

Interaction Between Electromagnetic Field and Optical Signal Transmission in Fiber Optics

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Introduction

The need for broadcasting information is determined by the up-to-date progress, since the electronic communication is now changing from passive modes (reviewing the internet home pages, sending e-mails, etc.) to active ones (video-conferences, activities in virtual environment, etc). The increasing need to access information generates progress of wide development in the field of fiber optics communication systems, especially wavelength division multiplexing (WDM). WDM provides transmission of high bitrate optical signals and dense optical channel spacing to increase the data transmission capacity [1].

The area of electromagnetic (EM) field influence to FOTS has not been widely studied. Main reason is that for data transmission speeds used in optical fibers nowadays there are no indication of EM influence. But we propose that EM interference with optical radiation could become a limiting factor for much higher data transmission speeds. Therefore the aim of this research is to evaluate external EM field influence to fiber optics WDM transmission system with standard data transmission speed per channel 10.52, 12.5 and 40.0 Gbps and two different modulation formats: amplitude and polarization state modulation. This is done by performing calculations using simulation software OptSim 5.2 that is developed by RSoft Design Group, Inc.

Theoretical background

External EM fields affect light transmission in the optical fiber through electro-optic Kerr effect and Faraday effect. It manifests itself as a rotation of the light polarization plane in the fiber due to the previously mentioned effects. Generally Kerr effect is material refractive index change depending on the electromagnetic field strength. This causes light birefringence in the medium. Meanwhile optical Kerr effect is the refractive

index dependence on the intensity of light beam in the optical fiber [1]. Kerr effect is proportional to the outer square of the field and depends on the refractive index n and temperature T . Difference in the refractive indices in the optical medium due to electro-optic Kerr effect can be calculated using equation [2]

$$\Delta n = \lambda K(\lambda) E^2, \quad (1)$$

where Δn – refractive index difference between two orthogonal optical waves in the optical medium; λ – wavelength; E – electric field intensity; $K(\lambda)$ – Kerr coefficient.

The Kerr coefficient is dependent on the wavelength and assuming that the solids approximation anisotropic molecules turning in a similar way as a liquid or gaseous substance that is obtained [2]

$$K = \frac{1}{30} \frac{(n^2 - 1) \cdot (n^2 + 2)}{n} \cdot \frac{m \varepsilon_0}{\lambda k T \rho}, \quad (2)$$

where ε_0 – electric constant; m – particle mass of mater; λ – wavelength; k – Boltzmann's constant; T – absolute temperature (Kelvin's).

Optical fiber inhere birefringence. It manifests as small difference in refractive indices for two orthogonally located optical waves (ordinary and extraordinary ray) in the optical fiber. The cause of this is a bit oval shape of optical fiber core and its material anisotropy. Birefringence is a cause for polarization mode dispersion (PMD) occurrence in the OF. PMD is an undesirable effect that limits high speed (more than 10Gbps) data transmission. Obviously electric field impact to the optical fiber shows up as an increase in PMD due to higher birefringence.

Faraday effect or Faraday rotation is a magneto-optical phenomenon. It gets as an interaction between light and a magnetic field in a medium. The Faraday effect causes a rotation of the plane of optical radiation polarization state. Angle β by which this rotation occurs is linearly proportional to the component of the magnetic

field that is oriented to the direction of light propagation. Following equation shows relation between turn angle of polarization state and magnetic field [2]

$$\beta = \vartheta Bd, \quad (3)$$

where ϑ – Verdet constant; B – magnetic flux density; d – the length of the path where the light and magnetic field interacts.

Research of author [2, 3] shows, that turning the plane of polarization can occur even up to 45° to 90° if optical fiber affects strong lighting. Change in the state of polarization can produce errors in the data transmission especially for modulation formats where coherent detection is used. Also double refraction occurs that causes two mutually orthogonal wave components occurrence in the optical fiber [4].

Simulation scheme and parameters

This research is based on WDM system performance analysis using RSoft Design Group, Inc. simulation software OptSim 5.2. The method of calculation implemented in this software is based on solving the non-linear Schrödinger equation. The non-linear Schrödinger equation is the partial differential equation and is a classical optical wave propagation approximation in the optical fiber [5].

To evaluate EM field influence to FOTS we propose to use a 9 channel WDM transmission system working in the C band (conventional band: from 1530 to 1565nm). This band is most often used for WDM systems because it coincides with erbium doped fiber amplifier amplification range. Whole system can be divided into three main parts: transmitter, transmission line and a receiver part (Fig.1).

