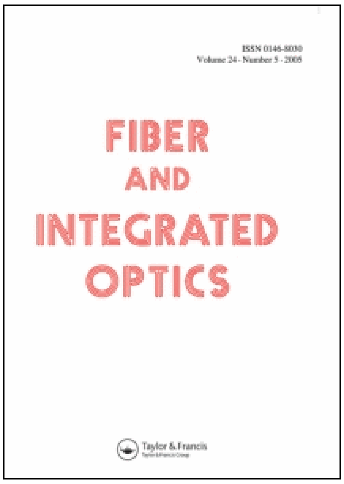

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Simulation Results for DWDM Systems with Ultra-High Capacity

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We present stimulation results for DWDM systems with an ultra-high capacity up to 1.28 Tbit/s and spectral efficiency approaching 0.4 bit/s/Hz. The impact of signal-to-noise ratio (SNR) on parameters such as channel spacing, length of fiber, dispersion, and number of channels has been investigated and the results obtained have been explained on the basis of fiber nonlinear effects. It has been shown that with an increase in channel spacing, the SNR increases to the maximum optimum value and then decreases to a steady value. With an increase in number of channels, the SNR decreases for small wavelength spacing. For large wavelength spacing, it becomes independent of the number of channels. Keeping channel spacing constant, the SNR decreases with an increase in the length of the fiber. The SNR also improves with a small increase in dispersion of the fiber. Further, it is observed that, with increase in length over dispersion-shifted fiber, the received power decreases and the bit error rate increases.

Keywords signal-to-noise ratio, channel spacing, dense wavelength division multiplexing, dispersion, fiber nonlinearities, bit error rate

The major challenges of today's telecommunications networks are to provide more and cheaper bandwidth and integrated services using different technologies over the same physical infrastructure. The Dense Wavelength Division Multiplexed system (DWDM) emerges as an optical technology that promises to meet these challenges. Transmission systems based on optical fiber (DWDM) technology have indeed revolutionized the field of communication. This is because the usable transmission bandwidth on the optical

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fiber is so enormous that it is capable of transmitting multichannels over long distances. The revolutionary growth in Internet traffic is forcing network operators to deploy ever higher transmission capacities in their terrestrial fiber backbone networks. It is anticipated that in the near future, it will be necessary to offer multiterabit capacities over a single fiber, based on the use of this DWDM technology. To cope with this demand, it is likely that the next generation of Wavelength Division Multiplexing (WDM) systems will use a 40 Gbit/s or higher bit rate [1, 2]. DWDM is a technology that uses multiple wavelengths to transport a large number of individual channels, typically at bit rates of 2.5 Gbits/sec or higher. Over the next few years, advances in fiber, amplifiers, and other components will see the emergence of channel counts as high as 1000 per fiber offering fiber capacities close to 40 Tbits/sec per fiber over a spectral range from 1240 nm to 1640 nm. But major limitations in the development of these futuristic DWDM systems are signal degradation due to chromatic dispersion and nonlinear effects such as Self Phase Modulation (SPM), Cross Phase Modulation (XPM), Four Wave Mixing (FWM), Stimulated Raman Scattering (SRS), and Stimulated Brillouin Scattering (SBS). Each nonlinearity manifests itself in a specific way. However, by cleverly designing the system, the effects of nonlinearities can be minimized. SBS can be avoided by broadening the carrier component of the signal. SPM degrades the systems with dispersive fibers. The effects of SPM and XPM can be reduced by appropriate use of dispersion shifted fibers. Degradations caused by XPM and FWM are reduced by the effects of dispersion. SRS, however, affects all WDM systems at 1.55 μm.

Further, EDFAs are used as line amplifiers to extend the system span. At the receiver end, the individual channels are demultiplexed and routed to individual receivers. Typically system spans of 600–700 km are currently possible using optical line amplifiers only. Beyond this distance full "3R" electronic regeneration is required. The channel spacing and wavelengths are defined by the ITU-T standards body. Channel spacing generally ranges from 1.6 nm (200 GHz) to 0.4 nm (50 GHz). The industry is moving toward wider wavelength ranges with narrower channel spacing down to 0.2 nm (25 GHz) and below. Products with higher channel counts, utilizing the L-band are becoming increasingly available.

