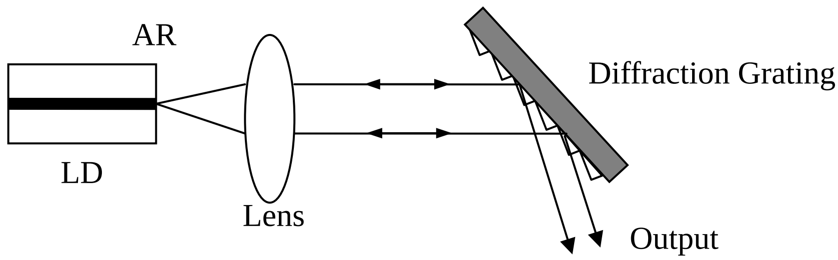
CHAPTER 2

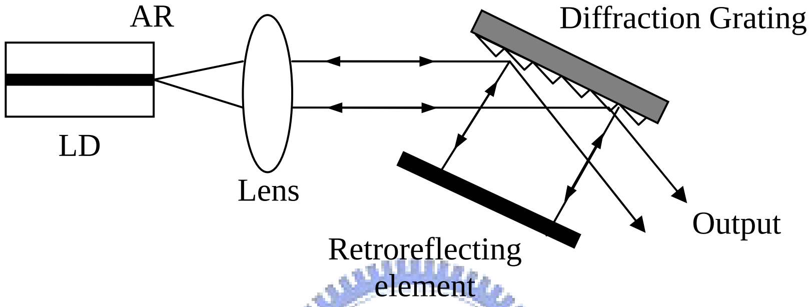
TUNABLE EXTERNAL-CAVITY DIODE LASERS

2.1 External-cavity diode lasers

The external-cavity diode laser (ECDL) comprises an optical gain media (a laser diode typically with an antireflection (AR) coating on one facet), optically coupled to the external cavity that includes a retroreflecting element, and one or more wavelength-selective filters. The earliest paper cited by many authors is published by Fleming and Mooradian in 1981 [10], since they were the first to study the spectral properties of ECDL's in detail. A number of different types of wavelength-selective elements have been used in the ECDL's including diffraction gratings, Fabry-Perot étalons, birefringent filters, etc. The most commonly used filters are the diffraction gratings. Since the diffraction gratings in the ECDL combine the functions of the filter and external mirror. A number of ECDL arrangements employing diffraction gratings have been introduced. Among the most simple arrangements is a design similar to the one described by Ricci et al. [11]. In this design, the laser emitted from an AR-coated front facet of a LD is collimated and hits a grating under Littrow angle. The light diffracted in the first order is reflected back into the LD, whereas the light diffracted in the zeroth order is coupled out and can be used for the experiments. A second concept is an external cavity in a grazing-incident configuration similar to the design from Littman and Metcalf [12]. They used the dye cell as the gain medium. The output beam of a LD is directed on to a grating. The first diffraction order of the grating hits a reflecting element, e. g. mirror, and reflected back on to the grating. The laser resonate cavity is set up between the back facet of the LD and the reflecting element. Basic designs of the Littrow and Littman-Metcalf ECDL's are schematically shown in Fig. 2.1. The optical feedback of the grating or the reflecting element results in single longitudinal mode operating of the diode [10]. The arrangements reduce the critical dependence of the output frequency on the laser current and temperature, and allows coarse wavelength tuning over the wide gain bandwidth of the LD through the rotation of the grating or the reflecting element.



(a)



(b)

Fig. 2.1 ECDL of (a) Littrow (b) Littman-Metcalf type mounting. LD: laser diode; AR: anti-reflection coating

The basic model for an external-cavity laser is based on a 3-mirror compound cavity with amplitude reflectivity r_1 at the left facet of the LD, r_2 at the right facet of the LD and r_{ext} at the external reflector. The effective reflectance of the extended cavity is given by [13]

$$r_{eff}(\nu) = \frac{r_2 + r_{ext}(\nu)\exp(i2\pi\nu\tau_{ext})}{1 + r_2 r_{ext}(\nu)\exp(i2\pi\tau_{ext})} \tag{2.1}$$

τ_{ext} is the round-trip time of extended cavity section. In any external-cavity design, one should try to maximize the external feedback strength and wavelength selectivity of the cavity. Strong external feedback is desirable to avoid a number of undesirable phenomena such as tuning nonlinearities and axial mode instabilities caused by the LD-cavity étalon effect. Excellent optical performance can be obtained by an excellent AR coating applied to the LD. However, even with a high quality facet coating, effects of the residual diode cavity resonances are still observable and are sometimes the cause of non-ideal behavior.

