receiver [5]. At the receiving end, a triple cascaded double-pass style optical filter [6] was employed to demultiplex the WDM signals.

Results and discussions: Measured optical spectra after 1655 km transmission are shown in Fig. 2. Fig. 2*a* shows the spectrum for all 50 channels, and Fig. 2*b* shows the spectrum without channels 16, 28, and 40. As seen in Fig. 2*b*, even though the channel separation was as small as 0.3nm, the four-wave mixing (FWM) was not observed after 1655km transmission. The reason for not observing the FWM could be attributed to the large chromatic dispersion of the constituent transmission fibre, the low nonlinearity (i.e. large A_{eff}) of the DSF, or the small optical power per channel.

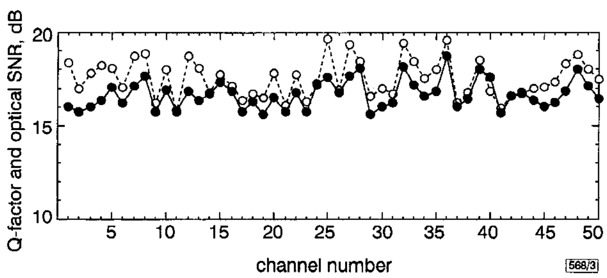

Fig. 3 *Measured Q-factor and optical SNR for 50 WDM channels after 1655km transmission*

● Q-factor
○ optical SNR

The Q-factor was measured to characterise the transmission performance. Fig. 3 shows the measured Q-factor of 50 WDM channels after 1655km transmission. The optical SNR estimated from Fig. 2 is also shown. More than a 15.6dB Q-factor (corresponding to a bit error rate of 10^{-9}) was achieved for all the WDM channels after transmission. The averaged Q-factor, and an optical SNR of 0.1nm resolution over 50 channels were 16.7 and 17.5dB, respectively. As shown in Fig. 3, the response of the optical SNR with respect to the channel is quite similar to that of the Q-factor. In fact, the correlation coefficient between the Q-factor and the optical SNR was as large as 0.78. This result implies that the impairment due to the nonlinear effect should be small. The reason for the small impairment is due to the low nonlinearity of the DSF, and the small optical power per channel of –7dBm.

Conclusions: A 0.5Tbit/s (533Gbit/s), 1655km straight-line transmission experiment was successfully demonstrated. This is the first demonstration of 0.5Tbit/s transmission over 1000km. The result proved the possibility of the sub-terabit per second class optical communication system for terrestrial and regional submarine applications.

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Analysis of co-channel crosstalk interference in optical networks

Keang-Po Ho

Co-channel crosstalk interference with the same wavelength as the signal causes severe system performance degradation in optical networks by competing with the desired signal. While a Gaussian approximation overestimates the performance degradation, for a single dominant crosstalk source, the exact noise probability distribution and closed-form error probability are provided.

Introduction: The basis of the future information infrastructure will build upon multi-wavelength optical networks. Wavelength-routers are used in optical networks for channel routing and add-drop. A fundamental difficulty of the wavelength router is co-channel crosstalk originating from neighbouring inputs with a similar or an identical wavelength to the signal channel. This causes severe degradation in system performance. Co-channel crosstalk is difficult to eliminate by filtering, which will compete with the signal and generate a new kind of noise at the receiver [1 – 7].

Representing a worst-case assumption, and working for a conservative system design [4, 6, 7], a Gaussian approximation was used in previous studies on wavelength router co-channel crosstalk [1, 3 – 6], although there were reports and evidence that the Gaussian assumption is questionable [4, 7, 8]. From central-limit theorems, the Gaussian assumption is convincing for the combination of a large number of more or less identical and independent interference sources [3]; but in most cases, the number of dominant interference sources is limited to one or two due to the near-far effect in the optical network. Therefore, a non-Gaussian model may estimate the system performance more accurately. Here, we present an exact analysis for a single dominant co-channel crosstalk source. A closed-form bit error rate (BER) formula is also provided.

