INTRODUCTION

In a wavelength-division multiplexed (WDM) network carrying 128 wavelengths of information, we have 128 different lasers giving out these wavelengths of light. Each laser is designed differently in order to give the exact wavelength needed. Even though the lasers are expensive, in case of a breakdown, we should be able to replace it at a moment's notice so that we don't lose any of the capacity that we have invested so much money in. So we keep in stock 128 spare lasers or maybe even 256, just to be prepared for double failures.

What if we have a multifunctional laser for the optical network that could be adapted to replace one of a number of lasers out of the total 128 wavelengths? Think of the money that could be saved, as well as the storage space for the spares. What is needed for this is a “tunable laser,”

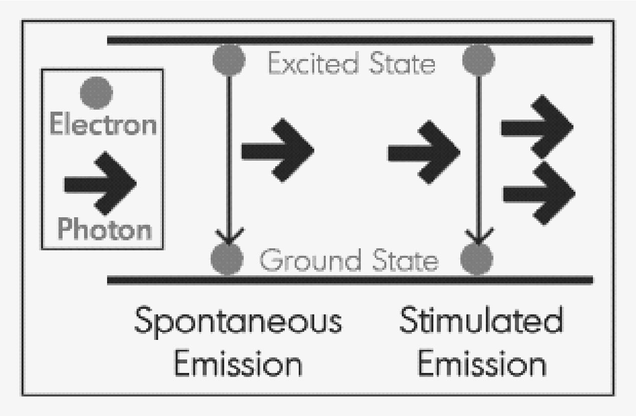
Tunable lasers are still a relatively young technology, but as the number of wavelengths in networks increases so will their importance. Each different wavelength in an optical network will be separated by a multiple of 0.8 nanometers (sometimes referred to as 100GHz spacing. Current commercial products can cover maybe four of these wavelengths at a time. While not the ideal solution, this still cuts your required number of spare lasers down. More advanced solutions hope to be able to cover larger number of wavelengths, and should cut the cost of spares even further.

The devices themselves are still semiconductor-based lasers that operate on similar principles to the basic non-tunable versions. Most designs incorporate some form of grating like those in a distributed feedback laser. These gratings can be altered in order to change the wavelengths they reflect in the laser cavity, usually by running electric current through them, thereby altering their refractive index. The tuning range of such devices can be as high as 40nm, which would cover any of 50 different wavelengths in a 0.8nm wavelength spaced system. Technologies based on vertical cavity surface emitting lasers (VCSELs) incorporate moveable cavity ends that change the length of the cavity and hence the wavelength emitted. Current designs of tunable VCSELs have similar tuning ranges.

LASERS

Lasers are devices giving out intense light at one specific color. The kinds of lasers used in optical networks are tiny devices — usually about the size of a grain of salt. They are little pieces of semiconductor material, specially engineered to give out very precise and intense light. Within the semiconductor material are lots of electrons — negatively charged particles. Not just one or two electrons, but billions and billions of them. Some of these electrons can be in what is known as an "excited" state, meaning that they have more energy than regular electrons. An electron in an excited state can just spontaneously fall down to the regular "ground" state. The ground state has less energy, and so the excited-state electron must give out its extra energy before it can enter the ground state. It gives this energy out in the form of a "photon" — a single particle of light.

In a laser we want lots of light to come out. If we just wait for electrons to spontaneously "decay" from the excited state to the ground state, we are not going to get much light out at all. So what we need to do first is to get lots of electrons into the excited state. To do this we apply an electric current to the laser, which puts lots of electrons up into this excited state (sometimes referred to as "population inversion").

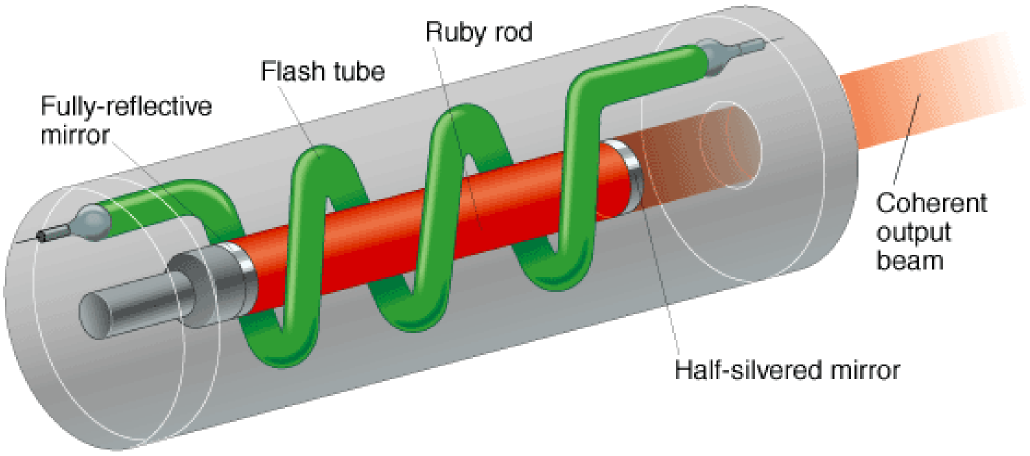


So we now see more and more spontaneous emission of photons caused by electrons decaying from the excited state to the ground state. But this is still not enough light for what we need. We want lots of these electrons to decay at the same time to give lots of light out, and we want this to be happening all the time so that we have a steady stream of light.