2.2 Wavelength tuning mechanisms

A number of different types of wavelength-selective elements have been used to tune the ECDL's. The ideal wavelength filter for an ECDL has a bandwidth that is less than the axial mode spacing of the cavity and has no insertion loss at its peak. The filters can be grouped according to whether they are actuated mechanically (e.g., have moving parts) or electronically (no moving parts).

2.2.1 Mechanical tuning

2.2.1.1 Diffraction gratings

The grating-tuned ECDL is the most commonly reported type of ECDL [14-19]. The laser wavelength is tuned as the grating rotates in the "standard" Littrow configuration. Grating tuning for broad range of several tens nanometers and as high as 100 nm are possible, depending on wavelength and diode material family. In the Littman-Metcalf configuration, widely wavelength tuning is achieved by rotating the optical feedback end mirror [20-22]. With simple grating or mirror feedback, an ECDL will usually tune by hopping from one longitudinal mode to the next over the laser's entire gain bandwidth. To deal with this issue, a mechanical approach by mounting the feedback element on a pivot arm is well-known [23-27]. The idea is based on scanning the cavity length and the grating feedback angle simultaneously. The geometric requirements for a widely mode-hop-free tunable Littman-Metcalf cavity are shown in Fig. 2.2 [28].

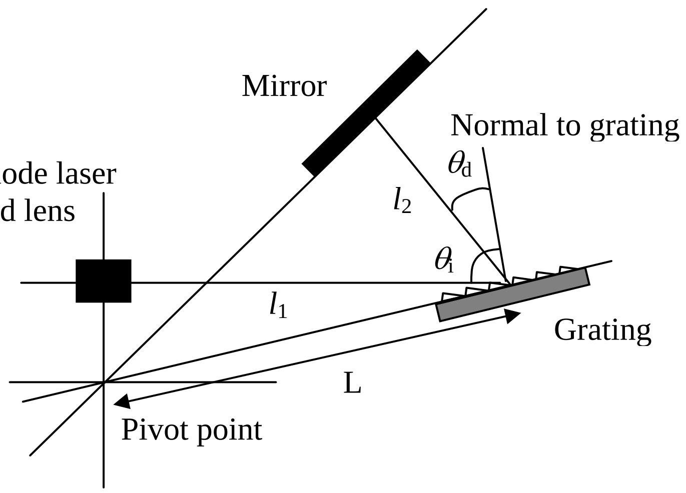
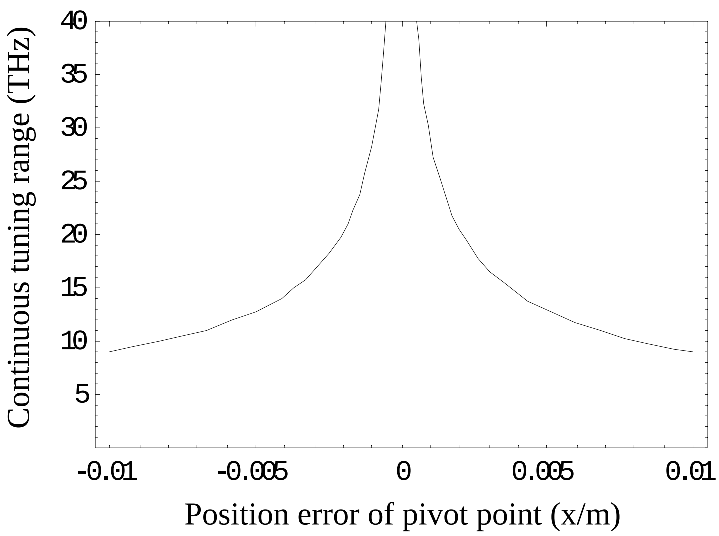


Fig. 2.2 Geometric requirements for a widely mode-hop-free tunable ECDL [28]

