable laser using a semiconductor optical amplifier and an acousto-optic tunable filter", *Electron. Lett.* **40**, 1187–1188 (2004).
17. J. De Merlier, K. Mizutani, S. Sudo, K. Naniwae, Y. Furushima, S. Sato, K. Sato, and K. Kudo, "Full C-band external cavity wavelength tunable laser using a liquid-crystal--based tunable mirror", *IEEE Photonic. Techn. L.* **17**, 681–683 (2005).
18. T. Sato, F. Yamamoto, K. Tsuji, H. Takesue, and T. Horiguchi, "An uncooled external cavity diode laser for coarse-WDM access network systems", *IEEE Photonic. Techn. L.* **14**, 1001–1003 (2002).
19. V. Crozatier, B.K. Das, G. Baili, G.Gorju, F. Bretenaker, J.L. Le Gouët, I. Lorgeré, and W. Kohler, "Highly coherent electronically tunable waveguide extended cavity diode laser", *IEEE Photonic. Techn. L.* **18**, 1527–1529 (2006).
20. I.H. White, K.O. Nyairo, P.A. Kirkby, and C.J. Armistead, "Demonstration of a 1×2 multichannel grating cavity laser for wavelength division multiplexing (WDM) applications", *Electron. Lett.* **26**, 832–834 (1990).
21. I.H. White, "A multichannel grating cavity laser for wavelength division multiplexing applications", *J. Lightwave Technol.* **9**, 893–899 (1991).
22. J.B.D. Soole, A. Scherer, H.P. LeBlanc, N.C. Andreadakis, R. Bhat, and M.A. Koza, "Monolithic InP/InGaAsP/InP grating spectrometer for the 1.48-1.56 μm wavelength range", *Appl. Phys. Lett.* **58**, 1949–1951 (1991).
23. O.K. Kwon, K.H. Kim, E.D. Sim, J.H. Kim, and K.R. Oh, "Monolithically integrated multiwavelength grating cavity laser", *IEEE Photonic. Techn. L.* **17**, 1788–1790 (2005).
24. Y. Arakawa and A. Yariv, "Quantum well lasers-gain, spectra, dynamics", *IEEE J. Quantum Elect.* **QE-22**, 1887–1899 (1986).
25. R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties", *IEEE J. Quantum Elect.* **QE-16**, 347–355 (1980).
26. M. Bagley, R. Wyatt, D.J. Elton, H.J. Wickes, P.C. Spurdens, C.P. Seltzer, D.M. Cooper, and W.J. Devlin, "242 nm continuous tuning from a GRIN-SCH-MQW-BH InGaAsP laser in an extended cavity", *Electron. Lett.* **26**, 267–269 (1990).
27. A.S. Arnold, J.S. Wilson, and M.G. Boshier, "A simple extended-cavity diode laser", *Rev. Sci. Instrum.* **69**, 1236–1239 (1998).
28. K.C. Harvey and C.J. Myatt, "External-cavity diode laser using a grazing-incidence diffraction grating", *Opt. Lett.* **16**, 910–912 (1991).
29. J.E. Epler, G.S. Jackson, N. Holonyak, Jr., R.L. Thornton, R.D. Burnham, and T.L. Paoli, "Broadband operation of coupled-stripe multiple quantum well AlGaAs laser diodes", *Appl. Phys. Lett.* **47**, 779–780 (1985).
30. D.C. Hall, J.S. Major, Jr., N. Holonyak, Jr., P. Gavrilovic, K. Meehan, W. Stutius, and J.E. Williams, "Broadband long-wavelength operation (9700 Å ≥ λ ≥ 8700 Å) of $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ quantum well heterostructure lasers in an external grating cavity", *Appl. Phys. Lett.* **55**, 752–754 (1989).
31. M. Mittelstein, D. Mehuys, and A. Yariv, "Broadband tunability of gain-flattened quantum well semiconductor lasers with an external grating", *Appl. Phys. Lett.* **54**, 1092–1094 (1989).
32. A. Lidgard, T. Tanbun-Ek, R.A. Logan, H. Temkin, K.W. Wecht, and N.A. Olsson, "External-cavity InGaAs/InP graded index multiquantum well laser with a 200 nm tuning range", *Appl. Phys. Lett.* **56**, 816–817 (1990).
33. C.P. Seltzer, M. Bagley, D.J. Elton, S. Perrin, and D.M Cooper, "160-nm continuous tuning of an MQW laser in the external cavity across the entire 1.3 μm communications window", *Electron. Lett.* **27**, 95–96 (1991).
34. J.N. Walpole, E.S. Kintzer, S.R. Chinn, C.A. Wang, and L.J. Missaggia, "High-power strained-layer InGaAs/AlGaAs tapered travelling wave amplifier", *Appl. Phys. Lett.* **61**, 740–742 (1992).

