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The Tunable Telecosm

Once Avanex's thousands of lambdas can be muxed onto a single fiber, the active devices of the lambdasphere will come into New Focus

On the Forum, in the GTR, in my books, and on the road, for the last decade I have been celebrating the lightwave or "lambda" network—a circuit switched system as simple and robust and enduring for multimedia communications as the public switched telephone network has been for voice. Essential to fulfill the dreams and business plans of Internet entrepreneurs, such a broadband bonanza can spur the economy out of its current doldrums. Enabled by Wavelength Division Multiplexing (WDM) many colors of infrared light on each fiber thread, this new lambdasphere can both fuel and fund a multi-trillion dollar agenda for thousands of vendors of optical equipment over the next decade. Leaders will be **Avanex** (AVNX), **Nortel** (NT), **JDS Uniphase** (JDSU), and **Corning** (GLW), but they will be joined by several other contenders in a new industry of mass produced components.

Creating end-to-end connections, the network would link the world over myriad colors of light in much the way that the voice network connected billions of customers over analog carriers on myriad copper wires. First introduced to me in the late 1980s by Will Hicks, the co-inventor of single mode fiber, the concept of the lambda based network—with every terminal eventually bearing a wavelength address—provided an ultimate standard by which to gauge progress in the industry.

For most of the decade, however, this vision remained in the shadows of an awesome campaign by the fiber optics industry for ever expanded bandwidth, measured first in megabits, then in gigabits, and now in terabits per second, first over tens, then over hundreds, and now over thousands of kilometers. Focusing on point-to-point connections, mostly in the backbone trunks of the system, this drive has succeeded beyond all expectations. As I have often pointed out, the industry now knows how to put not terabits but petabits (ten to the 15th or thousands of millions of millions of bits per second) on a single fiber cable. This capacity per *second* is close to the total of Internet traffic per *month* in recent years (some estimates show a petabyte per month in 1999).

To achieve the petabit per second cable, Nortel proposes next year to put 80 gigabits per second on 80 wavelengths or 6.4 terabits per second on a single fiber. With an easily manageable 150 fiber cable (**Metromedia Fiber** (MFNX) is deploying 864 fiber cables in 69 cities), the petabit per second flood in a single optical

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sheath draws ever nearer. Still required will be much heroic engineering and much capital investment. But the conceptual problems of putting petabits on a single network path are all understood.

Today the key issue is not bandwidth but connectivity. Putting petabits on the fiber is practical; measured by the bit, it is even cheap. But getting the bits off the fiber is often a prohibitive goal. My home in the Berkshires is just three miles from the Massachusetts Turnpike, along which run terabits per second of potential bandwidth from **Global Crossing** (GX), **Williams** (WCG), **Qwest** (Q), **360 Networks** (TSIX) and **WorldCom** (WCOM), all Telecosm companies or contenders. But as far as I am concerned the bandwidth might as well be on the moon. At home, indeed, I get my downstream bits from the Telecosm Lounge on the Forum through a fitful link to a DirecPC satellite that functions essentially like a simulated moon, in orbit some 23,600 miles above the earth.

The potential tunable laser winners can be separated from the likely losers by the filter of manufacturability and scalability

What can fulfill the promise of the fibersphere and save the scores of thousands of broadband Internet business plans is not the endowment of yet more petabits per second but the enablement of the lambda network. The defining test of telecosmic technology is now the total number of lambda addresses or ports or lightpaths. Setting the pace in putting lambdas on a fiber and taking them off has been Simon Cao's Avanex technology (GTR, April 2000 and October 2000), which supplies the passive side of the lambdasphere. But once hundreds and then thousands of wavelengths can be multiplexed (muxed) onto a single fiber optic thread and then demuxed off it at the other end, the active devices of the lambdasphere will come to the fore. We will need a tunable telecom with wavelengths alterable or convertible into other wavelengths. In optics and electronics, the key to tunability is *resonance*—the defining characteristic of circuits that show a sharp peak of output or gain at a particular frequency.

Green's broadcast network

The most familiar method of tunability is the dial on an ordinary radio receiver. Employing a system called broadcast and select, radio stations each broadcast in an assigned band of electromagnetic frequencies. The radio's antenna picks up all frequencies. The receiver rotates a point of resonance (where capacitance and inductance cancel out) through its entire range until it reaches the desired radio signal. At the resonant frequency band, the chosen channel or "station" then resonates and "comes in." Similar techniques appear in broadcast television, both over cable or the air.

The early proponents of all optical networks, led by Paul Green of IBM who wrote the initial text and created the first commercial network, envisaged broadcast and select as the most promising optical topology. Each transmitter would employ a different lambda and at the other end users would tune their photo-detector receivers to a desired wavelength station. An optical filter would invoke resonant tuning by altering the distance between mirrors in a cavity and thus the wavelength that is amplified. Called a Fabry-Perot interferometer, the coupled mirrors play the role of the tunable resonator in an ordinary radio receiver.

This system foundered, however, on a crucial difference between electronic technology and fiber optics. Most electronic circuits work by dividing voltages without depleting them. The ability of a voltage or electrical field to be divided as often as needed through an electronic tree and branch topology without reducing power is the basis for the phenomenon of fanout, crucial in computing and broadcast technology. Divide a photonic signal, however, and it loses power proportionately. Attenuation is a fundamental reality of optics. The process of broadcasting photons through a fiber optic tree to very many terminals yields a signal too weak to be received. The broadcast and select model thus was doomed by the fundamental physics of photons.

