Direct Measurement of Pump Intensity Distributions in an Optically Pumped Vertical-Cavity Surface-Emitting Laser

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We have mapped the internal pump intensity distribution by monitoring the spontaneous emission intensity along the cleaved edge of an optically pumped vertical-cavity surface-emitting laser (VCSEL) using the high spatial resolution and shallow depth of field provided by near-field scanning optical microscopy (NSOM) [1]. The spontaneous emission of quantum wells placed throughout the distributed Bragg reflectors (DBR) is correlated to the pump intensity. Simulations performed using the transfer matrix method match well with the measurements presented.

Viable optically pumped and hybrid optically-electrically pumped VCSELs and their applications have been limited by poor pump coupling sensitivity and the high cost associated with the required tunable pump laser. Devices eliminating the need for a tunable pump laser have been demonstrated through direct optimization of the optical pump intensity distribution [2]. Collection of the spontaneous emission along the cleaved edge of the VCSEL provides a direct measurement of the spatial distribution of the pump intensity as a function of wavelength.

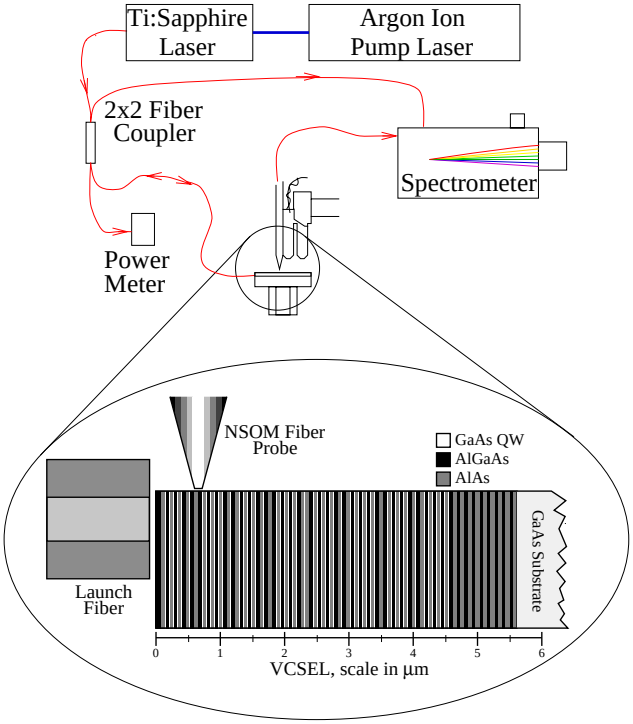

Fig. 1. The experimental setup includes NSOM equipment, pump, collection, and feedback optical paths. The scaled insert of the device structure shows the distributed quantum wells including the tip drawn on the same scale (the launch fiber is not on the same scale).

While most VCSELs have quantum wells only in the resonant cavity region, the optically pumped device measured here was grown with a quantum well at every interface of the $Al_{0.2}Ga_{0.8}As/AlAs$ quarter wave mirror layers (Fig. 1 inset) [3]. The pump field excites electrons and holes in each quantum well and the resulting spontaneous emission rate is linearly proportional to the pump intensity as long as the pump intensities are well below the VCSEL lasing threshold. As the incident intensity increases, the spontaneous emission profile becomes a superposition of the pump intensity distribution and the resonant cavity mode.

The VCSEL was pumped using light from a Ti:Sapphire laser, launched into a 2x2 fiber coupler (Fig. 1). The high power output leg was simply butted against the sample, and the low power output leg was used to monitor the optical power incident on the sample. Since the pump and lasing axes are the same, the launch fiber was used to collect the emission in the pump intensity direction which was directed to a spectrometer through the fourth leg of the coupler.

The NSOM probe, a single-mode fiber with a tapered end of aperture ∼100 nm in diameter, was held at a constant height of 10 nm above the cleaved edge while being scanned along the lasing axis. Light collected at each position by the fiber probe was dispersed by a 0.6 m spectrometer.

