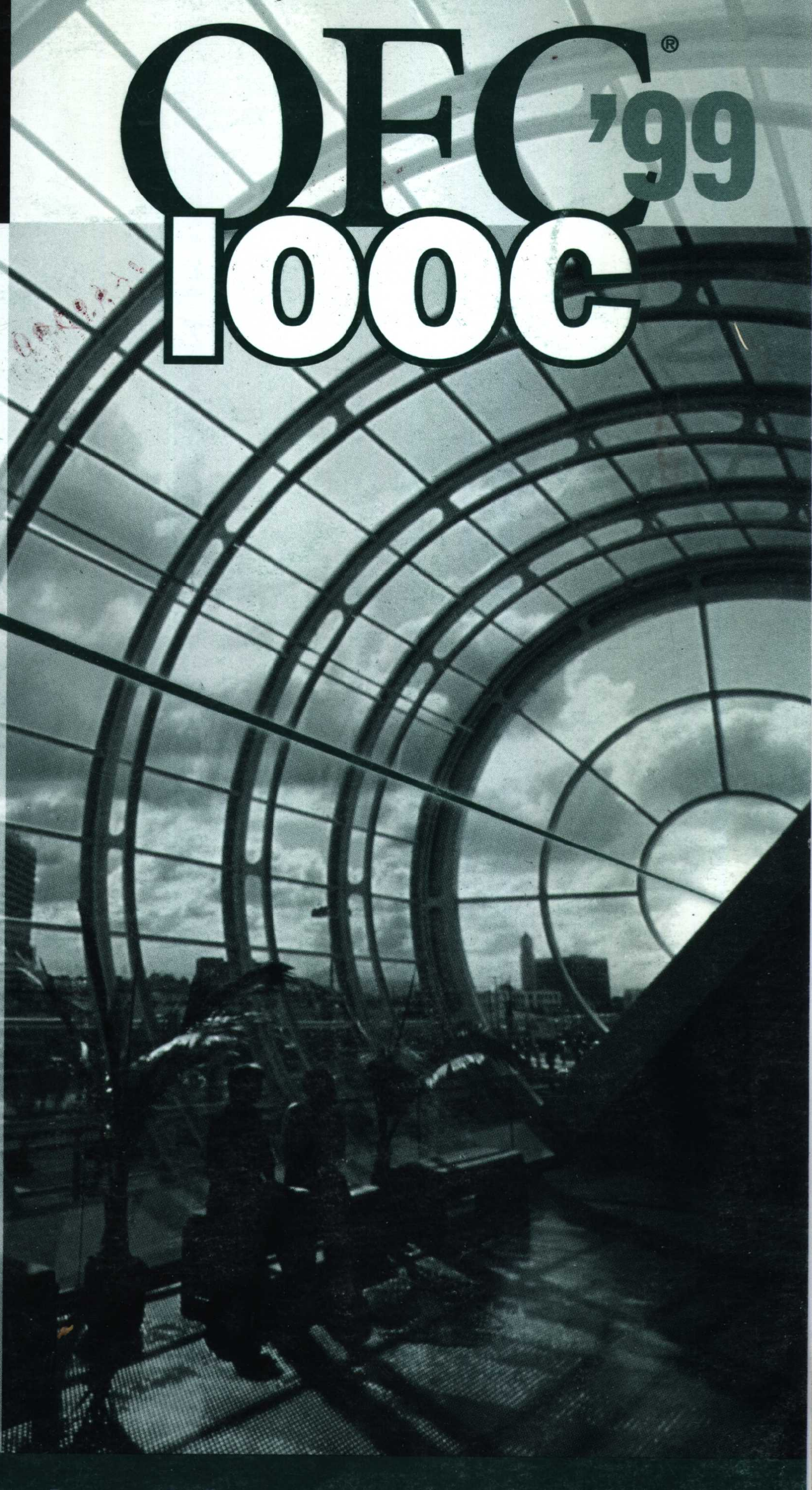
Optical Fiber Communication Conference (OFC®) and the International Conference on Integrated Optics and Optical Fiber Communication (IOOC)

OFC® '99 IOOC

TECHNICAL DIGEST SERIES

POSTCONFERENCE EDITION



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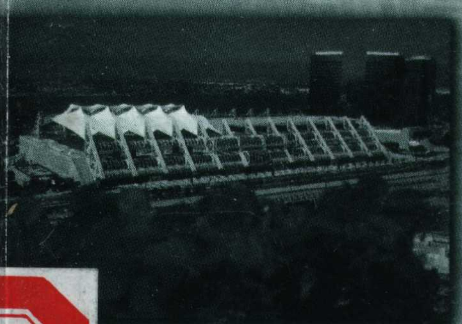

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Postdeadline Papers

OFC/IOOC '99 Postdeadline Papers

Thursday, February 25, 1999

Room 6A
Robert W. Tkach, ***AT&T Labs-Research, USA, Presider***

5:45pm
PD1—3 Tbit/s (160 Gbit/s x 19 ch) OTDM-WDM Transmission Experiment, S. Kawanishi, H. Takara, K. Uchiyama, I. Shake, and K. Mori, *NTT Network Innovation Laboratories, Japan.* 3 Tbit/s (160 Gbit/s x 19 channels) optical signal is successfully transmitted over 40 km dispersion-shifted fiber. Low noise supercontinuum signal pulse sources and 70 nm bandwidth tellurite-based optical amplifiers are used for 3 Tbit/s signal generation and amplification.

5:55 pm
PD2—640 Gb/s Transmission of Sixty-four 10 Gb/s WDM Channels Over 7200km with 0.33 (bits/s)/Hz Spectral Efficiency, N.S. Bergano, C.R. Davidson, C.J. Chen, B. Pedersen, M.A. Mills, N. Ramanujam, H.D. Kidorf, A.B. Puc, M.D. Levonas, and H. Abdelkader, *Tyco Submarine Systems, Ltd., USA.* Sixty-four 10 Gb/s WDM channels were transmitted over 7200 km is a spectral bandwidth of 15.1 nm for a spectral efficiency of 0.33 (bits/s)Hz. Error free operation was achieved for all channels.

6:05pm
PD3—1220 km Propagation of 40 Gbit/s single Channel RZ Data Over Dispersion Managed Standard (Non-dispersion Shifted) Fibre, S.B. Alleston, P. Harper, I.S. Penketh, I. Bennion, N.J. Doran, *Photonic Research Group, UK,* A.D. Ellis, *BT Labs, UK.* Error free propagation of a single polarisation optical time division multiplexed 40Gbit/s dispersion managed puls data stream over dispersion shifted) fibre. This distance is twice the previous record at this data rate.

6:15pm
PD4—Narrow Band 1.02 Tbit/s (51 x 20 Gbit/s) Soliton DWDM Transmission Over 1000km of Standard Fiber with 100 km Amplifier Spans, D. LeGuen, S. DelBurgo, M.L. Moulinard, D. Grot, M. Henry, F. Favre, and T. Georges, *France Telecom CNET, France.* 1.02 Tbit/s (51-wavelength each at 20 Gbit/s) dense WDM (0.4 nm channel-spacing) soliton transmission over 1000 km of standard step-index fiber with 100 km (21 dB loss) amplifier spans was successfully achieved for the first time.

6:25pm
PD5—500 Gb/s (50 x 10)Gb/s) WDM Transmission Over 4000km Using Broadband EDFAs and Low Dispersion Slope Fiber, K. Imai, T. Tsuritani, N. Takeda, K. Tanaka, N. Edagawa, and M. Suzui, *KDD R&D Laboratories, Inc., Japan.* 500 Gb/s, over 4000km transmission was moderated with 22nm-bandwidth EDFAs and low dispersion slope fiber. By reducing the dispersion slope and fiber nonlinearity, the transmission distance was almost doubled compared to the previous experiments with similar capacity.

