Tunable Semiconductor Lasers: A Tutorial

Larry A. Coldren, *Fellow, IEEE*, G. A. Fish, Y. Akulova, J. S. Barton, L. Johansson, and C. W. Coldren, *Member, IEEE*

Tutorial Paper

***Abstract*—Tunable semiconductor lasers have been listed in numerous critical technology lists for future optical communication and sensing systems. This paper summarizes a tutorial that was given at OFC '03. It includes some discussion of why tunable lasers might be beneficial, an outline of basic tuning mechanisms, some examples of tunable lasers that have been commercialized, and a discussion of control techniques. More extensive data is given for the widely-tunable sampled-grating distributed-Bragg-reflector (SGDBR) type of laser, including data for such lasers integrated monolithically with modulators to form complete transmitter front ends. A summary of reliability data for the SGDBR laser is also given. It is concluded that tunable lasers can reduce operational costs, that full-band tunability is desirable for many applications, that monolithic integration offers the most potential for reducing size, weight, power and cost, and that sufficient reliability for system insertion has been demonstrated.**

***Index Terms*—Photonic integrated circuits, semiconductor lasers, tunable lasers.**

I. Introduction

TUNABLE lasers have been of interest for some time [1]. Applications range from sources for fiber optic telecommunication systems to broadband sensors. About three or four years ago, the telecom application began to drive significant investments into this field to support the perceived need for dynamic networks and wavelength reconfigurability in wavelength division multiplexing (WDM) systems. Vast reductions in operational costs were predicted for such flexible fiber-optic networks that were thought to be necessary for the rapidly expanding demand for bandwidth. However, as many new companies joined this effort, there was a large overbuild of capacity, and the need for the new networks vanished, or more accurately, was pushed back to least the present time. The good news for the industry is that the demand for bandwidth continues to nearly double each year.

Although the potential to reduce operational costs with more dynamical networks still exists, the delay in significant network expansion has led to a reappraisal of the value proposition for tunable lasers. Today, the main value for telecom networks appears to be in the areas of inventory reduction, both in the manufacture and operation of WDM systems. With fixed frequency distributed-feedback (DFB) lasers, dozens of different wavelength codes must be manufactured and inventoried, and perhaps more importantly, dozens of different wavelength-specific line cards must be manufactured and inventoried. Since the cost of line cards is measured in multiples of $10 k, this can be a significant overhead. Thus, even for this less glamorous application, the savings are finite, but as a result, today's tunable laser solutions are compared to fixed-frequency DFBs for both cost and performance.

Bearing all of this in mind, it is generally agreed that if tunable lasers with the same performance specs as DFBs were available, most systems companies would select them over DFBs for a small price premium. As we will show in this report, some tunable embodiments appear to have reached specification parity with DFBs, so the situation may indeed be favorable for tunables in future WDM networks. By the time one considers the price of a line card, the increased cost of incorporating the tunable laser can be quite small, relatively speaking, and one can gain the functionality of a "universal" line card, which can be programmed to function at any wavelength over the tuning range of the laser [2]. Of course, this is a strong argument for full-band tunability in the laser, because only one part would then be necessary for any slot. Finally, there is still the compelling argument that the line card can be re-provisioned at some later point in time, should the network architecture evolve to accommodate this, and again, full-band tunability would be desired.

The situation in the sensor area is perhaps even more attractive for tunable lasers. Here many sensor types rely upon the ability to sweep the laser frequency over a wide range for their basic functionality, so they are essential. This, perhaps, is a subject for a different audience than those attending the Optical Fiber Communication conference, the audience for which this tutorial was designed.

II. Why Tunable Lasers?

Although we have already stated that the current justification for wanting tunable laser solutions is in reduced manufacturing and operational costs deriving from inventory reduction, there are still a number of potential applications in the telecom area that might be important in the near future [3]. The first to be mentioned is in reconfigurable optical-add-drop multiplexers (ROADMs). As illustrated in Fig. 1 these allow single (or multiple) optical channels to be removed and replaced on a fiber without de-multiplexing, regenerating, and re-multiplexing the entire array of wavelengths contained in the fiber. In applications where this functionality is desired, the ROADM can vastly reduce the cost of dropping and/or adding a relatively small amount of information from or to the fiber.

Manuscript received July 2, 2003; revised October 10, 2003.

L. A. Coldren is with the Departments of Materials and Electrical & Computer Engineering, University California, Santa Barbara, CA 93106 USA, and is also with the Agility Communications, Incorporated, Santa Barbara, CA 93117 USA.

G. A. Fish, Y. Akulova, and C. W. Coldren are with the Agility Communications, Incorporated, Santa Barbara, CA 93117 USA.

J. S. Barton and L. Johansson are with the Departments of Materials and Electrical & Computer Engineering, University California, Santa Barbara, CA 93106 USA.

Digital Object Identifier 10.1109/JLT.2003.822207

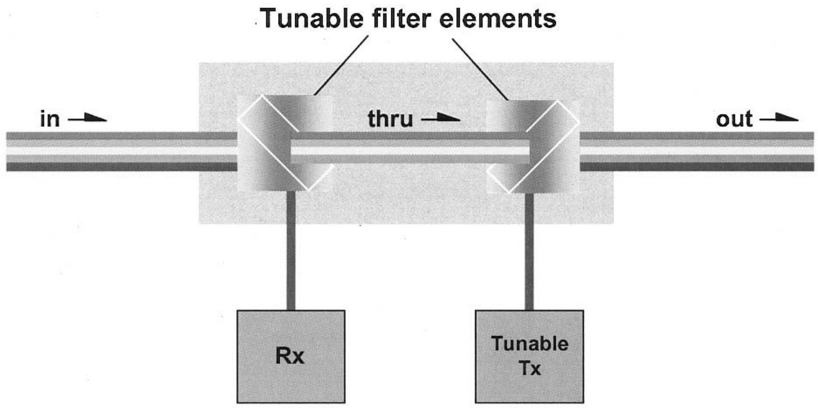


Fig. 1. Reconfigurable optical add/drop port. A tunable filter selectively removes (or adds) a single (or several) optical WDM channel from the fiber. A tunable transmitter is needed to insert any desired channel at the add port.

Tunable lasers are also natural complementary components in optical switches of various kinds. Here they generally are used for the function of wavelength switching or "wavelength conversion," in which an incoming signal on one wavelength is remodulated onto another wavelength on the output [4]. This can be accomplished in numerous ways, the most straightforward of which is to incorporate a tunable laser within a line card or transponder, so that the output can be set to any wavelength value. These "optical-electronic-optical" (OEO) components include 3R regeneration to reconstitute the signal to its original form. One can also make "all optical" wavelength converters that use the incoming signal on one wavelength to drive a modulator that applies the signal directly to a second selectable output wavelength generated by a tunable laser. Recently, this function has been demonstrated with a single monolithic chip [5], [6]. However, in these "all-optical" approaches 3R or even 2R regeneration of the signal is generally not provided, so that these elements can only work with relatively clean data, and they can only be cascaded a few times before a 3R regeneration is necessary.

