Emission in Fabry-Perot Cavities in Weak and Strong Coupling Regimes

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Abstract: We have studied spectra and angular distribution of emission of Rhodamine 6G dye in Fabry-Perot cavities in weak and strong coupling regimes and demonstrated control of the strong coupling with the pumping intensity.

We have studied frequency, angular, and polarization dependence of emission in Fabry-Perot cavities formed by two parallel silver mirrors separated by a layer of polymer (PMMA) doped with Rhodamine R6G (R6G) laser dye in low (c=20 g/l) and high (c=200 g/l) concentrations. The cavity sizes d were sufficiently large for the cavity branch of the dispersion curve to be positioned below the horizontal exciton branch, Figs. 1 a-d.

The frequency of emission originating from the cavity branch of the dispersion curve was larger at large outcoupling angles – the "rainbow" effect, Figs. 1a and 1c. Furthermore, the angle (and the frequency) of the strongest emission were determined by the cavity size: the larger the cavity, the larger is the angle – another realization of the rainbow effect, Fig 1d.

The angular distribution of emission (measured in a horizontal plane) is commonly dominated by two symmetrical lobes pointing to the left and to the right of the normal to the sample.

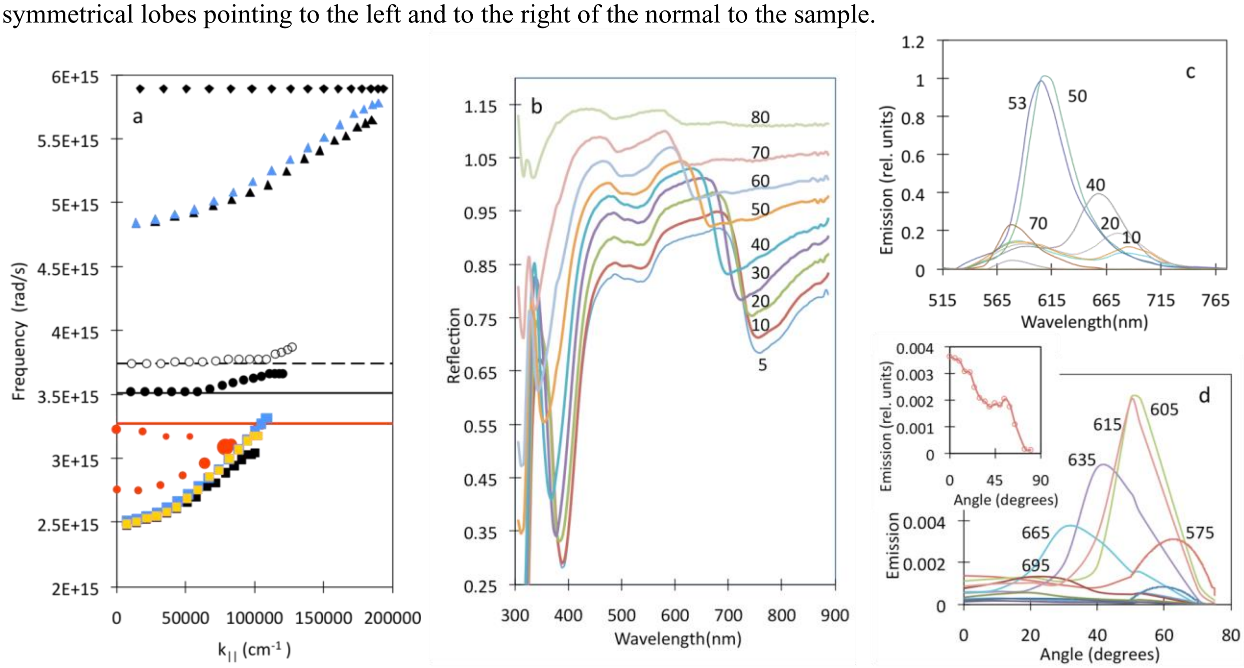

Figure 1. REFLECTION SPECTRA, EMISSION SPECTRA AND DISPERSION CURVES IN A FABRY-PEROT CAVITY WITH R6G DYE. (a) Dispersion curves of the d=205 nm cavity at the dye concentration c=200 g/l. Black characters – dispersion curves derived from the s polarized reflection measurements; blue characters – fitting the experimental dispersion curves using the transfer matrix calculator; yellow squares – dispersion of an undoped cavity calculated analytically. Black horizontal lines: absorption maximum (solid line) and absorption shoulder (dashed line) of R6G:PMMA deposited on glass. Red circles: "cavity emission" and "exciton emission" branches of the dispersion curve (in s polarization). The sizes of the red circles are proportional to the emission intensities. *The lower, "cavity emission" branch demonstrates the "rainbow" effect.* Red horizontal line: emission maximum of R6G:PMMA deposited on glass. (b) Reflection spectra recorded, in s polarization, at multiple incidence angles (written next to the traces). (c) Emission spectra recorded, in s polarization, at multiple detection angles (demonstrating the "rainbow" effect). (d) Angular emission profiles recorded, in s polarization, at multiple wavelengths (demonstrating the "rainbow" effect). Inset: angular dependence of emission originating from the exciton emission branch in a smaller cavity (d=185 nm, c=200 g/l).

Intriguingly, despite the strong Stokes shift in R6G dye, causing the emission frequency to be smaller than the absorption frequency, the branch of the cavity dispersion curve obtained in the emission experiment has higher energy than the one obtained in the reflection experiment, Fig. 1a. This effect is not fully understood. At the same time, the emission originating from the exciton branch of the dispersion curve has very broad angular distribution with the maximum at θ=0º.

The signatures of strong cavity-exciton coupling were observed at high dye concentration (c=200 g/l), but not at low concentration (c=20 g/l). The effect of the strong coupling on the cavity's emission is exemplified by a dramatic difference in the angular distribution of emission in d≈200 nm cavities with high dye concentration (c=200 g/l, strong coupling) and low dye concentration (c=20 g/l, weak coupling).

Most importantly, we demonstrated the possibility to control the ground state concentration, the coupling strength, and the dye emission spectra with Q-switched laser pumping, Fig. 2. More theoretical and experimental studies are required to fully explore this intriguing phenomenon.