Transmitter part consists of 9 multiplexed optical channels or transmitters each working at different wavelength. Central channel (in our case 5th) carrier wavelength is 1550nm but others are located symmetrically around with even wavelength spacing. Interval between adjacent channels is chosen according to data transmission speed. For 10 Gbps data transmission speed the adjacent channel interval is set to 0.3nm accordingly to research [6]. For 12.5 and 40.0 Gbps data transmission speed this interval is set to 0.4 and 1.2nm

accordingly.

Each transmitter consists of random data generator (PPG), code driver (NRZ_driver), laser source (CW_laser) and electro-optical modulator (MZ_modulator). The laser is always switched on and its lightwaves are modulated via external electro-optic Mach-Zender (MZ) modulator by random data pulse sequence output of a pulse pattern generator (PPG). Data signal from PPG are coded using non-return-to-zero (NRZ) pulse shapes. MZ modulator performs electrical signal conversion to optical one. Each transmitters' MZ modulator output is connected to an optical coupler. This ensures channel multiplexing to one output optical signal. Further multiplexed optical signal is sent to a standard single mode fiber (SSMF) ITU-T G.652D, where optical pulses are propagating via 40 km length. The optical fiber end is connected to a 1x9 optical splitter that splits whole optical signal into 9 equal outputs. In the receiver each channel is optically filtered by Bessel filter (Optical_filter) to separate each channel.

Filter bandwidth is set accordingly to the transmission data rate. Optical filter output is connected to polarizer (polariz). That simulates polarization dependent losses at the receiver part. After polarizer optical signal is converted to electrical signal using photodiode (PIN) whose sensitivity is -15dBm. Then electrical signal is filtered using Bessel-Thomson electrical filter (electrical_filter). By this we reduce photodiode induced noise. To evaluate the data transmission performance eye diagram measurements of electrical signal have been taken at the output of each channel. From eye diagrams it is possible to determine signal quality factor Q and therefore the bit error rate (BER). BER parameter is a very good assessment of received signal. If signal parameters deteriorates it will definitely reflect in BER value increase because receiver part of transmission system has to cope with disturbances. In the fiber optics there are several typical signal deterioration causes like attenuation, signal dispersion, jitter and noise due to amplification, nonlinear optical effects etc. In our case we are interested in assessment of electro-optic Kerr effect induced fiber PMD and Faraday effect induced state of optical polarization change influence to optical signal transmission.

To determine electric and magnetic field influence we will artificially introduce changes in the proposed WDM transmission system.

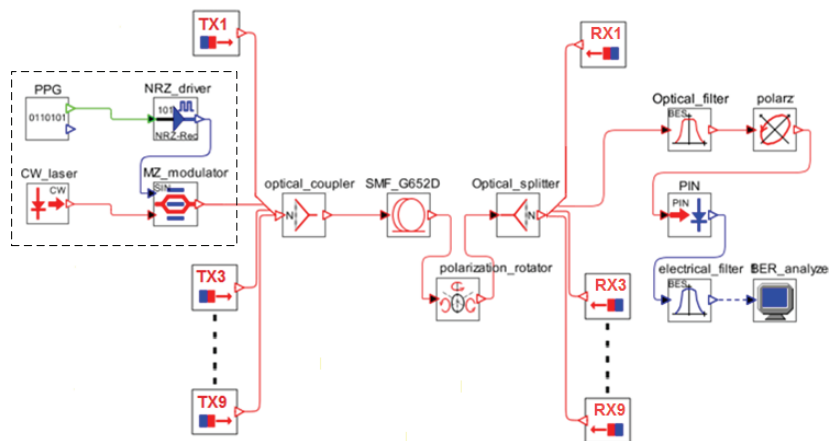


Fig. 1. Simulation scheme of 9 channel WDM system

Electric field influence due to electro-optic Kerr effect can be evaluated by increase in optical fiber PMD value. Whereas magnetic field influence due to Faraday effect will be simulated by inserting optical signal polarization rotator at the output of fiber. EM field influence to the WDM system performance will be evaluated by the output signal BER value.

