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Influence of Nonlinear Optical Effects on the NRZ and RZ Modulation Signals in WDM Systems

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Introduction

An optical modulation format is the method used to impress data on an optical carrier wave for transmission over optical fiber. The simplest optical modulation format is on-off-keying (OOK) intensity modulation, which can take either of two forms: non-return-to-zero (NRZ) or return-to-zero (RZ). Conventional NRZ modulation format has been used extensively in many data communications systems mainly because of its relative ease of generation and because of its signal bandwidth, which is about 50% smaller than the RZ format, and is less costly. From the one side the NRZ modulation format is more suitable for WDM systems, from another side the RZ modulation is found to be less susceptible to inter-symbol interference (ISI), and typically achieves better performance compared to NRZ [2]. Two more benefits of RZ modulation format exist, first, that this modulation method is self-synchronized, and the second, laser life time is prolonged. For these reasons, RZ modulation is currently favored in submarine systems where the use of more costly transmitters and receivers is justified. Terrestrial wavelength division multiplexing (WDM) transmission systems, where cost is a primary driving factor, typically employ NRZ modulation [2].

RZ modulation has become a popular solution for 10 Gbit/s systems because it has a higher peak power, a higher signal-to-noise ratio, and lower bit error rate that NRZ encoding. It also offers better immunity to fiber nonlinear effects (NOE). NOE are often categorized into two sets of effects, those resulting from the propagation of a single channel and those resulting from the interactions between WDM channels. Single-channel nonlinear effects manifest mainly through self phase modulation (SPM), whereby each channel alters its own phase. SPM translates into pulse distortions through chromatic dispersion. WDM nonlinear effects are often split into cross phase modulation (XPM), whereby the phase of each channel is modified by the power of the neighboring channels, and four wave mixing (FWM), whereby three channels interact to transfer a fraction of their energy to a fourth one [2].

We foresee that WDM systems, which have already become quite common all over the world, will be rapidly developed in the nearest future in Baltic countries as well; therefore, the complete understanding of NOE effects is mandatory for WDM system engineers.

System setup

Our research is based on evaluating such system parameter as optical signal-to-noise ratio (OSNR) and bit error rate (BER) using powerful techniques, which are incorporated in OptSim 4.6 simulation software. OSNR fully characterizes the noise performance of the system. We have also decided to show spectrum diagrams for various simulation setups, since they are a fast way how to approximately evaluate a system performance. The reason why we have chosen a simulation – based research was the wish and opportunity to save on buying without expensive optical devices and materials. The use of simulation software allows for preliminary results, though precise enough to be considered as true.

The method of calculation is based on solving a complex set of differential equations, taking into account optical and electrical noise, linear and nonlinear effects. We used model where signals are propagating as time domain samples over a selectable bandwidth (in our case, a bandwidth that contains all channels). The Time Domain Split Step (TDSS) method is used to simulate linear and nonlinear behavior for both optical and electrical components. The Split Step method is used in all commercial simulation tools to perform the integration of the fiber propagation equation:

$$\frac{\partial A(t,z)}{\partial z} = \{L + N\}A(t,z). \qquad (1)$$

In equation (1) $A(t,z)$ is the optical field, L – linear operator that stands for dispersion and other linear effects, N – operator that is responsible for all nonlinear effects. The idea is to calculate the equation over small spans of fiber Δz by including either linear or nonlinear operator. For instance, on the first span Δz only linear effects are considered, on the second – only nonlinear, on the third – again only linear and so on. Two ways of calculation are possible: Frequency Domain Split Step (FDSS) and Time Domain Split Step (TDSS) methods. These methods differ in how linear operator L is calculated: FDSS does it in frequency domain, though TDSS calculates L in the time domain by calculating the convolution product in sampled time. The first method is easy to fulfill, but it may insert severe errors during computation. In our simulation we used the second method, TDSS, which despite its complexity grants an effective and time - efficient solution [3].

