Polarization methods for raising the level of an intelligence signal in fiber optical sensors using a single light guide

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ABSTRACT

The paper describes the means of raising the sensitivity of fiber-optical sensors involving single multimode and one-mode light guides. First, this is the use of a polarizational beam splitter which is installed in front of the inlet face of a multimode light guide and which fully transmits the polarized radiation from the source to the light guide and reflects half the power of the depolarized output beam to the photodetector. The scheme allows one to raise the output signal level by more than a factor of two as compared with the traditional scheme. Second, in an ordinary one-mode light guide, it is recommended to place a compensator between a polarizational beam splitter and the light guide face. And third, in the case of the use of a single polarized one-mode light guide the compensator should be replaced by a nonmutual magnetooptical element. It is shown that in the circuits with one-mode light guides one can virtually fully eliminate separation power losses of the output beam.

1. INTRODUCTION

Realization of the majority of fiber-optical sensors can be achieved with the use of a single light guide. Such a design is already available in some of the sensors. However, despite the distinct advantages, the application of the single light guide circuit cannot be regarded as common enough. To a great extent, this fact is associated with large radiation flux losses during spatial separation of a probing (input) beam introduced into the light guide and an information (output) beam directed to a photodetector.

Usually, to separate the input and output beams, either a semitransparent beam splitter, or a fiber branching device, is used which is installed between the radiation source and a light guide. In our subsequent analysis we shall limit our discussion solely to a circuit with a beam splitter. This circuit is shown in Fig. 1.

When radiation falls on a semitransparent beam splitter, a portion of the flux is absorbed and scattered, whereas the other portion is distributed almost equally between the reflected and transmitted beams. In qualitatively manufactured beam splitters the

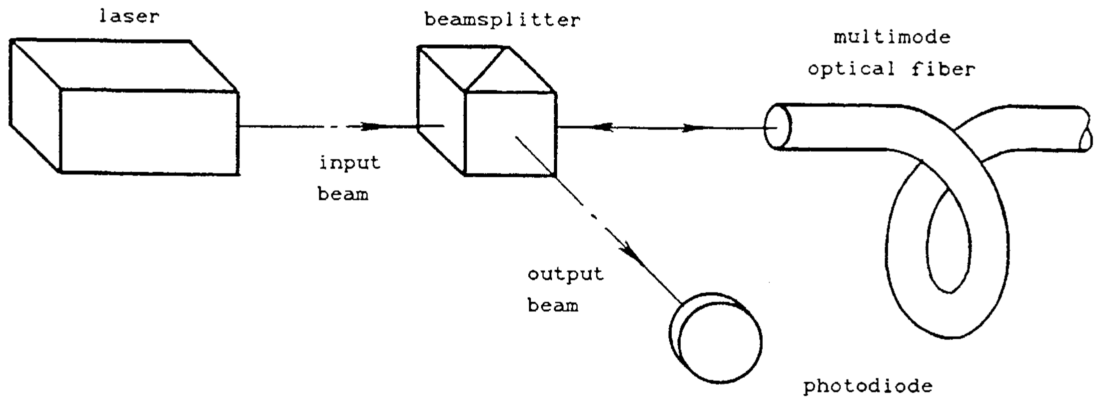

Fig. 1. Scheme of separation of the input and output beams in fiber-optical sensors with a single multi-mode light guide.

light scattering may be neglected. If separation is effected by means of dielectric interference coating, the absorption of radiation in the beam splitter is also insignificant. In this case, the main causes of losses are:

1) the reflection of light during the input beam passage through the beam splitter to the light guide inlet face;

2) the transmission of a portion of radiation when the beam splitter reflects the output beam to a photodiode.

The efficiency of such a practically realized scheme of separation amounts to nearly 20%.

2. FIBER-OPTICAL SENSORS WITH MULTIMODE LIGHT GUIDES

To increase the efficiency of separation, one may take advantage of the fact that, on the one hand, the radiation from many types of lasers has linear polarization and, on the other hand, multimode light guides depolarize the beam that passes through them. Let us consider in more detail the scheme with the separation of the input and output beams by the Müller method[1]. We will use the Cartezian coordinate system XY. The X axis is directed parallel to the plane of polarization of the original laser beam. The coefficients of the reflection and transmission of the corresponding polarization components by the beam splitter will be denoted by R_X, T_X and R_Y, T_Y. Moreover,

$$R_X + T_X = R_Y + T_Y = 1. \tag{1}$$

The losses of power during the passage of radiation through the light guide are considered to be negligibly small. In this case Müller's matrix elements for the light guide m_{ij} are equal to zero at i=1 or j=1, except for the element $m_{11}=1$. We also assume that the measuring element of the sensor lowers the radiation power κ times without changing its state of polarization. Correspondingly, the Stokes vector of the output beam S′, which impinges on the photodiode, is determined by the matrix equation

