A packed OFC BREAKS RECORDS

OFC 2001, held March 17-22 at the Anaheim Convention Center, was both exhilarating and exhausting. The source of the exhilaration: an opportunity to view an incredible number of amazing achievements across a broad range of fiber-related technologies, from high-speed transmission to exotic new fibers.Exhausting because of the sheer scale of a meeting that roughly doubled in size compared to last year.

JEFF HECHT

With 970 exhibitors, anyone trying to touch base at every OFC booth during the 24 hours the show floor was opened over the course of three days would have had less than 1.5 minutes to visit each one. That was barely enough time to walk through Corning's display, among the biggest on the floor. When asked to look back, Don Keck, a co-inventor of the first low-loss fiber, now vice president and technology director of the Optical Physics Technology Group at Corning, reflected that this year's Corning exhibit probably could have contained everyone who attended the first Topical Meeting on Optical Fiber Communications in 1975. Now the conference is so big that only a handful of convention centers in the world can hold it.

Hero experiments

Attendance wasn't the only record broken at OFC. The postdeadline sessions heard separate groups from Japan and France report sending over 10 billion bits per second through a single fiber, breaking the 7 Tbit/s record set last September at the European Conference on Optical Communications in Munich. The record-setting feats were highlights in an informal tradition of "hero experiments" reported at OFC.

Kiyoshi Fukuchi and seven coworkers at the NEC Computer and Communication Media Research Center in Kawasaki set the raw speed record by sending 10.92 Tbit/s through two fiber spans totaling 117 kilometers. The key to their success was packing 40-Gbit/s optical channels at 50-GHz spacing in the short-wavelength S band, as well as using the longer wavelength bands of erbium-doped fiber amplifiers. To isolate adjacent channels,they alternated signal polarization. Using these techniques, they packed 85 channels into the S band between 1476.81 and 1508.01 nm, 92 channels into the erbium C band at 1526.83 to 1563.05 nm, and 96 channels into the L band at 1570.01 to 1610.06 nm—a total of 273 wavelengths.

The NEC team balanced dispersion with spans containing 40 km of pure silica core fiber and 18 or 19 km of reverse dispersion fiber, with dispersion-compensating fiber added at the receiver. They used distributed Raman amplification, plus three thulium-doped amplifiers for the S band, one following the transmitter, a second in the middle of the span, and the

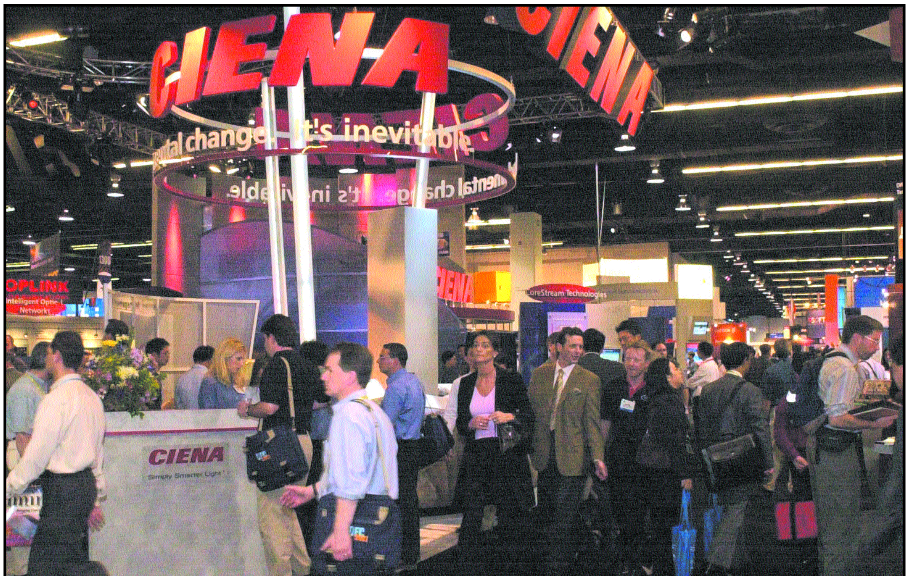
1047-6938/01/05/0048/5-$0015.00 © Optical Society of America

third before the receiver. The combination yielded a transmission efficiency of 0.8 bit/s/per Hertz of optical bandwidth.

