Vertical-cavity surface-emitting lasers: computer-aided modal and polarization engineering

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PhD Thesis Abstract

In this work, we address the modeling and design of vertical-cavity surface-emitting lasers (VCSELs) featuring large-active-area non-circular geometries and elliptical polarization states. This is motivated by novel applications such as chip-scaled atomic clocks, quantum gyroscopes and atomic magnetometers, requiring high-power single-mode emission and circular polarization for optical atomic pumping. Traditional VCSELs, based on circular oxide apertures, featuring a relatively low optical power and linear polarization, are not suited for these needs, thus demanding new device architectures and accurate simulation tools.

To this end, a comprehensive and physics-based mathematical framework has been developed, capable of describing the electromagnetic modal behavior of VCSELs with arbitrary transverse geometries. The resulting simulation tool, our VCSEL ELectroMagnetic Suite (VELMS), supports both full-wave 3D simulations and simplified 1D scalar and vectorial formulations. The framework allows an efficient computation of optical modes and polarization states, only relying on the refractive index distribution of the VCSELs, and can also include self-heating and surface patterning effects.

The developed model was applied to two classes of VCSELs. The first focuses on large-area rectangular VCSELs for high-power, single-mode operation. These devices exploit surface grating reliefs to achieve single-mode emission by matching the relief positions with the intensity peaks of the desired optical mode. High-power single-mode devices relying on this strategy were realized and measured in terms of near and far-field profiles, confirming our simulation results. Further optimizations involved far-field shaping for a better coupling with optical fibers and the modification of the grating reliefs' design at high bias currents, where thermal lensing strongly affects the topography of the optical modes.

The second application concerns VCSELs that can directly emit elliptically and circularly polarized light, targeting the elimination of bulky quarter waveplates in chip-scale atomic devices, needed to convert the polarization from linear to circular. A new approach to achieving polarization control was introduced, based on the concept of 3D cavity chirality, obtained from the interaction of tilted optical anisotropies. We simulated and measured a fabricated device, which combines the anisotropy arising from the electro-optic effect, aligned with the semiconductor crystal axes, and a tilted subwavelength grating. By doing so we confirmed the model's ability to predict the Stokes parameters associated to the lasing polarization, thus further validating the simulation tool. Parametric optimizations were performed to maximize the degree of circular polarization and explore the role of strain, which introduces additional optical anisotropies through the elasto-optic effect.

This work provides both a rigorous theoretical foundation and practical design strategies for next-generation VCSELs. Thanks to its generality, the developed framework is applicable to a wide variety of VCSEL architectures, including different wavelengths, and material systems, making it a versatile asset for current and future photonic applications.