Invited Paper

Tunable laser sources for (D)WDM

Jens Buus

Gayton Photonics, Gayton, Northants, UK

ABSTRACT

For several years tunable lasers and other WDM sources has been as one of the hottest components topics in photonics, but like other areas the downturn has hit hard. In this paper we will describe the latest developments in the area of optical sources for DWDM systems, including tunable lasers and multiwavelength sources, and we will look at the companies (still) competing in this area.

We will start by introducing the basic technologies used for DWDM sources. After that we will give an overview of the source options, and discuss tuning methods and wavelength control issues. The source options under discussion will include monolithic tunable lasers, hybrid structures and external cavity lasers, wavelength selectable laser arrays, tunable VCSELs, and non-semiconductor alternatives. Numerous examples will be shown, and the characteristics and performance of the various devices will be discussed. The key performance parameters, such as tuning range, power and switching speed will be related to the expected areas of application. These areas include sparing, fixed wavelength transmitter replacement, and use in wavelength switched networks.

Keywords: WDM, lasers, transmitters, tunable lasers

1. TUNABLE LASER APPLICATIONS AND REQUIREMENTS

The ability to choose a particular wavelength of operation makes tunable lasers, or wavelength selectable laser arrays, with an uncommitted and adjustable wavelength attractive for applications such as sparing in DWDM optical networks. Instead of keeping a large number of spare transmitter cards (one for each wavelength used), a system operator only needs a limited number of spares. If tunable lasers become sufficiently cheap, one might even consider replacing fixed wavelength lasers by tunable lasers.

Tunable lasers also support new network features based on the use of wavelength routing. One can use wavelength switching either as circuit switching or as packet switching.

In addition, tunable lasers are also of interest in test and measurement applications as well as for various sensors.

The key performance parameters are:

- Power. For sparing and replacement applications the optical power level has to be comparable to that of present DFB lasers.
- Tuning range. A wide tuning range reduces the number of lasers required to cover a given spectral range, but for widely tunable lasers there may be trade-off between tuning range and power level.
- Tuning speed. For sparing applications tuning speed is not an issue, but for optical packet switching it is of prime importance.
- Reliability. In addition to the usual requirements, wavelength stability has to be ensured.

2. DEVICE OPTIONS AND TUNING MECHANISMS

A large number of laser structures have been proposed. The most important types are:

- Monolithic tunable lasers (DBR, SGDBR, GCSR, DSDBR).
- External cavity lasers including hybrid structures and MEMS devices.
- Tunable VCSELs.
- DFB laser arrays.
- Fiber based lasers.

---

[*] buus@compuserve.com; Phone: +44 (0)1604 859253; Fax: +44 (0)1604 859256; Gayton Photonics, 6 Baker Street, Gayton, Northants, NN7 3EZ, UK.

Materials, Active Devices, and Optical Amplifiers, edited by Connie J. Chang-Hasnain,
Dexiu Huang, Yoshiaki Nakano, Xiaomin Ren, Proceedings of SPIE Vol. 5280
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.529498

- Lasers based on active waveguides.

In a monolithic laser structure, tuning can be achieved by changing the carrier density (ΔN) or the temperature (ΔT), since these changes will lead to a change in the refractive index (Δn). However, if the refractive index is changed in a part of the optical waveguide, then a confinement factor, Γ, must be included to translate the change into a change in the effective refractive index. Tuning is also possible by using the quantum confined Stark effect (QCSE) in a quantum well structure. In a traditional external cavity laser or a tunable VCSEL, the cavity length is changed directly. The following table compares some of the characteristics of the various tuning mechanisms, and gives typical numbers for the tuning range $\Delta\lambda$ and the tuning speed t_{tune}.

	ΔN	QCSE	ΔT
Δn	≤ 0.05	≤ 0.01	≤ 0.01
Γ	~0.5	~0.2	1
$\Delta\lambda$	≤ 15 nm	≤ 1 nm	≤ 5 nm
t_{tune}	< 10 ns	< 0.1 ns	> 1 µs

Table 1. Tuning mechanisms.

The tuning ranges given in table 1 are the *maximum possible continuous tuning ranges*, wider (non-continuous) tuning ranges are possible for example by using the Vernier effect in the Sampled Grating (SG) DBR. The tuning speeds are the ultimate values, limited by carrier lifetime for the case of carrier density tuning and the thermal properties of the laser structure for thermal tuning. In practice tuning speeds will be limited by the control electronics.

3. SPECIFIC EXAMPLES

In the following we will consider a number of specific tunable or wavelength selectable laser structures, including both some well established structures as well some recently published work.

