Hidden polarization of unpolarized light

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(Received 29 May 2018; published 5 October 2018)

We consider polarization properties of the unpolarized emission of an ensemble of classical emitters with randomly varying polarization. The light is supposed to be unpolarized in the sense that all three polarization-related components of its Stokes vector are zero. At the same time, the mean-square values of these components should not be necessarily zero, may differ from each other, and, therefore, may provide additional information about properties of individual emitters. Experimentally, this information is revealed as dependence of the *polarization noise* on the azimuth of the quarter-wave plate placed before the polarization-sensitive detector. This dependence appears to be different for the emitters randomly polarized over the equator of the Poincaré sphere, or preferentially located on its poles, or uniformly covering the whole sphere. We show that full quantitative analysis of the polarization-noise anisotropy allows one, in the framework of the proposed model, to get information about polarization characteristics of individual emitters hidden in the emission of the ensemble. Vitality of the method is illustrated by its application to polarization analysis of the polariton laser emission, which is shown to predominantly arise from linearly polarized emitters.

DOI: 10.1103/PhysRevA.98.043810

I. INTRODUCTION

Polarization properties of light are often described in terms of the Stokes (Poincaré) vector that is capable of evaluating preferential polarization of the beam or absence of any preferential polarization. In the latter case (when all the polarization-related components of the Stokes vector are zero), the light is considered to be unpolarized. Such a light may be a result of averaging of the light-field polarization over time, over the spectrum, or in some other way, but the Stokes vector does not contain any information about these details. The problem of storing properties of individual emitters in the emission of their isotropic ensemble is not new. The first consistent analysis of statistical properties of resonant scattering (fluorescence) of random dipole emitters (perhaps overseen in due time) was performed in publications [1,2] which were adequately evaluated and reviewed only recently [3,4]. Publications [1,2] describe a method that allows one, by studying polarization characteristics of the light emitted by isotropic ensemble of scatterers, to determine the type of scatterer (linear, circular, or elliptical dipole). In [5], a version of synthesis of unpolarized light from phase-uncorrelated orthogonally polarized emitters was considered and hidden anisotropy of such an unpolarized light was analyzed. In recent years, a considerable interest has been drawn to the "anatomy" of the unpolarized or partially polarized beams [6–11],which makes it possible to disclose hidden anisotropy of the light field at high spectral or temporal resolution and to get a deeper insight into its polarization properties. A fascinating area of research where hidden polarization characteristics of unpolarized light are of fundamental interest is related to studying emission of the exciton-polariton laser. Intimate polarization properties of this emission, in the continuous mode of excitation, may provide unique information about the condensate dynamics [12].

In this paper, we propose a method of polarization analysis of a stationary light field created by an ensemble of classical emitters with polarizations randomly varying in time, so that the detected emission appears to be completely unpolarized. The light is assumed unpolarized by definition when all three polarization-related Stokes parameters of the beam vanish or, which is the same, when the length of its Poincaré vector turns into zero [14]. The proposed method is appropriate, e.g., for description of the polarization properties of an amplified spontaneous emission [7], or of a polariton laser [12], or of a superposition of many independent classical emitters. We show that the light that is unpolarized in the above sense and thus revealing no polarization anisotropy in the intensity measurements, can exhibit this anisotropy in its *polarization noise* after passing through a phase plate. Note that this fact may appear to contradict our intuitive feeling that unpolarized light after passing through a phase plate remains unpolarized as before and cannot be distinguished from the initial beam. This is really true if the description of the light polarization is restricted to its Stokes vector (or, better to say, to the mean values of the Stokes vector components), but it is not true if we consider mean-square values of these components. We show that dependence of the polarization noise power on the azimuth of the quarter-wave plate contains information about the polarization distribution of emitters over the Poincaré sphere.

The paper is organized as follows. In Sec. II, we formulate the problem and describe the experimental technique. In Sec. III, we derive a general equation for the output signal of the differential detector in the considered experimental arrangement. In Sec. IV, we describe the polarization noise of the light created by a single randomly polarized emitter and by an ensemble of such emitters for some particular cases of randomization of their Jones vectors. In Sec. V, we apply the proposed method to extract information on the polarization of individual emitters in the Bose-Einstein condensate of polaritons.