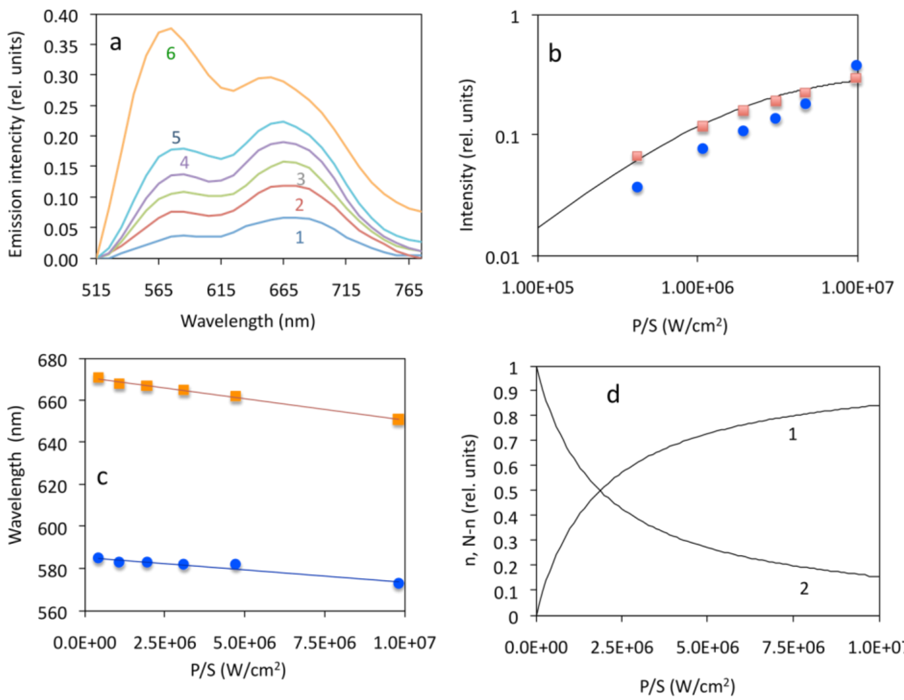

Figure 2. CONTROL OF STRONG COUPLING WITH PUMPING INTENSITY. (a) Emission spectra of the Fabry-Perot cavity (d=205 nm, c=200 g/l) measured in p polarization at different peak pumping intensities: 4.2×10^5 W/cm^2 (trace 1), 1.1×10^6 W/cm^2 (trace 2), 1.9×10^6 W/cm^2 (trace 3), 3.1×10^6 W/cm^2 (trace 4), 4.7×10^6 W/cm^2 (trace 5), 9.8×10^6 W/cm^2 (trace 6). *The spectra demonstrate the saturation of the emission intensity and its spectral shift with increase of the pumping power.* (b) Pumping power dependence of the emission intensity originating from the lower "cavity emission" branch of the dispersion curve (orange squares) and the upper "exciton emission" branch of the dispersion curve (blue circles). Solid line is the fitting with the analytical model. (c) Wavelengths positions of the emission maxima at different pumping intensities. Orange squares: "cavity emission" branch, blue circles: "exciton emission" branch. (d) Saturation of the population of the excited state n, trace 1, and depopulation of the ground state (N-n), trace 2, calculated using analytical model.

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ABSTRACT

We have studied spectra and angular distribution of emission of Rhodamine 6G dye in Fabry-Perot cavities in weak and strong coupling regimes and demonstrated control of the strong coupling with the pumping intensity.

MOTIVATION

- We have studied frequency, angular, and polarization dependence of emission in Fabry-Perot cavities formed by two parallel silver mirrors separated by a layer of polymer (PMMA) doped with Rhodamine R6G (R6G) laser dye in low (c=20 g/l) and high (c=200 g/l) concentrations.
