Optics of spin-noise-induced gyrotropy of an asymmetric microcavity

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The optical gyrotropy noise of a high-finesse semiconductor Bragg microcavity with an embedded quantum well (QW) is studied at different detunings of the photon mode with respect to the QW exciton resonances. A strong suppression of the noise magnitude for the photon mode frequencies lying above exciton resonances is found. We show that such a critical behavior of the observed optical noise power is specific to asymmetric Fabry-Perot resonators. As follows from our analysis, at a certain level of intracavity loss, the reflectivity of the asymmetric resonator vanishes, while the polarimetric sensitivity to the gyrotropy changes dramatically when moving across the critical point. The results of model calculations are in a good agreement with our experimental data on the spin noise in a single-quantum-well microcavity and are confirmed also by the spectra of the photoinduced Kerr rotation in the pump-probe experiments.

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I. INTRODUCTION

Optical resonators comprised of two plane-parallel mirrors (Fabry-Perot cavities) play an important role in many optical applications and are studied in great detail presently [1]. The growth of interest in this simple resonant system in the last decade is related to advances in technology of small-size optical resonators (microcavities) and the possibility to place structures with material resonances inside the cavity (quantum wells or quantum dots), whose interaction with the optical mode of the microcavity gives rise to a number of interesting optical effects [2].

The ability of the cavity to amplify various optical effects including the magneto-optical Faraday and Kerr rotation (see, e.g., Refs. [3–5]) is highly valuable for the spin-noise spectroscopy [6,7] gaining, in the last years, particular popularity as a method of nonperturbative study of magneto-spin properties of atomic and semiconductor systems [8–10]. In the experiments of this kind (one of which will be considered below), the above ability of the microcavity makes it possible to observe the spin-induced gyrotropy noise of a thin intermirror gap, whose detection without the microcavity would have been greatly hampered.

The microcavities currently used in experimental studies are, most frequently, made purposely asymmetric to compensate for the difference of reflectivities of the front and rear mirrors caused by difference of refractive indices of air and substrate and to make the resonant (nonresonant) reflectivity close to zero (to unit). It is highly important to pay special attention to unusual polarization properties of such microcavities in the presence of the intracavity absorption. In this paper, we study the dependence of the optical spin-noise (OSN) spectra [11,12] on the detuning of the microcavity photon mode with respect to the exciton resonance [13]. Our experiments show that a shift of the photon mode frequency below the exciton resonance leads to a sharp increase in the sensitivity of the polarization-dependent microcavity reflectivity to fluctuations of the gyrotropy, which cannot be simply ascribed to the finesse changes. The main result of our paper is that this critical behavior can be attributed to specific phase characteristics of the used asymmetric Bragg microcavity [14,15].

II. EXPERIMENT

In this study, we used the sample described in Refs. [13,16], representing an asymmetric λ microcavity (15 and 25 periods of GaAlAs/AlAs layers in the top and bottom mirrors, respectively) with a GaAs single QW (102/200/102 Å AlAs/GaAs/AlAs) in the center of the intermirror gap. In our experimental setup (Fig. 1), a monochromatic beam of tunable laser (i) transmitted through an attenuator and linear polarizer (ii), was focused by lens (iv) onto the sample (v) placed into a closed-cycle cryostat (vi) cooling the sample down to ~5 K. The beam reflected from the sample was directed to a polarimetric detector comprised of phase plate (ix), polarization beam splitter (Wollaston prism) (x), and broadband ($\delta\nu = 200$ MHz) balanced detector (xi).

The noise signal from the sample, as a rule, was observed in the presence of an additional illumination of the spot by a cw red light (photodoping) [13,16], created by a laser diode (viii) (~2 mW, λ ~630 nm). Fluctuations of spin polarization of the carriers photogenerated in the cavity gave rise to fluctuations of the reflected beam polarization and appearance of the noise signal at the output of the photodetector (11). A typical experiment on spin-noise spectroscopy [6,8–10] implies studying the radio-frequency (RF) spectrum of this signal as a function of the transverse magnetic field. This spectrum is detected using a spectrum analyzer and, in the simplest case, has a Lorentzian shape with its peak shifting linearly with magnetic field. Since the task of this paper was to study optical (rather than RF) noise spectrum, the experiments were performed using a new scheme of the measurements. The output of the balanced detector (xi) was fed not to a spectrum analyzer, but rather to a short-wavelength radio receiver (resonant amplifier with an output linear, rather than quadratic, detector) tuned to the frequency $\omega = 35$ MHz. With the aid of a sound oscillator, the illumination was modulated

