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ULTRALOW THRESHOLD QUANTUM WELL LASERS FOR COMPUTER INTERCONNECTS

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ABSTRACT

Optical computer interconnects appear very attractive when integration of state of the art technology of quantum well GaAs/GaAlAs lasers is considered. These ultralow threshold lasers provide the very high transmission rates and the inherent simplicity required for such systems. A detailed design is presented for a 5 Gbit s^{-1} transmission rate, suppression of pattern effects, and a system power supply of approximately 25 mW per laser. Existing experimental data show that little extrapolation is required to reach that kind of performance from state of the art technology.

1. INTRODUCTION

The replacement of electrical interconnects with optical interconnects for board-to-board communications will necessitate a large number of optical emitters and detectors[1]. It is estimated that a typical supercomputer will require as many as 10^5 emitter/detector pairs.

Conventional semiconductor lasers, having threshold currents of 20 mA or so, fall short of meeting the requirements for these interconnects for two reasons[2]. First, these lasers must be prebiased to the lasing state in order to achieve high speed switching operation. This continuous current flow leads to excessive power dissipation in the computer. Secondly, and more importantly, the required bias current varies from device to device, over the life of the device, and over temperature. The conventional approach of sampling the emission from the rear facet of the laser and applying this signal as feedback to a bias current controller is too cumbersome in terms of size, complexity, and cost.

The use of ultralow threshold current lasers substantially eliminates both of the above mentioned objections to the use of lasers[2]. The ultralow threshold current laser does not require prebiasing to achieve fast turn-on because they can be driven with current pulses exceeding threshold by significantly more than a factor of ten. Without prebiasing power dissipation is reduced and feedback circuitry is eliminated.

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SQW BH (single quantum well buried heterostructure) lasers having threshold currents as low as 0.55 mA have been fabricated[3]. The SQW structures were grown by MBE (molecular beam epitaxy), and more recently by MOCVD (metal-organic-chemical vapor deposition). The SQW active layer material displays much lower transparency current densities than conventional double heterostructure material that have a much thicker active region. The low value of the transparency current density is converted to a low value of threshold current by fabricating devices having narrow stripe widths and short cavities to cut down the area of the pumped region, and higher mirror reflectivity to keep the required optical gain down at a moderate level.

Experiments to demonstrate the high speed switching characteristics of devices without prebias have been performed[2]. Switch-on delays of less than 70 ps have been observed with no subsequent ringing.

The following is the list of the subjects to be discussed in this paper:

2) Why Quantum Well Lasers
3) Performance of Single Quantum Well Structures
4) Scaling the Size for Communication Lasers
5) Experimental Findings to Date
6) Projected Performance Figures
7) Alternate Schemes for Vertical Coupling
8) Future Improvements

2. WHY QUANTUM WELL LASERS

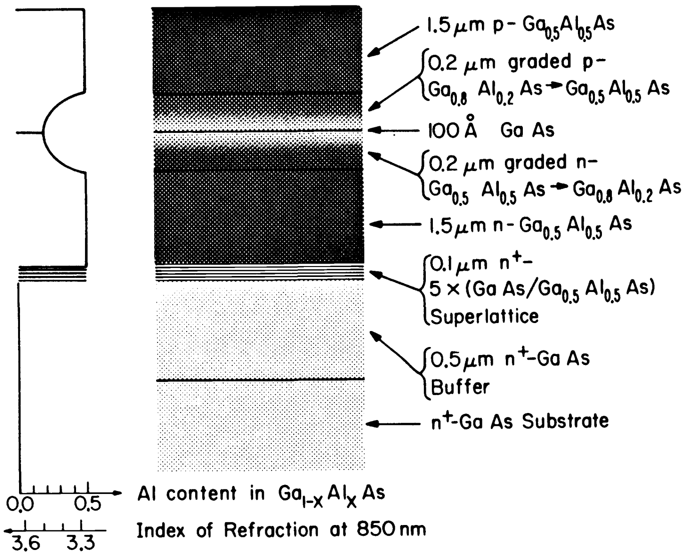
The benefits of quantum well lasers over conventional double heterostructure lasers have been investigated (e.g. Ref. 4). Fundamentally, the double heterostructure is capable of producing high optical gain; in nearly all applications, this capability is not taken advantage of[5]. By carefully optimizing the structure to provide the moderate amount of gain actually used, the design ends up with a very small thickness of the active region. Devices with very thin active regions (<200 Å at room temperature operation) show quantum effects and are therefore called quantum well lasers. In most applications, the quantum structure effects are not the major benefit; the sheer small size of the active region is what is taken advantage of. Because the gain produced by quantum well lasers is moderate, careful attention has to be paid to the design of the optical cavity[6,7]. The major benefit of suitably designed quantum well lasers is reduced threshold current density with respect to conventional double heterostructure lasers.