Fig. 2 shows an all-optical space switch that uses wavelength converters at the input and a passive optical router switching fabric to provide space switching. In this case the input signal is placed on the wavelength that the passive "lambda router" will route to the desired output port. If the signal is to be re-multiplexed, it would then have to be again converted to the desired wavelength to enter the optical multiplexer. This sort of switching architecture is also currently being investigated by several groups for all-optical packet switching [7], [8]. In this case, the tunable lasers in the front-end wavelength converters (shown as line cards with tunable lasers in Fig. 2) must switch wavelengths very fast—typically in the nanosecond range. Such a criterion will favor the tunable laser types that are controlled electronically versus the ones that have thermal or mechanical tuning elements.

Again, the sensor application area has already been mentioned, so it shall not be discussed further here.

III. Basic Tuning Mechanisms

Fig. 3 gives a schematic of a generic tunable laser together with the relative spectra of the necessary filter and gain elements as well as the location of the various cavity modes that all must be properly aligned and translated to create a tunable, single-frequency laser. Of course, in most practical embodiments, the

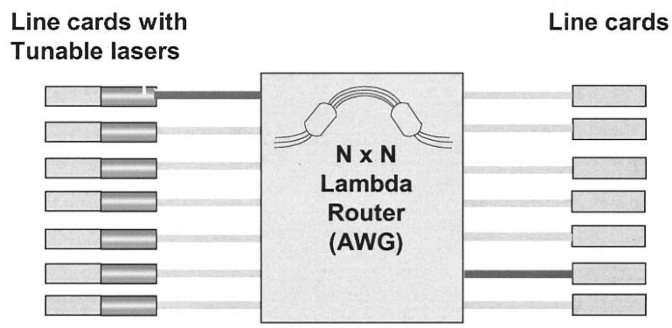


Fig. 2. Transparent optical space switch composed of a wavelength converter array and a passive router such as an arrayed-waveguide-router (AWG). Line cards with tunable lasers can more generally be replaced by wavelength converters.

filter, mirror and phase-shifting elements are combined in some way to create a unique physical structure for the different kinds of tunable lasers. Fig. 3 can be used to see how a tunable semiconductor laser evolves from the most basic "Fabry-Perot" laser, which has just the gain and the two simple mirror elements, to a "single-frequency" laser, which adds the mode-selection filter, to a "tunable single-frequency" laser, which adds possible adjustment of the mirror position and the center frequency of the mode-selection filter, as well as adding a new adjustable cavity phase element. For more analytical discussion, the reader is referred to [9], [10].

The most common Fabry-Perot laser is composed of a uniform cleaved semiconductor chip that is structured to provide gain for a guided optical mode with the cleaves functioning as the mirrors. The most common single-frequency laser is probably the DFB laser, illustrated in Fig. 4(a), in which an index grating is formed near the optical waveguide to provide a continuous reflection that gives both the mirror functionality as well as the mode selection filter. The vertical-cavity surface-emitting laser (VCSEL) as illustrated in Fig. 4(b), is also a single-frequency laser, but in this case the cavity is vertical and the grating mirrors sandwich the gain region. Although the distributed-Bragg-reflector (DBR) mirrors are frequency selective, the primary mode selection is done by the finite width of the gain spectrum in this case, because both the mirror spectrum and the mode spacing are made large by the short cavity length—a somewhat different case than that suggested in Fig. 3.

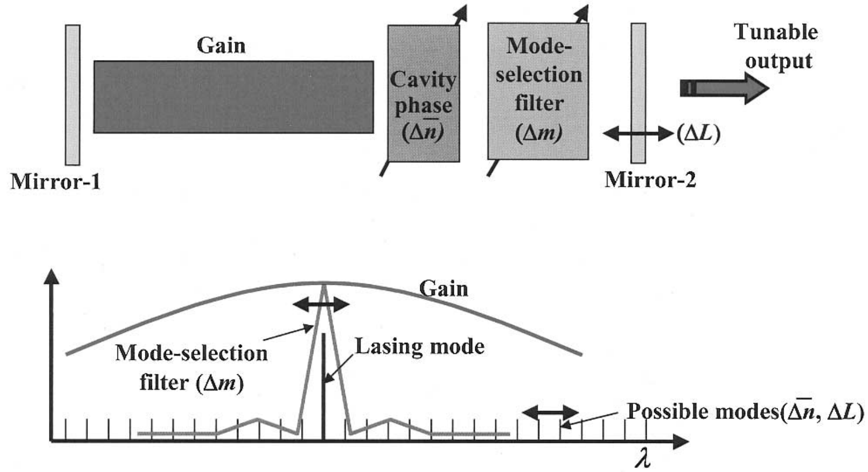
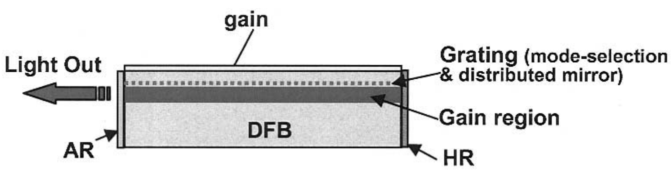
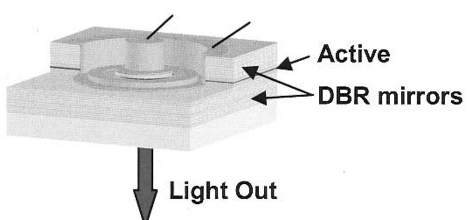


Fig. 3. Schematic of generic tunable laser together with relationship of the spectra of each element.



(a)



(b)

Fig. 4. Examples of single-frequency lasers (not tunable): (a) DFB laser and (b) VCSEL.

Equation (1) gives the relationship between the lasing wavelength, λ, and the cavity mode number, m, effective index of refraction seen by the cavity mode, $\bar{n}$, and the effective cavity length, L. Quite obviously, if one changes m, $\bar{n}$, or L, the wavelength must also change. The relative change in wavelength derived from (1) is given in (2). As indicated the relative wavelength change is directly proportional to the relative change in either the length, index or mode number

Mode number ↘ Effective cavity length ↙

$$\frac{m\lambda}{2} = \bar{n}L \tag{1}$$

Wavelength ↗ Effective index ↖

Tuned by mode-selection filter (via index or grating angle) ↓

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\bar{n}}{\bar{n}} + \frac{\Delta L}{L} - \frac{\Delta m}{m} \tag{2}$$

Tuned by net cavity index change ↗ Tuned by physical length change ↖

IV. Examples of Tunable Semiconductor Lasers

Fig. 5 shows several different types of tunable single-frequency lasers that have been commercialized. (Since tunable lasers need to be single frequency to be of much use, we will now drop this qualifier.) In the figure we have only included the widely-tunable varieties that are capable of full *C* or *L*-band coverage from a single device.

The first example shows a selectable array of DFB lasers that are combined in a multimode interference coupler. The DFBs are excited one at a time and each is manufactured with a slightly different grating pitch to offset their output wavelengths by about 3 or 4 nm. The chip is then temperature tuned by some 30–40 C to access the wavelengths between the discrete values of the array elements. With N-DFB elements, then, a wavelength range of up to about $4N$ nm can be accessed, or with 8–10 elements the entire *C*-band can be accessed. The schematic included in Fig. 5(a) is from NEC[11]; however, similar work is also being carried out at Fujitsu [12] and other mostly Japanese labs. Santur Corporation uses a similar concept, but with an external micro-electromechanical (MEMs) mirror to select which element is coupled to the output fiber [13], thus eliminating the $1/N$ combiner loss, but at the expense of one more element to package and control. In all cases, this approach must deal with the requirement of having a number of closely spaced DFBs all working to tight specifications. The losses in combining, inherent in most varieties, are also significant, and the need to temperature tune over a fairly large tuning range leads to relatively high power dissipation for this approach.

