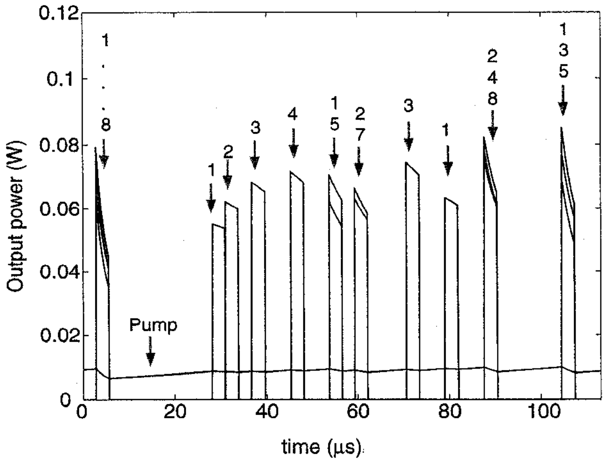
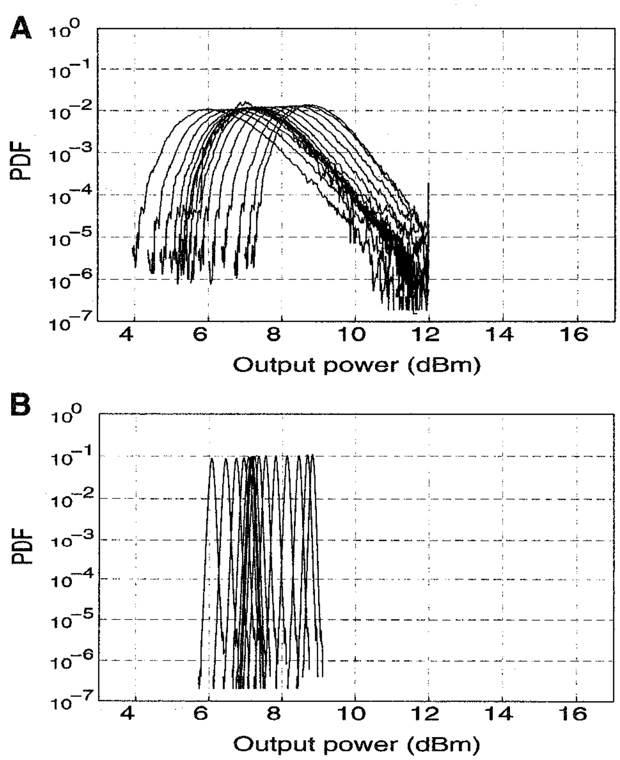
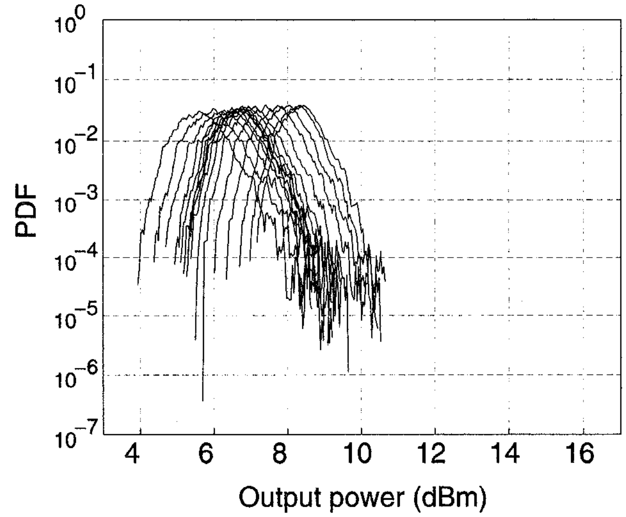


WM31 **Fig. 1.** Numerical evaluation of power at output of an EDFA fed by an 8-channel WDM system, with ATM streams at 150 Mbit/s on each channel. −2 dBm/channel input power; active channel number(s) indicated above arrow.

Figure 2(a) shows a histogram of the output power distribution on slots carrying a cell on each channel when the packet input power per channel is −3 dBm, with the 16 channels having 1-nm spacing over the range 1544–1559 nm; remaining parameters are unchanged. The ON times T_{on} were generated as: $T_{on} = \lfloor 1/(1-U)^{1/\alpha_{on}} \rfloor$, where U is a random variable uniform on [0, 1], $\lfloor x \rfloor$ indicates the floor function. This implements a (rounded) Pareto distribution, which has infinite variance when $1 \leq \alpha_{on} \leq 2$.[2] Here $\alpha_{on} = 1.2$, giving a mean (before rounding) equal to six slots. The OFF periods were generated with $\alpha_{off} = \alpha_{on}$. The simulation was run for a million slots, corresponding to 3 s of traffic at 150 Mbit/s. The width of the histogram for each channel at a probability of 10^{-6} is about 7 dBm, constraining the dynamic range of the receiver. Such power spread is due to the long "lulls" during which the EDFA has no power in, and the pump has time to re-invert the erbium ions, thus increasing the gain for the next cell arrival. Figure 2(b) shows similar histograms for the case $\alpha_{on} = \alpha_{off} = 5$, for which the ON/OFF times (before rounding) have mean equal to 1.25 and finite variance equal to 0.1. In this finite-variance case the interarrival times have less variability, giving shorter lulls, and thus smaller swings on the cell following the lull.



