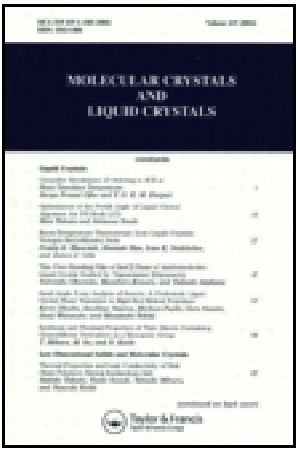

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The Stokes parameters pattern in Young's interference experiment with N pinholes are derived. Our calculations allow us to separate the information on the amplitude, absolute phase and polarization by mean of correlation functions; one correlation for intensity, one correlation function for the absolute phase and four correlation functions for the polarization (one for each Stokes Parameter). Then the visibility of certain Stokes parameter is the product of the correlation function of intensity, of absolute phase and of the polarization correlation function of that Stokes Parameter.

1. Introduction

The concept of optical coherence (see [1] and its citations for the story of these studies) has long been associated with interference, because it is the simplest phenomenon that reveals correlation between light beams and Young's interference experiment has played a pivotal role in the development of optic and quantum physic [2]. Initially, the analyses have been performed almost exclusively in scalar description. From the first studies on the effect of light polarization on the phenomena of interference [3] there were many studies on the interference of polarized light, see [4–11] just to list few schemes. It has been known for quite long time that though two coherent but orthogonally polarized beams do not give rise to intensity-interference fringes, they lead to a spatially varying polarization pattern, that is very suitable for the fabrication of holographic grating in polarization-sensitive materials [12–15]. A mathematical description for Young double slit experiment with polarized light was presented characterizing the resulting field by the Stokes parameters SP [16]. For a suitable exposition of coherency matrix theory and of the SP see [17]. Despite of long history of this problem, it has again become urgent in last years and has attracted the attention of many researchers (see for example [18–28]).

The Jones vectors of quasi-monochromatic light beam at a fixed point in space and at a certain fixed time can be represented as

$$\mathbf{E}_i = \begin{pmatrix} A_x^{(i)}\, e^{i\delta_x^{(i)}} \\ A_y^{(i)}\, e^{i\delta_y^{(i)}} \end{pmatrix} \tag{1}$$

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where $A_x^{(i)}$and $A_y^{(i)}$ are the amplitudes, $\delta_x^{(i)}$ and $\delta_y^{(i)}$ are the phases and "i" indicates the i-th beam of N beams (Jones vectors are explained in [17], the meaning of x and y is obvious). For brevity, we omit on the time and space dependence of various quantities, but they are assumed to vary with time unless we don't specify the contrary, i.e. the intensities, the polarization, etc. may fluctuate with time for example in random manner. The SP of the electric fields expressed in (1) are

$$\begin{aligned} &S_0^{(i)}= I_i; && S_1^{(i)}= I_i \cos(2\theta_i); \\ &S_2^{(i)}= I_i \sin(2\theta_i)\cos\delta^{(i)}; && S_3^{(i)}= I_i \sin(2\theta_i)\sin\delta^{(i)} \end{aligned} \tag{2}$$

where $I_i = \sqrt{(A_x^{(i)})^2 + (A_y^{(i)})^2}$ is the intensity, $\theta_i = \mathrm{arctn}(A_y^{(i)}/A_x^{(i)})$ is the azimuth and $\delta^{(i)} = \delta_y^{(i)} - \delta_x^{(i)}$ is the relative phase. Moreover we will use the absolute phase $\delta_m^{(i)} = (\delta_x^{(i)} + \delta_y^{(i)})/2$. Recently in [29] the superposition of N quasi-monochromatic coaxial light beams has been studied. The SP of the resulting beam S_a^{TOT} (the superposition of the beams) have been calculated in a given time instant and in a certain space position

$$S_a^{TOT} = \sum_{i=1}^{N} S_a^{(i)} + 2\sum_{(i,j)} \sqrt{I_i I_j}\mathbf{P}_a^{(i,j)} \cdot \mathbf{M}^{(i,j)} \tag{3}$$

