Experimental Evaluation of Optical Crosstalk Mitigation Using Phase Scrambling

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Abstract—In this letter, we report an experimental study of mitigation of optical homodyne crosstalk by phase scrambling. This mitigation is obtained by frequency shifting the signal-crosstalk beating noise power out of the receiver bandwidth. An increased tolerance to crosstalk of 7 and 5 dB is measured in a 2.5-Gb/s link of 100 and 200 km of standard single mode fiber, respectively. This result indicates the feasibility of optical networking in the LAN/MAN domain, by tolerating the relatively high crosstalk levels of present optical switching technology. Our experiment is in good agreement with theoretical results.

Index Terms—Error analysis, interferometric noise, optical crosstalk, phase scrambling.

I. INTRODUCTION

The impact of homodyne crosstalk has proven to be a major limiting factor in optical networks [1], [2]. For instance, optical crosstalk levels less than −35 dB should be used to prevent power penalties of more than 1 dB, even when a small number of crosstalk interferers are present [1]. This is still a tough requirement on the performance of monolithically integrated optical devices at the present state-of-the-art [3]. Although improvements in device performance are foreseen, a substantial relaxation of the crosstalk requirements from individual components in optical networks is necessary to work with the presently available devices. An interesting approach has been put forward by Pepeljugoski and Lau [4], where high frequency phase modulations were proposed to reduce interferometric noise in fiber-optic links. We adopted this approach as a way to bridge the gap between the stringent crosstalk requirements and the unsatisfactory achievable crosstalk values with the present integrated technology. In this letter, we demonstrate experimentally (including transmission) that a network’s tolerance toward homodyne crosstalk can be enhanced by 7 dB by using phase scrambling. Power penalties less than 2 dB for crosstalk levels up to −15 dB have been measured in a 2.5-Gb/s link of 100 km of standard single mode fiber (SMF) and −16 dB of 200 km. This result demonstrates the feasibility of optical networking in a LAN/MAN domain with the current state-of-the-art in integrated optical technology.

Moreover, values predicted by theory are in good agreement with experiments.

II. THEORY

If an optical signal and a crosstalk interferer are present at the input of a photodetector, the total optical field is given by their superposition. The output of a photodetector is a photocurrent proportional to the squared magnitude of the detected signal and crosstalk field. This nonlinear operation on the detected field results in a photocurrent composed of three terms. Two of those terms are the contribution of the average optical power in the signal and the crosstalk, respectively. The other term is a fluctuating term due to the randomly changing phase difference between the signal and crosstalk. This is the interferometric crosstalk noise term. Postdetection filtering is used in optical receivers. The interferometric crosstalk contribution to the filtered photocurrent can be mathematically described as

\[
\xi(t) = h(t) * \sqrt{g_s(t)g_c(t - \tau_c)} \cos[\phi_s(t) - \phi_c(t - \tau_c)]
\]  

(1)

if we consider a postdetection filter with impulse response \(h(t)\). The convolution operation is denoted by \(*\). The magnitude \(g_{s,c}(t)\) is the phase, and \(g_{s,c}(t) > 0\) is the optical pulse shape. The interferometric delay time is denoted by \(\tau_c\). We have assumed a worst case of polarization alignment. We applied phase scrambling with a signal \(\psi(t) = \alpha n(t) \cos\omega_f t\), where \(\alpha\) is the modulation index and \(n(t)\) is a bandpass Gaussian noise centered at a frequency \(\omega_f\). The interferometric crosstalk contribution to the photocurrent is then of the type

\[
\xi(t) = \cos[\Delta \psi(t) - \Delta \psi(t)]
\]  

(2)

in which \(\Delta \psi(t)\) and \(\Delta \psi(t)\) are the phase difference of the laser field and the imposed phase modulation, respectively. It can be shown that the autocorrelation function of \(\xi(t)\), for the incoherent crosstalk regime, is given by

\[
R_\xi(\tau) = \frac{1}{2} e^{-2\pi |\Delta \psi|} e^{-(n^2/2)[R_o(0) - R_o(\tau) \cos \omega_f \tau]}
\]  

(3)

where \(R_o(t)\) is the autocorrelation function of \(n(t)\) and \(\Delta \psi\) is the 3-dB linewidth of the Lorentzian shaped laser spectrum. The variance of this noise can be found by using the following relation

\[
\sigma^2 = 2 \int_0^\infty S_f(f) |H(f)|^2 df
\]  

(4)

where \(H(f)\) is the transfer function of the postdetection filter and \(S_f(f)\) is the interferometric crosstalk power spectrum obtained by Fourier transforming (3). It is shown in [4] that the
variance of filtered interferometric crosstalk, $\sigma_c^2$, can be effectively reduced by increasing the modulation index of the phase modulating signal. From our simulations and measurements we observed that at 2.5-Gb/s transmission, crosstalk mitigation is achieved by using a modulating noise source centered at an arbitrary frequency $\omega_f$ and with equivalent noise bandwidth of some hundreds of megahertz. A model for the performance analysis of systems using phase scrambling has been developed. We present here the results of the model while the computation is performed following the same strategy as in [5] to obtain a closed expression for power penalties.

