Resonant Faraday rotation in a semiconductor microcavity

A. V. Kavokin, M. R. Vladimirova, and M. A. Kaliteevski
A.F. Ioffe Physico-Technical Institute, 26 Politechnicheskaya, St. Petersburg, Russia

O. Lyngnes, J. D. Berger, H. M. Gibbs, and G. Khitrova
Optical Sciences Center, University of Arizona, Tucson, Arizona 85721

(Received 30 December 1996; revised manuscript received 6 March 1997)

Faraday rotation at quantum well exciton resonances is enhanced in a microcavity due to multiple round-trips of light between the mirrors when the cavity mode is strongly coupled to the exciton and is accompanied by resonant redistribution of the signal between right- and left-circular polarization. A resonant Faraday rotation of about 3° is detected in reflected light from an (In,Ga)As/GaAs quantum well microcavity in an 11.25 T magnetic field when the cavity mode is resonant with either heavy- or light-hole excitons. [S0163-1829(97)04028-9]

Although initial works on the magneto-optics of normal mode coupling in semiconductor microcavities have appeared very recently, a number of striking effects have already been found including magnetic field induced vacuum Rabi splitting, normal mode coupling to magnetoexcitons with high Landau indices, and an increase of the cavity-polariton splitting with magnetic field.[1–4] Here we present an experimental and theoretical study of the magnetic field effect on the polarization of light propagating in a semiconductor microcavity.

It is well known that the electric field vector of a linearly polarized light wave experiences a rotation when propagating through a semiconductor in the presence of a magnetic field (Faraday rotation). In the vicinity of an exciton resonance this effect has a resonant character that is governed by the exciton g factor and oscillator strength. The resonant Faraday rotation in transmission has been studied recently for semimagnetic quantum well (QW) systems, where excitons have giant g factors due to their exchange interaction with magnetic ions.[5] Detected rotation angles were on the order of tenths of degrees for a double-QW system, and are expected to be much smaller in similar nonmagnetic QW's.

This work is aimed at studying the magnetic field effect on the polarization of light reflected from a microcavity tuned onto resonance with an exciton transition of embedded quantum wells. The Faraday rotation of the light propagating in the microcavity is enhanced by multiple round trips during the lifetime of the exciton-polariton mode.

Consider reflection of linearly polarized light from some planar structure at normal incidence. Let the incident light be polarized along the x axis, so that it can be represented as

$$\begin{pmatrix}1\\0\end{pmatrix}=\frac{1}{2}\begin{pmatrix}1\\i\end{pmatrix}+\frac{1}{2}\begin{pmatrix}1\\-i\end{pmatrix}, \tag{1}$$

where upper and lower components of the vectors correspond to the electric field projections in the x and y directions, respectively, and the two terms in the right part describe σ^+ and σ^- polarized waves, respectively.

If the structure is placed in a magnetic field, the reflection coefficients for σ^+ and σ^- polarized waves can be different, so that the reflected light can be represented as

$$\hat{I}=\frac{1}{2}A\ \exp(i\varphi_+)\begin{pmatrix}1\\i\end{pmatrix}+\frac{1}{2}B\ \exp(i\varphi_-)\begin{pmatrix}1\\-i\end{pmatrix}, \tag{2}$$

where amplitudes A and B and phases φ_+ and φ_- coincide in the absence of the field but may be different in the presence of the field. $\hat{I}$ is elliptically polarized light, which can be conveniently represented as a sum of waves linearly polarized along the main axes of the ellipse:

$$\hat{I}=\frac{i}{2}(B-A)\exp(i\psi)\begin{pmatrix}\sin(\phi)\\-\cos(\phi)\end{pmatrix}+\frac{1}{2}(A+B)\exp(i\psi)\times\begin{pmatrix}\cos(\phi)\\\sin(\phi)\end{pmatrix}, \tag{3}$$

