Report from OFC/NFOEC 2005

Turning Cutting-Edge Optical Technology into Practical Applications

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The 2005 Optical Fiber Communications Conference (OFC), held March 6-11 at the Anaheim Convention Center, showcased the changing shape of the global fiber-optic industry. Fiber to the home took the spotlight, with talks on the experience of Japanese companies in deploying systems and new technology for cutting costs and improving performance.

This year, for the first time, OFC merged with the National Fiber Optics Engineers Conference (NFOEC)—a change that was reflected by added content on network management and operation. As always, innovative technology was prominent on the agenda, but there was little evident interest in increasing optical channel counts

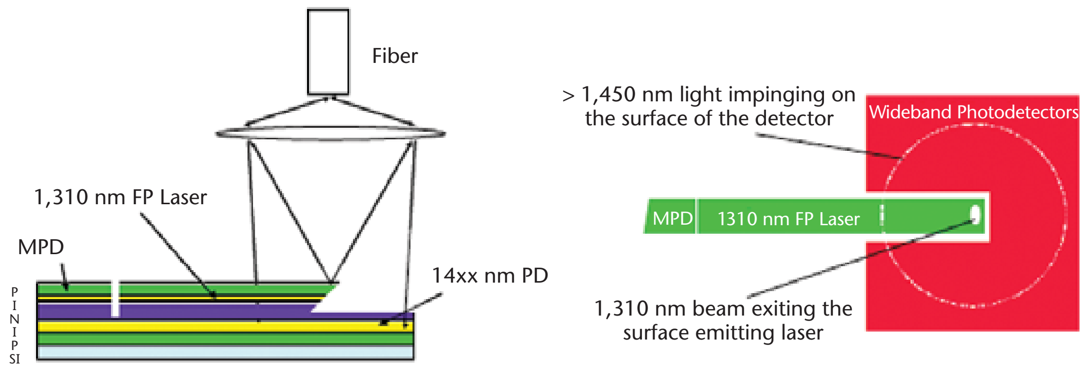

Figure 1. PON diplexer chip developed by BinOptics integrates a 1,310 nm InGaAlAs laser with a InGaAs *pin* photodiode (Paper OTuM5, Fig. 1). The surface-emitting horizontal cavity stripe laser emits upward, so its light is collected by the lens at top and focused on the fiber end. The input optical signal is focused by the lens onto the larger area of the photodiode, as shown in the right half of the figure.

to squeeze more terabits per second through single fibers.

The Thursday-evening postdeadline sessions focused on the traditional "hero experiments," which are designed to break capacity or distance records for optical transmission. These sessions turned to more practical achievements that were still on the cutting edge. Three groups reported ways to stretch transmission distances at 10 Gbits per second without using conventional dispersion-compensating fibers. Another described how Gbit passive-optical networks (PON) could be stretched to span 135 km. New work on microstructured fibers included fabrication of one extending 100 km, and of another with record nonlinearity. Among the surprises was a report of light pressure bending a micro-toroid resonator.

Technology for fiber to the home

Japanese telephone companies began installing fiber to the home systems well ahead of their American counterparts, giving two teams from NTT, the Japenese telecom giant, valuable insight into how to reduce costs and assure reliability. Hiroyuke Hayashida of NTT's systems management and operation headquarters in Osaka and colleagues described progress in bringing fiber costs down to the same level as copper, which at first cost 25 percent less.

The team reduced fiber costs by 20 percent by using the same home enclosure for fiber and copper connections, picking nonconductive drop cables and mechanically splicing fibers. To further bring fiber costs down to match those of copper, they recommend switching to a more flexible drop cable, with a 15 mm bend radius, and using a new connector that can be field assembled by clamping onto the cable, thus avoiding the need for mechanical or fusion splicing.

The first Japanese home fiber systems were 30 percent more likely to suffer flaws than their copper counterparts, reported a group led by Itsuo Kuramoto of the NTT systems management and operation headquarters in Osaka. Altogether, 37 percent of failures came from problems with fiber and cable installation, including bad connector joints and excessive bending of the fiber. Some of those problems were due to bugs in the system—literally. Cicadas damaged some fiber cables by laying eggs in a notch made in the drop cable to expose the fiber; to address this, the NTT team shifted to a cable without a notch. Better connector installation procedures and more flexible fiber cables could eliminate many installation problems, Kuramoto said.

