Interferometric Crosstalk Reduction by Phase Scrambling

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Abstract—**Interferometric crosstalk, arising from the detection of undesired signals at the same nominal wavelength, may introduce large power penalties and bit-error rate (BER) floor significantly restricting the scalability of optical networks. In this paper, interferometric crosstalk reduction in optical wavelength-division-multiplexing (WDM) networks by phase scrambling is theoretically and experimentally investigated. Enhancement of 7- and 5-dB tolerance toward crosstalk is measured in a 2.5-Gb/s transmission link of 100 km and 200 km of SSMF, respectively. This result proves the feasibility of optical networking in the local area network/metropolitan area network (LAN/MAN) domain while tolerating the relatively high crosstalk levels of present integrated optical switching and cross-connect technology. Experiment is in good agreement with theory. Recommendations on the use of phase scrambling to reduce crosstalk in WDM systems are given.**

Index Terms—**Error analysis, interferometric noise, optical communication, optical crosstalk, phase scrambling, wavelength-division multiplexing (WDM) networks.**

I. INTRODUCTION

PERFORMANCE imperfections of optical components (e.g., optical switches, (de)multiplexer and routers) are sources of interferometric crosstalk which constitutes a major limiting factor for the scalability of optical networks, e.g., [1]–[4]. Wavelength-division-multiplexing (WDM) systems impose strict requirements on the optical crosstalk isolation within the comprising elements. For instance, crosstalk isolation levels better than 35 dB should be used to have power penalties smaller that 1 dB when even a moderated small number of crosstalk interferers are present [2]. This is still a high requirement for the performance of integrated optical switches and cross connects at the current state-of-the-art [5]. Although improvements in device performance are foreseen, a substantial relaxation of the crosstalk requirements from individual components in optical networks can be achieved by using phase scrambling [6]. In this way, the gap between the stringent crosstalk isolation requirements and the current, still unsatisfactory, achievable values is closed. In this paper, we report that power penalties smaller than 1 dB for crosstalk values up to -18 dB are measured in a 2.5-Gb/s link of 100 km of standard single-mode fiber (SSMF). Power penalties smaller than 2 dB for crosstalk values up to -15 dB and -16 dB are measured after transmission over 100 km and 200 km of

SSM fiber. This corresponds to an enhancement of the system tolerance to crosstalk of 7 and 5.3 dB, respectively. This result demonstrates the feasibility of optical networking in a local area network/metropolitan area network (LAN/MAN) domain with the current state-of-the-art in integrated optical technology.

The main contribution of this paper is a complete assessment, experimentally and theoretically, of interferometric crosstalk reduction (including transmission) by phase scrambling. This paper is organized as follows. The phase scrambling principle is described in Section II. Implications for transmission over dispersive fibers are studied inSection III. Section IV covers the performance analysis. The experimental details are given in Section V. Experimental and theoretical results are presented and discussed in Section VI. Finally, summarizing conclusions and recommendations are outlined in Section VII.

II. PHASE SCRAMBLING PRINCIPLE

This section presents the theoretical framework of phase scrambling. First, the receiver model under consideration is introduced. Second, the model for interferometric crosstalk is explained. The influence of filtered interferometric crosstalk is quantified by its variance which is mainly determined by the relation between the spectrum of the interferometric crosstalk noise and the postdetection filter bandwidth. Third, the phase scrambling technique to reduce the influence of filtered interferometric crosstalk is introduced.

A. Receiver Model

Lets consider the case of an optical signal disturbed by a number N of interferers operating at the same nominal wavelength. The optical field of the information signal $\vec{E}_s(t)$ and the interferers $\vec{E}_x(t)$ are given by their complex amplitude vectors

$$\vec{E}_s(t) = \sqrt{b_k^s P_0 g_s(t)}\, \vec{r}_s e^{j\phi_s(t)} \tag{1}$$

$$\vec{E}_x(t) = \sum_{n=1}^{N} \sqrt{\epsilon_n b_k^{x,n} P_0 g_{x,n}(t)}\, \vec{r}_{x,n} e^{j\phi_{x,n}(t)} \tag{2}$$

where ϵ is the crosstalk parameter: the ratio of leakage crosstalk to signal power. The indicator b_k is introduced to represent the binary symbols: $b_k \in \{\rho, 1\}$ $(0 \le \rho < 1)$ at time slot k. For the case of perfect extinction the ratio $\rho = 0$. $\phi_{s,x}$ is the phase of the signal and interferer, respectively. $\vec{r}_s$ and $\vec{r}_x$ are unit vectors representing the signal and interferer polarization state, respectively. The optical peak power is denoted by P_0 and $g(t)$ is the pulse shape.
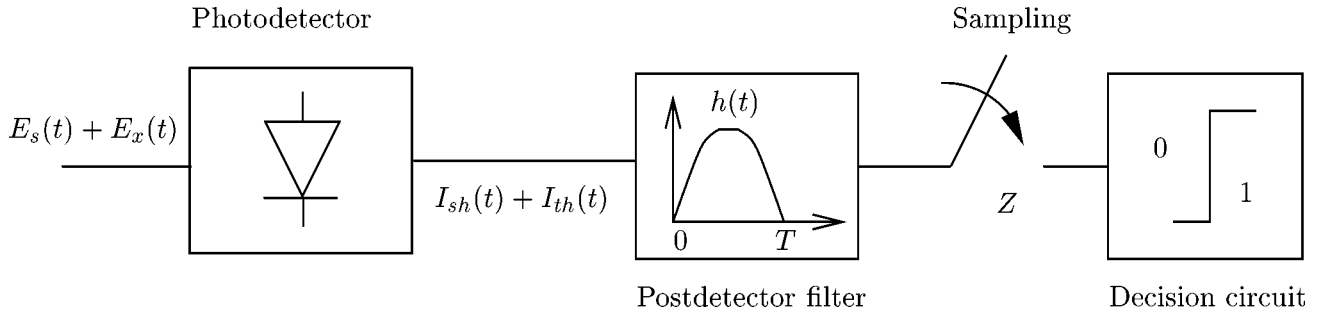
Fig. 1.   Schematic diagram of an ASK/DD receiver. At the receiver input $E_s(t)$ represents the optical signal while interferometric crosstalk is denoted by $E_x(t)$.