Experimentally, it is found that with respect to internal quantum efficiency and distributed losses, laser performance is improved if the threshold current density is kept low. It is advantageous to use a low loss resonator design with a single quantum well structure rather than using a somewhat higher loss cavity with a conventional double heterostructure simply because the current density is significantly reduced. Some of the quantum characteristics provide further improvement on the basic performance gain.

3. PERFORMANCE OF SINGLE QUANTUM WELL STRUCTURES

If quantum well structures are used, a choice has to be made as to how many quantum wells are to be incorporated. A multiple quantum well structure is the structure of choice if a single quantum well structure cannot provide sufficient gain. If the design is free to be optimized for a low threshold current laser, the gain requirement is a parameter to be determined. Therefore, the optimum choice is to operate the laser with the low gain requirement which is ideally provided by a single quantum well laser.

Single quantum well structures have been studied extensively (e.g. Ref. 8, 9). An example of the vertical structure of a "standard" single quantum well lasers is shown in Fig. 1 [10]. The structure incorporates a graded region around the quantum well to guide the optical mode. The effective widths of the optical mode in this structure is approximately 3000 Å. Based on extensive calculations[5], Fig. 2 shows the modal gain of this structure in comparison to the double heterostructure with the same optical mode width. The significant improvement for low modal gains is evident.



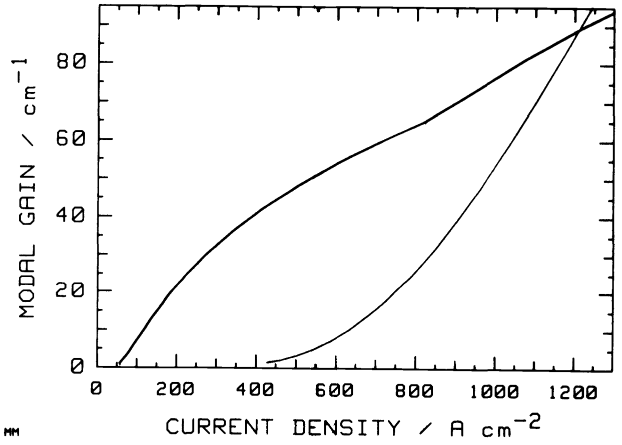


Fig. 1 Single quantum well layer structure[10]. On the left, the profile of the Al-concentration is illustrated as well as the approximate index of refraction of the material.

Fig. 2 Calculated modal gain vs. pump current density[5]. The upper trace applies for the single quantum well structure shown in Fig. 1 the lower right trace applies to a conventional double heterostructure laser.

High quality material single quantum well lasers with long resonators will exhibit threshold current densities of approximately 200 A cm^{-2}. If the gain requirement is kept low, corresponding to a modal gain around 20-30 cm^{-1}, this current density can be maintained even in shorter cavities. The requirement is then to increase the reflectivites such that the output coupling, when considered as a distributed loss, is kept constant. This is the preferred operational condition for a short cavity single quantum well laser.

For a conventional double heterostructure, the calculated modal gain to current density ratio is monotonically increasing for modal gains of up to 100 cm^{-1} and beyond (Fig. 2). For single quantum well lasers a maximum is reached near 30 cm^{-1} of modal gain, at a current density so low that the conventional laser cannot produce any gain.

The dependence of modal gain on current density is the main distinguishing feature of the two structures. Experimentally, it is found that the calculated values of modal gain are too optimistic for current densities higher than 500 A cm^{-2}. This leads to a pronounced flattening of the available modal gain at high pump current densities. Resonator designs which require low modal gain are clearly desirable.