where $\psi=(\varphi_+ + \varphi_-)/2$ and $\phi=(\varphi_- - \varphi_+)/2$ is the *Faraday rotation* angle. The reflection coefficient of the structure for light detected in x polarization is

$$R_\parallel=\frac{1}{4}|A\ \exp(i\varphi_+)+B\ \exp(i\varphi_-)|^2; \tag{4}$$

the reflection coefficient for light detected in y polarization (cross polarization) is

$$R_\perp=\frac{1}{4}|A\ \exp(i\varphi_+)-B\ \exp(i\varphi_-)|^2. \tag{5}$$

$R_\parallel$ and $R_\perp$ are connected with the amplitude reflection coefficients in right- and left-circular polarizations r_+ and r_-, respectively, by the simple relations

$$R_\parallel=\frac{1}{4}|r_+ + r_-|^2, \quad R_\perp=\frac{1}{4}|r_+ - r_-|^2. \tag{6}$$

The Faraday rotation angle can be found as

$$\phi=(\arg r_- - \arg r_+)/2. \tag{7}$$

0163-1829/97/56(3)/1087(4)/$10.00

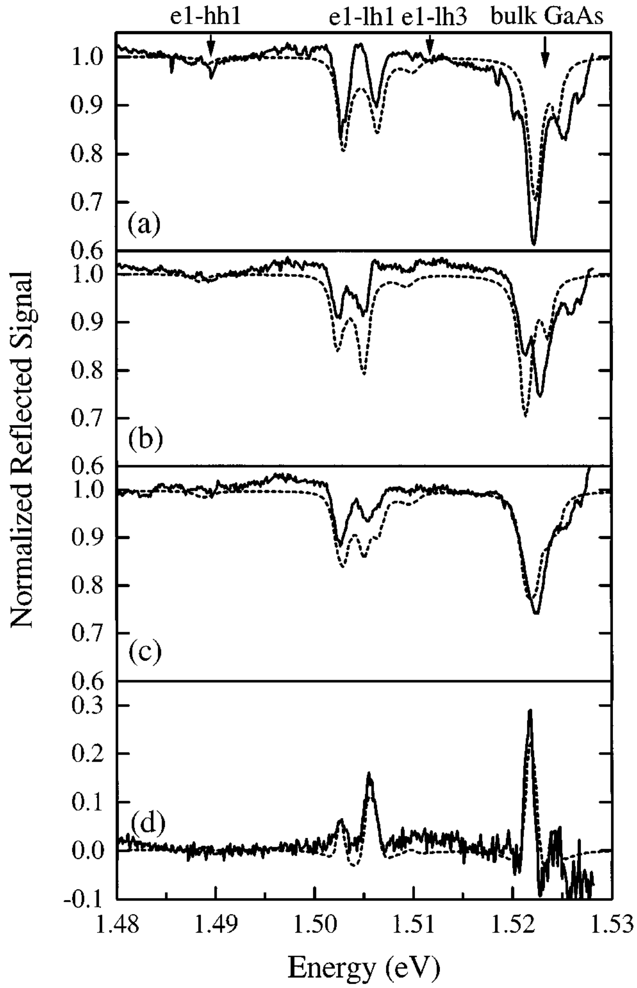

FIG. 1. Measured (solid) and calculated (dashed) microcavity spectra in an 11.25 T magnetic field when the cavity mode is tuned to the $e1$-lh1 exciton resonance and (a) probed and detected in reflection geometry in σ^- polarization, (b) probed and detected with σ^+ polarization, (c) probed with linear polarization and detected in reflection geometry in the same polarization, and (d) probed with linear polarization and detected in the linear polarization perpendicular to the incident polarization.