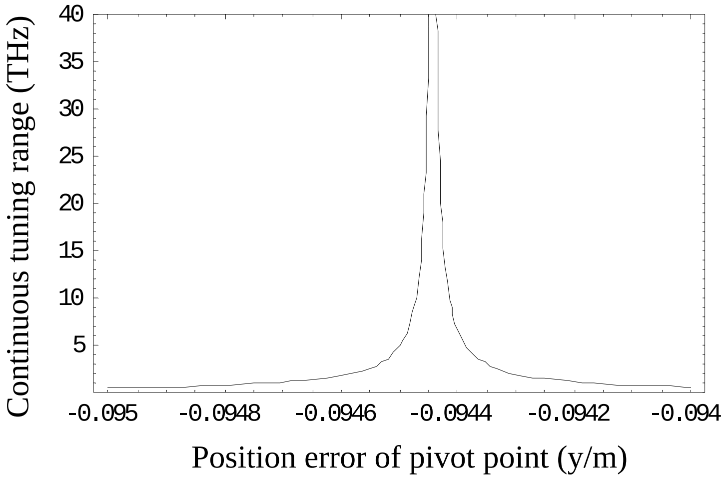
The pivot point links the source, grating and mirror such that adjusting the angle of the mirror about this point meets the requirements for single mode tuning without mode hops. When the adjustment is done correctly, the physical length of the cavity and the selected wavelength are changed simultaneously. The requirement for position of the pivot point is that the optical path from emission point to the pivot point must balance the path from the mirror to the pivot point. The geometric relation of l_1, the cavity length from source to diffraction grating, l_2, the cavity length from grating to feedback mirror, l, distance between the pivot point and grating and the grating pitch a is thus given as

$$(l_1+ l_2)/\lambda=l/a \qquad (2.2)$$

The continuous tuning without mode-hopping requires delicate adjustments and a high mechanical stability. The mode-hop-free tuning range is quite sensitive to the precise location of the rotation axis. The task then becomes setting the pivot point correctly. In any real ECDL there will be some error in positioning the pivot point. Assume the laser is positioned at the origin with the output in the positive x direction. The optimum pivot point $(x,y)=(0, -l\cdot cot\theta)$ of Littrow configuration is derived by equating the modal and the grating tuning rates as a function of the rotation angle [29-31]. As an example, the continuous tuning range as a function of x and y pivot-point error with respect to the optimum pivot point is plotted in Fig. 2.3, assuming a 1200-line/mm grating, a center wavelength λ=780 nm and a 5-cm cavity length.

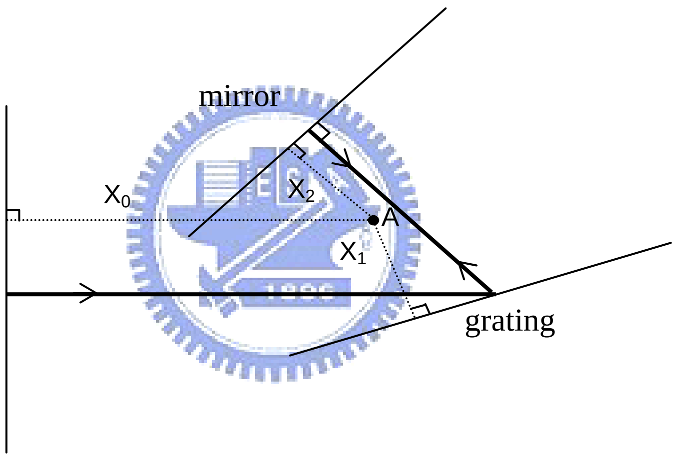


(a)

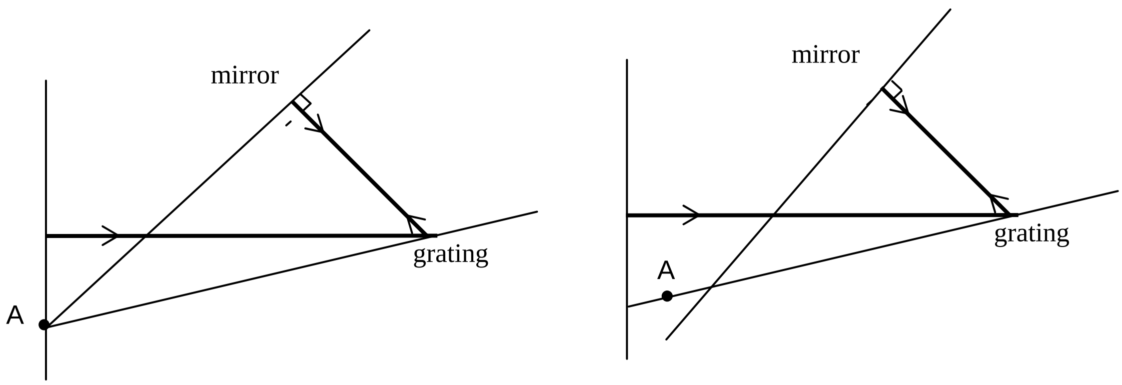


(b)