- We studied the spectra, and the angular distribution of the emission. We also studied the ground state concentration of quantum emitters, the coupling strength, and the emission spectra can be controlled by strong laser pulses populating the excited state and depopulating the ground state.
- The cavity sizes d were sufficiently large for the cavity branch of the dispersion curve to be positioned below the horizontal exciton branch, Figs. 1 a-d.
- The frequency of emission originating from the cavity branch of the dispersion curve was larger at large outcoupling angles – the "rainbow" effect, Figs. 1a and 1c. Furthermore, the angle (and the frequency) of the strongest emission were determined by the cavity size: the larger the cavity, the larger is the angle – another realization of the rainbow effect, Fig 1d.
- The angular distribution of emission (measured in a horizontal plane) is commonly dominated by two symmetrical lobes pointing to the left and to the right of the normal to the sample.
- Intriguingly, despite the strong Stokes shift in R6G dye, causing the emission frequency to be smaller than the absorption frequency, the branch of the cavity dispersion curve obtained in the emission experiment has higher energy than the one obtained in the reflection experiment, Fig. 1a. This effect is not fully understood. At the same time, the emission originating from the exciton branch of the dispersion curve has very broad angular distribution with the maximum at θ=0°.

SAMPLE SCHEMATICS AND EXPERIMENTAL SETUP

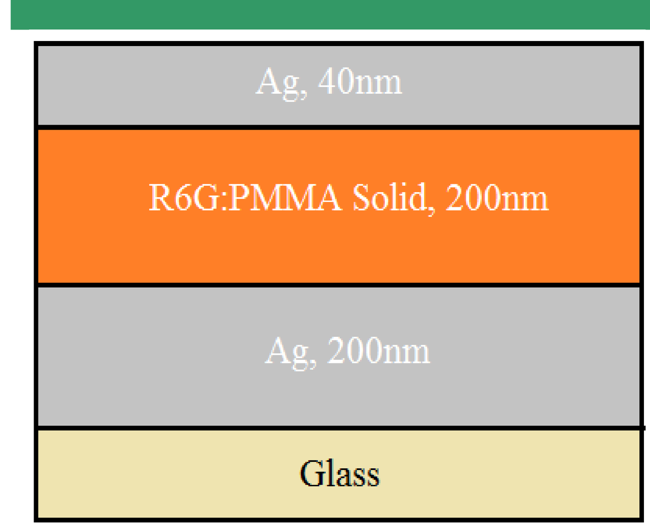

Fig. 1. Schematics of the experimental sample.