6:35pm
PD6—80 Gbit/s Single Wavelength OTDM Soliton Transmission Over 172km Installed Fiber, J. Hansyrd, B. Bakhshi, B.E. Olsson, P.A. Andrekson, J. Brentel, E. Kolltveit, *Photonics Laboratory, Chalmers University of Technology, Sweden.* Single wavelength soliton transmission at 80 Gbit/s has successfully been performed over 172km installed fiber. Soliton data with pulse widths of 4.5ps was transmitted with an average power penalty for all eight time-division-multiplexed channels of 1.3 dB.

6:45pm
PD7—1-Tb/s (40-Gb/s x 25ch) WDM transmission experiment over 342km of TrueWave® (non-zero dispersion) fiber, C.D. Chen, I. Kim, O. Mizuhara, T.V. Nguyen, K. Ogawa, R.E. Tench, L.D. Tzeng, and P. D. Yeates, *Bell Laboratories, Lucent Technologies, USA.* We have demonstrated a successful, error-free 1-Tb/s transmission experiment over 342km of TrueWave® fiber using 40Gb/s OTDM (optical time-division-multiplexing) transmitter and 3R receiver. Fiber chromatic dispersion was effectively compensated for using negative-slope dispersion compensating fiber.

6:55pm
PD8—Dense Wavelength-Division Multiplexed Transmission in "Zero-Dispersion" DSF by Means of Hybrid Raman/Erbium-Doped Fiber Amplifiers, P.B. Hansen, A. Stentz, T.N. Nielsen, R. Espindola, L.E. Nelson, A.A. Abramov, *Bell Labs, Lucent Technologies, USA*. Transmission of 25 and 50 equally 100-GHz and 50-GHz spaced 10-Gb/s (OC-192) channels on the ITU grids is demonstrated over eight and four 83.8-km long spans, respectively, of DSF with the zero-dispersion wavelength within the signal wavelength band. Significant performance improvements are obtained with a pump power of only 440 mW with 55-μm^2 dispersion-shifted fibers because of their relatively high Raman efficiency.

7:05pm
PD9—32 x 10 Gb/s Distributed Raman Amplification Transmission with 50 GHz Channel Spacing in the Zero-Dispersion Region Over 640km of 1.55-μm Dispersion-Shifted Fiber, N. Takachio, H. Suzuki, H. Masuda, and M. Koga, NTT *Network Innovation Laboratories, Japan*. 50-GHz-spaced, 32-channel, 10-Gb/s transmission in the zero-dispersion region over 80 x 80km of 1.55-μm dispersion-shifted fiber was successfully conducted by employing distributed Raman amplification. This paper demonstrates a feasibility of dense WDM systems in zero-dispersion region.

Room 6B
Rick Barry, *Sycamore Networks, USA, Presider*

5:45pm
PD10—A Programmable Rate Detector for Rapid-Reconfigurable Rate-Transparent Optical Networks, T.C. Banwell, and N.K. Cheung, *Bellcore, USA*. We report a programmable, rapid-response bit-rate detection and selection circuit that can handle a discrete and continuous range of data rates from 10 Mb/s to 1.3 Gb/s for programming burst mode and conventional clock data regeneration (CDR) functions.

5:55pm
PD11—4 x 2.5 Gb/s 4.4km WDM Free-Space Optical Link at 1550nm, G. Nykolak, P.F. Szajowski, J. Jacques, H.M. Presby, J.A. Abate, G.E. Tourgee, and J.J. Auborn, *Lucent Technologies, USA*. We describe a new world's record for Free-Space Optical Communications realized with a 4-channel, 2.5 Gb/s per channel system, operating error-free over a free-space horizontal distance of 4.4km. This is made possible by three key developments: 1) Specialized optical telescope-transceiver terminals, 2) Multimode Fiber DWDMs and 3) High power 1550nm Er/Yb optical amplifiers.

6:05pm
PD12—Long term field demonstration of optical PMD compensation on an installed OC-192 link; M.W. Chbat, T. Fuerst, J.T. Anthony, H Février, A.H. Bush, *Alcatel USA, Optical Networks*, J.-P. Soigné, B.M. Desthieux, *Alcatel, CIT, France*, S. Lanne, and D. Pennindkx, *Alcatel Corporate Research Center, France*. We demonstrate the world's first long term optical PMD compensation for an OC-192 (9.95328Gb/s SONET) signal on the installed fiber infrastructure of a network operator in East Texas. With a line PMD of 30ps, BER improvement greater than 4 orders of magnitude has been achieved.

6:15pm
PD13—Field trial experiment of CDMA fiber-optic microcellular system:FoMiCell; J.M. Cheong, S.H. Seo, Y.S. Son, T.G. Kim, H. Kim, Y.C. Chung, and S. Park, *SK Telecom Central R&D Laboratory, Korea*. We report on the filed trial experiment of a bi-directional passive optical network for CDMA mocrocellular systems. This network is useful not only for implementing cost-effective microcellular systems but also for covering the radio-blind areas such as underground shopping malls.

6:25pm
PD14—11Gb/sec Data Transmission Through 100m of Perfluorinated Graded-Index Polymer Optical Fiber, G. Giarett, W. White, M. Wegmueller, *Bell Laboratories, Lucent Technologies, USA*, R.V. Yelamarty, *Microelectronics, Lucent Technologies, USA*, T. Onishi, *Asahi Glass, Japan*. We report for the first time data transmission at 11 Gb/sec through 100m of low loss (33dB/km) perfluorinated graded index plastic optical fiber using inexpensibe, uncooled, unisolated, Fabry Perot lasers at 1.3μm and a simple InGaAs pin photodetector.

6:35pm
PD15—Ultra-Wideband WDM Transmission Using Cascaded Chirped Fiber Gratings, L.D. Garrett, A.H. Gnauck, R.W. Tkach, *AT&T Labs-Research, USA*, B. Agogliati, L. Arcangeli, D. Scarano, V. Gusmeroli, C. Tosetti, G. DiMaio, and F. Forghieri, *Pirelli Cavi i Sistemi, Italy*. We demonstrate 32-channel WDM transmission at a per-channel rate of 10 Gb/s over 375km (five amplified fiber spans) of conventional fiber. Chirped-fiber-grating modules provide dispersion compensation over an 18-nm bandwidth, and a swept-frequency measurement confirms continuous good performance across the entire band.

6:45pm
PD16—765 Gb/s over 2,000km Transmission Using C- and L-Band Erbium Doped Fiber Amplifiers, M.X. Ma, M. Nissov, H. Li, M. A. Mills, G. Yang, H.D. Kidorf, *Tyco Submarine Systems, Ltd., USA*, A. Srivastava, J. Sulhoff, C. Wolf, Y. Sun, and D. W. Peckham, *Lucent Technologies, USA*. We report 100-channel transmission of both C- and L-band with 765 Gb/s capacity over a distance of 2,000. To achieve this transmission result, we utilized dispersion flattened transmission and broadband medium gain erbium doped fiber amplifiers.

6:55pm
PD17—Full 40 Gbit/s OTDM to WDM Conversion: Simultaneous Four Channel 40:10 Gbit/s All-Optical Demultiplexing and Wavelength Conversion to Individual Wavelengths, M. Duelk, St. Fischer, E. Gamper, W. Vogt, E. Gini, and H. Melchior, *Institute of Quatum Electronics, Swiss Federal Institute of Technology (ETH), Switzerland*, W. Hunziker, *Opto Speed SA, Switzerland*, M. Puleo, R. Girardi, *CSELT, Centro Studi e Laboratori Telecommunicazioni, Italy*. 40 Gbit/s signals are simultaneously all-optically demultiplexed and wavelength converted into four 10 Gbit/s channels of individual wavelengths with a penalty below 1.5 dB, using only one monolithically integrated Mach-Zehnder interferometer with semiconductor optical amplifiers.