Even higher transmission efficiency—a record 1.28 bit/s/Hz—was reported by Sebastien Bigo of Alcatel Research and Innovation in Marcoussis, France, and 13 other Alcatel developers. They crossed the 10-Tbit threshold without using the S band by packing a total of 256 optical channels, each carrying 40 Gbit/s, into the erbium amplifier C and L bands. They placed pairs of fiber amplifiers on both ends of a 100-km span, but none in the middle.

Instead of transmitting adjacent channels with alternating polarization, the Alcatel group transmitted channels at the same polarization, but alternated spacings of 50 and 75 GHz. They controlled interchannel interference by vestigial side-band filtering, an idea adapted from radio transmission. Modulating an optical carrier creates two side bands above and below the center frequency. The two contain the same information, so filtering out one narrows the signal bandwidth but leaves the information intact. Bigo's group selected the desired side bands by using 30-GHz filters at the receiver; their center frequencies were shifted toward the sides with 75-GHz spacing. This packed 128 channels into the C and L bands of erbium-fiber amplifiers operating at 1529.94 to 1561.22 nm and 1569.59 to 1602.53 nm respectively, a narrower range than NEC used. They doubled that to 256 channels by adding a second set of channels at the orthogonal polarization, for a total data rate of 10.2 Tbit/s.

The serious interest in hero experiments is in how they foreshadow the future state of the art. At last year's OFC, 3 Tbit/s was the cutting edge in the laboratory. This year, the postdeadline session included a field trial of 3.2 Tbit/s transmission using standard step-index single-mode fiber that WorldCom had installed between Dallas and Richardson, Texas. Hardware from Siemens transmitted a total of 80 channels, each carrying 40 Gbit/s, at 100-GHz spacing through three 82-km fiber spans. Engineers deployed an array of advanced technologies including forward error correction, distributed Raman amplification, dispersion compensation after each span for all channels, and tunable dispersion compensation for individual channels at the receiver. "This field trial demonstrates the feasibility of multi-terabit transmission of voice, video and data traffic over network field fiber," declared D. Chen of WorldCom.



38,000 flock to OFC 2001–
100% increase in attendees and exhibits.

	OFC 1997 Dallas	OFC 1998 San Jose	OFC 1999 San Diego	OFC 2000 Baltimore	OFC 2001 Anaheim
Attendance					
Technical	2,139	2,672	3,331	6,636	11,588
Exhibitors	2,704	3,596	4,390	5,912	12,651
Exhibit-Only	1,803	2,178	2,485	4,386	13,776
Total	6,646	8,446	10,206	16,934	38,015
Exhibiting Companies	296	342	389	483	970
Net Square Feet	48,000	61,000	83,700	121,300	270,000
Papers					
Contributed	536	501	624	618	859
Invited	43	57	53	45	51
Tutorials	11	8	9	10	8
Total # Accepted	285	289	320	302	482

Doubts about 40-Gigabit systems

Both component and system manufacturers at the show heralded prospects for 40-Gbit equipment. Yet more cautious observers pointed to some major obstacles.

Receiver sensitivity depends on photons delivered per bit, and moving from 10 to 40 Gbit/s means the photons have to arrive in one-quarter the time. That translated into a hefty 6-dB increase in average power, which could raise the level of signal-distorting nonlinearities, warned Fred Leonberger of JDS Uniphase at the Photonics & Telecommunications Executive Forum OSA conducted just before OFC. He said distributed Raman amplification might circumvent the problem by spreading gain over a long length of fiber, so powers did not reach levels that could cause nonlinear effects.

Chromatic dispersion is a bigger issue because its impact increases with the square of data rate. Leonberger said a fiber which can carry a 2.5 Gbit/s signal 1000 kilometers without dispersion compensation could transmit a 40 Gbit/s signal a mere 4 km. "You're worried about the dispersion of everything" at 40 Gbit/s, he told a packed meeting room. He added that tunable dispersion compensators might be needed on every span between amplifiers in 40-Gbit/s systems.

"Nearly all 40 Gbit/s systems will require compensation for polarization-mode dispersion," said Jon Nagel of TerraWorx in Shrewsbury, NJ, in an OFC tutorial on fiber issues for system deployment. Because polarization-mode dispersion changes with environmental fluctuations, the compensators would have to be active.

