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Polarization Multiplexing Modulation in Fiber-Optic Communication Lines

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Abstract: ***The possible losses are analyzed in prospective method of coherent polarization multiplexing. The loss associated with a fully polarized and non-polarized components are considered. The adaptive method for compensation of non-polarized components is recommended. To eliminate the distortion caused by the rotation of the polarization plane of the received signals it is recommended to use circular polarizations.***

Keywords: polarization mode dispersion; polarization degree; anisotropy; coherent determination; adaptive compensation

1. Introduction

To solve the problems of multiplexing, modulation and signal processing, along with traditional physical parameters (frequency, time, space, energy), implementation of polarization is increased. Being an equal type of the physical resource, the polarization can successfully solve a lot of practical problems, apart from those have been mentioned: monitoring of transmitter state, diversity reception, noise control, etc. In a number of cases the polarization is the only resource due to which it is possible to solve a specific problem.

The polarization signals play the fundamental role in fiber-optic systems (FOSs), where due to the polarization multiplexing it is possible to achieve rates of hundreds of Tbit/s. However, the presence of uncompensated distortions does not allow increasing the transmission rate due to multi-position of polarized signals. Analysis of the main components of the partially polarized signals allows finding additional resources.

2. Presentation of Partially Polarized Signals

Due to the anisotropy of FOCLs the broadcasted signal undergoes splitting into two mutually orthogonal components, the polarization of which is determined by its own polarization of the given anisotropic medium. These ordinary and extraordinary components (modes) are propagated with different phase rate components and attenuation.

The discrepancy between the phases of modes has negative effects and leads to a broadening of the information signal pulses. The received resulting signal is partially polarized; moreover, the parameters of completely polarized component (the angle of inclination and angle of ellipticity) are undergoing significant changes, resulting into energy loss. The given distortions caused by polarization are interpreted as polarization mode dispersion (PMD).

The quality of problem solving using the polarization depends on the degree of polarization in the observed electromagnetic (optical) field of a signal [1,2]:

$$m_c = I_{fp} / I_{\Sigma} = \frac{I_{fp}}{I_{fp} + I_{np}}, \qquad (1)$$

where I is the intensity of the observed field at the receiving point, Σ, pf, nf are accordingly: indices of the total, fully polarized and non-polarized fields.

Types of polarization: linear, elliptical and circular depend on both the radiator polarization and the medium, in which the signal propagates. Typically, the line communication power is invariant with respect to all types of polarization. In the isotropic medium parameters of the completely polarized component remain unchanged, whereas in the anisotropic medium there is transformation of parameters and rotation of the polarization plane.

The level of PPS received by the antenna with the effective area A_{eff} is as follows [2,3]:

$$P_c = 0{,}5 \varPi A_{eff} (1 + m \cos\delta), \qquad (2)$$

where δ is the angle between points on the Poincare sphere, which determine the state of polarization and antenna (in the case of linear polarization $\delta = 2\varphi$, φ is the angle between the current length of the antenna and the strength of the signal field). $\varPi$ is the magnitude of the Poynting vector, characterized by the density of power flow of signal field at the reception point.

In the case of a fully polarized signal ($m = 1$), the reception level $P_s = A_{eff} \varPi \cos^2(\delta/2)$ depends on the angle of antenna orientation with regard to the signal: under $\delta/2 = 90^0$ the reception level is equal to zero, and under $\delta/2 = 0$ the level is $P_s = P_{\max}$ and it is interpreted as polarization-matched reception.

3. Analysis of Applicable Multiplexing Techniques

All demands for bandwidth in the infocommunication networks are associated with the rapid growth in popularity of applications such as IPTV, VoD and 3D. It is known that the total demand for the Internet is increasing by 40% per year. This growth is even more accelerated due to Internet access possibilities of mobile users as the client programs installed to watch the video on smartphones and tablet PCs provide easy viewing of video content through the network at any time and any place.

Client servers using Ethernet-connection when traffic is transmitted between service provider and enterprise customers already require rates up to 100 Gbit/s and even 1 Tbit/s. The fiber-optic communication lines (FOCLs) used in such systems, and corresponding systems (FOSs) allowed to meet the requirements and gradually increase the throughput according to the growth of rate. Such an increase was possible due to two trends. The first one is associated with the number of spectral channels (spectral multiplexing) and the corresponding reduction of the interval between carrier wavelengths λ_i. The second one uses efficient modulation types that provide an increase in spectral efficiency.