where a = 0,1,2,3 and (i,j) indicates all the pairs of SP with i > j. In equations (3) the information on polarization, absolute phase and intensity is separated by introducing the vectors $\mathbf{P}_0^{(i,j)}$, $\mathbf{P}_1^{(i,j)}$, $\mathbf{P}_2^{(i,j)}$ and $\mathbf{P}_3^{(i,j)}$, which contain information only on the polarization, and the vector $\mathbf{M}^{(i,j)}$, that gives information on absolute phases. Now the information on intensities is only a factor, which is shared by all the interference terms. You can find the definition of these vectors in [29], but for completeness we report their values

$$\begin{aligned}
\mathbf{P}_0^{(i,j)} &= \left(\cos(\theta_j - \theta_i)\cos\left(\frac{\delta^{(j)} - \delta^{(i)}}{2}\right),\quad \cos(\theta_j + \theta_i)\ \sin\left(\frac{\delta^{(j)} - \delta^{(i)}}{2}\right)\right); \\
\mathbf{P}_1^{(i,j)} &= \left(\cos(\theta_j + \theta_i)\ \cos\left(\frac{\delta^{(j)} - \delta^{(i)}}{2}\right),\quad \cos(\theta_j - \theta_i)\ \sin\left(\frac{\delta^{(j)} - \delta^{(i)}}{2}\right)\right); \\
\mathbf{P}_2^{(i,j)} &= \left(\sin(\theta_j + \theta_i)\ \cos\left(\frac{\delta^{(j)} + \delta^{(i)}}{2}\right),\quad \sin(\theta_i - \theta_j)\ \sin\left(\frac{\delta^{(j)} + \delta^{(i)}}{2}\right)\right); \\
\mathbf{P}_3^{(i,j)} &= \left(\sin(\theta_j + \theta_i)\ \sin\left(\frac{\delta^{(j)} + \delta^{(i)}}{2}\right),\quad \sin(\theta_j - \theta_i)\ \cos\left(\frac{\delta^{(j)} + \delta^{(i)}}{2}\right)\right); \\
\mathbf{M}^{(i,j)} &= \left(\cos(\delta_m^{(j)} - \delta_m^{(i)}), \sin(\delta_m^{(j)} - \delta_m^{(i)})\right).
\end{aligned} \tag{4}$$

Generally a measurement of SP is an average in the time, then in [29] the time-average of equations (3) was been calculated

$$\langle S_a^{TOT}\rangle = \sum_{i=1}^{N}\langle S_i^{(i)}\rangle + 2\sum_{(i,j)}\left\langle\sqrt{I_i I_j}\right\rangle\ \left|\langle\mathbf{P}_i^{(i,j)}\rangle\right|\ \left|\langle\mathbf{M}^{(i,j)}\rangle\right|\ \cos\overline{\delta}_a^{ij} \tag{5}$$

where $\overline{\delta}_i^{12}$ is the angle between $\langle\mathbf{P}_i^{(1,2)}\rangle$ and $\langle\mathbf{M}^{(1,2)}\rangle$ and with a = 0,1,2,3. We denote the time-average of the function f(t) by ⟨f(t)⟩, i.e.

$$\langle f(t)\rangle = \frac{1}{T}\int_0^T f(t)\ dt \tag{6}$$

where T is an interval of time long enough to make the time-average integral independent of T itself. The physical interpretation of these quantities is of correlations. In fact the module of vectors $\left|\left\langle \mathbf{P}_a^{(1,2)} \right\rangle\right|$, with a = 0,1,2,3, is polarization correlation functions. We have a polarization correlation function for each SP (the correlation function of the first Stokes parameter first was introduced in [30] in order understand a depolarization effect caused by non-uniform polarization distribution over the beam cross section which was discussed [31–33]). These correlations depend only from polarizations of the superposed beams. The function $2\left\langle \sqrt{I_1 I_2} \right\rangle$ normalized with $\langle I_1 + I_2 \rangle$ is the intensity correlation function, and $\left|\left\langle \mathbf{M}^{(1,2)} \right\rangle\right|$ is the absolute phase correlation function. We note $\left|\left\langle \mathbf{M}^{(1,2)} \right\rangle\right|$ is the classical correlation function in the scalar theory [1]. The quantities $\mu_i\,(Q_1, Q_2, \omega_0)$ (with i = 1,2,3) used to calculate interference terms, for example see [23], depend on intensity, polarization and absolute phase and never first of now was possible treads separately the information on all these quantities.

In this paper we predicts polarization modulation in Young's interference experiment with N pinholes, separating information on intensity, polarization and absolute phase.