II. STARTING POINTS

Polarization measurements underlying the proposed experimental approach imply the use of the conventional polarimetric technique (Fig. 1). The polarization state of the beam is measured with a differential detection unit comprised of a polarization beamsplitter (4) and two photodetectors (5), with their photocurrent subtracted at the exit of the circuit. A quarter-wave plate (3) is placed in front of the beamsplitter, and the effect of its orientation on the detected polarization noise is studied. A specific feature of this situation is that the light beam incident upon the beamsplitter is supposed to be unpolarized, and no time-averaged output signal of the detector should be observed at any mutual orientation of the beamsplitter and phase plate. The detected polarization noise, however, does not necessarily vanish under balanced conditions and may vary with orientation of the phase plate. For definiteness, the axes of the laboratory coordinate system x and y are assumed to be horizontal and vertical, whereas polarizing directions of the beamsplitter are fixed at an angle of 45° with respect to x and y.

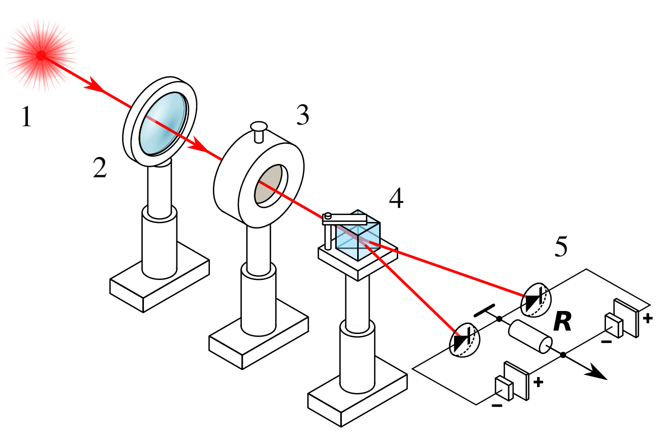

FIG. 1. Schematic of the measurement. 1 – light source, 2 – lens, 3 – quarter-wave plate, 4 – polarization beamsplitter, 5 – balanced photoreciever.

Note that the case of completely unpolarized light is chosen to simplify description of the measuring procedure and processing of the experimental data. Actually, the same approach, with some modifications, can be applied to the analysis of a partially polarized light.

We will assume that the detected light admits representation in the form of sum of contributions (rays), with each of them being polarized (in this case, the sum of these contributions may not have any definite polarization). Then, polarization state of each of the rays can be described by the Jones vector [13]

$$|E_0\rangle = \begin{pmatrix} \sin\alpha/2 \\ e^{\imath\beta}\cos\alpha/2 \end{pmatrix}, \tag{1}$$

representing the vector of electric field strength of the ray normalized to unity. At $\beta = 0$, the ray is polarized linearly and the angle α is equal to the azimuth of its linear polarization; at $\alpha = \pi/2$ and $\beta = \pi/2$, the ray is polarized circularly. In the general case, the angle α indicates the azimuth of the polarization plane of the ray, while β characterizes its ellipticity. As is known [14], polarization of the ray, in some cases, can be conveniently characterized also by the quasi-spin vector $\mathbf{L}$ (Poincaré vector), whose components can be calculated through the Jones vector of Eq. (1) as $L_i \equiv \langle E_0|S_i|E_0\rangle$, $i = x, y, z$, where S_i are the doubled Pauli matrices [15]

$$\mathbf{L} = \begin{pmatrix} \sin\alpha\cos\beta \\ \sin\alpha\sin\beta \\ \cos\alpha \end{pmatrix}. \tag{2}$$

Below, we will need the expression for the signal s arising at the exit of the polarization photodetector with the quarter-wave plate in front of it when it is illuminated by the ray of unit intensity with polarization corresponding to the Jones vector (1). Direct calculations show that

$$\begin{aligned} s = f(\alpha,\beta,\phi) &\equiv -\tfrac{1}{2}\{\cos\alpha\ \sin 4\phi \\ &\quad -2\sin\alpha\sin\beta\ \cos 2\phi\ +2\sin\alpha\ \cos\beta\ \sin^2 2\phi\} \\ &= -\tfrac{1}{2}\{L_z\ \sin 4\phi - 2L_y\ \cos 2\phi + 2L_x\ \sin^2 2\phi\}. \end{aligned} \tag{3}$$

Here, ϕ describes orientation of the quarter-wave plate in the laboratory coordinate system.