We want to catch, or “confine,” the spontaneously emitted photons within the laser. We want them to travel back and forth through the laser time and time again, because these photons can encourage other excited electrons to fall to the ground state and give out more photons. These photons are stimulating emission of further photons, and therefore effectively amplify the light within the device. And all the time an electric current is putting more electrons into the excited state where they wait to fall to the ground state and give out light. Hence we have a LASER — Light Amplification by Stimulated Emission of Radiation (the radiation in this case is light).

Different materials can be used to obtain different wavelengths from the laser. In actual fact, most lasers used in optical networks will operate at wavelengths of around 1300nm or 1550nm, as these are points of minimum loss within optical fibers.

The operation of a ruby laser illustrates the basic lasing principle. When optically "pumped" by light from the flash tube, the ruby rod becomes a gain medium with a huge excess of electrons in high-energy states. As some electrons in the rod spontaneously drop from this high-energy level to a lower ground state, they emit photons that trigger further stimulated emissions. The photons bounce between the mirrors at the ends of the ruby rod, triggering ever more stimulated emissions. Some of the light exits through the half-silvered mirror.



NEED FOR TUNABLE LASERS

Today, single fiber-optic strands carry multiple wavelengths of infrared radiation across entire continents, with each wavelength channel carrying digital data at high bit-rates. Known as wavelength-division multiplexing (WDM), this process greatly expands the capacity of fiber-optic communications systems. Currently, WDM transponders, which include the laser, modulator, receiver, and associated electronics, incorporate fixed lasers operating in the near-infrared spectrum, at around 1550 nm. A 176-wavelength system uses one laser per wavelength, and must store 176 additional transponders as spares to deal with failures. These devices therefore account for a high percentage of total component costs in an optical network.

Tunable lasers offer an alternative. A single tunable laser module can serve as a backup for multiple channels, so that fewer transponders need to be stocked as spares. The result: cost savings and simplification of the entire sparing process, including inventory management. While applications in inventory reduction will drive much of the initial demand for tunable lasers, the real revolution will come when they are applied to make optical networks more flexible.

Fiber-optic networks today are essentially fixed: the optical fibers are connected into pipes with huge capacity but little re-configurability. It is well-nigh impossible to change how that capacity is deployed in real time. Part of the problem is the difficulty of choosing a wavelength for a channel: as traffic is routed through a network, certain wavelengths may be already in use across certain links. Tunable lasers will ease a switch to alternative channels without swapping hardware or reconfiguring network resources.

Tunable lasers can also provide flexibility at multiplexing locations, where wavelengths are added to and dropped from fibers, by letting carriers remotely reconfigure added channels as needed. Such lasers can help carriers more effectively manage wavelengths throughout a network, based on different customer requirements. The benefits gained are a far greater degree of flexibility in provisioning bandwidth and a reduction in the time it takes to actually deliver new services.

TUNABLE LASERS

A laser's wavelength is determined by its optical cavity, or resonator. Like an organ pipe, it resonates at a wavelength determined by two parameters: its length--the distance between the mirrors--and the speed of light within the gain medium that fills the cavity. Accordingly, the wavelength of a semiconductor laser can be varied either by mechanically adjusting the cavity length or by changing the refractive index of the gain medium. The second approach is most easily done by changing the temperature of the medium or injecting current into it.

In 2001, Nortel Networks demonstrated a tunable laser in Atlanta, Georgia. It incorporates an OPTera Metro 5200 with tuning capability remotely managed from a PC workstation. A wavelength meter is used to monitor the wavelength of the laser output in real-time. The laser shown was a Vertical cavity surface emitting laser (VCSEL). The tuning is done electro statically with a cantilevered micro-electromechanical system (MEMS) mirror.

