Romanian Reports in Physics, Vol. 67, No. 4, P. 1363–1372, 2015

Dedicated to
International Year of Light 2015

NEW PROSPECTS OF USING TESTED PARTICLES FOR INVESTIGATING OPTICAL FIELDS AND OPTICAL FLOWS

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Received September 28, 2015

Abstract. We have shown that internal energy flows (spin and orbital) can be diagnosed by test particles of different sizes and properties using the methods of singular optics. The motion velocity of these particles both in the energy and polarization inhomogeneous optical fields can be employed as a diagnostic parameter of the degree of coherence of mutually orthogonal linearly polarized in the incidence plane superposing waves. The feasibilities of using the above mentioned approach, its shortcomings and its advantages over the interfering method for estimating the degree of coherence is analyzed.

Key words: spin and orbital flows, scattering particles, degree of coherence.

1. INTRODUCTION

Alternative ways of creating optical manipulators and optically controlled systems are proposed in this paper. Optical flows are attractive for use to diagnose spatially inhomogeneous in energy optical fields where classical methods cannot be applied. The paper proposes to use the Rayleigh light scattering mechanism for studying and diagnosing optical fields. The distinctive feature of this work is its experimental explanation of the effect of spin flows and optical forces on particle motion. It is the mechanical action of inner energy fluxes on Rayleigh particles that permits to separate and define the effect of spin and orbital flows. Thus, the aim of this paper is to study the influence of optical fields and optical flows on particles of the nanometer range for manifold investigations of the optical field structure. Particles of about $\lambda/100$ have been chosen to estimate spin internal flows and to diagnose the degree of coherence of superposing mutually orthogonal linearly polarized in the incidence plane waves. The application of optical flows for analyzing correlation properties allows to avoid technological difficulties in estimating the degree of coherence of interacting fields, which occur when interference is used to transform the modulation of polarization into the modulation of intensity [1].

2. RESULTS OF THEORETICAL AND EXPERIMENTAL OBSERVATIONS OF SPIN AND ORBITAL FLOWS

Generally the macroscopic energy flow can be subdivided into “orbital” and “spin” parts, which show the peculiarities of orbital and spin degrees of freedom of the light field [2, 3]. Modern investigations of orbital and spin energy flows are performed by studying the behavior peculiarities of the tested particles [4]. The diagnostics of the spin flow can be performed by analyzing the effect of the optical field on the particle, namely, by investigating the peculiarities of transmitting a part of the inner angular momentum to the particle, followed by the absorption of this angular momentum and the rotation of the particle about its mass centre. Such a rotational motion can be explained by the effect of the circular polarized wave and the inner spin angular momentum. In some field configurations the influence of the circular polarized field with a smooth wave front upon the particle manifests itself as an orbital particle motion [5]. Not only the transmission of the intrinsic “pure” angular momentum of the circularly polarized wave may be responsible for the rise of orbital and, in some cases, transmission motion. The physical mechanism of the impact and interaction between the field and the particles is much wider and is complicated by the reverse influence of the particles on the field. The resulting field may be considered responsible for the complicated behavior of the tested particles.

Prof. Bekshaev [3, 5] proposed a theoretical model which made it possible to separate, investigate and calculate spin and orbital flows. According to his theory it is possible to define the optical field energy density and the components of the spin and orbital momentum densities, using the mathematical model of the superposition of two plane waves. The results of calculation show that the orbital momentum is absent in the x-direction. In this case the whole flow and the generated force, which is calculated with allowance made for the changes of the scattered field momentum, will be of spin nature. The x-component of the optical force is determined only by the scattered field.