III. RANDOMIZATION OF THE STOKES VECTOR

A. Single fluctuating emitter

In what follows, we will consider behavior of the signal s when the Jones vector of the ray randomly varies in time so that the light on average appears to be unpolarized. One can easily see that this can be made in different ways.

It is clear, in particular, that if there is no preferential azimuth α and no preferential ellipticity β, and, in addition, there is no correlation between α and β, then $\langle\cos\alpha\rangle = \langle\sin\alpha\cos\beta\rangle = \langle\sin\alpha\sin\beta\rangle = 0$ ($\langle\mathbf{L}\rangle = 0$), and $\langle s\rangle = 0$. In other words, under these conditions, the light, in terms of the quasi-spin (Stokes) vector, appears to be unpolarized. This does not mean, however, that $\langle s^2\rangle = 0$, and it is not clear whether this quantity depends on ϕ or not. Moreover, the light unpolarized on average ($\langle s\rangle = 0$) can be obtained

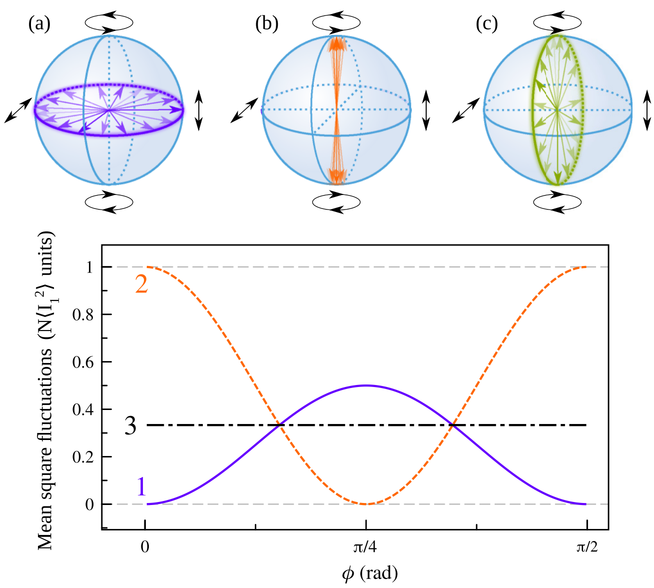

FIG. 2. Lower panel represents calculated dependences of the polarization noise $\langle \delta s^2\rangle$ on the angle ϕ for different models of ensembles of random emitters: curve 1 – linearly polarized emitters [illustrated by Poincaré sphere (a) of the upper panel], curve 2 – circularly polarized emitters [sphere (b)], and curve 3 – emitters uniformly distributed over the Poincaré sphere (not shown on the upper panel). Sphere (c) illustrates the case of emitters uniformly distributed over a meridian of the Poincaré sphere (discussed in the text).

from randomly varying polarizations with strong preference for certain Jones vectors. For instance, if the light beam is polarized linearly in a random way, i. e., $\beta = 0$, and α is distributed uniformly over the interval $[0, 2\pi]$, then, as can be easily shown,

$$\langle \delta s^2\rangle = \tfrac{1}{2}\sin^2 2\phi \quad \text{(random linear polarization)}. \qquad (4)$$

If the light is polarized circularly in a random way, then $\alpha = \pm\pi/2$, β acquires the values $\pm\pi/2$ with equal probability, and

$$\langle \delta s^2\rangle = \cos^2 2\phi \quad \text{(random circular polarization)}. \qquad (5)$$

Though ensembles of linear oscillators are encountered more frequently, the case of circular emitters is not unique either. A good example of circularly polarized emitters is provided by exciton-polariton condensates. In [16], in particular, the circular polarization of polariton emission has been controlled by the polarization of the pumping laser, while in [17], it has been built up spontaneously and was stochastically changing from right to left circular between different realizations of the condensate.

Arrangement of emitters over the Poincaré sphere, in the two above cases, is shown schematically in Figs. 2(a) and 2(b) [18]. Polarization of this light does not have any preferential direction, but these directions arise after the light is transmitted through the phase plate. As a result, polarization fluctuations of the light acquire orientational dependence described by Eqs. (4) and (5).