 

35. C.F. Lin, Y.S. Su, and B.R. Wu, "External-cavity semiconductor laser tunable from 1.3 to 1.54 μm for optical communication", *IEEE Photonic. Tech. L.* **14**, 3–5 (2002).
36. H.S. Gingrich, D.R. Chumney, S.Z. Sun, S.D. Hersee, L.F. Lester, and S.R.J. Brueck, "Broadly tunable external cavity laser diodes with staggered thickness multiple quantum wells", *IEEE Photonic. Techn. L.* **9**, 155–157 (1997).
37. L. Goldberg, D. Mehuys, and D.C. Hall, "3.3 W CW diffraction limited broad area semiconductor amplifier", *Electron. Lett.* **28**, 1082–1084 (1992).
38. D. Mehuys, D. Welsh, and D. Scigres, "1 W CW, diffraction-limited, tunable external-cavity semiconductor laser", *Electron. Lett.* **29**, 1254–1255 (1993).
39. D. Wandt, M. Laschek, K. Przyklenk, A. Tünnermann, and H. Welling, "Continously tunable 0.5 W single-frequency diode laser source", *Opt. Commun.* **148**, 261–264 (1998).
40. S. Stry, L. Hildebrandt, J. Sacher, Ch. Buggle, M. Kemmann, and W. von Klitzing "Compact tunable diode laser with diffraction limited 1 Watt for atom cooling and trapping", e-mail: sandra.stry@sacher-laser.com
41. R.J. Jones, S. Gupta, R.K. Jain, and J.N. Walpole, "Near-diffraction-limited high power (~1 W) single longitudinal mode CW diode laser tunable from 960 to 980 nm", *Electron. Lett.* **31**, 1668–1669 (1995).
42. M. Notomi, O. Mitomi, Y. Yoshikuni, F. Kano, and Y. Tohmori, "Broad-band tunable two-section laser diode with external grating feedback", *IEEE Photonic. Techn. L.* **2**, 85–87 (1990).
43. J. De Merlier, K. Mizutani, S. Sudo, K. Sato, and K. Kudo, "Wavelength channel accuracy of an external cavity wavelength tunable laser with intracavity wavelength reference etalon", *J. Lightwave Technol.* **24**, 3202–3209 (2006).
44. A. Lohman, and R.R.A. Syms, "External cavity laser with a vertically etched silicon blazed grating", *IEEE Photonic. Techn. L.* **15**, 120–122 (2003).
45. E.G. Loewen, M. Neviere, and D. Maystre, "Grating efficiency theory as it applies to blazed and holographic gratings", *Appl. Optics* **16**, 2711–2721 (1977).
46. R.R.A. Syms, A. Lohman, "MOEMS tuning element for a littrow external cavity laser", *J. Microelectromech. Syst.* **12**, 921–928 (2003).
47. M.C. Hutley, *Diffraction Gratings*, Academic Press Ltd., London, 1990.
48. B. Mroziewicz, T. Piwoński, E. Kowalczyk, A. Szerling, and S.J. Lewandowski, "External cavity diode lasers with ridge-waveguide type broad contact semiconductor optical amplifiers", *Proc. SPIE* **5958**, J1–J8 (2005).
49. B. Mroziewicz, E. Kowalczyk, L. Dobrzański, J. Ratajczak, and S.J. Lewandowski, "External cavity diode lasers with E-beam written silicon diffraction gratings", *Opt. Quant. Electron.* **39**, 585–595 (2007).
50. D. Rosenblatt, A. Sharon, and A.A. Friesem, "Resonant grating waveguide structures", *IEEE J. Quantum Elect.* **33**, 2038–2059 (1997).
51. A.S.P. Chang, H. Tan, S. Bai, W. Wu, Z. Yu, and S.Y. Chou, "Tunable external cavity laser with a liquid-crystal subwavelength resonant grating filter as wavelength-selective mirror", *IEEE Photonic. Techn. L.* **19**, 1099–1101 (2007).
52. S. Block, E. Gamet, and F. Pigeon, "Semiconductor laser with external resonant grating mirror", *IEEE J. Quantum Elect.* **41**, 1049–1053 (2005).
53. S.Y. Chou, P.R. Krauss, and P.J. Renstrom, "Imprint of sub-25 nm vias and trenches in polymers", *Appl. Phys. Lett.* **67**, 3114–3116 (1995).
54. I. Avrutsky and R. Rabady, "Waveguide grating mirror for large-area semiconductor lasers", *Opt. Lett.* **26**, 989–991 (2001).