WM31 **Fig. 2.** Simulated probability density function (PDF) of power at the output of the EDFA, for a 16-channel input WDM system, with ON/OFF ATM sources at 150 Mbit/s with peak input power −3 dBm/channel and Pareto distribution of ON and OFF times, with (top) $\alpha_{on} = \alpha_{off} = 1.2$ (infinite variance), and (bottom) $\alpha_{on} = \alpha_{off} = 5$ (finite variance). Leftmost curve: channel at 1544 nm. Rightmost curve: channel at 1559 nm.



WM31 **Fig. 3.** Same as Fig. 2, but with ATM cells at 2.5 Gbit/s and $\alpha_{on} = \alpha_{off} = 1.2$.

A similar swing appears even with 2.5-Gbit/s ATM sources, with much shorter cell duration (0.17 μs). Figure 3 shows the power histograms, for a simulation of 10^6 slot times, at 2.5 Gbit/s, for $\alpha_{on} = \alpha_{off} = 1.2$. The histogram width at a probability of 10^{-6} can be extrapolated to about 6 dBm.

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WM32

Crosstalk rejection requirements for hybrid WDM system with analog and digital channels

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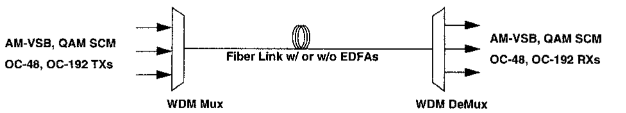
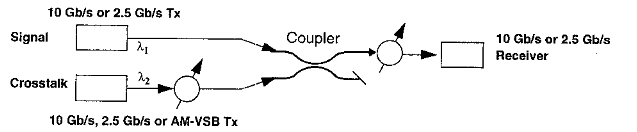
Wavelength-division multiplexed (WDM) systems can utilize the vast bandwidth provided by a single-mode optical fiber. Most WDM



WM32 Fig. 1. An example of hybrid WDM systems.



WM32 Fig. 2. Experimental setup to evaluate power penalty due to analog and digital cross talk to digital channel.

systems distribute homogeneous traffic, for example, all channels transmitted OC-48 (2.5 Gbit/s) signal or OC-192 (10 Gbit/s) signal. Hybrid WDM systems had been proposed to transmit both FM-TV and 622 Mbit/s baseband digital video,[1] AM-VSB and uncompressed (PCM) video,[2] AM-VSB and 622-Mbit/s B-ISDN signal[3] (WDM in 1310 nm and 1550 nm), digital QAM and OC-48/OC-192 channels,[4,5] and AM-VSB and OC-48.[6] Figure 1 shows an example of a general hybrid WDM system. A WDM multiplexer combines a number of digital and analog channels at the transmitter and a WDM demultiplexer separates all channels at the receiver. Depending on the link budget, the fiber link in between may include erbium-doped fiber amplifiers (EDFAs) to compensate for fiber loss. Each WDM channel can transmit AM-VSB subcarrier multiplexed (SCM) channel, QAM-SCM channel, hybrid AM-VSB/QAM SCM channel, OC-192/48 channel, or other special digital or analog signals. Although WDM channels are almost transparent to the signal format, due to the differences in sensitivity requirement, hybrid WDM systems require special attention on EDFA operating point[2,4–6] and crosstalk rejection in the WDM demultiplexer. In this paper, crosstalk rejection requirements are analyzed based on experimental measured data.

Table 1 shows the sensitivities of different type of signal provided by our previous experiments.[4–6] While AM-VSB SCM channel requires an input power around 0 dBm to achieve a CNR requirement of 55 dB, SONET OC-48 signal requires about -30 dBm to achieve a bit-error-rate (BER) requirement of 10^{-9}. Usually, the signal power of different signals in the fiber is different such that no extra optical power is wasted.[2,4–6]. For example, the optical signal of OC-48 signal may be -30 dB lower than that of the AM-VSB SCM signal such that BER of 10^{-9} for OC-48 signal and CNR of 55 dB for AM-VSB signal can be achieved simultaneously. The difference in optical power requires higher crosstalk rejection in the WDM demultiplexer.

