Polarization based control of optical hysteresis in coupled GaAs microdisks

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Optical microresonators crafted from semiconducting materials are powerful systems for both understanding and harnessing the interactions between light and matter. We report an all-optical method of controlling the hysteretic emission of evanescently coupled GaAs microdisk pairs. Under partial excitation, the coupled lasing emission demonstrates optical bistability caused by saturable absorption. We observe that the presence of hysteresis can be modulated by the polarization state of the incident excitation. This optical control is an important functionality which, if extended to a large array, could lead to the creation of optical flip-flop and gated logic devices with multinode capabilities. © *2010 American Institute of Physics*. [doi:10.1063/1.3462309]

Semiconductor microcavities have generated interest as test beds for light-matter interactions such as those between excited electron spins and photons confined in a cavity.[1–4] Disk cavity geometries result in many attractive qualities including relatively high Q factors, low lasing thresholds, and strong in-plane emissions manifest in the form of electromagnetic whispering-gallery modes.[5,6] Additionally, both weak[7] and strong[8] coupling between electrons and photons have been observed in single microdisks containing quantum dots, providing possible avenues for quantum information processing schemes.[9,10] To address some of the issues present in single microdisks such as inefficient power output and lack of emission directionality,[11,12] arrays of microdisks coupled via the evanescent electric field at the disk edges have been proposed and fabricated.[13] These coupled states are observed in a variety of cavity geometries[13–17] where the individual electromagnetic modes blend to form "photonic molecule" (PM) modes, much like the atomically shared electronic states in a chemical molecule. In this paper we investigate the PM states formed in coupled circular and elliptical microdisks using high resolution static and dynamic optical spectroscopy techniques. We observe bistable lasing of selectively coupled emission modes and demonstrate that the bistability is controllable by the incident excitation polarization. This polarization control gives us an all-optical and noninvasive means of manipulating the hysteretic emission intensity of the coupled system.

Our microdisks are fabricated from GaAs/AlGaAs heterostructures grown by molecular beam epitaxy. The active regions of the 120 nm thick disks consist of six 4.2 nm GaAs quantum wells with interface-fluctuation quantum dots.[2,5] Both circular and elliptical PMs are fabricated. The circular microdisks have a radius of 1 μm [Fig. 1(a)] and the elliptical microdisks have a major axis length of 2 μm with an aspect ratio of 0.75 [Fig. 2(a)].

We begin by studying coupled circular disks[18] [Fig. 1(a)]. To allow efficient mode coupling, the interdisk distance is nominally designed to be 200 nm, well within the regime of evanescent decay.[6,13] Figure 1(b) shows the emission from the coupled modes at temperature $T=20$ K. The individual emission modes of each cavity are replaced by two resonant modes labeled bonding ("b," lower energy) and antibonding ("ab," higher energy). In an efficiently coupled system, neither mode is localized on any particular disk.[11] In reality however, no two disks are identical, which gives rise to a detuning in individual mode energies. When this detuning is small compared to the coupling strength of PMs, the

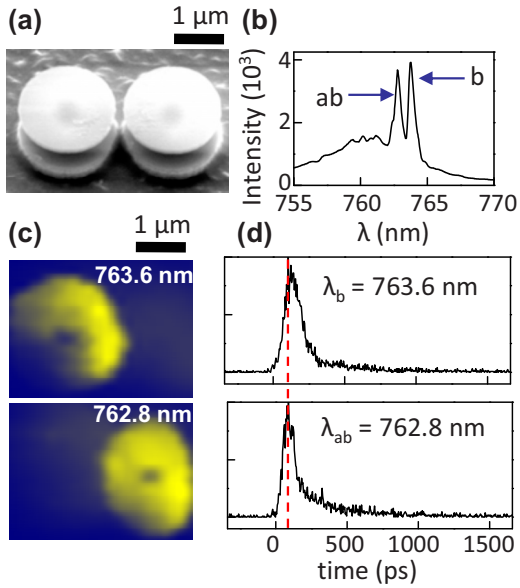

FIG. 1. (Color online) (a) Scanning electron microscopy (SEM) image of coupled circular disks. (b) Spectral emission showing coupled modes at $T=20$ K. The modes are labeled as bonding ("b") and antibonding ("ab"). (c, top) Spatially resolved PL scan at 763.6 nm, the bonding mode emission. (c, bottom) Similar scan centered on the antibonding mode wavelength of 762.8 nm. (d) Time-resolved PL for the two modes. Dashed line compares the two "delay times".

