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The influence of lightning discharge on the stability of a coherent communication system: rapid polarization rotation and a jump in the differential group delay

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It has been established that disruption of the operational stability of a coherent communication system using an optical ground wire (OPGW) during a lightning strike is caused, in addition to rapid polarization rotation, by a sharp change in the differential group delay (DGD) of polarization modes. It has been established for the first time that a significant DGD change in a long fiber-optic communication line (FOCL) caused by lightning strike can occur even under conditions where the DGD variation in the section struck by lightning is negligible.

Keywords: polarization rotation, differential group delay, optical ground wire cable, fiber-optic communication line, digital signal processing.

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Suspended fiber optic communication lines (FOCL) using an optical cable built into an optical ground wire (OPGW) protection cable, have become widely used, since they combine the cost-effective method of fiber optic communication arrangement with the function of the power line protection against lightning discharges. However, a direct lightning strike into a ground wire may cause a short-term failure in the operation of high-speed coherent optical data transmission systems [1–6]. It is known that when a lightning strikes a cable, a longitudinal magnetic field is generated, a variation of which causes fast rotation of the signal polarization state due to Faraday effect [1–10]. Fast rotation of polarization may cause errors in coherent communication systems, sensitive to the polarization state (PS), which use multi-level modulation formats and polarization multiplexing. Some papers set and solved the task of investigation of the Faraday effect in optical telecommunication cables and calculation of the shape of timé dependence of the light signal PS variation speed at the output of the multihop communication line [6–9]. These papers present a mathematical model of a lightning strike and a method to calculate the timé profile of PS quick changes with account of a random linear birefringence of the fiber and dynamic effects related to the finite times of propagation of the electromagnetic and light waves along the optical cable. In paper [5] the computational modeling method is used to investigate the resistance of operation of the digital signal processing (DSP) algorithms in a coherent receiver to the fast rotation of polarization caused by a lightning strike at OPGW. It was found that the speed of PS variation was the most important parameter that determines the growth of the error coefficient in the receiver. In this paper the differential group delay (DGD) will mean a current delay between polarizations, and a vector of polarization mode dispersion (PMD) will be a vector, whose direction describes the signal polarization state, and the module — the current DGD. In papers [11,12] it is shown that when polarization modes are present in the DGD line, the task of compensating the polarization rotation in the digital signal processing is complicated. In this paper DGD is believed to be a constant value. The effect of the lightning discharge on the DGD variation of polarization modes outside the area of lightning discharge effect has not been studied previously. The possible reason is that DGD variations caused by the Faraday effect in a short section of the cable exposed to the lightning discharge are negligibly low (much lower than tenths of a picosecond). In this paper it was found that DGD variations in a long line caused by a lightning discharge in general case significantly exceeded the DGD value related to the Faraday effect in a short section of the cable, which was directly exposed to the lightning discharge. It was established that DGD variations of the long line that contains a section, in which polarization rotates, may achieve the values of the DGD magnitude for the entire line even at zero growth of DGD in the section that was exposed to the lighting discharge as such.

A lightning strike into an optical ground wire causes fast rotation of the output polarization state of optical emission. A model of FOCL exposed to a lightning strike is shown in Fig. 1. A lightning discharge, as shown in papers [1,5,6], affects a small section of the line near the lightning strike area between the closest supports. Let us break the FOCL into three sections: short section 2 exposed to the lightning

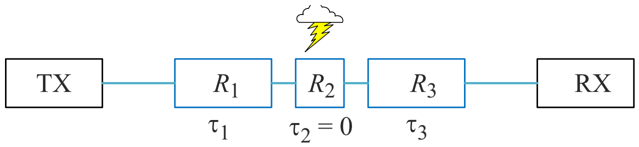

Figure 1. Optical scheme of fiber optic data transmission system (Fiber Optic Transmission Line, FOTL), which contains a section hit by a lightning. FOTL comprises a transmitter (TX) and a receiver (RX) connected by a multihop FOCL. The multihop FOCL contains section 2 hit by a lightning, and sections 1 and 3 located accordingly upstream and downstream section 2. Each section is characterized by the corresponding Muller matrices R_1, R_2, R_3 and PMD vectors $\boldsymbol{\tau}_1$, $\boldsymbol{\tau}_2$, $\boldsymbol{\tau}_3$.

strike, first lengthy section 1 (from the start of the line to section 2) and end lengthy section 3 (from section 2 to the end of the line).

Each of the three FOCL sections is characterized by the Muller matrices R_1, R_2, R_3 and PMD vectors $\boldsymbol{\tau}_1$, $\boldsymbol{\tau}_2$, $\boldsymbol{\tau}_3$. The Muller matrices are presented in the size of 3×3, when one size responsible for the signal power is omitted, since in the case we consider the power is constant. A lightning discharge causes a strong current pulse only in a small section of a ground wire (approximately 300 m) between the supports. The magnetic field related to current causes fast and rather significant changes in time of the Muller matrix $R_2(t)$ of short section 2. Muller matrices of two other sections (R_1 and R_3) and their PMD vectors $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_3$ do not change over the duration of lightning discharge ($R_1 = \text{const}$ and $R_3 = \text{const}$), since the lightning has no effect on them.