Here we consider cross talk from different wavelength instead of cross talk from the same wavelength.[6,7] The effect of digital signal and analog signal is different. The carrier-to-cross talk-interference ratio (CCIR) of digital channel to analog channel can be evaluated as[3]

$$20 \log(m/r) + 10 \log(R) - 66.2 \text{ db} \qquad (1)$$

where m is the modulation index of analog channel, γ is the crosstalk level, R is the data rate of digital channel, and $66.2 = 10 \log(4.2 \times 10^6)$ is the bandwidth of analog channel.

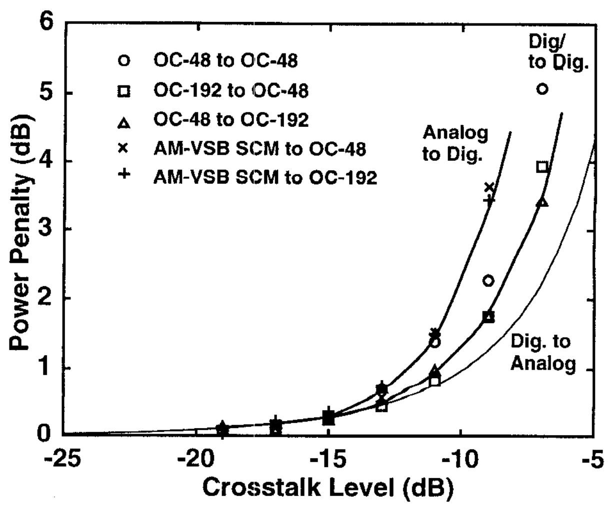
The degradation to analog signal can be evaluated easily by calculating the CNR. The effect to digital channel must be evaluated by BER measurement. Figure 2 shows the experimental setup to measure the effect of cross talk to digital channel. A 2.5-Gbit/s directly modulated or 10 Gbit/s externally modulated transmitter is employed as signal and an AM-VSB SCM channel, 2.5 Gbit/s or 10/Gbit/s channel is employed as the crosstalk interference, separately. The wavelengths of signal and cross talk are different to eliminate coherent effect.

Figure 3 shows power penalty as a function of cross talk. The power penalty is evaluated at a BER of 10^{-9} for digital channel. The power penalties of cross talk induced by both digital cross talk have insignificant different in low level of cross talk (cross talk <-13 dB). However, analog cross talk induces larger penalty than digital cross talk in high level of cross talk (cross talk >-10 dB). For example, for a crosstalk level of -9 dB, analog channel induces 3.5-dB power penalty but digital channel induces only 2 dB of power penalty. Analog channel induces a BER floor of 10^{-9} for digital channel with a cross talk of about -8 dB but a digital channel induces the same BER floor for another digital channel with a cross talk of about -6 dB. Figure 3 also shows solid curves by fitting the experimental points and that of Ref. 1.

From Figure 3, a crosstalk level <-15 dB is acceptable. The optical powers in the hybrid WDM system for different signals can be adjusted according to their differences in sensitivities, for example, AM-VSB is 18 dB more powerful than QAM-SCM, 20 dB more powerful than OC-192, 30 dB more powerful than OC-48. Under this assumption, Table 1 shows the crosstalk rejection requirements between different kind of signals. The crosstalk rejection ratio to AM-VSB and QAM-SCM channel is calculated according to Ref. 1 for a 66 dB CCIR and 36 dB CCIR, respectively, all with a $m = 4\%$ modulation index. From Table 1, while a crosstalk rejection of 3 dB is required from OC-48 to AM-VSB channel, a crosstalk rejection of 45 dB is

WM32 Table 1. Typical Sensitivity of Different Signal

		Required Crosstalk Rejection (dB)			
Signal Channel	Sensitivity (dBm)	OC-48	OC-192	AM-VSB SCM	64-QAM SCM
SONET OC-48	-30	15	25	45	27
SONET OC-192	-20	5	15	35	17
AM-VSB SCM	0	3	10	33	15
64-QAM SCM	-18	6	13	36	18



WM32 Fig. 3. Power penalty as a function of a crosstalk level for a hybrid WDM system with analog and digital channels.

required from AM-VSB to OC-48 channel due to the high optical power of AM-VSB channel.

In summary, we have studied the required crosstalk rejection ratio in the design of hybrid WDM systems. A crosstalk level < -15 dB is acceptable for digital to digital and analog to digital channel. Assuming that the differences in optical powers for a hybrid WDM system is the same as their differences in sensitivities, the required crosstalk rejection ratio is provided.