Quantum well lasers benefit from two more properties of the quantum well structure. The internal quantum efficiency of these structures has been found to be superior to double heterostructures. Reproducible values close to 90% have been measured [9,11,12]. Secondly, the distributed losses of single quantum well structures are the lowest of all semiconductor lasers. These low internal losses lead to higher output efficiencies even if the low output coupling is selected.

4. SCALING THE SIZE OF A COMMUNICATION LASER

For short distant communication, as in a computer, the optical losses of the communication link can be expected to be moderate. Therefore, no premium has to be placed on the absolute output power of the emitting laser. Consequently, lasers as small as possible are advisable. Scaling the size of the laser down reduces the total threshold current.

Assuming the vertical structure is not changed and remains as shown in Fig. 1, the widths and lengths of the laser can be scaled. Proven technology allows to scale the widths down to 1 micrometer. Typically the buried heterostructure design is used for such narrow lasers (Fig. 3). At about 1 micrometer width of the active region, typically an optical mode width close to twice as wide as the active region is to be expected. This has two consequences. The modal gain as provided by the quantum well is reduced to nearly one half, and the buried structure typically also exhibits increased distributed losses. Measured values indicate 10 cm^{-1} or lower. This puts a constraint on the scaling for the lengths of the laser unless we consider extremely high reflectivities.

A good high reflectivity coating should provide 95% reflection. If the device is made asymmetric to emit most of the light on one side as it is advantages for optical communication, that side should have a lower reflectivity. For example, an output reflectivity of 83% results in cavity lengths of approximate 120 micrometers to meet the above introduced criteria.

5. EXPERIMENTAL FINDINGS TO DATE

For the experiments, a structure as shown in Fig. 1 was optimized for liquid phase epitaxy regrowth to produce buried single quantum well laser structures. The quantum well structure was grown using a molecular beam epitaxy facility at the California Institute of Technology by Pamela L. Derry. Buried lasers 1 micrometer wide and 250 micrometer long were fabricated. After increasing the reflectivity to about 0.7, those laser exhibited threshold currents as low as 0.95 mA [13]. These lasers were used in high speed digital modulation experiments where rectangular current pulses of different amplitude were applied to the laser without biasing. The resulting large signal response is shown in Fig. 4. Note that the leading edges show delays depending on the amplitude of the current pulse, while the time of the falling edge of the light pulse seems to be independent of the amplitude of the current pulse.

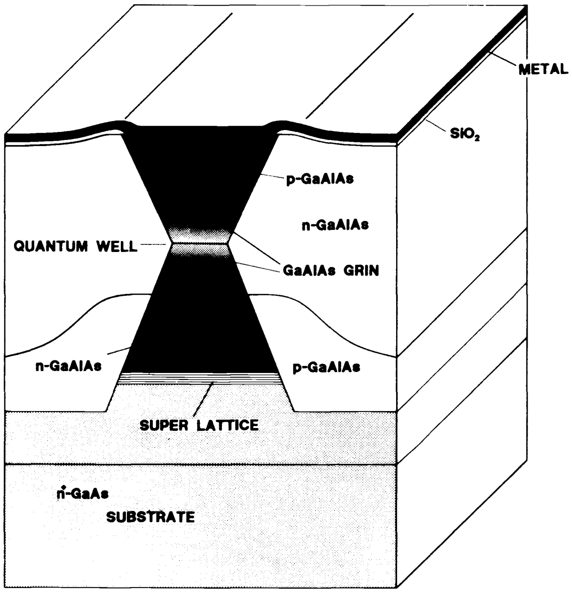


Fig. 3 Structure of the buried heterostructure quantum well laser.

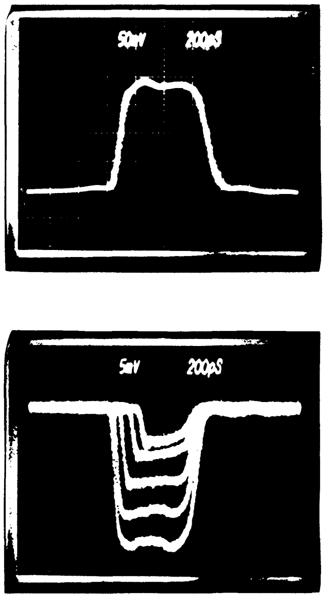


Fig. 4 Pulse response of 0.95 mA threshold quantum well laser. At the top a typical drive current pulse. At the bottom (inverted scale) light output response at peak currents of 7.4, 10.8, 16.8, 23 and 30 mA [2].