2. Theoretical Approach

Consider a random, wide-sense stationary, electro-magnetic field. We assume that the field is a quasi-monochromatic beam, which propagates close to the z-directions. This restriction to beams implies that the Cartesian components of the field vectors along the z-direction can be neglected [17]. Suppose that an opaque screen A is placed in the path of the beam at right angle to the axis and containing small opening at point Q_1 and Q_2 (see Figure 1). We want determine SP of the transmitted light at the point P on a screen B parallel to A at some distance away from it.

The electric fields at the pinhole Q_1 and Q_2 are $\mathbf{E}_1$ and $\mathbf{E}_2$ (explained in equation (1)) respectively. The electric field in P is given by the formula

$$\mathbf{E}(P) = K_1 \mathbf{E}_1 \frac{e^{ikR_1}}{R_1} + K_2 \mathbf{E}_2 \frac{e^{ikR_2}}{R_2} \tag{7}$$

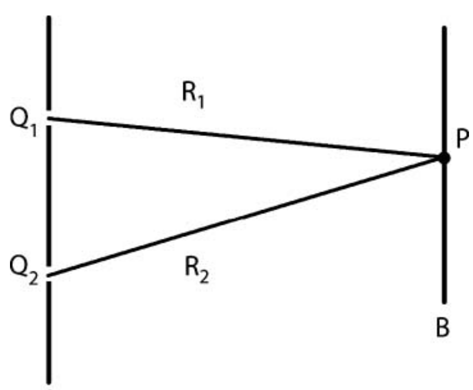

Figure 1.

where $R_1$and $R_2$are the distances Q_1P and Q_2P respectively and $k = 2\pi/\lambda$, where λ is the wavelength. K_1 and K_2come from elementary diffraction theory and we have $K_i = -i\ dA_i/\lambda$, where dA_i is the area of pinholes (see [18] and its citations for more details). Substituting equation (1) in equation (7) and introducing the absolute phase $\delta_m^{(i)} = (\delta_x^{(i)} + \delta_y^{(i)})/2$ and the relative phase $\delta^{(i)} = \delta_y^{(i)} - \delta_x^{(i)}$, we can rewrite equations (7) and $\mathbf{E}_2$we have

$$\mathbf{E}(P) = \left[\frac{|K_1|\sqrt{I_1}}{R_1}\begin{pmatrix}\cos\theta_1\ e^{-i\delta^{(1)}/2}\\ \sin\theta_1\ e^{+i\delta^{(1)}/2}\end{pmatrix}e^{i\left(\delta_m^{(1)}+kR_1\right)} + \frac{|K_2|\sqrt{I_2}}{R_2}\begin{pmatrix}\cos\theta_2\ e^{-i\delta^{(2)}/2}\\ \sin\theta_2\ e^{+i\delta^{(2)}/2}\end{pmatrix}e^{i\left(\delta_m^{(1)}+kR_2\right)}\right]e^{-i\pi/2}. \tag{8}$$

We calculate the SP of $\mathbf{E}$(P) confronting equation (8) with equation

$$\mathbf{E}_{TOT} = \sqrt{I_1}\begin{pmatrix}\cos\theta_1\ e^{-i\delta^{(1)}/2}\\ \sin\theta_1\ e^{+i\delta^{(1)}/2}\end{pmatrix}e^{i\delta_m^{(1)}} + \sqrt{I_2}\begin{pmatrix}\cos\theta_2\ e^{-i\delta^{(2)}/2}\\ \sin\theta_2\ e^{+i\delta^{(2)}/2}\end{pmatrix}e^{i\delta_m^{(2)}} \tag{9}$$

obtained in [29] for the overlapping of two coaxial light beams. We note that we can obtain equation (8) from equation (9) making the replacements $\sqrt{I_i} \to |K_i|\sqrt{I_i}/R_i$ and $\delta_m^{(i)} \to \delta_m^{(i)} + kR_i$ ($e^{-i\pi/2}$ does not give a contribute, i.e. the SP do not change if you rotate $\mathbf{E}_1$ and $\mathbf{E}_2$ of the same phase). Making the previous substitutions equations (3) in the case $N = 2$ gives

$$S_a^{TOT} = \left(S_a^{(1)}\right)' + \left(S_a^{(2)}\right)' + 2\sqrt{\left(S_0^{(1)}\right)'\left(S_0^{(2)}\right)'}\,\mathbf{P}_a^{(1,2)} \cdot \mathbf{M}^{(1,2)} \tag{10}$$

for a = 0,1,2,3, where $(S_a^{(i)})' = \left|K_i\right|^2\ S_a^{(i)}/R_i^2$ for i = 1,2. $\mathbf{P}_i^{(1,2)}$ is still given from equations (4) while

$$\mathbf{M}^{(1,2)} = \left(\cos\left[\delta_m^{(2)} - \delta_m^{(1)} + k(R_2 - R_1)\right],\quad \sin\left[\delta_m^{(2)} - \delta_m^{(1)} + k(R_2 - R_1)\right]\right). \tag{11}$$