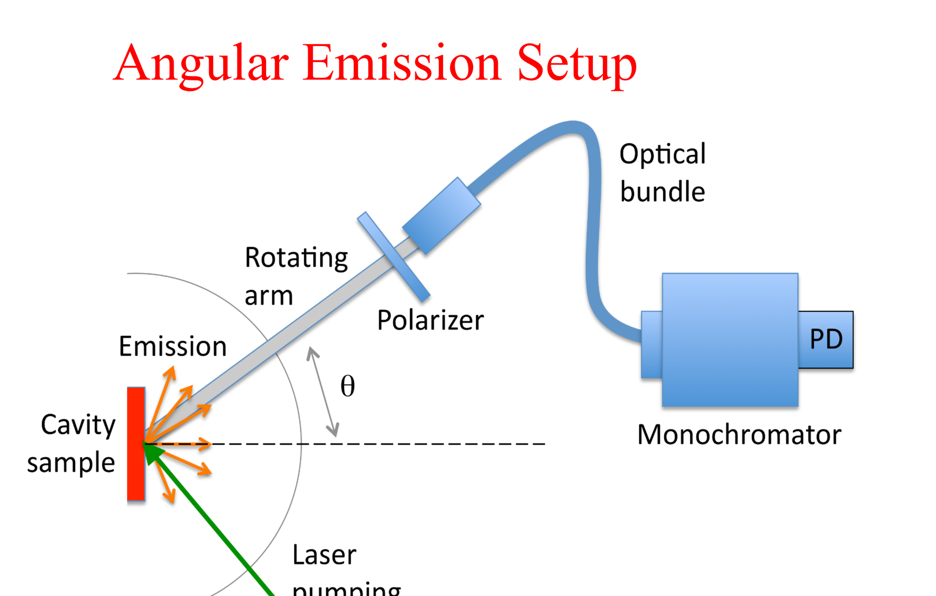

Fig. 2. Schematics of the experimental setup used in the studies of emission.

Sample Specs.
R6G:PMMA: 200 nm
R6G:PMMA: 20 g/L or 200g/L
Top Ag layer thickness: ~40 nm
Bottom Ag layer thickness: ~ 200 nm