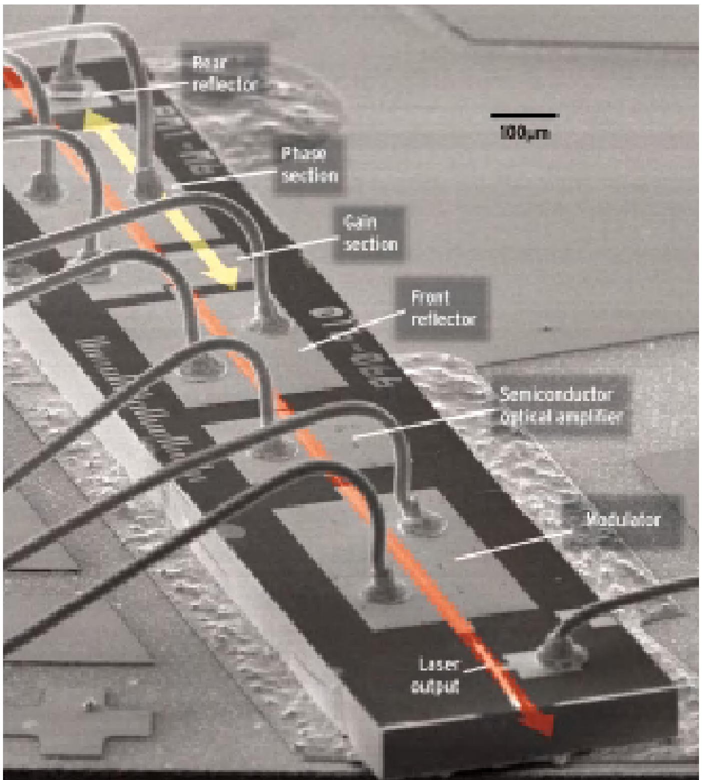
Recently a wide range of tunable lasers have emerged in the 1550-nm region of the infrared for use in WDM optical communication systems. There are basically four types of tunable lasers:

1.) Distributed Feedback (DFB)
2.) Distributed Bragg Reflector Laser (DBR)
3.) External Cavity Laser diode (ECDL)
4.) Vertical-Cavity Surface-Emitting Lasers (VCSEL)

THE DISTRIBUTED FEEDBACK LASER

Among the most common diode lasers used in telecommunications today are distributed feedback (DFB) lasers. They are unique in that they incorporate a diffraction grating directly into the laser chip itself, usually along the length of the active layer (the gain medium). As used in DFB lasers, the grating reflects a single wavelength back into the cavity, forcing a single resonant mode within the laser, and producing a stable, very narrow-bandwidth output.

DFB lasers are tuned by controlling the temperature of the laser diode cavity. Because a large temperature difference is required to tune across only a few nanometers, the tuning range of a single DFB laser cavity is limited to a small range of wavelengths, typically under 5 nm. DFB lasers with wide tuning ranges therefore incorporate multiple laser cavities.



In a variation on the distributed feedback approach, the front and rear reflectors are external to the gain medium. This sampled-grating distributed Bragg reflector device from Agility Communications integrates a tunable laser with a semiconductor optical amplifier and a modulator onto a single chip.

One laser producer, Fujitsu Ltd., Tokyo, has developed a four-channel tunable DFB laser, which has been deployed in operational networks. More recently, the company announced a 22-channel device. The four-channel device has one cavity, which changes of temperature can tune to four standard communications wavelengths spaced 0.8 nm (100 GHz) apart.

THE DISTRIBUTED BRAGG REFLECTOR (DBR)

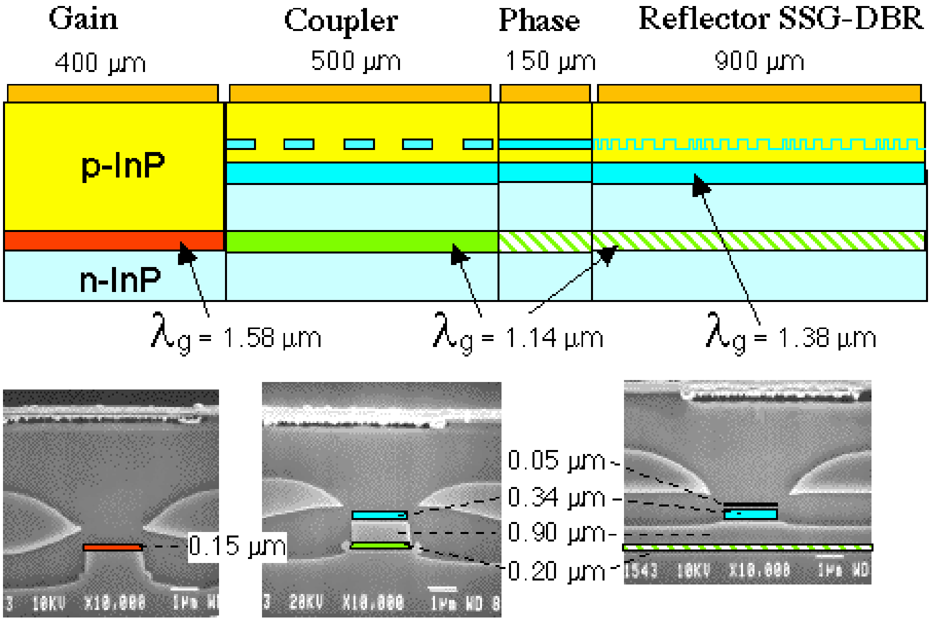
A variation of the DFB laser is the distributed Bragg reflector (DBR) laser. It operates in a similar manner except that the grating, instead of being etched into the gain medium, is positioned outside the active region of the cavity. Lasing occurs between two grating mirrors or between a grating mirror and a cleaved facet of the semiconductor. Tunable DBR lasers are made up of a gain section, a mirror (grating) section, and a phase section, the last of which creates an adjustable phase shift between the gain material and the reflector. Tuning is accomplished by injecting current into the phase and mirror sections, which changes the carrier density in those sections, thereby changing their refractive index.