3.1 Monolithic structures

In a conventional DBR (Distributed Bragg Reflector) laser, tuning is accomplished by changing the carrier density, and thereby the refractive index) of a grating section in the laser. A schematic diagram is shown in figure 1.

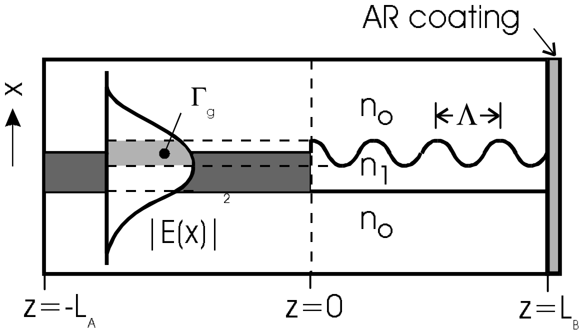

Figure 1. Schematic diagram of DBR laser.

A closer analysis of the tuning behavior shows that the tuning will occur in steps, with each step given by the frequency spacing of the cavity modes. In order to get access to frequencies in the "gaps", a passive *phase control section* is inserted between the active section and the grating. By changing the carrier density in this section, the cavity modes can be moved, hence ensuring access to all the intermediate frequencies, and achieving what is called *quasi continuous tuning*. According to table 1, the total tuning range can be up to about 15 nm.

In order to extend the tuning range, more complicated structures and tuning schemes are required. One solution is to have two reflectors each with a comb-like reflection spectrum. Such a reflection characteristic can for example be achieved by using a *sampled grating* as shown in figure 2 [1]. The front reflector will have reflection peaks with a spacing proportional to the inverse of the sampling period in the front reflector, $L_{s,f}$, and the rear reflector will have reflection peaks with a spacing proportional to the inverse of the sampling period in the rear reflector, $L_{s,r}$. As illustrated in figure 3, a small change in the refractive index of either the front or the rear section will lead to a large change in the wavelength where a front and rear reflection peak coincide.

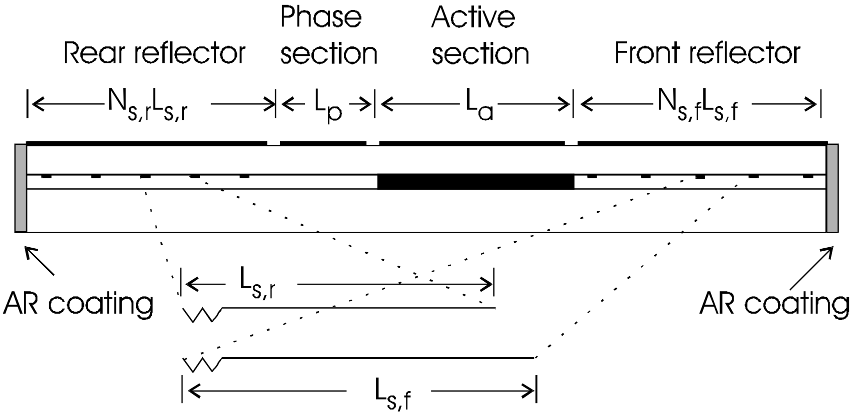

Figure 2. Schematic diagram of a sampled grating (SG) DBR laser.

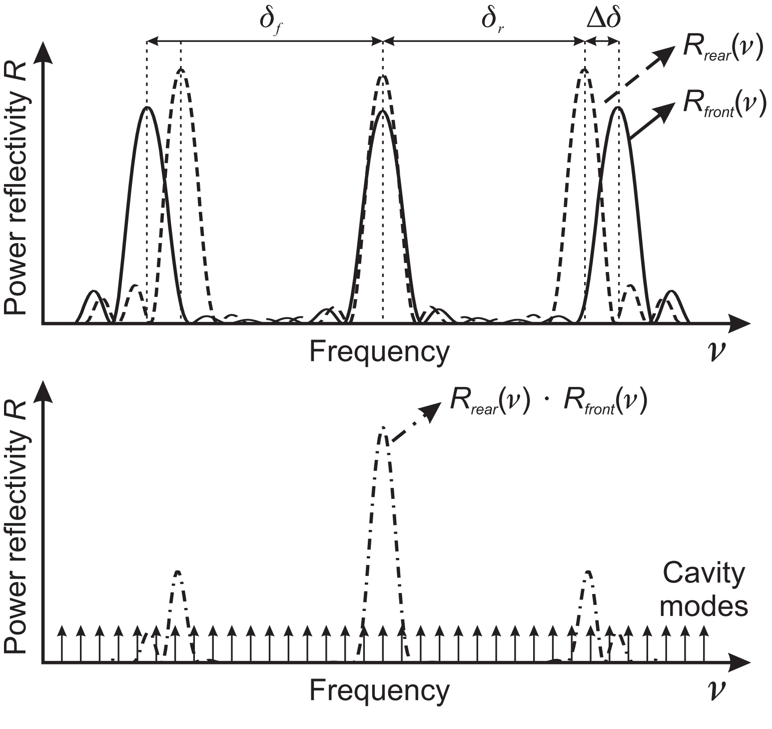

Figure 3. Use of the Vernier principle to extend the tuning range.