EXPERIMENTAL RESULTS: REFLECTION AND EMISSION

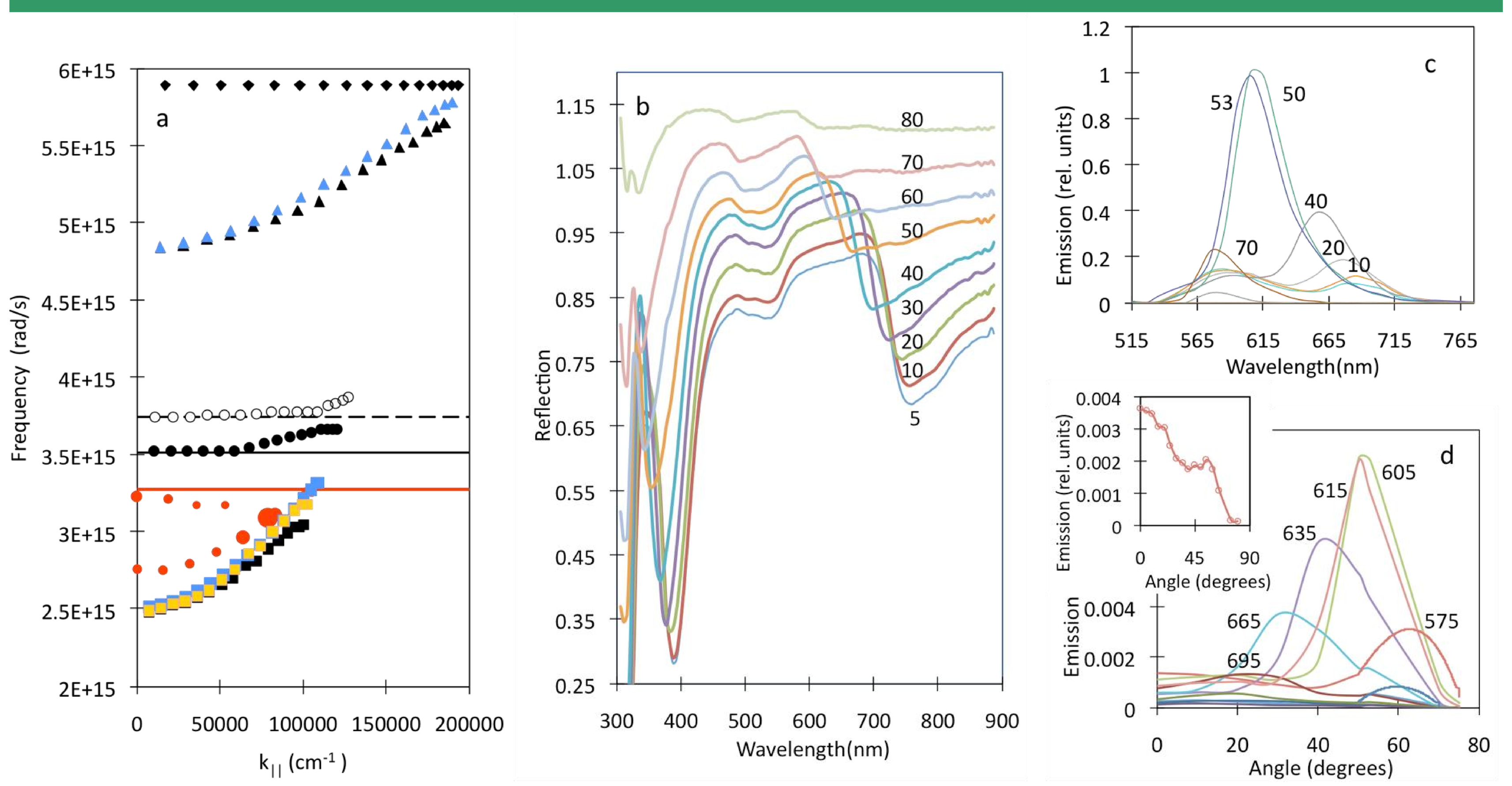

Fig. 3. REFLECTION SPECTRA, EMISSION SPECTRA AND DISPERSION CURVES IN A FABRY-PEROT CAVITY WITH R6G DYE. (a) Dispersion curves of the d=205 nm cavity at the dye concentration c=200 g/l. Black characters – dispersion curves derived from the s polarized reflection measurements; blue characters – fitting the experimental dispersion curves using the transfer matrix calculator; yellow squares – dispersion of an undoped cavity calculated analytically. Black horizontal lines: absorption maximum (solid line) and absorption shoulder (dashed line) of R6G:PMMA deposited on glass. Red circles: "cavity emission" and "exciton emission" branches of the dispersion curve (in s polarization). The sizes of the red circles are proportional to the emission intensities. *The lower, "cavity emission" branch demonstrates the "rainbow" effect.* Red horizontal line: emission maximum of R6G:PMMA deposited on glass. (b) Reflection spectra recorded, in s polarization, at multiple incidence angles (written next to the traces). (c) Emission spectra recorded, in s polarization, at multiple detection angles (demonstrating the "rainbow" effect). (d) Angular emission profiles recorded, in s polarization, at multiple wavelengths (demonstrating the "rainbow" effect). Inset: angular dependence of emission originating from the exciton emission branch in a smaller cavity (d=185 nm, c=200 g/l).