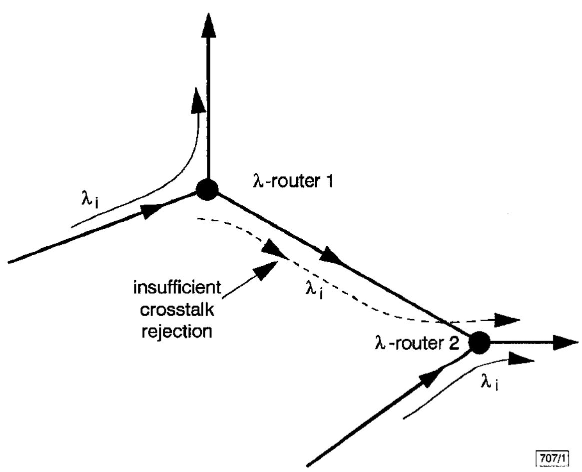

Fig. 1 *Example of an optical network configuration that may induce co-channel crosstalk interference*

Analysis of co-channel crosstalk: Fig. 1 shows a configuration of an optical network that may induce co-channel crosstalk with a similar or identical wavelength to the signal wavelength. While the channel at wavelength λ_i at the input of wavelength router 1 should not appear at the input of wavelength router 2, due to insufficient crosstalk rejection in router 1, a small amount of crosstalk appears at the input of wavelength router 2 as co-channel interference. This co-channel crosstalk will compete with the signal wavelength and severely degrade the system performance.

For simplicity, first assuming an optical signal without modulation, the electrical intensity of the desired optical signal is $E_i(t) = E_i e^{-j\omega_i t - j\varphi_0(t)}$, and a small co-channel crosstalk originating from a neighbouring node is $E_{i,x}(t) = \sqrt{x}E_i e^{-j\omega_i t - j\varphi_1(t)}$, where x is the crosstalk level in optical power, ω_i is the angular frequency of the optical signal, and $\varphi_0(t)$ and $\varphi_1(t)$ is the random phase due to laser phase fluctuation.

Without loss of generality, for a unit detector responsivity and identical polarisation, the photocurrent is $i(t) = |E_i + \sqrt{x}E_i e^{-j\varphi(t)}|^2$, where $\varphi(t) = \varphi_1(t)$. Ignoring the small term in order of x first, the overall receiver noise in the photo-detector is [1 – 6],

$$n(t) = A\cos[\varphi(t)] + n_0(t) \tag{1}$$

where $A = 2\sqrt{x}E_i^2$ is the crosstalk amplitude, and $n_0(t)$ is the usual Gaussian noise in the receiver. To calculate the BER, the probability density function (p.d.f) of $n(t)$ has to be evaluated.

The pdf of $A\cos[\varphi(t)]$ is given by $p(x) = (1/\pi)(A^2 - x^2)^{1/2}$ for $-A < x < +A$ [4, 7, 8] which yields the characteristic function of $J_0(A\omega)$, where $J_0(\cdot)$ is the Bessel function. The characteristic function of $n(t)$ then becomes $\Psi_n(\omega) = J_0(A\omega)\exp(-\sigma^2\omega^2/2)$, where σ^2 and $\exp(-\sigma^2\omega^2/2)$ are the variance and the characteristic function of the receiver Gaussian noise $n_0(t)$, respectively. The pdf of $n(t)$ is [9, 10] (§9.3)

$$p_n(r) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{k=0}^{\infty}\frac{(-r^2/2\sigma^2)^k}{k!}\,{}_1F_1\left(k+\frac{1}{2};1;-\frac{A^2}{2\sigma^2}\right) \tag{2}$$

or

$$p_n(r) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{k=0}^{\infty}\frac{(A^2/2\sigma^2)^k}{2^k(k!)^2}H_{2k}\left(\frac{r}{\sigma}\right)\exp\left(-\frac{r^2}{2\sigma^2}\right) \tag{3}$$

where $A^2/2\sigma^2$ is the ratio of crosstalk to Gaussian variance, ${}_1F_1(a; b; x)$ is the confluent hypergeometric function [10], (A.1.2), and $H_n(x) = (-1)^n e^{x^2/2}d^n e^{-x^2/2}/dx^n$ is a Hermitian polynomial of order n. The pdf provided by eqn. 2 is useful when r/σ is reasonably small, while eqn. 3 is convenient for large r/σ or small A/σ.

