PERGAMON

Solid State Communications 123 (2002) 59–62

solid state communications

www.elsevier.com/locate/ssc

Nonlinear magneto-optic Kerr effect in semiconductor microcavities

Robert Frey[a,*], Maxime Clusel[b], Adrian Radu[b], Régis André[c], Christos Flytzanis[d,e]

[a]*Laboratoire Charles Fabry de l'Institut d'Optique, Ecole Supérieure d'Optique, Centre Scientifique Paris Sud, CNRS and Université Paris Sud, Bat. 503, B.P.147, F-91403 Orsay cédex, France*

[b]*Laboratoire d'Optique Quantique, Ecole Polytechnique and CNRS, F-91128 Palaiseau cédex, France*

[c]*Laboratoire de Spectrométrie Physique (CNRS UMR 558), Université J. Fourier-Grenoble, B.P. 87, F-38402 Saint Martin d'Hères cédex, France*

[d]*Laboratoire de Physique de la Matière Condensée, Ecole Normale Supérieure and CNRS, 24 rue L'Homond, F-75231 Paris cédex, France*

[e]*Lawrence Berkeley Radiation Laboratory, Department of Physics, Materials Science Division, University of California, Berkeley, CA 94720, USA*

Received 1 February 2002; accepted 24 April 2002 by B. Jusserand

Abstract

The photo-induced modifications of the strong magneto-optic Kerr effect have been studied in a semimagnetic semiconductor microcavity operated in the strong coupling regime. These are traced to the saturation and many body interaction blue shift of the exciton transition frequency, which result in a photo-induced reduction of the effective exciton–cavity coupling. Its impact is most striking in the case of initially tuned microcavity, where a modification of the exciton–cavity coupling results in photo-induced polarization rotations of about 30 degrees for laser fluences as low as 1 $\mu J/cm^2$ and magnetic field intensities of 0.2 T.

PACS: 42.65 − k; 42.72.Np; 78.67.De

Keywords: A. Nanostructures; D. Optical properties; E. Nonlinear optics

The study of exciton–polariton modes received a renewed attention in the recent years with the use of quantum microcavities [1,2]. A particular interest is brought to the strong coupling regime when the coupling strength between the material (exciton) and electromagnetic (photon) components, measured by the Rabi splitting, is larger than the exciton and cavity linewidths.

Recent studies have shown that the spectral features of the quantum cavity polaritons are affected by static electric and magnetic fields [2–10]. The exciton–polariton features are very sensitive to light intensity changes as well and here we assess the photo-induced modifications of the effective exciton–cavity coupling (including detuning effects) in asymmetric semimagnetic semiconductor microcavities in the presence of a static magnetic field in the magneto-optic Kerr configuration. These modifications are observed with moderate laser fluences and magnetic field amplitudes because in such cavities the magneto-optic coupling and contrast ratios are substantially enhanced by the combined effect of spin exchange interaction and cavity asymmetry [10].

In our experiments, normal incidence reflectivity and magneto-optic Kerr spectra from an asymmetric quantum semimagnetic semiconductor microcavity were recorded by using a tunable parametric generator-amplifier system that was pumped by a frequency tripled Neodymium-YAG laser operated in the mode coupling regime. The sample was placed inside a magnetic cryostat and the measurements were performed at $T = 5$ K for a magnetic field amplitude of 0.2 T. This sample was grown by molecular beam epitaxy on a $Cd_{0.88}Zn_{0.12}Te$ [100] oriented substrate. The back and front cavity mirrors, of respective reflection coefficients $R_2 = 0.96$ and $R_1 = 0.76$, were formed by stacking $\lambda/4$ thick

* Corresponding author. Fax: +33-1-69-35-87-00.
E-mail address: robert.frey@iota.u-psud.fr (R. Frey).

0038-1098/02/$ - see front matter
PII: S0038-1098(02)00198-9

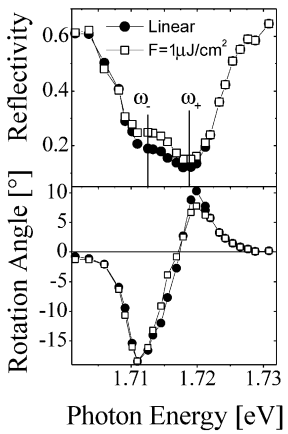

Fig. 1. Reflectivity and magneto-optic Kerr spectra in the linear and nonlinear regimes in the nonresonant case.