Spectral wavelength division multiplexing (WDM) allowed providing channel rate up to 10 Gbit/s using general amplitude modulation of carriers. Rates up to 50 Gbit/s have been achieved on the basis of 80-channel DWDM (Dense WDM) with co-channel offset of 50 GHz. Thus the rate limit for the selected modulation formats of signals has been obtained.

Further growth of rate was connected with the technology of optical signal phase implementation using the adaptive differential phase-shift keying (ADPSK), differential binary phase-shift keying (DBPSK), superchannels technology, FOS-DS with high-density arrangement of channels. As a result, it was possible to overcome the barrier of 100 Tbit/s [4,5].

The subsequent technological breakthrough is associated with the development of methods for coherent optical signals decoding. It was possible to achieve the results on the basis of the following developments:

- Amplitude and phase modulation of a high order.
- Polarization multiplexing.
- Coherent detection by the local heterodyne laser.
- High-speed digitizers and complex digital signal processors.

Polarization division multiplexing (PDH) is carried out with the help of transmission of two information streams in two orthogonal polarizations. Currently, linear polarizations are used but in terms of energetics all the polarizations are equivalent (linear, circular elliptical). However, circular polarizations possess a greater practicality due to the invariance to rotation of the plane of signal polarization, which is inherent to the linear and elliptical patterns.

The transition from linear to circular polarizations is simply realized on the basis of two orthogonal linearly-polarized coherent signals shifted relative to each other by $\varphi = \pm 90^0$.

The structure of the coherent optical signal receiver essentially differs from radioreceiver. Here the heterodyne structure is not relevant, because of the difficulty in obtaining the required nominal intermediate frequency. Therefore, a coherent receiver is performed by so-called homodyne scheme, when the reference signal and the carrier frequency of the optical signal coincide and these signals are mutually synchronized. Structural coherent receiver scheme is presented in Figure 1.

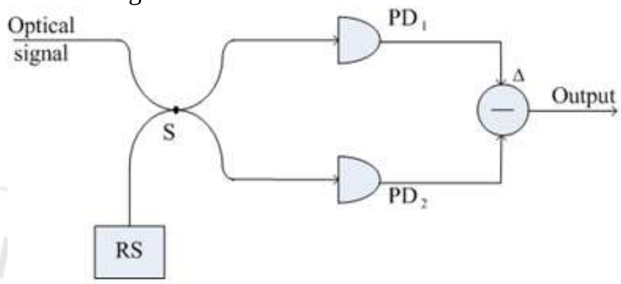

Figure 1: Block diagram of a coherent optical receiver built according to homodyne scheme. RS is the reference signal, S is mixer, PD_1, PD_2 are diodes that together with subtracting scheme form the balanced photodetector Δ [4]

The current at the output of the balanced photodetector:

$$I_{out} = 2R\sqrt{P_S \cdot P_L}\sin(\omega t + \Delta\varphi), \quad (3)$$

where R is sensitivity in amps/watts,
$P_S \cdot P_L$ are the power information signal and reference laser signal, respectively.
$\Delta\varphi$ is the difference of signal phases.

Optical receiver of polarized signals essentially consists of two coupled coherent receivers. In a coherent optical receiver analogue and phase information carried by the optical signal is converted into an electrical form and then converted into an information signal in a digital processing device.

Typically under these transformations the information about the phase and polarization structure of signals is saved. This allows implementing an adaptive distortion compensation using signal processors (DSPs).

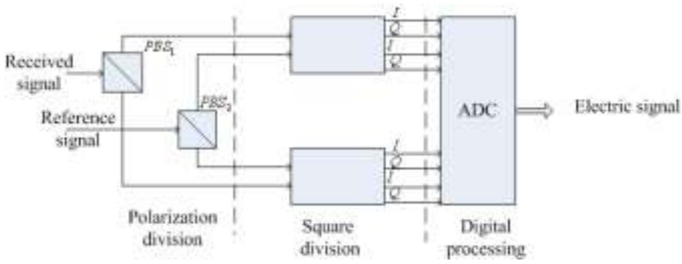

Figure 2: Structural diagram of a coherent receiver with the polarization and phase modulation. I, Q are quadrature components of information signals

Under the polarization multiplexing each of the two orthogonally polarized information streams is transmitted in the DP-QPSK format using 4-level phase QPSK modulation. As a result, each of the polarizations transmits 2 bits per symbol, i.e. a total of 4 bits per symbol.