Assuming a detection level of d, the error probability is

$$p_b = \frac{1}{2} - \frac{1}{\sqrt{2\pi}}\sum_{k=0}^{\infty}\frac{(-1)^k(d/\sigma)^{2k+1}}{2^k(2k+1)k!}\,{}_1F_1\left(k+\frac{1}{2};1;-\frac{A^2}{2\sigma^2}\right) \tag{4}$$

or

$$p_b = \frac{1}{2}\operatorname{erfc}\left(\frac{d}{\sqrt{2}\sigma}\right) + \frac{1}{\sqrt{2\pi}}\sum_{k=1}^{\infty}\frac{(A^2/2\sigma^2)^k}{2^k(k!)^2}H_{2k-1}\left(\frac{d}{\sigma}\right)\exp\left(-\frac{d^2}{2\sigma^2}\right) \tag{5}$$

The BER at the receiver can be evaluated according to the error probability p_b.

In optical communication, with only Gaussian noise, the BER of the system is $Q(\rho_G)$, $\rho_G = (I_1 - I_0)/(\sigma_1 + \sigma_0)$, where ρ_G is the Q-factor or signal-to-noise (SNR) ratio of the system, I_1, I_0, σ_1^2, σ_0^2 are the photocurrent and the noise variance at one and zero levels, respectively, and $Q(x) = \operatorname{erfc}(x/\sqrt{2})/2$ is the cumulative tail of Gaussian distribution. While the threshold level can be optimised in the laboratory for better performance, for field applications, the threshold is usually set to the middle of the 'eye' [8]. For an infinite extinction ratio (or I_1/I_0 larger than 20dB), and identical zero and one level Gaussian noise, the threshold level $d = I_1/2$ and $\sigma = \sigma_1 = \sigma_0$, the Q-factor $\rho_G = d/\sigma$.

In eqns. 4 and 5, $A^2/2\sigma^2$ is equal to the ratio of crosstalk to Gaussian noise. The co-channel crosstalk occurs only if both the signal and crosstalk channel are transmitted in one level, or $A = 2\sqrt{2d}\sqrt{2dx}$. After some algebra, we find that $A^2/2\sigma^2 = 8\rho_G^2 x$. The threshold at the middle of the 'eye' is $(1 + x)I_1/2$. Considering all combination of one and zero levels of the signal and crosstalk channel, with of x also taken into account, the closed-form BER formula corresponding to eqn. 5 is:

$$BER = \frac{1}{2}Q[\rho_G(1-x)] + \frac{1}{2}Q[\rho_G(1+x)] + \frac{1}{4\sqrt{2\pi}}\sum_{k=1}^{\infty}\frac{2^{2k}\rho_G^{2k}x^k}{(k!)^2}H_{2k-1}[\rho_G(1+x)]\exp\left[-\frac{\rho_G^2(1+x)^2}{2}\right] \tag{6}$$

where the first two terms are contributed by Gaussian noise, and the third term is contributed by the non-Gaussian nature of co-channel crosstalk. A similar formula corresponding to eqn. 4 can also be derived. The first-term in eqn. 6 is for the signal and the crosstalk channel in different levels. The second term in eqn. 6 is the effect of Gaussian noise for both the crosstalk and the signal channel in the same level. The third term in eqn. 6 is the effect of crosstalk for both the crosstalk and the signal channel in one level.

With Gaussian assumption, the BER can be approximated by

$$BER \simeq \frac{1}{2}Q[\rho_G(1-x)] + \frac{1}{4}Q[\rho_G(1+x)] + \frac{1}{4}Q\left[\frac{\rho_G(1+x)}{\sqrt{1+8\rho_G^2 x}}\right] \tag{7}$$

Usually, the BER in eqn. 7 is dominated by the last term. Note that $8\rho_G^2 x$ is the crosstalk-to-Gaussian noise ratio for both signal and crosstalk channel in one level; the average ratio is $4\rho_G^2 x$ [1, 3, 8].