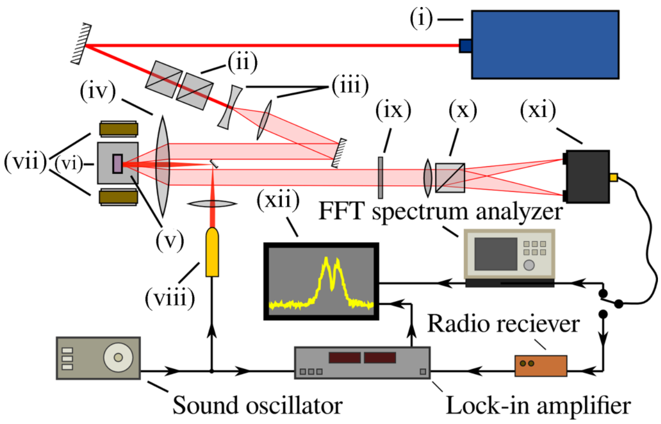

FIG. 1. (Color online) Schematic of the experimental setup.

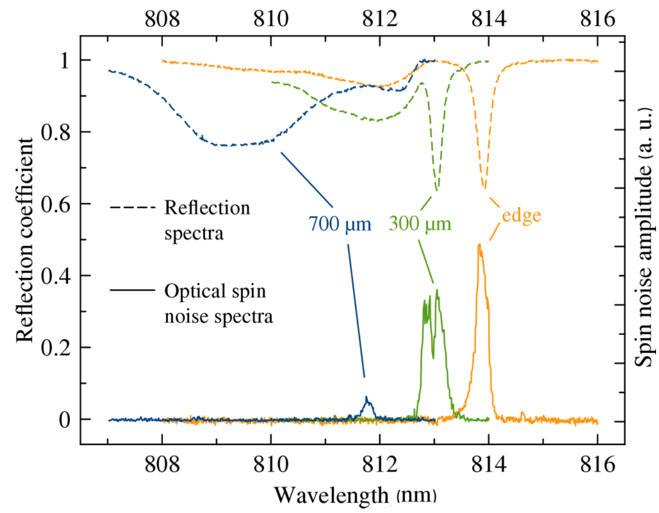

FIG. 2. (Color online) OSN spectra at different relative spectral position of the photon mode and exciton resonances of the QW (figures in μm indicate distance of the light spot from the edge of the sample). The photon mode frequency varies with position of the probe beam on the sample. Edge: the photon mode lies below the exciton resonance of the QW, and the OSN spectrum has a monomodal shape. In the vicinity of anticrossing of the polaritonic branches, the spectrum becomes bimodal (300 μm), then it decreases in amplitude (700 μm) and becomes unobservable at the photon mode frequency above the exciton resonances of the QW. The upper plots show the reflectivity spectra in corresponding points of the sample.

at the frequency $\Omega = 60$ Hz. This modulation produced synchronous modulation of the noise with corresponding periodic signal at the output of the radio receiver, with its amplitude proportional to that of the noise at the frequency 35 MHz. Note that, contrary to the experiments described in Ref. [13] in which the noise power P was studied, we here detect the noise amplitude A ($A \sim \sqrt{P}$). With the use of a lock-in amplifier (Fig. 1), we recorded the optical spin-noise (OSN) spectrum, i.e., dependence of the above noise signal versus the wavelength of tunable laser (i). The experiments were performed at zero magnetic field, because the noise amplitude at the frequency 35 MHz, in this case, was high enough for its detection (due to the large width of the spin-noise spectrum [13]). All OSN spectra have been normalized to the probe beam intensity.