Before presenting the experimental results let us analyze expected effects in the framework of simplified ''ray optics.'' Consider a cavity-polariton mode as a ray of light going forward and backward inside the cavity within its lifetime. In the nonpertubative regime the lifetime of cavity polaritons τ is

$$\tau=\frac{2}{(\gamma+\kappa)}, \tag{8}$$

where κ is the cavity decay rate dependent on the reflectivity of Bragg mirrors and γ is the exciton spontaneous emission rate.[6] The number of round trips of light inside the cavity is

$$N=\frac{\tau c}{2n_c L_c}, \tag{9}$$

where n_c is the cavity refractive index and L_c is its length. In the microcavity which we have studied $N\approx 70$ (for a complete set of parameters see Ref. 3).

TABLE I. QW exciton parameters in an 11.25 T magnetic field used in the calculations.

Exciton state	$\hbar\omega_0^+$ (eV)	$\hbar\omega_0^-$ (eV)	$\hbar\Gamma_0$ (μeV)	$\hbar\Gamma$ (meV)
$e1$-hh1	1.4891	1.4897	50	0.35
$e1$-lh1	1.5035	1.5048	σ_+ :14	0.5
			σ_- :18	
$e1$-lh3	1.5093	1.512	17	0.5
bulk exciton	1.5212	1.5222	$\hbar\omega_{LT}$=0.1 meV	0.6

The Faraday rotation angle for the cavity-polariton mode in this model is

$$\phi\approx 2N\phi_{\rm QW}, \tag{10}$$

where $\phi_{\rm QW}$ is the rotation angle in transmission through the QW. Using the formalism of a nonlocal dielectric response theory,[7,8] one can obtain

$$\begin{aligned}\phi_{\rm QW}&=\frac{1}{2}\left[\arctan\frac{(\omega_0^- -\omega)\Gamma_0}{(\omega_0^- -\omega)^2+(\Gamma+\Gamma_0)^2}\right.\\&\left.\quad-\arctan\frac{(\omega_0^+ -\omega)\Gamma_0}{(\omega_0^+ -\omega)^2+(\Gamma+\Gamma_0)^2}\right]\\&\approx\frac{(\omega_0^- -\omega_0^+)\Gamma_0}{(\Gamma+\Gamma_0)^2},\end{aligned} \tag{11}$$

where ω_0^+ and ω_0^- are the QW exciton resonance frequencies in σ^+ and σ^- polarizations, respectively.

For a Zeeman splitting of about 1 meV, one obtains from Eq. (10) a rotation angle of the cavity-polariton mode polarization of about π. This giant rotation angle however is not directly related to the rotation angles which may be measured in the reflection or transmission spectra of the cavities. The signal detected in reflection is a result of interference of an infinite number of plane waves circulating between mirrors. The first of them, which has the highest amplitude is reflected by the top mirror of the structure so that its polarization plane is not rotated at all. For the second wave the rotation angle is $2\phi_{\rm QW}$, for the nth wave the angle is $2\phi_{\rm QW}(n-1)$. Only the $(N+1)$th wave experiences the full rotation of Eq. (10), however its contribution to the spectrum is very weak. The rotation is larger in transmission since the first wave has propagated through the QW.

To obtain an analytical estimate of the rotation angle in reflection let us neglect waves reflected by the QW and only take into account multiple reflections between the two mirrors. After summation of all reflected waves one can write the total amplitude reflection coefficient in the polarization parallel and orthogonal to the polarization of the incident light as