To analyze the spin flows by assessing the mechanical effect of the spin momentum on the tested particles it is necessary to consider the experimental situation wherein the spin momentum manifests itself in a “pure” form [5, 6]. Let us assume that the resulting field affecting the particle is formed by superposing circular-polarized waves of the same handedness [3]. The spin flow will not be masked by the action of the orbital flow. In this case the result of the simulation essentially depends on the size of the particles ($\xi = ka$ is the particle size parameter, where a is the particle radius, $k = 1.33 \cdot 10^5 \,\mathrm{cm}^{-1}$ is the radiation wavenumber for He-Ne laser), their properties and parameter, which is a function of the angle of incidence and wave phase. In accordance with the particle size, the optical force component values F_x, F_y, F_z, are quite different. The force values connected with the effect of orbital and spin flows differ even for particles of the same order, *i.e.* Rayleigh particles of about $\lambda/100$. Because this way of interaction causes the formation of a field with corresponding distributions of intensity, the F_y component presets the action of the gradient force (*i.e.* the linear behavior of the force at small particle sizes), F_z determines the traditional effect of light pressure. The most interesting conclusions can be made by analyzing the F_x (F_{x+}, F_{x-}) component of the optical force. The direction and the size of the force x-component are changed with the change of the circular polarized beam helicity ($\sigma = \pm 1$). We analyze the mechanical effect of the *x*- or the *y*- polarized beams $\sigma = 0$, and see that the F_x component disappears completely. To differentiate the spin flows we analyze the behavior of the transverse spin flows [4], which arise in the dissipated field and are caused by the interaction of the field with hydrosol of gold particles ($m = 0.32 + 2.65i$) of different sizes and under different irradiation conditions (Fig. 1).

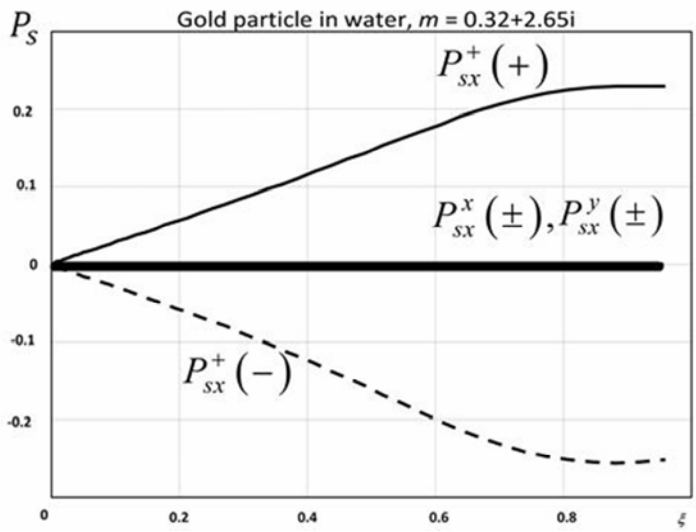

Fig. 1 – The dependence of the normalized transverse momentum flow components of the scattered field upon the particle size parameter.

Depending on the polarization state of the irradiated wave the value and the direction of the generated transverse spin momentum can be quite different (Fig. 1, curves $P_{sx}^{+}(\pm)$). If the particles are irradiated by linearly polarized light the rise of the transverse spin flow is not observed (Fig. 1, curves $P_{sx}^{xy}(\pm)$). Because Rayleigh scattering is characterized by symmetry, the redistribution of the scattered energy must be symmetrical in the forward- and backward- directions. Solid (dashed) lines describe the momentum flux into the forward (backward) directions (Fig. 1). In this case the scattered radiation must not hold flows of the transverse spin momentums when they are irradiated by linearly polarized light.

The irradiation of particles by circular polarized light, independent of helicity, causes the generation of *x*-directed transverse spin flows in the scattered field both in the direct and backward directions. The behavior of such generated momentums essentially differs in both directions. The difference between the absolute values of the momentum presets the force that is identified with the intrinsic noncompensated effect of the scattered field. The equilibrium of this force with the recoil force exerted on the particle causes the origin of the translatory ponderomotive motion in the inhomogeneous circular polarized field. Since the analysis of the momentum is performed in the *x*-direction, according to the mathematical model, the optical force, which arises in that direction, can be considered as a mechanical action of the energy spin flow [5, 6].

The results of the modulation are experimentally confirmed in the scheme (Fig. 2), where the interaction of two circular-polarized beams determine the interference distribution around the focus [4, 6]. An inhomogeneous intensity distribution is formed. A circulation of energy takes place within each maximum and it determines the rise of spin flows.