Fig. 5(b) is an example of an external-cavity laser. In this case a "gain block" is coupled to external mode-selection filtering and tuning elements via bulk optical elements. The cavity phase adjustment, necessary to properly align the mode with the filter peak and the desired ITU grid wavelength, can be included in one of several places—e.g., on the gain block or by fine tuning the mirror position. In most external-cavity approaches the mode selection filter is a diffraction grating that can also double as a mirror. The so-called Littman-Metcalf cavity arrangement is illustrated. In this case, a retro-reflecting mirror is translated as it is rotated. This combined motion changes the ef-

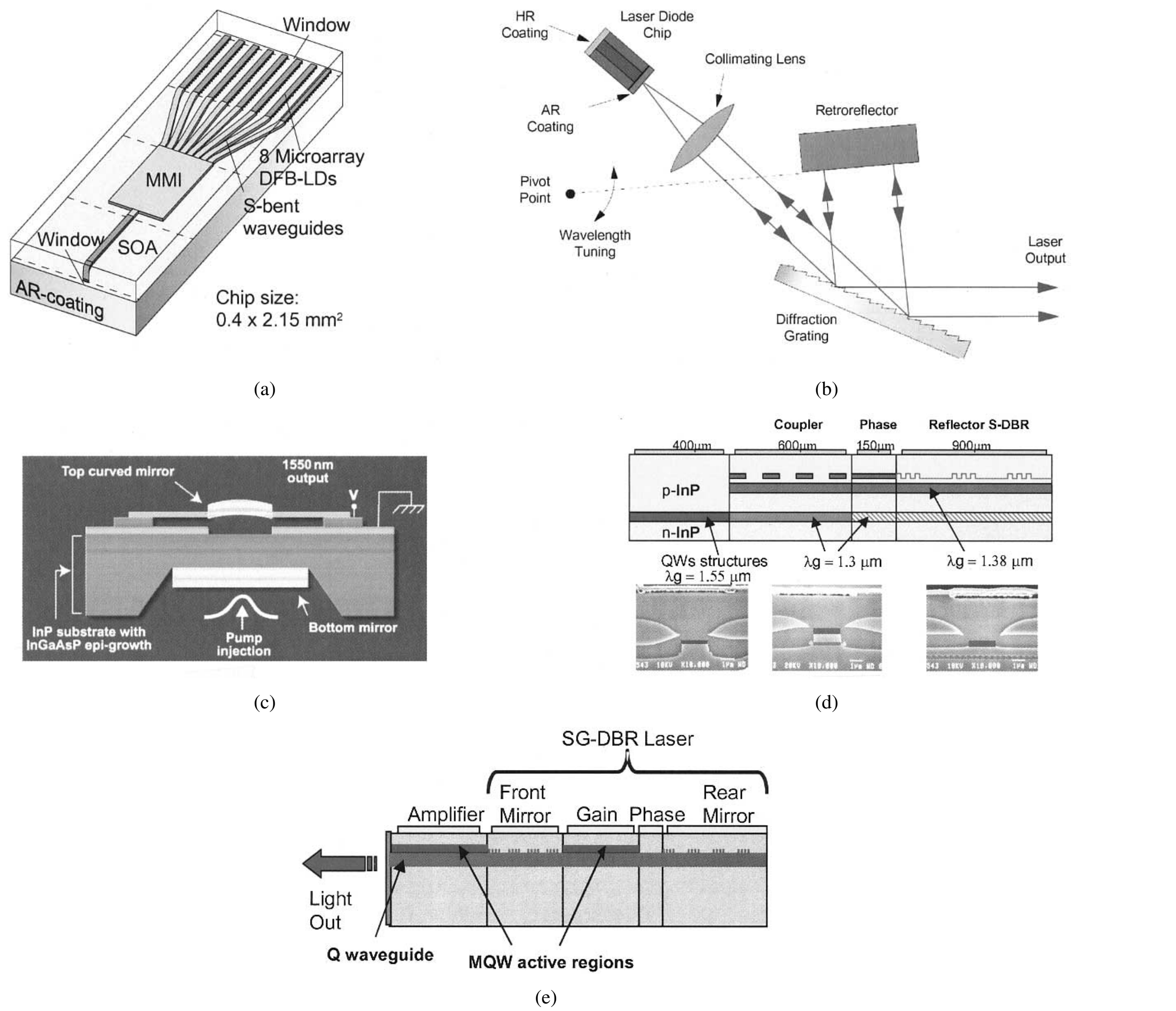
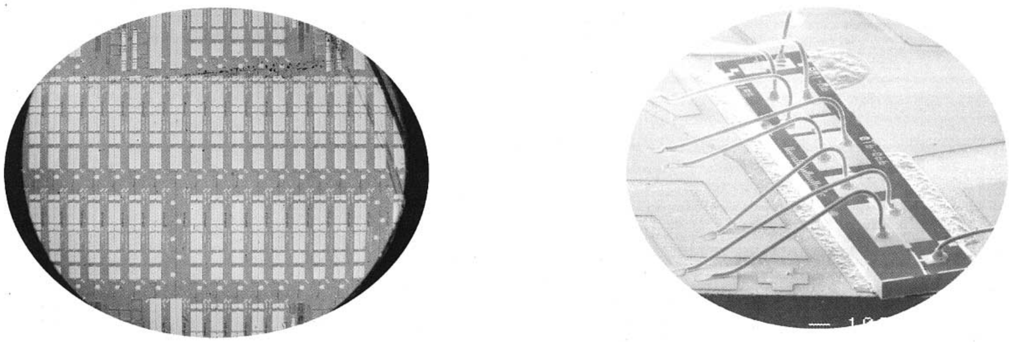


Fig. 5. Examples of widely-tunable laser types: (a) selectable DFB array, (b) external-cavity, (c) MEMs/VCSEL, (d) grating-coupled sampled-reflector (GCSR), and (e) sampled-grating DBR (SGDBR) with integrated SOA.

fective cavity length in proportion to the change in center wavelength of the mode-selection filter to track the movement of a single cavity mode. The Littman-Metcalf geometry provides continuous tuning over some range, but due to cavity dispersion, one in general still needs to correct the cavity phase at each ITU channel. This approach has been used by Iolon [14] and New Focus [15] in their products. Other companies tend to just rotate the mirror and let the mode selection filter scan across the modes. This is most common in scientific instruments, where the cavities are quite long and the mode spacing very small. Intel also has reported some research [16] in which the external cavity contains two temperature-tuned etalons with slightly different resonance frequencies, which act in combination to create a widely-tunable filter. A standard external mirror completes the cavity. All of the external cavity approaches appear to provide useable specs for telecommunications, although at this writing we are not aware of any that has completed the full Telcordia qualification exercise. An obvious concern with these structures is their manufacturability and reliability, given the need for assembling numerous micro-optical parts and holding them in precise alignment.