$$\mathbf{S}'=\frac{\kappa\ I}{4}\begin{pmatrix} R_X+R_Y & R_x-R_y & 0 & 0 \\ R_X-R_Y & R_X+R_Y & 0 & 0 \\ 0 & 0 & 2\sqrt{R_X R_Y} & 0 \\ 0 & 0 & 0 & 2\sqrt{R_X R_Y} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & m_{22} & m_{23} & m_{24} \\ 0 & m_{32} & m_{33} & m_{34} \\ 0 & m_{42} & m_{43} & m_{44} \end{pmatrix}$$

$$\times\begin{pmatrix} T_X+T_Y & T_x-T_y & 0 & 0 \\ T_X-T_Y & T_X+T_Y & 0 & 0 \\ 0 & 0 & 2\sqrt{T_X T_Y} & 0 \\ 0 & 0 & 0 & 2\sqrt{T_X T_Y} \end{pmatrix}\mathbf{S}\ , \qquad (2)$$

where **S** is the normalized Stokes vector of the original laser beam, I is the intensity of this beam.

Let us multiply the data of the matrices and the Stokes vector of the original laser beam $\mathbf{S}=(1,\ 1,\ 0,\ 0)^*$. Here, the asterisk denotes the transpose operation on the vector. The intensity of the output beam I' is equal to the value of the first element of the vector **S'**:

$$I' = \frac{1}{2}\ \kappa\ T_X\ [(R_X + R_Y) + m_{22}\ (R_X - R_Y)]\ I. \qquad (3)$$

The ratio $I'/(\kappa\ I)$ shows the efficiency of the scheme of the separation of beams. It will be denoted by the value η. Consequently

$$\eta = \frac{1}{2}\ (1 - R_X)\ [(R_X + R_Y) + m_{22}\ (R_X - R_Y)]. \qquad (4)$$

The maximum value of the separation efficiency η_{max} is attained at he following optinal parameters of the beam splitter:

$$\begin{cases} R_X=\dfrac{m_{22}}{1+m_{22}} \\ R_Y=1 \end{cases} \text{and} \quad \begin{cases} T_X=\dfrac{1}{1+m_{22}} \\ T_Y=0 \end{cases}, \text{ for } 0 \le m_{22} \le 1\ ;$$

$$\begin{cases} R_X=0 \\ R_Y=1 \end{cases} \text{and} \quad \begin{cases} T_X=1 \\ T_Y=0 \end{cases}, \text{ for } -1 \le m_{22} < 0\ . \qquad (5)$$

Here

$$\eta_{max} = \frac{1}{2\,(1 + m_{22})}\ , \text{ for } 0 \le m_{22} \le 1\ ;$$

$$\eta_{max} = \frac{1 - m_{22}}{2}\ , \text{ for } -1 \le m_{22} < 0 \qquad (6)$$

As is seen from Eq. (5), in the case of complete radiation depolarization by the light guide (m_{22}=0), the application of the polarizational beam splitter with R_X=0, R_Y=1, T_X=1, T_Y=0 would be optimal. Then, the efficiency of beam separation is equal to η=0.5. An extra advantage of the use of the polarizational beam splitter is that the radiation reflected from the outlet face of the light guide is made not to impinge on the radiation photodetector. The application of a semitransparent beam splitter with R_X= R_Y =0.5 gives the twice as smaller efficiency η=0.25 (see Eq. (4)). Since it is rather difficult to realize the beam splitting coating with such parameters, the value η=0.2 is usually obtained in practice.

3. FIBER-OPTICAL SENSORS WITH ONE-MODE LIGHT GUIDES

In fiber-optical sensors with a single one-mode light guide that has a small birefrigence, it is possible to apply the method which is used for separating the input and output beams in the optical pickup of a laser videodisc player[2]. This technique ensures virtually a 100 per cent separation efficiency which is more than 4 times exceeds the corresponding index in the scheme with a semitransparent beam splitter. The crux of the method is that in the path of a linearly polarized input beam a compensator is installed which separates the beam into two orthogonally polarized components of equal intensity and, in the case of double passage, shifts the components in phase by 180°. As a result, the polarization of the output beam becomes perpendicular to the polarization of the input beam, thus allowing their separation with the aid of a polarizational beam splitter. As the compensator in the optical pickup a quarter-wave plate is used. A special feature of the fiber-optical sensors is that the compensator should operate with a substantial relative phase shift between the polarizational modes of the light guide.

