Vertical-cavity surface-emitting lasers (VCSELs) are presently the subject of intense research due to their potential as compact, efficient, astigmatic laser sources for a number of important applications. Of special interest are the selectively-oxidized VCSELs that have recently set records for threshold current and wall-plug efficiency. The onset of higher-order modes at powers of a few milli-Watts, however, presently limits the wide utilization of these devices and indicates the need for improvements in design. Unfortunately, their complexity precludes optimization based solely upon empirical methods, and points instead to the need for better numerical models.

Modeling the optical field in a vertical-cavity laser, however, is especially difficult due to both the high Q of the optical cavity and the distributed reflectivity of the mirrors. The former precludes the use of several time-honored techniques such as SOR or ADI that depend on iteration to compute the field. Such techniques fail to converge at reasonable rates because several modes typically have round-trip gains close to unity. The latter renders suspect the use of beam-propagation methods that have been employed so successfully in the study of edge-emitting lasers. This method can still be used if an effective reflection plane is defined, but effects such as the contribution of nonuniform doping profiles to the free-carrier-absorption loss cannot be included accurately. More importantly, the calculation of scattering losses due to the oxide layers in selectively-oxidized lasers by this method is suspect because the Fresnel rings generated by diffraction from the low-index apertures tend to reflect and interfere in a complicated way from the mirrors. It is not clear exactly what errors may be introduced by modeling this phenomena by assuming reflection from a single plane.

Our approach to this dilemma has been the development of modeling techniques on two complexity scales. We first derived an effective-index model that is numerically efficient and thus can be included together with carrier transport and thermal models to make up a self-consistent modeling package. In addition to its use in the overall VCSEL model, this simplified optical model has been extremely valuable in elucidating the basic principles of waveguiding in VCSELs that in turn have led to new ideas in device design. More specifically, the derived expression for the effective index shows clearly that index guiding in a VCSEL depends only on variations in optical cavity length, and thus can be engineered without the need to alter the material index of refraction. This fundamental understanding is illustrated in Figure 1, in which the radiation in a simplified laser cavity that propagates normal to the device axis in the shorter region is forced to tilt as it diffracts into the longer region in order to maintain the Fabry-Perot resonance condition. But the tilt angle is exactly the internal reflection angle corresponding to materials with index difference given by the effective index expression. Following this new understanding of waveguiding, we have designed index-guided and antiguided devices whose cavity lengths are modified in certain regions by etching of the cavity material prior to growth of the second mirror. Fabrication of these new device designs is presently in progress.

Despite the success of the effective-index model, it is limited in its accuracy to devices in which the lateral cavity variations are minor. Other devices such as selectively-oxidized lasers that clearly do not fall in this category may not be accurately modeled. Thus we have explored other solution techniques for the laser field that are more general in applicability. This initiative has resulted in a highly-accurate finite-difference approach that solves the scalar Helmholtz equation for the laser mode in a general cylindrically-symmetric cavity. We have first of all used this technique to verify the predictions of the effective index technique for devices within its sphere of validity. Second, this approach requires no assumptions concerning the lateral device variations and thus is ideal for computing, for example, the scattering losses for various selectively-oxidized designs. We have recently computed the round-trip scattering loss for devices of various radii using this approach, and the results are shown in Figure 2, expressed as a ratio of the total...
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round-trip loss to the 1D loss (due to free-carrier absorption and outcoupling through the mirrors). Moreover, although this model is more numerically intensive than the effective index model, recent work has reduced both the computer memory and runtime required for its use, making it potentially available for future use on personal computers. The combined insights obtained from these two optical models is thus expected to have considerable impact on the design of a new generation of VCSELs.


Fig. 1. Schematic illustrating the way in which differing cavity lengths appear as index differences. The tilt angle shown corresponds to the angle of total internal reflection for a medium of higher index.

Fig. 2. Scattering loss of selectively-oxidized VCSELs with different radii and either one or two quarter-wave apertures as computed using the finite-difference numerical model.

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