# Modeling of Nonlinear Phenomena in Optical Multi-Channel Transmission Systems

Remigius Zengerle

University of Kaiserslautern, Lehrstuhl für Theoretische Elektrotechnik und Optische Kommunikationstechnik, 67663 Kaiserslautern, Germany
E-mail: zengerle@rhrk.uni-kl.de

**Abstract**

I order to increase the reliability of numerical models for the design of optical multi-channel WDM transmission systems all significant nonlinear effects are simultaneously included in our fiber model. Our improved model for the erbium-doped fiber amplifier also takes into account a significant nonlinear phase shift.

## 1. INTRODUCTION

Fiber-optical transmission systems using dense wavelength division multiplexing (WDM) with up to 100 channels or even more are presently under development. In order to transmit economically information over long distances the span for cascaded optical amplifiers or repeaters should be wide and the power level in every individual channel will be high. So in multi-channel systems power accumulation along one fiber increases drastically leading to nonlinear effects. However, reliable simulations of wave propagation are fundamental requirements for design and optimization of transmission systems. So the consequences of nonlinear effects like self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) should be included in addition to the well known linear effects.

In standard simulation tools self-phase modulation and group velocity dispersion (GVD) are treated by solving the nonlinear Schrödinger equation (NLSE) for each transmission channel. XPM and FWM are frequently included as additional noise. This way is no longer valid for a significant power accumulation especially in multi-channel systems with narrow channel spacing. Here we present a simulation model and examples for dense wavelength division multiplexing systems where all significant nonlinear effects are simultaneously included.

Optical amplifiers are key components in lightwave systems. So, we also developed an extended erbium-doped fiber amplifier (EDFA) model that includes phase modulation in the EDFA due to signal- and pump-induced change of the refractive index.

## 2. THE WDM TRANSMISSION SYSTEM

We use a standard WDM transmission system (Fig. 1) consisting of an array of ideal directly modulated semiconductor lasers at the transmitter side. For wavelength multi- and demultiplexing ideal wavelength-selective filters are supposed. The transmission line consists of a number of 80 km fiber spans including either a standard single-mode fiber (SMF) or a non-zero dispersion-shifted fiber (NZDSF) followed by a dispersion compensating fiber module (DCF) and an EDFA for compensation of loss. A standardized concept similar to that of "normalized transmission sections" [1] was used in order to simplify system layout and optimization.

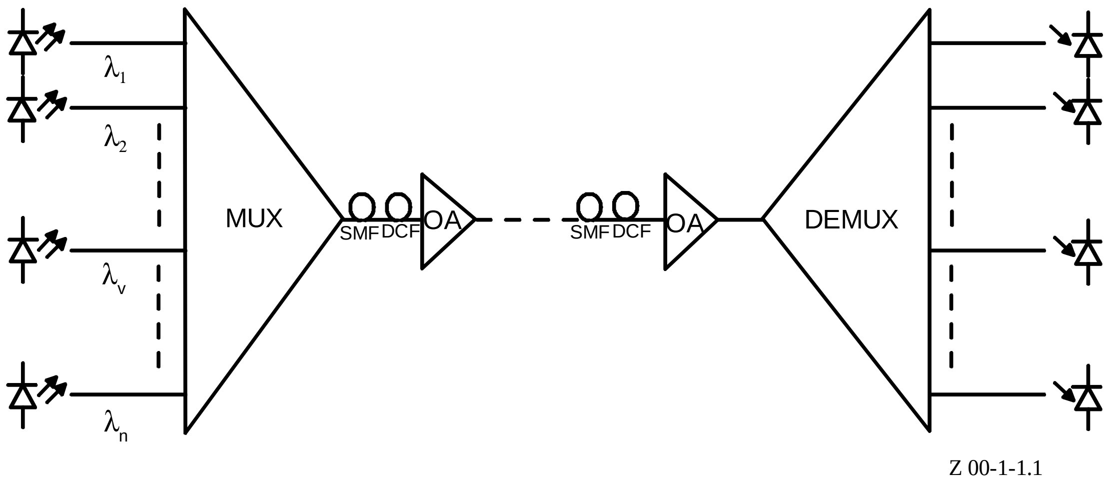


Fig. 1: WDM transmission model with normalized transmission sections in the field.

## 3. THE NONLINEAR FIBER MODEL.

The optical multi-carrier system with n channels is simulated by solving a system of n coupled nonlinear Schrödinger equations (NLSE) using the split-step Fourier algorithm [2,3]. All linear effects (attenuation, chromatic dispersion) and all nonlinear effects related to the Kerr-effect (SPM, XPM and FWM) are taken into account.