Figure 2 shows the OSN spectra obtained using the above method at different detunings of the photon mode of the cavity and the exciton resonance of the QW. Due to the spatial gradient of the intermirror gap thickness, the photon mode frequency could be shifted by moving the light spot of the probe beam at the surface of the microcavity. The relationship between the spatial position of the probe x (in microns) and the photon mode spectral position λ_p (in nanometers) for our sample has the form: $\lambda_p = 814.5–0.0059x$. It is seen from the figure that the evolution of the OSN spectrum with the photon mode frequency demonstrates three distinct regimes: (i) For the photon mode frequencies lying below the exciton resonance (the region of negative detuning), the OSN spectrum has a shape of a narrow peak with its spectral position coincident with that of the photon mode. In the spectral region of the QW exciton resonances, which are already noticeable in the reflectivity spectrum as a broad short-wavelength shoulder (see Fig. 2, upper curves, edge), the OSN spectrum amplitude is vanishingly small. (ii) As the photon mode frequency approaches those of the exciton resonances, the amplitude of the OSN spectrum decreases, while its shape deviates from monomodal, with arising two (or three) peaks. Spectral position of the peaks is close to the position of the photon mode of the microcavity. In the spectral region of the QW heavy-hole exciton resonance at 812 nm, amplitude of the OSN spectrum remains small despite the fact that the broad short-wavelength shoulder corresponding to QW excitons, becomes stronger (Fig. 2, upper curves at 300 μm). (iii) When the photon mode frequency starts to exceed those of the exciton resonances (the region of positive detuning), the OSN spectrum amplitude falls down to unobservable level. The amplitude of the reflectivity spectrum for this region of the sample is about 30–50% lower than for the region with negative detuning. Note that the width of the photon resonance, in the reflectivity spectrum, for the region with a positive detuning is by a factor of 3–4 larger than for the region with a negative detuning (the reflectivity spectra of different regions of the sample are given in Ref. [13]). Bearing this in mind, one should expect the same relative decrease (i.e., by a factor of 3–4) of the noise signal due to decreasing optical lifetime of the probe in the cavity. Recall that we observe the noise amplitude (rather than noise power), which should be proportional to the cavity Q factor. Therefore, the sharp decrease of the OSN amplitude when passing from negative to positive detuning, pointed out in item (iii) is inconsistent with the decrease of the microcavity finesse and looks surprising. The main goal of this paper is to interpret this unusual behavior of the Kerr-rotation noise.

III. DISCUSSION

Consider first, in more detail, the regime our cavity is operating in. As it has been found earlier [16], at low intensity of the probe, our cavity is operating in a strong coupling regime. The specificity of our experiment is that it requires tight focusing of the probe [13]. Under such conditions, bleaching of the exciton-related part of the QW susceptibility leads to a considerable modification of the reflectivity spectrum [13] removing the exciton-related spectral features and making anticrossing of the polariton branches less pronounced. At the same time, contribution to the QW optical susceptibility related to generation of uncoupled electron-hole pairs is not affected so much by the probe. This part of susceptibility manifests itself in the stepwise increase of the nonresonant absorption at the wavelengths shorter than the exciton resonance: the photon-mode-related dip of the cavity reflectivity in this spectral region appears to be, as was already mentioned, 3–4 times wider than that at the wavelengths well above the exciton resonance.

Since the OSN spectra exhibit no noticeable features in the exciton spectral region, in what follows we assume that the main role in formation of the OSN spectra is played by fluctuations of gyrotropy of the intermirror gap as a whole, rather than only of the QW layer. So, the role of the QW in formation of the OSN spectra is reduced to a decrease of the cavity Q factor at positive detunings. Since the transparent material of the intermirror gap ($Al_{0.1}Ga_{0.9}As$), whose spin fluctuations are assumed to play the main role in formation of the OSN spectrum, does not have any sharp spectral features in the considered wavelength range, we may neglect, in our qualitative treatment, spectral dependence of the gyrotropy δg responsible for the observed noise signal. Qualitative agreement of the model calculations (presented in the next section) with the experimental data are evidence in favor of all above assumptions.