Coding changes also will be needed. Most transmission at 10 Gbit/s and less relies on non-return-to-zero coding, but return-to-zero transmission is likely for

OFC in Numbers

The 26th annual Optical Fiber Communication Conference was a resounding success for OSA, IEEE/LEOS and IEEE/ComSoc. The conference drew 38,000 attendees—more than a 100% increase over OFC 2000. OFC 2001 was marked by tremendous growth in every area. Here are just some of the record-breaking statistics:

- Close to 1,000 exhibitors—a 100% increase over last year's total
- A 50% increase in technical paper submissions
- Over 800 technical program presentations
- More than 100 short courses, tutorials, and workshops
- 200 registered press attendees, compared to 58 in 2000

Tradeshow

Monday–Wednesday, March 19–21

At OFC's tradeshow, 970 exhibiting companies showcased their newest, most innovative products. Exhibitors hosted hands–on demonstrations featuring state–of–the–art fiber–optic technology, research, and applications. Product showcases were organized to provide attendees with detailed information about the products on display on the exhibit floor.

Plenary session

Monday, March 19

The keynote speakers at this year's OFC plenary session focused on the future of fiber optics and the Internet. Questions addressed included: Where is fiber–optic technology taking us, and where will the new opportunities be in the years ahead?

The first speaker, Vab Goel of Norwest Venture Partners, spoke on emerging opportunities in the changing networking industry. Interactive magazine has called Goel "one of the top 25 unsung heroes on the Net." He speaks both nationally and internationally on the future of the Internet. Goel pointed out in his speech that until 1995, the Internet was a non-profit network run by universities. In 1996, Internet Protocol (IP) constituted only 20% of all wide–area network (WAN) traffic. In 2001, that number rose to 80%. Rather than speculating on what the future holds in store in terms of new applications, Goel urged the audience to concentrate on the opportunities currently available in areas including multi-media, gaming, browsers, and file sharing.

Robert Lucky, corporate vice president of Telcordia Technologies, addressed the impact of changing technologies on networks, companies and economies. Inventor of the adaptive equalizer (a technique used in all high-speed data transmission to correct distortion in telephone signals), Lucky writes a bimonthly article on the engineering profession for *Spectrum* magazine. Citing examples such as Napster, which is generating traffic equivalent to 20 million phones, Lucky told the audience more and more bandwidth will be needed in the future to satisfy digital subscriber line (DSL) demand. When people really begin "collecting" items such as books and CDs over the Net, an enormous amount of traffic will be generated. On the whole, Lucky predicted the future would be populated with "glittering technologies" unimagined even by visionaries like H.G. Wells.

John Tyndall Award

Optical science pioneer Tatsuo Izawa, president of NTT Electronics Corporation (Japan), was presented with the 2001 John Tyndall Award at Monday's OFC plenary session.

The Tyndall Award, first presented in 1987, recognizes individuals who have made pioneering, highly significant, or continuing technical contributions to fiber–optics technology. Izawa was honored for "contributions to vapor–phase axial deposition for optical–fiber fabrication and pioneering work of silica–based planar lightwave circuits."

Anthony M. Johnson, OSA president-elect, presented the Tyndall Award to Izawa, citing Izawa's leadership in the field of lightwave communications.

OFC 2002

Thirty-eight thousand attendees and 970 exhibitors made OFC 2001 a huge success. The number of attendees doubled compared to 2000 figures, technical paper submissions increased by 50%, and an upgraded commercial technology program was part of the conference agenda.

Plans are already underway for OFC 2002, which promises to be equally exciting! Please mark your calendar now to join us March 16-22, 2002 at the Anaheim Convention Center, in Anaheim, California.

For conference information,
please call 202-416-1907
or visit www.ofc-online.org.

OFC is sponsored by OSA, IEEE/LEOS, and IEEE/ComSoc.

40-Gbit/s systems. Although RZ coding requires faster modulation, it is less sensitive to polarization-mode dispersion and reduces vulnerability to nonlinear effects. Forward error correction also is likely to become a must at 40 Gbit/s, to keep error rate low as system margins grow thin.

Observers cited many other uncertainties,including the availability of 40-Gbit/s multiplexing electronics and potential eye hazards of the high pump powers needed for distributed Raman amplification. Nonetheless, an industry panel at the OSA Executive Forum predicted commercial production of 40 Gbit/s systems in 2003 or 2004. "Components for mass deployment will be available starting in 2002," said Gerhard Elze, chief technology officer and vice president of business development at Alcatel Optronics. Forces driving higher speeds include shortage of electrical power and floor space in telecommunications operating centers, said Benoit Fleury of Nortel Networks.