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WM33

Measurement of the effect of fiber nonlinearities on signal variance and pulse distortion and comparison with models

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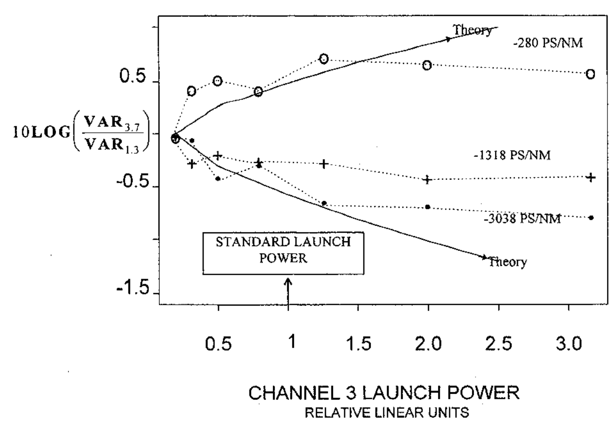
The effect of nonlinear fiber properties and dispersion on signal variance has been investigated theoretically in several works[1–4] and two of them include measurements of intensity noise.[1,4] Theory and measurement show that the signal variance is dependent on the cumulative dispersion when nonlinear effects are present. Without nonlinearities signal variance is independent of dispersion. These works show that by adjusting dispersion the variance can be reduced from the linear case and suggest that an improvement in error ratio performance may also be possible. An improvement in error ratio seems unlikely because, as we will show here, adjusting dispersion to reduce signal variance can increase pulse distortion and the latter appears to be a much stronger effect. The previous experimental work was for a few amplifier spans and was done under cw conditions so pulse distortion was not discussed. In this work nonlinear effects are investigated using a 4760-km 8-channel WDM test bed operating at 4.98 Gbit/s. No polarization scrambling was used because we wished to compare measurements with existing theory, which does not include this effect. The dispersion map for the test bed uses alternating sections of -2 ps/nm and 17 ps/nm fiber while dispersion compensation, added at the receiver, is adjusted to minimize pulse distortion. Without receiver compensation the dispersion varies from -3425 ps/nm for channel 1 to -1490 ps/nm for channel 8. In our measurements the signal variance was measured as signal power was increased for one of the channels, channel 3, while the launch power in other channels was held constant. The effects observed for channel 3 are expected to be similar in nature for other channels with the magnitude of the effects scaling with the amount of dispersion. The measurements used a receiver designed for operation at 4.98 Gbit/s with a 3.7-Ghz bandwidth. The signal variance per unit signal power, VAR, varies inversely with the optical signal-to-noise ratio (SNR). With increasing signal power VAR will decrease, aside from any nonlinear effects, simply because the optical signal-to-noise ratio will be increasing. In order to remove the dependence on SNR, VAR was also measured using a 1.3-Ghz filter for which the changes in variance due to nonlinearity are negligible.[2,4] Accordingly VAR obtained with the 3.7-Ghz filter, $VAR_{3.7}$, was divided by the VAR obtained with the 1.3-Ghz filter, $VAR_{1.3}$. The results for channel 3 are shown in Fig. 1. The vertical axis is the estimated reduction in dB of VAR resulting from the nonlinear effect. The horizontal axis is the launch power in linear relative units for channel 3. Relative launch power of unity represents standard operating power; "standard" means all channels, including channel 3, have the same power. Results for cumulative path dispersions of -3038, -1318, and -280 ps/nm are shown. The path dispersion is adjusted by adding positive dispersion at the receiver. Figure 1 shows that for a launch power of unity, and dispersion of -3038 ps/nm, the normalized variance would decrease by approximately 0.5 dB from the linear case. This benefit diminishes and becomes an impairment for small negative or positive dispersion, *i.e.*, the signal variance is larger than in the linear case. The solid line in Fig. 1 is the theoretical prediction. The theory and measurements are within a few tenths of a dB for launch power up to double standard power. We believe that the theory deviates from measurements beyond this point because the theory does not account for signal depletion due to nonlinear interaction with noise components.

Dispersion and fiber nonlinearities also affect pulse distortion, which is measured here in terms of eye closure. Eye closure is the separation in voltage, with no noise present, between the lowest logical ONE and the highest logical ZERO divided by the average separation between the ONEs and ZEROs. This measurement is made by recording a PRBS7 pattern with a digital scope, which allows the noise to be removed by averaging many waveforms. *Q*-factor, which is a measure of system performance, is approximately proportional to



WM33 Fig. 1. The dependence of normalized signal variance on launch power for channel 3 for three values of path dispersion.