A drawback of the SGDBR laser is that the optical output power goes through a relatively long tuning section which inevitable has (tuning dependent) loss. Consequently the output power is both reduced and tuning dependent. It is possible to reduce this problem by integrating an optical amplifier into the laser structure, as shown in figure 4, which also shows the integration of a modulator [2].

Since an SGDBR laser has at least 4 sections, each of which must be controlled in order to get a particular power level and a particular optical frequency, the calibration and control of these lasers is an important practical issue. For practical system use, the laser will have to be able to generate a particular optical frequency in response to a simple control signal. It is therefore necessary to have an electronic control system delivered with the laser, which has enough information stored about the laser. This information is generated by the manufacturer using a calibration system which is able to extract the required information.

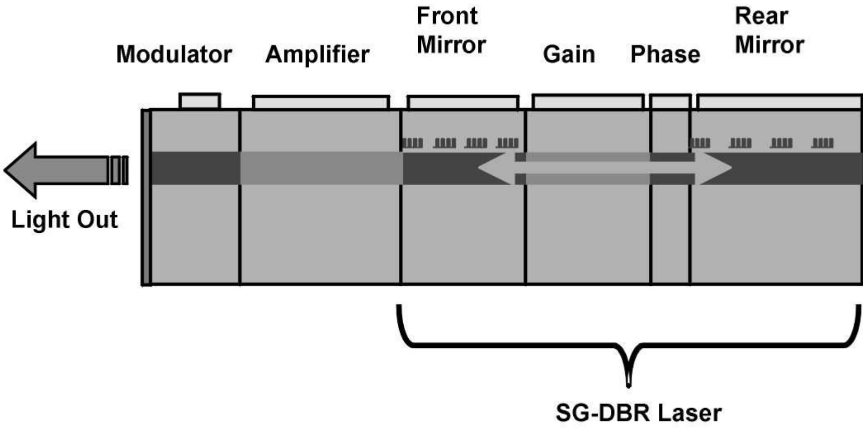

Figure 4. SGDBR laser with integrated amplifier and modulator. Courtesy Agility.

Bookham has recently been presented a laser structure which has a front tuning section with reduced tuning dependence of the loss, and with potentially easier control [3], figure 5. The rear reflector has a number of narrow, widely spaced reflection peaks as in the SGDBR. However, the front section consists of a number of short subsections, each with a spectrally broad and relatively weak reflection. When one of these subsections is biased, the reflection spectrum moves, and coincides with that of a neighbor subsection, thus forming a relatively broad reflector, which can pick out one of the peaks from the rear reflector. Since the whole front section is short, and only a relatively low tuning current is required, the front loss is low and has little tuning dependence.

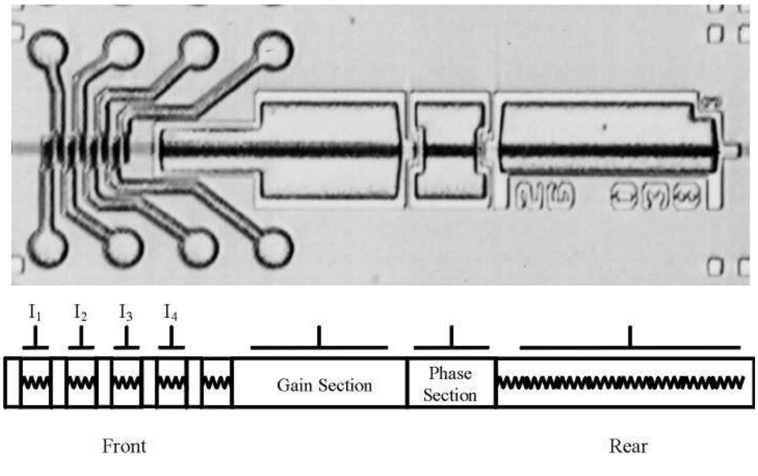

Figure 5. Digital supermode (DS) DBR laser. Courtesy Bookham.

An alternative monolithic widely tunable laser is the grating coupled sampled reflector (GCSR) [4] from ADC, figure 6. This structure also has a rear reflector giving a number of narrow and widely spaced reflection peaks, but in this case a separate peak is picked out by a widely tunable (but spectrally broad) codirectional coupler, which acts as a transmission filter. The combination of the broad transmission filter and the comb reflector is sufficient to select a single mode. Note that this laser does not have a passive section at the front, and therefore avoids the associated optical losses.