Fig. 5(c) shows a tunable VCSEL that is created by mounting one mirror on a flexible arm and using an electrostatic force to translate it up and down. This MEMs approach has been employed by Coretek [17]—later acquired by Nortel—[as shown in Fig. 5(c)] and Bandwidth 9 [18]. In Coretek's case external optical pumping was used, and in Bandwidth 9's case electrical pumping was employed. Both efforts appear to have been discontinued. The Coretek approach used dielectric mirrors for wide reflection bandwidth. Thus, it was able to show full *C*-band operation; the Bandwidth 9 device had a somewhat smaller tuning range. The use of optical pumping also provides for more power output, although advertised products from Nortel did include an external amplifier to boost the fiber-coupled power to the 20 mW range. A primary appeal for the VCSEL approaches is the wafer-scale manufacturing platform that it appears to provide. The hope here was to make tunable devices for nearly the same cost as the 850 nm VCSELs used in Gigabit Ethernet. However, at 1550 nm VCSEL construction is more difficult, and limited output power together with wide optical linewidth appear to be serious limitations with the VCSEL approaches at 1550 nm.



(a) (b)

Fig. 6. Photo of wafer and SEM of mounted single-chip transmitter.

Fig. 5(d) and (e) show monolithic widely-tunable semiconductor laser approaches that employ electronic tuning of the index in a single cavity to provide for full *C*- or *L*-band wavelength coverage. Both are variations on older DBR laser approaches [19]–[21], but both employ concepts to tune the relative wavelength by up to an order of magnitude more than the index of any section can be tuned. In the case of Fig. 5(d), the so-called grating-coupled sampled-reflector (GCSR) laser [22], [23], this is accomplished by using a property of a grating-assisted co-directional coupler which has a tuning proportional to the index tuning relative to the *difference* in index between two coupled waveguides, $\Delta n/(n_1 - n_2)$, rather than $\Delta n/n_1$ as in most other filters. However, because the filter is also broad, a back multiple-order sampled-grating reflector is required for good mode selectivity in this case. In the SGDBR of Fig. 5(e) [24], [25], the wider tuning range filter is provided by the product of the two differently spaced and independently tuned reflection combs of the SGDBRs at each end of the cavity. This product, R_1R_2, is what appears in the laser cavity loss factors, and the variation in the beating effect between the two different mirror reflection combs is sometimes referred to as the vernier effect. In this case the net mode selection filter wavelength tuning is that of a single grating, $\Delta n/n$, multiplied by $\delta\lambda/\Delta\lambda$, the difference in spacing between the mirror reflection peaks of the two mirrors, $\delta\lambda$, divided by the mean mirror peak spacing, $\Delta\lambda$. Similar physics is involved in the superstructure-grating DBR developed at NTT [26]. In both cases, good side-mode suppression has been demonstrated, and tuning of over 40 nm is easily accomplished, but due to grating losses resulting from current injection for tuning, the differential efficiency and chip output powers can be somewhat limited. In the case of the SGDBR, this is easily addressed by the incorporation of another gain section on the output side of the output mirror, and fiber-coupled powers of up to 40 mW have been reported. In fact, this is the embodiment illustrated in Fig. 5(e). Incorporating such a semiconductor-optical-amplifier (SOA) is not as easy for the GCSR, so fiber-coupled powers of typically less than 10 mW result. The integrated SOA also has other benefits for the SGDBR as will be discussed in the following.

V. Characteristics of SGDBR Lasers and Single-Chip Transmitters

Work at UCSB and Agility Communications has aimed to develop widely tunable lasers and transmitters with monolithically integrated modulators. A low-cost "platform technology" that is capable of providing a wide variety of photonic ICs (PICs) without changing the basic manufacturing process has been developed. Fig. 6 shows a photograph of a $2''$ InP wafer with arrays of seven-section photonic IC transmitters, each consisting of a full-band-tunable four-section SGDBR laser integrated with a monitoring detector, optical amplifier, and modulator. The SEM inset shows one of these mounted on a carrier ready to be inserted into a package. It is important to note that the wafer layer structure and processing procedure used is identical to that developed for the SGDBR laser alone. This same structure and processing procedure is also used in the more complex laser PICs to be discussed below. Note also a key advantage of photonic integration—only one optical coupling to fiber is required, as would be necessary for a simple DFB laser alone.

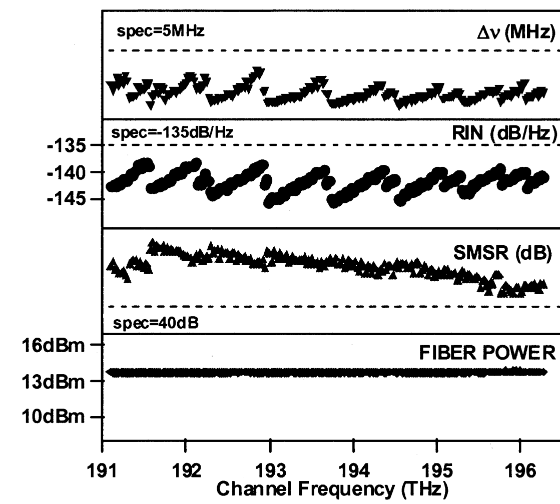


Fig. 7. CW characteristics of SGCBR-SOA device for 100 channels—calibrated for 20 mW of fiber power. The linewidth, $\Delta\nu$, relative intensity noise, RIN, and side-mode suppression ratio, SMSR shown for all *C*-band channels.

The basic SGDBR-SOA shown in Fig. 5(e) above as well as the integrated SGDBR-SOA-EAM transmitter illustrated in Fig. 6 have been productized and Telcordia qualified for telecom applications [27]. In Fig. 7 we give a summary of the characteristics of a 20 mW cw product similar to Fig. 5(e) at each of 100 channels spaced by 50 GHz across the *C*-band. A common quaternary waveguide extends throughout the entire device and offset quantum-well gain layers are included at the laser gain and SOA sections.

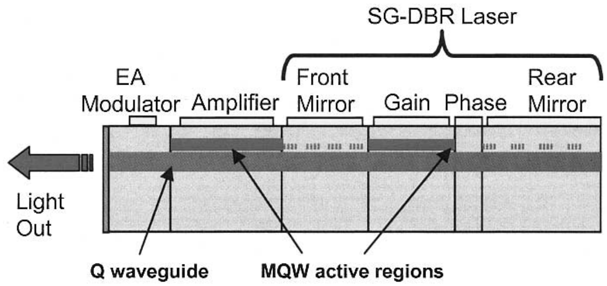
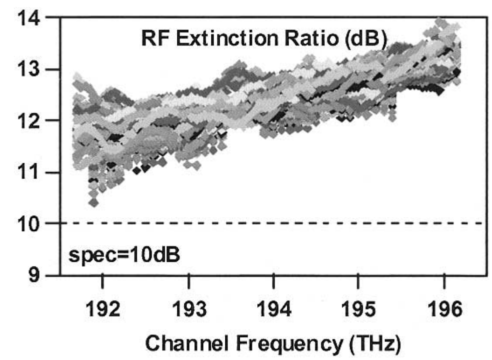
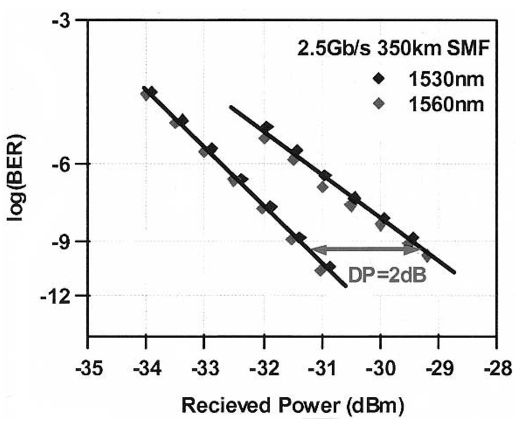


Fig. 8. Single-chip widely-tunable transmitter schematic showing a SGDBR laser integrated with an SOA and EAM.