The expressions (4) and (5) can be easily understood in terms of the Poincaré vector. As seen from Eq. (3), our detecting system (polarization photodetector with the quarter-wave plate) can measure different components of the Poincaré vector depending on orientation ϕ of the quarter-wave plate. For example, if $\phi = 0$, the only Poincaré vector component of the incident beam that can be detected by the system is L_y. As is known, this component is associated with the degree of circular polarization. For this reason, it does not seem unexpected that the polarization noise produced by the ensemble of circular oscillators reveals the maximum at $\phi = 0$ [see Eq. (5)]. The same is valid for the case of linear emitters. The noise signal exhibits a maximum at $\phi = \pi/4$ when the only Poincaré vector component to which the system is sensitive is L_x, which describes the degree of linear polarization.

Another specific case of the unpolarized light can be realized by a randomly polarized emitter when the parameter α is fixed, while the random quantity β is distributed uniformly over the interval $[-\pi/2, \pi/2]$ [Fig. 2(c)]. In this case, the polarization state of the light is equivalent to that of the randomly linearly polarized light transmitted through the quarter-wave plate [see Eq. (4)]. In this case, the angular anisotropy of the polarization noise will be observed in the setup of Fig. 1 without any quarter-wave plate just by rotating the balanced detector around the beam axis (or by rotating a half-wave plate in front of the detector).

B. Ensemble of fluctuating emitters

In the above discussion, we have considered a single ray with a definite instantaneous polarization state. Consider now the model in which the detected light beam represents a set of such rays with random polarizations, so that the light beam on average appears to be unpolarized. This situation may occur when the detected light beam is created by N emitters, each having the intensity I_i and the polarization described by the Jones vector with the azimuth α_i and ellipticity $\beta_i (i = 1, \ldots, N)$. Such a model is used, for example, to describe polarization properties of some laser sources [7,11], for description of emission of the Bose-Einstein condensate of polaritons in semiconductor structures [12], and for some other cases of combined action of a multitude of classical emitters.

We will assume, for the beginning, that statistical properties of all the emitters are the same, with each emitter being unpolarized in the sense that $\langle f(\alpha_i, \beta_i, \phi)\rangle = 0$ [here $i = 1, 2, \ldots, N$, and the function $f(\alpha, \beta, \phi)$ is defined by Eq. (3)]. In this case, emission of the described ensemble of emitters appears to be, on average, unpolarized, while fluctuations of the polarization (polarization noise) may exhibit anisotropy and, thus, may contain information about the source of emission (e.g., about the spin state of the specific Bose-Einstein condensate of exciton-polaritons [19]).

The polarization noise can be observed using the above simple experimental setup (Fig. 1), with calibration of the observed polarization signal by the *intensity noise*. Let us calculate the values of both of the above noises (polarization and intensity). We introduce the following notation for the mean intensities of the emitters and their mean-square fluctuations $\langle I_i\rangle = \langle I_1\rangle$, $\langle I_i^2\rangle = \langle I_1^2\rangle$, and $\langle \delta I_i^2\rangle = \langle I_i^2\rangle - \langle I_i\rangle^2 = \langle I_1^2\rangle - \langle I_1\rangle^2 = \langle \delta I_1^2\rangle$. Then, the mean intensity of emission for the ensemble of N emitters $\langle I\rangle$ and its mean-square fluctuation

$\langle \delta I^2 \rangle$ are given by the equations

$$\langle I \rangle = N \langle I_1 \rangle, \quad \langle \delta I^2 \rangle = N\big[\big\langle I_1^2 \big\rangle - \langle I_1 \rangle^2\big]. \tag{6}$$

The quantities $\langle I \rangle$ and $\langle \delta I^2 \rangle$ can be measured experimentally and used to obtain mean values of $\langle I_1^2 \rangle$ and $\langle I_1 \rangle$:

$$\langle I_1 \rangle = \frac{\langle I \rangle}{N}, \quad \big\langle I_1^2 \big\rangle = \frac{\langle \delta I^2 \rangle}{N} + \frac{\langle I \rangle^2}{N^2}. \tag{7}$$