We consider an ASK direct detection system whose schematic diagram is given in Fig. 1. The photocurrent at the output of the photodetector, $I_{\text{sh}}(t)$, is a shot noise process which can be written as

$$I_{\text{sh}}(t) = \mathcal{R}|\vec{E}_s(t) + \vec{E}_x(t)|^2 \qquad (3)$$

where $\mathcal{R}$ is the detector responsivity.

The receiver thermal noise, denoted by $I_{\text{th}}(t)$, is modeled as an additive, zero mean, white Gaussian stochastic process. It is assumed that the optical pulses are of identical shape and confined in the time interval $[0, T]$, i.e., no intersymbol interference (ISI). The signal and the interferers are assumed to exhibit matched polarizations (worst case), and perfect bit alignment. With the abovementioned assumptions the photocurrent can be written as

$$\begin{aligned}
I_{\text{sh}}(t) &= P_0 g(t) b_0^s + 2 P_0 g(t) \\
&\quad \times \sum_{n=1}^{N} \sqrt{b_0^s b_0^x \epsilon_n} \cos[\phi_s(t) - \phi_{x,n}(t - \tau_{d,n})] \\
&\quad + 2 P_0 g(t) \sum_{n=l+1}^{N} \sum_{l=1}^{N-1} \sqrt{b_0^{x,n} b_0^{x,l} \epsilon_n \epsilon_l} \\
&\quad \times \cos[\phi_{x,n}(t - \tau_{d,n}) - \phi_{x,l}(t - \tau_{d,l})] \\
&\quad + P_0 g(t) \sum_{n=1}^{N} b_0^{x,n} \epsilon_n \qquad (4)
\end{aligned}$$

where τ_d is the interferometric delay time. The first term is the signal, the second the signal-crosstalk beating, the third the secondary crosstalk-crosstalk beating and the last term is the crosstalk beating with itself.

The photocurrent and thermal noise pass the postdetection filter $h(t)$ whose output is sampled to form the decision variable Z. By comparing the sample value with a preselected threshold α_{tr}, the decision circuit provides an estimate of a transmitted bit in a particular bit interval.

B. Interferometric Crosstalk

The interferometric crosstalk contributions to the photocurrent are of the type

$$\xi(t) = \cos[\phi_s(t) - \phi_x(t - \tau_d)]. \qquad (5)$$

The laser phase (variables $\phi_x(t)$, $\phi_s(t)$ in (1)), is modeled as a Wiener process [7]. Then the phase difference

$$\Delta\phi(t) = \phi_s(t) - \phi_x(t - \tau_d) \qquad (6)$$

is also a Wiener process, Gaussian distributed with zero mean and variance given by

$$\sigma_{\Delta\phi}^2 = 2\pi\Delta\nu\tau_d = B_L\tau_d \qquad (7)$$

where $\Delta\nu$ equals the 3-dB bandwidth of the Lorentzian shaped laser power spectrum [7].

The autocorrelation function of the process $\xi(t)$ is related to the autocorrelation function of the process $\Delta\phi(t)$ in the following way ([8, Sec. 8.3.2])

$$\begin{aligned}
R_\xi(\tau) &= \frac{1}{2}\exp(-[R_{\Delta\phi}(0) + R_{\Delta\phi}(\tau)]) \\
&\quad + \frac{1}{2}\exp(-[R_{\Delta\phi}(0) - R_{\Delta\phi}(\tau)]) \qquad (8)
\end{aligned}$$

where $R_{\Delta\phi}(\tau)$ is found to be

$$R_{\Delta\phi}(\tau) = \begin{cases} 2\pi\Delta\nu(\tau_d - |\tau|) & |\tau| \le \tau_d \\ 0 & |\tau| > \tau_d. \end{cases} \qquad (9)$$

Substitution of (9) in (8) yields

$$R_\xi(\tau) = \begin{cases} \frac{1}{2}e^{-B_L|\tau|}[1 + e^{-2B_L(\tau_d - |\tau|)}] & |\tau| \le \tau_d \\ e^{-B_L|\tau_d|} & |\tau| > \tau_d. \end{cases} \qquad (10)$$

1) Incoherent Interferometric Noise: We are interested in analyzing interferometric crosstalk arising from performance imperfections of optical cross connects (OXC) in WDM networks. We proceed by making the following assumptions. We assume that the crosstalk interferers come from different light sources in the network and that they have uncorrelated phases. Furthermore, we assume that the interferometric delay time is of a larger magnitude than the laser coherence time ($B_L\tau_d \gg 1$). We refer to this situation as the incoherent interferometric noise regime. Although interferometric crosstalk can be treated in a general way [cf., (10)], we focus our analysis on the above described regime based on the assumption that future WDM networks will make use of OXC's with optimized crosstalk performance. For instance, it has been shown that in integrated OXC's the circuit configuration can be chosen such that the amount of
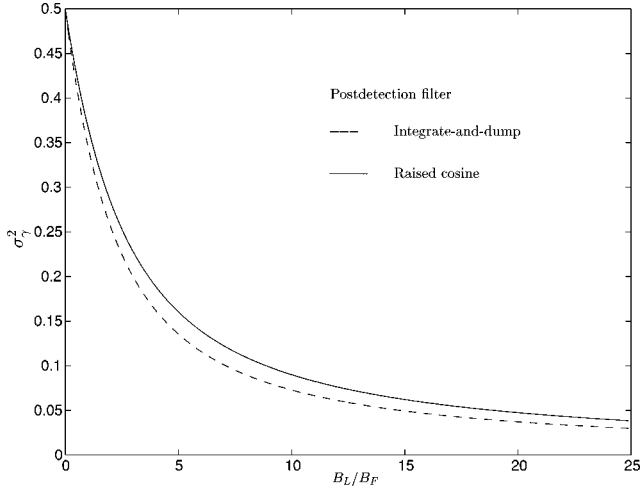
Fig. 2. Variance of filtered interferometric crosstalk as a function of B_L/B_F.