4. Analysis of Losses in Polarization Multiplexing

The PMD in FOCLs limits the bandwidth of lines and these restrictions are connected with the two basic types of losses:

- Broadening of information pulses due to the difference in the phase rates of polarization modes;
- Inconsistency of the receiver module with the received pps

There are a number of methods aimed at overcoming the pulse broadening by compensating phase incursion between polarization modes determined by the relation [4.5]:

$$\tau_{\phi} = D\sqrt{l}, \quad (4)$$

where D is the coefficient of specific polarization dispersion, l is fiber length [km].

Due to inconsistencies in polarization when receiving the signal the possible losses are determined by the coefficient

$$K_l = P_{rec} / P_{fall}, \quad (5)$$

where P_{rec}, P_{fall} are accordingly: the powers of received and falling (coming for reception) signals. Depending on the consistency quality K_l can take values from zero under orthogonality of receiver module with respect to the polarization of the received signal to 1 at fully matched polarization reception.

When receiving polarized signals in a fixed polarization basis, unit vectors can be linear, circular or elliptical, the fully polarized component is agreed with the corresponding basis. In the simplest case we assume only linearly polarized component. At the same time reception level of PPS is proportional [2.3].

$$P_c \approx I_{fp} \cos^2 \frac{\delta}{2} + 0.5 I_{np}, \quad (6)$$

where $\delta / 2 = \varphi$ is the angle of difference between the vectors of the signal field and receiving module.

Obviously, when using circular polarization, the losses caused by the rotation of the polarization plane $\delta/2$ are absent and that allows to obtain the maximum level value at the account of I_{np}. When linear polarization is used, the corresponding losses are minimized due to PMD compensators. It should be noted that actually present drift of the orientation angle and coefficient of polarization mode ellipticity can lead to a deep fading, and marked reduction in the quality of reception.

The reception of polarized signals with respect to the dynamic polarization basis allows implementing complete polarization PPS reception. In this case the unit vectors of the dynamic basis are transformed according to possible changes in the polarization of the PPS, respectively adjusting to the change in orientation angle, the shape of an ellipse, the direction of the vector rotation $\vec{E}$, while minimizing the non-orthogonality of modes that carry two information signal flows.

To organize the dynamic basis it is required to obtain an estimate of the amplitude-phase structure (APS) of received PPS and implement the appropriate correction of the quadrature components I and Q of the reference signal. The block diagram for the receiver of polarized optical signals is shown in Figure 3.

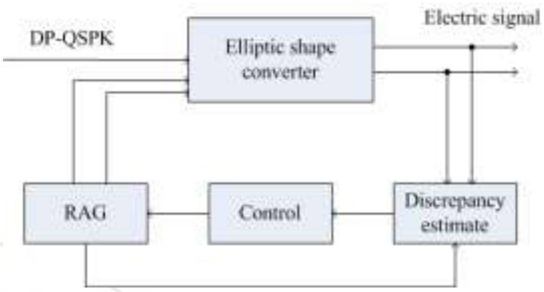

Figure 3: Block diagram of a coherent optical receiver with adaptive control of the polarization basis [3]

The polarization basis is managed on the basis of the discrepancy assessment between the APS of received polarization modes and APS of the reference azure generator (RAG).

Thus, polarization distortions of the received signal can be substantially minimized due to adaptive compensation of the slow changing of the non-polarized part of the signal and fully polarized reception in the dynamic basis.

5. Conclusions

1) The PMD in FOTSs leads to birefringence and distortion of received optical signals. These signals become partially polarized and require the implementation of complete polarization reception in the dynamic basis. This will maximize the level of reception of fully polarized and predictable non-polarized components of signals.
2) The use of polarization in problems of multiplexing and modulation of optical signals allowed reaching rates of hundreds of Tbit/s, moreover, on the basis of adaptive distortion compensation and full implementation of polarized reception of signals it is possible to further increase the rate.
3) In FOTSs it is appropriate to apply signals with circular polarization, which are not sensitive to the effect of rotation of the polarization plane at the reception.
4) Minimizing of polarization distortions in FOTSs using adaptive equalizers and fully polarized reception allows implementing multi-position polarized signals, that will be a further step in FOTSs development.

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