(a)



(b)

Fig. 9. (a) RF extinction ratio for 100 superimposed SGDBR/EAM transmitters across the *C*-band. (b) Bit-error-rate results after transmission through 350 km of standard fiber at 2.5 Gb/s.

Fig. 8 shows a schematic cross section of an InP-based transmitter chip [28] as included in the photos of Fig. 6. The modulator bias is varied across the 40 nm tuning range to enable efficient modulation and good extinction across this entire range.

Fig. 9(a) shows superimposed rf-extinction ratio versus wavelength characteristics for 100 transmitter chips across the *C*-band, and Fig. 9(b) shows the bit-error rate after transmission through 350 km of standard single-mode fiber for two different wavelengths. The data is applied directly to the EAM of the chip. The average modulated output power is about 3 dBm in this case. Error-free operation was observed.

The transmitter illustrated in Figs. 6 and 8 and characterized in Fig. 9 provides good results at 2.5 Gb/s for distances up to 350 km. However, for longer distances and/or higher bit rates, some sort of chirp control is necessary. Thus, work at both Agility [6], [29] and UCSB [30] has explored replacing the EAM with a Mach-Zehnder modulator (MZM) as shown in Fig. 10. Such modulators have been used widely for long-haul applications, and they allow negative chirp with only one drive signal, although dual drive of both arms of the MZM are necessary for truly programmable chirp. In the past, researchers have had difficulties in integrating such MZM's directly with lasers because of reflections. However, the UCSB-Agility effort appears to have solved these difficulties. By monolithically integrating the MZM a much smaller footprint and low power dissipation is possible as compared to hybrid packaged or fiber-coupled devices. In addition, the chirp can be tailored for each channel across the wavelength band by adjusting the biases to the two legs of the MZM. Chirp values from $+1$ to -1 are readily available. Error free transmission over 80 km of standard fiber was demonstrated for all channels at 10 Gb/s using a negative chirp configuration.

VI. Reliability of the SGDBR Laser

Fig. 11 summarizes some of the reliability data taken on the 10 mW cw product by Agility [31]. Both the integrated EAM transmitter and the 10 mW cw version have undergone complete Telcordia qualification. Because of the InP single-chip architecture, these PICs can be qualified in much the same way as simple laser chips. Such is not the case with other types of widely-tunable transmitters in which separated optical parts are involved in some sort of hybrid package.

A quantitative model of failure rates was developed for each section of the device by fully characterizing failure modes and determining failure mode accelerants. The activation energy, $E_a = 0.5$ eV was derived assuming an aging rate proportional to $\exp[E_a/kT]$. The current acceleration exponent, $n = 1.5$ was derived assuming the aging rate was also proportional to J^n, where J is the applied current density to the section in question. Mirror drift failure was set to be when the operating point moved half way from the center of a single-mode region toward a mode-hop boundary. For the SGDBRs in question this was equivalent to ± 100 pm of allowable open-loop wavelength drift of the mode boundaries. (Of course, with a wavelength locker in operation, the lasing mode wavelength only drifts as much as it does—typically <1 pm over life.) The aging criteria for the gain and amplifier sections are as for other semiconductor lasers. The same approximate activation energies and current acceleration factors were observed for all sections.

The data indicate that no updating of mirror currents is necessary for a FIT rate of <20 at 15 years. This includes reasonable margins for all device parameters. However, a mirror look-up table updating algorithm has also been developed that both monitors the mirror drift for setting possible alarms as well as updating the table. This mirror-control algorithm improves the FIT rate to <3 at 15 years. The lifetime distribution taken from 200 parts using accelerated aging procedures shows a classical log-normal relationship with a mean lifetime of 186 years for room temperature, but with maximum channel currents assumed. In a normal WDM system populated with such devices, the channel currents would be distributed over lower values for the various channels, so Fig. 11 should be taken as a worst case

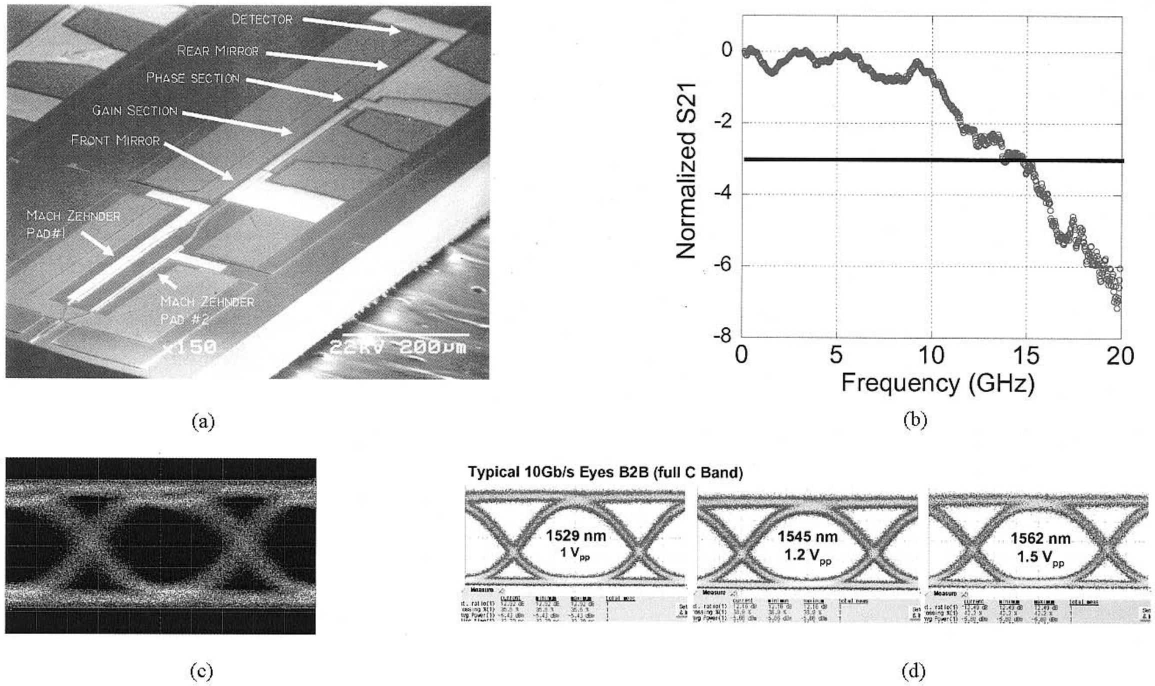


Fig. 10. (a) SEM photo of UCSB's SGDBR integrated with a Mach-Zehender modulator, (b) small-signal bandwidth, (c) unfiltered eye, and (d) filtered eye-diagrams at 10 Gb/s for three wavelengths across the band for Agility device.