The scheme of the polarizational separation of beams in such kind of fiber-optical sensors is shown in Fig. 2. To analyze its operation, we will use the same coordinate system, as that given above. Since in this case the radiation depolarization can be neglected, it is preferable that investigation be performed by the Jones method[1]. The reflection and tranmission coefficients of the polarizational beam splitter are equal to: R_X=0, R_Y=1, T_X=1, T_Y=0. Let us suppose that the light guide modes have linear polarization and that the measuring element of the sensor lowers the radiation

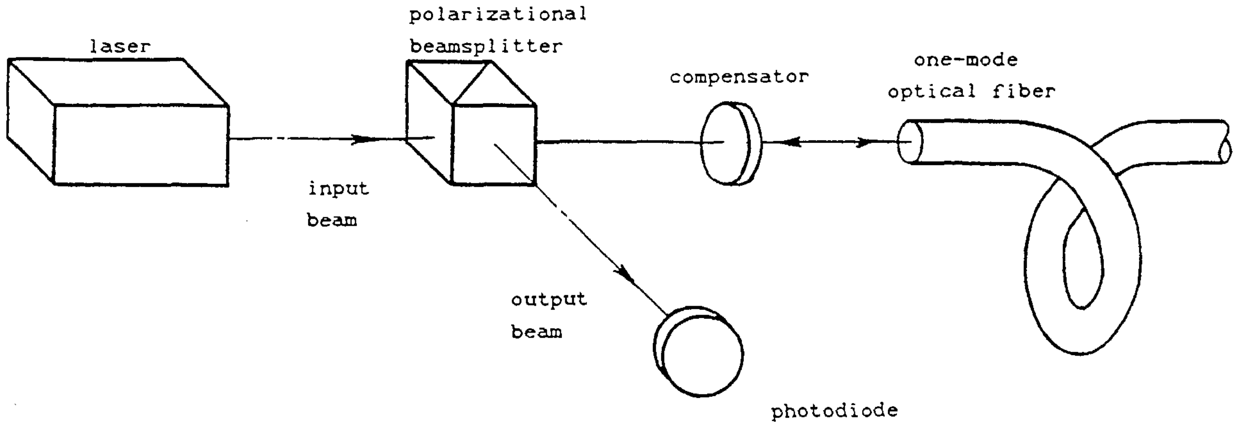

Fig. 2. Scheme of separation of the input and output beams in fiber-optical sensors with a single one-mode light guide.

power κ times without changing its state of polarization.

3.1. Single-component linear compensator

Let us consider the case when a solitary linear phase plate is used as a compensator[3]. Denote the azimuth of the fast axis and the value of the compensator phase shift as φ and δ, the polarization azimuth of a faster mode and the value of the phase shift between the modes of the light guide with single passage as φ and $\Delta/2$. The Maxwell vector of the output beam $\mathbf{E}'$ which impinges on the photodiode is defind by the matrix equation

$$\mathbf{E}'=\sqrt{I}\begin{pmatrix}0 & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\cos\varphi & \sin\varphi\\ -\sin\varphi & \cos\varphi\end{pmatrix}\begin{pmatrix}e^{i\delta} & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\cos\varphi & -\sin\varphi\\ \sin\varphi & \cos\varphi\end{pmatrix}\begin{pmatrix}\cos\psi & \sin\psi\\ -\sin\psi & \cos\psi\end{pmatrix}$$

$$\times\begin{pmatrix}e^{i\Delta/2} & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\cos\psi & -\sin\psi\\ \sin\psi & \cos\psi\end{pmatrix}\begin{pmatrix}-\sqrt{\kappa} & 0\\ 0 & \sqrt{\kappa}\end{pmatrix}\begin{pmatrix}\cos\psi & -\sin\psi\\ \sin\psi & \cos\psi\end{pmatrix}\begin{pmatrix}e^{i\Delta/2} & 0\\ 0 & 1\end{pmatrix} \qquad (7)$$

$$\times\begin{pmatrix}\cos\psi & \sin\psi\\ -\sin\psi & \cos\psi\end{pmatrix}\begin{pmatrix}\cos\varphi & -\sin\varphi\\ \sin\varphi & \cos\varphi\end{pmatrix}\begin{pmatrix}e^{i\delta} & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\cos\varphi & \sin\varphi\\ -\sin\varphi & \cos\varphi\end{pmatrix}\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}\mathbf{E},$$

where $\mathbf{E}$ is the normalized Maxwell vector of the original laser beam, I is the intensity of this beam.