Figure 2 displays the integrated intensity of the collected spontaneous emission as a function of position along the cleaved edge of the VCSEL for two different wavelengths of pump laser light, one centered within a reflectance null (780 nm) and one far away from the lasing wavelength above the $Al_{0.2}Ga_{0.8}As$ band gap (700 nm). Data points are shown as diamonds, with solid lines representing transfer matrix method [4] sim-

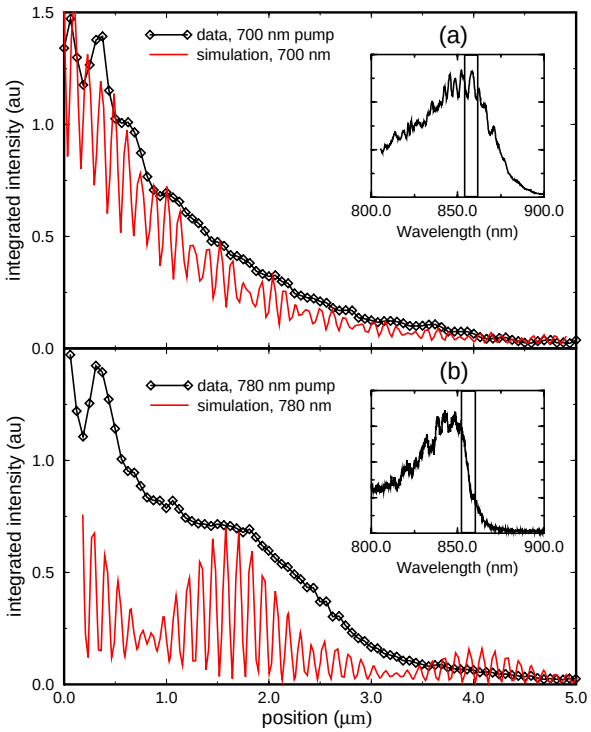

Fig. 2. Integrated spontaneous emission (diamonds) versus transfer matrix method simulations for 700 nm and 780 nm pump light wavelengths. The insets show individual spectra from the same point, including the spectral integration region.

ulations for the conditions illustrated. For the 700 nm excitation, Fig. 2a, the spontaneous emission profile is dominated by absorption in the $Al_{0.2}Ga_{0.8}As$, yielding an exponential decay into the stack, in agreement with the simulation. The measurement for excitation centered within a reflectance null (Fig. 2b), however, shows a distinct buildup of optical intensity inside the layer structure, also predicted by the simulation, where the light is absorbed only by the GaAs quantum wells. The measurement is unable to resolve the fine structure shown in the simulation, due to the resolution limit of NSOM.

The measured spontaneous emission displays a weaker minimum than the simulation results at a distance of $\sim$1 μm from the surface. This could be the result of additional excitation due to pump light scattering across the surface contributing to a nonlinear background or to the beam divergence of the pump field in the sample. Launching with an objective would result in very little pump beam divergence on the length scale of the sample. However, the fiber launch was used due to its alignment flexibility.

Unexpected spontaneous emission profiles are observed when the pump beam is displaced below the cleaved edge collection surface. In particular, when the launch fiber was placed 80-100 μm down from the sample edge, smooth periodic profiles along the lasing axis emerged in the spontaneous emission. The frequencies of the intensity variations do not correspond to any of the device's physical dimensions or tip-sample cavity effects. With the pump beam placed low on the sample edge, the spontaneous emission profile became much more sensitive to the spectral position of the integration range. When the integration region was moved from above the device lasing wavelength to below, the profile underwent a $\pi/2$ phase shift. Initial results from a finite difference time domain simulation suggest that the periodicity may be a super-mode due to a wave guiding effect from light propagating vertically along the layers.

In conclusion, we have demonstrated the direct mapping of the internal pump intensity distribution of an optically pumped VCSEL structure. The technique is made possible by the combination of distributed quantum wells through the mirror stacks and near-field scanning optical microscopy. This technique is a valuable tool for directly evaluating the spatial distribution of the pump field as a function of wavelength. These results will be extended in future work to optimize devices which tailor the thickness of the mirror layers to achieve a desired spectral and spatial function of pump field overlap with the active region.

References

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