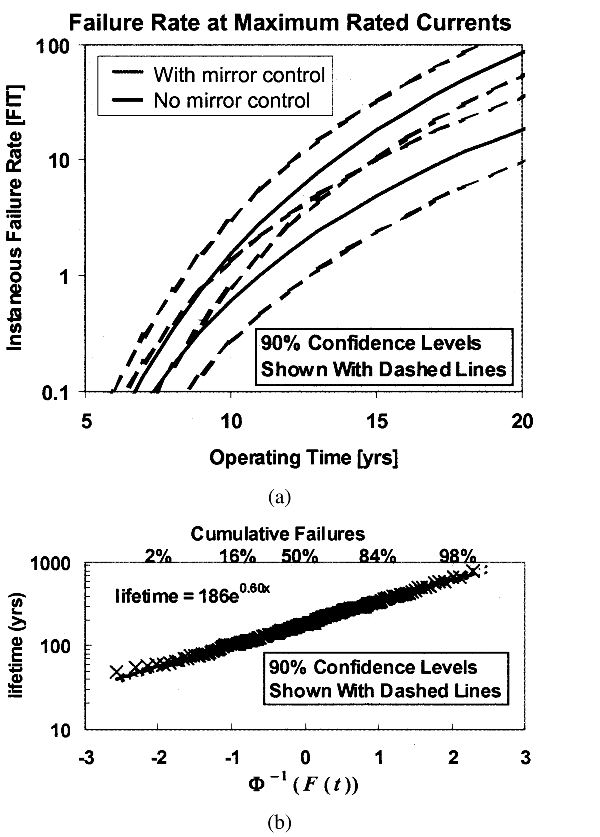


Fig. 11. (a) FIT rate versus time, assuming both original mirror biases as well as with bias updating-mirror control. (b) Lifetime distribution of 200 parts tested. Maximum channel currents assumed. Mean lifetime of 186 years shown.

result that would not occur over any distribution of components in a typical system. Taking a distribution of WDM channels into account, the "no mirror control" FIT rate is estimated to be about 2 @ 15 years.

This relatively low wavelength drift for the SGDBR has been ascribed to the relatively small percentage of grating that fills the sampled-grating mirrors. About 90% of the mirror area is free from gratings in a typical design. Studies have shown that this results in much higher material quality within the mirrors [31]. Lack of gratings in most areas permits very high quality regrowth of the InP cladding following grating formation. Not only is the surface more planar and free from defects, it can be composed of InP rather than InGaAsP quaternary waveguide material in the large regions between the grating bursts. Thus, while standard DBR lasers, which contain gratings throughout the mirror tuning sections, continue to have wavelength drift problems, the SGDBR has emerged as being surprisingly stable.

VII. Control of Widely-Tunable Lasers

The control of multi-element tunable lasers, such as those illustrated in Fig. 5, has been a roadblock to their general acceptance for some time. Most system engineers are accustomed to incorporating a two-terminal device, such as a DFB laser, in their optical transmitters. Of course, even for the DFB the device temperature is used to fine tune and lock the wavelength in WDM systems. For the widely-tunable devices of Fig. 5, it seems apparent that we must simultaneously control some additional parameters, although in some cases we may only need to dynamically control the same number as in the DFB to lock the amplitude and wavelength at a given channel. However, there is always a need for a "look-up table" to give the specific set of currents or voltages for each channel to the several sections, and this indeed, does add a complication for the user. To gain

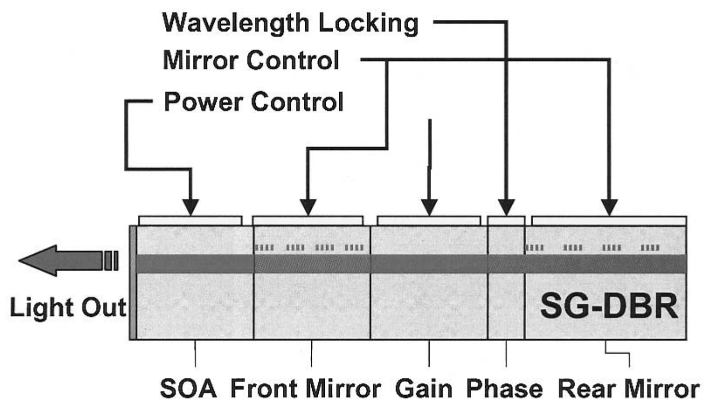


Fig. 12. SGDBR/SOA with connections for control circuit.

more wide-spread acceptance, suppliers of the multiple-section lasers in recent years have provided automatic control systems within the laser module so that the user doesn't have to deal with the control problem. The wavelength and amplitude are set via a digital command through a common interface. Nevertheless, users are justifiably concerned with the reliability and stability of such systems. So they remain of great interest.

The control system must be capable of two basic functions: 1) staying accurately on the desired wavelength channel and 2) reliably finding a new desired channel when a channel change is requested at some later time, and this time could be near the end of life. To accurately stay on a desired wavelength channel most lasers require a separate wavelength locker. If the wavelength channel plan is relatively coarse, perhaps >100 GHz, this locker may not be necessary. For example, given the low wavelength drift of the SGDBR outlined above, this locker may not be necessary for even 100 GHz channel spacing if a modest FIT rate is tolerable. But, more generally a locker is required. It usually contains an etalon with a free-spectral range roughly equal to the channel spacing, so that it can provide a feedback signal to capture and lock the wavelength within about one-third of a channel spacing on either side of some ITU frequency.

Switching to a new channel after some time is generally a more difficult problem. The immediate question is, will the original look-up table from factory calibration be good enough, or will aging have changed the values? To be able to use the original look-up table, the settings must get us to the correct channel within the capture range of the locker. For embodiments where tuning requires mechanical motion or significant swings in temperature, hysteresis and charging of MEMs elements tend to shift the look-up table. In some DBR structures, changes in carrier lifetime also may result in a shift in wavelength that exceeds the locker capture range. Possible solutions to these problems involve either some sort of global wavelength monitor, a channel counting algorithm, or some means of updating the look-up tables over life. All of these approaches have been demonstrated, but all require a more complex control system.

Fig. 12 illustrates the control signals necessary to operate the SGDBR/SOA. An electronic circuit supplies control currents in response to amplitude and wavelength errors derived from the locker. The temperature and the current to the gain section are held constant at factory-set values, so they are not part of the control system. All other currents are contained in a look-up table for each channel. The locker signals are converted to error currents for that are added to the SOA and phase sections. The SOA is used to lock the amplitude and the phase section is used to lock the wavelength. In normal operation no corrections are supplied to the mirrors—this is called the "no mirror control" case referred to in Fig. 11. In this mode of operation then, the actual feedback control system is about the same as for the DFB, with the amplitude correction being added to the SOA instead of the DFB gain section and the wavelength correction being added to the phase section instead of the thermoelectric cooler of the DFB. Of course, there is a look-up table to set different initial values for each channel in the SGDBR case, but this involves no dynamic control, just set points.

It may also be seen that the use of an external SOA for amplitude control is desirable in a tunable laser relative to adjusting the gain current in the cavity. This is because the wavelength would also change in response to changing the gain current. In fact, this is one of the primary limitations on wavelength stability in widely-tunable laser embodiments that do not have the external SOA to level the amplitude as the device ages.