Fig. 2.3 The continuous tuning range as a function of (a) *x* and (b) y pivot-point error with respect to the optimum pivot point



(a)



(b) $X_0=X_1=X_2=0$ (c) $X_1=0$ and $X_0+X_2=0$

Fig. 2.4 Optimum pivot points of ECDL in the Littman-Metcalf configuration

The tolerance to pivot error in the *y* direction is much restrictive than in the *x* direction. To obtain a continuous tuning range of 10 THz (20 nm), the pivot point must be placed within a region roughly 4 mm long in the *x* direction and 50 μm wide in the *y* direction.

For Littman-Metcalf configurations, Liu and Littman [32] first pointed out that a suitable choice exists for the axis of rotation of the mirror so that the cavity mode scan will exactly match the feedback wavelength scan. There are two possibilities for the optimum pivot point [33]. The configurations are illustrated in Fig. 2.4, where X_j are perpendicular distances from point A to the surfaces of the element. A is the pivot point of rotation. A change of 2π in the round trip phase results in one complete step of the cavity mode structure relative to the feedback frequency. Thus the change in this phase is angle scanned over the specified range should be a small fraction of 2π to ensure continued single-mode operation. The configuration tolerance is plotted in Fig. 2.5, assuming an 1800-line/mm grating, a center wavelength λ=780 nm and a conventional phase tolerance of $2\pi/10$.

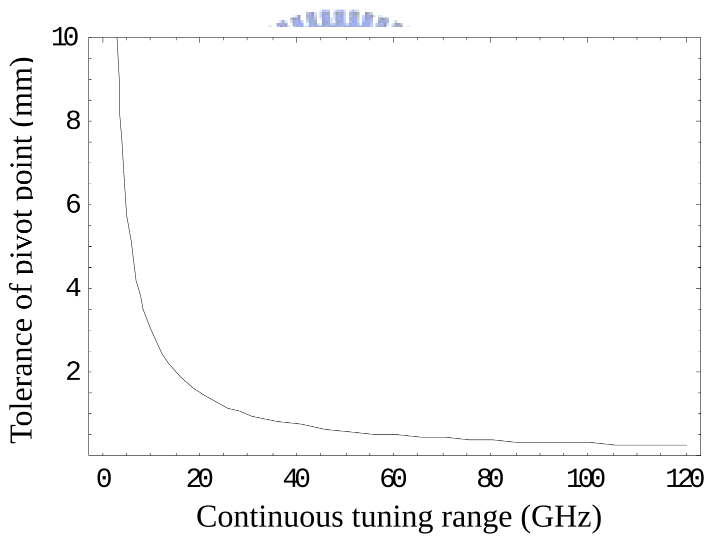


Fig. 2.5 The tolerance of pivot point position (Littman-Metcalf configuration)

The X-axis in Fig. 2.5 is the synchronous scan range and Y-axis is the tolerance of pivot point position. For scan range of 10 GHz, the tolerance of pivot point position is 3 mm. For scan range of 100 GHz, the tolerance of pivot point position is restricted to only 0.3 mm.

2.2.1.2 Fabry-Perot étlons or interference filters

Instead of the diffraction gratings Fabry-Perot étlons can be inserted into the coupled external cavity as the wavelength-selected elements. The Fabry-Perot étalon has periodic transmission peaks at wavelength that satisfy the relation

$$2nd\cos\theta = m\lambda \tag{2.3}$$

Where d is the mirror spacing, n is the refractive index of the space between the mirrors, θ is the angle of incidence, and m is an integer. Tuning can be accomplished by changing the mirror separation or by varying the angle of incidence. C. Voumard [34] has demonstrated an external-cavity-controlled GaAlAs diode laser containing two glass-plate Fabry-Peror étalons as the dispersive elements. The angles of the two Fabry-Perot étalons can be adjusted independently. The emission spectrum was reduced to one single-axial mode of the external-cavity without decrease of output power. M. J. Chawki *et al.* [35] demonstrated an all-fiber semiconductor ring laser with a fiber Fabry-Perot (FFP) filter. Wavelength tuning was possible by changing the voltage of the FFP thus scanning the center frequency of the FFP over the period modes of the semiconductor FP cavity.