$$r_\parallel=r_1+\sum_{n=1}^{\infty}\eta\nu^{N-1}\cos(2n\phi_{\rm QW})$$

and

$$r_\perp=\sum_{n=1}^{\infty}\eta\nu^{N-1}\sin(2n\phi_{\rm QW}), \tag{12}$$

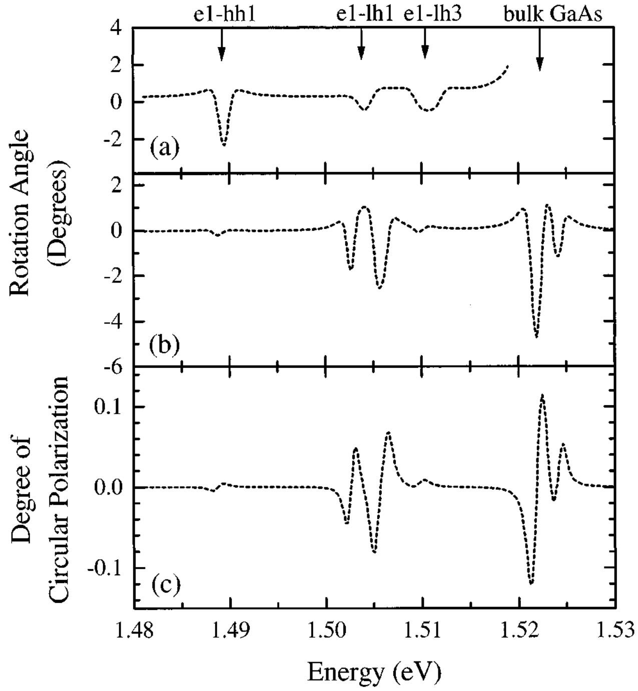

FIG. 2. (a) Faraday rotation angle in transmission through the central cavity layer. (b) Calculated Faraday rotation angle and (c) degree of circular polarization for the reflected light from the microcavity when the cavity mode is tuned to the $e1$-lh1 exciton resonance.

respectively, where $\eta \equiv t_1 \tilde{t}_1 r_2 \exp(2i\varphi)$, and t_1, $\tilde{t}_1$ are the transmission coefficients of the first mirror from left to right and from right to left, respectively, r_2 is the reflection coefficient of the second mirror, φ is the phase gained by light between the two mirrors, $\nu = \tilde{r}_1 r_2 \exp(2i\varphi)$, and $\tilde{r}_1$ is the reflection coefficient of the first mirror for light going from the inside. One can express the rotation angle via coefficients $r_\parallel, r_\perp$ as

$$\phi = \frac{1}{2}[\arg(r_\parallel + i r_\perp) - \arg(r_\parallel - i r_\perp)]$$

$$= \frac{1}{2}\left\{ \arg\left[r_1 + \frac{\eta \exp(-2i\phi_{\mathrm{QW}})}{1-\nu \exp(-2i\phi_{\mathrm{QW}})} \right] - \arg\left[r_1 + \frac{\eta \exp(2i\phi_{\mathrm{QW}})}{1-\nu \exp(2i\phi_{\mathrm{QW}})} \right] \right\}. \quad (13)$$

For a reasonable set of parameters Eq. (3) yields a rotation angle of a few degrees, i.e., two orders of magnitude less than the rotation angle of the net cavity polariton.

Due to the redistribution of the intensity between left and right circularly polarized components of light, the reflected wave is elliptically polarized giving rise to magnetic circular dichroism (MCD). Just as optical absorption and the index of refraction are intimately connected at an optical resonance, MCD and Faraday rotation are also connected. MCD is proportional to the difference in amplitude for the two circular polarizations while Faraday rotation is proportional to the phase difference.[9,10] The reflected polarization is only purely rotated for wavelengths where the amplitudes of the reflected circular polarization components are equal.