Now $\mathbf{M}^{(1,2)}$ depends on $R_2 - R_1$ and this vector changes continually direction as $R_2 - R_1$ varies. In certain time $\mathbf{P}_a^{(1,2)} \cdot \mathbf{M}^{(1,2)}$ varies on screen B (because change the direction of $\mathbf{M}^{(1,2)}$ respect $\mathbf{P}_a^{(1,2)}$) and then SP also changes. Given that the average of a product of independent variables equals product of the average, we obtain time average of equations (10) are

$$\left\langle S_a^{TOT}\right\rangle = \left\langle(S_a^{(1)})'\right\rangle + \left\langle(S_a^{(2)})'\right\rangle + 2\left\langle\sqrt{(S_0^{(2)})'(S_0^{(2)})'}\right\rangle\left\langle\mathbf{P}_a^{(1,2)}\right\rangle \cdot \left\langle\mathbf{M}^{(1,2)}\right\rangle, \tag{12}$$

where the average of a generic vector $\mathbf{V}$ mean $\langle\mathbf{V}\rangle = (\langle V_1\rangle, \langle V_2\rangle)$ and still a = 0,1,2,3. Equation (12) can be rewrite in this way

$$\left\langle S_a^{TOT}\right\rangle = \left\langle(S_a^{(1)})'\right\rangle + \left\langle(S_a^{(2)})'\right\rangle + 2\left\langle\sqrt{(S_0^{(2)})'(S_0^{(2)})'}\right\rangle\left|\left\langle\mathbf{P}_a^{(1,2)}\right\rangle\right|\ \left|\left\langle\mathbf{M}^{(1,2)}\right\rangle\right|\cos\left(\bar{\delta}_a^{12} + k(R_2 - R_1)\right), \tag{13}$$

where $\bar{\delta}_i^{12}$ is the angle between $\langle\mathbf{P}_i^{(1,2)}\rangle$ and $\langle\mathbf{M}^{(1,2)}\rangle$ which does not depend on the point P. The meaning of each factor in the interference term is clear, $2\langle\sqrt{(S_0^{(2)})'(S_0^{(2)})'}\rangle$ normalized with $\langle(S_0^{(1)})' + (S_0^{(2)})'\rangle$ is the correlation between intensities, which depends from the intensity fluctuation of the electric field at the pinholes, and from the ratio of $R_1$and R_2, moreover from the ratio of K_1 and K_2. $|\langle \mathbf{P}_a^{(1,2)} \rangle|$ is the correlation between the state of polarization and does not change respect the case discussed in [29]. $|\langle \mathbf{M}^{(1,2)} \rangle|$ is the absolute phase correlation and does not depend on point P.

Performing same easy calculation we obtain that the contrast (see [23] for more details) $V_a = (\langle S_a^{TOT} \rangle_{MAX} - \langle S_a^{TOT} \rangle_{MIN})/(\langle S_0^{TOT} \rangle_{MAX} + \langle S_0^{TOT} \rangle_{MIN})$ of the SP depends on the respective correlation functions

$$V_a = \frac{2\left\langle \sqrt{(S_0^{(2)})'(S_0^{(2)})'} \right\rangle}{\left\langle (S_0^{(2)})' + (S_0^{(2)})' \right\rangle} \left|\left\langle \mathbf{P}_a^{(1,2)} \right\rangle\right| \; \left|\left\langle \mathbf{M}^{(1,2)} \right\rangle\right| \tag{14}$$

i.e. the visibility of each SP is the product of the intensity correlation function, absolute phase correlation function and the polarization correlation function of the Stokes parameter "a" with a = 0,1,2,3. Moreover the four visibilities differ only for the polarization correlation function of the relative Stokes parameter $|\langle \mathbf{P}_a^{(1,2)} \rangle|$, while they share the other two correlations.

