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Semi-analytic modeling of FWM noise in dispersion-managed DWDM systems with DQPSK/DPSK/OOK channels

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ABSTRACT

Semi-analytic models are developed to deterministically calculate the variances of degenerate and non-degenerate four-wave-mixing (FWM) noises for dispersion-managed dense wavelength division multiplexing (DWDM) systems with pure and mixed differential quadrature-phase-shift keying (DQPSK)/differential phase-shift keying (DPSK)/on-off-keying (OOK) channels. The semi-analytic models include various important propagation effects for exact numerical results. The novel dispersion map used here for dispersion management is composed of effective-area-enlarged positive dispersion fiber (EE-PDF), dispersion slope and dispersion compensating fiber (SCDCF) and nonzero dispersion-shifted fiber (NZ-DSF). It is numerically validated with the new models that, under the condition that all channels have the same average launch powers and baud rates, the impact of FWM noise for mixed DQPSK/OOK channels are more severe than that for pure DQPSK and mixed DQPSK/DPSK channels. It is also shown that the FWM efficiency is strongly dependent on the peak power of launched optical pulse for a large number of channels, as can be mainly attributed to the quasi-linear evolution of pulse shapes in pump channels induced by cross-phase modulation (XPM). Compared with some commercial optical-fiber transmission simulators, massive time-consuming can be avoided by using the newly derived semi-analytic models when transmission performances of such DWDM systems are numerically optimized and evaluated.

1. Introduction

The internet traffic growth calls for an increased capacity of dense wavelength division multiplexing (DWDM) optical transmission systems. In order to increase the system capacity, spectrally efficient modulation formats are of interest. An obvious way of increasing the spectral efficiency of systems is using advanced multilevel modulation formats, where more than a single bit is transmitted by each symbol [1]. These formats include four-level amplitude shift keying (4-ASK), differential quadrature-phase-shift keying (DQPSK), and combined differential-phase-amplitude shift-keying (DPASK) [2]. Another approach of increasing the spectral efficiency of system is using narrow channel spacing. When the channel spacing becomes narrow, four-wave mixing (FWM), one of dominant nonlinear effects, is dramatically elevated, potentially leading to severe impair of system performance. It is mandatory for DWDM system designer to evaluate various nonlinear impairments. Based on Volterra series transfer function, a 2-D (time and wavelength) discrete-time input–output model has been developed for the evaluation [3,4]. FWM tones acts as noise due to randomness of bit-sequences in all channels. When we calculate the variance of FWM noise, directly using a well-known spilt step Fourier (SSF) method with the aid of some commercial optical-fiber transmission simulators, large computation time is needed because a lot of random trials must be run in order to get a good estimate of many random factors such as birefringence strength and orientation along transmission fiber. Especially, in case of a large number of channels, the computation time is almost prohibitive, so statistical methods are needed to evaluate the FWM noise [5–7]. A finite-bandwidth noise theory was introduced to calculate the variance of FWM noise for single span transmission in [8,9]. For multi-span dispersion-managed (DM) transmission, the calculation model was further developed in [10]. The dependence of FWM light on randomly changing polarization states along fiber was analyzed in [11,12]. The analyses mentioned above are all for on-off-keying (OOK) format. For return-to-zero (RZ) frequency-shift-keying (FSK), statistical model of FWM noise was derived in [13]. For differential phase-shift keying (DPSK) format, a semi-analytic model was obtained to evaluate the FWM noise for single span transmission in [14]. The calculation models mentioned above all include the effect of walk-off between channels and a notion of channel overlap function is introduced for it in [8].

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Although advanced modulation formats allow us to design optical systems with a bit rate per channel of 40 Gb/s or higher and good tolerance against linear and nonlinear impairments, complete substitution of deployed OOK system is a very expensive option, thus a cost effective solution is to upgrade one or more selected channels following the market demand. Systems that employ two or more modulation formats are referred to as "mixed" or "hybrid" [15].

To the best of our knowledge, so far, based on statistical method, no analytic model to evaluate the FWM noise was presented for some pure and mixed DQPSK/DPSK/OOK systems including various important propagation effects. These effects mainly include walk-off between channels, stochastic variation of birefringence along fiber and quasi-linear evolution (QLPE) of pulse shape with distance due to the interaction of dispersion and various fiber nonlinearities. In this paper, semi-analytic models for some pure and mixed DQPSK/DPSK/OOK systems are developed and some numerical results are given by using these models.