The tuning range in a standard DBR laser seldom exceeds about 10 nm. But wider tuning ranges can be achieved using a specialized grating, called a sampled grating, which incorporates periodically spaced blank areas. A tunable sampled-grating DBR (SG-DBR), for instance, uses two such gratings with different blank area spacing. During tuning, the gratings are adjusted so that the resonant wavelengths of each grating are matched. The difference in blank spacing of each grating means that only a single wavelength can be tuned at any one time.

Since tuning with this sampled-grating technique is not continuous, the circuitry for controlling the multiple sections is far more complex than for a standard DFB laser. Also, the output power is typically less than 10 mW. On the plus side is the SG-DBR laser's wide tuning range. Agility Communications has announced a 4-mW SG-DBR laser capable of tuning from 1525 to 1565 nm--enough to span 50 channels at the standard channel spacing of 0.8 nm.

Epitaxy and etch technologies permit the realisation of complicated laser structure like the Super Structure Grating Distributed Bragg Reflector (SSG-DBR) laser [1] or Grating assisted co directional Coupler with rear Sampled reflector (GCSR) laser. The last one, only demonstrated in our laboratory, has an unambiguous current control which makes it a promising component.

The GCSR laser is a monolithic widely tunable laser on InP based on a codirectional coupler cascaded with a sampled Bragg reflector. The laser structure is schematically shown and the SEM pictures of the cross section in the different parts of the laser are also shown. The laser is a four-electrode device where three of them are used for tuning the wavelength. The tuning performances are a discontinuous tuning range over 100 nm [2], and full wavelength coverage, i.e. any wavelength can be accessed by a setting the rigth combination of the three tuning currents, over 67 nm [3]. These may give access to a huge bandwidth in fibers, i.e. 12.5 THz, or be used for multiple sensor or measurement applications.



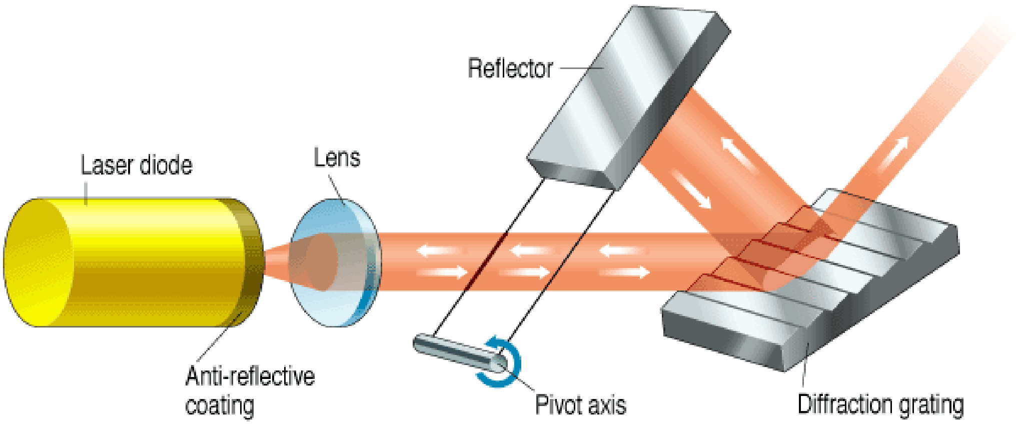
Another variation of the DBR laser is a grating-assisted co-directional coupler with rear sampled reflector. Patented by Altitun, ADC's Swedish acquisition, the structure uses a three-section DBR tunable across 40 channels, from 1529 to 1561 nm.

THE EXTERNAL CAVITY DIODE LASER

It uses a conventional laser chip and one or two mirrors, external to the chip, to reflect light back into the laser cavity. To tune the laser output, a wavelength-selective component, such as a grating or prism, is adjusted in a way that produces the desired wavelength.

This type of tuning involves physically moving the wavelength-selective element. One ECDL implementation, for example, is the Littman-Metcalf external cavity laser, which uses a diffraction grating and a movable reflector. ECDLs can achieve wide tuning ranges (greater than 40 nm), although the tuning speed is fairly low--it can take tens of milliseconds to change wavelengths. External cavity lasers are widely used in optical test and measurement equipment.

A great advantage of this Littman-Metcalf external cavity laser from New Focus is that it is built around a standard, fairly inexpensive, solid-state laser diode. Its external diffraction grating and movable reflector together constitute a variable-wavelength filter, which adjusts the output wavelength. The movable reflector gives the laser both its great advantage and its main weakness--a wide tuning range and a low tuning rate, respectively.



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ECDLs are attractive for some applications because they are capable of very high output powers and extremely narrow spectral widths over a broad range of wavelengths. Whether they will prove cost-effective in telecommunications applications remains to be seen. Still, last year New Focus Inc., in San Jose, Calif., introduced an external cavity diode laser for such applications. The fairly high-power (20-mW) device can tune across 40 nm (50 channels). It includes a wavelength locker, power control, and control electronics.