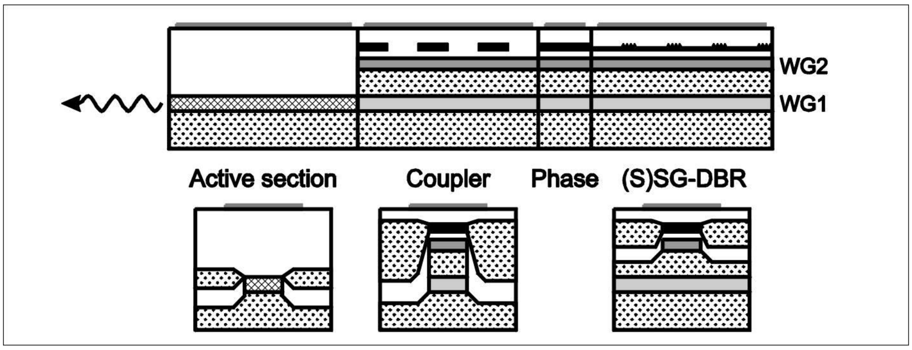

Figure 6. GCSR laser with cross sections of the different laser sections. Courtesy ADC.

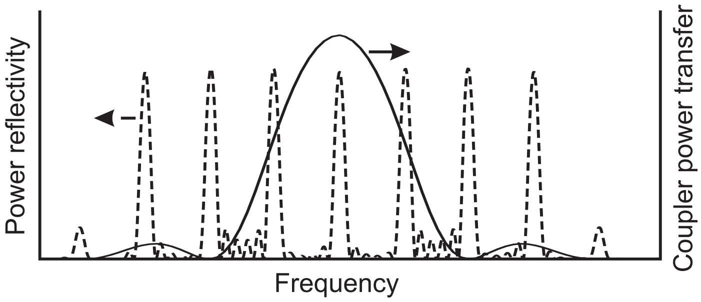

Figure 7. Reflector spectrum and coupler transfer function for the GCSR laser.

3.2 External cavity lasers

A traditional external cavity laser (ECL) consists of a laser chip and an external grating reflector. In order to suppress multi-cavity effects, the laser facet facing the external cavity is usually anti reflection (AR) coated. The laser output is usually taken from the facet at the other end of the laser; the reflectivity of this facet may also be modified by a coating in order to increase the available power. Turning the grating changes the angle of incidence of the laser light, and hence tunes the wavelength. However, when the wavelength changes, the ratio between the wavelength and the cavity length changes, leading to hops between cavity modes. In order to achieve phase continuous tuning (i.e. tuning with the laser remaining in the same longitudinal mode), it is necessary to change the cavity length by exactly the same relative amount as the wavelength. Simultaneous change of the cavity length and the grating angle can be achieved with a special mechanical mounting of the grating, or by rotating the grating around an optimized pivot point.

A particular advantage of ECLs is that they can use semiconductor lasers which are specifically designed for high output power, and in addition there is a degree of freedom in the selection of facet reflectivities; this makes it possible to have a structure with a high power efficiency. However, the traditional ECLs involve delicate mechanics, they tend to be quite bulky, and in order to ensure spectral stability the demand on mechanical stability is very high. Consequently, they have remained a specialist, low volume product with a relatively high unit price

A relatively new development is the use of a micro-electro-mechanical (MEM) structure to form a micro-ECL. The device described in [5], and shown in figure 8, has a footprint of only about 2 mm by 3 mm. The small size means that the device is mechanically robust. Although this MEM-ECL is clearly aimed at the telecom transmitter market, its performance (40 nm continuous tuning, +7 dBm fiber coupled power over the whole range) certainly makes it a candidate for test and measurement applications as well. Switching from one WDM channel to another is relatively slow (15 ms), but wavelength stabilization, using a wavelength locker, is simple. Truly continuous tuning is possible, and probably a good deal faster than for a standard ECL.