An interference filter is a multilayer thin-film device. It can be treated as a Fabry-Perot étalon with a small thickness. The interference filter is tuned by tilting it in the incident beam. P. Zorabedian and W. R. Trutna, Jr. demonstrated an interference-filter-tuned ECDL, and compared the angular alignment tolerance and the tuning range with a conventional grating-tuned ECDL [36]. They concluded that the interference-filter laser had a 260 fold greater alignment tolerance and nearly the same tuning range as the grating laser. Gratings can be used in tandem with Fabry-Perot étalons to tune ECDL’s as demonstrated by Olsson and Ziel [1]. In their approach, the grating is illuminated with a broad beam and provides most of the spectral selectivity. An étalon improves the stability of single-mode operation. They divided the tuning of an ECDL into a coarse, medium, and fine tuning regime. Coarse tuning was obtained by rotating the grating reflector and selecting the internal mode (longitudinal modes of the solitary laser without the external cavity) which is closest to the desired wavelength. The medium tuning was achieved by adjusting the intracavity étalon in combination with a fine rotation of the grating. Fine tuning is done by fine adjustments to the external cavity length.

2.2.2 Electronically tuning

Mechanical controlled wavelength tuning filters require mechanical movement of relatively bulky components. It is desirable to be able to tune the laser frequency electronically by varying the driving voltage applied to the tuning element only. The electronic tuning provides rapid voltage-controlled cavity length scan and hence output wavelength tuning. Birefringent filters [37-41], acousto-optic (AO) filters [42-44] and microelectromechanical systems (MEMS) [45, 46] have been used for electronic wavelength tuning. Electronically tuned birefringent filters can be realized using electro-optic effect, either in bulk crystals or in birefringent lithium niobate waveguides [37-41]. The liquid crystal cells can also be used. The birefringent filters using liquid crystals will be discussed in details in the next chapter.

2.2.2.1 Birefringent filters tuning — electro-optic crystals

The electro-optic crystal (EOC) provides rapid voltage-controlled cavity-length scans and hence output frequency tuning. Several groups of researchers have successfully built ECDL's with intracavity EOC. J.-P. Goedgebuer *et al.* [37] reported a tunable ECDL using a bulk $LiNbO_3$ crystal inside the cavity as the wavelength selective element. Wavelength tuning was achieved by varying the optical delay introduced by the $LiNbO_3$ tuner. The $LiNbO_3$ crystal forming the tuner is 70 mm long. Its half-wave voltage is V_π=2400 V at the wavelength of 1500 nm. A tuning rate of 1 GHz/V over a tuning range of about 4 nm was obtained. B. Boggs *et al.* [38] has built a simple electro-optically activated ECDL with an intracavity lithium tantalite EOC (Fig. 2.6). The half-wave voltage is V_π=475 V. Continuous tuning over approximately 3 GHz for 5-cm optical-path-length external cavity and tuning as fast as 23 GHz/μs over gigahertz frequency ranges was demonstrated.