The signal s arising at the exit of the polarimetric detector with the quarter-wave plate, when it is illuminated by the light from N emitters, is given by

$$S = \sum_{i=1}^{N} I_i f(\alpha_i, \beta_i, \phi). \tag{8}$$

Since, in our case, emission of the ensemble of emitters is unpolarized, the mean value of the signal at the exit of the detector is zero $\langle S \rangle = 0$. Thus, the mean-square fluctuation of this signal is determined by the formula

$$\begin{aligned}\langle \delta S^2 \rangle &= \sum_{i,k=1}^{N} \langle I_i I_k \rangle \langle f(\alpha_i, \beta_i, \phi) f(\alpha_k, \beta_k, \phi) \rangle \\ &= N\big\langle I_1^2 \big\rangle \langle f^2(\alpha_1, \beta_1, \phi) \rangle \\ &= \left[\langle \delta I^2 \rangle + \frac{\langle I \rangle^2}{N} \right] \langle f^2(\alpha_1, \beta_1, \phi) \rangle. \end{aligned} \tag{9}$$

Here, for $\langle I_1^2 \rangle$, we use Eq. (7). We will use this formula to analyze some particular models of ensembles of randomly polarized emitters.

IV. SEVERAL PARTICULAR CASES

We will consider three models of the polarization-noise formation (already mentioned above) and will show that dependence of the mean-square fluctuations $\langle \delta S^2 \rangle$ on orientation of the quarter-wave plate ϕ appears to be, for these models, essentially different.

In the first model, the emission of each emitter is supposed to be linearly polarized [i.e., all the quantities $\beta_i (i = 1, \ldots, N)$ are zero], while the azimuth α_i of linear polarization of each emitter acquires with equal probability all values within the interval $[0, 2\pi]$ [see Fig. 2(a)]. By calculating the mean square $\langle f^2(\alpha, 0, \phi) \rangle$ [Eq. (3)], we come to the following expression for the value of the polarization noise $\langle \delta S^2 \rangle$:

$$\langle \delta S^2 \rangle_1 = \frac{N\big\langle I_1^2 \big\rangle}{2} \sin^2 2\phi. \tag{10}$$

In the second model, we assume that polarization of each emitter is circular, with its sign being random [see Fig. 2(b)]. In this case, $\alpha_i = \pi/4$, and $\beta_i = \pm\pi/2$, $i = 1, \ldots, N$, and the expression for the polarization noise $\langle \delta S^2 \rangle$ gains the form

$$\langle \delta S^2 \rangle_2 = N\big\langle I_1^2 \big\rangle \cos^2 2\phi. \tag{11}$$

These equations are, in fact, the dimensional presentations of Eqs. (4) and (5) with explicit values of the factors providing quantitative description of the polarization noise.

Finally, in the third model, we assume that the quasi-spin [Eq. (2)] describing polarization of each emitter is distributed uniformly over the Poincaré sphere. In this case

$$\langle S \rangle = \frac{1}{4\pi} \int_0^{\pi} d\alpha \sin\alpha \int_0^{2\pi} d\beta\, f(\alpha, \beta, \phi) = 0, \tag{12}$$

and the mean square of function (3) can be obtained from the formula

$$\langle f^2(\alpha, \beta, \phi) \rangle = \frac{1}{4\pi} \int_0^{\pi} d\alpha \sin\alpha \int_0^{2\pi} d\beta\, f^2(\alpha, \beta, \phi) = \frac{1}{3}. \tag{13}$$

Thus, for the third model, the mean-square variation of the polarization signal does not change with orientation of the quarter-wave plate (ϕ) and is equal to

$$\langle \delta S^2 \rangle_3 = \frac{N\big\langle I_1^2 \big\rangle}{3}. \tag{14}$$

The three above models of unpolarized light, as one can see, are characterized by the essentially different dependence of the noise polarization signal on orientation of the quarter-wave plate placed in front of the differential polarimetric detector (see Fig. 2, lower panel).

When the angular dependence of the polarization noise is measured, qualitative information on the polarization characteristics of individual emitters can be immediately obtained from the "phase" of this curve: for linearly polarized emitters and circularly polarized emitters the noise power will be the greatest when the axes of the phase plate, respectively, coincide with polarizing directions of the beamsplitter ($\phi = \pi/4 \pm \pi/2$) or rotated by $\pi/4$ with respect to them ($\phi = 0 \pm \pi/2$). As can be shown, this qualitative conclusion remains valid when polarizations of the emitters are *preferentially* polarized linearly or circularly.