III. EXPERIMENTAL SETUP

Our technique to mitigate crosstalk is based on the intentionally spreading of the spectrum of the information channel and the interfering channel. In this way, a substantial part of beating noise will fall outside the receiver bandwidth. Only noise falling within the receiver bandwidth plays a major role in the performance degradation. The experimental setup for measuring the effectiveness of interferometric crosstalk mitigation by phase scrambling is shown in Fig. 1. A DFB laser with a measured linewidth of 45 MHz provides a continuous wave (CW) source at 1544.5 nm. The CW light is injected to an external modulator which is driven by a pseudorandom binary sequence (PRBS) producing an encoded repetitive sequence of nonreturn-to-zero (NRZ) pulses. The sequence length is $2^{23} - 1$ and the bitrate is 2.5 Gb/s. The generated NRZ signals have a 20-dB extinction ratio. In this experiment, we have intentionally used an external modulator because of its low chirp properties. In this way, the spectral broadening is determined mainly by the driving current of the phase scrambler. The phase scrambler consists of a phase modulator, which is driven electrically by a band-limited noise source superimposed on a high frequency sinewave signal source. Fig. 2 shows the spectrum of the phase modulator driving signal with a modulation index equal to $\gamma$ and with a bandpass filtered noise source centered at 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 optical signal is plotted in Fig. 3. In comparison to the original spectrum (mark “No PS”), we measured a slight increase in spectral bandwidth after phase scrambling (mark “PS”) of 75 pm. The spectrum top is slightly flattened by the phase scrambler. We observed also that this flattening is largely affected by the noise source parameter rather than by the sinewave. Moreover, increasing the noise level does not show any significant change in the spectrum shape. The signal bandwidth varies significantly if the modulation index is changed to take a value around two. This phenomenon was also observed and already explained in [4]. After the phase scrambler, the signal is coupled into an unbalanced Mach–Zehnder interferometer (MZI) structure in which one arm is 7 km longer than
the other. This length difference is much greater than the coherence length of a 45-MHz linewidth laser, and therefore the interference occurs in the incoherent regime. Polarization alignment between the signal and interferer, to create a worst-case condition, is carried out by adjusting the polarization controller. Two optical variable attenuators are involved: one 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 with a 1.9-GHz GaAs pre-amp to boost the received photocurrent. After the photodiode, a clock and data recovery module is located for bit error rate (BER) evaluations. The decision threshold is automatically optimized, taking a value somewhere between the level for received binary “one” and “zero,” to result in the lowest error rate.

IV. DISCUSSIONS

The performance assessment of the setup using phase scrambling is summarized in the power penalty curves shown in Fig. 4. The power penalties are measured as a function of crosstalk relative to signal power for a fixed BER of $10^{-6}$. Solid curves are theoretical results.

![Fig. 4. Power penalties versus relative crosstalk power for a fixed BER of $10^{-6}$. Solid curves are theoretical results.](image)

Due to spectral broadening is still small (0.4 dB). Increasing the transmission span to 200 km ($\Delta$) and using two optical amplifiers spaced with 100 km, the phase scrambling resulted in a maximum tolerable crosstalk level of $-21$ dB, decreasing the mitigation factor to only 2 dB. However, even for low crosstalk powers, the penalty is relatively high (0.7 dB). This is due to the fiber dispersion as a consequence of the spectrum broadening. It can also be observed that if we relate to a 2-dB penalty level, crosstalk values up $-15$ and $-16$ dB are tolerable after transmission over 100 ($\nabla$) and 200 km ($\Delta$). This corresponds to an enhancement of the system tolerance toward crosstalk of, respectively, 7 and 6 dB. Although the theoretical results, shown in Fig. 4 as solid curves, are slightly lower than the experiment, there is a good agreement in trend between theory and measured results. These discrepancies are believed to be due to simplifications made in the modeling such as neglecting beating terms between RIN and ASE noise of the EDFA.

V. CONCLUSION

We have reported that phase scrambling substantially relaxes the crosstalk requirements on optical components. This relaxation is at expenses of network span due to dispersion limitations. However, by using a proper phase scrambling format, significant crosstalk mitigation is assured while power penalty due to fiber dispersion is kept small. Transmissions with satisfactory BER performance in a link of 100 and 200 km of SMF has been demonstrated: $-18$ and $-21$ dB for a 1-dB power penalty. These transmission spans represent the situation in a LAN/MAN, allowing for optical networking using the relatively high crosstalk values of present monolithically integrated optical switching and cross-connect technology.

REFERENCES