External cavity lasers with continuous tuning have been traditionally used in optical test and measurement equipment since they provide high power, large tuning range, and narrow line widths with high stability and low noise. Furthermore, they provide continuous tuning through the entire spectrum of the gain medium, where other common laser technologies (like DBR's) exhibit mode hops between stable points in the spectrum. However, ECLs were generally too large, costly, and sensitive to shock and other environmental influences to be used in telecom components.

Recent technological advances, however, have brought ECLs to the forefront of optical networking component technology. In particular, the application of MEMS to optical component designs produces high performance micro-optics that readily fit on standard transmitter cards, and that can be manufactured at competitive costs in the optical networking industry.

THE VERTICAL CAVITY DIODE LASER

The alternative to edge-emitting lasers is the vertical-cavity surface-emitting laser (VCSEL). Rather than incorporating the resonator mirrors at the edges of the device, the mirrors in a VCSEL are located on the top and bottom of the semiconductor material. This setup causes the light to resonate vertically in the laser chip, so that laser light is emitted through the top of the device, rather than through the side. As a result, VCSELs emit much more nearly circular beams than edge-emitting lasers do. What's more, the beams do not diverge as rapidly. These benefits enable VCSELs to be coupled to optical fibers more easily and efficiently.

Since fabricating VCSELs requires only a single process growth phase, manufacturing them is much simpler than producing edge emitters. VCSEL manufacturers can also exploit wafer-stage testing, thus eliminating defective devices early in the manufacturing process, saving time, and improving overall component manufacturing yields. (Edge-emitting lasers cannot be tested until the wafer is separated into individual dice because only then do the light-emitting edges become accessible.) Because of these features, VCSEL chips can be produced far less expensively than edge-emitting lasers.

Unfortunately for VCSEL manufacturers, the dominant cost of a telecommunications laser is not the chip but the package that houses it. According to Tim Day, chief technology officer at New Focus, laser chips themselves account for no more than 30 percent of the cost. Most of the rest goes for the precision-machined hermetic package in which the chips are mounted.

Another plus is that VCSELs need less power and can be directly modulated at relatively high speeds--up to 10 Gb/s. With no need for an external modulator, direct modulation leads to simpler drive circuitry and lower-cost transmitter modules.

While VCSELs outdo the edge-emitters in many respects, they do have a weak spot: their inability to generate a lot of optical power. Because the beam in a VCSEL traverses the thin dimension of the wafer--typically less than 500 µm--it gets to interact with only a thin layer of gain medium, and therefore can build up only a little power. Edge emitters, in contrast, are limited by wafer diameter, usually more than 100 mm across. Thus, today

VCSELs are used mostly in enterprise data communications applications that run at 850 nm. Optical output power for 1550-nm tunable VCSELs is just a fraction of a milliwatt, whereas many of the standard 1550-nm edge-emitting lasers now used in telecommunications deliver 10-20 mW.

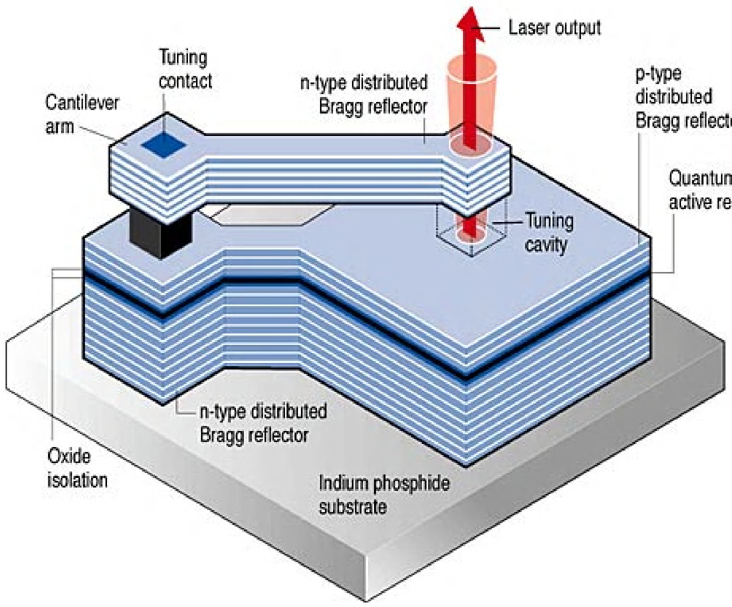
Still, VCSELs operating at 850 nm have proven ideal in short-reach applications--in buildings, say--where low output power is not an issue. Several companies are currently working on commercializing VCSELs at 1310 and 1550 nm for telecommunications networks.

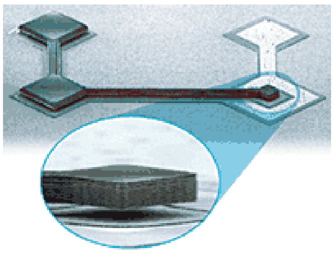
TUNING WITH MICROMECHANICAL ELEMENTS

In tuning VCSELs, the technique used is based on mechanical modification of the laser cavity using micro electro mechanical systems (MEMS) technology. With MEMS, a movable mirror can be fabricated at one end of the laser cavity. This approach enables VCSEL/MEMS devices to achieve a relatively wide tuning range--preliminary specifications from manufacturers quote tuning ranges of 28-32 nm, enough to cover 35-40 channels at the standard 0.8-nm channel spacing.