Another 23 percent of failures were in customer routers or computers. NTT's connections to customer equipment were through VDSL, a high-speed version of DSL, which, together with optical network units, caused remaining failures. Early U.S. installations of DSL were also plagued with problems.

Other reports covered efforts to drive down costs of components for passive optical networks, which are generally preferred for home fiber connections. Home optical network units now cost about $100 each. With phone companies planning to install millions of them, the numbers add up quickly.

One new idea is the monolithic diplexer chip shown in Fig. 1, developed by BinOptics Corporation (Ithaca, N.Y.), and described in the technical sessions by CEO Alex Behfar. The chip both generates the 1,310 nm upstream signal and detects the 1,490-nm downstream data signal transmitted through the same fiber. It integrates a 1,310 nm InGaAlAs laser with an InGaAs *pin* photodiode.

The laser has a ridge-type horizontal cavity with an output facet etched at a 45° angle to direct the output beam upward, where it is collected by a lens that focuses it onto the end of the fiber reaching the optical network unit. The same lens collimates the 1,490 nm downstream light emerging from the fiber and focuses it onto the larger area of the photodiode. Behfar reported that the company has demonstrated crosstalk of 20 to 30 dB between input and output channels, but believes they can reach 40 dB isolation.

A planar lightguide triplexer developed by Xponent Photonics (Monrovia, Calif.) can handle the 1,550 nm downstream video channel in a passive optical network (PON) as well as the 1,310- and 1,490 nm channels, but it isn't monolithic. The assembly uses planar silica waveguides on a silicon substrate and filters to separate the 1,490- and 1,550-nm channels and deliver each to a separate photodiode.

Hank Blauvelt, chief technology officer of Xponent, said the most challenging interface in the entire structure is the one that transfers the upstream data signal from a 1,310-nm ridge-waveguide laser to the silica waveguide structure. He reported that crosstalk from the 1,310-nm upstream data signal was -55 dB to the video signal and -60 dB to the downstream data channel.

Other developers are working to increase PON performance, such as by stretching their reach beyond the local access network. A 2.5-Gbit/s PON that stretched an impressive 135 km was described at the postdeadline session by Russell Davey of BT (the former British Telecom) in Martlesham Heath, United Kingdom, and colleagues. They spanned that distance by converting the 1,490 nm downstream data signal to 1,552.924 nm and placing that signal on one optical channel in a 125-km metro DWDM (dense wavelength-division multiplexing) system.

Then, a customized transponder converted the signal back to 1,490 nm and relayed it through 10 km of standard single-mode fiber in a PON serving 64 terminals. Upstream data signals traveled in the opposite direction, and were converted to a second DWDM wavelength, 1,559.412 nm, for upstream transmission through the metro network. The PON standard allows a bit error rate of 10^{-9} for a maximum distance of 60 km, but the BT experiment measured a bit error rate of 10^{-10} over more than twice that distance.

The signal's round-trip time was 2.55 ms, within the 3 ms allowed by the standard. Davey's group said that, by using an amplified 40-channel DWDM system, they could serve up to 2,560 terminals through a single pair of DWDM fibers, each transmitting in one direction, thereby saving fiber while extending reach.

In an NFOEC paper, Frank Wiener of Calix in Petaluma, Calif., pondered the benefits of two ways to deliver video to homes over fiber—as an analog signal like those used in modern cable television networks on a separate wavelength, or as switched digital packets. Verizon, the first regional phone company to start widespread fiber installations, picked an analog overlay at 1,550 nm specified in the Broadband PON standard, allowing it to plug into existing coaxial cables that distribute signals in homes.