$Cd_{0.4}Mg_{0.6}Te/Cd_{0.75}Mn_{0.25}Te$ pairs. A 70 nm thick $Cd_{0.95}Mn_{0.05}$ Te quantum well was grown in the middle of the $\lambda/2$ thick $Cd_{0.4}Mg_{0.6}$ Te intracavity material. This configuration of the asymmetric microcavity operated in the limit of the strong coupling regime (for a cavity–exciton coupling strength only slightly larger than the polariton linewidth) was chosen in order to maximize magneto-optic Kerr rotation angles in the presence of small amplitude magnetic fields [10].

In the strong coupling regime the cavity mode and exciton transition couple together and give rise to the so-called polariton modes [1]. In the simplest approach of two coupled oscillators, the frequencies ω_+ and ω_- of the upper and lower polariton branches are given by

$$\omega_{\pm} = \frac{\omega_C + \omega_E}{2} \pm \frac{1}{2}\sqrt{(\omega_C + \omega_E)^2 + \Omega^2} \quad (1)$$

where the Rabi frequency Ω represents the coupling strength of the cavity and exciton modes [11]. Eq. (1) was experimentally verified in our wedged sample by measuring the polariton frequencies when the cavity frequency was varied. From the measured polariton frequencies a value of 5.3 meV was deduced for the Rabi frequency Ω for the tuned cavity ($\omega_C = \omega_E$).

At high laser fluences, when the laser frequency ω is near ω_E, high exciton densities are generated which influence the characteristics of the exciton transition, especially its oscillator strength and its resonance frequency, through band filling effects and many body interactions [12]. When the quantum well is located in a microcavity, these modifications in their turn strongly influence the coupling between the exciton and cavity modes: a reduction of the exciton oscillator strength induces a concomitant diminution of the Rabi frequency Ω, which in turn reduces the frequency difference between the polariton modes (Eq. (1)), and the many-body interaction induced blue shift of ω_E directly modifies the polariton frequencies.

First experiments concerning the role of the laser fluence in the coupling between cavity and polariton modes were performed for an untuned microcavity with an exciton–cavity frequency mismatch $\omega_E - \omega_C = 4.6$ meV. Fig. 1(a) and (b) shows the reflectivity and magneto-optic Kerr spectra, respectively. In this figure spectra recorded in the linear (low intensity, for fluences of 200 nJ/cm^2) and nonlinear (high intensity, for fluences of only 1 μJ/cm^2) regimes are plotted as a function of the photon energy using closed circles and open squares, respectively. The low and high intensity reflectivity spectra of Fig. 1(a) only differ in the onset of saturation appearing around the two polariton modes at high fluences but the polariton line energies and shapes remain almost constant. This observation is consistent with an exciton–cavity frequency mismatch for those experiments as large as Ω: it can be easily derived from Eq. (1) that under such conditions $\omega_\pm$ are not sensitive to small changes in coupling strength or exciton energy. The fact that the polariton frequencies are weakly affected is also clearly evidenced by the magneto-optic Kerr spectra, which are almost identical at low and high intensity (Fig. 1(b)). Indeed, in this off resonant case, the frequency changes due to exchange interaction ($\omega_E^{\pm} - \omega_E = \mp 1.5$ meV,) to many-body interactions (a small blue shift of the exciton transition of about 1 meV at the 1 μJ/cm^2 laser fluence used in our experiment) and to saturation (a small decrease of about 20% of the coupling strength Ω in this experiment) were small when compared to $\omega_E - \omega_C$, and the counter-rotating polarized polariton modes kept the exciton and cavity characters that they had in the linear regime. In such a situation, the magneto-optic Kerr rotation exhibited then two peaks corresponding approximately to the exciton and cavity modes that were unaltered at high laser fluences (at least at the 1 μJ/cm^2 laser fluence used in our experiment).