One concern with using MEMS is that their long-term mechanical reliability has yet to be proved. So before these devices are incorporated into actual telecommunications systems, they must pass stringent reliability testing by Telcordia Technologies Inc., Morristown, N.J. Many tunable laser manufacturers are now involved in these reliability tests, both at their own labs and in trials at networking systems manufacturers.

To boost a VCSEL's optical output power, some manufacturers are including an optical pump source (typically a laser diode at a slightly lower wavelength). Using pump lasers, though, makes the laser module more complex, increases power requirements, and raises costs. The California start-up, Bandwidth9, is currently developing a tunable VCSEL laser using MEMS as the tuning element. But without an optical pump, the laser is capable of producing only 100-200 μW of output power.





Higher output powers are possible. Bandwidth9 claims to have exceeded 1 mW in the laboratory with a device fabricated with an integrated MEMS-based cantilever arm. The arm is used to adjust the length of the laser cavity and thus tune the output wavelength.

THE RELATIVE ADVANTAGES AND DISADVANTAGES OF THE LASER TECHNOLOGIES DISCUSSED.

Laser	**Advantages**	**Disadvantages**	**Market Applications**
DFB	Wavelength stability Established fab process	Low output power Limited tuning range	Narrowly tunable apps
DBR	Fast switching speed Established fab process	Broad linewidth Wavelength instability	Access Switching OADM
SGDBR	Broad tuning range Fast switching speed	Low output power Broad Linewidth Non-continuous tuning	Access Metro Switching OADM
VCSEL	Narrow linewidth (for O/P) Low power consumption Mode stability Circular beam emitted Test at wafer level	Low output power (for E/P) Traditionally confined to short wavelengths (850/1300nm)	Access Metro
Micro-ECL	High power Narrow linewidth Low RIN Continuous tuning Broad tuning range	Switching speed Shock vibration sensitivity	Long haul Ultra long haul Metor OADM switching

TUNABLE LASERS IMPROVE NETWORK EFFICIENCY

Reducing Risk of Human Error

Furthermore, because a tunable line card can be placed in any channel slot, it reduces the opportunity for human error in the manual replacement of line cards. For current generation systems with wavelength-specific multiplexers, placement of fixed wavelength line cards is critical. As an example, if a fixed-wavelength line card for channel 41 is incorrectly placed in the slot designated for channel 14, the optical signal from the transmitter cannot be multiplexed into the system. In contrast, the use of tunable lasers would allow point-and-click control from the central office, reducing the urgency for field maintenance in the event of failure.

Better Use of Expensive Network Bandwidth

Tunable lasers provide an advantage over fixed sources even when service providers employ an alternative “hot-backup” approach to sparing — that is, maintaining idle channels which are only activated when a backup is required. In this application, up to 50% of the system bandwidth can be rendered unusable when using fixed wavelength lasers because network carriers must maintain a spare channel for each wavelength used. With tunable lasers, however, only a small number of line cards are held in reserve slots, since each spare can tune to any required wavelength. Thus tunable lasers can restore usable system bandwidth to 90% or better.

Moreover, in the event of a channel failure, a tunable backup card can be quickly configured to resume communications, providing nearly seamless restoration in the event of malfunction and allowing SONET protection to be implemented entirely in the optical domain. As a further guarantee of service continuity, tunable lasers therefore present additional opportunities for revenue generation.

Flexible Provisioning

Tunability allows carriers to allocate bandwidth on an as-needed, where-needed basis—a capability that is increasingly useful to both network planners and end users. The ability to deliver “flexible provisioning” will simplify the process of planning and forecasting network growth while allowing the optimal utilization of available resources. For example, if incoming data is on a channel already in use along a needed network segment or route, widely tunable lasers can perform a wavelength conversion to an unblocked channel, thus ensuring continuity of service.

Simplified Capacity Planning and Expansion

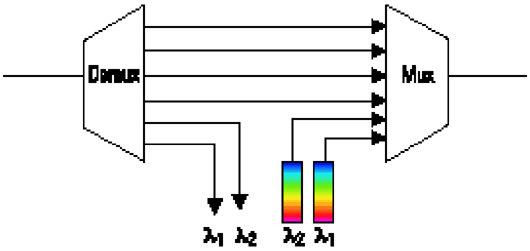
Similarly, as conditions in the rest of the network change, service providers need the flexibility to change wavelength assignments in the network in order to ensure non-locking pathways. If the system relies on fixed-wavelength lasers, then nodes along the route must all be equipped with unique line cards for every possible channel, even though only a limited number will be used at any one time. With tunable lasers in the network, the nodes would only need to be stocked with the number of line cards needed to meet actual demand. This simplifies capacity planning to forecasting overall demand and allocating the appropriate number of needed channels.