What photonics takes away with one hand, however, it gives back abundantly with the other. While divergence fails, convergence thrives. Although broadcast and select was impractical, an amazing bounty of wavelength circuits is possible on a single fiber. As Simon Cao of Avanex proposes, many thousands of different frequencies can be merged in one fiber and separated passively at the other end. But to achieve this goal flexibly and efficiently requires tunable lasers. If the sender of a message finds a particular lightpath blocked by another user, he must be able to use a remaining open lightpath. In a national network, scaled down to the campus and the neigborhood, this means an astronomical number of tunable lasers. One interpretation of Cao's Law projects that the number of lambdas needed in the network rises in proportion to the product of bandwidth of each terminal and the square of the number of terminals.

Today the dominant lasers used to transmit signals down fiber optic lines are "fixed." They can only emit a single frequency band. If the user wants to shift to another, he must invoke a different laser permanently tuned to another lightpath. Over the last year, however, scores of companies have emerged to pursue the dream of a laser that can be tuned over an increasingly wide band of potential "colors" of infrared light. They are using a baffling diversity of tunable technologies. But the potential winners can be simply separated from the likely losers by the filter of manufacturability and scalability.

Enabling the advances of WDM bandwidth, the optical components business today consists of a medley of specialized crafts performed by skilled manual workers in white cleanroom apparel hunched over complex manually operated gear, contriving intricate combinations of discrete devices and fiber "pigtails," with custom assembly, packaging, and cooling. In Clayton Christensen's useful model, this labor intensive craft is characteristic of an "undershoot" industry—an industry that cannot supply the cheap high performance modules that customers demand as they upgrade their backbones from 2.5 gigabits per second per wavelength to 10 gigabits per second, and now to 40 and 80 gigabits per second. In an undershoot industry, every interface and every component must be optimized and systems must be vertically integrated. Hence, after **Ciena** (CIEN) pioneered the technology in 1996, large systems houses such as Nortel, Corning, **Alcatel** (ALA), and **Lucent** (LU) have dominated long-haul WDM, and when **Corvis** (CORV) entered the fray, it was with a completely integrated proprietary system.

Cisco's thicket

While this approach made WDM possible and prosperous, it also restricted the technology to point-to-point long-haul applications with relatively low unit requirements. Fabulous feats of terabit transmission over thousands of kilometers ended in opto-electronic bogs and metro mazes on the edge. Bandwidth mounts at a pace three times Moore's Law. But connectivity counts, and it actually shrinks as backbone bit rates rise by tens of gigabits per second per year. The WDM network becomes an ever more costly and costive labyrinth. Messages must scale seven layers of analog to digital, optical to electronic, and telco to Internet conversions accomplished in giant **Juniper** (JNPR) and **Avici** (AVCI) routers and **Tellabs** (TLAB) SONET add drop multiplexers, and **Lucent** (LU) 5ESS central office switches and **Cisco** (CSCO) computer network hubs and **EMC** (EMC) storage area channels that present a polyglot tangle of physical signals, protocol changes, framing schemes, data codes, and file layouts.

For this switchy thicket, Simon Cao would substitute the ideal of the switchless network, in which devices on the edges transmit data on prescribed wavelength paths. Cao estimates that 250 thousand lambdas can sustain a national network comprising four all optical islands—with switches only between the islands—that can supply 20 million users with gigabit per second connections. **Telenor** in Norway and **Sprint** (FON) in the U.S. have tested the essential configuration of such a network. Transmitters on the edge program lasers to define their paths across the web by selecting particular wavelength routes. Identified by its lambda, the signal goes directly to its final destination without any processing, switching, or reconfiguration at the intermediate nodes. Tunable lasers and receiver terminals collaborate to open an end-to-end circuit across the network for the duration of the call.

This topology is far simpler and cheaper than the complex long-haul systems that are currently the stars of the WDM firmament. Likely to prevail first in metro and campus deployments, switchless channels relax the constraints of high port count optical cross-connects, superfast routers, signal regenerators, Raman amplifiers, soliton super streams, dispersion compensators, and other high end equipment that has made the all optical network practical in the core of the fibersphere but impractical everywhere else.

Avanex's multi-lambda multiplexers and demultiplexers that put the bits on the fiber and take them off are obviously crucial parts of the mostly switchless lambdasphere. But to create a network will also require millions of cheap tunable lasers. These active devices must command closely coupled or integrated modulators that inscribe the message on the carrier frequency. The lasers must have wavelength lockers consisting of filters with feedback loops that keep the signal on its frequency target. All these devices must be manufactured in large enough volumes so that the price can be cheap. Thus the emergence of this new topology can lay the foundations for a new industry of mass produced and prudently integrated photonic devices.

An old-timer on the growing list of tunable laser companies, ADC Altitun was the first to ship tunable transmission lasers commercially

Tunable lasers are the future. Perhaps Jozef Straus of JDSU occasionally dreams of supplying single-frequency lasers to source thousands of lambdas per fiber, hundreds of fibers per cable, at add/drops across the Telecosm. But even JDSU might get lost in the manufacturing maze. Faced with burdensome stock and maintenance challenges, fiber-optic networks aspire to a different model. Replace a thousand WDM source lasers per fiber with one or several tunable lasers and you reduce transmission complexity a million-fold. You also break free of the straightjacket of a fixed and limited photon palette.