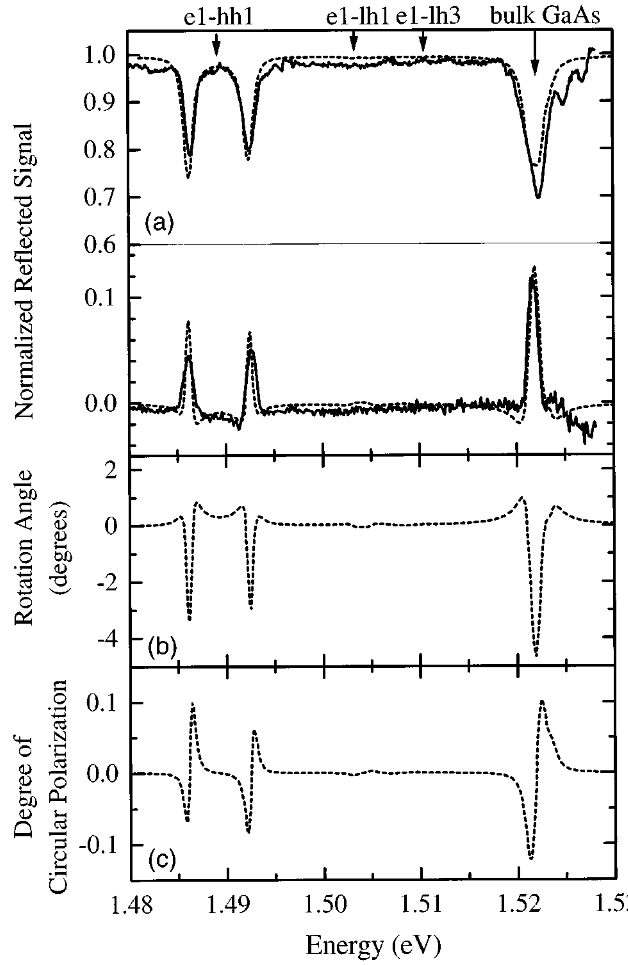

FIG. 3. (a) Measured (solid) and calculated (dashed) microcavity spectra in an 11.25 T magnetic field when the cavity mode is tuned to the $e1$-hh1 exciton resonance and probed with linearly polarized light and detected in reflection geometry in the polarization parallel (top) or perpendicular (bottom) to the incident polarization. (b) Calculated Faraday rotation angle and (c) degree of circular polarization.

The degree of circular polarization of the reflected wave is given by

$$P_{\mathrm{circ}} = \frac{R_+ - R_-}{R_+ + R_-}. \quad (14)$$

The positions of cavity-polariton eigenmodes do not coincide in different circular polarizations due to the Zeeman splitting. Considering the large reflectivity modulation in the vicinity of eigenmode energies, P_{circ} can be quite substantial.

In the numerical calculations we have used the transfer matrix technique combined with a nonlocal dielectric response theory to fit circularly polarized spectra of the semiconductor microcavity. Then linearly polarized spectra, Faraday rotation angle, and circular polarization degree of the reflected light have been obtained using Eqs. (6), (7), and (14), respectively.

For experimental studies two identical 8 nm $In_{0.04}Ga_{0.96}As$ QW's were grown inside a $3\lambda/2$ microcavity with symmetric 99.6% reflectivity mirrors consisting of 14 and 16.5 period GaAs/AlAs Bragg reflectors. The QW's were placed in the antinodes of the intracavity field. By moving across the sample, the cavity mode could be brought into resonance with various exciton transitions. Reflection measurements were performed in Faraday geometry at T=1.8 K using a superconducting magnet cryostat.

Figure 1 shows the microcavity reflection spectra in 11.25 T magnetic field detected in σ^- and σ^+ circular polarizations, linear polarization, and linear cross polarization, i.e., detected in the linear polarization orthogonal to the polarization of the incident light. The cavity mode is coupled to the $e1$-lh1 exciton resonance which experiences an unusually large Zeeman splitting of 1.3 meV. One can see that the positions of the spectral dips are substantially different in σ^- and σ^+ polarizations which results in the appearance of a resonant signal in the linear cross polarization. Also seen is a series of strong dips corresponding to optically coupled bulk GaAs exciton-polariton states in the cavity and mirrors. The total thickness of GaAs layers in the cavity and Bragg mirrors is about 2 μm, whereas the total thickness of the two (In,Ga)As QW's in the cavity is only 16 nm. Nevertheless, the QW resonant signal in linear cross polarization, which is a measure of the Faraday effect, is half as large as the bulk exciton resonance, even though it has less than 1% of the path length. When we tune the cavity mode away from the QW exciton resonance, the resonant signal in the linear cross-polarization vanishes.