In mid-2000, two experimental laboratory systems using this channel rate demonstrated that a total throughput of 3 Tbit/s [3] could be achieved by making use of the C and L bands with Erbium-Doped Fiber Amplifiers (EDFA). At the European Conference on Optical Communication (ECOC) in September 2000, even higher capacities were reported using the 40 Gbit/s channel bit rate. A team from NEC [4] used polarization division multiplexing to reach 6.4 Tbit/s over 186 km of fiber, while a team from Siemens [5] achieved 7 Tbit/s over a more limited 50 km using bidirectional transmission. However, the Alcatel contribution to ECOC 2000 [6] reported the largest ever capacity and distance product at 40 Gbit/s [7]. Moving from a 10 Gbit/s channel rate to a 40 Gbit/s channel rate in WDM systems is expected to offer cost benefits, not only because only one quarter the number of channels is required to provide the same capacity, but also because it makes optical network management easier [8–10]. However, a greater advantage is that operation at 40 Gbit/s makes it possible to achieve higher throughputs than at 10 Gbit/s.

In today's most advanced 10 Gbit/s DWDM systems, channels are spaced every 50 GHz. In such systems, the amount of information per unit optical bandwidth, also known as the spectral efficiency, corresponds to h = 0.2 bit/s/Hz, where h = bit rate/spectral spacing of the optical channels. However, 10 Gbit/s DWDM system using a 25 GHz channel spacing are now being considered to realize a spectral efficiency of 0.4 bit/s/Hz. With respect to such systems, moving from the 10 Gbit/s channel rate to

40 Gbit/s is beneficial in terms of total capacity only if, at the same time, the channel spacing is less than 100 GHz, so that the efficiency h is increased beyond 0.4 bit/s/Hz. In this article, we realize systems with spectral efficiency approaching 0.4 bit/s/Hz.

The most common optical parameters for DWDM systems include channel center wavelength, channel spacing, per channel power level, number of channels, dispersion, length of fiber and signal-to-noise ratio [11]. The ITU-T specifies the emission wavelengths to be used in DWDM systems. This article reports results of simulations up to 128 WDM channels. Different simulation setups have been taken by choosing different parameters to compile different comparison results. The simulated bit rate is 10 Gbit/s through 128 simulated bits. The lowest channel frequency is 193.1 THz. The channel spacing has been maintained from 3.6 nm to 0.2 nm. The transmitter has been chosen to be externally modulated at 10 Gb/s with a CW Lorentzian laser with 0 dBm launch power and 10 MHz line width. The driver is NRZ rectangular with Elbassels filter and ideal multiplexer. The gain and noise figure of EDFA is 10 dB and 4.5 dB, respectively. The multiplexers and demultiplexers are assumed to be ideal. The receiver is a sensitivity receiver with an optical Gaussian optical filter and an avalanche photodetector (APD). The SNR per channel is measured at the output of the last channel. The bit error rate assumed is 10^{-12} unless stated (last two simulations). All fiber nonlinear, birefringence, and polarization mode dispersion effects are considered in the simulations. The PMD coefficient of the fiber is 0.1 ps/$\sqrt{\text{km}}$.

