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Minimum Pulsewidth and Delay for Multiple Quantum Well Vertical Cavity Lasers

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Short pulse generation capability of multiple quantum well vertical cavity surface emitting lasers (VSELs) is confirmed by numerical and experimental results. Picosecond optical pumping effects, such as bleaching and gain saturation, are modeled within the context of the rate equations, yielding an accurate description of cavity response in terms of minimum pulsewidth and delay. Different input pumping conditions and cavity designs are examined, predicting parameters for an optimized structure with minimum output pulsewidth and delay.

1. Introduction

VSELs represent a viable and advantageous technology for optoelectronic integrated circuits (OEICs) and laser arrays [1-2]. In addition to their monolithic structure, narrowly diverging beam and single longitudinal mode operation, they have the potential to operate at high modulation bandwidths.

Their short cavity length can be linked to a short internal lifetime, implying a fast cavity response to high-speed input drives. This has been demonstrated by calculation of the resonance frequency in terms of the laser design parameters [3]. It is useful to understand in some detail the mechanisms of short optical pulse generation, so that new lasers can be designed for optimum switching speed.

2. Analysis

Runge-Kutta numerical integration of the rate equations is used to develop a theoretical model for pulsewidth and delay. Several terms are of particular importance for accurate modeling of the cavity dynamics in a VSEL. These are the confinement factor, carrier dependent gain, and carrier dependent absorption.

Confinement to the gain region of the laser is vertical, and described by a fill-factor, $F = d/Leff$, where d is the width of the active material, and $Leff$ is the effective cavity length, including penetration depth into the dielectric mirrors.

In order to more accurately model the material effects in the structure, a different numerical model is used to give a set of carrier dependent values for both the gain and the bleaching observed in the laser [4]. This model describes carrier overflow from the confined quantum states in the quantum well gain region to the barrier regions between wells.

Cavity dynamics over time are examined, as well as cavity response to different optical input powers and pulsewidths.

3. Results

The device modeled and measured is shown in Figure 1. Cavity length is 3.6 μm (assuming a 0.5 μm penetration depth into each mirror). Top and bottom mirror reflectivities are 0.922 and 0.981, respectively, and there are 20 quantum wells of 300 Å each in the active region.

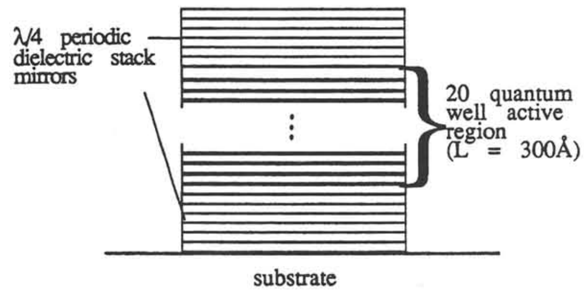

Figure 1. Simulated and optically pumped structure.

Optical input is modeled by 6 ps full width half maximum (FWHM) pulses with a hyperbolic secant pulseshape. Gain switching is observed in the output, as expected given the short risetime of the input. Bleaching is an important effect in restricting the minimum output pulsewidth, since it retards the maximum electron density. Figure 2 shows the electron and photon densities over time for the bleached and unbleached case.