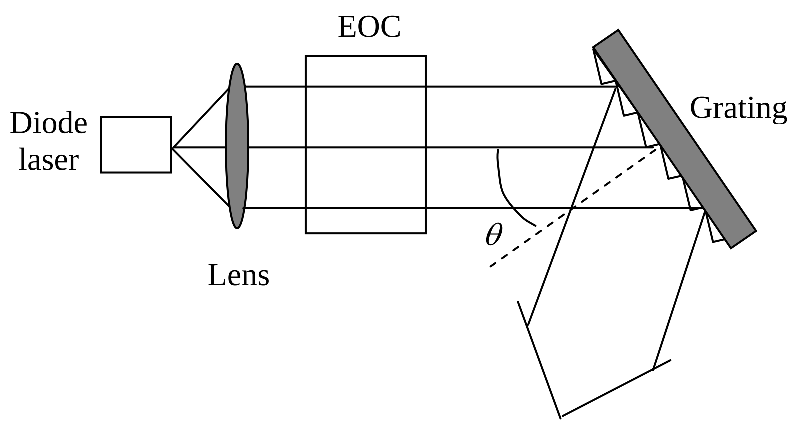


Fig. 2.6 ECDL tuned with an intracavity EOC [38]. EOC: electro-optic crystal

L. Ménager *et al.* [39] has demonstrated a cavity contains a $LiNbO_3$ electro-optic 25° prism for synchronous tuning the cavity length and the grating's incident angle. A mode-hop-free tuning of 12 GHz with high linearity and reproducibility for a 4-kV voltage variation was reported. L. Levin [40] designed a Littrow type ECDL with a 1~1.51-mm-thick intracavity $LiTaO_3$ crystal. He increased the sensitivities of the frequency change-voltage ratio and the frequency-tuning interval by making the crystal thinner. The change in cavity length that is imposed by the EOC is inversely proportional to the crystal thickness. A mode-hop-free single-mode tuning range of 50 GHz and tuning speeds of 1.5 GHz/μs is demonstrated. An electro-optical scanner consisting of a $LiNbO_3$ crystal with a series of domain inverted triangular prisms used in a Littrow-type ECDL was reported by M. Laschek *et al.* [41]. With the configuration, a wavelength tuning of more than 1 nm was realized. The tuning coefficient is 2 nm/kV.

A disadvantage of electro-optic birefringent tuning is that the large voltage required tends to limit the tuning to significantly less than the full semiconductor gain bandwidth.

2.2.2.2 Acousto-optic tuning

Acousto-optic (AO) filters are an advantageous means for rapid, electronic wavelength control of ECDL's. The wavelength range of an AO tunable filter is typically much broader than the gain bandwidth of an individual diode laser, so there are no wavelength range limitations imposed by the filter. Narrow bandwidth and high transmission are required for the AO filters when applied to tuning applications. In the study reported by Coquin and Cheung [42, 43], a pair of AO devices, an AO tunable filter and an AO modulator, are used as the wavelength selective element in an ECDL. Tuning is accomplished by varying only the drive frequency of the AO devices. The AO tunable filter used for the experiments has an optical bandwidth of 3 nm. The chief drawback of AO tuning is that the filter spectral width is much greater than the spectral width that can be readily obtained with the diffraction grating. This means that the AO-tuned ECDL's must have excellent suppression of LD cavity modes in order to achieve good tuning fidelity. Use of an AO tunable filter inside a laser cavity results in a repeated frequency shift on each pass of the optical signal through the filter. Putting a second AO device with a frequency shift equal and opposite to that of the first one, makes a stable single-mode operation is possible. A 3-μs tuning rate over an 83 nm tunable wavelength at λ=1.3 μm was demonstrated. An approach for achieving rapid and phase-coherent continuous broadband tuning of a single-mode ECDL using two internal AO devices was reported by M. Kourogi *et al.* [44]. Instead of tunable filters, a grating and a pair of AO modulators were used as wavelength-selective elements (Fig. 2.7). Compared with the method in which AO filters are used, the approach gives high-resolution wavelength selectivity and enables single-mode operation of the laser. The AO modulators control the angle of incident light on a diffraction grating and the effective round-trip optical phase. To control the round-trip phase, a long delay line to generate a modulation signal of the AO device. Single-mode operation and electric tuning over 2 nm were achieved. To achieve mode-hop-free tuning over a broad wavelength range a long optical delay line with a digital phase-locked oscillator should be implemented in their present design.