Formation of the polarimetric signal detected in our experiment can be presented in the following way. The linearly polarized beam incident upon the sample is a superposition of two circularly polarized components σ_+ and $\sigma_-$of equal magnitudes. In the presence of gyrotropy in the microcavity, positions of resonant features of its reflectivity spectrum for the σ_+ and σ_- components of the incident light appear to be shifted with respect to each other by the quantity proportional to this gyrotropy. Thus, at $\delta g \neq 0$, the σ_+ and σ_- components of the incident beam will experience, upon reflection, different phase shifts and different amplitude changes. The former corresponds to polarization plane rotation of the reflected beam, while the latter manifests the appearance of its ellipticity. Both types of the polarization changes in the reflected beam can be detected independently. In particular, if the phase plate (ix in Fig. 1) is half-wave (quarter-wave) and is oriented by its axis at the angle $\pi/8$ ($\pi/4$) with respect to the vertical, the output signal of the balanced detector (xi in Fig. 1) will be proportional to the polarization plane rotation angle (ellipticity) of the reflected beam. Note that, at a fixed frequency shift of the phase characteristics of reflectivity for the σ_+ and σ_- components of the incident light, the changes in the reflected beam polarization will increase with increasing steepness of the frequency dependence of these characteristics. Thus, for interpretation of the above experiment, we have to analyze the behavior of the complex reflection coefficient of the microcavity with the variation of optical parameters of the cavity. This kind of analysis has been performed for interpretation of a number of other experiments (see, e.g., Refs. [4,5,14]) and for development of interferometric devices with specific dispersion characteristics [17,18]. The analysis presented below is aimed at interpretation of our particular spin-noise-related experiment.

As we have already mentioned, a specific feature of the microcavity used in our experiment is its asymmetry. The complex reflection coefficient of such a microcavity reveals a specific critical behavior, which can be qualitatively explained as follows.

Consider an ultimately asymmetric cavity, with its bottom mirror having reflectivity exactly equal to unity, while reflectivity of the top mirror is slightly smaller. If the absorption in the intermirror gap and top mirror is absent, then the reflectivity module of such a cavity is unity at any frequency of the incident light. As can be shown by direct calculations, the phase of the reflection coefficient is zero (2π) at frequencies much lower (higher) than the resonant one, and it rapidly changes from zero to 2π in the vicinity of the resonance whose spectral width is controlled by the cavity finesse, which, in turn, depends on the top mirror reflectivity. Thus, upon variation of the incident light frequency, the complex reflection coefficient can be represented by a vector that circumvents a full circle moving over it counterclockwise from the real unity [Fig. 3(a)].

Let us now assume that the cavity is filled by an absorbing material. In this case, at the frequencies far from the resonance, the reflectivity of the cavity will be controlled by reflectivity of the top mirror and, since we assume this mirror to be highly reflecting, will be, as before, close to unity. In the region of the resonance, the reflectivity will reveal a small

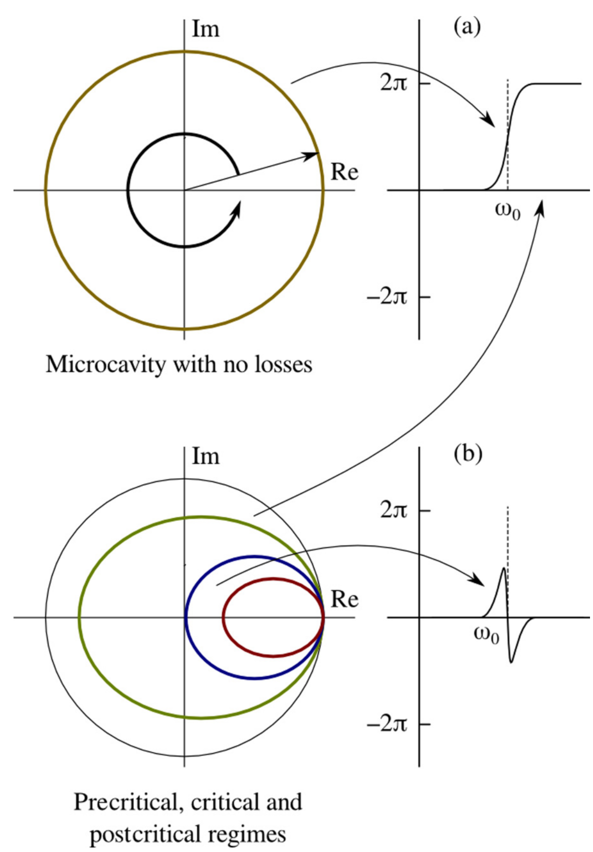

FIG. 3. (Color online) Dynamics of the complex reflectivity vector of the asymmetric cavity upon passing through the resonance. (a) Ideal (ultimate) asymmetric cavity; (b) asymmetric cavity at different absorption in the intermirror gap. The right plots show phase of the cavity reflection coefficient in the precritical and postcritical regime.