The dashed lines in Fig. 1 show theoretical fits of the spectra with the excitonic parameters listed in Table I. Excellent agreement between theory and experiment allows us to obtain with good accuracy the Faraday rotation angle and the degree of circular polarization in reflection for linearly polarized incident light (see Fig. 2). Figure 2(a) shows the calculated Faraday rotation angle for one-way propagation through the central cavity layer with two embedded QW's. By comparison with Fig. 2(b), one can see that coupling of the light-hole exciton resonance to the cavity mode drastically influences the spectral dependence of the Faraday rotation angle. The rotation angle is strongly increased at the cavity-polariton eigenmode frequencies. The reflection spectra of Fig. 1 show almost no resonant rotation at the heavy-hole exciton resonance although a significant rotation takes place in one-way transmission through two QW's. This is because in this case the heavy-hole exciton is not coupled to the cavity mode, so that its contribution to the reflection spectrum of the entire structure is very weak.

In contrast, when the QW heavy-hole exciton is coupled to the cavity mode, a strong (about 3°) resonant rotation appears (see Fig. 3). In spite of the fact that the Zeeman splitting of the heavy-hole exciton resonance is less than half the splitting of the $e1$-lh1 exciton, the $e1$-hh1 resonant Faraday rotation effect is stronger than the $e1$-lh1 effect because its oscillator strength is three times larger. A rotation of about 6° was calculated for transmission. However, all experimental results were obtained in reflection geometry.

In conclusion, semiconductor microcavities provide a resonant amplification of the Faraday effect due to multiple round trips of light at the cavity-polariton eigenfrequencies, and induce a redistribution of light intensity between σ^+ and σ^- polarized components.

We gratefully acknowledge support from the National Science Foundation Divisions of Material Research, International Programs, and Physics; the Joint Services Optics Program (U.S. Air Force Office of Scientific Research and U.S. Army Research Office); the Defense Advanced Research Projects Agency, and the Center for Optoelectronics, Devices, Integration and Packaging.

[1] J. Tignon, P. Voisin, C. Delalande, M. Voos, R. Houdre, U. Oesterle, and R. P. Stanley, Phys. Rev. Lett. **74**, 3967 (1995).

[2] T. A. Fisher, A. M. Afshar, M. S. Skolnick, D. M. Whittaker, and J. S. Roberts, Phys. Rev. B **53**, R10 469 (1996).

[3] J. D. Berger, O. Lyngnes, H. M. Gibbs, G. Khitrova, T. R. Nelson, E. K. Lindmark, A. V. Kavokin, M. A. Kaliteevski, and V. V. Zapasskii, Phys. Rev. B **54**, 1975 (1996).

[4] T. Tanaka, Zhenlong Zhang, M. Nishioka, and Y. Arakawa, Appl. Phys. Lett. **69**, 887 (1996).

[5] J. J. Baumberg, D. D. Awschalom, N. Samarth, H. Luo, and J. K. Furdyna, Phys. Rev. Lett. **72**, 717 (1994); J. J. Baumberg, S. A. Crooker, D. D. Awschalom, N. Samarth, H. Luo, and J. K. Furdyna, Phys. Rev. B **50**, 7689 (1994).

[6] V. Savona, L. C. Andreani, P. Schwendimann, and A. Quattropani, Solid State Commun. **93**, 733 (1995).

[7] L. C. Andreani, F. Tassone, and F. Bassani, Solid State Commun. **77**, 641 (1991).

[8] E. L. Ivchenko and G. Pikus, *Superlattices and Other Heterostructures* (Springer-Verlag, Berlin, 1995), Chap. 6.5.

[9] Y. R. Shen, Phys. Rev. **133**, A511 (1964).

[10] D. A. Van Baak, Am. J. Phys. **64**, 724 (1996).