Fig. 3. The signal is phase modulated with noise $\psi(t)$, centered at an arbitrary frequency ω_f. The modulation index is denoted by a.

crosstalk is minimized and that the dominant crosstalk contributions are in the incoherent regime [5], [9]. For the case considered here ($B_L\tau_d \gg 1$) the autocorrelation function of interferometric crosstalk is given by

$$R_\xi(\tau) = \begin{cases} \frac{1}{2}e^{-B_L|\tau|} & |\tau| \le \tau_d \\ 0 & |\tau| > \tau_d. \end{cases} \quad (11)$$

2) Filtered Interferometric Crosstalk: At the output of the postdetection filter, $h(t)$, the filtered interferometric noise is denoted by

$$\gamma(t) = \xi(t) \star h(t) \quad (12)$$

where $\star$ represents the convolution operation.

If we consider an integrate-and-dump postdetection filter, then the variance for filtered crosstalk is given by [10]

$$\sigma_\gamma^2 = \frac{e^{-B_LT} + B_LT - 1}{(B_LT)^2}. \quad (13)$$

In the incoherent regime, the mean of filtered interferometric crosstalk approaches the value zero. We may also consider a wider class of postdetection filters. In that case the variance for filtered interferometric crosstalk can be found by using the following relation:

$$\sigma_\gamma^2 = 2 \int_0^\infty S_\xi(f)|H(f)|^2 \, df \quad (14)$$

where $H(f)$ is the transfer function of the postdetection filter and $S_\xi(f)$ is the interferometric crosstalk power spectrum obtained by Fourier transforming (11).

For comparison reasons we introduce an effective electrical filter bandwidth $B_F = 1/T$. In Fig. 2 is shown the variance of filtered interferometric crosstalk using two different filters: an integrate-and-dump, and a full raised cosine filter. We observe that by increasing the value of B_L/B_F a significant reduction of the noise variance is achieved. This is an important
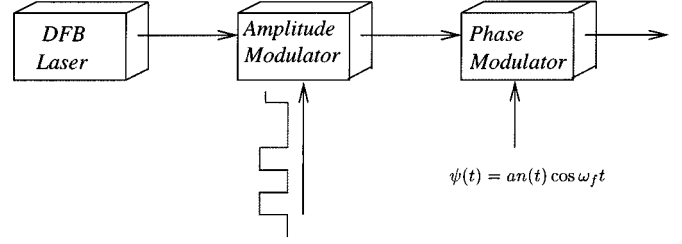
characteristic of filtered interferometric crosstalk. It indicates that we can reduce interferometric crosstalk by strong filtering or by dithering the phase of the light source. As the postdetection filter bandwidth is governed by the operating data rate, we propose to exploit the second fact to reduce the effect of interferometric crosstalk in WDM networks. Namely, we will, intentionally, perform phase modulation of the signals with noise: phase scrambling.

C. Phase Scrambling

Interferometric noise reduction by broadening the spectrum (by, e.g., phase dithering or phase noise modulation) has already been proposed [6], [11], [12]. However, as to our knowledge, a complete assessment of crosstalk reduction by phase scrambling, including transmission, has not been reported yet. This section introduces the theoretical framework of interferometric crosstalk reduction by phase scrambling. The schematic diagram of phase scrambling is presented in Fig. 3. Consider that the optical signals are phase modulated with noise $\psi(t)$. The optical field can be, generally, written as

$$\vec{E}(t) = \sqrt{b_k P_0(t)g(t)}\vec{r}e^{j[\phi(t)+\psi(t)]} \quad (15)$$

and the interferometric crosstalk contributions to the photocurrent are then of the type

$$\xi(t) = \cos[\Delta\phi(t) - \Delta\psi(t)] \quad (16)$$

in which $\Delta\phi(t)$ and $\Delta\psi(t)$ are the phase difference [cf. (6)] of the laser phase and the imposed phase modulation, respectively. By considering $\Delta\phi(t)$ and $\Delta\psi(t)$ to be independent stochastic processes, it can be shown that the autocorrelation function of $\xi(t)$ is given by

$$R_\xi(\tau) = \frac{1}{2}\exp(-[R_M(0) + R_M(\tau)]) + \frac{1}{2}\exp(-[R_M(0) - R_M(\tau)]) \quad (17)$$

in which $R_M(0) = R_{\Delta\phi}(0) + R_{\Delta\psi}(0)$ and $R_M(\tau) = R_{\Delta\phi}(\tau) + R_{\Delta\psi}(\tau)$. We proceed, similarly as in [6], by assuming that $\psi(t)$ is of the form

$$\psi(t) = an(t)\cos\omega_f t \quad (18)$$

where a is the modulation index, $n(t)$ is a bandpass Gaussian noise, and ω_f is the arbitrary central frequency. The autocorrelation function for $\Delta\psi(t)$ is given by

$$R_{\Delta\psi}(\tau) = \frac{a^2}{2}R_n(\tau)\cos\omega_f\tau + \frac{a^2}{2}R_n(\tau_d)\cos\omega_f\tau_d$$
$$- \frac{a^2}{2}R_n(\tau - \tau_d)\cos\omega_f(\tau - \tau_d)$$
$$- \frac{a^2}{2}R_n(\tau + \tau_d)\cos\omega_f(\tau + \tau_d) \qquad (19)$$

where $R_n(t)$ is the autocorrelation function of the Gaussian noise $n(t)$. We also define by τ_n the autocorrelation time of the noise $n(t)$. Further, we assume that the time delay exceeds the noise correlation time: $\tau_d \gg \tau_n$. This uncorrelated regime, as already mentioned above, is applicable in WDM networking. In this case, the calculations for $R_{\Delta\psi}(\tau)$ are simplified. The terms in (19) involving τ_d can be neglected and we get

$$R_{\Delta\psi}(\tau) = \frac{a^2}{2}R_n(\tau)\cos\omega_f\tau. \qquad (20)$$

Subsequently, we arrive at

$$R_\xi(\tau) = \frac{1}{2}e^{-B_L|\tau|}e^{-\frac{a^2}{2}[R_n(0) - R_n(\tau)\cos\omega_f\tau]}. \qquad (21)$$

Let us analyze the dependence of the variance of crosstalk on the parameters of the phase scrambling signal such as the central frequency ω_f, modulation index a and the equivalent noise bandwidth B_N of the modulating noise. The spectral shape of $n(t)$ is taken to be of a Lorentzian shape. It has been shown that the shape of the power spectral density of the modulating noise $n(t)$ is irrelevant for the crosstalk noise reduction [6]. A plot of the variance, given a value for ω_f, as a function of a and B_N is presented in Fig. 4. We observe that the variance decreases substantially as the modulation index increases. The same tendency is observed for the other studied values of ω_f. We also performed similar computations as in Fig. 4 for other combinations of parameters. From our study, we observe that the parameter of major influence is the modulation index a. Moreover, we also observe that for relative large values of B_N/B_F the value of the central frequency has little or insignificant influence on the crosstalk reduction. However, the central frequency should amount some hundreds of megaHertz to enhance the crosstalk reduction when fiber dispersion restricts the use of a wide bandwidth modulating noise.