7:05pm
PD18—340 Gb/s (34*10Gb/s, 50GHz Spacing DWDM) Straight Line Transmission Over 6380km with Full System Implementation Assessment, G. Vareille, F. Pitel, R. Uhel, G. Bassier, J.P. Collet, G. Bourret, and J.F. Marcerou, *Alcatel, France*. We report the first demonstration of 340Gb/s, 50GHz DWDM straight-line transmission over 6380km with performance fully consistent with transatlantic plant installation.

Room 6C/6F
Turan Erdogan, *University of Rochester, USA, Presider*

5:45pm
PD19—100nm Bandwdith Flat Gain Raman Amplifiers Pumped and Gain-Equalized by 12-Wavelength-Channel WDM High Power Laser Diodes, Y. Emori, S. Namiki, *Opto-Technology Laboratory, Furukawa Electric Co., Ltd., Japan*. We demonstrate 100nm bandwith Raman amplifiers using 12-wavelength channel WDM pump laser diode unit. The gain flatness is less than ±0.5Db, which is achieved through an asymetric channel allocation of pump ans without any gain equalization filters.

5:55 pm
PD20—Photosensitization of Optical Fiber by UV Exposure of Hydrogen Loaded Fiber, G.E. Knhnke, D.W. Nightingale, and P.G. Wigley, *Corning Incorporated, USA*, C.R. Pollock, Cornell University, USA. We report a photosensitization process in standard hydrogen loaded optical fiber. A persistent photosensitivity is produced by exposure to UV light that can be uniform or spatially tailored along the fiber length.

6:05pm
PD21—All-Fiber Wavemeter and Fourier-Transform Spectrometer, M. Froggatt, *NASA Langley Research Center, USA*, T. Erdogan, *University of Rochester, USA*. An all-fiber Fourier-transform spectrometer is proposed and demonstrated. The device is simple, compact, and functions as a wavemeter, a network monitor, or a tool for fabrication and testing of very long fiber Bragg gratings.

6:15pm
PD22—New Hydrogen Aging Loss Mechanism in the 1400nm Window, K.H. Chang, D. Kalish, and M.L. Pearsall, *Bell Laboratories, Lucent Technologies, USA*. A new type of hydrogen aging loss increase of up to 0.21 dB/km at the 1385nm OH peak can arise in some fibers when exposed to 0.01 atmospheres of hydrogen for less than 4 days at room-temperature.

6:25pm

PD23—Single-End Continuous-Wave Polarization Mode Dispersion Measurement in Long Single-Mode Fibers, F. Corsi, A. Galtarossa, L. Palmieri, *DEI, Universita di Padova, Italy*, M. Schiano, T. Tambosso, *CSELT, Italy*. Single-end measurement of statistical properties of polarization mode dispersion parameters was carried out by means of a continuous wave scheme based on the analysis of the Fresnel reflection at fiber far-end.

6:35pm

PD24—Sub-10 Femtosecond Timing Jitter of a 10-GHz Harmonically Mode-Locked Fiber Laser, T.R. Clark, T.F. Carruthers, I.N. Duling, III, and P.J. Matthews, *Naval Research Laboratory, USA*. We present the lowest measurements of timing jitter, to our knowledge, of a harmonically mode-locked fiber laser. Phase detection noise measurements demonstrate a timing jitter of less than 10fs from 100 Hz to 1 MHz.

6:45pm

PD25—CW Highly Efficient 1.24 μ Raman Laser Based on Low-Loss Phosphosilicate Fiber, E.M. Dianov, I.A. Bufetov, M.M. Bubnov, A.V. Shubin, S.A. Vasiliev, O.I. Medvedkov, S.L. Semjonov, M.V. Grekov, V.M. Paramonov, *Fiber Optics Research Center at the General Physics Institute of the Russian Academy of Sciences, Russia*, A.N. Gur'yanov, V.F. Khopin, *Institute of Chemistry of High-Purity Substances of the Russian Academy of Sciences, Russia*, D. Varelas, A. Iocco, D. Costantini, H.G. Limberger, R.-P. Salathé, *Institute of Applied Optics, Swiss Federal Institute of Technology, Switzerland*. We report the first demonstration of an extremely simple and efficient 1.24 μm phosphosilicate fiber-based Raman laser with Bragg gratings written directly in the fiber used. The laser pumped by Nd fiber laser exhibits a slope efficiency of 80%.

6:55pm

PD26—An Electrochromic Variable Optical Attenuator (ECVOA), N.A. O'Brien, J. Gordon, H. Mathew, B. P. Hichwa, *Optical Coating Laboratory, Inc. (OCLI), USA*. New electronically controlled infrared variable optical attenuators based on thin film electrochromic technology are presented. Initial ECVOA prototypes have up to 15 dB attenuation range, 0.5 dB insertion loss, and a switching rate of 5 dB/sec. These devices are broadband, continuously variable, compact and polarization insensitive.

Room 6D/6E

Bruce Nyman, *JDS Fitel, USA, Presider*

5:45pm

PD27—Electrically Tunable Power Efficient Dispersion Compensating Fiber Bragg Gratings for Dynamic Operation in Nonlinear Lightwave Systems, B.J. Eggleton, J.A. Rogers, P.S. Westbrook, and T.A. Strasser, *Bell Laboratories, Lucent Technologies, USA*. We demonstrate a power efficient (<0.5W) tunable dispersion compensating fiber Bragg grating device and show for the first time dynamic optimization of dispersion in a nonlinear lightwave system. Operation is demonstrated in a 20Gbit/s single channel NRZ system where the device was used to adjust the dispersion to the power-dependent optimal dispersion required for optimum performance.

5:55pm

PD28—Dynamic Erbium-Doped Fiber Amplifier with Automatic Gain Flattening, S.H. Yun, B.W. Lee, *FiberPro, Donam Systems, Inc., Korea*, H.K. Kim and B.Y. Kim, *Korea Advanced Institute of Science and Technology, Korea*. We demonstrate, for the first time to our knowledge, a dynamic EDFA based on automatic active gain flattening. Wide-dynamic-range gain/power control is achieved with <0.6dB signal ripple over 30nm in various operating conditions. We also show a significant advantage of the dynamic EDFA over conventional one in cascaded structures.

6:05pm

PD29—Polarization Mode Dispersion Compensation at 20Gb/s with a Compact Distributed Equalizer in $LiNbO_3$, C. Glingener, A. Schöpflin, A. Färbert, G. Fischer, *Siemens AG, Information and Communication Networks, Germany*, R. Noé, D. Sandel, S. Hinz, M. Yoshida-Dierolf, V. Mirvoda, G Feise, H. Herrmann, R. Ricken, W. Sohler, F. Wehrmann, Applied Physics and Integrated Optics, Germany. PMD of existing fibers impairs transmission as ≥ 10Gb/s. We present a 43ps PMD compensator in X-cut, Y-propagation LiNbO3 with cascaded TE-TM converters and demonstrate successful operation at 20 Gb/s.

6:15pm
PD30—Compact Integrated Dynamic Wavelength Equalizer, C.R. Doerr, P. Schiffer, L.W. Stulz, M. Cappuzzo, E. Laskowski, A. Paunescu, L. Gomez, and J. Gates, *Bell Laboratories, Lucent Technologies, USA*. An integrated dynamic wavelength equalizer that can control attenuation at 22 points across 35nm of spectrum in a smooth manner is presented. It achieves low loss and compactness because it consists of a Michelson interferometer with a waveguide grating router in only one arm.

6:25pm
PD31—Low-Loss Channelized WDM Spectral Equalizer Using Lightwave Micromachines and Autonomous Power Regulation, R. Giles, D. Bishop, V. Aksyuk, A. Dentai, R. Ruel, and E. Burrows, *Lucent Technologies, USA*. A 16-channel 100-GHz spacing WDM spectral equalizer having athermal grating multiplexer/deultiplexers and MEMS variable attenuators was demonstrated with <9.1dB excess loss, >50dB dynamic range and autonomous power regulation using self-powered optical limiters incorporating InGaAs photogenerators.

