Timing jitter in short-distance pulsed-analog optical fiber links

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Introduction

Studies of timing jitter associated with pulse propagation in optical fiber have focused on long-haul, digital optical communication systems [1]. These studies are concerned with the propagation of relatively low power pulses over megameters of fiber and quantifying how the induced timing jitter affects the bit-error rate. Recently, there has been interest in the use of short optical pulses to transmit analog information for applications such as high-precision optical clocks and optically sampled analog-to-digital converters [2]. These pulsed-analog applications require femtosecond timing accuracy in contrast to the picoseconds of jitter allowable in present-day digital communication systems. Additionally, much larger pulse energies (> 100 pJ) can be required in these pulsed-analog links to attain high signal-to-noise ratios (SNRs). At these high powers, fiber nonlinearities introduce significant timing jitter even when the transmission distance is a kilometer or less.

In this paper, we investigate the timing jitter generated by propagating high-power optical pulses through short lengths of optical fiber. Timing jitter is measured using the phase-encoded optical sampling technique. Comparisons are made between measured and simulated results.

Theory and Simulation Results

In pulsed-analog systems, large pulse energies are required to achieve high SNR. For example, to achieve a 60-dB SNR in our optical sampling system, the pulse energy E_P required at the sampling modulator input is 75 pJ. At this E_P, a 30-ps soliton in SMF would be of the order N = 5. This implies that high-order nonlinear effects such as pulse breakup and self-steepening need to be considered when analyzing pulse propagation in these systems.

To estimate the timing jitter generated by fiber nonlinearities, we determine the AM-to-PM conversion efficiency $\eta_{AM\text{-}PM}$ by simulating pulse propagation and calculating the propagation-time variation ΔT as a function of E_P. Pulse propagation is performed using the split-step Fourier method to solve the generalized Nonlinear Schroedinger Equation (NLSE) [3]. The generalized NLSE includes the effects of self-phase modulation, 2nd and 3rd order dispersion, loss, stimulated Raman scattering, and self-steepening. For a given length of fiber, $\eta_{AM\text{-}PM}$ is defined as the change in ΔT with respect to a fractional change in E_P for a specific input pulse width. At large E_P where pulse breakup occurs, ΔT is determined for the energy centroid of the pulse complex. Our analysis assumes that all of the fiber-induced timing jitter results from the conversion of amplitude noise to timing noise. The analysis does not include the effects of Gordon-Haus jitter or nonlinear polarization mode-dispersion.

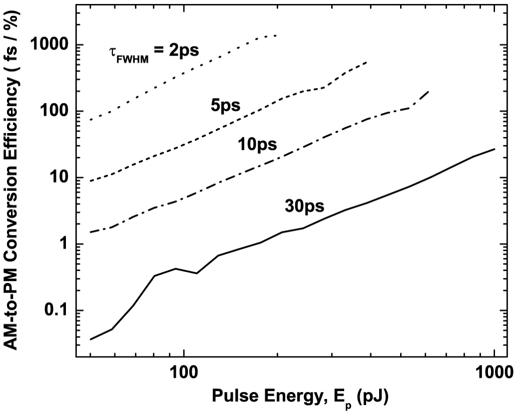

Fig. 1. Calculated AM-to-PM conversion efficiency versus pulse energy E_P of a 1.8-km length of SMF-28 fiber.

The calculated $\eta_{AM\text{-}PM}$ (Fig. 1) increases as a nonlinear function of E_P. It is also clear that $\eta_{AM\text{-}PM}$ is not a linear function of pulse intensity. As the pulse width decreases a factor of 15, the efficiency increases by 3 orders of magnitude. This is due to the higher-order nonlinearities that are dominant for the shorter pulses.

Timing Jitter Measurements

The setup used to measure the fiber-induced timing jitter (Fig. 2) consists of an optical pulse source, a pair of variable optical attenuators, a 1.8-km spool of SMF-28 fiber, and a phase-encoded optical sampling system [2]. The pulse source is a harmonically mode-locked erbium-doped fiber ring laser producing 30-ps pulses at a 59.4-MHz repetition rate (6th harmonic) with an average power of 0.5 mW. The pulses were amplified using a double-pass polarization-maintaining EDFA having an output power of 60 mW. The two optical attenuators were used to vary the launched pulse energy while maintaining constant EDFA output power and optical

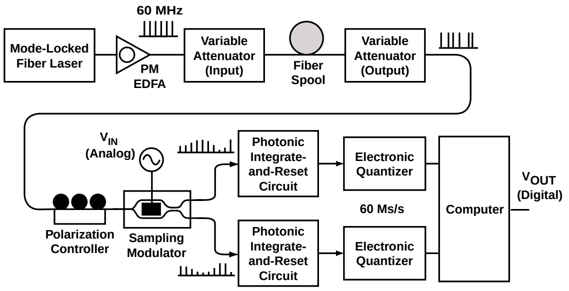

Fig. 2. Equipment configuration for measuring fiber-nonlinearity-induced timing jitter using the phase-encoded optical sampling technique.

sampling system input power. The dual-output $LiNbO_3$ sampling modulator has a bandwidth of 10 GHz. A polarization controller was used to match the signal polarization to that of the modulator.