The crucial economic issue is balancing the higher cost of 40-Gbit/s terminal equipment against the savings in transmission lines. That tradeoff becomes easier to justify as transmission distances increase, but technical problems such as dispersion also increase sharply with distance. The first deployment of 40-Gbit/s systems could be in dense urban centers like Manhattan, where distances are short but the costs of laying new cable are high.

High-speed submarine networks

Transoceanic submarine systems can justify heavy investments in terminal equipment, but so far 40-Gbit/s channels cannot stretch the required distances. The record distance reported at that speed in a postdeadline paper was 1200 km, achieved by B. Zhu of Lucent Technologies and 16 colleagues from Lucent, Bell Labs, and Agere Systems. They spaced 77 40-Gbit/s channels at 100-GHz intervals across the C and L erbium-amplifier bands, for a total data rate of 3.08 Tbit/s with forward error correction. Distributed Raman amplification in experimental non-zero dispersion-shifted fibers supplemented erbium amplifiers every 100 km. However, no one seems eager to install power-hungry Raman pump lasers on the ocean floor.

Packing 10-Gbit/s channels closer together allowed Alcatel to send 3-Tbit/s through 7380 km of fiber, a distance six times longer than Lucent managed with 40 Gbit/s channels. Alcatel packed a total of 300 channels spaced 25 GHz apart into the C and L erbium fiber bands. Each fiber span consisted of two-thirds pure silica-core fiber, and one-third reversed dispersion fiber, so average dispersion over the span was about 3 ps/nm-km, G. Vareille, F. Pitel and J. F. Marcerou said in a postdeadline paper. They used only erbium-fiber amplifiers and fiber spans averaging 52.7 km.

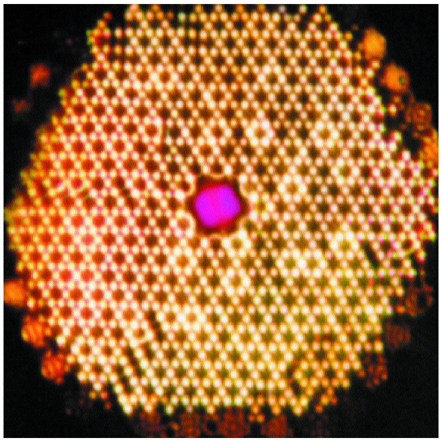
An experiment at TyCom Laboratories in Eatontown, NJ, showed promise for 20 Gbit/s channel rates across transatlantic distances. J.-X. Cai and 11 colleagues spaced 120 channels at 42-GHz intervals between 1525 and 1570 nm. They launched adjacent channels with orthogonal polarization to reduce crosstalk. Using return-to-zero coding and forward error correction, they reported a total data rate of 2.4 Tbit/s through 6200 km of fiber. Each fiber span included 33 km of large effective area fiber and 16 km of inverse dispersion slope fiber, and ended at an erbium-amplifier. Thanks to careful dispersion management, they said, "The resulting dispersion slope of the mixed fiber spans was 200 times smaller than is typical in today's systems." Their spectral efficiency was 0.48 bit/Hz of transmission bandwidth.

Stretching the distance to 9000 km, enough to cross the Pacific, imposes more serious limits. Another TyCom Labs team led by B. Bakhshi spaced 101 channels transmitting 10 Gbit/s at 33-GHz intervals, using only wavelengths of 1537 to 1564 nm in the erbium-fiber C band. Another group had reported transmitting the same 1 Tbit/s rate over similar distances last fall, but their experiment used Raman amplification. Bakhshi's group said their demonstration is more practical because it "is based on a simple system design utilizing only the EDFA C band and technologies that are easily qualified for undersea use." They attribute their success to a careful dispersion management, return-to-zero modulation format, low power per channel, and advanced gain-flattening filters. By launching adjacent channels with orthogonal polarization,they achieved spectral efficiency of 0.3 bit/Hz.

Raman amplifiers

In an invited paper, E. M. Dianov of the fiber optics research center at the General Physics Institute in Moscow described refinements being made to Raman amplifiers. Raman gain is material-dependent. Most work has focused on common silica glasses, but the Raman cross-section of germania glass is 10 times higher than silica. Although germanium increases fiber attenuation, high-germania fibers have been made with loss of only 0.5 dB/km at 1550 nm. Phosphorus also has a higher Raman cross-section, as well as a large frequency shift and two gain bands rather than silica's one.