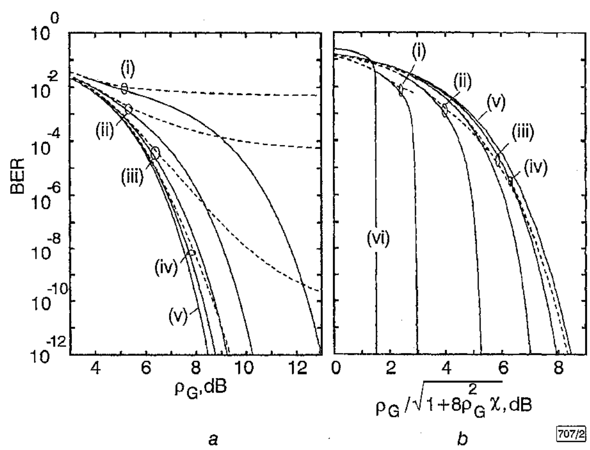

Fig. 2 *BER against SNR for different crosstalk levels*

SNR represented by both ρ_G and $\rho_G/\sqrt{(1+8\rho_G^2 x)}$ are shown for comparison
a BER against ρ_G
b BER against $\rho_G/\sqrt{(1+8\rho_G^2 x)}$
(i) $x = -15$dB, (ii) $x = -20$dB, (iii) $x = -25$dB
(iv) $x = -30$dB, (v) no *xt*, (vi) *xt* only

Fig. 2*a* and *b* shows the BER against the SNR of ρ_G and $\rho_G/\sqrt{(1 + 8\rho_G^2 x)}$, respectively. The SNR of $\rho_G/\sqrt{(1 + 8\rho_G^2 x)}$ is the dominated term in eqn. 7. Fig. 2 shows that Gaussian approximation overestimates the degradation induced by co-channel interference. While the Gaussian approximation in eqn. 7 is valid in the range of small SNR, the BER provided by the Gaussian approximation in eqn. 7 is always higher than that provided by the exact analysis in eqn. 6. For example, the Gaussian approximation provides a BER floor of around 10^{-2} for a crosstalk level of –15dB, but exact analysis shows no BER floor.

Conclusion: In optical networks, severe system performance degradation is induced by co-channel crosstalk interference with identical wavelength to the signal channel. Conventionally, even for a single interference source, Gaussian approximation is used to estimate the BER performance for a conservative system design. An exact analysis and a closed-form BER formula of co-channel crosstalk interference is provided here for a single interference source.

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Expansion of tolerable dispersion range in a 40Gbit/s optical transmission system using an optical duobinary signal

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The authors demonstrate the high dispersion tolerance of a 40Gbit/s optical duobinary signal. The tolerable dispersion range of the signal was 175ps/nm. This dispersion range is more than twice that obtained using a binary non-return-to-zero intensity-modulated signal.

Introduction: To construct future ultra-high-capacity networks, high-speed optical transmission technologies are very important. The transmission capacity of a single carrier has recently reached 40Gbit/s in electrical time-division multiplexing systems [1, 2]. In such high-speed optical transmission systems, the tolerable dispersion range is very small and precise dispersion control is indispensable [3]. To expand the dispersion range, an optical duobinary transmission technique is useful [4, 5]. It is expected that the optical duobinary technique will be applied to 40Gbit/s optical transmission systems.

In this Letter, the high dispersion tolerance of a 40Gbit/s optical duobinary signal is demonstrated. The tolerable dispersion range obtained was 175ps/nm, which was more than twice that obtained using a binary non-return-to-zero (NRZ) intensity modulated (IM) signal. To the best of our knowledge, this is the highest dispersion tolerance achieved for 40Gbit/s optical transmission systems.

Experiment: Fig. 1 shows a schematic diagram of our experimental setup. A 2^7–1 pseudo-random binary sequence (PRBS) 40Gbit/s signal was generated by an InP-HEMT selector IC [6] from two 2^7–1 PRBS 20Gbit/s signals. The 40 Gbit/s binary signals (data and complementary data) were converted to duobinary signals by using fifth-order Bessel-Thomson lowpass filters (LPFs), with a 3dB bandwidth of 12GHz, as a duobinary filter. The duobinary signals were supplied to two electrodes of a push-pull type $LiNbO_3$ Mach-Zehnder (MZ) modulator with an electrical 3dB bandwidth of 30GHz [7].