dip connected with absorption in the intermirror gap. As a result, dynamics of the complex reflection coefficient, upon passing the resonance, will differ from that for the above ultimate cavity: the corresponding complex vector will now circumvent a certain oval lying inside the above unity circle [Fig. 3(b)]. If the absorption in the cavity is not high, this oval will not much differ from the unity circle, and the increment of the phase of the reflection coefficient, upon passing through the resonance, as before, will be equal to 2π. With further growth of the absorption, the oval will contract to the point of real unity, because, even at very high absorption in the cavity, the reflectivity far away from the resonance will be determined by the top highly reflecting mirror. It follows that, at some critical value of the absorption, the oval will pass through the coordinate origin and will appear to be entirely at the right side of this point [Fig. 3(b)]. It is seen from Fig. 3(b) that, after that, the total increment of the phase of the reflection coefficient, upon passing through the resonance, turns into zero. This means that the phase, which changes monotonically in the precritical regime from 0 to 2π (Fig. 3, right plot), will experience, in the postcritical regime, a relatively small ($<\pi/2$) sign-alternating change [Fig. 3(b), right plot].

As was already noted, the gyrotropy of the intermirror gap gives rise to mutual shift of the phase of the reflection coefficients for the σ_+ and σ_- components of the incident light, with the magnitude of the polarimetric signal being higher for steeper phase characteristics. Since the phase of the reflection coefficient of the precritical cavity [Fig. 3(a)] is much steeper than of the postcritical one [Fig. 3(b)], one can expect that the polarimetric signal of the precritical cavity will be much larger than that of the postcritical one. Besides, the transition of the cavity through the critical point should be accompanied by a change of optical spectrum of the polarimetric signal, because this spectrum (at least, qualitatively) is controlled by the frequency derivative of the phase of the reflection coefficient. In the precritical regime, the phase is monotonic, which leads to the monomodal shape of the optical spectrum of the polarimetric signal. In the postcritical regime, the nonmonotonic dependence of the phase over the detuning should result in the sign-alternating shape of spectrum of the polarimetric signal.

The property of the asymmetric cavity described above seems to be important for the following reasons. First, the Bragg microcavity used in our experiments is essentially asymmetric (15 periods in the top mirror and 25 periods in the bottom one), and the above reasoning is applicable to it. Second, when the spectral position of the photon mode moves towards shorter wavelengths, absorption in the microcavity increases: this is confirmed by more than threefold broadening of the photon-mode-related line in the reflectivity spectrum. And, finally, third, the observed evolution of the optical spectra of Kerr rotation from monomodal to sign alternating (Fig. 4) also correlates with passing of the used asymmetric microcavity through the critical point.

For all the above reasons, the sharp fall in the OSN amplitude observed in our experiment can be attributed to passing through the above critical point of the microcavity. The direct model calculations described in the next section support this supposition.

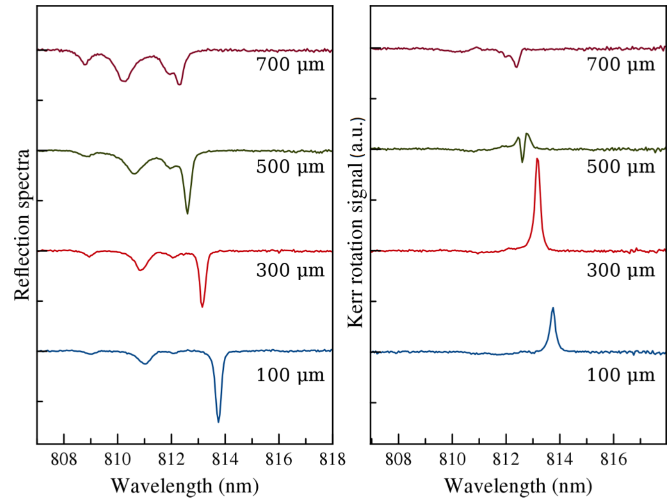

FIG. 4. (Color online) Right: evolution of shape of the Kerr rotation spectra upon shifting of the photon mode of the cavity towards shorter wavelengths. The measurements were performed in the pump-probe configuration. The gyrotropy of the sample was induced by a high-power pulse of circularly polarized light and was detected by a weak probe light, whose Kerr rotation was measured as a function of its wavelength. The figure shows the results of the measurements for different points on the sample: from point 100 μm to point 700 μm, position of the photon mode shifts towards shorter wavelengths. Left: the corresponding reflection spectra.