Switched video services operate differently, delivering only selected video signals to homes, and requiring a set-top box or digital gateway to process the signals. Wiener concluded that, although analog overlays have some advantages, switched video delivered over Internet Protocol (IP) will offer more flexibility, particularly as the United States moves to digital television. However, in an OFC paper, Curtis Knittle of Harmonic Inc. (Boulder, Colo.) argued that the most cost-effective approach is to use an analog overlay for broadcast video and transmit only programs targeted to individual homes in digital IP format.

Simpler high-speed transmission

Transmission of high-speed signals over long lengths of fiber requires some compensation for chromatic dispersion. Some systems have been built using fiber tailored to have low dispersion in the 1,550 nm window, but many use "standard" step-index single-mode fiber, which has relatively large dispersion at 1,550 nm. Adding lengths of fiber designed to have chromatic dispersion opposite in sign to standard single-mode fiber can offset its high dispersion.

However, such dispersion-compensating fibers have higher loss than standard fibers, and are more vulnerable to nonlinear effects. In addition, they provide a fixed compensation selected to match the system configuration, so any changes in the network may require altering the amount of compensation. At the post-deadline session, three groups reported progress on alternative approaches.

The most striking results came from the most complex technique—optical phase conjugation. Sander Jansen of Eindhoven University of Technology reported 10-Gbit/s transmission through a record 10,200 km of standard single-mode fiber, with total chromatic dispersion more than 80,000 ps/nm of source bandwidth.

Jansen's group started by modulating 44 DWDM channels with return-to-zero differential quadrature phase-shift keyed signals, which they transmitted 18 times through a recirculating loop. At that point they discarded half the channels and passed the others through a phase conjugation subsystem based on periodically poled lithium-niobate waveguide, which shifted the signals on those channels to wavelengths in the band that had been discarded. Jansen reported "only minor evidence of nonlinear phase noise" after the signals went through the loop another 18 times.

Second place went to electronic dispersion compensation, which treats dispersion as a linear operation on the optical signal's electric field that can be undone by filtering at the receiver; this is potentially an easier process than optical phase conjugation. According to Doug McGhan of Nortel (Nepean, Ontario), this strategy allowed detection of a single 10-Gbit/s optical channel after it had passed through 5,120 km of standard single-mode fiber and accumulated 82,400 ps/nm of chromatic dispersion. Pre-compensation was added to an RZ-DPSK input signal in a Mach-Zehnder modulator, and the signal was recovered by filtering at the receiver.

In third place was a compact, inexpensive transmitter that introduced a wavelength chirp into the pulses from a distributed-feedback laser that passed through filters before entering a fiber transmission line. The signals reaching the receiver passed through a 0.3-nm filter before going through a series of four dynamically tuned optical dispersion compensators.

At OFC, Sethumadhavan Chandrasekhar of Bell Labs (Holmdel, N.J.) reported the system could be dynamically tuned to compensate dispersion for signals sent through 0 to 675 km of fiber, with total chromatic dispersion of 11,500 ps. A big advantage, he said, is that the system could be dynamically tuned at the receiver to account for changes in network configuration.

Laser link from Mars

Astronauts first tested laser links between the ground and space in the mid-1960s, but the links weren't demonstrated between satellites orbiting the Earth until 2002. In an invited paper, Don Boroson of M.I.T.'s Lincoln Laboratory described NASA's ambitious plans to stretch the

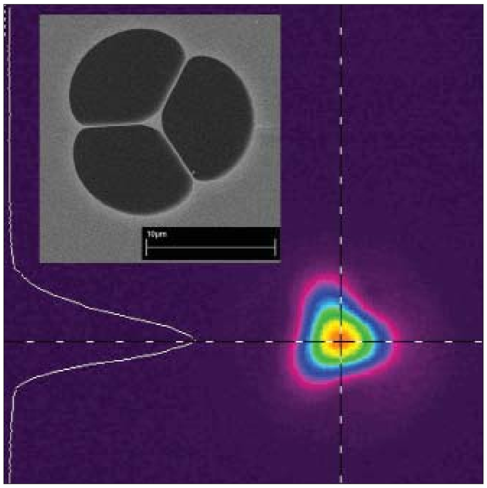

Figure 2. Mode profile of Southampton's high-nonlinearity holey fiber, with core structure shown at upper left (Paper PDP22, Fig 2a).