According to CIBC, "an OC-192 WDM transmission board may conservatively cost $50,000-plus per fixed wavelength." Lighting 320 lambdas on two fibers, Williams will be saddled with a $32 million inventory to back-up each wavelength in use in addition to the $32 million plus for the operating lasers. With a tunable laser module, only one or several transmission boards need be kept in inventory as spares.

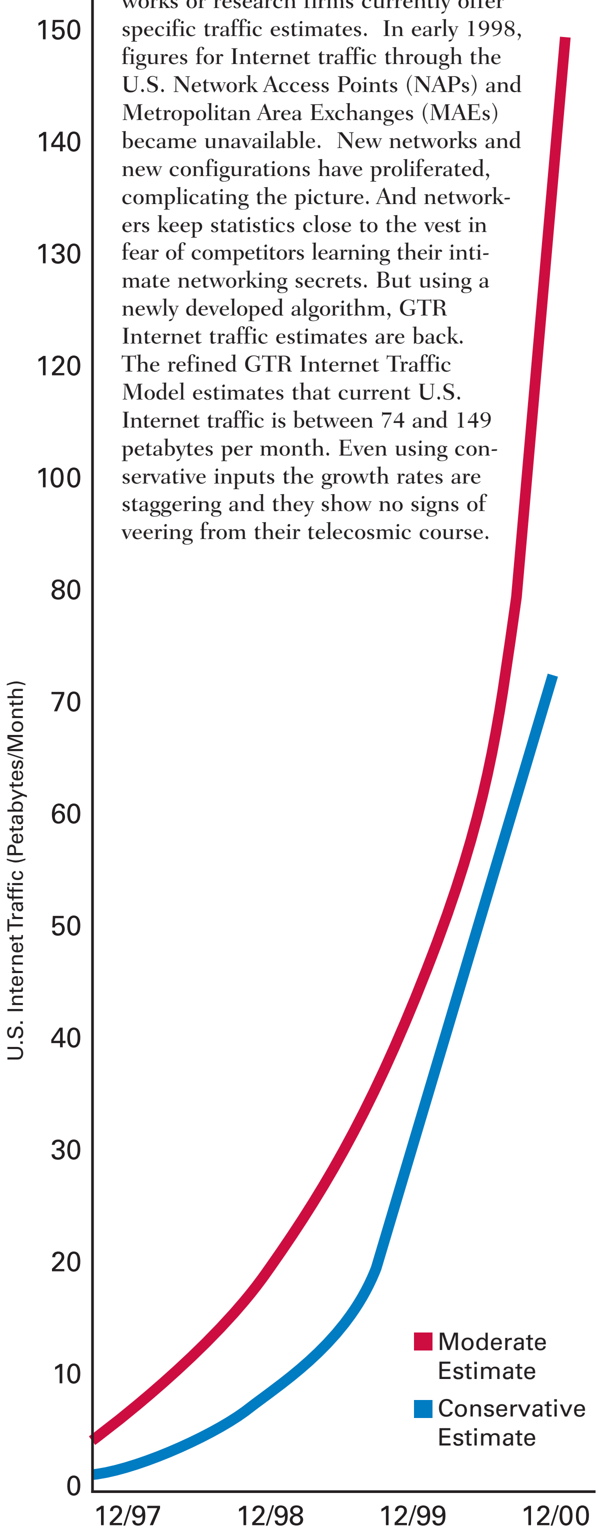
But more important than inventory costs, tunable lasers come with the promise of remote lambda provisioning, optical layer restoration, all-optical lambda conversion and regeneration, and massive scalability. Rising channel counts pose little challenge to light sources which can be tuned to any lambda. Amid these benefits, connectivity emerges as the most important. Connectivity challenged, fixed-wavelength lasers blindly mount photons one after another onto the same WDM lane, relying on a complex, intelligent network to switch them to their destinations.

WDM transmission requires a single mode, or wavelength orientation. The most popular single frequency transmission source is a distributed feedback (DFB) laser using an interferometric grating loop to select a desired wavelength. A Bragg grating, which replaces the mirrors at the cavity ends, reflects only a narrow spectral slice or "window" of light back into the laser. The distance between the lines of the grating (the Bragg grating period) and the refractive index of the cavity which governs the speed of the light in it, determine the center frequency of this window.

Amid a list of imposing technology titles, such as "Grating-assisted Co-directional Coupler with Sampled Reflector" made by **ADC Altitun** (ADCT), and a slew of big

U.S. Internet Traffic Estimates

UUNET estimates that Internet traffic doubles roughly every 4 months. AT&T's estimates are one-third that with traffic doubling only once a year. But few networks or research firms currently offer specific traffic estimates. In early 1998, figures for Internet traffic through the U.S. Network Access Points (NAPs) and Metropolitan Area Exchanges (MAEs) became unavailable. New networks and new configurations have proliferated, complicating the picture. And networkers keep statistics close to the vest in fear of competitors learning their intimate networking secrets. But using a newly developed algorithm, GTR Internet traffic estimates are back. The refined GTR Internet Traffic Model estimates that current U.S. Internet traffic is between 74 and 149 petabytes per month. Even using conservative inputs the growth rates are staggering and they show no signs of veering from their telecosmic course.