A careful reevaluation of the measurement shown in Fig. 4 is shown in Fig. 5. The problem is to find the absolute reference for the delay of the light output vs. current driving the laser. This parameter has been adjusted to obtain good agreement with a simple model. The model is based on an average carrier lifetime of 2 ns at threshold. The delay time is calculated as the time necessary to build up the carrier density to the threshold condition. At the highest pulse current measured (30 mA), the laser exhibits a delay of less than 70 ps in the light output in response to a current pulse. This time is essentially the lifetime of the carriers in the laser when operating at such a "high" current[5]. The other remarkable result is the absence of ringing. The laser seems to follow the current pulse very closely. Most likely, this is caused by the very short average lifetime of the carriers in the laser due to high rates of stimulated emission and the nonlinear gain current relation shown in Fig. 2 resulting in significant damping.

Similar lasers have been cleaved to resonators of a length of 120 micrometer and coated with high reflectivity coatings to obtain 0.55 mA threshold[3]. This shows that scaling to shorter devices length using higher reflectivity coatings follows theory closely. Further evidence is obtained from measuring the slope efficiency of these devices[14]. If the distributed losses in these lasers are low, the measured slope efficiency should change little when shorter devices with higher reflectivity coatings are used. Again, the theory is in good agreement with the experiments.

6. PROJECTED PERFORMANCE FIGURES

The good agreement of measured data with theoretical predictions allows us to scale the resonator size of the laser with high confidence. The purpose is to give an example of a possible design for the implementation of a high speed short distance communication laser. This is chosen in contrast to deriving exact optimization criteria and estimating all entering parameters to find optimized values. Consider the proposed laser of 1 micrometer width and 120 micrometer length with high reflection coatings of 0.83 and 0.95. Assuming a current density of 225 A cm^{-2} at threshold, 0.27 mA threshold current are predicted. If this device exhibits an internal quantum efficiency of 0.85, a total quantum efficiency at the output facet of 0.33 resulting in 0.5 W A^{-1} can be expected.

If an average carrier lifetime of 2.7 ns at threshold is assumed, the carrier density per area is 3.8 10^{12} cm^{-2}. If not more than 50 ps delay is required, the value for the drive current of the laser is 15 mA to reach that carrier density starting from zero within that delay time. At 15 mA, the laser is estimated to have a resonance frequency of about 9.5 GHz. This is of secondary importance as long as the laser is driven with large modulation depth. The intended operation is pulsing the laser from below threshold to 15 mA, which presents more than 50 times threshold current. Under these conditions, the actual variation in turn-on delay, known as the pattern effect, should be no more than 50 ps, depending on the presence or absence of a preceding pulse. If the laser is biased at about half the threshold current, (it is not lasing before the pulse arrives) the pattern effect should be decreased to about 20 ps. In the schematic Fig. 6, the response to a leading and immediately following pulse is indicated showing the full range of the pattern effect.

Assuming a less than 50% duty cycle for driving the laser and the use of a 3.3 V power supply, implies below 25 mW of average system power demand per laser. The obtainable transmitted bit rate for this laser should be at least 5 G bit s^{-1}.

7. ALTERNATE SCHEMES FOR VERTICAL COUPLING

In the preceding paragraphs, lasers with two facets have been considered. In the application of optical interconnects in computers, a different scheme which allows to couple light out of the laser without using facets perpendicular to the wafer surface may be preferred. Methods of applying second order grating distributed feedback lasers which provide vertical output seem promising[15,16,17]. An alternative scheme is to use an optical resonators in the vertical direction[18,19]. These two schemes have been worked on for quite a while. They have not yet shown performance approaching the kind of performance described for lasers with conventional resonators.