Pulse-to-pulse timing jitter of the pulse stream was estimated by optically sampling a high-frequency (~ 3 GHz) sinusoidal signal and computing the signal-to-jitter-noise ratio as described in Ref. [4]. The phase-encoded optical sampling technique provides 60 dB of amplitude jitter suppression. Even pulse splitting does not degrade the amplitude noise suppression since the detected photocurrent from each pulse is integrated for 10 ns. A low-frequency (13 MHz) sinusoid was sampled to determine the jitter-independent system noise. The sinusoid amplitudes were adjusted to ensure that the modulation index was the same for the high- and low-frequency measurements.

The power spectra of Fig. 3 compare the SNRs of the sampled 3-GHz signal with and without the fiber spool installed for E_P = 1 nJ. The 25-dB increase in the noise floor with the fiber installed is dominated by timing jitter. This was confirmed by varying the signal frequency f_0 and observing that the SNR varied as $1/f_0^2$ as expected [4]. Since the increased noise floor is white, the pulse-to-pulse fiber-induced jitter is random and not correlated with the supermode noise or laser relaxation oscillations.

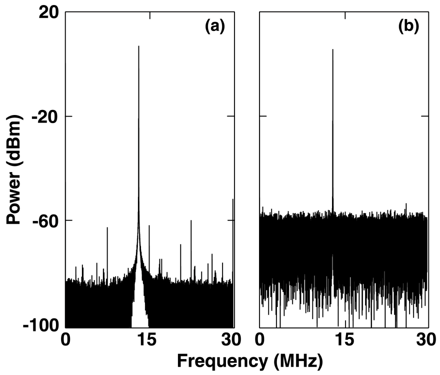

Fig. 3. Power spectra of optically sampled 3-GHz sinusoid for two different lengths of SMF fiber between EDFA and sampling modulator: (a) 10-m, and (b) 1.8-km. Pulse energy = 1 nJ. The 3-GHz frequency aliases to 13 MHz. FFT size = 64K.

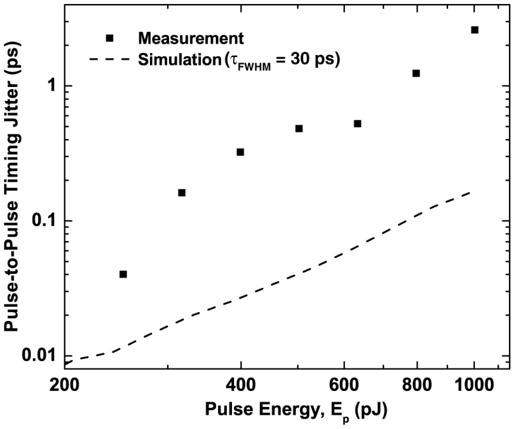

Fig. 4. Measured and simulated pulse-to-pulse timing jitter induced by transmission through 1.8-km SMF-28 fiber.

The pulse-to-pulse timing jitter generated by fiber transmission increased from ~50 fs to 2.6 ps as E_P increased from 250 to 1000 pJ (Fig. 4). The simulated data in Fig. 4 were obtained by multiplying the 30-ps $\eta_{AM\text{-}PM}$ curve (Fig. 1) by the measured laser amplitude noise at the input of the fiber (σ_{AM} = 6%). No fitting parameters were used. The measured and simulated data have similar slopes, but the simulation underestimates the jitter by about an order of magnitude. This difference in the absolute magnitude indicates that our simple model does not include all of the jitter mechanisms present in this highly nonlinear situation.

Conclusions

We have observed the generation of picoseconds of pulse-to-pulse timing jitter by propagating high-energy pulses through a relatively short length of SMF fiber. The induced timing jitter for these pulses is dominated by higher order nonlinearities such as self-steepening, Raman self-frequency shift, and pulse breakup. These jitter mechanisms will limit the distance that an optical sampling modulator may be remoted. The induced jitter is predicted to get dramatically worse as the pulse width decreases.

References

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