Transverse coupled-cavity vertical-cavity surface-emitting lasers (TCC-VCSEL) have emerged as a promising platform for beam steering, on-chip terahertz generation, and for surpassing the intrinsic modulation bandwidth limitations of conventional VCSELs through the photon–photon resonance (PPR) mechanism. Despite this potential, their practical exploitation remains strongly constrained by high sensitivity to technological imperfections, dynamical instabilities, and the absence of predictive design methodologies.

This thesis introduces a comprehensive, physics-based modeling framework for the multimode dynamics of VCSELs, derived from a modal expansion of the scalar wave equation. The resulting formulation provides a unified description of the rich phenomenology of TCC-VCSELs and, unlike existing phenomenological approaches, explicitly connects geometric and material parameters to the modal coupling coefficients governing device dynamics.

The model is validated through comparison with recent experimental measurements on bow-tie providing physical interpretation of the observed behaviors.

This work establishes a theoretical foundation for the systematic design of next-generation TCC-VCSELs as well as providing general, transferable insights into the multimode dynamics of VCSELs.