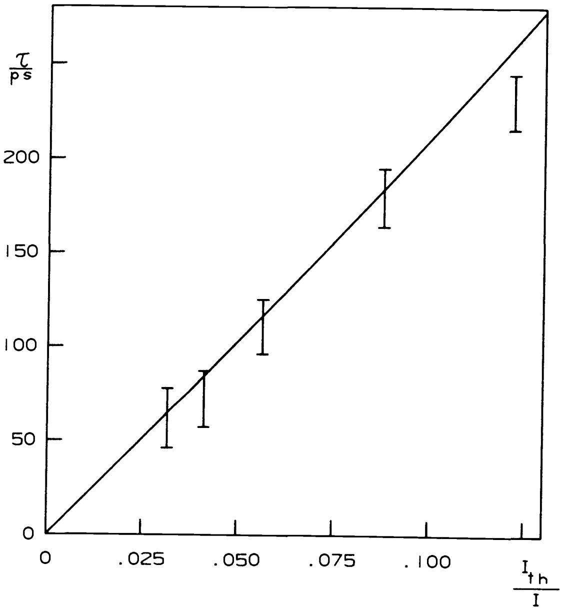


Fig. 5 Measured delay of laser output in response light to drive current pulse as a function threshold to pulse current ratio. The data are fitted to the calculation based on a 2 ns average lifetime of the carriers at threshold.

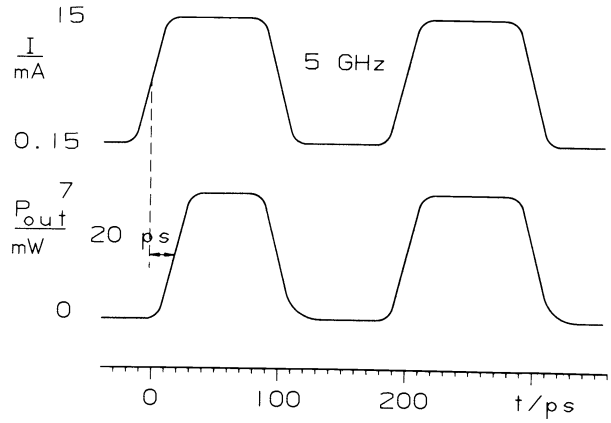


Fig. 6 Schematic of pulse response of proposed laser structure. Driven with 15 mA current pulses from an idle current of 0.15 mA (non-lasing) a pattern effect not exceeding 20 ps is expected.

8. FUTURE IMPROVEMENTS

Future improvements are expected from two main sources. First, improvements on the vertical structure should lead to even lower threshold current densities for the same gain requirement. Improvements have already been reported on MBE material reaching threshold current densities below 100 A cm^{-2} [20].

There is an estimate, that strained layer quantum well lasers incorporating InGaAs can improve the threshold current density one order of magnitude[20]. These structures will exhibit modified properties such as lasing wavelengths in the region near 1000 nm. This may be advantageous on one hand because GaAs and GaAlAs material is transparent at that wavelength. On the other hand, this may prove to be a problem because GaAs and GaAlAs structures cannot be used as a detector for that wavelength. Secondly, improvements could stem from new structures and geometries. Very narrow lasers have been demonstrated using pattern substrates and advance growth methods[22]. New structures may also involve novel resonator arrangements[23]. More basic alternative may include active regions of quantum wires or quantum dots[5,24,25,26].

The major improvements necessary for the application of optical interconnect in computers is the development of high yield processing techniques. This application probably calls for highly integrated chips which carry a large number of lasers. The present yield of individual lasers is not sufficient to produce chips containing many lasers reproducibly.

9. SUMMARY

Optical computer interconnects appear very attractive. Single quantum well lasers exhibit properties leading them to become a prime candidate for high speed communications in this application. For short distance links, there is no requirement for high output power. Optimized structures are, therefore, scaled down to lasers of very small size. Experimental findings to date give threshold currents as low as 0.55 mA. Test lasers indicate that scaling laws can be applied with high confidence. A laser designed with a threshold current of 0.27 mA is discussed leading to a 5 Gbit s^{-1} transmission rate with a system power supply requirement of only 25 mW per laser.

10. ACKNOWLEDGEMENTS

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