This reasoning allows us to make an important conclusion about the informative potential of the proposed experimental approach. One can see that if the angular dependence of the polarization noise $\langle \delta S^2 \rangle$ for any particular system can be approximately described by one of the above models (or by their combination, see below), then, by measuring the mean intensity of this emission $\langle I \rangle$, its variance $\langle \delta I^2 \rangle$, and polarization fluctuations $\langle \delta S^2 \rangle$, and using Eqs. (6), (10), (11), and (14), one can find the model parameters $\langle I_1 \rangle$, $\langle I_1^2 \rangle$, and N that characterize completely the system within the adopted model.

V. EXPERIMENTAL ILLUSTRATION

To illustrate applicability of the proposed approach to real experimental measurements, we have chosen the most interesting and most convenient, for our purposes, source: a semiconductor-based exciton-polariton laser [20]. Emission of this source, in the cw mode of excitation, is often unpolarized but is characterized by strong intensity and polarization fluctuations (because of relatively small number of emitters) [12]. Polarization characteristics of the polariton Bose-Einstein condensate emission were studied in many papers [19,21–23], but these studies were mostly restricted to conditions of pulsed excitation. In the cw nonresonant optical pumping regime one could expect strong polarization fluctuations of the polariton laser emission on a timescale of hundreds of picoseconds or longer. These fluctuations are usually washed out in a time-integrated measurement. This makes polarization noise studies in the cw regime especially valuable.

The sample is an ultrahigh finesse $\frac{5}{2}\lambda$ $Al_{0.3}Ga_{0.7}As$ microcavity with a top (bottom) distributed Bragg mirror (DBR) comprising 45 (50) periods of $AlAs/Al_{0.15}Ga_{0.85}As$. Four sets of three $Al_{0.3}Ga_{0.7}As/GaAs$ (9/12 nm) quantum wells are positioned at antinodes of the light wave field. The structure was designed to form an exciton-polariton condensate at high pump power density levels and is characterized by a very high level of homogeneity. The sample was excited nonresonantly at the wavelength of 751 nm at an angle of $\sim 60^\circ$ to the microcavity surface. The secondary emission of the sample was separated from scattered pump light with a long-pass filter with 800 nm cutoff wavelength and was collected in the normal direction [Fig. 3(a)]. Pump-power dependence of the emission intensity clearly demonstrated the threshold-type behavior [Fig. 3(b)]. The operation point was chosen essentially above the polariton lasing threshold, as shown in the figure. The results presented below, however, were also checked at lower pump power ($\sim$50 mW) and turned out to be qualitatively the same.

The emission was found to be strongly unpolarized (the degree of polarization was below 1%). The results of the measurements made according to the above protocol have shown that, indeed, the quarter-wave plate before the detector did not bring any imbalance to the differential detector, while the detected polarization noise exhibited a strong dependence on the phase-plate orientation [see Fig. 3(c)]. This dependence provided us with several informative parameters.

Polarization noise exhibited a distinct sinusoidal dependence on the phase-plate orientation ϕ [Fig. 3(c)]. The phase of this dependence, which corresponded to maximal noise upon coincidence of the phase-plate axes with polarizing directions of the beamsplitter, indicated the predominant role of linearly polarized emitters in the studied light. This conclusion agrees well with the results of Ref. [24] where the predominantly linear polarization of polaritons in the condensate was explained in terms of the anisotropic spin-dependent polariton-polariton interactions. It is also important to note that no modulation of the polarization noise power was observed with the half-wave plate rotating in front of the detector. This showed that the sample did not reveal any noticeable intrinsic birefringence and no polarization pinning [21] thus confirming the highest quality of the sample.