6:35pm
PD32—Photonic Spectral Encoder/Decoder Using an Arrayed-Waveguide Grating for Coherent Optical Code Division Multiplexing, H. Tsuda, H. Takenouchi, T. Ishii, K. Okamoto, T. Gosh, and C. Amano, *NTT Photonics Laboratories, Japan*, K. Sato, A. Hirano, *NTT Network Innovation Laboratories, Japan*, T. Kurokawa, *Tokyo University of Agriculture & Technology, Japan*. Error-free spectral encoding, 40-km transmission and decoding of 10 Gbit/s, 810 fs, return-to-zero signals are successfully demonstrated using a photonic spectral encoder and decoder pair that uses high resolutin arrayed-waveguide gratings and phase filters.

6:45pm
PD33—Spectral Phase Encoding and Decoding Using Fiber Bragg Gratings, A. Grunnet-Jepsen, A. Johnson, E. Maniloff, T.W. Mossberg, M.J. Munroe, J.N. Sweetser, *Templex Technology, Inc. USA*. We domonstrate a new all-fiber technique for coherent spectral encoding and decoding based on temporal-spectral dispersion and recombination using suitably chirped fiber Bragg gratings. Application potential to optical-code division multiple access telecommunication is discussed.

6:55pm
PD34—Wavelength Selective Cross Connect Using Arrayed Waveguide Lens Multi-Wavelength Filters; C.R. Doerr, B. Mikkelsen, G. Raybon, P. Schiffer, L.W. Stulz, M. Zirngibl, G. Wilfong, M. Cappuzzo, E. Laskowski, A. Paunescu, L. Gomez, and J. Gates, *Bell Laboratories, Lucent Technologies*. We present an experimental demonstration of a partially equipped 128 x 128 OC-192 novel wavelength selective cross connect using a broadcast-and-select architecture. Novel silica multi-wavelength filters are key elements in the cross connect.

Room 5B/5A
Chung-En Zah, *Corning, Inc., USA, Presider*

5:45pm
PD35—40Gbit/s Polarization-Independent, Push-Pull InP Mach-Zehnder Modulator for All-Optical Regeneration, O. Leclerc, P. Brindel, D. Rouvillain, E. Pincemin, B. Dany, and E. Desurvire, *Alcatel Corporate Research Center, France*, C. Duchet, E. Boucherez, and S. Bouchoule, *OPTO+, France*. A polarization-independent, push-pull InP Mach-Zehnder modulator for 40Gbit/s all-optical regeneration was implemented. Error-free regenerated transmission over more than 20,000km is demonstrated. Wavelength independence and immunity to crosstalk is also measured, showing potential for WDM transmission applications.

5:55pm
PD36—All-Optical 2R Regeneration at 40 Gbit/s in an SOA-Based Mach-Zehnder Interferometer, D. Wolfson, P.B. Hansen, A. Kloh, and T. Fjelde, *Research Center COM, Technical University of Denmark, Denmark*, C. Janz, A. Coquelin, I. Guillemot, F. Gaborit, F. Poingt, and M. Renaud, *OPTO+, France*. All optical 2R regeneration in an SOA-based Mach-Zehnder interferometer is demonstrated at 40 Gbit/s. The regenerative capabilities combined with an input power dynamic range of 16dB demonstrate the feasibility of this technique at very high bit rates.

6:05pm

PD37—C-Band to L-Band Shift of 80nm (10 THz) Using Four-Wave Mixing in a Semiconductor Optical Amplifier, T.J. Morgan, R.S. Tucker, *Australian Photonics Cooperative Research Centre, University of Melbourne, Australia*, J.P.R. Lacey, *Hewlett-Packard Laboratories, USA*. We present the first demonstration of an 80-nm wavelength shift by four-wave mixing from the C-band to the L-band. The power penalty at 10^{-9} BER for a 2.5 Gb/s signal is less than 1.0 dB.

6:15pm

PD38—160Gbit/s Optical Sampling by a Novel Ultra-Broadband Switch Based on Four-Wave Mixing in a Semiconductor Optical Amplifier, S. Diez, R. Ludwig, C. Schmidt, U. Feiste, H.G. Weber, *Heinrich-Hertz Institut für Nachrichtentechnik GmbH, Germany*. We demonstrate 160 Gbit/s all-optical sampling by a compact, ultra-broadband, and low noise switch based on four-wave mixing. The switch combines high contrast (>25dB), high linearity (>20dB), and high temporal resolution (1.7ps).

6:25pm

PD39—First Undersea-Qualified 980nm Pump Laser Diode Module Evaluated with Massive Life Test, M. Usami, N. Edagawa, Y. Matsushima, *KDD R&D Laboratories*, H. Horie, T. Fujimori, I. Sakamoto, and H. Gotoh, *Mitsubishi Chemical Corporation, Japan*. 980nm pump laser diode modules with a failure rate as low as 30FIT for 27 years likefime have been successfully developed. These are the first undersea-qualified 980nm pump sources and are to be used in upcoming transoceanic submarine systems.

6:35pm

PD40—Electro-Absorption Modulated 1.55μm Wavelength Selectable DFB Array Using Hybrid Integration, L.J.P. Ketelsen, J.E. Johnson, D.J. Muehlner, M. Dautartas, J.V. Gates, M.A. Cappuzzo, J.M. Geary, J.M. Vandenberg, S.K. Sputz, M.W. Focht, E.J. Laskowski, L.T. Gomez, K.G. Glogovsky, C.L. Reynolds, S.NG. Chu, W.A. Gault, M.S. Hybertsen, *Lucent Technologies, Bell Laboratories, USA*, J.A. Grenko, J.L. Zilko, *Lucent Technologies, Microelectronics Division, USA*. We demonstrate for the first time an EA-modulated hybrid integrated wavelength selectable laser comprised of 1.55μm DFB laser array and amplifier/modulator chips fabricated using a novel spon-size converter integration technique, and optically connected via silica-on-silicon waveguides. The device operates at 2.5 Gbit/s over 16 50GHz spaced channels with SMSR > 33dB, peak power from + 1.6 to -6.2dBm, and r.f. extinction ratio > 13dB for $2.6V_{p-p}$ drive.

6:45pm

PD41—A Simple Low-Cost Polymer PLC Platform for Hybrid Integrated Transceiver modules, T. Ido, H. Ichikawa, T. Kinoshita, M. Tokuda, S. Tsuji, and H. Sano, *Central Research Laboratory, Hitachi, Ltd., Japan*, A. Kuwahara, *Telecommunications Division, Hitachi Ltd., Japan*, T. Nagara, *Hitachi ULSI Systems, Co., Ltd., Japan*. A polymer planar lightwave circuit (PLC) platform with a simple structure for hybrid integrated optical modules is described and demonstrated. A transceiver module using this low-cost platform has shown high output power (>2 mW at 60 mA) and high responsivity (>0.39 A/W).

6:55pm

PD42—Integrated Planar Waveguide Amplifier with 15dB Net Gain at 1550nm, J. Shmulovich, A.J. Bruce, G. Lenz, P.B. Hansen, T.N. Nielsen, D.J. Muehlner, G.A. Bogert, I. Brener, E.J. Laskowski, A. Paunescu, I. Ryanzansky, D.C. Jacobson, and A.E. White, *Bell Laboratories, Lucent Technologies, USA*. A packaged Er-doped aluminosilicate planaar optical waveguide amplifier (POWA) has shown net gain of 15dB (22dB) at 1550nm (1532nm) with 150 mW/980 nm pump. Low loss (0.25 dB) mode converters that couple between the POWA and standard P-glass waveguides are also demonstrated.