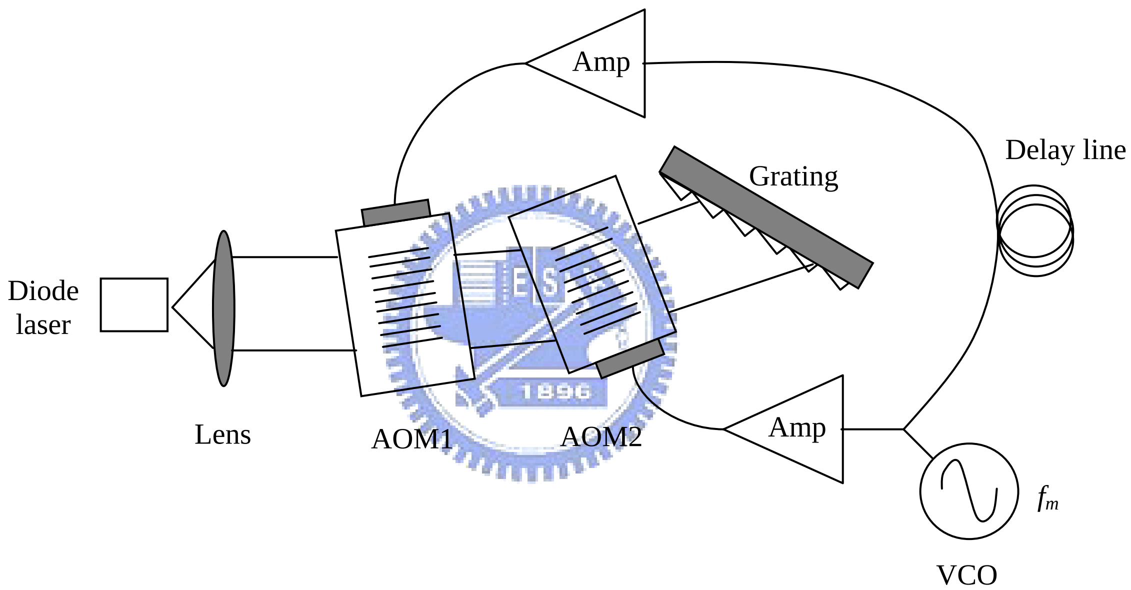


Fig. 2.7 ECDL tuned with two acousto-optic devices [44]. AOM: acousto-optic modulator; Amp: amplifier; VCO: voltage controlled oscillator

2.2.2.3 Microelectromechanical systems tuning

MEMS technology has been shown to be very promising in miniaturizing tunable ECDL's. The precision and stable movement of the microactuators enables fine wavelength tuning. The small size of the micromachined mirrors facilitates fast tuning speed and low power consumption. The Iolon Inc. [45] has developed a high power, widely tunable micro- ECDL based on a MEMS electrostatic actuator for telecommunication applications. It was designed in the Littman-Metcalf configuration. Wavelength tuning was achieved by applying a voltage to the MEMS actuator. The actuator is capable of rotating the mirror ±1.4° when a voltage of up to 140 V is applied to one of two sets of comb-drive elements. And the suspension in the actuator is designed to allow rotation of the mirror about a pivot point. The MEM-ECDL provides 7 dBm fiber coupled output power over a 40 nm tuning range, and exhibits all of the performance characteristics of traditional ECDL's, in a low cost, 5 mm×5 mm form factor (Fig. 2.8). Zhang *et al.* [46] demonstrated a MEMS discrete wavelength tunable laser formed by integrating a semiconductor laser, a single-mode optical fiber, and a MEMS mirror onto a single chip. It has overall dimensions of 1.5 mm×1 mm×0.6 mm. A tuning range of 13.5 nm and sweeping speed of about 1 ms was obtained.

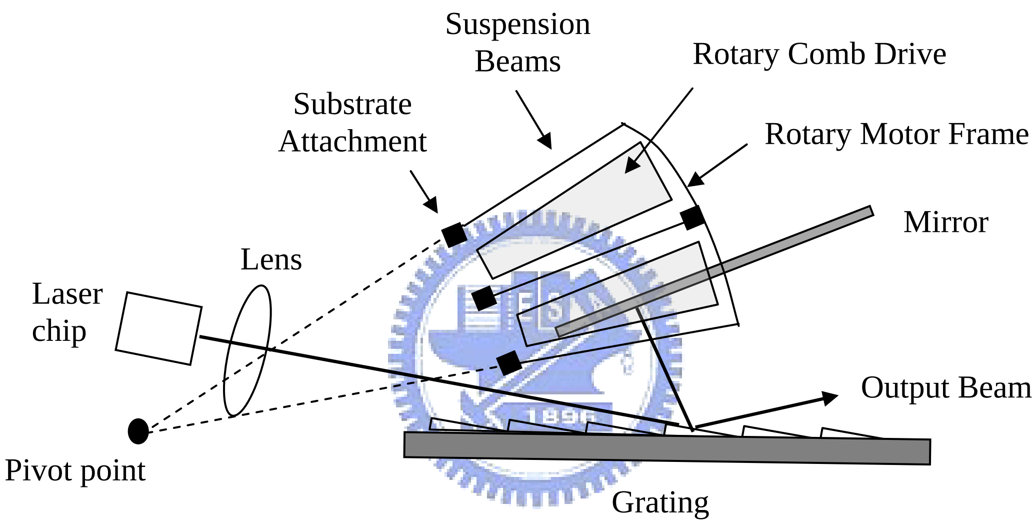


Fig. 2.8 ECDL based on MEMS electrostatic rotary actuator [45]

The MEMS based ECDL has advantages of wide tuning range, improved repeatability and stability compared to conventional ECDL's, and can be integrated in a very small size.