Source: Gilder Publishing, LLC

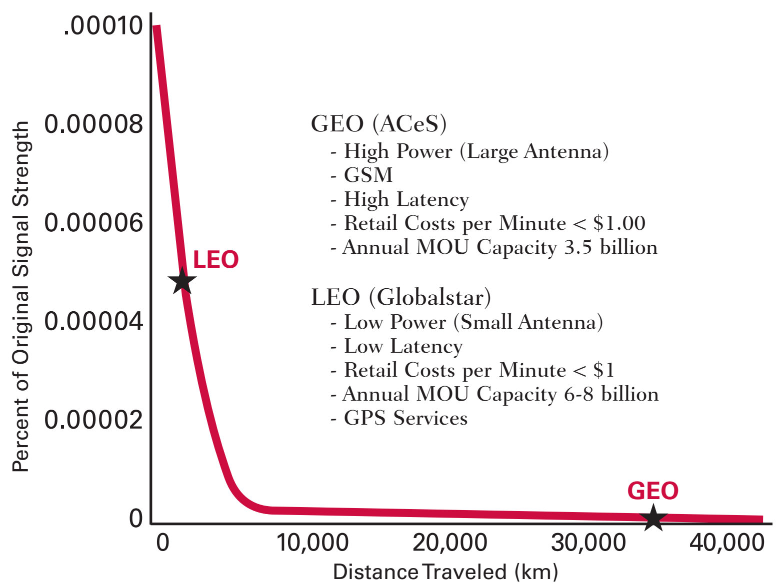
The Birth of a New Industry

Type of Laser		Vendor	Approx. Tuning Range	Approx. Power Out
DFB		Lucent, JDS Uniphase, Fijitsu, CoreTek (Nortel), QDI	15 nm	10 mW
DBR	DBR	Broad Tuning Range NTT Optoelectronics, Alcatel, Marconi (Caswell) Narrow Tuning Range Lucent, JDS Uniphase, Multiplex	Broad Tuning Range >40 nm (large five compartment device) Narrow Tuning Range 10-24 nm	Broad Tuning Range >10 mW Narrow Tuning Range 20 mW
	GCSR	Altitun (ADC)	10 nm . . . . . 40 nm (C-band) .	. . . .2 mW . . . 10 mW
	SG-DBR	Agility	37 nm (C-band)	4 mW
External Cavity		New Focus, iolon	Any transmission band	20 mW
VCSEL	MEMs-OP VCSEL	CoreTek (Nortel)	50 nm (C, L and S-band)	2 mW→10 mW
	MEMs-EP VCSEL	Bandwidth9	>40 nm (C and L-band)	0.45 mW 5 mW (with EDFA)

"→" *approaching value indicated,* "<" less than, ">" greater than

DFB (Distributed Feedback Laser)
DBR (Distributed Bragg Reflector Laser)
SG-DBR (Sampled Grating-DBR)
GCSR (Grating Coupled Sampled Reflector)

LEO vs. GEO



Source: Gilder Publishing, LLC, ING Barings

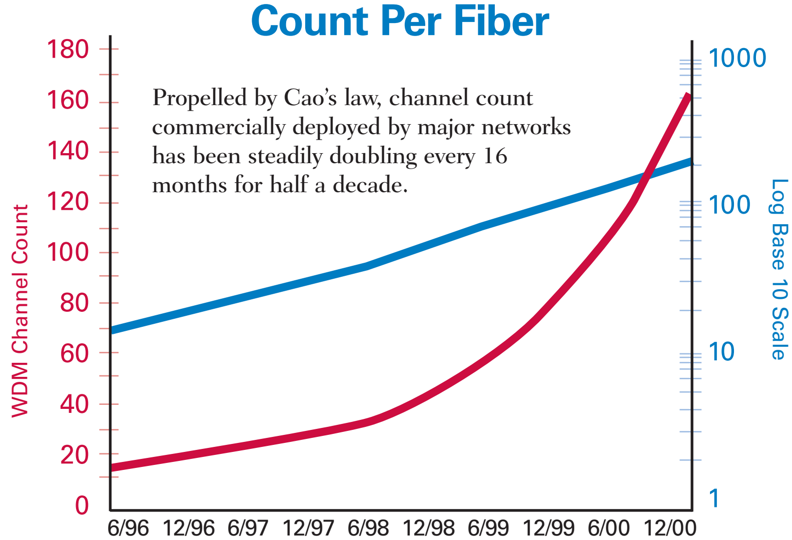
Tunable Transmission Lasers

ewidth	Tuning Time	λ Stability (+/-)	Pump Mechanism	Tuning Technique
MHz	>10 ms	1 GHz	Electrical	Thermal
d Tuning ange MHz arrow ng Range MHz	<10 ns (NTT) 1ms	3 GHz	Electrical	Electrical
MHz	<50 ms	3 GHz	Electrical	Electrical
GHz	<10 ms	3 GHz	Electrical	Electrical
MHz	15 ms	2.5 GHz (New Focus) iolon (n/a)	Electrical	Mechanical MEMS (iolon)
MHz	10 ms	2.5–3 GHz	Optical	MEMS
0 MHz	n/a	n/a	Electrical	MEMS