3 Tbit/s (160 Gbit/s x 19 ch) OTDM/WDM Transmission Experiment

S. Kawanishi, H. Takara, K. Uchiyama, I. Shake, and K. Mori

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Summary

Ultrahigh bit rate optical transmission technology that offers over Tbit/s will be needed due to the rapid growth in Internet traffic demand. Following the initial Tbit/s transmission experiments [1]-[3], many approaches have been reported to increase the bit rate and to date, 2.6 Tbit/s has been achieved [4]. In order to further increase the bit rate, broadband wavelength-division multiplexing (WDM) signal generation and broadband amplification techniques are necessary. We have reported 1.4 Tbit/s transmission by combining optical time-division multiplexing (OTDM) and WDM based on supercontinuum (SC) broadband WDM source [5]. Here we report 3 Tbit/s (160 Gbit/s x 19 channels) transmission through 40 km dispersion shifted fiber (DSF) using SC WDM sources that have flattened and broadened spectra and a gain flattened tellurite-based erbium-doped fiber amplifier (EDFA) [6].

Fig. 1 shows the experimental setup. The 3 Tbit/s OTDM/WDM signal was formed as 19 WDM channels of 160 Gbit/s OTDM signals. The wavelength of the 19 channels ranged from 1540 nm to 1609 nm with channel spacing of 480 GHz. The 3 Tbit/s signal generator consisted of two OTDM/WDM signal generators; one for the short wavelength region (1540 nm - 1566 nm) and one for the long wavelength region (1570 nm - 1609 nm). Each OTDM/WDM generator was composed of a 10 GHz mode-locked erbium-doped fiber laser, optical modulator, optical amplifier, and SC fiber. In order to stabilize the SC output spectrum, all components of the generator were polarization maintaining. The dispersion of the SC fiber decreases from anomalous to normal region from input to output and the group velocity dispersion (GVD) of the SC fiber is a convex function of wavelength and has two zero dispersion wavelengths when the peak GVD is in the anomalous region [7], which enabled the generation of a flattened and broadened SC spectrum. Fig. 2-(a) shows the generated SC spectra in the short wavelength region (pumped at 1532 nm) and the long wavelength region (pumped at 1556 nm), respectively. As seen in the figure, flat spectra were obtained for the entire signal wavelength region. The generated 10 Gbit/s SC signal pulses were then time-division multiplexed 16 times and spectrally sliced by arrayed-waveguide grating (AWG) filters [3] and re-combined to generate the 3 Tbit/s WDM signal. Fig. 3-(a) and (b) show the eye diagram of the 160 Gbit/s optical signal at 1552 nm before and after 40 km transmission, respectively. It is clear from the figure that good eye opening was observed. The 3 Tbit/s WDM signal was then amplified by a 70 nm bandwidth tellurite-based EDFA. In order to obtain the flat gain characteristics, we used two-stage tellurite-based EDFAs and an intermediate gain equalizer [8]. Figs. 2-(b) and (c) show the spectra of the signal at the input and output of the tellurite-based EDFA, respectively. As seen in the figure, 13 dB flat gain was achieved for all 19 channels. The total optical power launched into the transmission DSF was 20.2 dBm. The zero dispersion wavelength of the 40 km transmission fiber was 1535 nm, so all WDM channels were in the anomalous dispersion region. Fig.2-(d) shows the optical spectrum of the signal after transmission. Almost no degradation in the optical spectrum was observed.

At the receiver, each channel was split by an optical filter, optically pre-amplified, and then demultiplexed into a 10 Gbit/s signal by an all-optical time domain demultiplexer based on four-wave mixing driven by a 10 GHz clock extracted from the 160 Gbit/s signal channel [3] and the bit error rate was measured. Fig. 4 shows the measured sensitivity thresholds ($<10^{-10}$ bit error rate) for the base-line (filled circles) and the transmitted signal (open circles) for each channel. The 10 Gbit/s beseline signal at every wavelength showed good sensitivity characteristics below -30 dBm because we used polarization maintaining SC fiber, and therfore, the pumping condition of SC genaration was kept constant. As seen in the figure, error free operation was confirmed for all 19 channels. The large power penalty of the signals at 1540 nm, 1569 nm, and 1609 nm is mainly attributed to the gain fluctuation of the amplifiers in the transmitters because we used silica based EDFAs in the transmitters and the gain of the EDFAs at those wavelengths was less than that in other channels. Since the gain of the tellurite-based EDFAs is flat over the range 1540-1609 nm, longer transmission distance is possible if they are used as in-line repeater amplifiers.

In conclusion, we have successfully demonstrated 3 Tbit/s optical transmission over 40 km using supercontinuum WDM signal sources and a 70 nm bandwidth tellurite-based EDFA.

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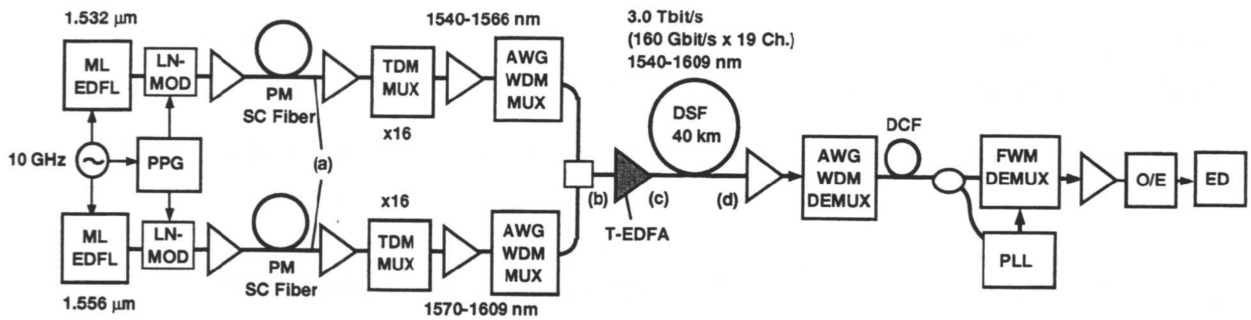


