Bose-Einstein Condensation of Light in a Semiconductor Vertical-Cavity Surface-Emitting Laser

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We present our observation of a Bose-Einstein Condensate (BEC) phase transition in a broad-area (23-μm diameter) oxide-confined vertical-cavity surface-emitting laser (VCSEL) designed for 980-nm optical data communication. To distinguish BEC from standard lasing action, we tested devices with different cavity mode-quantum well energy detuning $\Delta = \varepsilon_0 - \varepsilon_{QW}$, to operate the device below the Bernard-Duraffourg lasing condition and achieve photon gas thermalization. For the device close to resonant detuning $\Delta \approx 0$, we observed fundamental transverse-optical mode condensation with a characteristic thermalized tail of higher-order modes, closely following the Bose-Einstein distribution. Moreover, we experimentally extracted the parameters of the equation of state (EOS) of the photon gas in the probed VCSEL. We found perfect agreement with the EOS of a textbook 2D Bose gas, confirming its thermodynamic properties. On the contrary, for a negatively detuned device $\Delta < 0$, we observed a standard broad-area VCSEL behavior, with multi-mode lasing at higher-order modes above the threshold current. This device also showed poor thermalization, as evidenced by the deviations from the Bose-Einstein distribution.

Our discovery opens a new perspective on understanding semiconductor VCSELs, which can be used to test the BEC physics in table-top room-temperature and current-driven devices. We anticipate that VCSELs can operate in a thermalized regime below reaching positive gain. Finally, the thermalization mechanism and the BEC effect allow one to achieve single-mode coherent operation in a broad-area VCSEL, strongly contrasting the common belief of the behavior of these devices.