The remainder of this paper is organized as follows. In Section 2, a novel dispersion map is suggested and balanced detection for DQPSK is described. In Section 3, the variance of degenerate FWM noise is derived in detail for single-span transmission and pure DQPSK channels including walk-off between channels. In Section 4, the variance of non-symmetric non-degenerate FWM Model for single-Span transmission and a special mixed combination of DQPSK/DPSK/OOK channels is derived in detail including walk-off between channels. In Section 5, the expressions of variances of FWM noises for multi-span transmission and various combinations of DQPSK/DPSK/OOK channels are presented. In Section 6, the impact of randomly varying polarization states along fiber link on variance of FWM noise on is given. In Section 7, a parameter, used to quantify the FWM induced degradation of Q-factor is expressed. Numerical results are given in Section 8. We summarize our conclusion in Section 9. In Appendix A, the solving process of channel overlap function for multi-span transmission is given when quasi-linear evolution of pulse shape with distance is taken into account. Expressions of variances of some noises except FWM for DQPSK receiver are given in Appendix B.

2. Dispersion map and balanced detection for DQPSK

In order to obtain better transmission performance than conventional dispersion management, a novel dispersion map, shown by Fig. 1, is proposed in this paper. The dispersion map consists of three fiber sections which are effective-area-enlarged positive dispersion fiber (EE-PDF), dispersion slope and dispersion compensating fiber (SCDCF) and nonzero dispersion-shifted fiber (NZ-DSF), respectively. If fiber loss is not considered, the third fiber section should be EE-PDF also for a symmetrical dispersion map, but, in practice, optical power is apparently smaller for the third fiber section than the first one for the given amplifier position allocation shown by the figure. Fiber nonlinearities strongly depend on optical power will become too weaker if EE-PDF with large effective-area and dispersion is still adopted for the third fiber section. When the balance of dispersion and fiber nonlinearities for better transmission performance is considered, NZ-DSF with smaller effective-area and dispersion should replace EE-PDF for the third fiber section.

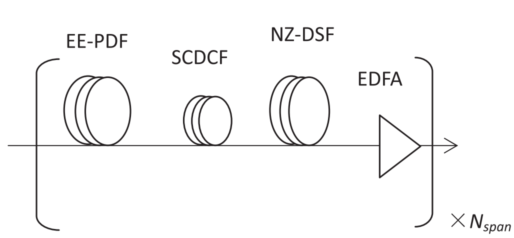

Fig. 1. Dispersion map.

Table 1
Parameters for three types of fiber.

	EE-PDF	SCDCF	NZ-DSF
Dispersion (ps/(nm.km))	18	−22	3
Dispersion slope (ps/(nm2.km))	0.06	−0.12	0.045
Aeff (μm2)	100	30	50
Loss (dB/km)	0.2	0.23	0.2
Lengths of fiber sections in per span (km)	15	15	20

The subscripts of "*fir*", "*sec*" and "*thi*" denote quantities evaluated within the first, second and third fiber sections of each repeater span, respectively. For example, L_{fir} denotes the length of the first fiber section. The nonlinear refractive index n_2, assumed to be same for the three fibers, is $2.43 \times 10^{-20}\text{m}^2/\text{W}$, A_{eff} is the effective area, and the nonlinear coefficient γ is known to satisfy $\gamma \approx 2\pi n_2/\left(\lambda_c A_{eff}\right)$. Wavelength of central channel λ_c is 1550 nm. Other fiber parameters are given in Table 1. The number of such repeater span is written as N_{span}. Optical preamplifier is not adopted before the receiver, so the number of Erbium-doped fiber amplifiers (EDFAs) is $\left(N_{span} - 1\right)$.

More FWM products will fall on the central channel than other channels, so the central channel is supposed to be the detected channel in this paper as the worst case and the central channel is supposed to be DQPSK modulated. Fig. 2 shows a differential detection scheme for DQPSK format, which consists of a pair of asymmetric Mach–Zehnder interferometers (AMZs), with a one-symbol delay between their arms, followed by two balanced avalanche photodiodes (APD). The two AMZs need to be accurately phase tuned so that the differential optical phase between the interferometer arms is equal to $\pi/4$ and $-\pi/4$ for the upper and lower AMZs, respectively [16].

3. Degenerate FWM model for single-span transmission and pure DQPSK channels

In this section, the variance of degenerate FWM noise is firstly derived in a simple scenario. The scenario corresponds to two basic assumptions. One of them is that all channels are DQPSK modulated and co-polarized. The other is that the fiber link is single-span transmission and polarization effects along the fiber

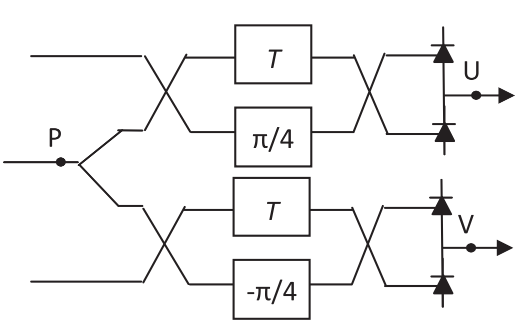

Fig. 2. Balanced detection for DQPSK.