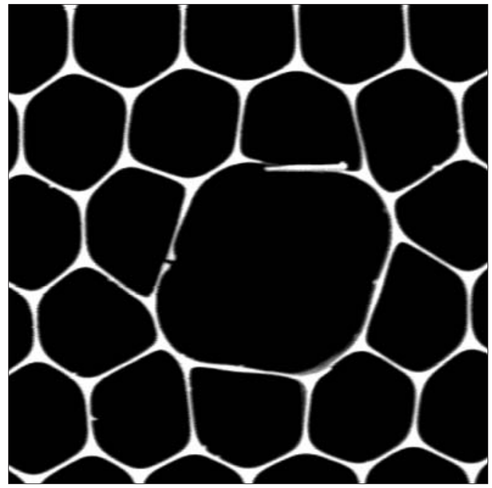

Figure 3. Cross-section of Corning's birefringent hollow-core photonic bandgap fiber. Dark regions are air; light regions are glass (Paper OTuI1, Fig. 1).

technology to reach all the way to Mars. Seeking to increase data transmission rates across interplanetary space, NASA plans to demonstrate a laser link to Earth on its Mars Telecommunications Orbiter, which will be launched in 2009.

Major challenges for the Mars Laser Communications project include pointing the beam accurately across 70 million to more than 300 million km and detecting the faint signal that remains after about 80 dB of attenuation. Plans call for a grating-stabilized fiber laser to generate pulses with peak power of 320 W for transmission through a 30-cm telescope.

A beacon beam transmitted from Earth, which can carry commands at up to 100 bits per second, will help guide the beam. However, the planets are moving too fast to aim directly at the guide beam; the Mars orbiter will have to aim its four-μrad beam up to 400 μrad from the beacon position.

To pick up the faint signals reaching Earth, NASA has lined up two weeks per month of time on the five meter Palomar telescope. A filter with a one-Å passband will reduce background light, and sophisticated electronics will analyze the output of a photon-counting detector.

Boroson said that Palomar should be able to receive several hundred kilobits to 30 megabits per second from Mars, with an array of small telescopes to be built to receive signals when Palomar is not available.

Microstructured fibers

OFC also heralded important advances in microstructured, or "holey," fibers. Previously, fabrication difficulties had limited the available lengths to several kilometers. However, in a postdeadline session, Kenji Kurokawa and colleagues from the NTT Access Networks Service Systems Laboratories in Tsukuba, Japan, described a single photonic-crystal fiber 100 km long. They observed no discontinuities in the solid-core fiber drawn from a preform 40 mm in diameter and 1.2 m long.

Other groups have measured lower attenuation than their minimum, 0.3 dB/km at 1,550 nm, but half of their loss came from imperfections, and they say the Rayleigh scattering coefficient of 0.85 dB/km/μm^4 is the lowest yet reported. They also showed that the fiber could carry signals, transmitting dispersion-managed solitons at 10 Gbit/s through four, 25 km segments, separated by dispersion-compensating fiber and erbium-doped fiber amplifiers, with bit error rate of 10^{-11}.

Other important progress came in making holey fibers with novel optical properties. Record nonlinearity of 1,860 $W^{-1}m^{-1}$ at 1,550 was reported in a postdeadline paper by Julie Leong and colleagues of the University of Southampton. Using highly nonlinear lead silicate glass, they made a fiber with a 1-μm solid core supported in air by three fine filaments, as shown in Fig. 2.

The high numerical aperture and tiny core confined the single mode much more tightly than is possible in conventional fibers, approaching the maximum nonlinearity for lead silicate fibers. Pumping the fiber with 200-fs pulses generated a supercontinuum more than 750 nm wide.

In the regular OFC sessions, Xin Chen reported that a team at Corning Inc. (Corning, N.Y.) has produced the first highly birefringent hollow-core photonic bandgap fiber. The birefringence comes from the shape of the core, shown in Fig. 3, which is 9.4 μm wide and 8.1 μm wide. Fiber loss is about 1.5 dB per m at 1,500 to 1,625 nm. Chen reported group birefringence of 0.025 at 1,550 nm, but added that the mechanism producing such high birefringence has yet to be fully explained.