Fig. 1 Experimental setup

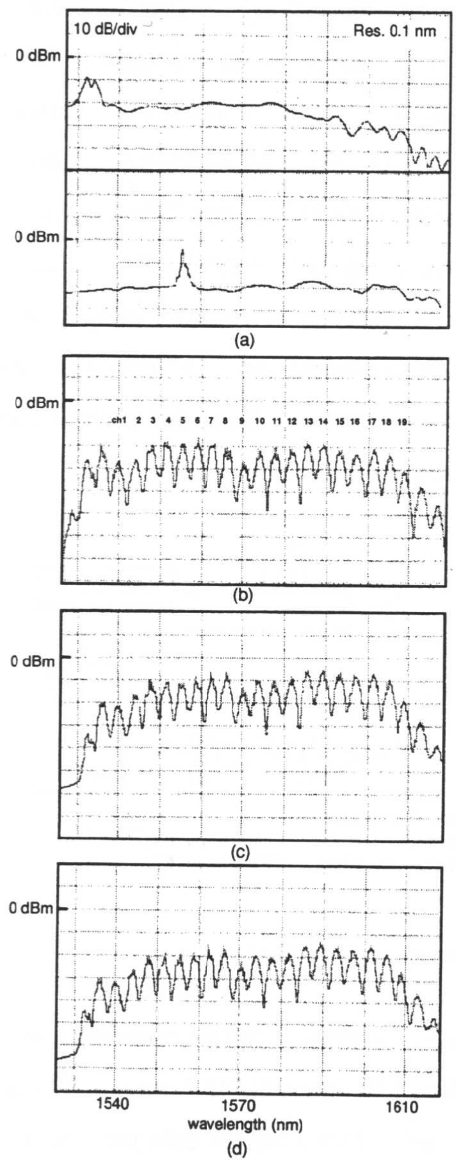


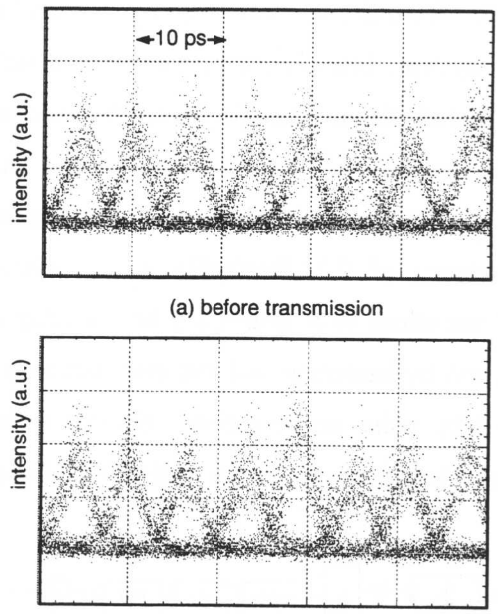
Fig. 2 Spectra

(a) SC

(b) signal before T-EDFA

(c) signal after T-EDFA

(d) signal after 40 km transmission



(a) before transmission

(b) after transmission

Fig. 3 Waveform of 160 Gbit/s optical signal at 1552 nm

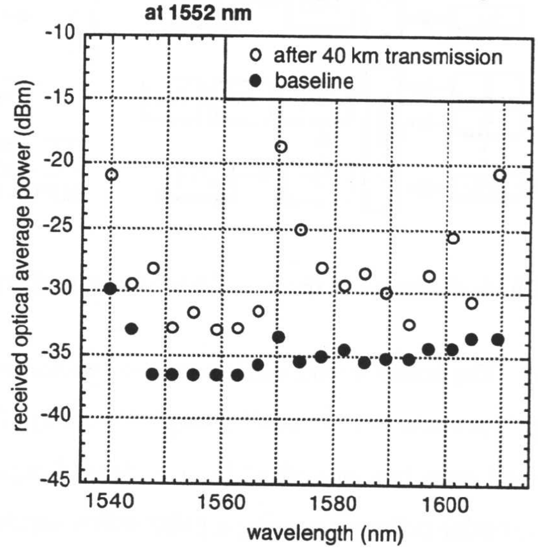


Fig. 4 Sensitivity thresholds for baseline and transmitted signal for each channel

640 Gb/s Transmission of Sixty-four 10 Gb/s WDM Channels Over 7200km With 0.33 (bits/s)/Hz Spectral Efficiency

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Introduction: To make a significant improvement in the spectral efficiency of a long-haul WDM transmission system, interactions between the closely spaced channels must be managed. These interactions include linear crosstalk caused by spectral overlap at the transmitter, non-linear crosstalk caused by the transmission fiber's non-linear index, and linear crosstalk caused by non-ideal filtering at the receiver. In this work we achieved a total transmission capacity of 640 Gb/s over 7200 km, with a spectral efficiency of 0.33 (bits/s)/Hz using sixty-four 10 Gb/s channels spaced 30 GHz apart. Non-linear interactions were minimized by operating the system at relatively low power, using a large mode fiber, and by launching odd and even channels in orthogonal polarizations. The potential error floors caused by noise accumulation, channel overlap,[1] and operation far from the average zero dispersion wavelength were removed with a Reed-Solomon *F*orward *E*rror correcting *C*ode (FEC).[2,3]

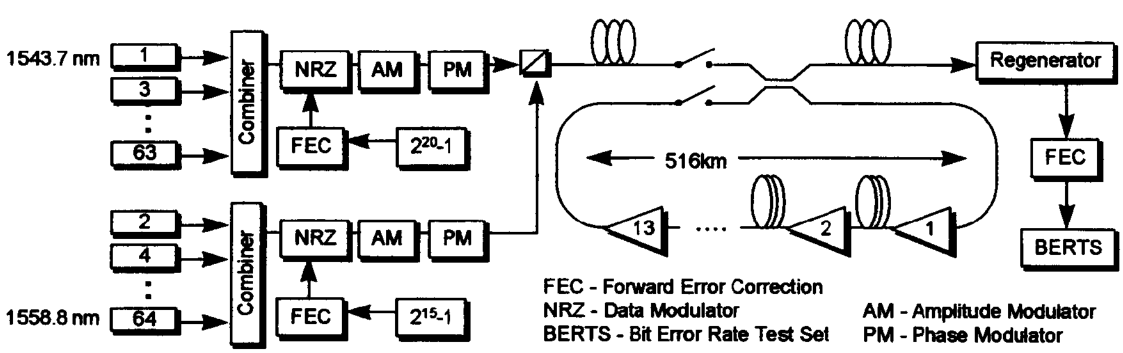

Figure 1 - Block diagram of the 640 Gb/s 64 channel transmission experiment.

Experiment: The transmission experiment was performed using a 64 channel WDM transmitter and a 516 km amplifier chain in a circulating loop[4] (Figure 1). Sixty-four CW lasers (1543.7 nm - 1558.8 nm) were combined onto two optical paths, modulated separately using two different data patterns, then combined pair-wise orthogonal using a polarization dependent beam combiner.[5] Using the two different data patterns for the even and odd channels insured that any nearest neighbor crosstalk caused by the closely spaced channels appeared as a random interference at the receiver. The transmission format was a chirped return-to-zero waveform with a pulse width of ~40 psec FWHM. The actual transmission bit rate was increased by 7% to 10.7 Gb/s with the addition of the 255/239 Reed-Solomon FEC frame format. The binary data in the FEC frame's payload section contained a pseudo-random word of length 2^{20}-1 and/or 2^{15}-1. The FEC decoder could correct randomly distributed errors occurring at a rate of 10^{-4} to a rate well below 10^{-10}.

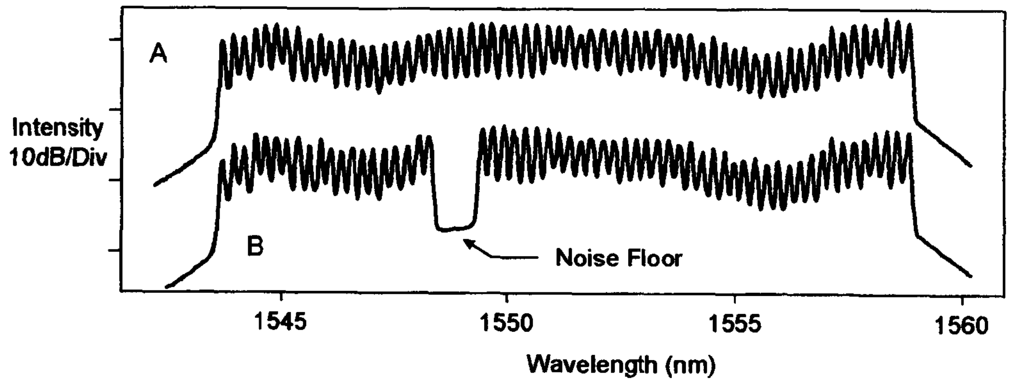

Figure 2 - A) Received optical spectrum for the 64 channels at 7,200 km. B) Received optical spectrum with channels 21 through 24 turned off to show the true noise floor.

The amplifier chain used ten 50 km transmission spans and 13 single-stage co-pumped EDFAs with a noise figure of 4 dB, and a total launch power of 13.5 dBm, or 350 μW/Channel. Nine of the ten spans were a hybrid configuration made from large-mode fiber, and dispersion shifted fiber.[5] These spans had an average dispersion of -2 ps/km-nm at the center wavelength. One span of conventional single-mode fiber was used to balance the dispersion, making the average zero dispersion wavelength ~1551 nm, with a dispersion slope of <0.09 psec/km-nm^2. Two gain equalizing filters were used to increase and flatten the gain shape of the amplifier chain, for an equalized bandwidth of 16 nm.