CONTROL OF CAVITY EMISSION WITH TUNABLE STRONG COUPLING

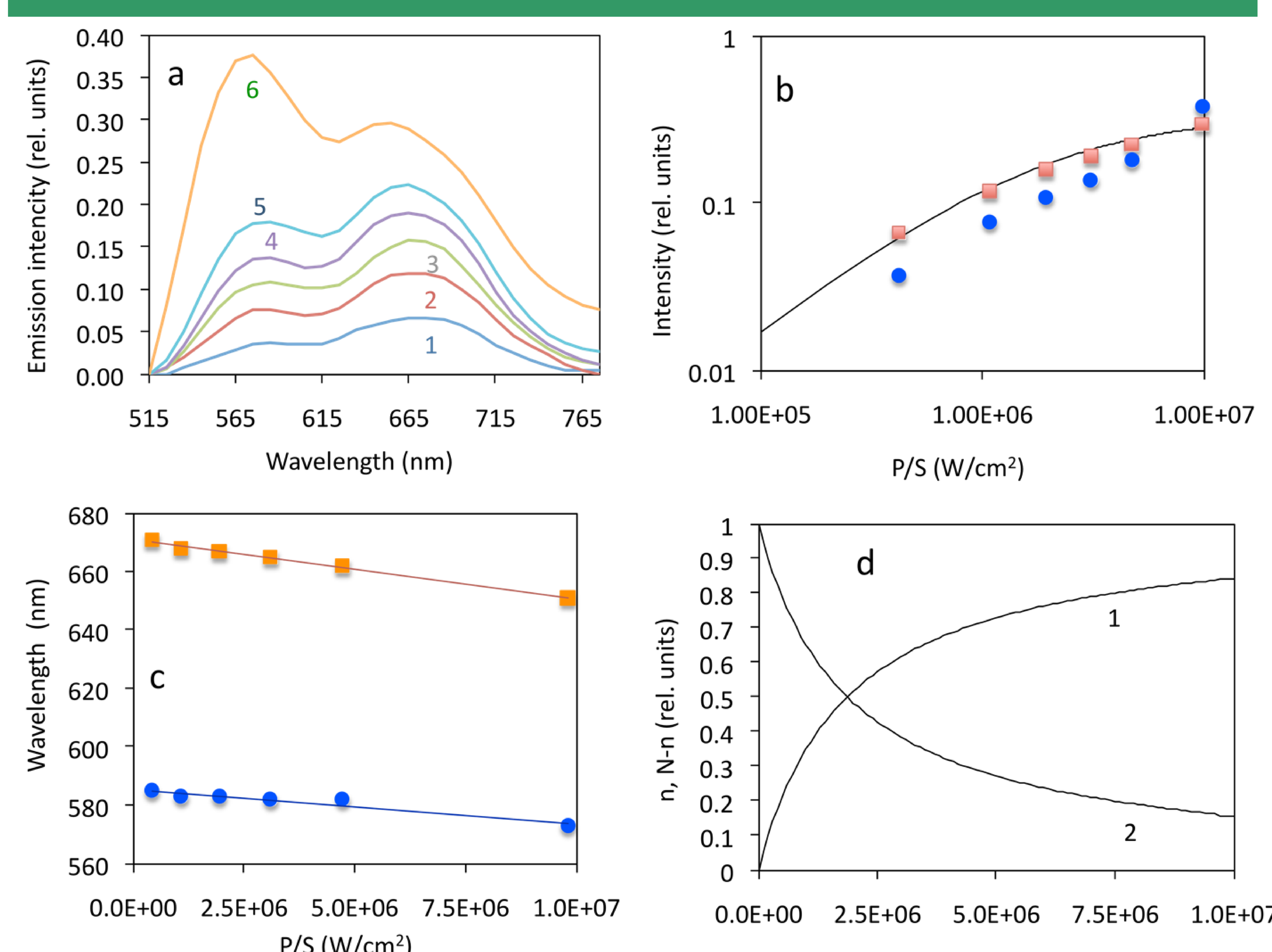

Fig. 4. CONTROL OF STRONG COUPLING WITH PUMPING INTENSITY. (a) Emission spectra of the Fabry-Perot cavity (d=205 nm, c=200 g/l) measured in p polarization at different peak pumping intensities: 4.2×10^5 W/cm^2 (trace 1), 1.1×10^6 W/cm^2 (trace 2), 1.9×10^6 W/cm^2 (trace 3), 3.1×10^6 W/cm^2 (trace 4), 4.7×10^6 W/cm^2 (trace 5), 9.8×10^6 W/cm^2 (trace 6). *The spectra demonstrate the saturation of the emission intensity and its spectral shift with increase of the pumping power.* (b) Pumping power dependence of the emission intensity originating from the lower "cavity emission" branch of the dispersion curve (orange squares) and the upper "exciton emission" branch of the dispersion curve (blue circles). Solid line is the fitting with the analytical model. (c) Wavelengths positions of the emission maxima at different pumping intensities. Orange squares: "cavity emission" branch, blue circles: "exciton emission" branch. (d) Saturation of the population of the excited state n, trace 1, and depopulation of the ground state (N-n), trace 2, calculated using analytical model.

CONCLUSIONS

- We have studied the frequency, angular, and polarization dependence of emission in Fabry-Perot cavities formed by two parallel silver mirrors separated by a layer of polymer (PMMA) doped with R6G laser dye in low (20 g/L) and high (200 g/L) concentrations. The cavities studied were sufficiently large, for the cavity branch of the dispersion curve to be positioned below the horizontal exciton branch.
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- The emission originating from the exciton branch of the dispersion curve has a very broad angular distribution with the maximum at θ=0°.
- Even more importantly, in our experiments, we demonstrated the possibility to control the ground state concentration, the coupling strength, and the dye emission spectra with Q-switched laser pumping.
- More theoretical and experimental studies are required to fully explore this intriguing phenomenon.

ACKNOWLEDGEMENT

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