Local thermodynamic properties of a photon gas in a broad-area VCSEL

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

[1] *Department of Experimental Physics, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland*
[2] *Institute of Physics, Łódź University of Technology, ul. Wólczańska 219, 90-924 Łódź, Poland*
[3] *Institute of Solid State Physics and Center of Nanophotonics, Technical University Berlin, Hardenbergstraße 36, 10623 Berlin, Germany*

The thermalized photon gas trapped in a semiconductor optical microcavity has the potential to act as a Bose-Einstein condensate of photons [1]. The chemical potential, a crucial parameter for determining the thermodynamic state of the photon gas, plays a pivotal role in this process. As for Bose-Einstein condensate, the chemical potential value should vanish at the transition point, approaching from negative values. However, recent theoretical developments [2] have predicted that a photon gas can experience nonuniform thermodynamic properties in real-world devices under nonuniform excitation. This underscores the importance of a detailed understanding of the local chemical potential of a gas of photons in a microcavity, which is necessary to quantify semiconductor lasers as BEC of photons accurately.

Large-area electrically pumped vertical-cavity surface-emitting lasers (VCSELs) often suffer from inhomogeneous light emission due to the uneven distribution of current and temperature within the laser cavity. The nonuniform current density in VCSELs with wide apertures leads to localized distribution of the chemical potential, which is determined by the difference between quasi-Fermi levels for electrons and holes in the active region. Temperature inhomogeneities can also cause variations in the cavity width, affecting photon confinement and potentially altering the number of available states and the values of the Bose-Einstein distribution.

Our study outlines a new approach for determining the local chemical potential of photons in wide aperture oxide-confined VCSELs through fitting the Bose-Einstein distribution to the local spontaneous emission spectrum in wavevector space. We assume a constant density of states in spatially filtered local spontaneous emission of the real space spectrum. Our findings reveal varying values of the local effective chemical potential and effective temperature at different positions, with higher current densities at the edge of the aperture resulting in larger values of both. These results support recent theoretical predictions [2] and provide valuable insight for further experimentation.

Studies on the thermalized photon gas in semiconductor microcavities provide a new class of devices acting as room-temperature Bose-Einstein condensates of photons. Therefore, a detailed knowledge of the broad-area VCSELs' properties may allow for new, promising research possibilities in Bose-Einstein condensation physics.

[1] M. Pieczarka, M. Gębski, A. N. Piasecka, J. A. Lott, A. Pelster, M. Wasiak and T. Czyszanowski, *ArXiv*: https://arxiv.org/abs/2307.00081, 2023

[2] A. Loirette-Pelous, J.J. Greffet, *Laser Photonics Rev.* 17, 2300366, 2023