Simulation scheme and parameters

The main idea of our simulation is to demonstrate the influence of NOE optical effects to the NRZ and RZ modulation formats in WDM systems, respectively, self phase modulation, cross phase modulation and four waves mixing. We are not including the Raman scattering in the work, because the signal power levels what we are using for demonstration are not enough for Raman crosstalk generation, though our work presents the maximum possibility of WDM systems for 100 km transmission, using NRZ or RZ modulation formats [5].

The transmitter block consists of 8 multiplexed channels, each of them consist of data source, NRZ or RZ driver, and continuous wavelength laser source and external Mach-Zehnder modulator [4]. The data source produces a 10 Gbit/s bit stream, which represents the information we want to transmit via fiber optical link. Then we need a driver, which forms NRZ or RZ pulses from incoming bits. The pulses are then modulated with continuous wave laser radiation to obtain optical pulses. Such way of modulation is called "amplitude modulation", since information is presented by the change in signal amplitude. After transmission block the signal is sent directly to a single mode fiber (SMF), where optical pulses are propagating via 100 km length. The used fiber has a large core effective area 80 μm^2, attenuation α = 0.2 dB/km, and nonlinear refractive coefficient $n_k = 2.5\cdot10^{-20}$ cm/W at the reference wavelength λ = 1550 nm. The idea is to compare system performance when using different dispersion values, laser powers, and frequency intervals between the channels. At the end of the fiber channels are demultiplexed, each channel could be analyzed separately. After that, each channel is optically filtered, converted to electrical and then electrically filtered. To evaluate system performance we are interested in observing optical spectrum at the end of optical link [1].

Results and discussions

Nonlinear effects are often categorized into two sets of effects, those resulting from the propagation of a single channel and those resulting from the interactions between WDM channels. Single channel nonlinear effects manifest mainly through self phase modulation, whereby each channel alters its own phase Fig. 1, a phenomenon that leads to spectral broadening of optical pulses.

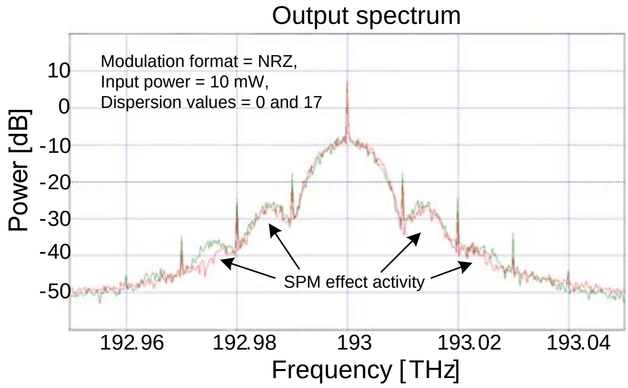

Fig. 1. Signal spectrum on output. NRZ system with different dispersion values

It is difficult to detect separately each of the NOE effects in complex WDM system [6]. Therefore for SPM effect realization we are using only one signal for performance estimation. As you can see, from Fig. 1, NRZ system signal output spectrum with different dispersion values as the same. But, compared with RZ system Fig. 2, it is better suitable for WDM systems, from spectrum eye of view.

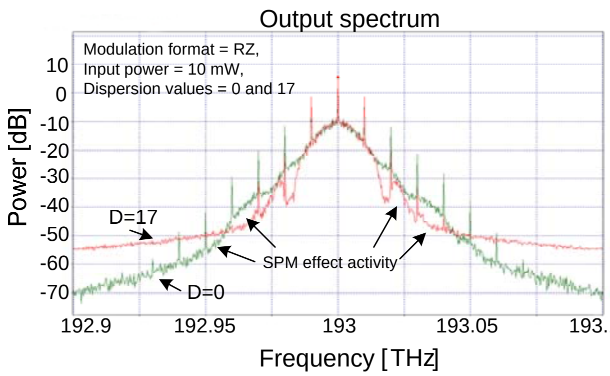

Fig. 2. Signal spectrum on output. RZ system with different dispersion values

As we can see from Fig. 2, RZ signal is unstable at zero dispersion level. For dispersion shifted fibers (DSF) it is dramatically, because those fibers were created exactly for third optical window, where attenuation is minimal, and dispersion level is reduced down to zero. From the one side designers got better linear parameters, from the other powerful SPM effect.