Results: Figure 2 shows the received optical spectrum. Here we note that the 0.08 nm resolution bandwidth of the optical spectrum was insufficient to resolve the data channels spaced at 0.24 nm. The second curve in Figure 2 indicates the true noise floor by showing the spectrum with a subset of the channels turned off. The accumulated dispersion of each channel was equalized using a combination of pre-compensation at the transmitter and post-compensation at the receiver.[6] Each channel was selected at the receiver using a narrow band optical filter with a 3 dB bandwidth of ~18 GHz, yielding >20 dB rejection of the nearest channels. The bit error rate of each channel was measured for a time period long enough to record about 10^{10} bits with the FEC decoder enabled (about 4 minutes of real time given the duty cycle of the circulating loop). The BER was measured a second time with the FEC decoder disabled (Figure 3). All 64 channels were error free over the measurement interval with the FEC decoder enabled; thus, with 95% confidence the actual error rate was below 3×10^{-10}. The average Q-factor for the channels was 12 dB, yielding an uncorrected bit error rate between 10^{-4} and 10^{-6}. To access the importance of the orthogonal polarization launch the performance of channel 34 was re-measured with a state-of-polarization parallel to it's nearest neighbors. This resulted in a 1.1 dB decrease in the Q-factor, as indicated with the (•) symbol in Figure 3.

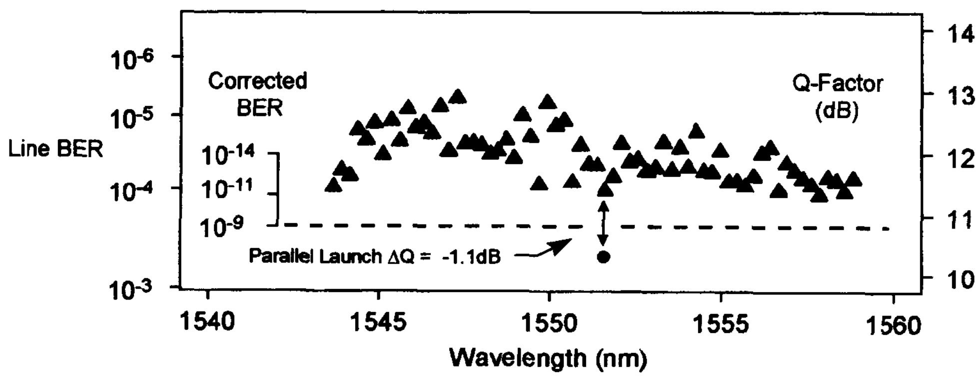

Figure 3 - Line BER, corrected BER and corresponding Q-Factor vs wavelength.

Conclusions: We have made a significant improvement in the transmission capacity and the spectral efficiency of a transoceanic length WDM transmission experiment. By managing the interactions between channels, sixty-four 10 Gb/s WDM channels were transmitted over 7200 km in a spectral bandwidth of 15.1 nm for a spectral efficiency of 0.33 (bits/s)/Hz. Forward error correction coding was used to remove any bit errors occurring in the experiment; thus, error free operation was achieved for all channels.

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1220km propagation of 40Gbit/s single channel RZ data over dispersion managed standard (non-dispersion shifted) fibre.

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Error free propagation of a single polarisation optical time division multiplexed 40Gbit/s dispersion managed pulse data stream over 1220km has been achieved in dispersion compensated standard (non-dispersion shifted) fibre. This distance is twice the previous record at this data rate.

We have recently reported preliminary transmission results at 40 Gbit/s over 509km of standard fibre using a simple dispersion compensation technique[1]. This compared favourably with alternative methods including polarisation multiplexing [2] and mid-span spectral inversion that acheived a 400km propagation distance at the same data rate[3,4]. However, numerical simulations have suggested that adoption of a modified dispersion compensation format should extend the acheivable 40 Gbit/s transmission distance to over 2000km of standard fibre[5]. We now report the experimental acheivement of error-free propagation of a single polarisation 40Gbit/s RZ data stream over a transmission distance of 1000km in standard fibre, representing the first demonstration of 40 Gbit/s transmission in standard fibre over this distance and exceeds our previous achievement by a factor of two. These results were obtained using a single length of dispersion compensating fibre in each amplifier span, and imply the realistic prospect of upgrading standard fibre systems to 40 Gbit/s by a straightforward passive scheme.

The experimental setup is shown in Fig 1. The 10 GHz external cavity mode-locked laser (ECMLL) source provided 7.2ps pulses with a time-bandwidth product of 0.45 at the operating wavelength of 1544nm. A 10Gbit/s 2^{31}-1 PRBS data pattern was imposed on the ECMLL pulse stream by a lithium niobate amplitude modulator (AM), and this bit stream was multiplexed up to 40Gbit/s using a fibre delay line multiplexer (MUX) in a now standard configuration.

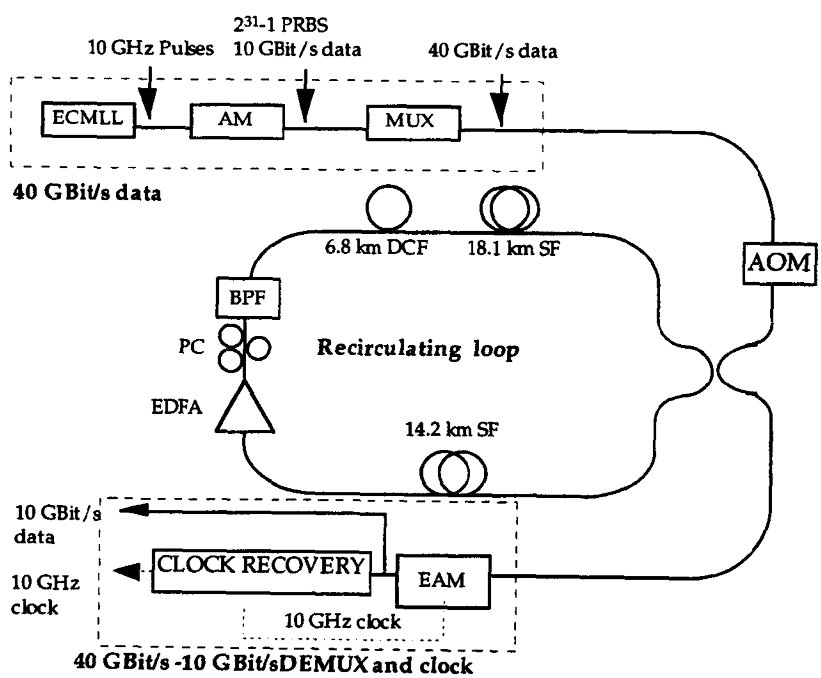

Fig. 1 Schematic diagram of experimental set-up showing the 40Gbit/s data generator, recirculating loop and 40Gbit/s to 10Gbit/s demultiplexer

The transmission experiments were carried out using a single span recirculating loop containing a single erbium doped fibre amplifier (EDFA) and a 2.3 nm optical bandpass filter. The loop itself consisted of 32.3km of standard fibre (SF), in section lengths of 14.2km before and 18.1km after the EDFA respectively, with an average dispersion of +16ps/(nm km) and 6.8km of dispersion compensating fibre (DCF) with a dispersion of -76ps/(nm km). The average dispersion zero wavelength was 1543nm and at the operating wavelength the overall average dispersion was +0.03ps/(nm km), the DCF also providing partial slope compensation resulting in a value of +0.03ps/(nm^2 km) for the fibre combination.

The 40Gbit/s data stream was demultiplexed to 10Gbit/s using an electroabsorbtion modulator (EAM) and a following 10 GHz Phase Locked loop (PLL) clock recovery unit[6]. The recovered clock was used as a trigger for both the bit error rate and sampling oscilloscope measurements, and to drive the EAM. Separate 10Gbit/s channels were selected by means of a microwave phase shifter (PS) connected to the EAM drive line. Fig. 2 shows eye diagrams corresponding to (a) the 10Gbit/s back-to-back performance, (b) the multiplexed 40Gbit/s data stream, and (c) ta demultiplexed 10Gbit/s channel, respectively,indicating little signal degradation after demultiplexing.