Let us multiply the matrices and the Maxwell vector of the original laser beam $\mathbf{E}=(1,\ 0)^*$. The intensity of the output beam I' is determined by means of complex conjunction of the vector $\mathbf{E}'$:

$$I' = \frac{\kappa\, I}{2}\{1 + 2\sin\Delta\ \sin\delta\ \sin 2\varphi\ (\sin 2\psi - \sin^2\frac{\delta}{2}\ \sin 2\varphi\ \cos 2(\varphi-\psi))$$

$$-\ [(\sin 2\psi - 2\sin^2\frac{\delta}{2}\ \sin 2\varphi\ \cos 2(\varphi-\psi))^2 - \sin^2 2\varphi\ \sin^2\delta]\ \cos\Delta$$

$$-\ [\cos 2\psi - \sin^2\frac{\delta}{2}\ \sin 2\varphi\ \sin 2(\varphi-\psi)]^2\}\ . \qquad (8)$$

In order to ensure a complete separation of the beams $\left(\frac{I'}{\kappa\, I}=1\right)$, the compensator parameters should have the following values:

I) for $\sin\frac{\Delta}{2}\ \cos 2\psi \neq 0$:

$$\begin{cases} \varphi = \frac{1}{2}\ \mathrm{arctg}\left[\dfrac{\sin\frac{\Delta}{2}\ \sin 2\psi\ \pm 1}{\sin\frac{\Delta}{2}\ \cos 2\psi}\right] \\ \delta = \mp\arcsin\left(\dfrac{\cos\frac{\Delta}{2}}{\sin 2\varphi}\right); \end{cases}$$

II) for $\sin\frac{\Delta}{2}\ \cos 2\psi = 0$:

1) $\Delta = 360^\circ\cdot m,\ \psi = \mathrm{var}$:

$$\delta = 90^\circ\ (2n+1),\ \varphi = \pm\ 45^\circ;$$

2) $\Delta = 180^\circ(2m+1),\ \psi = \pm\ 45^\circ$:

$$\delta = 360^\circ\ \cdot n,\ \varphi = \mathrm{var};$$

or $$\delta = \mathrm{var};\ \varphi = \psi \pm 45^\circ;$$

3) $\Delta \neq 180^\circ(2m+1),\ \psi = \pm\ 45^\circ$:

$$\delta = 90^\circ(2n+1) - \frac{\Delta}{2},\ \varphi = \pm\ \psi,$$

where n and m are arbitrary integers.

3.2. Double-component linear compensator

Since the phase shift between the polarization modes is directly proportional to the light guide length and to the difference between their propagation constants, it is necessary to carry out the tuning of the compensator for each specific sensor.

Therefore, a compensator should be used which ensures the possibility for adjusting phase shift between the components, say, Soleil's or Berek's compensator[4]. It is convenient to use a compensator which consists of a combination of two linear phase plates[5,6] or a compensator in the form of a quartz plate cut out perpendicularly to the optical axis which is viewed by an inlined light beam[7,8].

Below, expressions are given that describe the scheme of the polarizational separation of beams wit the compensators of the two indicated types. Suppose the light guide is orientated in such a way that the plane of polarization of the faster mode coincides with the axis X.

Let us consider the application of a compensator consisting of two linear phase plates. We shall denote the azimuth of the fast axis and the phase shift value of the first plate as φ and δ, the azimuth of the fast axis and the phase shift value of the second plate as γ and ϑ. Using a matrix equation similar to Eq. (7), we can determine the efficiency of the beam separation scheme

$$\eta=\frac{I'}{\kappa\ I}=4(N^2+M^2)[1-(N^2+M^2)]\ \cos^2\left[\frac{\Delta}{2} - \operatorname{arctg}\left(\frac{LN - KM}{KN + LM}\right)\right], \quad (9)$$

where

$$K = \cos\frac{\vartheta}{2}\cos\frac{\delta}{2} - \sin\frac{\vartheta}{2}\sin\frac{\delta}{2}\cos 2(\gamma - \varphi);$$

$$L = \sin\frac{\vartheta}{2}\cos\frac{\delta}{2}\cos 2\gamma + \cos\frac{\vartheta}{2}\sin\frac{\delta}{2}\cos 2\varphi;$$

$$M = \sin\frac{\vartheta}{2}\sin\frac{\delta}{2}\sin 2(\gamma - \varphi);$$

$$N = \cos\frac{\vartheta}{2}\sin\frac{\delta}{2}\sin 2\varphi + \sin\frac{\vartheta}{2}\cos\frac{\delta}{2}\sin 2\gamma.$$