As discussed previously in part two of this paper the EM field interaction to optical medium depends on material characteristics. For crystals the Kerr constant typically ranges from 10^{-18} to 10^{-14} m^2/V^2 [7]. Optical fiber is an optical radiation waveguide that is created from optical materials based on SiO_2 . But typically fibers contain also additional additives to change quartz refraction index. Kerr coefficient can be found for different optical medium including SiO_2 , but there is no data about optical fibers itself. For SiO_2 Kerr constant is $5.3 \cdot 10^{-16}$ m^2/V^2 at $\lambda=633\text{nm}$. If we take this Kerr constant and typical electric field intensity $E=3.2\text{kV/m}$ (research „Electric and Magnetic Field Strengths” performed by company Transpower New Zealand Ltd.) at ground level from 220kV power transmission overhead line we get negligible change in refractive indices $\Delta n=8.41 \cdot 10^{-18}$. To get more notable interaction it is worth to assume much higher electric field intensity. We prefer to study a case of approximately 1000 times higher intensity that would lead to a fiber PMD change from $0.16 \text{ ps}/\sqrt{\text{km}}$ to $0.3 \text{ ps}/\sqrt{\text{km}}$.

Faraday effect occurs when magnetic field direction match with optical radiation propagation direction. In the case of power transmission line maximum interaction with optical fiber occurs when both lines are located mutually orthogonal because magnetic field lines form in concentric circles around a cylindrical current-carrying conductor, such as a length of wire. Therefore in this case the interaction length is quite small (only the section of crossing). So for this interaction we chose a case of lightning induced electric flux density that can shift optical radiation polarization plane up to 90° .

Results and discussion

Simulations were performed using previously described WDM system. We decided to investigate the external EM field influence to different optical signal modulation formats and data transmission speeds. For comparison we will use two different modulation formats: amplitude modulation using NRZ code and polarization state modulation (POLSK). But random data pulse sequence rate at the output of PPG will be 10.52, 12.5 and 40 Gbps as these are standard data transmission rates. Data transmission speed for each channel in our WDM system is set to be equal.

Simulation results at two different modulation formats and three different data transmission speeds show that BER value increase at external EM field influence is rather small but it can be observed. All cases show that data transmission won't be completely interrupted because BER values are still sufficiently low. Table 1 shows all achieved results.

Table 1. BER values for different data rates and modulation formats

Amplitude modulation (NRZ code)				
Bitrate, Gbps	Electric field		Magnetic field	
	BER without EM field	BER with EM field	BER without EM field	BER with EM field
10.52	$1.77 \cdot 10^{-15}$	$2.53 \cdot 10^{-15}$	$2.31 \cdot 10^{-14}$	$9.49 \cdot 10^{-14}$
12.50	$6.05 \cdot 10^{-13}$	$5.37 \cdot 10^{-12}$	$3.19 \cdot 10^{-13}$	$4.90 \cdot 10^{-13}$
40.00	$2.13 \cdot 10^{-14}$	$6.66 \cdot 10^{-12}$	$1.81 \cdot 10^{-16}$	$1.16 \cdot 10^{-14}$

POLSK modulation				
Bitrate, Gbps	Electric field		Magnetic field	
	BER without EM field	BER with EM field	BER without EM field	BER with EM field
10.52	$3.45 \cdot 10^{-16}$	$5.58 \cdot 10^{-15}$	$1.07 \cdot 10^{-16}$	$1.56 \cdot 10^{-16}$
12.50	$1.15 \cdot 10^{-23}$	$2.77 \cdot 10^{-21}$	$9.24 \cdot 10^{-22}$	$7.22 \cdot 10^{-21}$
40.00	$7.58 \cdot 10^{-28}$	$1.64 \cdot 10^{-24}$	$3.70 \cdot 10^{-27}$	$7.46 \cdot 10^{-24}$

As we can see that for 40 Gbps data transmission speed the BER increase at simulated EM field influence is the highest. It appears for both modulation formats: amplitude and polarization state modulation. In the case of electric field influence BER increases from $2.13 \cdot 10^{-14}$ to $6.66 \cdot 10^{-12}$ for amplitude modulation using NRZ code and from $7.58 \cdot 10^{-28}$ to $1.64 \cdot 10^{-24}$ for POLSK modulation. Magnetic field influence simulation showed BER increase from $1.81 \cdot 10^{-16}$ to $1.16 \cdot 10^{-14}$ for amplitude modulation using NRZ code and from $3.70 \cdot 10^{-27}$ to $7.46 \cdot 10^{-24}$ for POLSK modulation. Comparison between BER level increase at different pulse sequence rates is shown in Fig. 2.