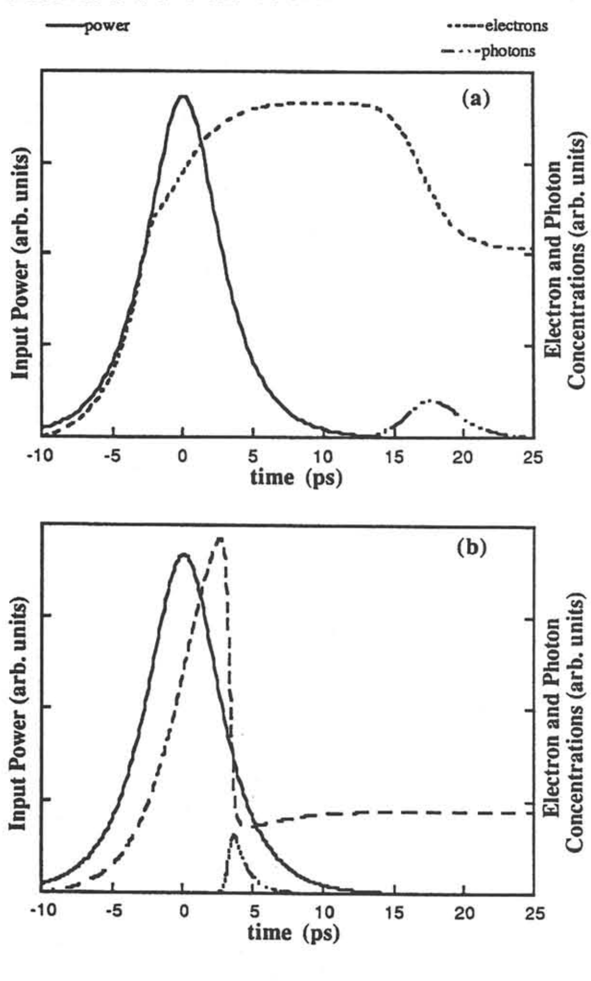

Figure 2. Comparison of cavity carrier densities for the case of (a) bleaching, and (b) no bleaching.

Optical pumping experiments are performed with a 6 ps FWHM sech(t) pump pulse from a mode-locked dye laser, and monitored by high-speed photodiode and background free autocorrelation, as described in [5]. Bleaching is seen to be critical for matching the simulations to the trends and magnitudes of the measured values for pulsewidth and delay (Figure 3). Figure 3 shows the variation of output pulsewidth and delay with optical input power. By similar comparison with measured results, the effect of gain saturation is found to be a small contribution to pulse broadening in the device.

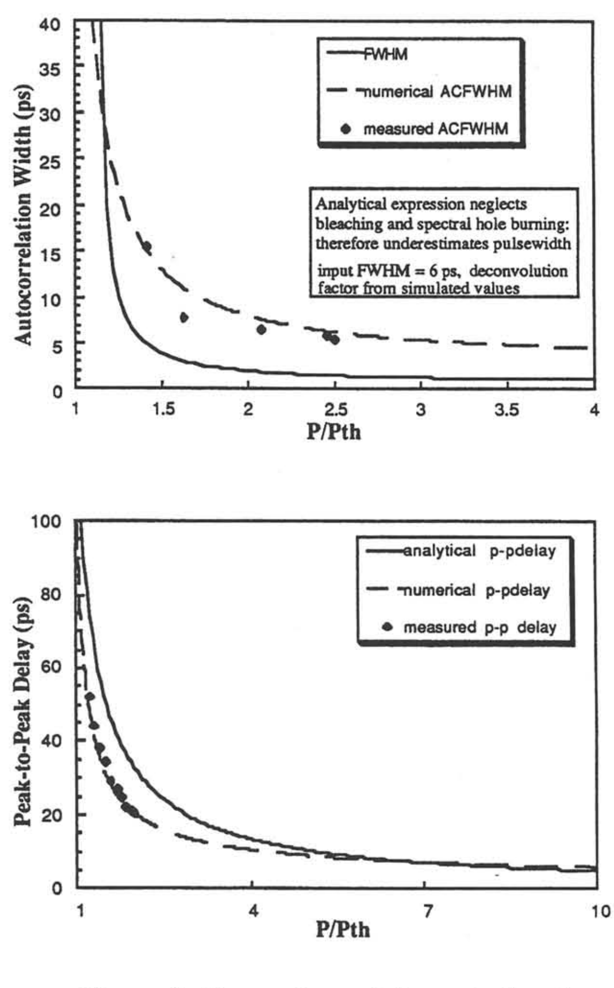

Figure 3. Comparison of theoretical and experimental autocorrelation pulsewidth and delay vs. normalized input power. Both graphs also show an approximate closed form expression derived from the rate equations.

The minimum output pulsewidth which is predicted for a 6 ps input pulse is ~2.5 ps, with a delay of 7.2 ps, at eight times threshold. These are not the shortest output pulses available, however. A shorter input pulse will produce a shorter output pulse until device limits are reached. The effect of varying input pulsewidth while maintaining constant total pump pulse energy is shown in Figure 4.