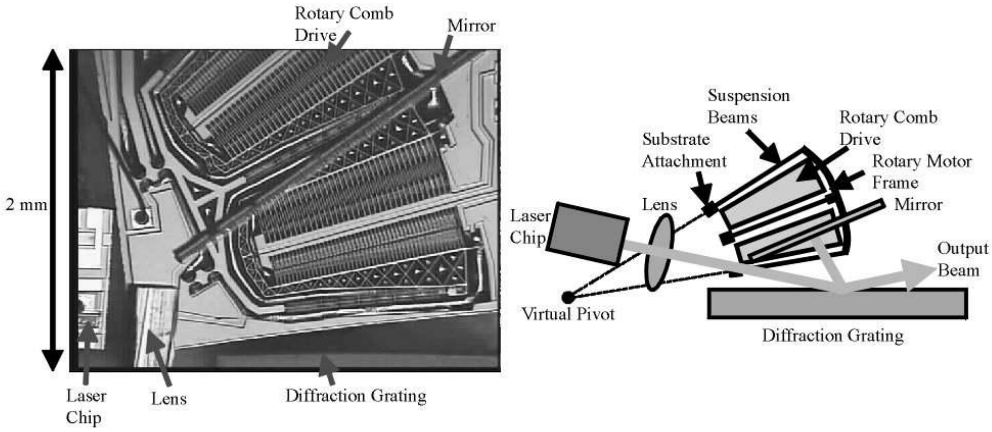

Figure 8. Micrograph and schematic of a MEM-ECL. Courtesy Iolon.

3.3 VCSELs

Vertical cavity surface emitting lasers (VCSEL) have emerged as relatively low cost transmitters for data links. In these lasers, the light propagates perpendicular to the plane defined by the active layer, and the optical feedback is provided by Bragg reflectors, consisting of layers with alternating high and low refractive indices, instead of the cleaved facets of edge emitting lasers. An advantage of the short cavity length is that the mode spacing is large compared with the width of the gain curve, such that, if the resonant wavelength is close to the gain peak, single-longitudinal-mode operation occurs without the need for any wavelength selective elements. As an example, a cavity length of about 10 μm will give a mode spacing of about 30 nm.

One of the particular advantages of VCSELs is that the spot size can be made compatible with that of a single-mode optical fiber, making the coupling from laser to fiber easier and more efficient. Most VCSELs are fabricated using the AlGaAs material system, with one or more strained InGaAs quantum wells as the active material; for these lasers, the wavelength is usually close to 1 μm. However, VCSELs are now also being fabricated in the InGaAsP material system which is suitable for longer wavelengths. A tunable VCSEL can be made by having an electrostatically deflectable mirror suspended over the active region. A wide continuous tuning range (limited by the longitudinal mode spacing), with a single voltage control is then possible. An example of a tunable VCSEL is shown in figure 9. Details of the VCSEL structure for this laser are given in [6].

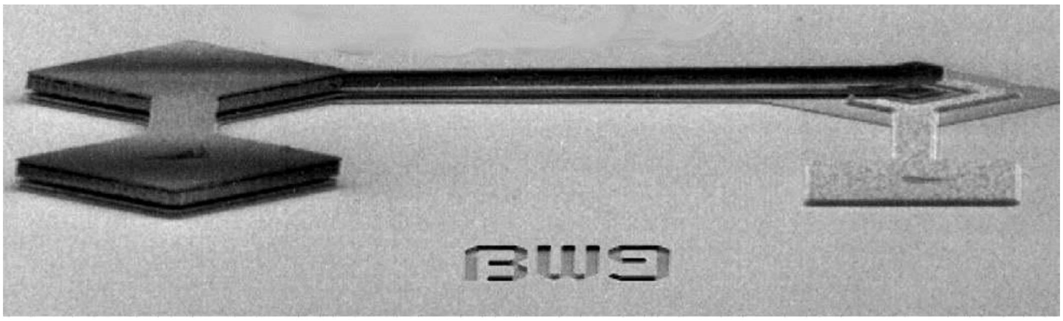

Figure 9. Tunable VCSEL with the top mirror formed by a deflectable cantilever. Courtesy Bandwidth9.

VCSELs are inherently low power devices, but higher optical power can be achieved by use of optical rather than electrical pumping, although this makes the whole laser assembly more complex, see [7] for details on such a laser.

3.4 Arrays

Arrays of DFB lasers can be made where all the array elements operate at different optical frequencies. The different frequencies can be obtained either by varying a structural parameter (e.g. stripe width) from laser to laser, thereby changing the effective refractive index of the structure, or by changing the grating period (this requires e-beam writing). However, in order to form a practical device the lasers must be integrated with a combiner in order to have a common output waveguide.

Standard DFB lasers usually have one anti reflection (AR) coated and one high reflection (HR) coated facet. For integrated lasers in an array the facets will have to be non-reflecting. This is necessary to avoid the spectral yield problem that occurs in AR/HR devices because the relative position of a facet relative to the grating cannot be controlled. In order to have a single, well defined, lasing mode, a DFB laser with two non-reflecting facets, must have a quarter wavelength phase shift in the center of the grating.