For "mirror control" the mirror currents are slowly dithered about their set points and the voltage on the gain section is monitored. Because the wavelength and amplitude locking circuits are operating, there is no change in external optical power or wavelength observed. Second order changes in cavity loss, caused by changing the mirror currents, are also removed in this process. The dithering of the reflectivity peaks of the mirrors cause the gain voltage to change slightly because it monitors the quasi-Fermi level separation in the gain region, and this is proportional to the cavity loss change. Thus, a local minimum in the gain voltage is observed when the mirror peaks are properly aligned with the mode wavelength, where the cavity loss is at a local minimum. The mode, of course, is set by the locker/phase-section feedback circuit to be at the proper ITU grid wavelength. So, it can be seen that this "mirror control" algorithm requires no additional optical elements or electrical connections. Again, this mirror control mode is probably not necessary for reliable device operation according to Fig. 11; however, monitoring of the mirror peaks relative to the cavity mode gives one assurance that the device is operating properly.

If the mirror currents must be corrected, then it may be assumed that the currents required to hit other channels must also change. This is the second aspect of control mentioned

TABLE I
CONTROL PARAMETERS FOR TUNABLE LASERS

Laser	Coarse Wavelength	Fine Wavelength	Amplitude	VOA
DFB Array/SOA	$V_{array}(j)$	T	$I_{gain}(j)$	ΔI_{SOA}
DFB/MEMs	V_{m1}, $V_{m2}(j)$	T	$I_{gain}(j)$	Vm1, $V_{m2}(j)$
SGDBR/SOA	I_{m1}, I_{m2}	I_{ϕ}	I_{SOA}	ΔI_{SOA}
Ext Cavity/ grating	$V_{m\theta}$	V_{mL} or I_{ϕ}	I_{gain}	$V_{mshutter}$
Ext. Cavity/ etalons	T_{et1}, T_{et2}	V_{mL} or I_{ϕ}	I_{gain}	---------
VCSEL/MEMs	V_{m1}	V_{m1}	I_{gain}	---------

above—finding a new channel. In the SGDBR case with mirror control the table can be updated dynamically without ever leaving the original channel. This is because the same reduction in carrier lifetime that requires a current increase to maintain a given carrier density and thus index of refraction, is also experienced by all the other channels. Most importantly, it has been verified that this carrier lifetime decrease is due to an increase in nonradiative recombination, and it is well known that this has a linear relationship to carrier density. Since carrier density is predominately determined by the radiative recombination rate, which depends upon the square of the carrier density, we can assume that the shift in the entire look-up table will be linear in the square root of current. Fortunately, extensive measurements have shown that this is indeed the case experimentally [31], [32], so updating the table is a valid approach in this case.

Table I summarizes the parameters that must be adjusted to enable the amplitude and wavelength of the various types of tunable lasers illustrated in Fig. 5 to be set. It also indicates the parameters for variable-optical-attenuator (VOA) operation. This function is desirable both to allow the user to adjust the amplitude as well as to blank the output during tuning between channels. As can be seen most of the widely-tunable lasers being considered require several parameters to be set, and in most cases, most of these must be controlled. In the VCSEL/MEMs case there are fewer parameters, but this is an example where changing channels requires some sort of global wavelength monitor or channel counting scheme, because one clearly can not depend upon the look-up table for channel selection, especially after some aging with the MEMs mirror. The case is similar in the other mechanically tuned embodiments.

VIII. CONCLUSION

As presented in the tutorial on tunable semiconductor lasers at OFC'03 we have outlined why tunable lasers might be beneficial, discussed basic tuning mechanisms involved in most tunable lasers, given some examples of tunable lasers that have been commercialized, discussed reliability issues, and outlined control techniques. A summary of performance data for the SGDBR type of laser and the monolithically integrated SGDBR with both electroabsorption and Mach-Zehnder modulators was given. It was argued that tunable lasers can reduce operational costs, that full-band tunability is desirable for many applications, that monolithic integration offers the most potential for reducing size, weight, power and cost, and that sufficient reliability for system insertion has been demonstrated, at least in the SGDBR case.

REFERENCES

[1] L. Coldren, "Monolithic tunable diode lasers," *IEEE J. Select. Topics Quantum Electron.*, vol. 6, p. 988, Nov./Dec. 2000.

[2] R.-C. Yu *et al.*, presented at the Proc. APOC'03, Wuhan, China, Sept. 3, 2003.

[3] G. Fish and K. Affolter, "Tunable lasers and their impact on optical networks," presented at the Communications Design Conf., San Jose, CA, Aug. 2002.

[4] D. J. Blumenthal, B. E. Olsson, G. Rossi, T. Dimmick, L. Rau, M. L. Ma'anovic', O. A. Lavrova, R. Doshi, O. Jerphagnon, J. E. Bowers, V. Kaman, L. A. Coldren, and J. Barton, "All-Optical label swapping networks and technologies," *IEEE J. Lightwave Technol., Special Issue Optical Networks*, vol. 18, pp. 2058–2075, Dec. 2000.

[5] M. L. Mašanović, V. Lal, J. S. Barton, E. J. Skogen, L. A. Coldren, and D. J. Blumenthal, "Monolithically integrated Mach-Zehnder interferometer wavelength converter and widely-tunable laser in InP," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 1115–1117, Aug. 2003.

[6] L. A. Coldren, "Widely-tunable chip-scale transmitters and wavelength converters," in *Integrated Photonics Research Tech. Dig.*, Washington, DC, June 2003, Paper IMB-1, pp. 6–8.

[7] A. Carena, M. D. Vaughn, R. Gaudino, M. Shell, and D. J. Blumenthal, "OPERA: An optical packet experimental routing architecture with label swapping capability," *IEEE J. Lightwave Technol., Special Issue Photonic Packet Switching Technologies, Techniques, and Systems*, vol. 16, pp. 2135–2145, Dec. 1998.

[8] M. Duelk, J. Gripp, J. Simsarian, A. Bhardwaj, P. Bernasconi, M. Zirngibl, and O. Laznicka, "Fast packet routing in a 2.5 Tb/s optical switch fabric with 40 Gb/d duobinary signal at 0.8 b/s/Hz spectral efficiency," presented at the OFC 2003, 2003, postdeadline paper PD8-1.

[9] L. A. Coldren and S. W. Corzine, *Diode Lasers and Photonic Integrated Circuits*. New York: Wiley, 1995.

[10] M. C. Amann and J. Buus, *Tunable Laser Diodes*. London: Artech, 1998.

[11] N. Natakeyama, K. Naniwae, K. Kudo, N. Suzuki, S. Sudo, S. Ae, Y. Muroya, K. Yashiki, S. Satoh, T. Morimoto, K. Mori, and T. Sasaki, "Wavelength -Selectable microarray light sources for S-, C-, and L-band WDM systems," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 903–905, 2003.

[12] M. Bouda, M. Matsuda, K. Morito, S. Hara, T. Watanabe, T. Fujii, and Y. Kotaki, "Compact high-power wavelength selectable lasers for WDM applications," in *Proc. OFC 2000*, vol. 1, Mar. 2000, pp. 178–180.

[13] J. Heanue, E. Vail, M. Sherback, and B. Pezeshki, “Widely tunable laser module using DFB array and MEM’s selection with iternal wavelength locker,” in *Proc. OFC 2003*, vol. 1, 2003, pp. 82–83.

[14] D. Anthon, J. D. Brerger, J. Drake, S. Dutta, A. Fennema, J. D. Grade, S. Hrinya, F. Ilkov, H. Jerman, and D. King, “External cavity diode lasers tuned with silicon MEMS,” in *Proc. OFC 2003*, 2002, pp. 97–98.