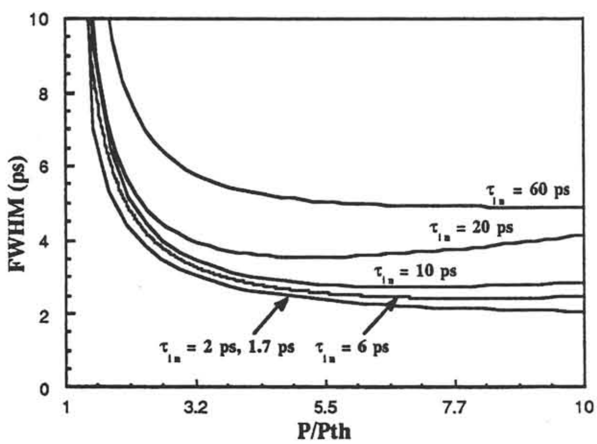

Figure 4. Output pulsewidth vs. normalized average input power for different input pulsewidths.

The shortest cavity limited pulses occur for ~1.7 ps FWHM input pulsewidth, which appears on the graph to be coincidental with the 2.0 ps input curve. These conditions yield a 2.0 ps output pulse with a delay of <10 ps. Further reduction in input pulsewidth results in no further decrease in output pulsewidth.

Input pulses in the middle of the range shown in Figure 4 (6 - 20 ps) will result in an output pulsewidth that grows larger with power after the minimum. Shorter and longer inputs simply reach a minimum, with no subsequent increase. Increase in pulsewidth with power occurs when the input and output pulses are coincident. This occurs for sufficiently short values of delay.

The difference in response for shorter and longer pulses can be explained as follows. For very short input pulses, the input and output will never occur simultaneously, since the delay will never decrease to a low enough value. For the case of input pulses longer than ~20 ps, the excess energy from simultaneous pumping and emission forms a relaxation oscillation, and allows the initial pulse to maintain a small FWHM.

4. Design Considerations

The simulation program may be used to design future generations of devices. Critical design parameters are the device length and mirror reflectivity. The dependence of pulsewidth on these two values, for an input power of 20 mW and input pulsewidth of 6 ps, is shown in Figure 5. At low values of reflectivity, threshold is too large for the device to lase. At high values, the photon density becomes too high, and again the output FWHM increases.

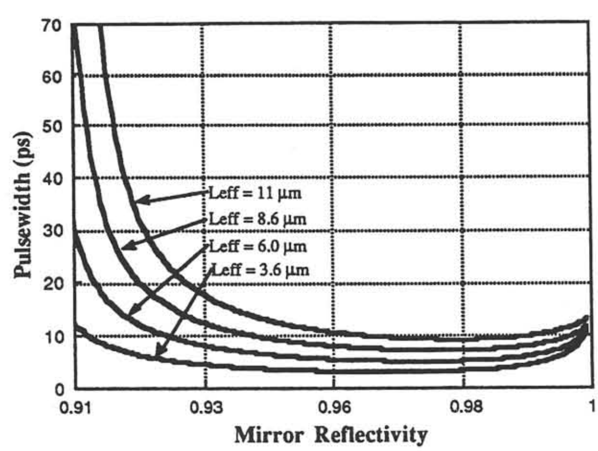

Figure 5. Output pulsewidth vs. mirror reflectivity for different values of cavity length.

Clearly the cavity length plays a critical role in reducing the minimum pulsewidth. Each curve in Figure 5 is placed vertically depending on this value, and even shorter pulses can be achieved if the cavity length is reduces to its minimum.

5. Conclusions

VSELs have been demonstrated to have gain switching characteristics comparable with those observed in horizontal-cavity laser technology.

With high-quality electrical contacts, these lasers should be capable of gigahertz modulation rates.

Computer simulations of the cavity dynamics have shown that material bleaching is a serious limitation to the speed of the device under optical pumping conditions. In the case of the 20-quantum well laser examined, minimum pulsewidth and delay are demonstrated to be quite short, on the order of 2 ps and 10 ps, respectively.

Simulations of cavity response can be used to design new lasers with even better perfomance than the one shown here. These same calculations can be used to choose a bias point for the devices, and correct, through CW biasing, any device-to-device variation.

References

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