If we have N electric fields $\mathbf{E}_i$ at the pinhole Q_i, with i = 1, ... , N, we can generalize equations (131) and we obtain

$$S_a^{TOT} = \sum_{i=1}^{N} \left\langle (S_a^{(i)})' \right\rangle + \sum_{(i,j)} 2\left\langle \sqrt{(S_0^{(i)})'(S_0^{(j)})'} \right\rangle \left|\left\langle \mathbf{P}_a^{(i,j)} \right\rangle\right| \; \left|\left\langle \mathbf{M}^{(i,j)} \right\rangle\right| \cos\left(\overline{\delta}_a^{ij} + k(R_j - R_i)\right) \tag{15}$$

for a = 0,1,2,3, $\mathbf{M}^{(i,j)} = (\cos(\delta_m^{(j)} - \delta_m^{(i)} + k(R_j - R_i)), \quad \sin(\delta_m^{(j)} - \delta_m^{(i)} + k(R_j - R_i)))$ and where R_i is the distance Q_iP. In the case the pattern is more complicate and it is not a simple modulation of the SP. Also in this case we define $V_a = (\langle S_a^{TOT} \rangle_{MAX} - \langle S_a^{TOT} \rangle_{MIN})/(\langle S_0^{TOT} \rangle_{MAX} + \langle S_0^{TOT} \rangle_{MIN})$ where $\langle S_a^{TOT} \rangle_{MAX}$ is calculated in the point of interference pattern where all $\cos(\overline{\delta}_a^{ij} + k(R_j - R_i))$ in (15) are 1, while $\langle S_0^{TOT} \rangle_{MIN}$ is calculated in the point of interference pattern where all $\cos(\overline{\delta}_a^{ij} + k(R_j - R_i))$ in (15) are is calculated in the point of interference pattern where all $\cos(\overline{\delta}_a^{ij} + k(R_j - R_i))$ in (15) are -1, then the visibilities become

$$V_a = \sum_{(i,j)} \frac{2\left\langle \sqrt{(S_0^{(i)})'(S_0^{(j)})'} \right\rangle}{\left\langle (S_0^{(i)})' + (S_0^{(j)})' \right\rangle} \left|\left\langle \mathbf{P}_a^{(i,j)} \right\rangle\right| \; \left|\left\langle \mathbf{M}^{(i,j)} \right\rangle\right| \tag{16}$$

3. Conclusion

In this paper we studied the polarization modulation in Young's interference experiment with N pinholes. At each pinholes we have an electric field with different proprieties. The intensity, the polarization and the absolute phase of these fields can fluctuate in time. We calculate the SP in a point P of screen B (see Figure 1). In our work we are able to separate information on intensity, polarization and absolute phase by the vectors $\mathbf{P}_0^{(1,2)}$, $\mathbf{P}_1^{(1,2)}$, $\mathbf{P}_2^{(1,2)}$ and $\mathbf{P}_3^{(1,2)}$, which contain information only on the polarization, and the vector $\mathbf{M}^{(1,2)}$, that gives information on absolute phases. These vectors are introduced initially in [29] for the superposition of coaxial electro-magnetic beams. In equation (10) we calculated the instantaneous SP (i.e. in an interval of time adequately small) for the case of two pinholes. We note there are differences with the case analyzed in [29]. The first one is that

$\sqrt{I_i} \rightarrow |K_i|\sqrt{I_i}/R_i$ that show as the intensities change when light beams go through the pinholes. The second one is the difference of path, that the two rays get in the point P, give contribute only in vector $\mathbf{M}^{(1,2)}$. In particular this contribute rotates the vector $\mathbf{M}^{(1,2)}$ in different position of the screen B and then intensity and polarization pattern is formed. In equations (12) and (13) we calculated the time average the instantaneous SP. In this way we can calculate the visibilities for each SP and we get that these visibilities are the product of three correlation functions, i.e. the visibility of the SP "a", where a = 0,1,2,3, is the product of the intensity correlation function $2\langle\sqrt{(S_0^{(i)})'(S_0^{(j)})'}\rangle/\langle(S_0^{(i)})' + (S_0^{(j)})'\rangle$, the absolute phase correlation function $|\langle\mathbf{M}^{(i,j)}\rangle|$ and the relative polarization correlation functions $|\langle\mathbf{P}_a^{(i,j)}\rangle|$. Then we generalize these results to the case of N pinholes.

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