What happens with WDM system if the power level will be higher than 10 mW, Fig.3? It is normally to use zero dispersion level at third optical window, because most of new installed WDM systems work with better linear parameters and dispersion shifted fibers.

In Fig. 3 and Fig. 4 we can see the signal deterioration which leads to a crucial spectral broadening of optical pulse.

As we can see, the power level increasing in both RZ and NRZ systems will decrease the WDM system potential resources near zero dispersion area.

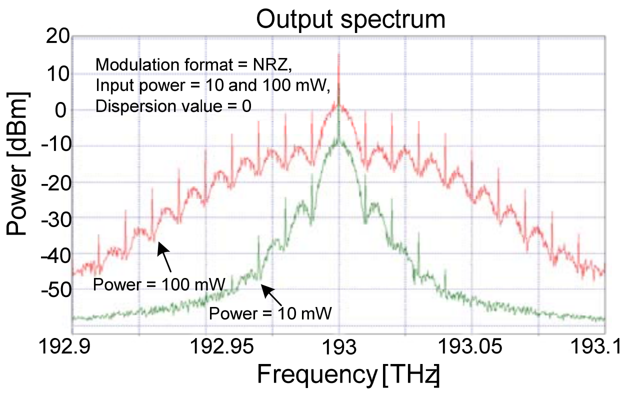

Fig. 3. Signal spectrum at output. NRZ system with different input power levels

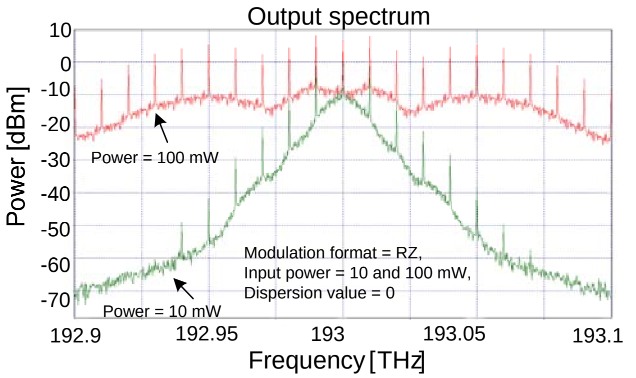

Fig. 4. Signal spectrum on output. RZ system with different input power levels

The SPM and other nonlinear effects such as XPM and four wave mixing, occur simultaneously inside optical fibers. Fiber nonlinearity can also couple two fields through XPM without inducing any energy transfer between them. XPM is always accompanied by SPM and occurs because the effective refractive index seen by an optical beam in a nonlinear medium depends not only on the intensity of that beam but also on the intensity of other co propagating beams. Similar to the case of SPM, XPM effect develops a spectrum multipeak structure, like FWM effect in WDM systems. Therefore it is difficult to detect each of those effects separately.

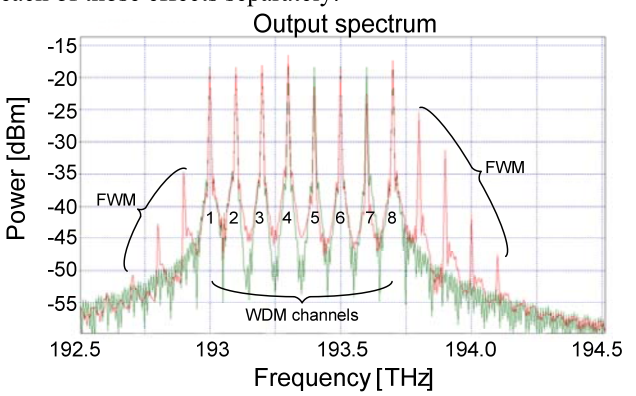

Fig. 5. Superimposed spectrum on output. NRZ modulation method, 10 mW input power, 100 GHz channels interval, and 0 and 17 ps/nm·km dispersion values

It has been already mentioned that FWM effect develops a spectrum negative multipeak structure. Let us present that structure with different modulation methods, dispersion and power levels. Numerical simulation for a 8-channel WDM system displays superimposed spectrum on output with different dispersion values in Fig. 5, and Fig. 6.