The structure described in [8] has six DFB lasers integrated with a combiner, an amplifier and a modulator, as well as monitor detectors (figure 10). The amplifier is included in order to compensate for the splitting loss caused by the combiner, and the insertion loss due to the modulator. The emission frequency of a given laser can be fine tuned by a moderate degree of temperature tuning, or a higher degree of temperature tuning can be used to tune each array element over a wider spectral range.

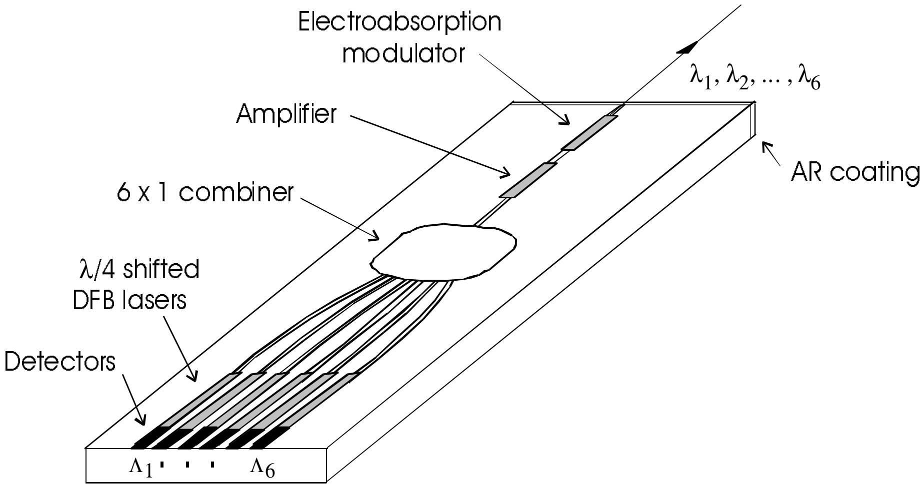

Figure 10. Wavelength selectable DFB array with 6 elements [8].

Fabrication of a DFB laser to a specified wavelength is very difficult, but in an array, the accuracy of the wavelength spacing can be very high. This means that if one array element is fine-tuned to its design wavelength (e.g. thermally), then all the other array elements will automatically be at, or very close to, their respective design wavelengths. Use of an array also makes it possible to have redundancy in order to improve the reliability, by ensuring that a given wavelength can be covered by more than one laser.

It is also possible to make an array consisting of DBR lasers. In such an array each element can be electronically tuned, i.e. the tuning is faster than for a DFB array. By using a relatively short active region it is possible to design each array element in such a way that it has a wide continuous tuning range. A range of 4.5 nm is reported in [9].

Arrays of DFB or DBR lasers are obviously not practical for addressing a large number of channels unless a high degree of temperature tuning is used. This will in turn reduce the tuning speed, and some of the control simplicity advantage will also be lost.

A key problem for DFB arrays is the combiner and its associated insertion loss, which is getting worse for arrays with a high element count. A new way of avoiding this problem has recently been published [10]. As shown in figure 12, the combiner is replaced by a MEMS mirror which can be controlled to provide coupling from a given array element to the output fiber.

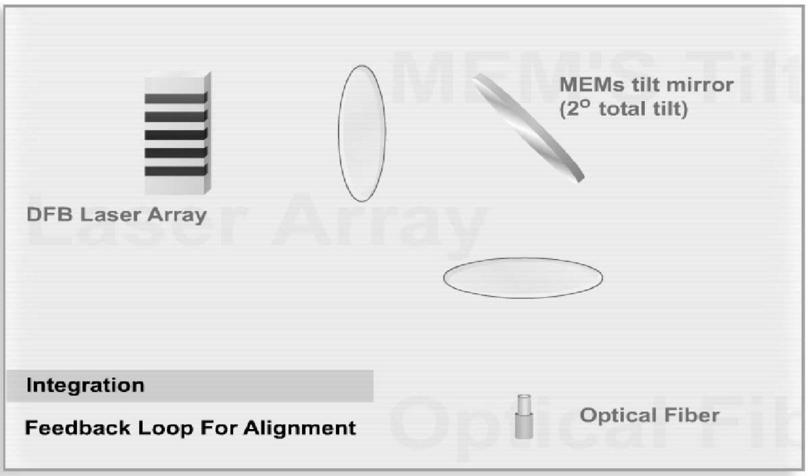

Figure 11. DFB array with MEMS mirror. Courtesy Santur.

4. WAVELENGTH STABILITY AND SWITCHING

Wavelength stability over time as the laser ages, is a major concern for tunable lasers, but it seems that using modern process technology very high levels of stability can now be achieved. As an example, figure 12 shows a 'mode-map', i.e. areas of single mode operation for a widely tunable SGDBR laser.