A strict focusing of the circular-polarized beam causes the transformation of the spin flow into the orbital one [4–6]. In this case the mechanical effect of the generated flow on the particles doesn't allow to separate the effects of the spin and orbital momentums. That is why to avoid this ambiguity, the focusing strength should not be high (in accordance with the known data [7], the spin-orbital conversion is negligible and does not exceed 1% at $NA \approx 0.2$, the focusing angle $\theta \approx 11^{\circ}$). Of course, this leads to a certain loss in the energy concentration. However, one can avoid essential reduction of the focal-region of the spin momentum density if the decrease of intensity is compensated by the increase of the beam inhomogeneity. Within an inhomogeneous optical field any tested particle is subjected to the gradient force [8, 9] that pulls the particle towards the intensity maximum. The radial orbital momentum of a divergent beam pushes the particle away from the axis. As a result, both forces can compensate each other at certain off-axial points within the central lobe of the interference pattern. The spin momentum in the two-beam interference pattern is approximately 2.5 times higher than in a single Gaussian beam focused with the same NA objective. The interference technique of the focal pattern formation facilitates the avoidance of this undesired spin to orbital conversion and promotes the observation of the mechanical action of the 'pure' spin flow without any contamination influence of the orbital one.

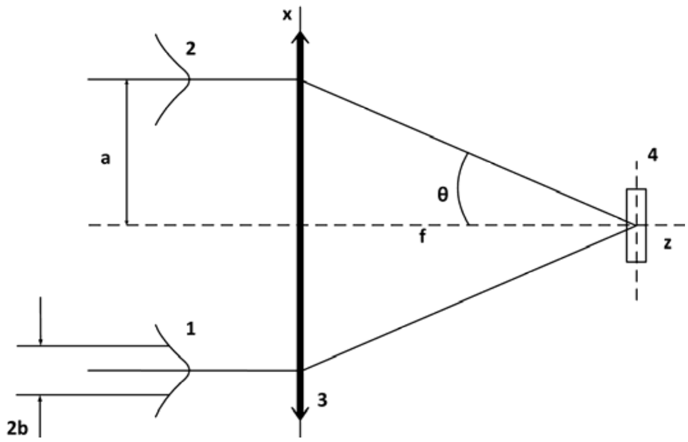

Fig. 2 – Schematic of the experimental setup: 1, 2 – input beams (b = 0.7 mm) of semiconductor lasers (λ = 0.67 μm), 3 – objective lens (f = 10 mm), 4 – cell with tested particles suspended in water, a = 1.3 mm, $\theta = 7.4^{\circ}$, NA = 0.16.

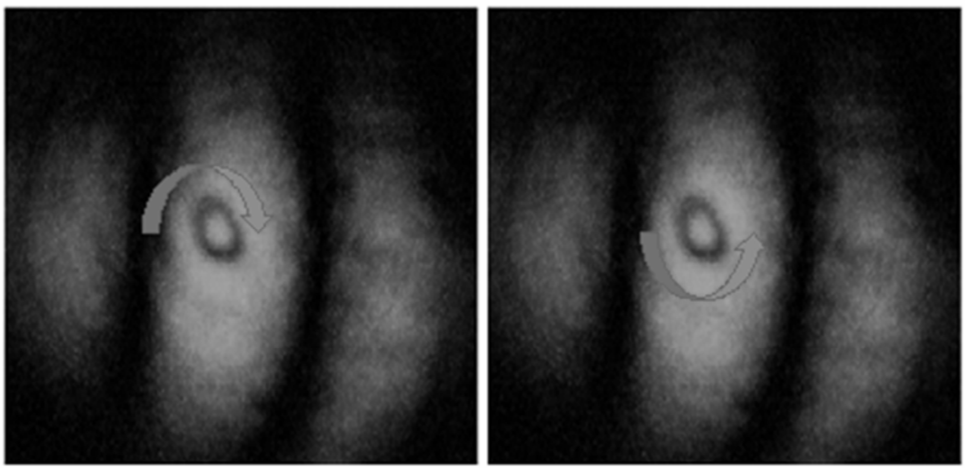

Fig. 3 – The picture of successive positions of particles in the optical field with the change of polarization of superposing beams.

To define the "pure" effect of spin flows in the experiment a cell was used that contained an ensemble of latex microparticles (refractive index 1.48) suspended in water. The particles were chosen so that their shape was close to ellipsoidal with approximate size 1.5 × 1 μm, which made it possible to observe individual particles within a single lobe of the interference pattern formed in the focal region. The asymmetric particle spins (Fig. 3) around its own centre of mass, which is explained by partial absorption of the incident circularly polarized light and its inherent angular momentum [5, 6]. A new observation is that simultaneously the particle's centre of mass performs an orbital motion, which can only be associated with the azimuthal light pressure originating from the spin momentum circulation. This attribution is confirmed by the reverse rotational direction when the sign of the circular polarization is changed. When both beams are linearly polarized the particle is stopped.

