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Quantum microcavities as efficient radiation sources

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A semiconductor microcavity consisting of a quantum well sandwiched between two mirrors may produce laser light with specific frequency, coherence, and polarization.

A laser is a radiation-emitting device that typically works through the stimulated emission of photons and has uses in fields from fundamental research to medicine and the military. One of the most important parameters of a laser is its threshold, the value of input power or current above which laser generation takes place, i.e., the radiation becomes coherent. The working principle of quantum-microcavity lasers, where the light is emitted spontaneously, is different from that of conventional devices: they are based on the stimulated scattering of radiation rather than on stimulated emission, which makes it possible to reduce the laser threshold dramatically.

A quantum microcavity is a microstructure where an active (light-emitting) layer, usually a quantum well, is placed between two mirrors. This enables a strong light-matter coupling where energy is coherently transferred back and forth between a photon trapped in the cavity and an exciton (electron-hole pair), the elementary excitation of the material: see Figure 1. This strong coupling, first observed in 1992,[1] results in the formation of novel half-light half-matter quasiparticles known as exciton-polaritons, which many researchers have studied in the past two decades.[2,3]

The fact that exciton-polaritons can condense to form a macroscopically coherent state opens up the possibility of creating a polariton laser with small emission threshold and extended temporal and spatial coherence of radiation.[4] The stimulated scattering of polaritons toward the ground state, which enhances the radiation of the microcavity, is created non-resonantly by optical or electronic pumping. The energy of the optical transition in the active layer determines the lasing energy. For gallium-nitride-based structures it amounts to about 3.4eV corresponding to the violet end of the visible spectrum. Structures based on cadmium telluride emit at about 1.7eV—i.e., red light—and gallium-arsenide-microcavity radiation reaches the near-IR

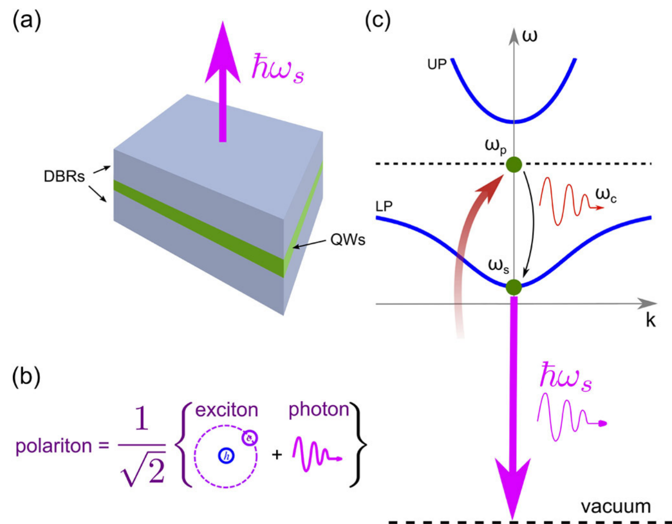

Figure 1. *(a) The structure considered in this work: a semiconductor microcavity consisting of an active layer containing quantum wells (QWs) sandwiched between two distributed Bragg reflectors (DBRs). (b) Illustrative scheme of the exciton-polariton as a coherent superposition of an exciton (electron-hole pair) and a photon. (c) Schematic of the polariton dispersion relation, showing the lower-polariton (LP) and upper-polariton (UP) branches. The emission of visible radiation with frequency $\hbar\omega_s$ is shown. The excited 2p exciton state with frequency ω_p and terahertz transition with frequency ω_c are also illustrated. k is the wavevector of the exciton-polariton.*

spectral range. The choice of proper material makes it possible to address a specific spectral part, while the fine tuning of emission energy can be realized by structure design and external factors: electric or magnetic fields, mechanical strain, and so forth. In our work, we theoretically studied the fundamental properties of quantum-microcavity lasers, namely, their coherence and polarization.

The key feature of the laser light is its coherence or ability to interfere. The temporal coherence related to the linewidth and spatial coherence are distinguished. The latter parameter, called

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$g^{(1)}(r)$, is related to the possibility for the system to share the same wavefunction at a distance r. Experiments show that if the condensate is formed, $g^{(1)}$ enhances strongly but still drops to zero for relatively large distance r, typically larger than 10μm. The origin of this decay may be related either to the phase fluctuations of the condensate or the fluctuations of the condensate amplitude.[5–7] Our recent work, carried out together with experimentalists from the Lebedev Physical Institute and the Institute of Solid State Physics, both of the Russian Academy of Sciences, aimed to clarify this issue.[8] We demonstrated that, at least for the pulsed excitation regime, the amplitude fluctuations are still large and limit the spatial coherence.

In addition to frequency and intensity, the radiation is characterized by its polarization, with the polarization state of the wave being directly related to the orientation of the photon spin. The condensate is usually linearly polarized due to the symmetry breaking that accompanies the condensation process. We recently predicted and observed the optical spin Hall effect, which results in the conversion of linear to circular polarization of light in a microcavity.[9,10] Of relevance for practical application, this effect can be used to generate polaritons and polariton fluxes with given spin or polarization state propagating over macroscopic distances.

As noted above, the emission of quantum microcavities usually corresponds to the visible range of the light spectrum. Our recent work suggests that such a structure can also be used to emit terahertz radiation.[11] The creation of a terahertz source is important due to various applications in modern technology such as information transfer and sensing.[12,13] The main obstacle in this field is the low rate of spontaneous emission of terahertz photons. According to Fermi's golden rule, this emission is proportional to the cube of the frequency and for terahertz transitions should be roughly tens of inverse milliseconds, while lifetimes of crystal excitations typically lie in the picosecond range. Strategies tried to improve the terahertz emission rate include using the bulky molecular or free-electron lasers,[13] the Purcell effect obtained by embedding the sample inside a terahertz cavity,[14,15] and the cascade effect in quantum-cascade lasers.[16,17]

We proposed a simpler route toward terahertz emission that uses two-photon pumping of the excited $2p$ exciton state: see Figure 1(c). This idea was inspired by other researchers who realized the two-photon pumping in gallium-arsenide-based quantum-well structures.[18] The direct transition to or from the $2p$ exciton state with emission or absorption of a single photon is forbidden by optical selection rules. Instead, a $2p$ exciton can radiatively decay to the lower exciton-polariton mode formed by the $1s$ (ground-state) exciton and cavity photon. This transition is accompanied by the emission of a terahertz photon. The terahertz transition from the $2p$ state pumps the lowest-energy exciton-polariton state, which eventually leads to polariton lasing (emission of coherent light). As a macroscopic occupation of the lowest-energy polariton state stimulates emission of terahertz photons, in the polariton lasing regime the cavity would ideally emit one terahertz photon for each optical photon emitted by the polariton laser. Our calculations show that such a situation is feasible.[11]

Quantum-microcavity systems can provide a playground for fundamental physics and may be useful for light-emitting-device applications. In our work, we suggested a way to control the polarization of quantum-microcavity emission based on the optical spin Hall effect and put forward a model of coherence propagation in exciton-polariton condensates. We anticipate that quantum microcavities can emit both visible light and terahertz radiation under specific conditions. In the future, we will theoretically model realistic devices to study the role of fluctuations in, e.g., the polarization of emission. Experiments in this area, in particular the detection of terahertz radiation from two-photon pumped quantum microcavities, are needed.

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