In general, we can conclude that phase scrambling with a Gaussian noise source reduces effectively the variance of interferometric crosstalk. The parameter of major influence on the reduction of crosstalk is the modulation index a. The modulating noise source can be centered at an arbitrary frequency ω_f and its equivalent noise bandwidth can be smaller than the bit rate (see Fig. 4). This agrees well with previous results [6] and it is confirmed in our experimental setup.

III. TRANSMISSION OVER DISPERSIVE FIBERS

In this section, the spectral broadening caused by the imposed phase modulation is determined. Subsequently, a model is pre-
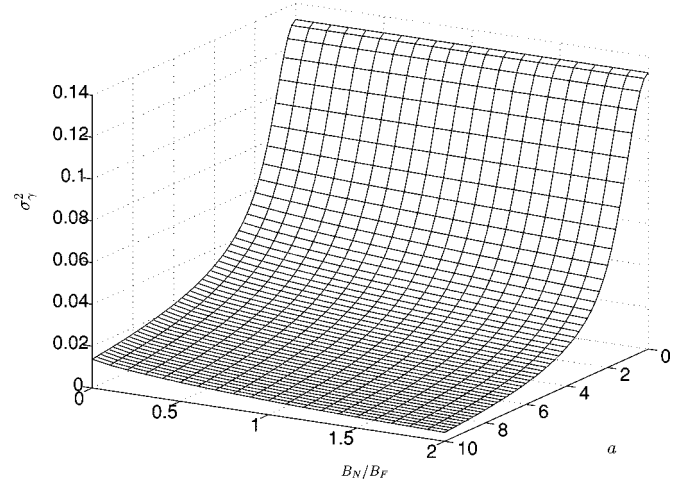

Fig. 4. Variance of filtered interferometric crosstalk as function of the parameters B_N and a for a fixed value of $\omega_f/B_F = 2$.

sented for the relative intensity noise due to phase-to-intensity noise conversion caused by chromatic dispersion.

A. Spectrum of Phase Modulated Signal with Gaussian Noise

Determining the spectrum of a phase modulated signal with a Gaussian noise is a topic widely studied in references like, e.g., [13], [14]. It is of common practice to specialize the analysis to certain cases. For instance, to the case of large or small modulation index. As we already observed in the previous section, we are interested in a phase modulation with a large modulation index to effectively reduce interferometric crosstalk. Therefore we will consider a large index phase modulation with a Gaussian noise. The spectrum shape of the modulating noise is assumed to be a Lorentzian function. This type of noise may be obtained by low bandpass filtering a white Gaussian noise; say by a resistance–capacitance (RC)-circuit.

From (15) we have that the phase modulating signal is given by

$$E_{\phi M}(t) = e^{j\phi(t)} \times e^{j\psi(t)} = E_\phi(t) \times E_\psi(t). \qquad (22)$$

The autocorrelation function of the phase modulated signal $E_\psi(t)$ is given by [14]

$$R_{E_\psi}(t) = e^{-k(\tau)} \qquad (23)$$

where

$$k(\tau) = R_\psi(0) - R_\psi(\tau)$$

with $R_\psi(\tau)$ the autocorrelation function of the modulating Gaussian noise.

The spectral density $S_{E_\psi}(f)$ of $E_\psi(t)$ is given by the Fourier transform of (23). For the case of large modulation index this spectral density can be approximated by a Lorentzian spectrum with a 3-dB bandwidth $\Delta\nu_\psi = B_N a^2$ [14]. The spectrum of the phase scrambled signal is given by the convolution of the spectrum due to the laser phase noise and the imposed phase modulation:

$$S_{\phi M}(f) = S_\phi(f) \star S_\psi(f). \qquad (24)$$

The spectrum due to the phase noise is known to be given by the Lorentzian shape with a 3-dB bandwidth $\Delta\nu$ [7]. The convolution of two Lorentzian-shaped spectra is again a Lorentzian spectrum with a 3-dB bandwidth given by the sum of their 3-dB bandwidth. So, we have that the (normalized) spectrum of the phase modulated signal is given by

$$S_{\phi M}(f) = \frac{1}{1 + \left(\frac{f}{\Delta\nu + \Delta\nu_\psi}\right)^2}. \tag{25}$$

From this result, we may conclude that the effect of phase scrambling on the signal spectrum is to cause spectral broadening yielding a resultant 3-dB bandwidth

$$\Delta\nu_{\phi M} = \Delta\nu + \Delta\nu_\psi = \Delta\nu + B_N a^2. \tag{26}$$

B. Propagation in Dispersive Fibers

Phase scrambling, as shown in the preceding section, reduces interferometric crosstalk, but at the same time the broadening of the laser spectrum may have detrimental effects on the system performance. Namely, laser phase-to-intensity noise conversion by chromatic dispersion may lead to power penalties in optical fiber transmission systems, e.g., [15], [16]. This section presents the analysis of phase-to-intensity noise conversion during transmission by determining the relative intensity noise (RIN) at the fiber output.

Propagation in a fiber of length L is described by the propagation term $e^{-j\beta L}$ where the phase function β can be expanded in a Taylor series and keeping only the first terms

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 \tag{27}$$

with the group delay per unit length β_1 and the group velocity dispersion

$$\beta_2 = \frac{-D\lambda^2}{2\pi c} \tag{28}$$

in which λ is the wavelength and c the velocity of light, and D the common dispersion parameter.