Results and Discussions

The simulation results for DWDM systems with an ultra-high capacity up to 1.28 Tbit/s and spectral efficiency approaching 0.4 bit/s/Hz are presented. The calculation of the propagation in the optical fibers is performed by a standard split-step algorithm with adaptive step-size [12]. The impact of SNR on parameters such as channel spacing, length of fiber, dispersion, and number of channels is investigated. Through our simulation results, we plot SNR for channel spacing, number of channels, length of fiber, and dispersion. In the first simulation, the total transmission capacity of 1.28 Tbit/s is achieved over five spans of dispersion shifted fibers ($5 \times$ 50 km) with loss 0.2 dB/km and zero dispersion wavelength of 1.55 μm. The dispersion slope and nonlinear coefficient of Dispersion Shifted Fiber (DSF) is 0.06 ps/nm^2/km and 2.6 W^{-1} km^{-1}. Five EDFA amplifiers with a gain of 10 dB are placed at the beginning of each span to amplify the signals in each span. Figure 1 shows the SNR plotted against channel spacing for different channels. It is seen that as the channel spacing is increased, the signal-to-noise ratio increases and the performance becomes better. This is because of the fact that as the wavelength spacing is decreased, the wavelengths tend to overlap each other causing more dominance of Cross Phase Modulation (XPM) effects caused by the optical Kerr effect resulting in more bit error rate. It is observed that the increase is linear up to wavelength spacing of 0.9 nm, indicating that the signal-to-noise ratio improves considerably with increase in wavelength spacing. After 0.9 nm, the slope decreases and SNR becomes maximum at 1.2 nm. We conclude that if the channel spacing is sufficiently large so that the wavelengths do not interfere, the performance becomes optimum and no further improvement is observed. After this optimum performance, SNR reduces to a steady value at 3.6 nm and becomes independent of the channels at still larger wavelength spacing. With an increase in number of channels, the SNR decreases but it is observed that almost the same steady value is reached for all the channels at larger wavelength spacing. The decrease in the SNR after the optimum value can be explained by the SRS effect that transfers power from shorter to longer wavelength channels. The power lost can degrade

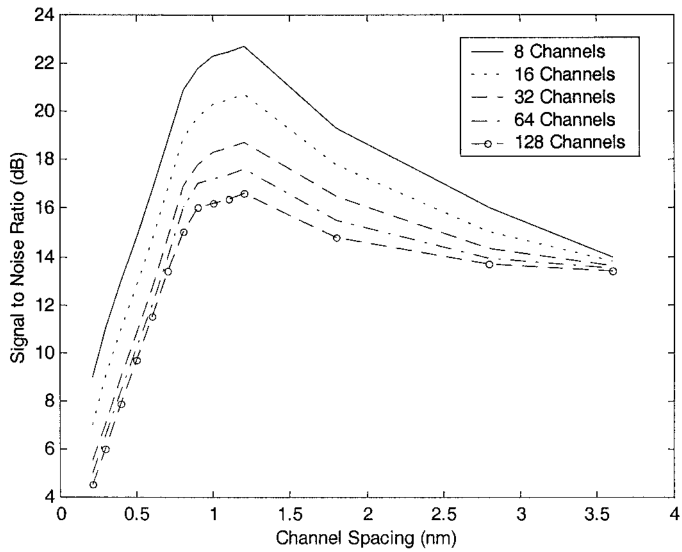

Figure 1. Signal-to-noise ratio plotted against channel spacing for different channels; launched power = 1 mW, five span DSF of length 50 km with EDFA in the beginning of the span.

the signal-to-noise ratio. So for a given system, there is an optimum wavelength spacing by which the XPM and SRS effects are minimized. Also if the channel spacing is less than 0.2 nm, the performance is not as good. As the channels increase from 8 to 128, the SNR decreases approximately by 4.3 dB at this channel spacing. Further narrow channel spacing puts more constraints on the DWDM devices.

Keeping all parameters in the simulation setup and taking 32 channels with channel spacing of 0.4 nm, the dependence of SNR on the transmission distance is shown in Figure 2. It is observed that the SNR decreases as the transmission distance is increased. Again if the wavelength spacing is decreased, the signal-to-noise ratio decreases. This is because of the nonlinear effects induced by EDFA amplifiers. However, if the power over the length is kept constant and at low levels, the signal-to-noise ratio will improve over distances. This is possible if the fiber span length is small and the number of amplifiers is greater.