New amplifier designs are flattening Raman gain across broader wavelength ranges. The gain peak is offset a fixed amount from the pump wavelength, so pumping at multiple wavelengths provides more uniform gain. Another development is cascading Raman fiber lasers with nested oscillator cavities, so an external pump source can produce a Raman line offset at a longer wavelength, which in turn can pump another Raman stage to generate another Raman line that itself can serve as a pump. These multistage Raman lasers can shift a powerful pump beam to successively longer wavelengths for pumping applications. Dianov noted growing interest in Raman fiber lasers, as well as distributed Raman amplification and separate discrete Raman amplifiers.



"Holey" fibers

An afternoon tutorial on photonic-crystal or "holey" fibers by Philip Russell of the University of Bath attracted a large audience interested in the hot field. The idea grew from Eli Yablonovitch's work on layered structures which could block light propagation at certain wavelengths by creating a "photonic band gap." Just as electronic band gaps can control current flow in a semiconductor device, photonic band gaps can direct the flow of light in optical materials.

WWW.CONNECTROCHESTER.COM

- Accuracy Microsensors
- Advanced Glass Industries
- Advanced Quickprinting, Inc.
- Amanl Precision Instruments, Inc.
- OPTEM International
- Ameritherm, Inc.
- Anson Instrument Corporation
- APOMA
- Applied Image Group, Inc.
- ASE Optics
- EMI / Astec America
- Automatic Recognition & Control, Inc.
- Automation Gages, Inc.
- Bruce-Anco
- Burleigh Instruments, Inc.
- Campus Crafts, Inc.
- Carlough Corporation
- Chapman Instruments, Inc.
- CMC Systems, Inc.
- Cohber Press
- Corning Monroe Park
- CPAC
- Cranfield Precision
- CVC Products, Inc.
- Danfoss Videk
- Dimension Technologies, Inc.
- Diversified Technologies International
- DYNACOMP, Inc.
- Eastman Kodak Co./Consumer Imaging
- Eastman Kodak Co./Kodak Professional
- Eastman Kodak Co./Microelectronics Technology Division
- Embassy, Ltd.
- EMF Corp.
- Evaporated Metal Films Corp.
- Ferro / Transelco Division
- Ferro / Specialty Ceramics Division
- FiberNet
- Fisba Optik
- Fresnel Optics, Inc.
- G-S Plastic Optics
- Gage-Line Technology, Inc.
- Germanow-Simon Corporation
- Glass Fab, Inc.
- Gradient Lens Corp.
- Great American Optics
- Gys Database, Inc.
- Heidelberg Digital Imaging
- Holotek Div. of ECRM
- IK Systems, Inc.
- Image Makers of Pittsford Practical Optics Division
- Industrial Indexing Systems, Inc.
- Irondequoit Industries
- Itek Graphix
- Ivax Industries
- John S. Herbrand, Esq.
- JML Optical Industries
- Kayex Corporation
- Largen, Inc.
- LaserMax, Inc.
- LaserSurge
- Lightwave Products, A Nylamoid Company
- LOH Optical Machinery
- Lucid Technologies, Inc.
- The Laser Center
- Matthew P. Kaufer
- Melles Griot Optical Systems Division
- Micropen, Inc.
- Mildex, Inc.
- Monarch, a division of Eltrex Industries Inc.
- Monroe Community College Optical Engineering Technology Department
- NAVITAR, Inc.
- NexPress Solutions LLC
- Nordic USA, Inc.
- OPKOM, Inc.
- Optical Gaging Products, Inc.
- Optical Prototypes, Inc.
- Optical Systems Engineering
- Optics Technology, Inc.
- Opticwerk, Inc.
- Optima
- Optimax Systems, Inc.
- OptiPro Systems, Inc. (Formerly CMC Systems)
- Opto Dynamics, Inc.
- Opto-Alignment Technologies
- Panther Graphics
- Paradigm Lasers, Inc.
- Photikon Corporation
- Photonamics, Inc.
- Pixel Physics, Inc.
- Planar Optics
- PODI
- PSC, Inc.
- Quality Measurement Systems
- R. Kraft, Inc.
- Reflectx
- Richardson Grating Laboratory
- RIT/Microelectronic Engineering
- RIT-Imaging Center
- RIT Research Corp.
- Rochester General Hospital Laser Center
- Corning Rochester Photonics
- Rochester Regional Photonics Cluster
- Schneider Optical Machines, LLC
- Scorrac, Inc.
- Sinclair Optics, Inc.
- Sine Patterns
- Spectra Services, Inc.
- Spectronic Instruments, Inc.
- Stefan Sydor Optics, Inc.
- Tandem Optics, Inc.
- Target Vision, Inc.
- Technology Interact, Inc.
- Trek, Inc.
- Tipton Lens Company, Inc.
- Tropel Corporation
- UML Enterprises, Inc.
- Upstate CTC
- Valmax, Inc.
- Vincent Associates
- Welch Allyn, Inc.
- WinSiz, Inc.
- Wollensak Optical, Inc.
- Xerox Corp.
- Zoomar