Faster, More Responsive Provisioning

Wide tunability also enables service providers to provision new services or capacity as demand changes. For example, the current service model requires that network operators “roll trucks” to provide service for a new customer — sending out technicians to manually reconfigure the network. Each truck roll can cost in excess of $500 per field call. Tunable lasers can reduce this practice to a “point-and-click” operation performed at the central office, thereby reducing activation times to minutes or even less. For service providers, not only are the operational cost savings enormous, but rapid, remote, and flexible provisioning is a value-added service enhancement that provides a significant competitive advantage. Fast provisioning allows them to more effectively manage available bandwidth, thereby increasing network efficiency, improving customer responsiveness, and driving top-line returns.

TUNABLE LASERS ENABLE NEXTG CAPABILITIES

Beyond the ability to address today's problems, tunable lasers will play a central role in allowing service providers to offer entirely new value-added services and generate new revenue streams. Next-generation services and functionality will initially be implemented in a new generation of optical add-drop modules (OADMs) and optical cross-connects (OXCs) that incorporate tunable lasers.



The use of tunable lasers in OADMs allows the device to add any wavelengths into the network.

Current-generation OADMs, which rely on fixed-wavelength lasers, are limited in their ability to add channels to the network. Changing traffic patterns, customer requirements, and new revenue opportunities require greater flexibility than static OADMs can provide, complicating network operations and planning. Incorporating tunable lasers removes this constraint altogether by allowing any channel to be added by the OADM at any time. With the deployment of tunable line cards at OADM sites, sparing and restoration capabilities become more economical as well. Optical cross-connects (OXCs) represent another opportunity for tunable lasers to improve network system efficiency. Line cards with widely tunable lasers covering the full C band enable physical-layer provisioning and switching in the optical domain, allowing an "any channel to any channel" connection to be made at network nodes. Widely tunable lasers simplify simplify OXC planning, since all wavelength channels are available from any tunable line card. Even if a particular channel is already in use, wide tenability allows a flexible, potentially automated determination of wavelength conversion, which further simplifies system planning by complementing and adding value to electrical-level provisioning, grooming, and switching. While today’s networks are large and complex, future networks are expected to be greatly simplified and more purely optical in nature, with significant reductions in both capital and operating costs. One scenario shows a “mesh” architecture in which nodal points on the network are designed to route signals on the basis of wavelength. In this example, tunable lasers can be deployed to route signals to their destination on the basis of wavelength. Tunable lasers will play a key role in these advanced telecom networks, since this type of architecture is unlikely to be fully realized with current-generation fixed-wavelength or even narrowly-tunable lasers.

KEY BENEFITS AND APPLICATIONS OF TUNABLE LASER TECHNOLOGY IN METROPOLITAN NETWORKS

The initial benefit of tunable laser technology is to reduce costly inventory management and sparing associated with fixed wavelength lasers, thereby dramatically reducing operational cost and complexity. With fixed-wavelength lasers the number of channels and types of lasers increases. For every wavelength, the operator would need a spare, which must be wavelength specific. This sparing methodology requires a redundant line card with fixed wavelength source and filters for each working wavelength at each add/drop node. This scheme can amount to high inventory costs per working wavelength for redundancy. Tunable lasers alleviate the need for backup lasers of each specific frequency. The operator would only need one board as backup, which can be tuned to any wavelength that has failed. The replacement of fixed-wavelength lasers by tunable lasers will therefore bring significant inventory and operational savings.

Going forward, when the price of tunable lasers allows operators to replace fixed-wavelength lasers with tunable lasers, this technology will improve network flexibility. With tunable lasers, the traffic can be rerouted to any node based on the dynamic requirements of the metropolitan network, in real time. Tunable laser is a major enabling technology for the "all-optical network," and it does its part toward increasing network efficiency and flexibility, and simplifying the process of service provisioning.

TUNABLE LASER PERFORMANCE REQUIREMENTS

In order to successfully implement next-generation networks, transmitters must offer a range of improved specifications in addition to tunability, including high output power, superior spectral purity, and excellent wavelength stability. These properties will enable network enhancements including higher data rates, higher channel counts (through increased channel density), longer span lengths for long-haul and ultralong-haul networks, greater functionality in the optical domain (thereby fewer expensive optical-to-electrical-to-optical conversions), and increased complexity for metro-area networks (required to handle the increasing demand for bandwidth).

High Power

High-power tunable lasers not only allow longer span distances in long-haul and ultralong- haul systems, but also mitigate the effects of an increasingly complex and therefore “lossy” environment in metro applications by increasing the available power budget. Higher output powers will also support higher data rates (OC-196, OC-768) by making more power available in the data stream. In combination with high power, enhanced spectral purity can reduce system costs by enabling ultralong-haul systems and more complex modulation schemes while reducing the amount of costly regeneration required in the transmission process. Even in metro applications, highpower tunable lasers allow for use of new, less expensive amplifiers, thus helping system providers reduce total system cost.