We aim to determine the variance due to RIN. The variance of the RIN contribution to the photocurrent, after postdetection filtering, can be found by

$$\sigma_{\text{RIN}}^2 = \int_0^\infty \text{RIN}(f)|H(f)|^2 \, df \tag{29}$$

where $\text{RIN}(f)$ is the normalized RIN power spectral density at the dispersive fiber output. The transfer function the postdetection filter is denoted by $H(f)$.

C. RIN Model

This section presents the model of the RIN for a systems using externally modulated light sources. This type of light source exhibits a low magnitude of chirp (spectral broadening) which means that insignificant crosstalk noise filtering will take place at the receiver end. In this case phase scrambling will assure the needed spectral broadening for substantial crosstalk filtering by the electrical postdetection filter. However, spectral broadening may introduce penalties due to dispersion. Yamamoto *et al.* [16] have studied the effect of phase-to-intensity noise conversion by

chromatic dispersion in intensity modulated and direct detected systems. The normalized RIN power spectral density at the dispersive fiber output is related to the laser phase noise and fiber dispersion as follows [16]:

$$\text{RIN}(f) = 8\left[\sum_{n=0}^\infty J_n(\alpha_0)J_{n+1}(\alpha_0) \right.$$
$$\left. \times \sin\left\{\frac{1}{2}(2n+1)\alpha_1\right\}\right]^2 \tag{30}$$

where $J_n(\cdot)$ is the Bessel function of the first kind, and

$$\alpha_0 = \frac{1}{f}\sqrt{\frac{2\Delta\nu}{\pi}} \tag{31}$$

$$\alpha_1 = (2\pi f)^2 \beta_2 L. \tag{32}$$

When phase scrambling is employed we proceed by assuming that the effect is equivalent to a laser source with a broader linewidth, namely the resultant 3-dB bandwidth $\Delta\nu_{\phi M}$. This can be deduced from the analysis in Section III-A. This fact has also been pointed out in [17].

Systems using directly modulated lasers experience substantial spectral broadening due to chirp which is intrinsic to this type of modulation. Although this spectral broadening results in crosstalk noise filtering at the receiver end, this filtering is not assured for all detection situations because of the bit pattern dependence of chirp. In these systems phase scrambling will also result in crosstalk mitigation. However, the enhancement of the tolerance to crosstalk is expected to be smaller than in the case of systems using externally modulated lasers, for the reason of the already present spectral broadening in directly modulated lasers.

IV. PERFORMANCE ANALYSIS

This section presents the performance evaluation for ASK/DD receivers using phase scrambling to reduce interferometric crosstalk. The question is to evaluate the average error rate P_e of the system under discussion (see Fig. 1). To account for all possible combinations of beat terms between the signal and crosstalk we proceed by assuming that μ sources are simultaneously a binary symbol "one," thus $N - \mu$ sources are "zero." The error probability analysis is then conducted by a weighted statistical average of the error probability for each value μ. This probability is given by the binomial distribution function. Hence, the average error probability P_e or bit-error rate (BER), for a given threshold α_{tr}, using the Gaussian approximation and assuming that the symbols are *a priori* equally probably $P_e(\mu)$ can be written as

$$P_e = \frac{1}{2^N}\sum_{\mu=0}^N \binom{N}{\mu}\left\{\frac{1}{2}Q\left(\frac{E_1(\mu) - \alpha_{\text{tr}}}{\sigma_1(\mu)}\right)\right.$$
$$\left. + \frac{1}{2}Q\left(\frac{\alpha_{\text{tr}} - E_0(\mu)}{\sigma_0(\mu)}\right)\right\} \tag{33}$$

where $E_{1,0}$ is the mean value of the receiver decision variable when a "one," and a "zero" is transmitted, respectively. The variance is denoted by $\sigma_{1,0}^2$. The function $Q(\cdot)$ is the standard
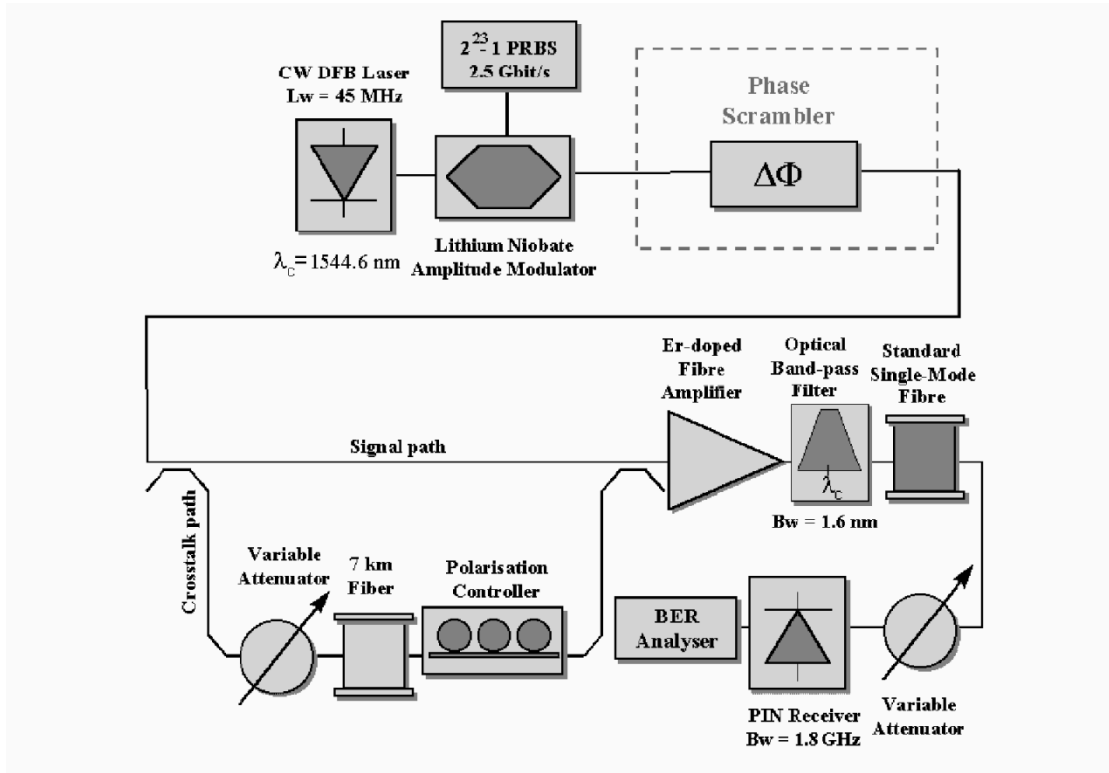
Fig. 5.   Experiment setup for the investigation of interferometric noise reduction by phase scrambling.

