Numerical Approach to Determine the Fourier Plane of Light Propagation Through Cartesian-Oval Shaped Microlenses

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Exciton-polaritons are quasiparticles emerging as a result of strong coupling between photons in optical microcavity and excitons confined in quantum wells. Exciton-polaritons, due to their bosonic nature, can undergo a non-equilibrium phase transition to the condensate state [1]. This process occurs as a result of the relaxation of excitons with high momentum to the minimum of the lower polariton branch. Unfortunately, the observation of the polariton relaxation processes is experimentally challenging due to the numerical aperture (NA) of the optical system that limits the observable range of in-plane momenta.

Our idea was to design a novel shape of oval microlenses with high numerical aperture that would allow for the detection of so far unavailable ranges of polariton in-plane momenta and the direct probing of the excitonic reservoir. Our idea is based on the recent realization of aspherical solid immersion microlenses that allowed to shape the light emitted form nanostructures into low-divergence beam [2]. Our design allow not only to extract high emission angles but additionally, the Fourier plane is formed into a flat surface that can be easily projected onto a planar surface of a CCD.

We considered microlenses with various sizes and shapes to optimize imaging of the reciprocal (Fourier) space. The simulations were based on geometrical optics. We started from setting three point sources of light within the cavity and propagated from them beams at a different emission angles. Fourier plane is plotted based on the positions where the beams were the closest to cross each other. Repeating the procedure for different emission angles, we could simulate the geometry of the full Fourier plane as shown in Figs. 1(a) and 1(b). We found out that Cartesian-oval shape of the microlens results in a plane which is approximately planar for a wide range of the emission angles [Fig. 1(a)]. In addition, we compared the typical dispersion relation of exciton-polaritons in planar microcavities [Fig. 1(c)] obtained by standard imaging optics composed of microscope objective of NA = 0.55 (green) with the dispersion relation that would be realized by our microlens (orange). We prove that our microlens allows to access much wider range of energies and in-plane momenta and enables the observation of excitonic reservoir.

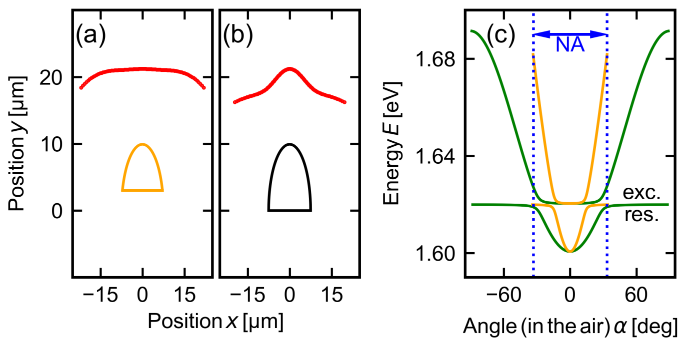

Figure 1: (a), (b) Fourier plane (red) determined for two different shapes of microlenses, (c) polariton dispersion relations obtained for the simulations of planar optical microcavity (green) and microcavity with printed microlens (orange) from (a).

[1] J. Kasprzak et al., *Nature* **443**, 409-414 (2006).

[2] A. Bogucki et al., *Light Sci. Appl.* **9**, 48 (2020).