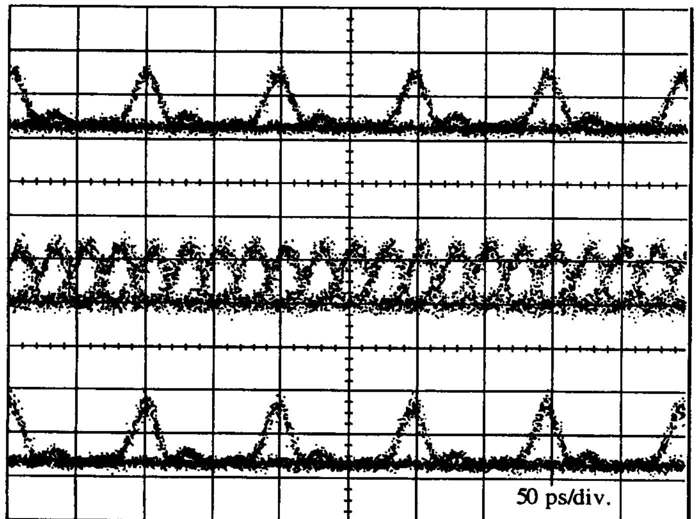

Figure 2. Eye diagrams for (a) 10Gbit/s back-to-back performance , (b) 40Gbit/s multiplexed data and (c) demultiplexed 10Gbit/s data

Identification of the correct location of the data insertion/extraction point in the fibre span represents a crucial aspect of these experiments. The high values of local dispersion and the relatively narrow pulse width employed combine to produce a large map strength [7] of 25, highlighting a significant issue for 40Gbit/s dispersion managed standard fibre systems. The correspondingly large amount of pulse breathing which can rapidly lead to unacceptable signal degradation through pulse interactions. In our experiment there was a rapid increase of the ~7ps pulse width away from the transform limited point in the dispersion map to as much as 100ps at the junction of the DCF and the SF. For error free detection, it is crucial that the data stream is extracted at a point close to the transform limited position in the dispersion map and, thus, that it is injected at an appropriate position in the loop. In our experiments, the injection point is close to the mid-point of the SF span, as depicted in figure 1. To simulate potential upgrade, the DCF was located adjacent to the EDFA, with lengths of SF before and after this combination. It is interesting to note that although dispersion managed soliton transmission techniques have been utilised here, as in the numerical simulations reported in [6], the quasi-linear RZ experimental pulses did not exhibit the usual energy enhancement associated with dispersion managed solitons. Indeed, the low value, ~11fJ, of the optimum pulse energy was comparable with that of a fundamental soliton in the equivalent uniform dispersion system.

The measured BER against propagation distance for a single channel is given in Fig. 3. These results demonstrate that a BER of $<10^{-9}$ was maintained after 32 recirculations of the loop, corresponding to a transmission distance of 1220km (1003km of standard fibre) or 1254 dispersion lengths. The Insets in Fig. 3 give the measured eyes corresponding to (a) 1220km and (b) 1411km transmission distances, and indicate that the eye closure after propagation was due to timing jitter. The most likely cause of this jitter is pulse interactions although Gordon-Haus effects may also contribute in small part. There was no significant eye closure ascribable to an increase in the noise level. Although the demonstrated propagation distance is the greatest yet achieved over standard fibre at 40Gbit/s, it falls short of the ~2000km limit predicted by numerical simulations[5]. One likely contributable reason is that lack of ideal fibre lengths for our experiments precluded positioning of the amplifier within the DCF span, corresponding to the optimum position determined numerically. Further investigation of this, along with further optimisation of the data insertion/extraction point in the SF span, should close the gap.

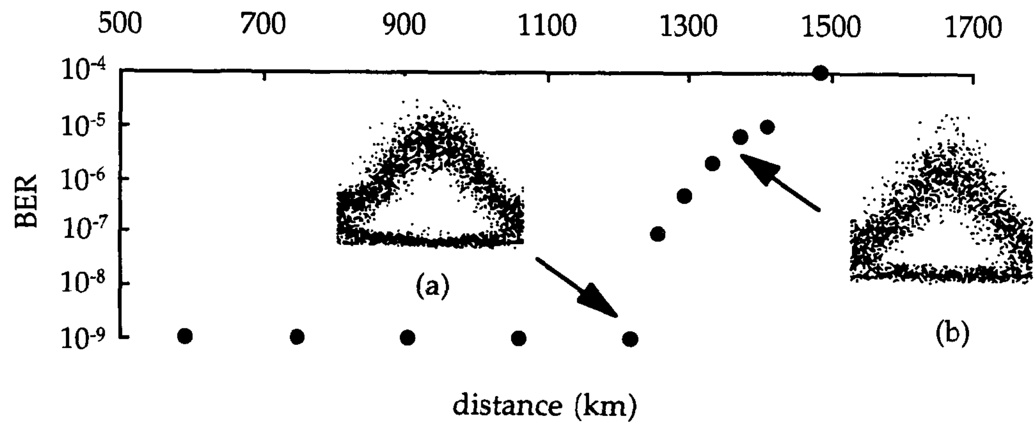

Figure 3. BER against propagation distance results for a 10Gbit/s demultiplexed channel showing demultiplexed eye (a) Back-to-back, (b) after 1220km (error free) and (c) after 1411km

In conclusion, we have performed a single polarisation, single channel 40Gbit/s transmission experiment over standard fibre with an error-free (BER $< 10^{-9}$) propagation distance of 1220km. This distance is a new record over standard fibre and furthermore it was achieved using the entirely passive technique of dispersion management. This result shows that existing short-haul standard fibre links can easily be upgraded to 40Gbit/s. Although the amplifier span in our experiment (39km) was restricted by the DCF available, the fact that the system was not noise limited is an indication that a larger amplifier spacing may be possible.

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Narrow band 1.02 Tbit/s (51 × 20 Gbit/s) soliton DWDM transmission over 1000 km of standard fiber with 100 km amplifier spans

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Pioneer Tbit/s experiments [1-5] used a single EDFA band and were achieved with a high spectral efficiency (0.25 to 1 bit/s/Hz). However the transmission distance (≤150 km) was limited by non linear effects. Larger transmission distances (4x100 km [6] and 10x60 km [7]) were achieved to the expense of a reduction of the spectral efficiency (≤ 0.2 bit/s/Hz) and the use of two EDFA bands.

Thanks to a proper control of the fiber non linearity with dispersion-managed solitons (DMS) [8], the 1 Tbit/s transmission distance is increased up to 1000 km without reducing neither the amplifier span loss nor the spectral efficiency.

The key figures of this experiment are **1.02 Tbit/s (51×20 Gbit/s)** capacity, **1012 km** standard step-index fiber **(SMF)** transmission distance, **101.2 km** amplifier span (**21 dB/span** loss), **0.4 bit/s/Hz** spectral efficiency (0.4 nm channel-spacing and 2/3 of the C-band used). A record **1032 kmTbit/s** distance bit-rate product on standard fiber is obtained.

The key elements of the success of this experiment are the use of soliton, a prechirp optimization and a dispersion slope reduction, which improves the stability of DMS for all channels.

The experimental setup is shown in Fig.1. The outputs of 51 lasers are multiplexed using two interleaved arrayed waveguide gratings (AWG) with 100 GHz periodicity and optical fiber couplers (OFC). The channel spacing is 50 GHz (0.4 nm). The multiplexed channels are then coded by a first $LiNbO_3$ Mach-Zehnder electrooptic modulator (EOM_1) fed with 2^{15}-1 pseudo random binary sequence at 10 Gbit/s. Polarization controllers at the output of each laser allow independent polarization control for each source in order to align all the polarizations with that of the modulator. Pulses are shaped with 25 ps FWHM by using a second modulator (EOM_2) fed with a combination of two electrical signals at 10 and 20 GHz . The amplified output of the modulator is optically multiplexed in time and in polarization. A polarization-maintaining optical line is used between the first modulator and the optical multiplexer to obtain a 20 Gbit/s signal. Prechirping is achieved by using a short length of dispersion-compensating fibre (DCF) with −150 ps/nm of cumulative dispersion. The 20