55. S.S. Wang and R. Magnusson, "Multilayer waveguide-grating filters", *Appl. Optics* **34**, 2414–2420 (1995).
56. M.G. Littman and H.J. Metcalf, "Spectrally narrow pulsed dye laser without beam expander", *Appl. Optics* **17**, 2224–2227 (1978).
57. P. McNicholl and H.J. Metcalf, "Synchronous cavity mode and feedback wavelength scanning in dye laser oscillators with gratings", *Appl. Optics* **24**, 2757–2761 (1985).
58. F. Favre, D. Le Guen, J.C. Simon, and B. Landousies, "External-cavity semiconductor laser with 15 nm continuous tuning range", *Electron. Lett.* **22**, 795–796 (1986).
59. F. Favre and D. Le Guen, "82 nm of continuous tunability for an external cavity semiconductor laser", *Electron. Lett.* **27**, 183–184 (1991).
60. H. Tabuchi and H. Ishikawa, "External grating tunable MWQ laser with wide tuning range of 240 nm", *Electron. Lett.* **26**, 742–743 (1990).
61. D. Wandt, M. Laschek, K. Przyklenk, A. Tünnermann, and H. Welling, "External cavity laser diode with 40 nm continuous tuning range around 825 nm", *Optics Commun.* **130**, 81–84 (1996).
62. K. Liu and M.G. Littman, "Novel geometry for single-mode scanning of tunable lasers", *Opt. Lett.* **6**, 117–118 (1981).
63. L. Nilse, H.J. Davies, and C.S. Adams, "Synchronous tuning of extended cavity diode lasers: the case for an optimum pivot point", *Appl. Optics* **38**, 548–553 (1999).
64. M. de Labachelerie and G. Passedat, "Mode-hop suppression of Littrow grating-tuned lasers", *Appl. Optics* **32**, 269–274 (1993)
65. W.R. Trutna and L.F. Stokes, "Continuously tuned external cavity semiconductor laser", *J. Lightwave Technol.* **11**, 1279–1286 (1993).
66. T.M. Hard, "Laser wavelength selection and output coupling by a grating", *Appl. Optics* **9**, 1825–1830 (1990).
67. C.J. Hawthorn, K.P. Weber, and R.E. Scholten, "Littrow configuration tunable external cavity diode laser with fixed direction output beam", *Rev. Sci. Instrum.* **72**, 4477–4479 (2001).
68. D. Wandt, M. Laschek, A. Tünnermann, and H. Welling, "Continuously tunable external-cavity diode laser with a double-grating arrangement", *Opt. Lett.* **22**, 390–392 (1997).
69. J.H. Lee, M.Y. Park, Ch.Y. Kim, S.H. Cho, W. Lee, G. Jeong, and B.W. Kim, "Tunable external cavity laser based on polymer waveguide platform for WDM access network", *IEEE Photonic. Techn. L.* **17**, 1956–1529 (2005).
70. M.C. Oh, H.J. Lee, M.H. Lee, J.H. Ahn, S.G. Han, and H.G. Kim, "Tunable wavelength filters with Bragg gratings in polymer waveguides", *Appl. Phys. Lett.* **73**, 2543–2545 (1998).

71. A. Andalkar, S.K. Lamoreaux, and R.B. Warrington, "Improved external cavity design for cesium D1 (894 nm) diode laser", *Rev. Sci. Instrum.* **71**, 4029–4031 (2000).
72. L. Hildebrandt, R. Knispel, S. Stry, J.R. Sacher, and F. Schael, "Antireflection-coated blue GaN laser diodes in an external cavity and Doppler-free indium absorption spectroscopy", *Appl. Optics* **42**, 2110–2118 (2003).
73. D.J. Lonsdale, A.P. Willis, and T.A. King, "Extended tuning and single-mode operation of an anti-reflection-coated InGaN violet laser diode in a Littrow cavity", *Meas. Sci. Technol.* **13**, 488–493 (2002).
74. R. Wyatt and W.J. Devlin, "10 kHz linewidth 1.5 µm InGaAsP external cavity laser with 55 nm tuning range", *Electron. Lett.* **19**, 110–112 (1983).
75. R. Wyatt, "Spectral linewidth of external cavity semiconductor lasers with strong, frequency-selective feedback", *Electron. Lett.* **21**, 658–659 (1985).
76. J. Mellis, S.A. Al-Chalabi, K.H. Cameron, R. Wyatt, J.C. Regnault, W.J. Devlin, and M.C. Brain, "Miniature packaged external-cavity semiconductor laser with 50 GHz continuous electrical tuning range", *Electron. Lett.* **24**, 988–989 (1988).
77. A.T. Schremer and C.L. Tang, "External-cavity semiconductor laser with 1000 GHz continuous piezoelectric tuning range", *IEEE Photonic. Techn. L.* **2**, 3–5 (1990).