VCEL (Vertical Cavity Surface Laser)
MEMS-OP (Optically Pumped Micro Machines)
MEMS-EP (Electrically Pumped Micro Machines)

Source: Gilder Publishing, LLC

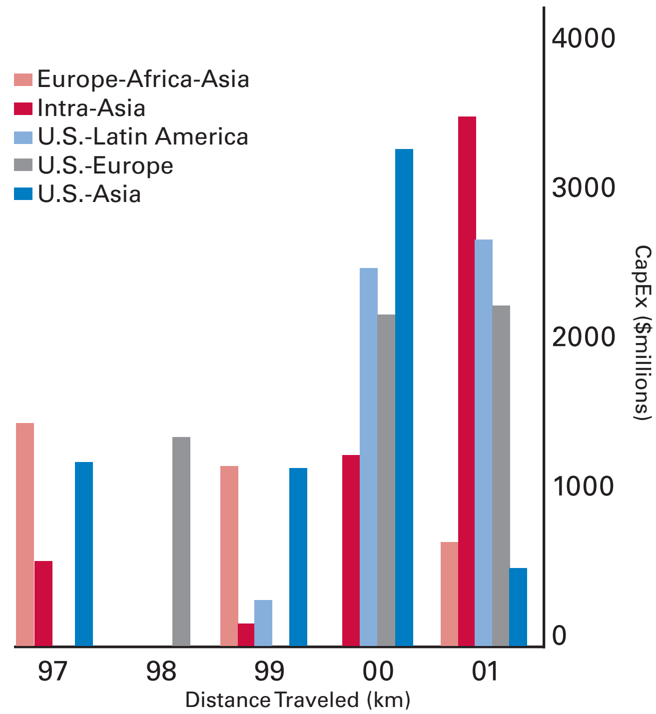
Maximum WDM Channel Count Per Fiber



Source: Gilder Publishing, LLC

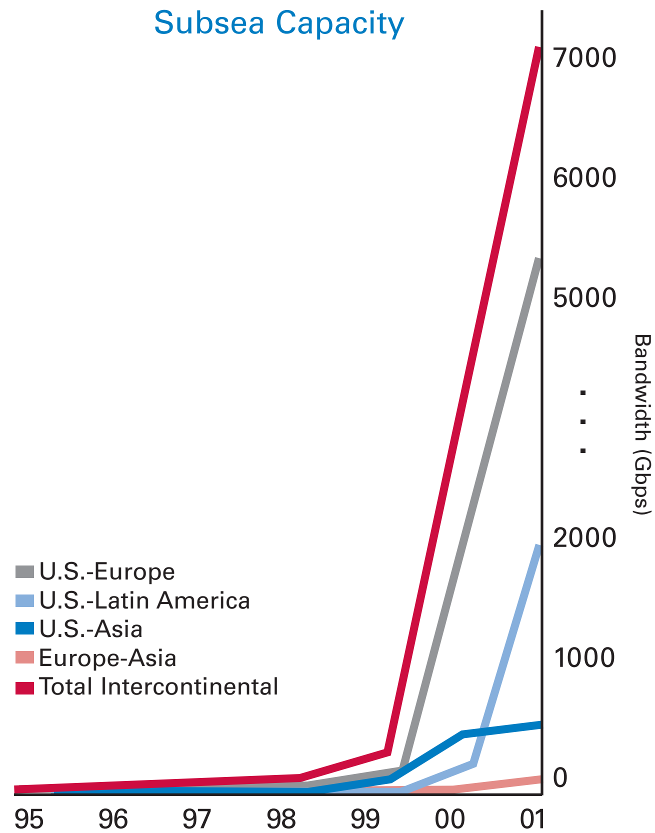
Undersea Update

Subsea CapEx



Source: Telegeography

Subsea Capacity



Source: Telegeography

and small companies such as JDSU, Lucent Microelectronics, and **Agility Communications**, there is an amazing variety of DBR tuning ranges (8–40 nm), power outputs (1–30 mW), tuning speeds (nanoseconds to milliseconds), and stages of development.

Bragging rights

An old-timer on the growing list of tunable laser companies, ADC Altitun was the first to ship tunable transmission lasers commercially. Founded in Stockholm in 1997 and recently purchased by ADC, Altitun offers a 4-stage GCSR that tunes between 1528 and 1565 nm, a 37 nm range that matches the gain bandwidth of the typical Erbium Doped Fiber Amplifiers in every optical network. The 2 mm long dual waveguide laser includes an InGaAsP (indium gallium arsenide phosphide) gain section to generate optical power, a waveguide coupler for coarse tuning, a phase section for fine-tuning, and a Bragg section with multiple grating sets.

Altitun CTO Rob Plastow told us last month in Charleston that demand for his tunable lasers continues to outstrip his increasing ability to produce them, even as competitors begin to introduce commercial products. He also forecasts price decreases as production volume ramps.