3. THE DIAGNOSTICS OF CORRELATION PROPERTIES OF OPTICAL FIELDS

The differences in the behavior of the optical force affecting the tested particles, enables one not only to separate the spin and orbital flows, but to use the behavior of the tested particles for diagnosing optical fields. Such an approach becomes actual when the classical methods of defining correlation properties are not effective.

We take as our example the investigation of interfering interaction of mutually orthogonal linearly polarized in the incidence plane waves when the visibility of the resulting picture is equal to zero and the longitudinal *z*-component essentially contributes to the resulting field distribution. The formalism of the Stokes parameters is not applicable. In this case the superposition of two waves results in spatial polarization modulation [10], and the last is realized in the incidence plane [11, 12].

Such situations are inherent in near-field optics, in optical microscopy, as well as in investigations and applications of evanescent waves [13]. In this case, the estimating of the degree of coherence of superposing waves requires the use of additional experimental interference approaches [1]. The necessity of studying model situations of the superposition of two optical beams, whose convergence angle is 90^{o}, stems from the need for extending the techniques of biostructure analysis in applied biomedicine [14, 15] and the techniques of singular optics [16].

Some technological difficulties derived from the necessity to register the polarization information on corresponding materials dictate the search for new methods, based on measuring kinematic values, such as the value of the motion velocity of the tested nanoparticles. Depending on the properties of the particles and the field intensity value the influence of the field on the tested particles will be different.

As stated above, the essential distinction in the value and order of the optical forces affecting the spherical particles, show up for the Rayleigh particles with the mass M and the radius r. We use precisely these particles for testing the optical field and its coherence properties. Let us discuss the formation of the optical force $\mathbf{F}_{opt}$ affecting the tested spherical particles. The direction of the gradient component of the optical force is stipulated by the distribution gradient of the energy volume density. The direction of the scattering ($\mathbf{F}_{\text{scat}}$) and absorbing ($\mathbf{F}_{\text{abs}}$)

components sets the direction of the energy flow propagation. At the same time the direction of the reflecting component is set by the orientation of the particle surface. The gradient component of the optical force, taking into account the polarization $\alpha = \alpha' + i\alpha''$ of the molecule m, can be calculated [8, 9] as $(F_{grad})_m = -\frac{2\pi n\alpha'}{c} K_m \sqrt{(\frac{1}{\Delta x_m})^2 + (\frac{1}{\Delta z_m})^2} \cdot \eta^{(1,2)}$. Here $\eta^{(1,2)}$ determines the degree of mutual coherence of the field, $\Delta x_m = x_{\min} - x_m$, $\Delta z_m = z_{\min} - z_m$ $(x_{\min}, z_{\min})$ – is the position of the nearest point in the energy minimum region to the investigated point m with the coordinates (x_m, z_m). Here $K_m = -2\frac{\sqrt{\varepsilon_0}}{\sqrt{\mu_0}} \sqrt{\mathrm{tr}[W(\mathbf{r}_1,\mathbf{r}_1,0)]\mathrm{tr}[W(\mathbf{r}_2,\mathbf{r}_2,0)]} \cdot (1 - \cos[(\delta_e)_m])$ is the parameter, which characterizes the energy density value for the chosen point m of the optical field, and depends on the phase difference between the initial waves at the corresponding point. Considering all components of the optical force, the resulting optical force can be rewritten as follows: $\mathbf{F}_{opt} = \mathbf{F}_{grad} + \mathbf{F}_{scat} + \mathbf{F}_{abs}$.

To obtain a direct linkage between the averaged velocity of the tested particles and the degree of coherence of the superposing fields we choose as an example particles characterized by the following set of properties: the Rayleigh mechanism of light scattering is peculiar to them, the values of the scattering and absorbing components of the optical force affecting these particles are much smaller than the value of the gradient component of the optical force.

