Impact of Nonlinearity in EDFAs on High-Speed Systems

Haixin Bi, Yan Ling Xue*
School of Communication and Electronics Engineering, East China Normal University, Shanghai, China
E-mail address: ylxue@ee.ecnu.edu.cn

ICOCN' 2021
The 19th International Conference on Optical Communications and Networks

Abstract

We model the nonlinear interaction of ultrashort pulse train in EDFAs in high-speed systems based on the semi-classical theory. The intra-channel crosstalk in optical comb due to the resonantly enhanced nonlinearity in EDFAs is simulated.

Introduction

- **As Networks are required to provide an enormous data transmission capacity, transmission has reached 1Tb/s per channel. Superchannel has enormous pontential for high-speed transmission but is highly vulnerable to the fiber nonlinear effects. EDFA is of great interest in the third telecommunications window. The modeling of nonlinear propagation in EDFA is the key research topic of modern optical fiber communication.**
- **Fiber amplifiers are commonly modeled by jointly solving rate equations and the generalized nonlinear Schrodinger equations. However, this approach cannot be directly applied in erbium-doped fiber. The complex atomic susceptibility of EDFA can be derived through semiclassical theory using the density matrix operator formalism and the classical electric field of Maxwell's theory. An analytical model of the nonlinear interchannel effects in EDFAs have been proposed occurring in the multiple WDM channels in 10 Gbit/s. However, for high-speed transmission system, the nonlinearity in EDFAs arisen from adjacent subcarriers or neighbouring pulses has not been explored yet.**

Analytical Model

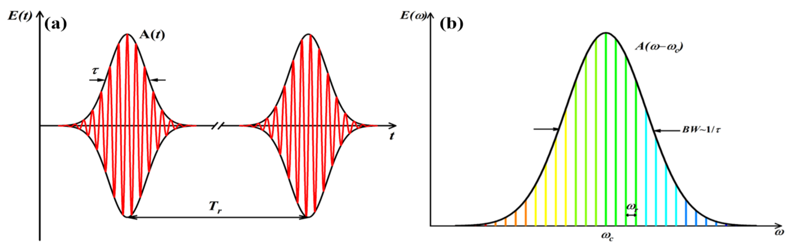
The temporal dynamics of the off-diagonal element and population inversion can be written as:

$$\frac{\partial \Delta N}{\partial t} = -\frac{\Delta N - \Delta N_E}{T} + 2(i\Omega_s \rho_{12} - i\Omega_s^{*} \rho_{21}) - 2CN_2^2$$

$$\frac{\partial \rho_{12}}{\partial t} = -(\overline{\gamma}_{12} - i\omega_{21})\rho_{12} + i\Omega_s^{*}\Delta N$$

The periodical pulse can be regarded as an optical frequency comb in frequency domain and the light field in time domain can be written as:

$$E_s(t) = A(t) \otimes \sum_{n=-\infty}^{\infty} \delta(t - nT_r)$$



Analytical Model

At high-repetition rate, the model can be assumed that the dipole transition and population inversion reaches steady state. We obtain the Fourier expansion coefficients at steady state:

$$\rho_n = \frac{i\frac{\mu}{\hbar}\sum_{m=-\infty}^{\infty} A_0\left[(n-m)\nu\right]\varepsilon_{n-m}^{*}\Delta N_m}{A_r + i(\omega_c + n\omega_r - \omega_{21})}$$

$$\Delta N_n = \frac{-2\Delta N_0}{\frac{P_p}{P_p^{th}} + 1 + in\omega_r\tau + C\tau\left(\frac{1}{2}\Delta N_0 + 1\right)} \times \sum_{m=-\infty}^{\infty}\frac{1}{I_m^{sat}}\left\{\begin{array}{l} A_0(m\nu)A_0\left[(m-n)\nu\right]\varepsilon_m^{*}\varepsilon_{m-n}(1-i\delta_m) \\ +A_0(m\nu)A_0\left[(m+n)\nu\right]\varepsilon_{m+n}^{*}\varepsilon_m(1+i\delta_m)\end{array}\right\}$$

According to the Maxwell equations, the light field propagation can be expressed by the wave equation:

$$\frac{\partial^2 E}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_0\frac{\partial^2 P}{\partial t^2}$$