The idea can be applied to fibers by creating arrays of holes that form a microstructure along the length of fiber. Rods and hollow tubes are stacked, fused together, and then drawn into composite fibers. The process is similar to fabrication of fused bundles of optical fibers, but intentionally leaves empty holes running the length of the fiber. Arrays of regularly spaced holes form photonic-band-gap microstructures that block the passage of light at certain wavelengths. In this way a cladding of microstructured material can guide light along a core of some other composition that does transmit light.

Russell described several types of holey fibers with light-transmission properties not achievable using conventional solid fibers. Filling in the central hole in a fiber with a regular hexagonal array of holes creates a solid core which guides light in a single mode regardless of wavelength. That discovery initially surprised Russell; later analysis showed that the air holes trapped the fundamental mode, but higher-order modes were small enough to escape into the microstructured cladding.

Another intriguing possibility is using photonic band gaps to guide light through hollow-core fibers. This type of transmission is impossible in conventional fibers because the hollow cores inevitably have lower refractive index than the surrounding solid, preventing total internal reflection. Yet it opens new possibilities for long-distance transmission by confining light in air, where chromatic dispersion and nonlinear effects are much weaker than in glass. That could avoid major limitations of current fibers. Other types of holey fibers can be made with dispersion profiles designed to compensate for dispersion effects in other types of fibers.

Developers have described a wide variety of light-guiding effects in holey fibers, but attenuation has remained stubbornly high—typically hundreds of decibels per kilometer. A postdeadline report of attenuation of only 0.82 dB/km at 1550 nm in a "hole-assisted lightguide fiber" was a welcome breakthrough. Takemi Hasegawa of Sumitomo Electric Industries Ltd. in Yokohama and colleagues from Sumitomo and Hokkaido University designed a new photonic crystal fiber in which four holes in a pure silica cladding surrounded a high-index glass core.

Hasegawa's team blames the high loss of other holey fibers on absorption by traces of water trapped in the holes themselves. To avoid that extra loss, their structure confines most of the guided light in the core, with little propagating in the holes. Their fiber's special property is a high anomalous dispersion of +34 ps/nm-km at 1550- nm, larger than attainable in a solid glass fiber.

Although the field is young, two new companies have spun out of university labs to develop holey fibers. Russell has formed Blaze Photonics with colleagues from Bath. A Danish company called Crystal Fibre is a spin-off of the photonic crystal fiber group at the Technical University of Denmark in Lygyby.

New twists on surface emitters

The postdeadline sessions included reports of two unusual new surface-emitting semiconductor lasers that separate companies are developing for fiber-related applications. Aram Mooradian of Novalux obtained 980-nm powers above 1 Watt suitable for pumping erbium-doped fibers from large-area surface-emitting lasers of gallium indium arsenide.

Like conventional vertical-cavity surface-emitting lasers, they have active layers confined between reflecting multilayer coatings that couple light out through the device surface. However, the Novalux laser adds a curved external output mirror, which concentrates emission from the large-area device into a beam suitable for pumping erbium-fiber amplifiers. Mooradian predicted output powers could reach several watts.

An even more unusual device is the linear optical amplifier described by D. A. Francis, S. P. DiJaili, and J. D. Walker of the Genoa Corp. in Fremont, CA. Their device is an InGaAsP semiconductor amplifier integrated with a VCSEL. The VCSEL mirrors are on top and bottom of the junction layer running the length of the device; light from an external fiber is directed in the junction plane, as if the device were an edge-emitting semiconductor optical amplifier.

In operation, a drive current is applied across the junction laser, generating excited carriers which can emit light either through the VCSEL cavity or to amplify the external signal. "The circulating optical power of the VCSEL overlaps with the amplifier waveguide and acts as a ballast to maintain a constant gain in the amplifier." This avoids large transients generated by switching conventional semiconductor optical amplifiers, Genoa says.