3.3. Nonlinear compensator (inclined quartz plate)

If an inclined plate of the type of Berek's compensator is used in the facility, the operation of the scheme of polarizational separation can be described by Eq. (8). For a quartz plate the picture becomes much more complicated because of the considerable ellipticity of the proper waves when the beam passes near the optical axis of the crystal. The efficiency of the scheme with a quartz plate is as follows:

$$\eta=4(\sin^2\frac{\delta}{2})\left[1-\left(\frac{1-\sigma^2}{1+\sigma^2}\right)^2\cos^2 2\varphi\right]\left\{1-(\sin^2\frac{\delta}{2})\left[1-\left(\frac{1-\sigma^2}{1+\sigma^2}\right)^2\cos^2 2\varphi\right]\right\}$$

$$\times\cos^2\left\{\frac{\Delta}{2} + \mathrm{arctg}\left(\frac{1}{\sin 2\varphi}\;\frac{2\sigma}{1-\sigma^2}\right) - \mathrm{arctg}\left(\frac{1-\sigma^2}{1+\sigma^2}\cos 2\varphi\;\mathrm{tg}\frac{\delta}{2}\right)\right\}, \qquad (10)$$

where σ and δ is the ellipticity and the relative phase shift of the natural waves, φ is the angle between the plane of the beam incidence on the plate and the X axis. The compensator parameters σ and δ are connected with the beam incidence angle ε and with the plate thickness t by the relations

$$\delta=\frac{360^\circ}{\lambda}\, t\, n_0 \left(\frac{\left(\dfrac{n_e^2 - n_0^2}{2n_e^2\, n_0^2}\sin^2\varepsilon\right)^2 + \left[n_0^2 G_{33} + (G_{11}-G_{33})\sin^2\varepsilon\right]^2}{1 - \dfrac{n_e^2 + n_0^2}{2n_e^2\, n_0^2}\sin^2\varepsilon} \right)^{\frac{1}{2}},$$

$$\sigma=\frac{n_0^2\, G_{33} + (G_{11} - G_{33})\sin^2\varepsilon}{\dfrac{n_e^2 - n_0^2}{2n_e^2\, n_0^2}\sin^2\varepsilon + \left[\left(\dfrac{n_0^{\,2} - n_e^{\,2}}{2n_e^{\,2} n_0^{\,2}}\sin^2\varepsilon\right)^2 + \left[n_0^2 G_{33} + (G_{11}-G_{33})\sin^2\varepsilon\right]^2\right]^{\frac{1}{2}}}$$

where G_{11} and G_{33} are the components of the giration pseudo-tensor in the crystallophysical coordinate system; n_0 and n_e are the refractive indices of the ordinary and extaordinary rays. In quartz, at the wave length of 633 nm, these values are equal to[9,10]: n_0=1.5426, n_e=1.5517, $G_{11}=-0.94\cdot 10^{-5}$, $G_{33}=1.79\cdot 10^{-5}$.

By equating expressions (9) and (10) to unity and solving the resulting equations with the aid of the iteration method, it is possible to find the optimal parameters of the compensators. For example, to attain η=1 at $\Delta=10^\circ$, a 1 mm - thick quartz plate should be inclined at an angle $\varepsilon=12.1^\circ$, if the angle between the X axis and the plane of inclination is $\varphi=31.4^\circ$.

4. FIBER-OPTICAL SENSORS WITH SINGLE-POLARIZATION ONE-MODE LIGHT GUIDES

Analysis shows that in fiber-optical sensors with a one-mode single-polarization fiber the above-described techniques of separation of the input and output beams do not allow one to attain the efficiency which would exceed 25%. The situation can be essentially improved by replacing the compensator (Fig. 2) by a nonmutual magnetooptical element which rotates the polarization plane by 45°. The light guide is orientated in such a way that the plane of polarization of the mode could make up an angle of 45° with the X axis. In the case of the double passage through the nonmutual element and the light guide, the plane of polarization of the output beam will rotate by 90° with respect to the X axis and the beam will be fully reflected by the polarizational beam splitter to the photodiode.

5. CONCLUSION

The results demonstrate that the polarizational methods of the separation of beams allow one to efficiently and rather simply raise the level of the information signal in fiber-optical sensors. The analytical expressions derived make it possible to determine the parameters for the elements of the polarizational separation scheme which are optimal when multi-mode or one-mode fibers with different characteristics are used. The methods can find a wide application in diverse types of fiber-optical sensors and especially in combined interferometric-polarimetric fiber optics sensors[11]. Note that in the case of a more detailed investigation of the separation scheme properties it is also necessary to take into account the distortions of the polarization of beams produced by launching lens[12] and by the measuring element of the sensor.

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