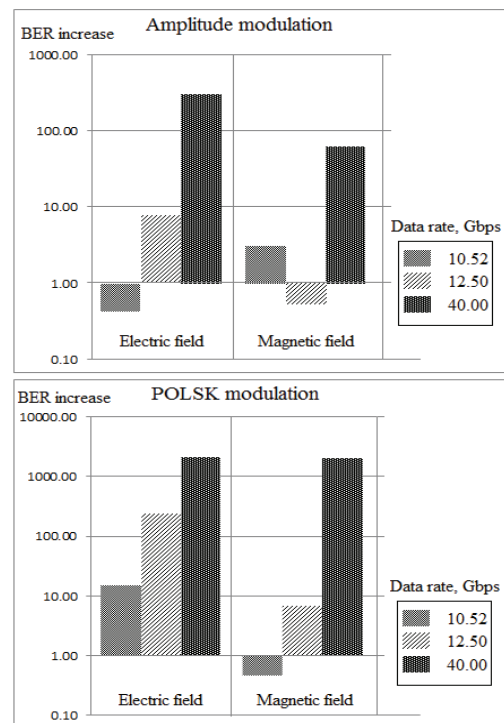


Fig. 2. WDM system BER level increase at external EM field influence in logarithmic scale for two different modulation formats and three data transmission speeds

Here y axis is relationship between BER value before and after EM influence in logarithmic scale for better comparison. In other words it illustrates how many times BER value worsen compared to system without any external influence. If we convert it to percentage, then 1.00 would mean worsening by 100%.

As we found out previously at higher data transmission speed the EM influence gives greater increase in BER. It is observed in both cases: amplitude and POLSK modulation. So influence of external EM field disturbance in optical fibers can become more common especially in a long-span high density WDM (HDWDM) systems with high data transmission speed. Results show that larger decrease in signal quality is in the case of POLSK modulation format. This take the form for both electrical and magnetic field. So modulation and multiplexing formats that uses state of polarization suffer the most from external EM influence.

If we compare electrical and magnetic field influence then it shows a similar results. But magnetic field influence is less likely to have serious problems to FOTS. Because it is most effective when magnetic field direction coincide with optical radiation propagation direction. In the case of power transmission lines this condition fulfills only in the case of optical fiber and power line being located mutually orthogonally.

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This paper gives results of research about interaction between external electromagnetic field and optical signal transmission in fiber optics transmission systems (FOTS). At first short explanation is given about physical reasons of electric and magnetic field interaction with optical media. This include electro-optic Kerr effect and Faraday effect explanation. Afterwards follows description about research method and achieved results. This research is based on calculations performed by RSoft simulation software OptSim 5.2 to evaluate FOTS performance at external EM field. Results show that in the case of electric field influence BER decreases from $2.13 \cdot 10^{-14}$ to $6.66 \cdot 10^{-12}$ for amplitude modulation using NRZ code and from $7.58 \cdot 10^{-28}$ to $1.64 \cdot 10^{-24}$ for POLSK modulation. Magnetic field influence simulation showed BER decrease from $1.81 \cdot 10^{-16}$ to $1.16 \cdot 10^{-14}$ for amplitude modulation using NRZ code and from $3.70 \cdot 10^{-27}$ to $7.46 \cdot 10^{-24}$ for POLSK modulation. Ill. 2, bibl. 7, tabl. 1 (in English; abstracts in English and Lithuanian).

A. Supe, J. Porins. Elektromagnetinio lauko ir optinio signalo perdavimo sąveika šviesolaidyje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 6(122). – P. 83–86.

Pateikiami elektromagnetinio išorinio lauko sąveikos su optinio signalo perdavimu šviesolaidinėse perdavimo sistemose tyrimo rezultatai. Pateikiamos elektrinio ir magnetinio laukų sąveikos su optine medija fizikinės priežastys. Tyrimui naudota RSoft modeliavimo įranga OptSIM 5.2 siekiant įvertinti išorinio elektromagnetinio lauko veikiamos sistemos našumą. Magnetinio lauko įtakos modeliavimas parodė, kad BER sumažėjo nuo $1,81 \cdot 10^{-16}$ iki $1,16 \cdot 10^{-14}$, amplitudinei moduliacijai naudojant NRZ kodą, ir nuo $3,70 \cdot 10^{-27}$ iki $7,46 \cdot 10^{-24}$ – esant POLSK moduliacijai. Il. 2, bibl. 7, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).