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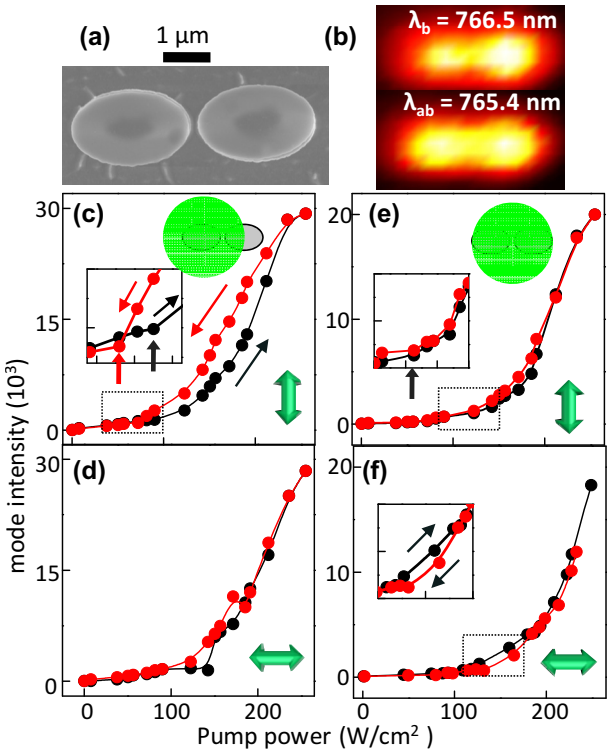

FIG. 2. (Color online) (a) SEM image of coupled elliptical microdisks. (b, top and bottom) Spatially resolved PL scans at $T=10$ K. The bonding mode (top) is slightly localized in the right disk, while the anti-bonding mode (bottom) is highly delocalized. (c) Nonuniform pumping (schematic) with $P=90°$ (double-headed arrows denote polarization state). Hysteresis is observed as the excitation power is first increased in steps and then decreased. Inset highlights the lasing threshold as the power is ramped up and down. (d) Non-uniform pumping with $P=0°$ (e) Uniform pumping with $P=90°$. Inset shows unchanged threshold for both branches. (f) Uniform pumping with $P=0°$. Magnified region in inset shows slight thermal hysteresis.

modes are highly delocalized between both disks. Spatially resolved photoluminescence (PL) measurements [Fig. 1(c)] demonstrate that the disk detuning is not negligible, with the bonding mode almost entirely localized in the left disk [Fig. 1(c), top] and the antibonding mode in the right disk [Fig. 1(c), bottom]. This detuning is likely caused by an unintentional diameter mismatch between the pair.[16] Time-resolved PL corresponding to these emissions is shown in Fig. 1(d). Alteration of carrier dynamics is usual when a system crosses over from spontaneous to stimulated emission at its resonance. The typical signatures include reduction in the carrier recombination time and the "delay time," defined as the time required for the emission to reach its maximum intensity. For this disk pair, the bonding (antibonding) recombination time of 120 ps (90 ps) are much shorter than the nonresonant emission time of 400 ps. The delay time of the antibonding mode is also shorter than the bonding mode and nonresonant PL delay times. These dynamical signatures indicate that the antibonding mode has a higher Q, attributed to this mode's electric field having deeper penetration in the interdisk gap.

Elliptical microdisks break the cylindrical symmetry of their circular counterparts. Fortunately, prior measurements on single elliptical disks[12] have shown that at least in the weak deformation limit of aspect ratio ≥ 0.75, the basic nature of whispering gallery modes is not destroyed. Evanescent fields are more prominent near the larger curvature regions of an elliptical disk which enhances the coupling between an elliptical disk pair in the geometry studied [Fig. 2(a)]. This enhancement is observed in Fig. 2(b) by the more delocalized bonding (top) and antibonding (bottom) mode profiles. Our measurements indicate that PMs composed of coupled elliptical disks show stronger coupling and more equitable spatial mode distributions than the circular PM samples, which leads us to investigate the possibility of bistable operation in these coupled systems. Bistability and mode-switching, driven by the phenomenon of saturable absorption, have been observed in a variety of semiconductor microcavities. The first proposed bistable laser[19] was based on nonlinear absorption resulting from inhomogeneous current injection in a two-segmented laser. Several studies have been done on phenomena of bistable operation in semiconductor lasers with a variety of schemes including inhomogeneous current injection[20] in multisegmented structures[21] and optical injection.[21] In optically excited cavities such as ours' this is attained easily by nonuniform pumping of the coupled pair,[16] as shown in Fig. 2(c). The preferentially pumped disk provides the gain while the partially pumped disk forms the loss region.

Figure 2(c) follows the emission intensity of the antibonding mode as a function of pump power at $T=10$ K. With the incident excitation polarization perpendicular to the coupling axis, (denoted $P=90°$) significant hysteresis is observed between the incident power ramping up and down when preferentially pumping only one disk. The anticlockwise nature of the hysteresis loop signifies that this is not a thermal effect. The inset shows that saturable absorption may be the cause as the lasing threshold is lower on the ramp down (75 W/cm^2) than on the ramp up (90 W/cm^2). This threshold reduction is consistently observed in multiple samples in the range of 15–20 W/cm^2. Repeating the same measurements under orthogonal polarization [$P=0°$, Fig. 2(d)] surprisingly reveals no bistability. When uniformly pumped [Figs. 2(e) and 2(f)] there is no carrier density differential in the coupled system, and therefore, bistability is not expected. The small clockwise hysteresis under uniform pumping [Fig. 2(f) inset] is the incorrect direction and is likely due to thermal effects.