IV. MODEL CALCULATIONS

Since the angle of incidence of the laser beam, in our experiments, was small ($\sim 5^\circ$), we will assume the incidence to be normal, in the model. Let us denote by r the complex reflection coefficient of the microcavity in the absence of gyrotropy in the intermirror gap. With appearance of the gyrotropy, the reflection coefficients $r_\pm$ for the $\sigma_\pm$ polarizations become different, and $r_\pm = r \pm \delta r$. The calculations show that if the beam incident on the microcavity is polarized vertically, the output signal S of the balanced detector (ix in Fig. 1) is given by the relationship

$$\begin{aligned} S = {} & 2|r|^2[\cos^2 2\phi + \cos\delta \sin^2 2\phi] \\ & + 2\sin[4\phi]\mathrm{Im}[\delta r r^*][1-\cos\delta] \\ & + 4\mathrm{Re}[\delta r r^*]\ \sin\delta\ \sin[2\phi], \end{aligned} \tag{1}$$

where δ is the phase shift introduced by plate (ix in Fig. 1) and ϕ is the angle of tilt of its axis with respect to the vertical. By choosing the angle ϕ, the contribution to the signal independent of δr [first line in Eq. (1)] can be vanished. For detecting fluctuations of the Kerr rotation (ellipticity) of the reflected beam, the phase plate (ix in Fig. 1) is chosen half-wave (quarter-wave). In this case, the detected signal can be presented in the form $S = 4\ \mathrm{Im}\ [\delta r r^*]$ ($S = 4\ \mathrm{Re}\ [\delta r r^*]$).

Calculation of the OSN spectrum was started from calculation of the reflection coefficient r entering into (1) and was performed using the standard transfer matrix technique [1], with the QW susceptibility $\varepsilon(\omega)$ taken in the model of independent electron-hole pairs:

$$\varepsilon(\omega) = \varepsilon_b + C\ln(\omega_0 - \omega + \imath\gamma), \tag{2}$$

where $\omega_0 = 1.516$ eV is the lowest frequency of transition between the two-dimensional (2D) electron and hole subbands of the QW, $\gamma = 0.001$ eV is the damping constant, and ω is the optical frequency. The parameters $\varepsilon_b = 34$ and $C = 3$ were chosen to obtain a qualitative agreement between the experimental and calculated reflectivity spectra. Susceptibility of a real QW contains along with (2), a resonant excitonic (or trionic) pole-type contribution: $\omega_1/[\omega_{ex} - \omega + \imath\delta]$. All parameters entering this expression (ω_{ex}, exciton/trion resonant frequency; ω_1 and δ, the amplitude and damping factor) may be spin dependent and may reveal noise modulation. However, the effect of this contribution, at large positive and negative detunings, is small, and its inclusion, as the calculations show, does not change qualitatively the OSN spectrum.

At the next step, the permittivity of the intermirror gap ε was provided with a small increment $\varepsilon \to \varepsilon + \delta\varepsilon$ ($\delta\varepsilon/\varepsilon \ll 1$) corresponding to noise fluctuation of the gyrotropy δg, and the corresponding change of the reflection coefficient δr was calculated. After that, the OSN spectrum of the Kerr rotation (ellipticity) was calculated using Eq. (1) at $\phi = \pi/8, \delta = \pi$ ($\phi = \pi/4, \delta = \pi/2$) in the range of the optical frequencies $\omega/\omega_0 \in [0.98, 1.02]$. The results of the calculations are given in Fig. 5, which shows a family of the phases of reflection coefficients [Fig. 5(a)], the OSN spectra of the Kerr rotation [Fig. 5(b)], and the reflectivity spectra [Fig. 5(c)] at different frequencies of the photon mode. The photon mode was shifted by changing the cavity width within the range of 6%. It is seen from Fig. 5 that, at the frequency of the photon mode below ω_0, the resonant absorption of the microcavity is small, and it lies in the precritical regime. This is indicated by monotonic behavior of the phase [Fig. 5(a)] varying within the interval from 0 to 2π. In this case, the OSN spectra have a monomodal shape and large amplitude [Fig. 5(b)]. As the frequency of the photon mode approaches ω_0, the absorption in the microcavity increases, the cavity passes through the critical point, and the phase of the reflection coefficient becomes sign alternating [Fig. 5(a)]. It is also seen from Fig. 5(b), that the shape of the OSN spectrum becomes, in this case, bimodal, and its amplitude decreases. After passing through the critical point, the reflectivity spectrum broadens by a factor of 3–4 and slightly drops in amplitude, while the amplitude of the noise spectrum decreases dramatically. Thus, the evolution of the calculated OSN spectra is characterized by three regimes listed in the end of Sec. II. Qualitative agreement between the behavior of the calculated and experimental OSN spectra confirms the validity of our model.