The propagation equations of the CW pumping and signal field can be obtained:

$$\frac{\partial \varepsilon_n}{\partial z} = -\frac{1}{2}\gamma_s\varepsilon_n + \frac{N}{2}\sigma_s^{peak}\frac{1+i\delta_n}{1+\delta_n^2}\sum_{m=-\infty}^{\infty}\frac{A_0\left[(n-m)\nu\right]}{A_0(n\nu)}\varepsilon_{n-m}\Delta N_m^{*}$$

$$\frac{\partial I_p}{\partial z} = -\gamma_p I_p - N\sigma_p^{peak} I_p \frac{1}{1+\Delta^2}\left(\frac{1 + 2\sum_{m=-\infty}^{\infty} A_0^2(m\nu)\frac{I_m}{I_m^{sat}}}{1 + I_p + 4\sum_{m=-\infty}^{\infty} A_0^2(m\nu)\frac{I_m}{I_m^{sat}}}\right)$$

Conclusion

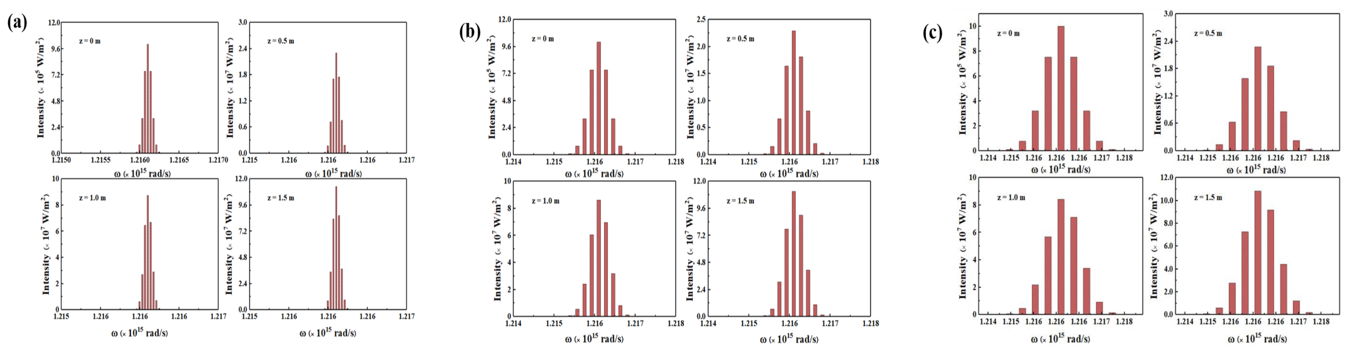
To conclude, we have studied the nonlinear crosstalk in high bit-rate systems due to the resonantly enhanced nonlinearity originated from the electronic transitions of erbium ions in an EDFA. We obtain the numerical model of a pulse train propagating along the EDFA and the analyses show the crosstalk increases monotonically with increasing line rata and decreasing pulse width.

Acknowledgment

This work was supported by The National Key Research and Development Program of China [Grant No. 2016YFA0302001]; the National Natural Science Foundation of China [Grant Nos. 11654005]; Quantum Information Technology, Shanghai Municipal Science and Technology Major Project [Grant No. 2019SHZDZX01].

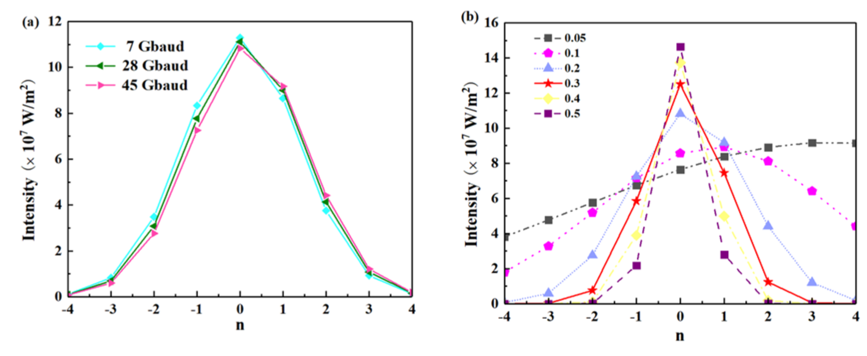
Results and Discussion

- **Intensity of each individual comb tooth at the different lengths (*z* = 0, 0.5, 1.0, 1.5 m) with the symbol rate 7 Gbaud, 28 Gbaud and 45 Gbaud.**



With the dissipation of the pump wave, the pulse train is amplified and then reach a maximum due to the saturation. Amplification is not equivalent for each comb tooth with the energy transfer from the low-frequency teeth to high-frequency ones and the comb spectrum envelope changes showing the crosstalk between the comb teeth.

- **The intensity distribution of the multiple comb teeth for different symbol rates at an EDFA output and the ratio of pulse width to periodical time at 45 Gbaud.**



The envelop of the optical comb is distorted and the impairment increases with the increase of the symbol rates. In addition, the ratio of pulse width to periodical time is one of the main limiting factors in high bit rate transmission systems. For 45 Gbaud, the shorter pulse width, corresponding to the increased resonantly enhanced nonlinearity, leads to more signal distortion.

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