The same measurements in circular coupled disks do not exhibit hysteresis with either polarization (fig. S10 in Ref. 18) while the effect shows up very reproducibly in the elliptical disks (figs. S4–S6, Ref. 18). In elliptical disks coupled along the minor axes (figs. S1 and S7–S9 in Ref. 18) there is a hint of hysteresis with $P=0°$ but not $P=90°$. This suggests the polarization dependence of bistability may follow the geometry of the elliptical cavity rather than the axis of coupling. It may be that the different pump polarizations relative to the major axis of an individual elliptical disk spatially excite carriers across the area of the disk in different ways. It would then not be surprising to see a change in emission dynamics if this spatial extent of gain was really varying with polarization because the coupling between a carrier recombination event to a specific cavity mode is highly dependent on position within the disk. Carrier diffusion and lifetime may then further enrich this gain structure effect, contributing to the observed polarization dependence of bistability in these disks. As a check, the magnitude of emission intensities of the elliptical disks do not show a marked difference under $P=0°$ or 90°; (fig. S2, Ref. 18), suggesting that the overall number of excited carriers in these disks is

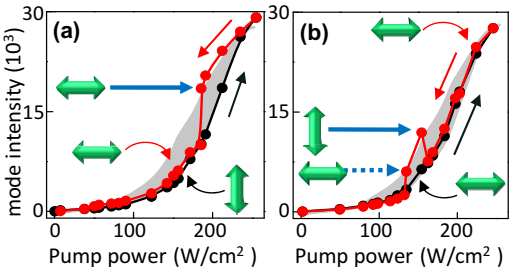

FIG. 3. (Color online) (a) Excitation signal power is stepped up with $P=90°$. At the power corresponding to the point on the ramp down curve highlighted by long bold arrow the polarization is switched ($P=0°$). Shaded area is the hysteresis curve of Fig. 2(c), shown for comparison. (b) Excitation is ramped up with $P=0°$, ramped down with $P=0°$, switched to $P=90°$ (solid arrow) at 152 W/cm^2 and switched back to $P=0°$ at 134 W/cm^2 (dotted arrow).

insensitive to the polarization despite the difference in observed dynamics. In the continuous wave measurements where the polarization dependence is observed, it is difficult to probe the time dependent dynamics of diffusion and carrier lifetime. Therefore, the true nature of this effect is difficult to probe experimentally and is not yet understood with current measurements.

The many degrees of freedom involved in coupled cavity dynamics make this emission modulation a complicated phenomenon whose complete understanding will require rigorous analytical and numerical treatment. However, our results so far do allow us to control the mode emission bistability by changing the incident polarization. In Fig. 3(a), the excitation power is ramped up with $P=90°$ on nonuniformly pumped elliptical disks. The excitation power is then ramped down with $P=90°$, but switched to $P=0°$ at a midway point, (bold arrow). The hysteresis disappears and mode intensity follows the lower branch as the feedback between the two disks is diminished. The shaded gray area is the hysteresis curve of Fig. 2(c) shown for comparison. In Fig. 3(b) we toggle the system between the two emission intensity states through polarization control. The excitation is ramped up with $P=0°$ until the emission intensity begins to saturate, then ramped down and switched to $P=90°$ (solid arrow) at 152 W/cm^2. The emission intensity jumps up to the value it would have had if the coupled system had achieved gain saturation at higher powers. It does not enter into this state irreversibly—switching to $P=0°$ at 134 W/cm^2 (dotted arrow) brings the emission intensity back down to the lower branch.

Bistable behavior in semiconductor microcavities has long been viewed as a viable option for designing optical memory devices and fast switches. The switching speed in a single microcavity can easily achieve gigahertz bandwidth. In a coupled system this speed would be limited by the time scale of gain saturation, and the recombination time of the carriers in the active region. Based on measurements and theoretical estimates[22,23] both these time scales can be as short as tens of picoseconds in a system such as ours, opening up possibilities for developing coupled arrays of ultrafast all-optical, on-chip devices with low operation thresholds and small footprints. In addition to applications in photonics, our results have important implications for solid state quantum information processing schemes centered on cavity quantum electrodynamics effects. In individual microdisks the quantum dot electron spins couple to the cavity modes. The coupled modes would allow scaling this electron-photon coupling across arrays of cavities and the switching protocol established here could potentially be developed into a means of manipulating spin coherence in such a multibit system.

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