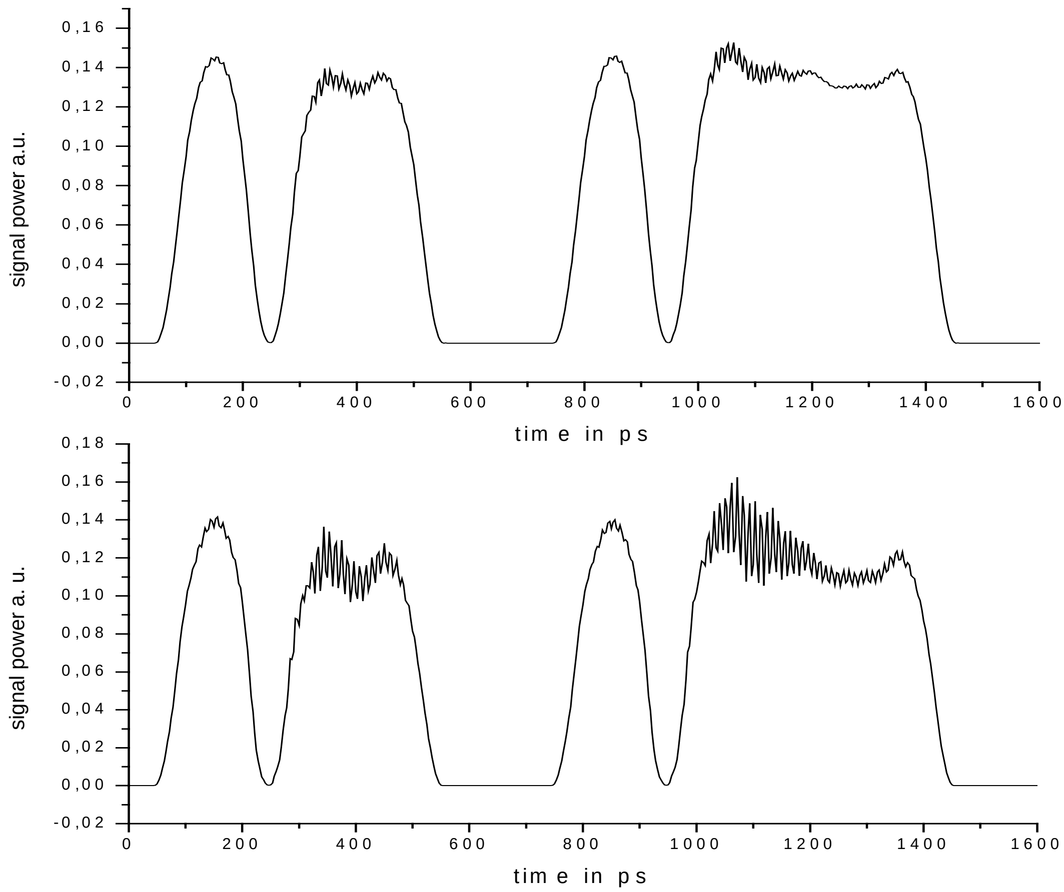


Fig. 2: 4-channel WDM transmission of 10 Gbit/s NRZ-signals including FWM after 480 km (upper trace) and after 640 km (lower trace)

A system with a small number of channels was simulated by a 4 channel 10 Gbit/s NRZ signal transmission with an equidistant channel spacing of 100 GHz according to the standard ITU-grid. The center wavelength was assumed to be around 1550 nm and peak power per channel launched into the fiber at the beginning of every section was 10mW. The entire system consists of eight 80 km sections of a NZDSF followed by 2 km of DCF for complete post compensation of the chromatic dispersion. Loss is compensated at the end of every section by an ideal fiber amplifier. After 480 km FWM here occurs as noise especially in bit patterns with many subsequent "ones" (Fig. 2). This noise, however, increases nonlinearly with the number of cascaded sections to about a factor of 4 after 640km.

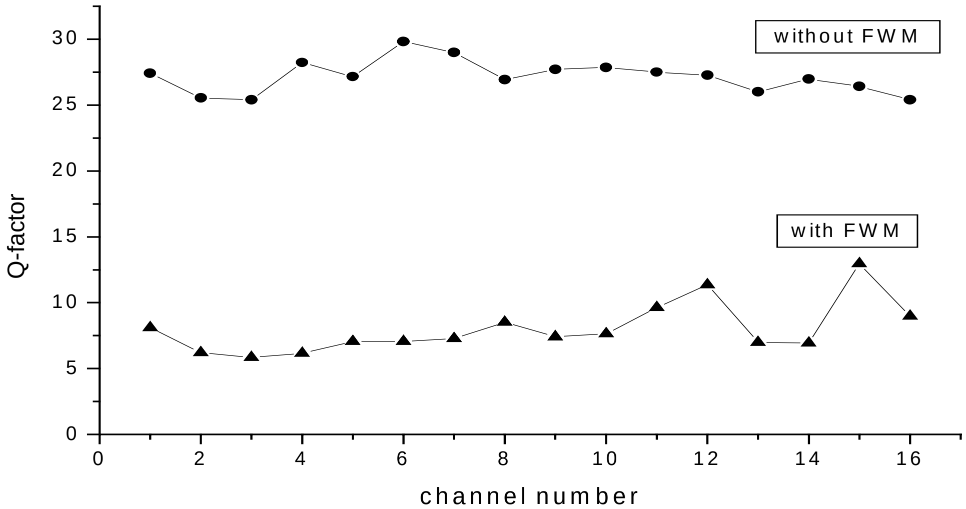


Fig. 3: 16-channel, 160km WDM transmission of 10 Gbit/s NRZ-signals including FWM. Influence of FWM on the Q-factor in every channel (10 mW peak power per channel)