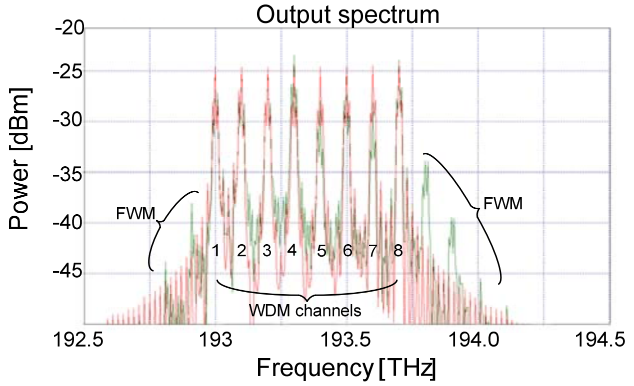

Fig. 6. Superimposed spectrum on output. RZ modulation method, 10 mW input power, 100 GHz channels interval, and 0 and 17 ps/nm·km dispersion values

As we can see from Fig. 5 and Fig. 6 the new harmonics generation directly depend on dispersion level. The newest harmonics is FWM result near zero dispersion area. In that case RZ modulation method is more suitable for WDM application and more settled for FWM effect. The highest output of new harmonics peak is two times lower compared with NRZ system.

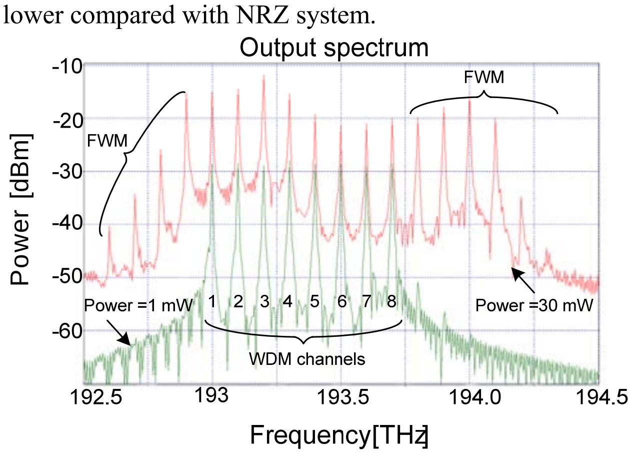

Fig. 7. Superimposed spectrum on output. NRZ modulation method, 100 GHz channels interval, and 0 ps/nm·km dispersion value, and different input power levels

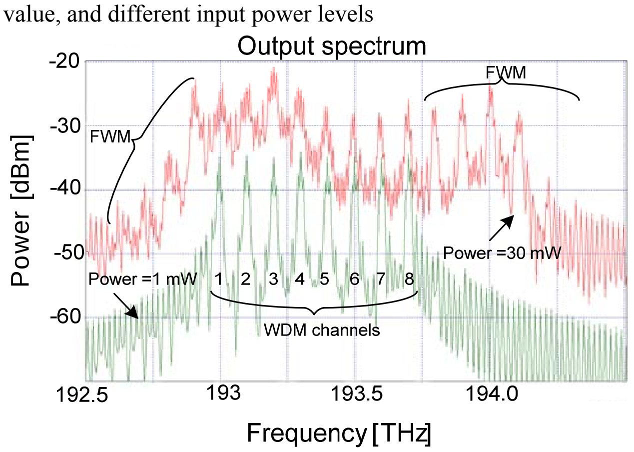

Fig. 8. Superimposed spectrum on output. RZ modulation method, 100 GHz channels interval, and 0 ps/nm·km dispersion value, and different input power levels

The need for signal to be more than 10 mW is normal, especially for long haul WDM networks. So, that is seen, what happens if input signal level increases Fig. 7, and Fig. 8.