Next experiments were performed for the tuned cavity. Applying the 0.2 T amplitude magnetic field gave rise to the more complicated linear magneto-optic Kerr spectrum depicted by closed circles in Fig. 2(b) [10]. At a laser fluence of 1 μJ/cm^2 the $\hat{\sigma}_\pm$ exciton transitions were blue shifted and saturated. As shown in Fig. 2(a) the high intensity reflectivity spectrum was consequently slightly blue shifted and narrowed and a Rabi frequency $\Omega' = 4$ meV deduced from the position of the polariton frequencies of the high intensity reflectivity spectrum (see open squares in Fig. 2(a)). As shown in Fig. 2(b) the modification of the coupling between the cavity and exciton mode was much more evident when comparing the high and low intensity magneto-optic Kerr spectra with a photo-induced rotation of the polarization direction of the laser beam of the order of 30° when the laser frequency was tuned to the lower polariton frequency.

In order to understand the physical origin of the giant change in the rotation angle around the lower polariton mode and the quasi-absence of modification around the upper polariton branch we considered the frequency changes of the $\hat{\sigma}_\pm$ exciton frequencies, since the rotation angle due to the magneto-optic Kerr effect was directly

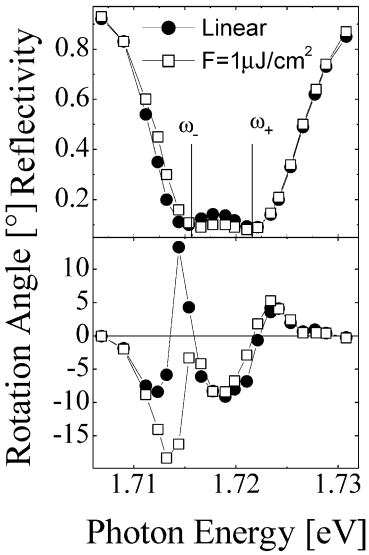

Fig. 2. Reflectivity and magneto-optic Kerr spectra in the linear and nonlinear regimes in the resonant case.

proportional to the difference existing between the $\hat{\sigma}_-$ and $\hat{\sigma}_+$ polarized refractive indices, the variation of which strongly depended on the resonance frequencies. For the $\hat{\sigma}_-$ polarization the exciton transition exhibited blue shifts of 1.5 and 1 meV due to magnetic field induced exchange interaction and to many-body interactions, respectively, and the coupling strength was reduced to 4 meV by saturation of the exciton transition. Using Eq. (1) it followed that the upper polariton frequency $\omega_+(\hat{\sigma}_-)$ was almost unchanged (an increase of 0.1 meV which was much smaller than the 5 meV exciton linewidth), while the lower one $\omega_+(\hat{\sigma}_-)$ was modified by about 1 meV when compared to the linear values. For the $\hat{\sigma}_+$ polarization which was red shifted by magnetic field induced exchange interaction and blue shifted by many-body interactions, the upper polariton frequency $\omega_+(\hat{\sigma}_+)$ only changed by 0.2 meV while the lower one $\omega_-(\hat{\sigma}_+)$ increased by 1.3 meV. The magneto-optic Kerr spectrum was expected to vary substantially at low laser frequencies while remaining practically unchanged at frequencies higher than the cavity resonance, as observed experimentally (see Fig. 2(b)).

Our results also indicate that the photo-induced interactions causing the level shifts and transition saturation can be split into isotropic and gyrotropic parts, the later being polarization state dependent and the main cause of the observed behavior; the former cancel out in the photo-induced change of the difference of the refractive indices for left and right circularly polarized light.

Actually the high intensity magneto-optic Kerr spectrum recorded at resonance when $\omega_E \approx \omega_C$ begins to look like the linear one recorded with a detuned cavity. This was due in fact to the saturation induced reduction of the coupling strength occurring at high laser fluences which made the exciton and cavity modes less coupled together. This

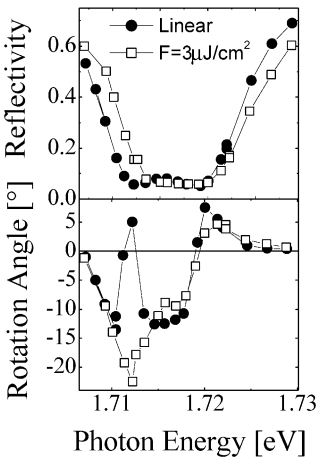

Fig. 3. Reflectivity and magneto-optic Kerr spectra in the linear and nonlinear regimes in the resonant case at higher laser fluences.

