Driven-dissipative Bose-Einstein condensation of photons in a VCSEL

Maciej Pieczarka[1], Marcin Gębski[2], Aleksandra N. Piasecka[1], Michał Wasiak[2], James A. Lott[3] and Tomasz Czyszanowski[2]

[1]*Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland*

[2] *Photonics Group, Institute of Physics, Lodz University of Technology, Łódź, Poland*

[3] *Institute of Solid State Physics and Center of Nanophotonics, Technical University Berlin, Berlin, Germany*

Photons are the first ever particles considered in the Bose-Einstein statistics and the most abundant bosons in nature. Surprisingly, photonic gases were among the latest to demonstrate Bose-Einstein condensation (BEC) [1], despite many analogies developed over the years between laser physics and BEC. Recently, semiconductor lasers have been proposed to be a promising direction in photon BECs at room temperature [2].

Here, we observe signs of a driven-dissipative BEC phase transition in a broad-area oxide-confined vertical-cavity surface-emitting laser (VCSEL) designed for 980 nm optical data communication. We tested devices with different cavity mode-quantum well energy detunings, following the conclusions of the photon BEC physics based on Rhodamine 6G-filled cavities. For negative detuning, we observed ground-state condensation, followed by a thermalised distribution of excited states, in agreement with the Bose-Einstein distribution. Remarkably, the photon gas thermalises to effective temperatures much lower than those of the device. We also extract the effective chemical potential from the spectrum and compare it to the theory recently developed in the ultra-fast thermalisation limit [3], which suggests the driven dissipative nature of the nonequilibrium BEC in the semiconductor resonantor. In contrast, for a positively detuned device, we observed a standard broad-area VCSEL behaviour with multimode lasing above the threshold current, with an absence of Bose-Einstein distribution. Furthermore, we discuss the issue of an accurate description of the density of states of a realistic device and the actual shape of the confining potential under different driving conditions.

Our results show a new perspective on semiconductor VCSELs, which can be used to test the nonequilibrium BEC physics in table-top room-temperature devices. Moreover, it opens the possibility to observe effective photon-photon interactions and collective superfluid phenomena in photon BECs, using the well-known ultrafast semiconductor nonlinearities, which has been impossible in rhodamine-based photon BECs limited by the slow thermo-optical nonlinearity. This would eventually link the worlds of polariton and photon superfluid physics into one device.

[1] J. Klaers et al., Nature 468, 545 (2010)
[2] S. Barland et al., Opt. Express 29, 8368 (2021)
[3] V. Y. Shishkov et al., Phys. Rev. Lett. 128, 065301 (2022)