To observe dependence of SNR on dispersion of the fiber, we take another simulation setup and replace the special fiber whose dispersion is varied. Five spans of this fiber ($5 \times 50 = 250$ km) are compensated by Bragg's grating for dispersion compensation at each span. The nonlinear coefficient of the fiber is 1.8 W^{-1} km^{-1}. Five EDFAs with a gain of 10 dB each are positioned at the beginning of the span and are used to amplify signals. The channel spacing chosen for this simulation is 0.4 nm and dispersion is varied in steps. The dependence of SNR on dispersion of the fiber is shown in Figure 3. It is observed that as the dispersion is increased, the system performance increases. In Figure 3, as the dispersion is varied from 2 to 3 ps/nm/km, the system performance improves significantly. But as the dispersion increases beyond 3 ps/nm/km, the slope decreases and later on becomes almost zero, indicating no further improvement. This can be explained by the fact that nonlinearities like FWM can be significantly reduced on increasing dispersion. Now if the number of channels is increased, the system performance deteriorates. As is clear from Figure 3, it degrades by 6 dB in the steady state as the number of channels increase from 8 to 128 at a dispersion of 10 ps/nm/km.

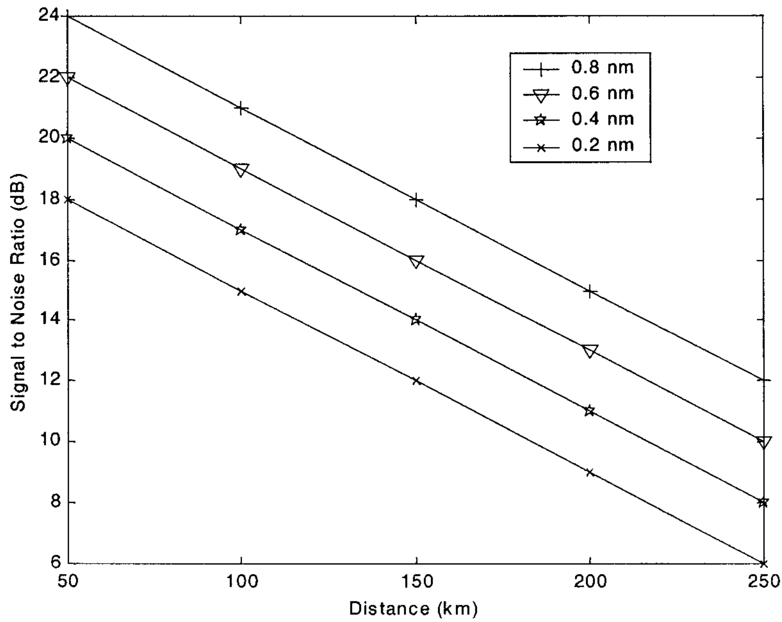

Figure 2. Signal-to-noise ratio plotted against distance for different channel spacing; launched power = 1 mW, five span DSF of length 50 km with EDFA in the beginning of the span; number of channels = 32.

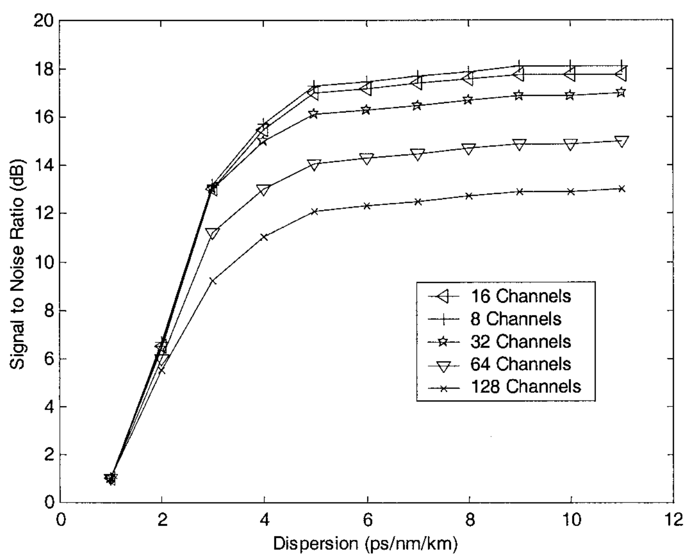

Figure 3. Signal-to-noise ratio plotted against dispersion for different channels; launched power = 1 mW, five spans of fiber of length 50 km each with EDFA in the beginning of the span, channel spacing = 0.4 nm.