Gaussian probability tail function. In the presence of interferometric crosstalk and RIN due to chromatic dispersion after propagation, the variance of the receiver decision variable is approximately given by

$$
\sigma_{0,1}^2 = \underbrace{2q\mathcal{R}P_0 b_0^s B_F I_2}_{\text{signal shot noise}} + \underbrace{2q\mathcal{R}P_0 \sum_{n=1}^{N} b_0^{x,n} \epsilon_n B_F I_2}_{\text{xtalk shot noise}}
$$

$$
+ \underbrace{(q\mathcal{R}2P_0)^2 \sum_{n=1}^{N} b_0^s b_0^{x,n} \epsilon_n \sigma_{\gamma_s,n}^2}_{\text{signal-xtalk beat}} + \underbrace{\sigma_{\text{th}}^2}_{\text{therm. noise}}
$$

$$
+ \underbrace{(q\mathcal{R}2P_0)^2 \sum_{n=l+1}^{N} \sum_{l=1}^{N-1} b_0^{x,n} b_0^{x,l} \epsilon_n \epsilon_l \sigma_{\gamma_x,l}^2}_{\text{xtalk-xtalk beat}}
$$

$$
+ \underbrace{(q\mathcal{R}2P_0)^2 b_0^s \sigma_{\text{RIN}}^2}_{\text{signal RIN}}
$$

$$
+ \underbrace{(q\mathcal{R}2P_0)^2 \sum_{n=1}^{N} b_0^{x,n} \epsilon_n \sigma_{\text{RIN}_{x,n}}^2}_{\text{xtalk RIN}} \tag{34}
$$

where q is the electron charge, and I_2 is the Personick parameter [18]. Given a number N of crosstalk sources, the error probability is expeditiously evaluated by (33) accounting for data statistics, and nonperfect extinction ratio. The analysis, however, assumes that RIN contributions due to the beating terms of signal and crosstalk are neglected.

Some words on the use of the Gaussian approximation. As the signal is phase modulated with a Gaussian noise process the RIN due to phase to intensity noise conversion after propagation can also be considered to have a Gaussian distribution. The distribution of filtered interferometric crosstalk may differ from Gaussian statistics, e.g., [10], [19]. However, a Gaussian approximation (using the effective variance given by (14)) works well for crosstalk values resulting in relatively small power penalties. Moreover, the statistics of filtered interferometric noise tends to a Gaussian shape if the signal bandwidth exceeds the electrical filter bandwidth (as in the case of phase scrambling) [10]. We have adopted the Gaussian approximation for assessing the system performance considering the above mentioned features and also in view of its numerical simplicity.

V. EXPERIMENTAL SETUP

The experiment setup for measuring the interferometric crosstalk reduction by using phase scrambling is shown in Fig. 5. The setup works as follows. A commercially available DFB laser with a measured linewidth of 45 MHz operating at a wavelength 1544.5 nm is the continuous-wave (CW) source for the system. The CW lightwave is injected into a LiNbO$_3$ external modulator, which is driven by a pseudorandom binary signal generator (PRBS) producing an encoded repetitive sequence of nonreturn-to-zero (NRZ) pulses. The sequence length is $2^{23} - 1$ and the bit-rate is 2.5 Gb/s. In this experiment, we have intentionally used an external modulator because of its low-chirp characteristic. In this way, the spectral broadening is determined mainly by the driving current of the phase scrambler. The generated PRBS NRZ format has a measurable
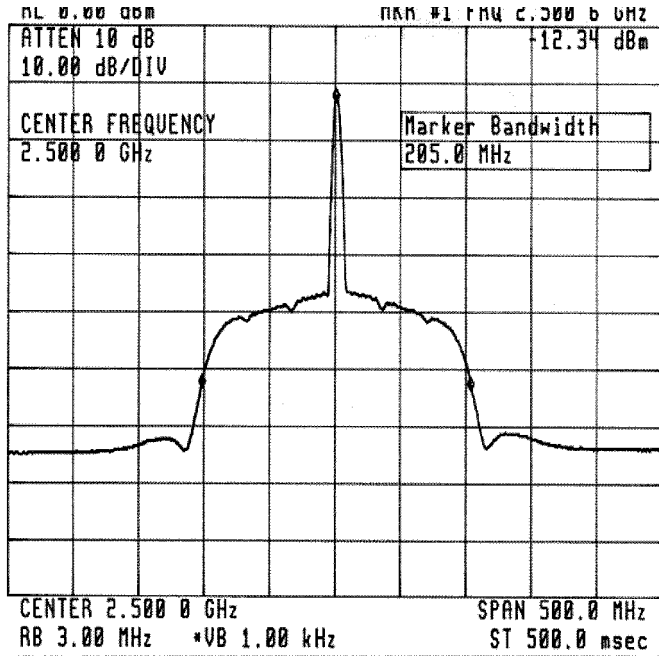
Fig. 6. Spectrum of the phase scrambling driving signal. The driving signal consists of a sinewave centered at 2.5 GHz and a filtered noise source with a bandwidth of 200 MHz.

20-dB extinction ratio and the receiver sensitivity has been measured to lie around -27 dBm.