The change in time of the Muller matrix of short section 2 causes a change in time of the Muller matrix of the entire FOCL:

$$R(t) = R_3 R_2(t) R_1. \tag{1a}$$

In virtue of a short length of section 2, its PMD vector is negligibly small, and one can assume that $\boldsymbol{\tau}_2 = 0$. Possibly, in connection therewith it was assumed previously that the change of the PMD vector of the entire line is also negligibly small, and no attention was paid to it. However, as analytical estimates and computational modeling have shown, the use of the PMD vector of the long line ($\boldsymbol{\tau}$) in the general case turns out to be significant even when the conditions $\boldsymbol{\tau}_2 = 0$ and $R_1 = \text{const}$, $R_3 = \text{const}$ [13] are met:

$$\boldsymbol{\tau}(t) = \boldsymbol{\tau}_3 + R_3 R_2(t) \boldsymbol{\tau}_1. \tag{1b}$$

A lightning strike into an optical ground wire causes fast rotation of the output polarization state of optical light in accordance with equation (1a). In accordance with equation (1b), the PMD vector $\boldsymbol{\tau}$ of the long line also varies in time in case of a lightning strike even at $\boldsymbol{\tau}_2 = 0$ (Fig. 2). The physical mechanism of this phenomenon is related to the rotation of the effective polarization vector $\boldsymbol{\tau}_1^{eff}(t) = R_3 R_2(t) \boldsymbol{\tau}_1$, which is summed up in a vector manner with vector $\boldsymbol{\tau}_3$.

In the case when the lightning strikes the middle part of FOCL, vectors $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_3$ are not equal to zero, and the rotation of vector $\boldsymbol{\tau}_1^{eff}(t) = R_3 R_2(t) \boldsymbol{\tau}_1$ causes a change in both the direction and the module of the total PMD vector $\boldsymbol{\tau}$ of the communication line. In the private case of the lightning strike at the beginning of FOCL, when the module of the PMD vector $\boldsymbol{\tau}_1$ is equal to zero, the total PMD vector of the line will not change. In another private case, when the lightning strikes the end of the line, the PMD vector turns, but its module will not change. The most prominent changes of the PMD module will be caused by the lightning strike approximately to the central region of FOCL, when the modules of the PMD vectors $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_3$ are equal.

Since in this case both the signal polarization state and the PMD vector change quickly, and their compensation in the DSP block of the coherent receiver becomes a more complicated task.

Therefore, the value of change of the PMD vector module under the effect of the lightning is determined by the values of PMD vectors $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_3$ of two FOCL sections adjacent to the lightning strike area, and the orientation of the rotation axis $\mathbf{n}$ of the PMD vector $\boldsymbol{\tau}$. The maximum change in the PMD vector module of the entire line is achieved in the case if the vector $\mathbf{n}$ is orthogonal to the vectors $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_3$. In this case the module of the PMD vector $|\boldsymbol{\tau}|$ will vary from the minimum value $||\boldsymbol{\tau}_1| - |\boldsymbol{\tau}_3||$ to the maximum value $|\boldsymbol{\tau}_1| + |\boldsymbol{\tau}_3|$. In all other cases the range of variation $|\boldsymbol{\tau}|$ will be smaller, and it means that the impact on the signal will be less.

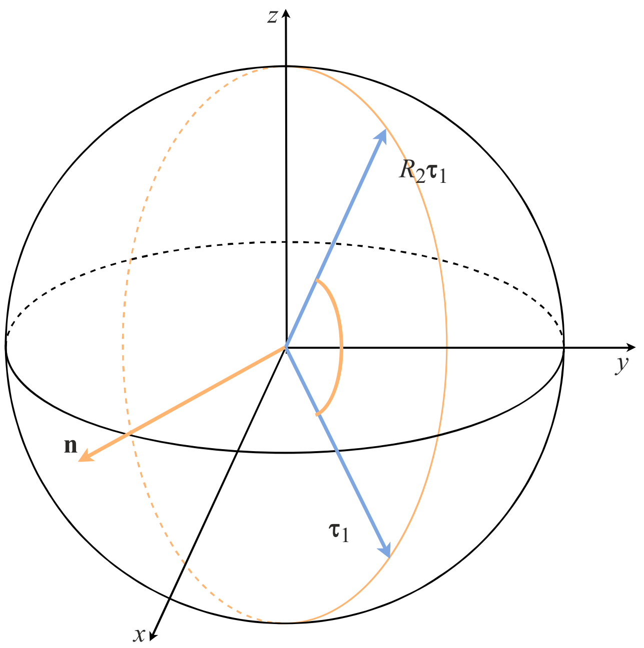

Figure 2. Change of the Muller matrix R_2 in the fiber section exposed to the lightning discharge, causing a change in the PMD vector of the entire line due to a turn in the space of the PMD vector of the first FOCL section ($\boldsymbol{\tau}_1$). The vector $\mathbf{n}$ is a normal line to the plane where the rotation of $\boldsymbol{\tau}_1$ happens.