Fig. 2 shows the eye-diagrams of 40Gbit/s electrical signals before optical modulation. The eye-diagram of the 40Gbit/s binary NRZ signal is shown in Fig. 2*a*. The upper and lower eye-diagrams are for binary data and complementary data, respectively. The eye-diagram of the 40Gbit/s duobinary signal is shown in Fig. 2*b*. The duobinary signal was generated by passing the binary NRZ signal shown in Fig. 2*a* through the duobinary filter. Fig. 2*c* shows the eye-diagram of the duobinary signal at the driver output. A high-power driver with a 20GHz bandwidth was used for 40Gbit/s duobinary modulation. The driving voltage was ~5$V_{p\text{-}p}$, as shown in Fig. 2*c*. The voltage is high enough to drive the MZ modulator completely because the half-wavelength voltage of the push-pull type MZ modulator was 3.9V during single-electrode operation.

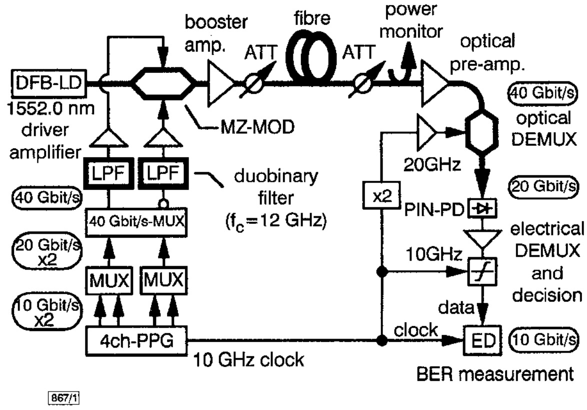

Fig. 1 *Schematic diagram of experimental setup*

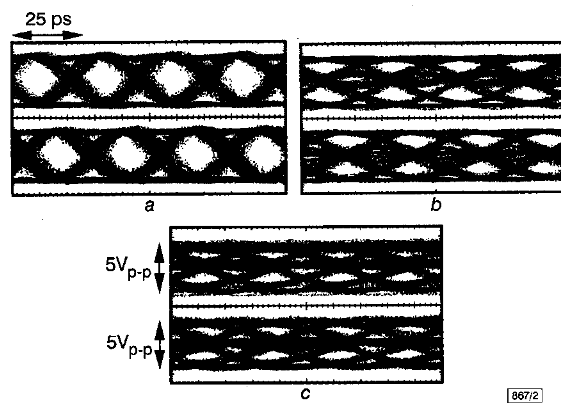

Fig. 2 *Eye-diagrams of 40Gbit/s electrical signals before optical modulation*

a Binary NRZ signal
b Duobinary signal at driver input
c Duobinary signal at driver output

Fig. 3 shows the optical power spectrum of the optical duobinary signal and the eye-diagram of the directly detected signal. The spectrum shows the characteristics of a narrow bandwidth and a suppressed carrier: basic attributes of an optical duobinary signal. The eye-diagram of the directly detected signal shown in Fig. 3*b* is clearly open enough to measure the bit error rate (BER) performance. At the receiver, the received 40Gbit/s optical duobinary signal was optically demultiplexed into a 20Gbit/s return-to-zero optical signal. The 20Gbit/s optical signal was detected by a PIN-photodiode and demultiplexed into a 10Gbit/s signal by a decision circuit. The BERs of four 10Gbit/s channels were measured and the receiver sensitivity was evaluated. The sensitivity was –22.0dBm at a BER of 10^{-9}.

The 40Gbit/s optical duobinary signal was transmitted through various high-dispersion optical fibres. The receiver sensitivities were measured at various values of dispersion. To avoid optical fibre nonlinearities, the fibre launched power was set to 0dBm. Fig. 4*a* shows the dispersion tolerance characteristics of the 40Gbit/s optical duobinary signal. The tolerable dispersion range, to achieve a penalty within 1dB of the best receiver sensitivity, was 175ps/nm. The optimum dispersion that maximised the receiver sensitivity was slightly positive. It is presumed that this shift was caused by the residual chirp in duobinary modulation. The chirp was generated by a small deviation in the centre level of the electrical duobinary signal, as shown Fig. 2*c*. Because of the negative