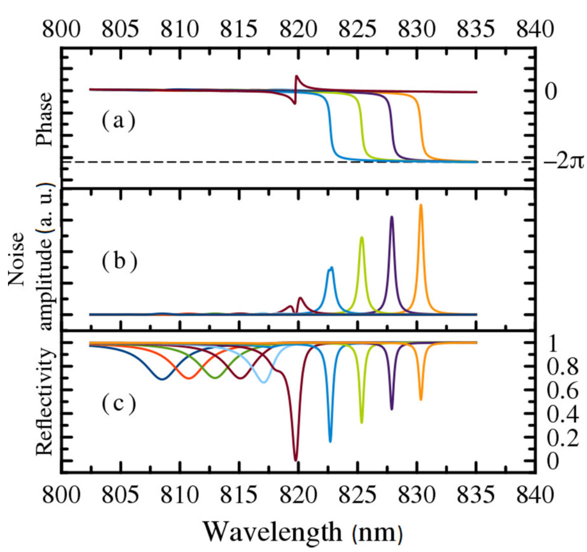

FIG. 5. (Color online) The calculated (a) phase of the reflection coefficient, (b) OSN spectra, and (c) reflectivity spectra of the asymmetric microcavity with QW at different spectral position of the photon mode. The QW permittivity was taken in the form $\varepsilon(\omega) = \varepsilon_b + C\ln(\omega_0 - \omega + \imath\gamma)$, with spectral position ω_0 corresponding to the center of the shown spectral range.

In the above treatment, we did not take into account the possible spectral dependence of the magneto-optical susceptibility connecting the magnetization and the optical gyrotropy. The detailed discussion of this dependence is out of the scope of our paper, and we restrict ourselves to a short comment. The strong spectral dependence of the magneto-optical susceptibility is usually observed in the region of strong spectral dependence of the optical susceptibility. In our case, there are no strong singularities in optical susceptibility of the intracavity medium at positive (negative) detuning. For this reason, we assume that spectral dependence of the magneto-optical susceptibility is not strong enough to be responsible for reduction of the OSN signal down to unobservable level at positive detuning. Moreover, the magneto-optical susceptibility of the intracavity $Al_{0.1}Ga_{0.9}As$ (which, is assumed to be the main source of the noise signal) increases (not much [19]) at shorter wavelengths close to the band gap of $Al_{0.1}Ga_{0.9}As$. It should have caused rather an increase of the OSN signal in the spectral region of positive detuning, where we observe no OSN signal at all. For all these reasons, we believe that spectral dependence of the magneto-optical susceptibility is not of essential importance for the observed effect and may be neglected in our treatment.

V. CONCLUSIONS

We have studied the behavior of the Kerr rotation noise spectrum of light reflected from an asymmetric Bragg λ microcavity with an embedded GaAs quantum well for different detunings between the photon mode and exciton resonances. The Kerr rotation noise has been found to exhibit an unusual critical dependence on the detuning. At negative detunings, the OSN spectrum shows a relatively high amplitude and monomodal shape. When passing to positive detuning, the shape of the spectrum is getting more complicated, and the amplitude of the signal sharply drops. The effect is explained by the fact that the phase of the reflection coefficient of the used asymmetric cavity, when passing to positive detuning, shows a critical change of its steepness. The results of this paper show that the cavity enhancement of the Kerr (or Faraday) rotation in an asymmetric microcavity may strongly depend on its phase characteristic. This critical dependence of conversion of intracavity gyrotropy to the polarization-plane rotation may be highly important for experimental studies of spin noise and other effects of cavity-enhanced optical anisotropy.

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