As one can see from Fig. 3(c), angular dependence of the polarization noise appears to be not as pronounced as it should be for pure linearly polarized emitters (the noise signal does not vanish at $\phi = 0$). Taking into account the above evidence of absence of any intrinsic anisotropy in the sample, we suggest that the most likely reason for this discrepancy is that not all emitters are polarized linearly. In particular, this dependence may be a result of combined action of random linearly and circularly polarized emitters (with numbers N_1 and N_2, respectively). In this case, calculations of the polarization noise, similar to those performed above, lead to the expression

$$\langle \delta S^2 \rangle = \frac{\langle I_1^2 \rangle N_1}{2} \left[x + \frac{1}{2} + \left(x - \frac{1}{2} \right) \cos 4\phi \right], \tag{15}$$

where $x \equiv N_2/N_1$. By fitting the experimental angular dependence of the polarization noise [Fig. 3(c)] with this formula, we can find x. In our case, the ratio of the sinusoidal component of the angular dependence of the polarization noise A to the pedestal B [see Fig. 3(c)] is $A/B = [x - 1/2]/[x + 1/2] \approx -0.4 \Rightarrow x \approx 0.2$.

We do not analyze here another possible reason for the reduced amplitude of the experimental curve in Fig. 3(c), namely, random emitters with slightly elliptical polarization. At this stage of the research, we cannot distinguish between these two cases. Still, these simple measurements with cw excitation of the polariton emission allowed us to get reliable information about the predominant type of emitter in the polariton laser, in spite of the fact that the emission did not show any preferential polarization.

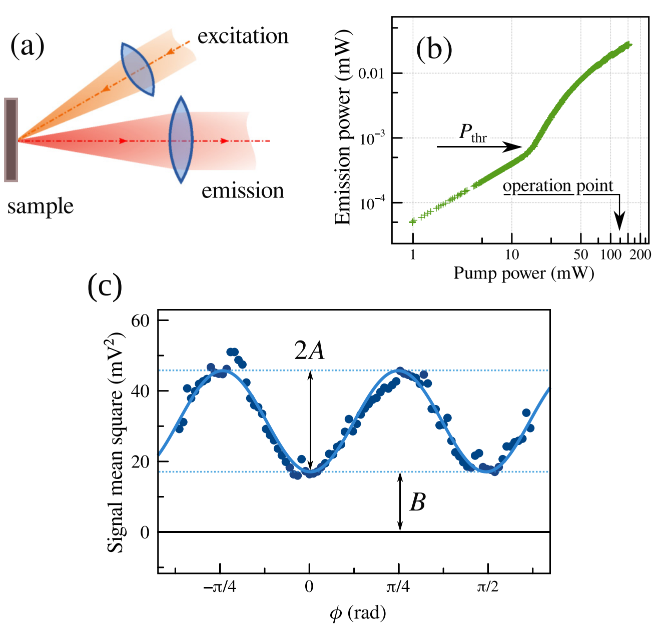

FIG. 3. Experimental illustration. (a) Geometry of the polariton emission excitation. (b) Polariton emission intensity versus pump power. (c) Experimental dependence of the polarization noise power versus the quarter-wave-plate orientation.

VI. CONCLUSIONS

In this paper, we analyze polarization characteristics of unpolarized light produced by an ensemble of randomly fluctuating classical emitters and show that by studying angular anisotropy of the polarization noise of this emission one can obtain information about the distribution of individual emitters over the Poincaré sphere. In the experimental arrangement considered here, this polarization anisotropy is revealed as dependence of the polarization noise power (polarization noise squared) on the azimuth of the quarter-wave plate placed in front of the polarization detector. Thus we can distinguish the cases of emitters arranged over the equator of the Poincaré sphere, over its near-pole regions, or over its meridian. In principle, this approach can be extended to the analysis of higher powers of the Stokes-vector noise that may contain, as we believe, additional information about the hidden anisotropy of the ensemble. Still, even in this simplest version, the proposed method, in our opinion, may be useful for analysis of emission of different ensembles of emitters.

ACKNOWLEDGMENTS

The authors are thankful to M. M. Glazov for useful discussions. Financial support from the Russian Foundation for Basic Research (RFBR) and Deutsche Forschungsgemeinschaft (DFG) in the framework of International Collaborative Research Center TRR 160 (Project No. 15-52-12013) and from RFBR Grant No. 17-02-01112 is acknowledged. The authors acknowledge financial support from Saint-Petersburg State University (Research Grant No. 11.34.2.2012). P.S. acknowledges bilateral Greece-Russia "Polisimulator" project co-financed by Greece and the EU Regional Development Fund. The work was carried out using the equipment of SPbU Resource Center "Nanophotonics" [25].

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