Radiation pressure and mechanical oscillation

Microresonators have also been a hot research topic lately, and some have demonstrated quality factors on the order of 10^8. Microtoroids with such high Q factors can build up circulating powers of more than 100 W with input pump powers of only a mW. At a postdeadline session, Hossein Rokhsari of the California Institute of Technology reported taking advantage of that concentration of optical power to excite mechanical resonances of a microtoroid ring.

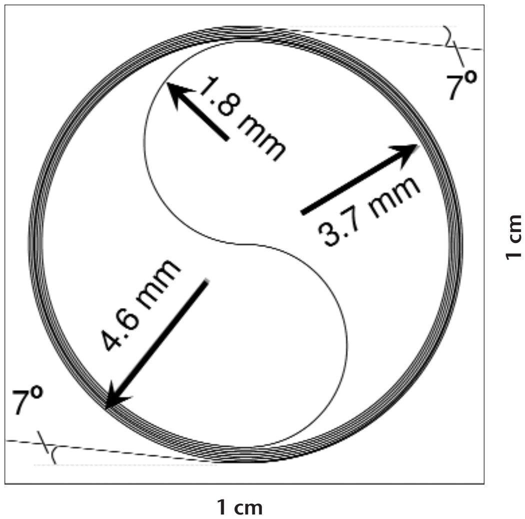

Figure 4. An erbium-doped bismuthate glass waveguide amplifier is wound many times in a loop to fit onto a one-cm substrate at Asahi Glass (Paper PDP2, Fig. 1).

Rokhsari and others in Kerry Vahala's group at Caltech excited the toroid with a continuous wave laser at a frequency close to an optical mode of the structure. As internal radiation pressure grows, it deforms the microtoroid—which changes its resonant optical frequency. If the changes shift the toroid away from resonance with the circulating light, they transfer power from the optical pump to mechanical vibrations of the toroid at radio frequencies, thereby modulating the intracavity optical wave with the radio frequency of the mechanical vibration.

The Caltech group also observed the phenomenon in micro-spheres, indicating that other optical cavities may be susceptible to them. Potential applications include precision quantum-limited measurements of position and entangling light with macroscopic objects.

New optical amplifiers

Thulium-doped fiber amplifiers, first developed for wavelengths in the S window between 1,460 and 1,530 nm, are now being investigated for the 850 nm "first window" of optical fibers. The high attenuation and chromatic dispersion of conventional fibers have long limited that wavelength to short data links. However, the emergence of 10-Gbit Ethernet and low-cost VCSELs has revived interest in amplifiers that might stretch transmission distances, particularly now that photonic crystal fiber can offer zero dispersion near 850 nm.

Two types of first-window thulium amplifiers were described at OFC. Youichi Akasaka of Sprint's advanced technology labs (Burlingame, Calif.) showed that fluoride fibers doped with thulium have gain from about 790 to 850 nm when pumped simultaneously by 690- and 1,400-nm sources.

Both should be available inexpensively, because lasers at the shorter wavelength are used for DVD recording and those at the longer wavelength are used for distributed Raman pumping. Pramod Watekar of the Gwangju Institute of Science and Technology in Korea took a different approach, pumping a thulium-doped double-clad silicate fiber at 1,060 nm, and reported peak gain of 22.5 dB at 843 nm.

In a postdeadline paper, Yuki Kondo the Asahi Glass Company in Yokohama, Japan, reported that an erbium-waveguide amplifier on a substrate just one centimeter square had gain of more than 15 dB from 1,530 to 1,565 nm. He made the spiral-shaped waveguide by depositing erbium-doped bismuthate glass on a glass substrate. The waveguide made looped waveguides stretching 24 cm onto the tiny substrate (see Fig 4). With modest gain to stretch the range of metropolitan networks, this compact and inexpensive amplifier is a new twist on erbium-doped amplifiers in the 1,550 nm band.

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