From Fig. 7 and Fig. 8 we can see a new harmonics generation in complex WDM system. The power level of these harmonics is enough for new channels detection at output. This example shows that an optimal input power level would located between 10 and 30 mW, so this optimization is one of the tasks of designer. In this publication we will not cover an optimization of input power; such analysis is envisaged in our future research.

Conclusions

In this work we have been presented the influence of nonlinear optical effects on the NRZ and RZ modulation signals. The results show the nonlinear changes in different WDM systems, where different dispersion levels and input signals powers were presented. As an engineer tries to reach better linear parameters, and moves zero dispersion level to the third optical window, they got worse nonlinear effects inside the optical fiber.

Results present NOE dependency on dispersion and input power levels. As designer try to get smaller dispersion value as SPM occur more in RZ systems. It is dramatically for DSF fibers. If input power level increases XPM can distort both WDM systems performances.

FWM effect occurs more in NRZ systems near zero dispersion value. New generated harmonics peak power is two times lower in RZ systems compared to NRZ systems. That is allows us to install more optical channels. FWM influence will be reduced, if channel interval will be at least two times greater than 100 GHz.

When signal power values are higher than NOE threshold it is better to use dispersion compensation technique like a dispersion compensation fibers or dispersion compensators not to use DSF.

For the next WDM generation, where the bit rates will be more than 40 Gbit/s for each channel new modulation methods are needed, because of ISI and NOE; such research will be provided in our future works.

Acknowledgement

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The influence of nonlinear optical effects to the NRZ and RZ modulation methods and parameters dependence in WDM systems have been studied with OptSim 4.6 simulation software. The obtained results show nonlinear optical effect dependency on dispersion and input power levels and modulation methods. SPM effect occur more in RZ, but FWM effect occurs more in NRZ systems near zero dispersion value. New generated harmonics peak power is two times lower in RZ systems. FWM influence will be reduced, if channel interval will be at least two times greater than 100 GHz. Ill. 8, bibl. 6 (in English; summaries in English, Russian and Lithuanian).

В. Бобровс, Ю. Поринс, Г. Ивановс. Влияние оптических эффектов для методов кодирования в системах WDM // Электроника и электротехника. – Каунас: Технология, 2007. – № 4(76). – С. 55–58.

Анализируются разные методы кодирования для учета нелинейных оптических эффектов. Предлагаются использовать OptSim 4.6 программы моделирования. Это позволяет учесть дисперсию сигналов, их уровень и способы кодирования. Найдено, что лучшие результаты получаются, когда используются RZ кодирование, особенно NRZ при нулевом значении дисперсии. Подчеркнуто, что FWM влияние может быть уменьшено почти в два раза, когда широта канала высше 100 ГГц. Ил. 8, библ. 6 (на английском языке; рефераты на английском, русском и литовском яз.).

V. Bobrovs, J. Porins, G. Ivanovs. Netiesinių optinių efektų įtaka NRZ ir RZ kodavimo metodams WDM sistemose // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 4(76). – P. 55–58.

Išnagrinėta netiesinių optinių efektų įtaka NRZ ir RZ kodavimo metodams ir parametrų priklausomybė WDM sistemose naudojant OptSim 4.6 modeliavimo programą. Gauti rezultatai rodo netiesinių optinių efektų priklausomybę nuo dispersijos, įėjimo signalo lygių ir kodavimo metodų. SPM efektas gaunamas naudojant RZ koduotę, bet FWM efektas dažniau pasireiškia NRZ koduotėje esant beveik nulinei dispersijos reikšmei. Naujai sukurtų harmonikų maksimalios reikšmės yra du kartus mažesnės RZ sistemose. FWM įtaka gali būti sumažinta, jei kanalo plotis bus mažiausiai du kartus didesnis nei 100 GHz. Il. 8, bibl. 6 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

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