The phase scrambler consists of a commercially available phase modulator, which is driven electrically by a high-frequency modulated noise source. In Fig. 6 is shown the spectrum of the phase modulator driving signal with a modulation index equal to π and with a bandpass filtered noise source centered at a frequency of 2.5 GHz. In the spectrum, the high-frequency sinewave signal is clearly observed as a sharp peak surrounded by the bandpass filtered noise. The modulating noise bandwidth is measured to be around 200 MHz and the ratio between peak power of the sinewave and the noise amounts approximately 35 dB. The spectrum of the resulting phase scrambled (using a driving signal whose spectrum is shown in Fig. 6) optical signal is given in Fig. 7. In comparison with the original spectrum (curve **a** in Fig. 7), we measured an increase in spectral bandwidth after phase scrambling of approximately 74 picometers (curve **b** in Fig. 7). Moreover, the top is flattened by the phase scrambling. We observed that this flattening is largely affected by the noise source parameter rather than by the sinewave. Furthermore, increasing the noise level does not show any significant change of the spectrum shape. The signal bandwidth varies significantly if the modulation index is varied to values up to approximately 2. This phenomenon has also been observed earlier in the theory section. After the phase scrambler, the 2.5-Gb/s modulated signal is coupled into an unbalanced Mach–Zehnder structure in which the signal is split into two paths. One path is 7 km longer than the other. This length difference largely surpasses the coherence length of a 45-MHz linewidth laser. Then, the two signals are mixed to produce interferometric beating noise at the incoherent regime. Polarization alignment between the signal and interferer, to create a worst-case condition, is done by adjusting the polariza-
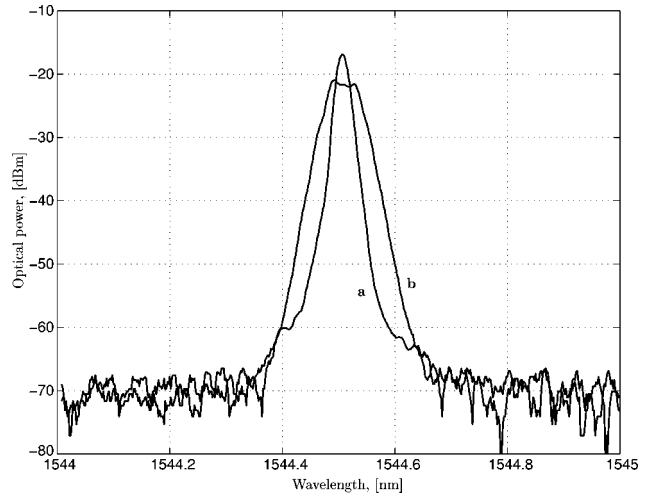

Fig. 7. Spectrum of the 2.5-Gb/s optical signal: (a) without and (b) with the phase scrambling.
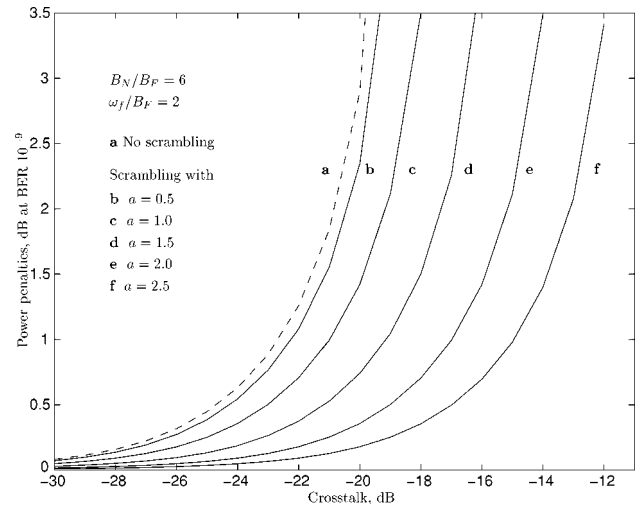

Fig. 8. Reduction of power penalty by phase scrambling as a function of the modulation index a. Theoretical results. The dotted line is the case of no phase scrambling. A fixed value for $B_N/B_F = 6$ and $\omega_f/B_F = 2$ is used. No transmission case.

tion controller. Two optical variable attenuators are used. One attenuator adjusts the level of the interferometric crosstalk and the other varies the level of received signal power.

The receiver section consists of an InGaAs PIN photodiode module followed by a variable gain GaAs electrical amplifier to boost the received photocurrent. The electrical bandwidth of the receiver circuit is approximately 1.85 GHz, which is suitable to detect signals at a bit-rate of 2.5 Gb/s without any distortion. The system performance is evaluated by using a BER analyzer. During the BER measurements the decision threshold is automatically optimized, taking a value somewhere between the level for the received binary "one" and "zero," to result in the lowest error probability.

The performance assessment of the system using phase scrambling is summarized in the power penalty curves shown in Fig. 9. The power penalties are related to a BER level of 10^{-9}. As reference we use a back-to-back measurement (no fiber transmission between the MZ and receiver section). In

the back-to-back situation (curve **a** in Fig. 9), crosstalk levels less than −23 dB result in a penalty less than 1 dB. Using the phase scrambling technique, the crosstalk level causing the same penalty can be increased to around −16 dB. With a transmission span of 100 km SSMF and using an optical amplifier to compensate for the fiber-induced loss, we still obtained a good performance even for crosstalk levels up to −18 dB. This means a crosstalk relaxation of 5 dB. Increasing the transmission span to 200 km and using a second amplifier, resulted in a tolerable crosstalk level of −21 dB. However, even for small values of the crosstalk the power penalty is relatively high, approximately 0.7 dB. This is due to the dispersion as a consequence of the spectrum broadening. We also observe that if we relate to a power penalty level of 2 dB, crosstalk values up to −15 dB and −16 dB are tolerable after transmission over 100 km and 200 km of SSM fiber. This corresponds to an enhancement of the system tolerance to crosstalk of 7 and 5.3 dB, respectively. In conclusion, we have demonstrated in a simple experimental setup that significant mitigation of interferometric crosstalk can be achieved using a phase scrambling technique, even for high levels of crosstalk. Transmission with satisfactory BER performance in a link of 100 and 200 km of SSM fiber has been demonstrated. These transmission spans represent the situation in a LAN/MAN network. The power penalty due to dispersion was measured to be 0.4 and 0.7 dB for 100- and 200-km transmission, respectively.