Also in Charleston, Greg Fish, chief development engineer and co-founder of Santa Barbara-based Agility Communications, brashly claimed that his 5-section DBR lasers will be "easy" to manufacture, robust, reliable, and so inexpensive that they will successfully compete with fixed wavelength lasers. Packaging semiconductor tunable lasers—providing fiber connections and wiring them up to control systems—is challenging and time consuming. So it remains to be seen if Agility's sampled grating (SG) device with two grating sections, a phase section, and a semiconductor amplifier section in addition to the gain block can meet Fish's expectations. Though complex, this SG-DBR laser calls for fewer manufacturing steps than rival Altitun's 2-stage GCSR which may require 2 to 3 times the number of etch and regrowth processes.

The beauty of New Focus's EXO-laser is free-space optics, as in Simon Cao's PowerMux

Agility claims for itself another plus—the ability to integrate other devices on its SG-DBR substrate. In the works is a chip that combines its laser, which pumps out light continuously, with a modulator, saving the cost of separate modulators which run about $1,500 apiece. An integrated wavelength locker is also planned. Lockers are critical elements in laser technology, necessary to stabilize the center frequency and keep it from drifting off the mark. As WDM channels squeeze closer together, locking needs to be more precise. At 100 GHz channel spacing, lambdas need to lock to within +/-5 GHz of the true center frequency; the 25 GHz spacing required for more than 40 channels demands a +/-1 GHz lock, the limit of today's commercial locking technology.

The proof will come in manufacturing yield, and the next year or two should separate the giants from the pygmies among tunable-DBR rivals. But in the long run, both of these now dominant architectures—the DFB and DBR—are likely to founder on their ever increasing complexity. Neither seems likely to survive the filter of mass manufacturability.

A better way to tune semiconductor lasers, propounded by **New Focus** (NUFO), our Telecosm company of the month, is to move the tuning structure outside the chip and create an external, free-space tuning cavity. EXOs, external cavity lasers, often include several MEMS or other small mechanical filters for tuning. To tune this basic EXO, you simply rotate the grating which changes the tilt angle and hence the grating period, thereby reflecting a different slice of frequencies back to the laser cavity.

The Telecosm's new focus

EXO tunable laser technology is well understood and is widely used in the demanding laboratory and test and measurement environment because of its high power (the simple filtering wastes little power from the laser), large tuning range, and narrow linewidths with high stability and low noise. Just as important, *it is possible to tune continuously throughout the laser's entire gain spectrum,* unlike the common Distributed Bragg Reflector lasers which must settle for mode hops between zones of stability.

The beauty of EXO-laser free-space optics, as in Simon Cao's PowerMux, is freedom from environmental dependence (wavelength stabilization accomplished without thermal tuning) and relative ease of manufacturing when compared to the testing and production challenges of multisectional DBR lasers. The standard Fabry-Perot diode laser used in an EXO requires no additional sections and gratings. Concerns about age in an EXO are limited to the laser, since the grating and mirror always tune to the same frequencies at given angles.

The key trait that has confined EXOs to laboratory use until now is their size: too large to fit on a standard telecommunications transmitter card. That may be about to change. New Focus, a veteran and leading commercial supplier of high-performance laboratory EXOs, claims its new tunable EXOs, due out early next year, will fit on standard transmitter cards. With an internal wavelocking filter, New Focus also plans to take advantage of EXOs' natural ability to tune stably over the entire current fiber band without temperature controls.

Based on a radical new cavity design, New Focus's single mode EXOs currently emit at 10 mW and the company projects 20 mW power for its next generation product which should approach the cost of a similar fixed DFB laser in 2001. In the backbone, where performance is more important than cost, New Focus could well have the most promising tunable laser technology. If they pass through the manufacturability filter, they could capture much of the industry.

Two small startups lacking the experience of New Focus and still in semi–stealth mode are nonetheless trying to give New Focus a run for its money. Later this year, **iolon** of San Jose plans to offer beta samples of an external cavity tunable laser based on MEMS with a tuning range greater than 40 nm and output power up to 20 mW using a "standard" F-P laser source. iolon is also developing an integrated wavelength locker.

Zia is a startup founded in May by four researchers affiliated with the University of New Mexico. It expects product samples in the next few months of tunable lasers that will cover 1400 to 1650 nm with a uniquely low threshold current that eliminates heat problems. Their secret is *quantum dots,* tiny particles of semiconductor, typically 100 atoms across, embedded in a host material (another semiconductor). When an electric current is applied to this arrangement, light is thrown out—and the wavelength of this light depends on the precise size of the particles.

Recently having tuned across 1000 to 1200 nm, Zia faces a challenge moving to 1500 nm for WDM long-haul and even most metro systems.

Going vertical

In contrast to all these edge emitting lasers (EELs), the other major tunable source technology, VCSELs (vertical-cavity surface-emitting lasers), resonate light vertically between mirrors above and below the junction. Light escapes from a round opening on the top surface of the wafer. The beam retains its nice circular shape and does not diffract as much as an EEL beam. This makes it more effective in coupling light to a fiber.

The success of the VCSEL's alternative semiconductor laser design depends heavily on the effectiveness of its mirrors. These multilayered structures reflect light based on changes in the refractive index. The strength of the reflection depends not only on the number of layers but also on the absolute value of the refractive index change between layers.