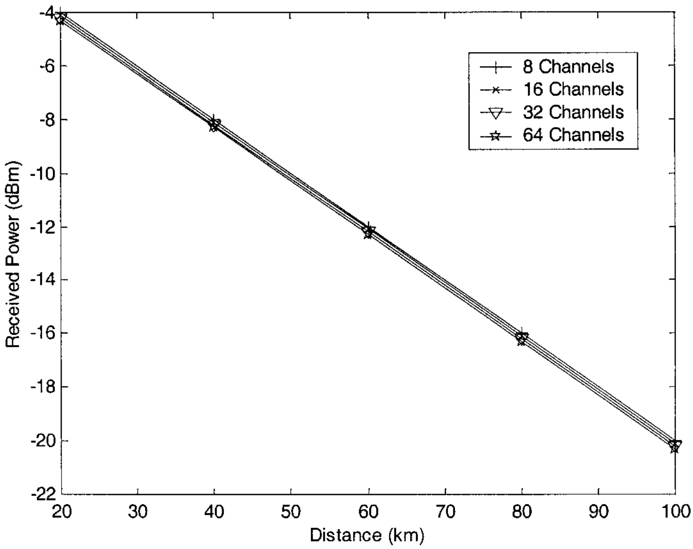

Figure 4. Received power plotted against distance for different channels of dispersion shifted fiber single span with length 100 km; launched power = 1 mW, channel spacing = 0.4 nm.

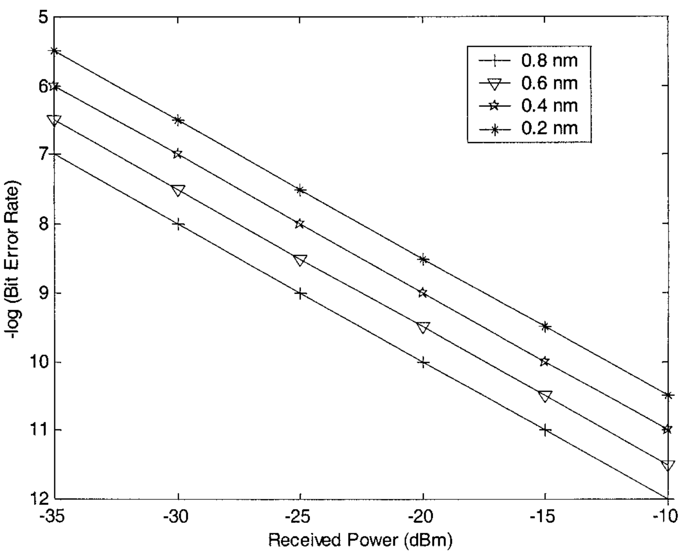

Figure 5. Bit error rate ratio plotted against received power for different channel spacing in dispersion shifted fiber with length 100 km; launched power = 1 mW, five span DSF of length 50 km with EDFA in the beginning of the span, number of channels = 32.

To study variance of received power over fiber length, let us take another simulation setup. Here, only a single span of anomalous dispersion shifted fiber 100 km long is taken. No BER is specified for this simulation. The parameters of DSF are the same as that of the first simulation. There is EDFA before the span only, i.e., there is no EDFA after the span. The power meter is used to measure the received power. Figure 4 shows the received power as a function of distance. It is apparent that the received power decreases with distance and, further, the number of channels have no impact on the received power.

Now, in order to see the performance of multispan dispersion shifted fibers, we increase the number of spans to five each with a length of 50 km. Five EDFAs with gain of 10 dB are again placed at the beginning of the span. The number of channels is 32. The power meter and BER meter at the output measure the received power and bit error rate. For this received power, the bit error rate is shown in Figure 5. It is seen that as the received power is increased, the bit error rate decreases. Again, with decrease in the wavelength spacing, the bit error rate increases. The results agree with the experimental results reported in [13, 14]. In [13], 8 channels at 20 Gb/s with six 50-km spans were transmitted and bit error was plotted against received power. Similarly, bidirectional DWDM transmission [14] using the beat-frequency locking method was demonstrated at 10 Gb/s and 0.4 nm channel spacing and bit error rate was measured. These experimental results validate our simulation results.