VI. RESULTS AND DISCUSSIONS

1) Phase Scrambling—No Transmission: In Fig. 8 is displayed how power penalties due to interferometric crosstalk are reduced by using phase scrambling. These theoretically obtained curves for a fixed value of $B_N T$ and $\omega_f T$ assume no transmission over dispersive fibers. The dotted line represents the power penalties without phase scrambling. As the modulation index increases, we can observed that system tolerance towards interferometric crosstalk is substantially enhanced.

2) Phase Scrambling and Transmission: We examine power penalties after 100- and 200-km transmission over SSM fiber with $D = 17$ ps/nm km. Phase scrambling is applied with a modulation index $a = \pi$. In Fig. 10 are presented the power penalties as function of the crosstalk parameter ϵ. The modulating noise bandwidth is $B_N = 200$ MHz. The parameters used in the theoretical computations are in correspondence with the experimental setup to simulate the measurements. We observe in Fig. 10 that phase scrambling effectively enhance the tolerance towards crosstalk. However, additional power penalties associated with RIN due to dispersion are incurred. We can conclude that phase scrambling mitigates crosstalk penalties at expenses of network reach. We may compare the theoretical results shown in Fig. 10 with the measurements presented in Fig. 9. We observe good agreement between theory and experiment. The theoretical model predicts well the performance tendency of the system and can therefore be used to determine the proper parameters for phase scrambling in WDM networks.

The scalability of optical networks using phase scrambling is strongly governed by the limitations imposed by fiber dispersion. However, selecting appropriate parameters for
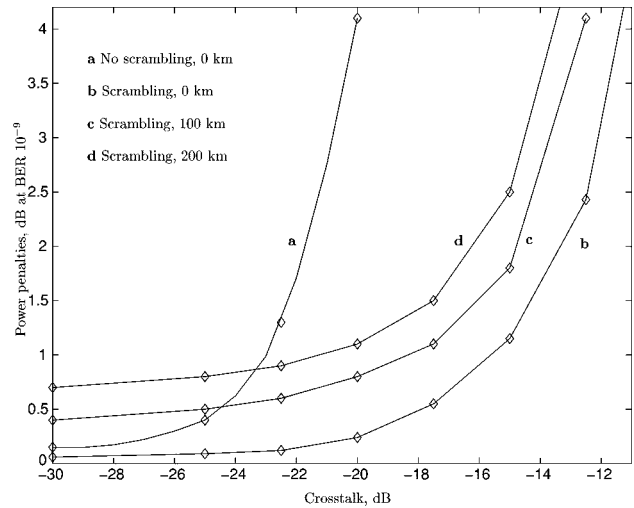

Fig. 9. Measured power penalties. (a) Back-to-back situation and with phase scrambling (b). Results with phase scrambling and transmission over (c) 100 km and (d) 200 km of SSMF.
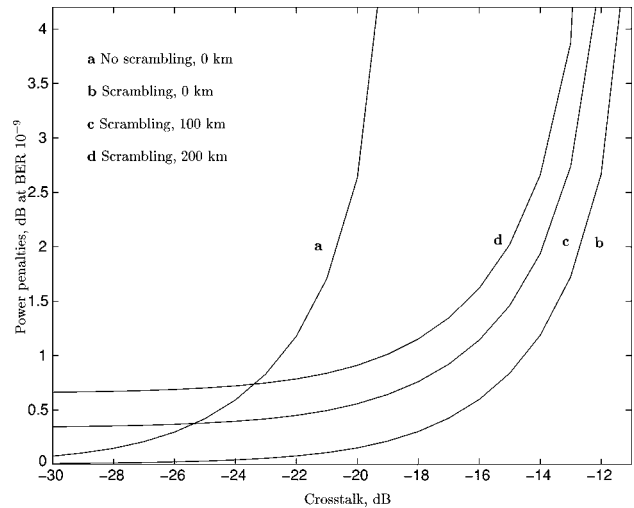

Fig. 10. Theoretical results for power penalties. (a) Back-to-back situation, (b) phase scrambling and no transmission. Results with phase scrambling and transmission over: (c) 100 km and (d) 200 km of SSM fiber.

the phase scrambling dispersion penalties can be kept small while crosstalk is still significantly filtered out at the receiver end. Limitations caused by the spectral broadening are further reduced in optical networks using dispersion compensating strategies. From our study, significant enhancement of the tolerance to crosstalk and transmission over 200-km SSMF are proven feasible for a system operating at 2.5 Gb/s.

Besides phase scrambling other methods of crosstalk suppression have been proposed [3], [20]. These include bit pattern misalignment, error correcting codes, among others; see [3, Table III]. Among these methods phase scrambling is a proven crosstalk mitigating technique, but at expenses of network reach due to dispersion penalties.

VII. CONCLUSIONS AND RECOMMENDATIONS

A complete assessment, theoretical and experimental, of crosstalk reduction by phase scrambling, including transmission, is presented. It is experimentally demonstrated that phase

scrambling substantially reduces interferometric crosstalk, enhancing the system tolerance to crosstalk. For instance, crosstalk values of -16-dB results in power penalty less than 2 dB after transmission over 200-km SSM fiber. Such crosstalk values when no phase scrambling is applied would make any transmission of information impossible. Hence, phase scrambling has been proven to effectively mitigate crosstalk extending the scalability properties of WDM optical networks. It is also shown that by properly choosing the noise source for the phase scrambling power penalties due to phase to intensity noise conversion can be kept small. For instance, transmission over 200 km of SSM fiber is successfully demonstrated. This results indicates that phase scrambling make WDM networking in a LAN/MAN environment feasible while making use of the current integrated switching and cross-connect technology.

Phase scrambling mitigates the limitations imposed by interferometric crosstalk at the expense of network reach. Care should be taken to assure that small power penalties due to dispersion are incurred. The presented theoretical model can be used to compute the optimal parameters for phase scrambling. The modulation index a is the parameter of major influence on the crosstalk mitigation. A fast crosstalk reduction is observed for values of a up to π. Larger values of a show an slow rate of reduction of crosstalk variance (see Fig. 4). The modulating noise source can be centered at an arbitrary frequency ω_f and its equivalent noise bandwidth can amount some hundreds of MHz.

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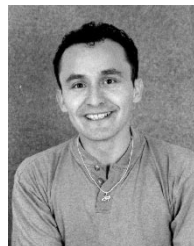
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