That's why VCSELs have traditionally been confined to short wavelengths. It happens that Gallium Arsenide (GaAs) semiconductor materials (with an intrinsic "band gap" suitable for lambdas under 1000 nm) make much better multilayer mirrors than Indium Phosphide (InP) based compounds which emit light with longer wavelengths above 1000 nm. Since the junction and the surrounding substrates must be chemically compatible to be grown on top of each other, VCSEL can most readily be composed of GaAlAs which lases between 780 nm and 850 nm.

A second challenge is power. Low-powered VCSELs are fine for sourcing LANS at 810 nm. But as you move to 1310 nm and 1550 nm you migrate from the LAN to the MAN to the WAN, where low-gain InGaAsP becomes power-challenged in a short electrically pumped VCSEL cavity.

What makes VCSELs attractive as a tunable source is that they emit narrow linewidths, they consume little power for higher reliability, and, importantly, lase at only one mode because of their short cavity length and hence, ensure mode-hop-free, continuous tunability. By making the top mirror a MEMS device, VCSELs can be tuned over a range of 50 nm to potentially 100 nm by simply changing the cavity length.

Bandwidth9 battles CoreTek

Both **CoreTek** (Nortel) and startup **Bandwidth9** are going down this tunable MEMS route. CoreTek expects to have products to show customers a few months before Bandwidth9. They have also been working with VCSEL technology much longer. But to achieve up to 10 mW of power in the future, which may not be enough, CoreTek uses a 1310 nm pump laser. This builds all the complexity and expense of complex semiconductor pumps into the CoreTek VCSEL.

For real products, revenues, and earnings, and for the simplest manufacturable devices, New Focus is the winner in tunable lasers

Bandwidth9, on the other hand, dismisses the idea that VCSELs can be used in the backbone, and instead hopes to harness their inherent cost advantages by sticking with electrical pumping and shooting for LAN and MAN applications where cost is paramount. Indeed, they believe they have improved on process efficiencies with a proprietary innovation that enables them to manufacture their VCSELs using a one-step epitaxial growth process. This apparent breakthrough would eliminate the tricky step of bonding the top mirror to the laser cavity. Going further on the integration front, Bandwidth9 recently acquired **Verifiber Technologies** in order to make complete transmission modules incorporating its lasers.

Well, what about power? Bandwidth9 recently sent 2.5 Gbps signals successfully down 50 km of singlemode fiber—enough reach for most metro applications—with a source power of .45 mW. New Focus informs us that MAN networkers believe power will *become* important there in an all-optical environment because of the tremendous loss due to Optical Add Drop Muxes and switches. So Bandwidth9 may be confined to the LAN and WAN edge, where they may have a huge market.

For real products, revenues, and earnings, and for the simplest most manufacturable devices, however, we choose New Focus as the obvious winner in tunable lasers. While rivals are facing the challenges of WDM by adding new stages and complexities, New Focus is moving ahead by simplifying their lasers, eliminating the moving parts and exploiting the bandwidth and power of the simple Fabry Perot model. From the beginning Fabry Perot etalons—two facing mirrors that manipulate interference effects—have offered the widest tunability and simplest structure for a laser. But the technology has always been disparaged as too slow. Switching speed, though, is otiose in the lambdasphere, where lightwave circuits are opened across the web and maintained for the duration of the call. While rivals distract themselves with tuning speed, New Focus offers enough power for a long-haul laser and a virtually unlimited tuning range. New Focus offers a powerful complement to Avanex and joins the Telecosm list.