Spectral Purity / Wavelength Stability

In order to increase capacity economically, some systems developers are using coherent modulation techniques to pack an increasing amount of information onto the fiber. Here it is important that the laser deliver clean, narrow linewidths with high wavelength accuracy and stability, along with excellent spectral purity and high side-mode suppression ratio (SMSR), to allow for increased channel density. (High SMSR significantly reduces cross talk in systems with high channel counts, especially in networks that are based upon periodic multiplexing architectures that lack the input selectivity of fiber-Bragg gratings, thin film, or other narrowband technologies.) Indeed, improved optical performance specifications will provide many distinct advantages for next-generation systems developers.

Tunable laser attributes	**Next-generation network benefits**
High Power	Longer spans (LH & ULH) Higher data rates Increasing network complexity, density
Wide tuning range	Reduce costs in high channel count systems Enable “non-blocking” OXCs Enable fully flexible OADMs Switching
Wavelength locking and stability	Narrow channel spacing (^{2}25 GHz) Coherent communication (side-band transmission) Overall system noise performance
Spectral purity	Higher data rates Coherent communications (side-band transmission) Ultralong-haul transmission

FUTURE OF TUNABLE LASERS

People are logging on to the Internet by the millions, but today's numbers are tiny compared to projections for Internet traffic in just a few years. IDC estimates the number of Internet users will increase from 150 million today to more than 500 million in four years. Those users won't want to hear about huge growth posing major challenges for service providers. They'll expect excellent, no-excuse service for low prices. In this demanding environment, providers must maximize capacity in every part of their networks to deliver more bandwidth for the buck. Fiber-optic networks are now able to carry extremely high capacity, greater than 1 Tbps, on a single fiber thanks to DWDM and ever increasing line rates. Multiple wavelengths, or channels, can now be transmitted over long distances operating at 10 Gbps. While 10 Gbps has become the bit rate of choice, this will soon migrate to 40 Gbps and higher. Since the first DWDM systems were deployed in the mid-1990s, the number of wavelengths supported on a fiber has increased from less than 16 to more than 160. Each wavelength currently requires a dedicated, fixed wavelength laser. This approach is scalable and satisfies the raw demand for bandwidth but does not give service providers the level of flexibility they require in bandwidth allocation and provisioning.

One emerging technology leverages a dual sampled-grating design to achieve ranges of several tens of nanometers from a single waveguide output. Line width and modal purity of these devices can rival the best commercial DFB (distributed feedback) lasers. Some manufacturers are also choosing to integrate high- bit-rate modulators and amplifier functions on the same platform. This drastically reduces the cost and size of a tunable solution to the system vendor. For example, integration of a semiconductor amplifier can increase output power and provide the function of a VOA (variable optical attenuator) to level, or pre-emphasize output power across the band. This means the system vendor does not have to allow additional board space for an external VOA. With a wavelength range of up to 40 nm, these lasers can cover either the full C band or full L-band with support for channels on 50-GHz spacing and high output power.

Because of this market's dynamic nature, providers have very little reliable information about future demand, making accurate forecasts nearly impossible. Yet, the inflexible nature of fixed lasers requires providers to plan networks far in advance and then live with the result, with little or no margin for growth or change.

Tunable lasers are increasingly deployed in networks throughout the world, but they are still relatively new. As a result, manufacturers are going through a learning curve: Tunable lasers have not yet demonstrated the same reliability as fixed wavelength lasers, nor do service providers have many manufacturers from which to choose. Industry watchers are excited about the advent of widely tunable lasers, however, the challenge for vendors will be to overcome the difficulties of manufacturing reliable products in high volume. Demand for tunable lasers is high. RHK forecasts that the optical component market for terrestrial optical networking will exceed $8.6 billion by 2003. Ultimately, demand will drive quality up and prices down. To take full advantage of the dynamic capabilities of widely tunable lasers, providers need to evolve their infrastructure and software systems to change laser channels as needed on the fly. Because such systems are not yet widely deployed, the most common application for tunable lasers today is sparing. However, as organizations deploy widely tunable lasers and systems to support them, fiber-optic networks will fully realize the potential of DWDM, dramatically increasing their ability to handle both metropolitan and long-haul traffic.

CONCLUSION

Recent advances in tunable laser technology have brought the promise of tunable networks into clear focus. Widespread adoption of tunable lasers will not only eliminate logistical and inventory problems and the associated costs that result from fixed-wavelength line cards— but will also enable novel network architectures with dynamic functionality such as dynamic add-drop, thus enabling new value-added services and creating new sources of top-line revenue for system providers.

Will tunable lasers revolutionize optical networks? With many of the technologies just now becoming commercially available, it is still too early to say. What is evident is that tunable lasers can dramatically improve network efficiency and will play an important role in enabling future dynamically reconfigurable optical networks, along with optical switches and semiconductor optical amplifiers. One recent advance especially worth keeping an eye on is the work done by some manufacturers in integrating laser diodes with other functional elements, such as the wavelength locker, modulators, and optical amplifiers--all on a single chip.