[15] T. Day. “External-cavity tunable diode lasers for network deployment”. presented at Proc. OFC 2001. [Online]. Available: http://www.newfocus.com/Online_Catalog/Literature/Tunable2.pdf

[16] *Intel Work* [Online]. Available: http://www.commsdesign.com/story/OEG20 030 110S0053

[17] K. J. Knopp, D. Vakhshoori, P. D. Wang, M. Azimi, M. Jiang, P. Chen, Y. Matsui, K. McCallion, A. Baliga, F. Sakhitab, M. Letsch, B. Johnson, R. Huang, A. Jean, B. DeLargy, C. Pinzone, F. Fan, J. Liu, C. Lu, J. Zhou, H. Zhu, and R. Gurjar, “High power MEMs-tunable vertical-cavity surface-emitting lasers,” in *Proc. Advanced Semiconductor Lasers, Dig. LEOS Summer Topical Meet.*, Copper Mountain, CO, July–Aug. 30–1, 2001, pp. 31–32.

[18] C. J. Chang-Hasnain, “Tunable VCSEL’s,” *IEEE J. Select. Topics Quantum Electron.*, vol. 6, pp. 978–987, Nov.–Dec. 2000.

[19] T. L. Koch, U. Koren, and B. I. Miller, “High-performance tunable 1.55 mm InGaAs/InGaAsP multiple-quantum-well distributed-bragg-reflector lasers,” *Appl. Phys. Lett.*, vol. 53, pp. 1036–1038, 1988.

[20] J. E. Johnson, L. J. Ketelsen, D. A. Ackerman, L. Zhang, M. S. Hybertsen, K. G. Glogovsky, C. W. Lentz, W. A. Asous, C. L. Reynolds, J. M. Geary, K. K. Kamath, C. W. Ebert, M. Park, G. J. Przybylek, R. E. Leibenguth, S. L. Broutin, and J. W. Stayt Jr, “Fully stabilized electroabsorption-modulated tunable DBR laser transmitter for long-haul optical communications,” *IEEE J. Select. Topics Quantum Electron.*, vol. 7, pp. 168–177, Mar.–Apr. 2001.

[21] H. Debregeas-Sillard, A. Vuong, F. Delorme, J. David, V. Allard, A. Bodere, O. LeGouezigou, F. Gaborit, J. Rotte, M. Goix, V. Voiroit, and J. Jacquet, “DBR module with 20 mW constant coupled output power, over 16 nm (40×50 GHz spaced channels),” *Photon. Technol. Lett.*, vol. 13, no. 1, pp. 4–6, Jan. 2001.

[22] M. Oberg, S. Nilsson, K. Streubel, J. Wallin, L. Backborn, and T. Klinga, “74 nm wavelength tuning range of an InGaAsP/InP vertical grating assisted codirectional coupler laser with rear sampled grating reflector,” *IEEE Photon. Tech. Lett.*, vol. 5, pp. 735–738, 1993.

[23] B. Broberg, P. J. Rigole, S. Nilsson, L. Andersson, and M. Renlund, “Widely tunable semiconductor lasers,” in *Proc. OFC/IOOC ’99*, vol. 2, Feb. 1999, pp. 137–139.

[24] V. Jayaraman, A. Mathur, L. A. Coldren, and P. D. Dapkus, “Theory, design, and performance of extended tuning range in sampled grating DBR lasers,” *IEEE J. Quantum Electron.*, vol. 29, pp. 1824–1834, June 1993.

[25] B. Mason, J. Barton, G. A. Fish, L. A. Coldren, and S. P. Denbaars, “Design of sampled grating DBR lasers with integrated semiconductor optical amplifiers,” *IEEE Photon. Technol. Lett.*, vol. 12, pp. 762–764, 2000.

[26] Y. Tohmori, Y. Yoshikuni, H. Ishii, F. Kano, T. Tamamura, Y. Kondo, and M. Yamamoto, “Broadrange wavelength-tunable superstructure grating 9SSG) DBR lasers,” *IEEE J. Quantum Electron.*, vol. 29, pp. 1817–1823, 1993.

[27] C. Coldren *et al.*, “Workshop on tunable lasers,” presented at the OFC’03 Proc., Atlanta, GA, Mar. 2003.

[28] 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, and L. A. Coldren, “Widely tunable electroabsorption-modulated sampled-grating DBR laser transmitter,” *IEEE J. Select. Topics Quantum Electron.*, vol. 8, no. 6, pp. 1349–1357, 2002.

[29] T. Wipiejewski, Y. Akulova, G. Fish, P. Koh, C. Show, P. Kozodoy, A. Dahl, M. Larson, M. Mack, T. Strand, C. Coldren, E. Hegblom, S. Penniman, T. Liljeberg, and L. Coldren, “Performance and reliability of widely-tunable laser diodes,” in *Proc. Electronic Components and Technology Conf.*, New Orleans, LA, May 2003, pp. 789–795.

[30] J. S. Barton, E. J. Skogen, M. L. Masanovic, S. P. DenBaars, and L. A. Coldren, “Widely-tunable high-speed transmitters using integrated SGDBR’s and Mach-Zehnder modulators,” *IEEE J. Select. Topics Quantum Electron.*, vol. 9, 2003.

[31] C. Coldren, T. Strand, E. Hegblom, Y. Akulova, G. Fish, M. Larson, and L. Coldren, “Reliability of widely-tunable SGDBR lasers suitable for deployment in agile networks,” in *OFC Tech. Dig.*, Atlanta, GA, Mar. 2003, Paper MF60.

[32] D. A. Ackerman, J. E. Johnson, G. Chu, S. Nee, Z. Liming, E. J. Dean, and L. J.-P. Ketelsen, “Assessment and modeling of aging in electro-absorption distributed bragg reflector lasers,” *IEEE J. Quantum Electron.*, vol. 37, pp. 1382–1387, Nov. 2001.

Larry A. Coldren (S’67–M’72–SM’77–F’82) received the Ph.D.d egree in electrical engineering from Stanford University, Stanford, CA, in 1972.

He is the Fred Kavli Chair of Optoelectronics and Sensors at the University of California, Santa Barbara (UCSB). He is also Chairman and Chief Technology Officer of Agility Communications Inc., Santa Barbara, a company he cofounded in 1998 to develop widely tunable transmitters for wavelength-division multiplexed networks. After 13 years in the research area at Bell Laboratories, he joined UCSB in 1984, where he now holds appointments in Materials and Electrical & Computer Engineering and is Director of the Optoelectronics Technology Center. At UCSB, his efforts have included work on guided-wave and vertical-cavity modulators and lasers as well as the underlying materials growth and fabrication technology. His current work includes the integration of these devices to create novel optical transmitters, receivers, and wavelength converters for optical networking and interonnection. He has authored or coauthored over 500 papers, 5 book chapters, 1 textbook, and has been issued 36 patents.

Prof. Coldren is a Fellow of the Optical Society of America and the Institute of Electrical Engineers (U.K.).

G. A. Fish, photograph and biography not available at the time of publication.

Y. Akulova, photograph and biography not available at the time of publication.

J. S. Barton, photograph and biography not available at the time of publication.

L. Johansson, photograph and biography not available at the time of publication.

C. W. Coldren (S’97–M’00), photograph and biography not available at the time of publication.