Conclusions

We have presented results for DWDM systems with an ultra-high capacity up to 1.28 Tbit/s and spectral efficiency approaching 0.4 bit/s/Hz. The impact of signal-to-noise ratio on parameters like channel spacing, length of fiber, dispersion, and number of channels has been investigated. It is seen that as the channel spacing is increased, the signal-to-noise ratio increases and the performance becomes better. This is because of the fact that as wavelength spacing is decreased, the wavelengths tend to overlap each other, causing a dominance of XPM effects caused by the optical kerr effect resulting in more crosstalk. The SNR increases to a maximum value as the channel spacing is increased. With further increase, the SNR reduces to a steady value and no further change is observed. The decrease in the system performance can be explained by the SRS effect, which transfers power from shorter to longer wavelength channels. The power lost can degrade the signal-to-noise ratio. So for a given system, there is optimum wavelength spacing where the XPM and SRS effects are minimized. With an increase in number of channels, the SNR decreases. It becomes independent of the channels if channel spacing is very large. The dependence of signal-to-noise ratio on the length of a fiber is further investigated. It is observed that the signal-to-noise ratio decreases as the transmission distance is increased. This is because of the nonlinear effects induced by EDRA amplifiers. However, if the power over the length is kept constant and at low levels, the signal-to-noise ratio will improve over distances. This is possible if the fiber span length is small and number of amplifiers is greater. The dependence of SNR on dispersion is next investigated. It is found that as the dispersion is increased the system performance increases. For initial changes in the dispersion values, the signal-to-noise ratio increases more rapidly but later it becomes steady. This is because nonlinearities like FWM can be significantly reduced on increased dispersion. If the number of channels is increased, the system performance decreases. Again, if the wavelength spacing is decreased, the signal-to-noise ratio decreases. The received power as a function of distance for single-span anomalous dispersion shifted fiber shows that the received power decreases with distance and, further, that the number of channels has no impact on the received power. As the received power is increased, the bit error rate decreases. Again with decrease in the wavelength spacing, the bit error rate increases. The experimental results reported [13, 14] validate our simulation results.

References

1. Nielsen, T., and L. Nelson. 2000. 3.28 Tbit/s (82 × 40 Gb/s) transmission over 3 × 100-km nonzero-dispersion fiber using dual C- and L-band hybrid Raman/Erbium-doped inline amplifiers. *OFC 2000*. Postdeadline paper 23.
2. Bonati, A., J. Chesnoy, M. Erman, P. M. Gabla, B. Paicentini, and C. Reinaudo. 1999. Global turnkey solutions for backbone transmission networks. *Alcatel Telecommunications Review*.
3. Elbers, J. P., and C. Glingener. 3.2 Tbit/s (80 × 40 Gbit/s) bi-directional DWDM/ETDM transmission. *ECOC'99*. Nice. Postdeadline paper 2-5.
4. Ito, T., Y. Nakanishi, and K. Fuji. 6.4 Tbit/s (160 × 40 Gb/s) WDM transmission experiment with 0.8 bit/s/Hz spectral efficiency. *ECOC 2000*. Postdeadline paper 1.1.
5. Färbert, Y. Takeshi, and K. Kunio. 7 Tbit/s (175 × 40 Gb/s) bidirectional interleaved transmission with 50 GHz channel spacing. *ECOC 2000*. Postdeadline paper 1.3.
6. Bigo, S., G. Belloti, and S. Gauchard. 5.12 Tbit/s (128 × 40 Gbit/s WDM) transmission over 3 × 100 km of TeraLight Fiber. *ECOC 2000*. Postdeadline paper 1.2.
7. Hanik, N., C. Caspar, and F. Schmidt. Optimized design of transparent optical domains. Proc. ECOC 2000, paper 3.5.
8. Bigo, S., G. Belloti, and S. Gauchard. 1.28 Tbit/s WDM transmission of 32 ETDM channels at 40 Gbit/s over 3 × 100 k distance. *ECOC 2000*. Munich. Paper 10.1.3.
9. Miyamoto, Y., S. Kinoshita, and K. Okubo. 1.2 Tb/s (30× 42.7 Gbit/s ETDM optical channel) WDM transmission over 376 km with 125-km spacing using forward error correction and carrier-suppressed RZ format. *OFC 2000*. Baltimore. Postdeadline paper 26.
10. Bigo, S., G. Belloti, and S. Gauchard. 1.5 Terabit WDM transmission of 150 channels at 10 Gbit/s over 4 × 100 km of TeraLight Fiber. *ECOC 99*. Nice. Postdeadline paper 2-9.
11. Bertaina, A., A. Jourdan, S. Bigo, and S. Gauchard. 1998. Fiber infrastructure impact in WDM transmission. *Alcatel Telecommunications Review*. Third Quarter, 1998.
12. Aggrawal, G. P. 1995. *Nonlinear Fiber Optics*. San Diego, CA, Academic.
13. Gnauck, A. H., A. R. Chraplyvy, R. W. Tkach, and R. M. Derosier. 1994. 160 Gb/s (8 × 20 Gb/s WDM) 300-km transmission with 50-km amplifier spacing and span-by-span dispersion reversal. *Electronics Lett.*, 30(15):1241–1242.
14. Ahm, Y.-S., S.-Y. Kim, K. Yung, and A. Blokstra. 2001. Bidirectional DWDM transmission using beat frequency locking method. *IEEE Photonics Technol. Lett.*, 13(8).