As an example for a transmission system with a large number of channels we investigated a two-section 16-channel WDM system operating around 1550 nm with a channel spacing of 100 GHz. Each transmission section consisted of a 80 km SMF and 14 km DCF for entire post compensation, followed by an ideal optical amplifier. In order to characterize the transmission behavior, we calculated the Q-factor for each channel without taking into account FWM as well as using all significant side-channels arising at FWM (Fig. 3). Due to multiple interactions between the channels, FWM significantly reduces the Q-factor. Presently systems with 32 channels and more are under investigation.

## 4. THE IMPROVED EDFA MODEL

The EDFA is described by our extended model. This model starts with the classical model which takes into account saturation and the amplified spontaneous emission noise (ASE) [4]. The extended model additionally describes the phase modulation by means of the atomic susceptibility (atomic phase) and uses the slowly-varying envelope (SVE) equation of a signal passing the EDFA.

We investigated the influence of the atomic phase shift on the performance of an optical transmission system and include the spontaneous emission noise in the SVE equation [5]. The transmission link in our simulations consists of one transmitter, 5 DSFs each 100 km long, 4 EDFAs, and one receiver. The EDFAs are backward pumped with 25 mW at 1480nm.

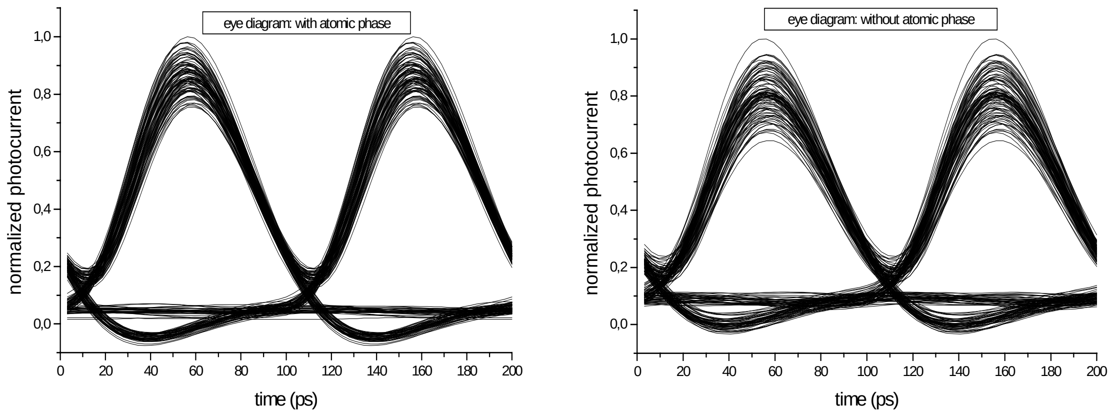


Fig. 4: Eye diagrams of the received 10 Gbit/s 16 bit pseudo-random RZ bit sequence at 193 THz with and without atomic phase. The impulse width (FWHM) of the sech-shaped input sequence was 20 ps with a peak power of 12 mW.

The atomic phase shifts the carrier frequency of the impulses to a higher value. As in the anomalous dispersion regime the dispersion decreases for higher frequency values, the vertical eye opening increases. This has a strong influence on the bit-error rate. The Q-factor was calculated by 50 simulative runs according to [6]. Under the assumption of a Gaussian noise distribution on both the “zero” and “one” at an input peak power of 6 mW the bit-error rate is reduced from about $6 \cdot 10^{-14}$ to less than $10^{-20}$. In the normal dispersion regime, however, our improved model leads to higher bit-error rates.

## 5. CONCLUSIONS

We have developed improved simulation tools for optical multi-channel WDM systems. This was achieved by direct inclusion of all significant nonlinear effects in our algorithms for wave propagation in the optical fibers itself in order to take correctly into account the consequences of power accumulation. So, our model is also well suited for testing the validity of approximations in systems simulations in order to save time for calculation.

Additionally we examined with our extended EDFA model the influence of the nonlinear atomic phase shift of an EDFA on the performance of an optical transmission system. Depending on the dispersion regime, a significant influence on bit-error rates was shown. Thus, the atomic phase must also be included for reliable system simulations.

## 6. REFERENCES


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