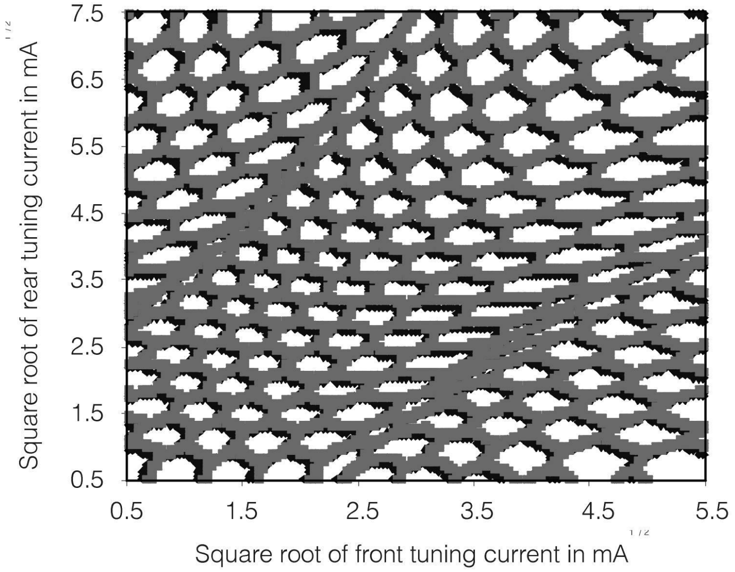

Figure 12. Mode-map for SGDBR laser after 100 hours (underlying black contours) and after 2300 hours (top grey contours) of accelerated ageing. Courtesy Agility.

Another interesting practical issue is wavelength switching of a widely tunable laser. Although lasers like DBRs and SGDBRs in principle can switch wavelength in a few ns (limited by the carrier lifetime), switching times will be limited by the control electronics. An example of a control card for a tunable laser, and switching times for a DBR are shown in figure 13.

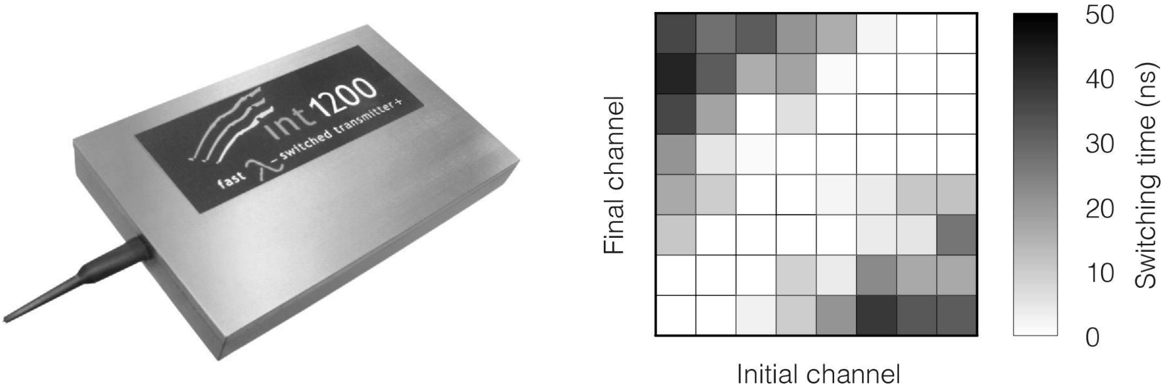

Figure 13. a) Transmitter module for tunable lasers. b) Switching time matrix for 8 channels of a DBR laser using a 100 GHz grid. The worst case switching time is 43 ns for an accuracy of ±1.5 GHz. Courtesy Intune Technologies.

5. PERFORMANCE SUMMARY

The fundamental tuning range limitations for various types of tunable lasers are listed in table 2.

DBR	carrier density change
SSG-DBR, GCSR	control and stability
External cavity	gain spectrum
VCSEL	cavity mode spacing
Array or cascaded DFB	temperature range, element count

Table 2. Tuning range limitations.

The achieved and expected performance for a number of tunable laser structures and arrays is summarized in table 3.

	DBR	SGDBR	GCSR	Ext. cavity	VCSEL	DFB array
Power >10mW	√	with SOA	√	√	?	√
Max range in nm	≤15	50-100	50-100	>100	<50	15-30
Tuning speed	ns	ns	ns	~10ms	~200µs	ms
Direct modulation	2.5G 10G EA	(2.5G)	(2.5G)	?	2.5G	?

Table 3. Tunable laser performance comparison.
√ = achieved or possible, ? = questionable, ( ) = borderline.