In this case the value of the averaged motion velocity of nanoparticles in the optical field, or more precisely, the velocity of trapping the given particles by the field in the viscous medium η is determined by the degree of mutual coherence of superposing fields and is written down as

$$\bar{v}(t) = \frac{1}{M}(e^{-\frac{6\pi\eta r}{M}t} - 1)\,\frac{2\pi n}{c}\alpha'\eta^{(1,2)}\,\frac{1}{m}\sum_m K_m \sqrt{(\frac{1}{\Delta x_m})^2 + (\frac{1}{\Delta z_m})^2}\,.$$

If we normalize the change of the averaged velocity with time to the maximum of the trapping velocity for each corresponding moment of time obtained in the absolutely coherent field, we get $\bar{v}_{rel}(t) = \eta^{(1,2)}$.

Thus, the relatively averaged motion velocity of nanometer range particles in the energy inhomogeneous optical field, created by the interaction of partially coherent optical fields converging at the angle of 90°, enables us to estimate the degree of mutual coherence of these fields. The field gradient is able to move the Rayleigh particles of about $\lambda/100$ nm in size into the maximum region, where the trapping takes place.

The motion velocity of nanoparticles depends on the distribution of the energy volume density in the observation plane, and, accordingly, on the degree of coherence of superposing waves. The change of the degree of coherence causes the change of the normalized value of the averaged velocity of particle redistribution. Their trapping in the optical field under the effect of optical forces takes place (Fig. 4).

As it is shown by the results of the computer simulation, the particles are practically immediately "trapped" into the region of the maximum gradient value of the Poynting vector. The maximum normalized value of the averaged motion velocity is realized at the initial moments of time. At the same time, nanoparticles, possessing a certain mass, are characterized by some insignificant inertia. Due to this a certain period of time is needed after "trapping", a period of "relaxation", for the particles to take a stable position. It is explained by the progressive decrease of the velocity after "trapping". The maximum motion velocity is chosen as an estimating criterion for the field inhomogeneity gradient and, consequently, for the degree of coherence.

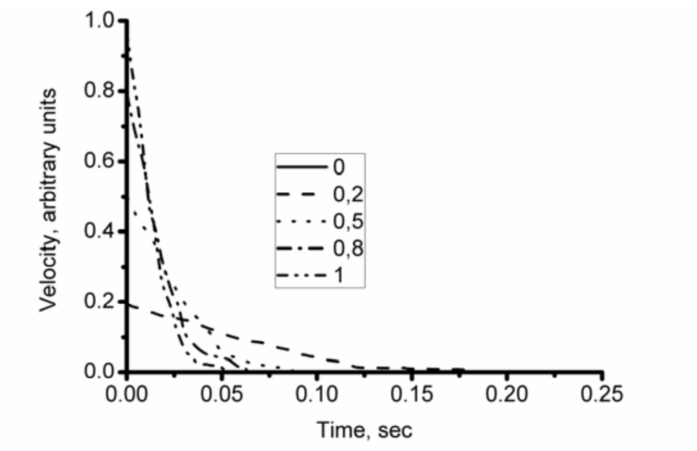

Fig. 4 – The change of the normalized value of the averaged motion velocity of Rayleigh particles (the particles of about $\lambda/100$) with time and with the change of the degree of coherence of interacting waves ($\eta^{(1,2)}$): the legend shows different degrees of coherence that correspond to different curves.

In this case the particle motion velocity is rather easily measured and can be chosen as an estimating parameter for the degree of coherence of interacting fields.

Some restrictions on the use of the given model are explained by the dependence of the optical force upon the force causing the Brownian motion. At temperatures higher than 350–400 K the uniqueness of the particle motion velocity and the degree of coherence of the optical field are lost [4]. In this case the Brownian motion disguises the information about the coherence and polarization properties preset in the optical field under investigation. Moreover, nonlinear effects arise at these temperatures. The inclusion of these effects distorts the general force distribution, masking the information about the optical field properties.

4. CONCLUSIONS

The use of specially chosen interference schemes made it possible to create situations for experimental and theoretical investigations of spin and orbital flows. It is shown that in the energy inhomogeneous circular polarized field it is possible to distinguish mechanical forces, acting from the optical field, which are connected with the spin angular momentum. The forces that arise in the optical field essentially depend upon the size and properties of the particles. It is shown that the selection of the mechanical optical field effect upon the particles becomes possible for the particles of the Rayleigh mechanism of light scattering. Corresponding peculiarities forming optical force components set the prerequisites for using particles of the Rayleigh light scattering mechanism not only for diagnosing optical flows but for defining the correlation features of superposing mutually orthogonal linearly polarized in the incidence plane fields as well. The proposed method has no disadvantages that are peculiar to the interference method of transforming the polarization modulation into the intensity modulation. The investigation of the motion dynamics of the tested particles permits to diagnose optical fields as well.