Biographies

R. S. Kaler was born in Kausoli, Himachal Pradesh, India on December 31, 1968. He obtained his bachelor's degree in electronics and communication engineering with distinction from the Department of Electronics Technology, Guru Nanak Dev University, Amritsar, India. He obtained his master's degree in electronics engineering from Punjab University, Chandigarh, India. He worked in Punjab Communication Limited, Mohali and Electronics Systems Punjab Limited, Mohali from 1990–1994. He then joined BBSEC Fatehgarh Sahib as lecturer and became Assistant Professor in 1998. He then joined Sant Longowal Institute of Engineering and Technology, Longowal, Punjab, India as assistant professor in the department of electronics and communication engineering in 1999. Since then, he is working for his PhD degree in the field of optical communication from Punjab Technical University, Jalandhar, Punjab, India. His present interests are fiber dispersion and nonlinearities. He has over thirty research papers in international and national journals and conferences. He is a life member of the Institution of Engineers (India) and the Indian Society of Technical Education.

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Ajay K. Sharma received his BE degree in electronics and electrical communication engineering from Punjab University, Chandigarh, India in 1986, his MS is in electronics and control engineering from Birla Institute of Technology and Science, Pilani in 1984, and his PhD in electronics, communication and computer engineering from Kurukshetra University, Kurukshetra, India in 1999. His PhD dissertation was on "Studies of Broadband Optical Communication Systems and Networks." From 1986–1990, he was with the Technical Teacher Training Institute and DTE, Chandigarh, and Indian Railways New Delhi, Sant Longowal Institute of Engineering and Technology, Longowal at various positions and was responsible for teaching and research in the field of electronics circuits and telecommunication links. He joined Regional Engineering College, Hamirpur (HP) in 1991 where he has worked on the faculty of Electronics and Communication Engineering and was involved in teaching R & D in the field of electronics circuits and broad band optical communication systems and networks. He worked as Assistant Professor from 1996–2001 at Regional Engineering College, Jalandhar, and since November 2001, he is working as Professor in the same department. He is responsible for teaching, department development, and research in the field of dispersion compensation and WDM systems. He has been involved in various sponsored R & D projects in the field of optical communication systems and networks. He has authored nine books. He has more than four research papers published and presented in international and national journals and conferences to his credit. His current interests include dispersion compensation for linear and nonlinear optical communication systems, soliton transmission, and WDM Networks. He is acting as technical reviewer for Journal of SPIE—The International Society for Optical Engineering, USA. He is also life member of the Indian Society of Technical Education (ISTE).