George Gilder with Charles Burger
December 4, 2000

TELECOSM TECHNOLOGIES

ASCENDANT TECHNOLOGY	COMPANY (SYMBOL)	REFERENCE DATE	/ PRICE	NOV '00: MONTH END	52 WEEK RANGE	MARKET CAP
WINGS OF LIGHT						
Wireless, Fiber Optic Telecom Chips, Equipment, Systems	Lucent (LU)	11/7/96	11 25/32	15 9/16	15 1/2 - 84 3/16	52.0B
Wave Division Multiplexing (WDM) Systems, Components	Ciena (CIEN)	10/9/98	4 9/32	75 15/16	21 1/2 - 151	21.6B
Wireless, Fiber Optic, Cable Equipment, Systems	Nortel (NT)	11/3/97	11 1/2	37 3/4	31 7/16 - 89	115.4B
Optical Fiber, Photonic Components	Corning (GLW)	5/1/98	13 41/64	58 1/2	30 3/4 - 113 5/16	53.4B
Wave Division Multiplexing (WDM) Components	JDS Uniphase (JDSU)	6/27/97	3 5/8	50 1/16	50 1/16 - 153 3/8	48.1B
Adaptive Photonic Processors	Avanex (AVNX)	3/31/00	151 3/4	46 1/2	46 1/2 - 273 1/2	3.0B
All-Optical Cross-Connects, Test Equipment	Agilent (A)	4/28/00	88 5/8	52 3/16	38 1/16 - 162	23.7B
Tunable Sources and WDM Components	New Focus (NUFO)	11/30/00	20 5/16	20 5/16	16 - 165 1/8	1.3B
THE LONGEST MILE						
Cable Modem Chipsets, Broadband ICs	Broadcom (BRCM)	4/17/98	6*	97 1/2	84 9/16 - 274 3/4	22.9B
S-CDMA Cable Modems	Terayon (TERN)	12/3/98	15 13/16	12 3/8	12 3/8 - 142 5/8	815.4M
Linear Power Amplifiers, Broadband Modems	Conexant (CNXT)	3/31/99	13 27/32	20 5/16	20 5/16 - 132 1/2	4.6B
THE TETHERLESS TELECOSM						
Satellite Technology	Loral (LOR)	7/30/99	18 7/8	4 5/16	3 3/4 - 25 3/4	1.3B
Low Earth Orbit Satellite (LEOS) Wireless Transmission	Globalstar (GSTRF)	8/29/96	11 7/8	1 5/8	1 9/16 - 53 3/4	166.0M
Code Division Multiple Access (CDMA) Chips, Phones	Qualcomm (QCOM)	7/19/96	4 3/4	80 1/4	51 1/2 - 200	60.1B
Nationwide CDMA Wireless Network	Sprint (PCS)	12/3/98	7 3/16 *	22 11/16	21 7/8 - 66 15/16	21.2B
CDMA Handsets and Broadband Innovation	Motorola (MOT)	2/29/00	56 53/64	20 1/16	20 - 61 1/2	43.8B
Wireless System Construction and Management	Wireless Facilities (WFII)	7/31/00	63 5/8	31 15/16	27 1/8 - 163 1/2	1.4B
THE GLOBAL NETWORK						
Metropolitan Fiber Optic Networks	Metromedia (MFNX)	9/30/99	12 1/4	11 11/16	9 1/8 - 51 7/8	6.4B
Global Submarine Fiber Optic Network	Global Crossing (GX)	10/30/98	14 13/16	12 3/8	12 3/8 - 61 13/16	11.0B
Regional Broadband Fiber Optic Network	NEON (NOPT)	6/30/99	15 1/16	6	5 - 159	99.9M
Telecommunications Networks, Internet Backbone	WorldCom (WCOM)	8/29/97	19 61/64	14 15/16	14 1/2 - 59 3/4	43.0B
Global Submarine Fiber Optic Network	360networks (TSIX)	10/31/00	18 1/8	10 3/8	10 3/8 - 24 3/16	8.4B
CACHE AND CARRY						
Directory, Network Storage	Novell (NOVL)	11/30/99	19 1/2	5 5/16	5 5/16 - 44 9/16	1.7B
Java Programming Language, Internet Servers	Sun Microsystems (SUNW)	8/13/96	13 3/4	76 1/16	64 3/16 - 129 5/16	122.5B
Network Storage and Caching Solutions	Mirror Image (XLA)	1/31/00	29	5 1/16	4 1/2 - 112 1/2	537.1M
Disruptive Storewidth Appliances	Procom (PRCM)	5/31/00	25	12 11/16	11 1/2 - 89 3/4	146.9M
Remote Storewidth Services	Storage Networks (STOR)	5/31/00	27*	29 3/8	19 - 154 1/4	2.8B
Complex Hosting and Storewidth Solutions	Exodus (EXDS)	9/29/00	49 3/8	22 3/4	19 7/16 - 89 13/16	9.7B
THE MICROCOSM						
Analog, Digital, and Mixed Signal Processors	Analog Devices (ADI)	7/31/97	11 3/16	49 5/8	28 5/16 - 103	17.7B
Silicon Germanium (SiGe) Based Photonic Devices	Applied Micro Circuits (AMCC)	7/31/98	5 43/64	48 7/16	20 11/16 - 109 3/4	14.3B
Programming Logic, SiGe, Single-Chip Systems	Atmel (ATML)	4/3/98	4 27/64	9 21/32	10 - 30 11/16	4.5B
Digital Video Codes	C-Cube (CUBE)	4/25/97	23	15 1/8	14 1/4 - 106 1/4	748.1M
Single-Chip ASIC Systems, CDMA Chip Sets	LSI Logic (LSI)	7/31/97	15 3/4	18	19 3/16 - 90 3/8	5.7B
Single-Chip Systems, Silicon Germanium (SiGe) Chips	National Semiconductor (NSM)	7/31/97	31 1/2	18 9/16	18 9/16 - 85 15/16	3.3B
Analog, Digital, and Mixed Signal Processors, Micromirrors	Texas Instruments (TXN)	11/7/96	5 15/16	37 5/16	35 - 99 3/4	64.5B
Field Programmable Gate Arrays (FPGAs)	Xilinx (XLNX)	10/25/96	8 7/32	39	38 - 98 5/16	12.9B
Seven Layer Network Processors	EZchip (LNOP)	8/31/00	16 3/4	13 1/16	5 3/8 - 43 3/4	84.3M
Network Chips and Lightwave MEMS	Cypress Semiconductor (CY)	9/29/00	41 9/16	21 1/8	21 1/8 - 58	2.8B

ADDED TO THE TABLE: NEW FOCUS

* INITIAL PUBLIC OFFERING

NOTE: The Telecosm Table is not a model portfolio. It is a list of technologies in the Gilder Paradigm and of companies that lead in their application. Companies appear on this list only for their technology leadership, without consideration of their current share price or the appropriate timing of an investment decision. The presence of a company on the list is not a recommendation to buy shares at the current price. Reference Price is the company's closing share price on the Reference Date, the day the company was added to the table, typically the last trading day of the month prior to publication. Mr. Gilder and other GTR staff may hold positions in some or all of the stocks listed.

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