behavior was confirmed by an experiment performed at higher laser fluences ($F = 3$ μJ/cm^2). Results are shown in Fig. 3(a) and (b) showing the reflectivity and magneto-optic Kerr spectra, respectively. Linear and nonlinear spectra recorded at a fluence of 3 μJ/cm^2 are plotted using closed circles and open squares, respectively. The quasi-absence of exciton–cavity coupling is quite apparent in the blue shifted high intensity reflectivity spectrum of Fig. 3(a) which does not exhibit any modulation around the presumed polariton frequencies, contrary to the linear reflectivity spectrum also presented in this figure. As it can be seen in Fig. 3(b), in accordance with our expectations, the high intensity magneto-optic Kerr spectrum is very similar to the spectra shown in Fig. 1(b) when the frequency mismatch is high enough to strongly decouple the exciton and cavity modes.

In conclusion we have shown that the modification of the coupling between exciton and cavity modes of a semimagnetic semiconductor microcavity can be studied at low laser fluences (only few μJ/cm^2) by exploiting the high sensitivity of magneto-optic Kerr rotation measurements with respect to changes in the frequency resonance of the counter-rotating polarized exciton transitions. For untuned microcavities (different exciton and cavity resonance frequencies), the saturation and many body interaction induced blue shift of the exciton transition did not modify the initial low coupling of the cavity and exciton modes, and the magneto-optic Kerr rotation was unmodified. On the contrary, for tuned microcavities, saturation and many body interaction induced blue shift of the exciton transition strongly modified the coupling between the cavity and exciton modes and markedly altered the magneto-optic Kerr spectrum around the lower polariton frequency with induced rotations as high as 30° at laser fluences as low as 1 μJ/cm^2.

Note that the magneto-optic Kerr technique is very efficient whatever the physical origin of the modifications of the exciton transition are and in particular could be useful for the study of the magnetization that can be induced by

circularly polarized laser pulses in microcavities containing magnetic quantum wells such as semimagnetic semiconductors. Moreover, due to the high contrast allowed by the polarization sensitive measurements, such microcavities are very promising on a practical point of view concerning fast optical signal processing.

References

[1] C. Weissbuch, M. Nishioka, A. Ishikawa, Y. Arakawa, Phys. Rev. Lett. 69 (1992) 3314.
[2] M.S. Skolnick, T.A. Fisher, D.M. Whittaker, Semicond. Sci. Technol. 13 (1998) 645.
[3] T.A. Fisher, A.M. Afshar, D.M. Whittaker, J.S. Roberts, G. Hill, M.A. Pate, Phys. Rev. B 51 (1995) 2600.
[4] T.A. Fisher, A.M. Afshar, D.M. Whittaker, J.S. Roberts, G. Hill, M.A. Pate, Solid State Electron. 40 (1996) 493.
[5] J. Tignon, P. Voisin, C. Delalande, M. Voos, R. Houdré, V. Oesterle, R.P. Stanley, Phys. Rev. Lett. 74 (1995) 3967.
[6] J. Tignon, P. Voisin, C. Delalande, M. Voos, R. Houdré, V. Oesterle, R.P. Stanley, Phys. Rev. B 56 (1997) 4068.
[7] T.A. Fisher, A.M. Afshar, M.S. Skolnick, D.M. Whittaker, J.S. Roberts, Phys. Rev. B 53 (1996) R10469.
[8] A. Armittage, R.P. Stanley, M.S. Skolnick, D.M. Whittaker, P. Kinsler, J.S. Roberts, Phys. Rev. B 55 (1997) 16395.
[9] J.D. Berger, O. Lyngues, H.M. Gibbs, G. Khitrova, T.R. Nelson, E.K. Lindmark, A.V. Kavokin, M.A. Kaliteevskii, V.V. Zapasskii, Phys. Rev. B 54 (1996) 1975.
[10] M. Haddad, R. André, R. Frey, C. Flytzanis, Solid State Commun. 111 (1999) 61.
[11] J.J. Sanchez-Mondragon, N.B. Narozhny, J.H. Eberly, Phys. Rev. Lett. 51 (1983) 550.
[12] S. Schmitt-Rink, D.S. Chemla, D.A.B. Miller, Phys.Rev. B 32 (1985) 6601.