78. C. Petridis, I.D. Lindsay, D.J.M. Stothard, and M. Ebrahimzadeh, "Mode-hop-free tuning over 80 GHz of an extended cavity diode laser without antireflection coating", *Rev. Sci. Instrum.* **72**, 3811–3815 (2001).
79. E. Ip, J.M. Kahn, D. Anthon, and J. Hutchins, "Linewidth measurements of MEMS-based tunable lasers for phase-locking applications", *IEEE Photonic. Techn. L.* **17**, 2029–2031 (2005).
80. K. Sato, J. De Merlier, K. Mizutani, S. Sudo, S. Watanabe, K. Tsuruoka, K. Naniwae, and K. Kudo, "A compact external cavity wavelength tunable laser without an intracavity etalon", *IEEE Photonic. Techn. L.* **18**, 1191–1193 (2006).
81. U.H. Jacobs, K. Scholle, E. Heumann, G. Huber, M. Rattunde, and J. Wagner, "Room-temperature external cavity GaSb-based diode laser around 2.13 µm", *Appl. Phys. Lett.* **85**, 5825–5826 (2004).
82. E. Geerlings, M. Rattunde, J. Schmitz, G. Kaufel, H. Zappe, and J. Wagner, "Widely tunable GaSb-based external cavity diode laser emitting around 2.3 µm", *IEEE Photonic. Techn. L.* **18**, 1913–1915 (2006).
83. F. Capasso, R. Paiella, R. Martini, R. Colombelli, C. Gmachl, T.L. Myers, M.S. Taubaman, R.M. Wiliams, C.G. Bethea, K. Unterrainer, H.Y. Hwang, D.L. Sivco, A.L. Cho, A.M. Sergent, H.C. Liu, and E.A. Whittaker, "Quantum cascade lasers: ultrahigh-speed operation, optical wireless communication, narrow linewidth, and far-infrared emission", *IEEE J. Quantum Elect.* **38**, 511–532 (2002).
84. L. Hildebrandt, S. Stry, R. Knispel, J.R. Sacher, T. Beyer, M. Braun, A. Lambrecht, T. Gensty, W. Elsässer, Ch. Mann, and F. Fuchs, "Quantum cascade external cavity and DFB laser systems in the mid-infrared spectral range: devices and applications", e-mail: lars@sacher-laser.com
85. G.P. Luo, C. Peng, H.Q. Le, S.S. Pei, W.Y. Hwang, B. Ishaug, J. Um, J.N. Baillargeon, and C.H. Lin, "Grating-tuned external-cavity quantum-cascade semiconductor lasers", *Appl. Phys. Lett.* **78**, 2834–2836 (2001).
86. Y. Uenishi, K. Honna, and S. Nagaoka, "Tunable laser diode using a nickel micromachined external mirror", *Electron. Lett.* **32**, 1207–1208 (1996).
87. M.-H. Kiang, O. Solgaard, R.S. Muller, and K.Y. Lau, "Silicon-micromachined micromirrors with integrated high-precision actuators for external-cavity semiconductor lasers", *IEEE Photonic. Techn. L.* **8**, 96–97 (1996).
88. A.Q. Liu, X.M. Zhang, V.M. Murukeshan, and Y.L. Lam, "A novel integrated micromachined tunable laser using polysilicon 3-D mirror", *IEEE Photonic. Techn. L.* **11**, 427–429 (2001).
89. J.B.D. Soole, K. Poguntke, A. Scherer, H.P. LeBlanc, C. Chang-Hasnain, J.R. Hayes, C. Caneau, R. Bhat, and M.A. Koza, "Multistripe array grating integrated cavity (MAGIC) laser: a new semiconductor laser for WDM applications", *Electron. Lett.* **28**, 1805–1807 (1992).
90. P.A. Kirkby, "Multichannel wavelength-switched transmitters and receivers-new component concepts for broad-band networks and distributed switching systems", *J. Lightwave Technol.* **8**, 202–211 (1990).
91. O.K. Kwon, K.H. Kim, E.D. Sim, H.K. Yun, J.H. Kim, H.S. Kim, and K.R. Oh, "Proposal of electrically tunable external-cavity laser diode", *IEEE Photonic. Techn. L.* **16**, 1804–1806 (2004).
92. O.K. Kwon, J.H. Kim, K.H. Kim, E.D. Sim, H.S. Kim, and K.R. Oh, "Monolithically integrated grating cavity tunable lasers", *IEEE Photonic. Techn. L.* **17**, 1794–1796 (2005).
93. O.K. Kwon, J.H. Kim, K.H. Kim, E.D. Sim, and K.R. Oh, "Widely tunable multichannel grating cavity laser", *IEEE Photonic. Techn. L.* **18**, 1699–1701 (2006).


 