Let us consider as an example a situation when the DGDs of two sections were equal to the average value of DGD (DGD_{avg} — differential group delay) for the half of the line with the length of 900 km with the PMD coefficient α, equal to 0.1 ps/$\sqrt{\text{km}}$, which yields DGD equal to 3 ps, in accordance with the formula

$$\mathrm{DGD}_{avg} = \alpha\sqrt{L}. \tag{2}$$

The polarization rotation speed is not a constant value for the time of the lightning strike. The specific appearance of the timé profile of the rotation speed of the polarization state caused by the lightning strike is presented in Fig. 3, it can also be found in [5]. In this paper the rotation speed module was taken in accordance with the specific modules, and the direction of rotation was selected as constant, and at the same time $\mathbf{n} \perp \boldsymbol{\tau}_1$ and $\mathbf{n} \perp \boldsymbol{\tau}_3$.

The vector was changed using formula (1b) with the profile presented in Fig. 3. The results are illustrated in Fig. 4. One can see that different profiles of rotation do not impact the maximum of the vector module, however, they impact the frequency of its variation.

One can see that for the time of duration of the lighting front lasting around several microseconds [2] at maximum values of the rotation speed of the polarization state of several dozens Mrad/s, the PMD vector makes several full rotations, passing through all values of the module $|\boldsymbol{\tau}|$ possible for this configuration.

Fast rotation of polarization causes a strong distortion of the signal and at rather high speeds of rotation makes it impossible to deode a signal. Distortions arising in process of signal transmission are compensated by DSP algorithms [14–21], however, most of these distortions vary in time slowly (with the frequency of the order of kHz). And fast rotation of polarization and the corresponding quick change of DGD happen with the frequencies of the order of MHz. Such distortions require separate compensation on the receiver with the help of the DSP algorithm, which may quickly follow the signal polarization state. However, a high DGD in

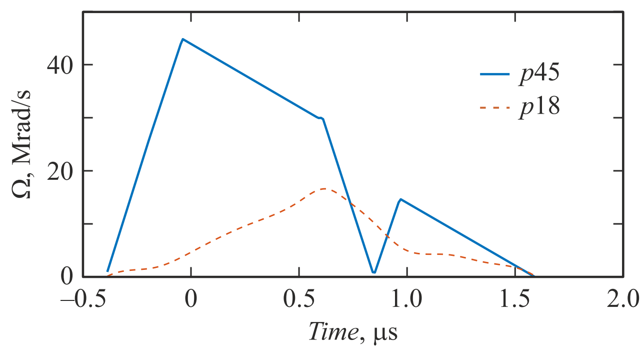

Figure 3. Time profile of polarization state rotation speed used to simulate the vector according to formula (1b). $p45$ — maximum rotation speed 45 Mrad/s, $p18$ — maximum rotation speed 18 Mrad/s.

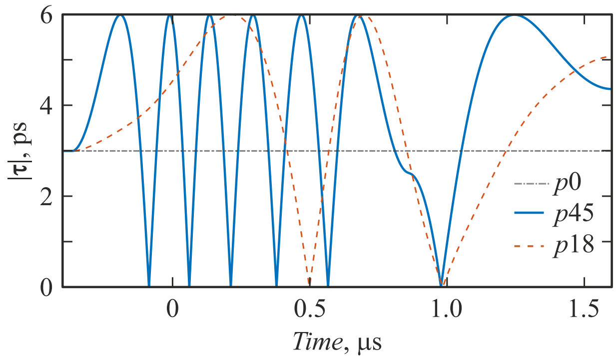

Figure 4. Change of the module of the PMD vector of the entire line during a lightning discharge in accordance with formula (1b) and the profile shown in Fig. 3. The lightning starts rotating the vector at the moment of time $-0.4\,\mu$s. $p0$ — no polarization rotation, $p45$ — maximum rotation speed 45 Mrad/s, $p18$ — maximum rotation speed 18 Mrad/s.

the line complicates the objective of polarization rotation compensation, since it is necessary to compensate the polarization rotation and delay. Both these values are quick-changing multi-parameter and require the use of the adaptive compensation algorithm. Modern digital signal processors may compensate the polarization state rotation up to the values of the order of 10 Mrad/s with a fine within the limits of 3 dB for 100G DP-QPSK-signal, DGD in long lines at the same time may amount to the value of the order of a hundred of picoseconds or several symbols. Therefore, it is feasible to study the fast rotation compensation algorithms in the presence of DGD.

In this paper it was shown that as a result of the lightning discharge both fast (frequency of changes of the order of MHz) rotation of the polarization state and the same fast DGD change (frequency of changes may also be of the order of MHz, and the amplitude of the changes of the order of the initial vector of DGD) take place. Quick change of DGD in the line may cause an additional fine that must be studied further. A fine occurs, since the DPS algorithms at reception have the final adjustment speed. The limit frequency of changes in the compensated rotation of polarization at the current moment of time is around 10 Mrad/s. However, further research is necessary on the impact of the limit fast changes of DGD on the existing DSP algorithms, as well as the development of algorithms that reduce the fine from this effect.

Conflict of interest

The authors declare that they have no conflict of interest.

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