REFERENCES

1. O. V. Angelsky, S. G. Hanson, C. Yu. Zenkova, M. P. Gorsky, N. V. Gorodyns'ka, *On polarization metrology (estimation) of the degree of coherence of optical waves*, Optics Express, **17**, *18*, 15623–15634 (2009).
2. A. Ya. Bekshaev, *Spin angular momentum of inhomogeneous and transversely limited light beams*, Proc. SPIE, **6254**, 625407, 625407–8 (2006).
3. A. Ya. Bekshaev, O. V. Angelsky, S. G. Hanson, C. Yu. Zenkova, *Scattering of inhomogeneous circularly polarized optical field and mechanical manifestation of the internal energy flows*, Phys. Rev. A, **86**, *2*, 023847 (2012).
4. C. Yu. Zenkova, *Interconnection of polarization properties and coherence of optical fields*, Applied Optics, **53**, *10*, B43–B52 (2014).
5. O. V. Angelsky, A. Ya. Bekshaev, P. P.Maksimyak, A. P. Maksimyak, I. I. Mokhun, S. G. Hanson, C. Yu. Zenkova and A. V. Tyurin, *Circular motion of particles suspended in a Gaussian beam with circular polarization validates the spin part of the internal energy flow*, Optics Express, **20**, *10*, 11351–11356 (2012).
6. O. V. Angelsky, A. Ya. Bekshaev, P. P. Maksimyak, A. P. Maksimyak, S. G. Hanson and C. Yu. Zenkova, *Orbital rotation without orbital angular momentum: mechanical action of the spin part of the internal energy flow in light beams*, Optics Express, **20**, *4*, 3563–3571 (2012).
7. T. A. Nieminen, A. B. Stilgoe, N. R. Heckenberg, H. Rubinsztein-Dunlop, *Angular momentum of a strongly focused Gaussian beam*, Pure Appl.Opt., **10**, *11*, 115005 (2008).

8. C. Yu. Zenkova, I. V. Soltys, P. O. Angelsky, *The use of motion peculiarities of particles of the Rayleigh light scattering mechanism for defining the coherence properties of optical fields*, Optica Applicata, **2**, *43*, 297–312 (2013).
9. O. V. Angelsky, C. Yu. Zenkova, M. P. Gorsky, I. V. Soltys and P. O. Angelsky, *The Use of New Approaches to Estimating the Coherence Properties of Mutually Orthogonal Beams*, The Open Optics Journal, 5–12 (2013).
10. T. Tudor, *Polarization waves as observable phenomena*, J. Opt. Soc. Am. A, **14**, *8*, 2013–2020 (1997).
11. O. V. Angelsky, S. B. Yermolenko, C. Yu. Zenkova, A. O. Angelskaya, *Polarization manifestations of correlation (intrinsic coherence) of optical fields*, Applied Optics, **47**, *32*, 5492–5499 (2008).
12. O. V. Angelsky, N. N. Dominikov, P. P. Maksimyak, T. Tudor, *Experimental revealing of polarization waves*, Appl. Opt., **38**, *14*, 31123117 (1999).
13. A. Apostol, A. Dogariu, *Non-Gaussian statistics of optical near-fields*, Phys.Rev. E, **72**, 025602 (2005).
14. O. V. Angel`skii, A. G. Ushenko, A. D. Archelyuk, S. B. Ermolenko, D. N. Burkovets, *Structure of matrices for the transformation of laser radiation by biofractals*, Quantum Electronics, **29**, *12*, 1074–1077 (1999).
15. O. V. Angelsky, Yu. Ya. Tomka, A. G. Ushenko, Ye. G. Ushenko, Yu. A. Ushenko, *Investigation of 2D Mueller matrix structure of biological tissues for pre-clinical diagnostics of their pathological states*, Journal of Physics D: Applied Physics, **38**, *23*, 4227–235 (2005).
16. O. V. Angelsky, S. G. Hanson, A. P. Maksimyak, P. P. Maksimyak, *On the feasibility for determining the amplitude zeroes in polychromatic fields*, Optics Express, **13**, *12*, 4396–4405 (2005).