The price of a conventional fixed wavelength DFB laser can be broken down into the following elements: chip cost, testing, control and bias circuit, and packaging (including: optical elements, fiber alignment and fixing, isolator, possible modulator, possible wavelength locker). Under stable and high volume production conditions, the first 3 cost elements are all relatively minor compared to the packaging costs. For tunable or selectable lasers the situation is as follows:

- The chip cost can be low provided the chip yield is satisfactory.

- The testing cost can be low provided the testing (including the extraction of operating points) is automated and fast.
- The cost of the control board can be low provided the volume is sufficient.

It follows from this line of argument that if/when the areas of yield, test and control are sorted out, the dominant cost element for a tunable or wavelength selectable laser is also the packaging. However, the packaging costs do not differ from those of a fixed wavelength DFB (with otherwise similar performance requirements), and consequently the price premium for a tunable or selectable laser could become low, thereby fueling a virtuous circle of increased volume and reduced price.

5. REFERENCES

1. V. Jayaraman, Z.-M. Chuang, L.A. Coldren, "Theory, design, and performance of extended tuning range semiconductor lasers with sampled gratings", IEEE J. Quantum Electron., Vol. 29, pp. 1824-1834, 1993.
2. Y.A. Akulova, G.A. Fish, P.-C. Koh, C.L.Schow, P. Kozodoy, A.P. Dahl, S. Nakagawa, M.C. Larson, M.P. Mack, T.A. Strand, C.W. Coldren, E. Hegblom, S.K. Penniman, T. Wipiejewski, L.A. Coldren, "Widely tunable electroabsorption-modulated sampled-grating DBR laser transmitter", IEEE J. Selected Topics in Quantum Electron., Vol. 8, pp. 1349-1357, 2002.
3. D.C.J. Reid, D.J. Robbins, A.J. Ward, N.D. Whitbread, P.J. Williams, G. Busico, A.C. Carter, A.K. Wood, N. Carr, J.C. Asplin, M.Q. Kearley. W.J. Hunt, D.R. Brambley, J.R. Rawsthorne, "A novel broadband DBR laser for DWDM networks with simplified quasi-digital wavelength election", OFC'2002, Paper ThV5, Anaheim 2002.
4. P.-J. Rigole, S. Nilsson, L. Bäckbom, T. Klinga, J. Wallin, B. Stälnacka, E. Berglind, B. Stoltz, "114nm wavelength tuning range of a vertical grating assisted codirectional coupler laser with a super structure grating distributed Bragg reflector", IEEE Photonics Technol. Lett., Vol. 7, p. 697-699, 1995.
5. J.D. Berger, Y. Zhang, J.D. Grade, H. Lee, S. Hrinya, H. Jerman, "Widely tunable external cavity diode laser based on a MEMS electrostatic rotary actuator", OFC'2001, Paper TuJ2, Anaheim 2001.
6. W. Yuen, G.S. Li, R.F. Nabiev, J. Boucart, P. Kner, R.J. Stone, D. Zhang, M. Beaudoin, T. Zheng, C. He, K. Yu, M. Jansen, D.P. Worland, C.J. Chang-Hasnain, "High-performance 1.6µm single-epitaxy top-emitting VCSEL", Electron. Lett., Vol. 36, pp. 1121-1123, 2000.
7. D. Vakhshoori, P. Tayebati, C.-C. Lu, M. Azimi, P. Wang, J.-H. Zhou, E. Canoglu, "2mW CW singlemode operation of a tunable 1550nm vertical cavity surface emitting laser with 50nm tuning range", Electron. Lett., Vol. 35, pp. 900-901, 1999.
8. M.G. Young, U. Koren, B.I. Miller, M. Chien, T.L. Koch, D.M. Tennant, K. Feder, K. Dreyer, G. Raybon, "Six wavelength laser array with integrated amplifier and modulator", Electron. Lett., Vol. 31, pp. 1835-1836, 1995.
9. N. Fujiwara, T. Kakitsuka, F. Kano, H. Okamoto, Y. Kawaguchi, Y. Kondo, Y. Yoshikuni, Y. Tohmori, "Mode-hop-free wavelength-tunable distributed Bragg reflector laser", Electron. Lett., Vol, 39, pp. 614-615, 2003.
10. B. Pezeshki, E. Vail, J. Kubicky, G. Yoffe, S. Zou, P. Epp, S. Rishton, D. Ton, B. Faraji, M. Emanuel, R. King, X. Hong, M. Sherback, V. Agrawal, T. Razazan, "12 element multi-wavelength DFB arrays for widely tunable laser modules", OFC'2002, Paper ThGG71, Anaheim 2002.

6. FURTHER READING

1. M.-C. Amann, J. Buus, "Tunable laser diodes", Artech House, Norwood, 1998. An expanded and updated edition will be published by Wiley/IEEE in late 2003.