Optical Concepts, Inc.

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Contract # N00014-94-C-0173

Technical Report

UV, Blue and Green Vertical Cavity Lasers

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1. Introduction

Many potential military and commercial applications exist for compact visible lasers, such as high density storage and readout, and high definition, high brightness displays. At present there are no reliable compact laser sources available operating at shorter wavelengths than red. Blue and green lasers using II-VI materials been demonstrated but only last a few minutes at best. New developments in material growth, fabrication and laser device design have made near UV, blue and green semiconductor lasers a realistic possibility. In particular, vertical cavity lasers (VCLs) have some inherent properties which allow for the formation of these visible lasers.

Vertical cavity lasers can be used to form efficient frequency doubling structures. Vertical cavity lasers have been made which operate CW at room temperature at wavelengths from 650 to 1050 nm.; therefore it is possible to produce second harmonic light at wavelengths between 325 and 525 nm. Efficient internal second harmonic conversion is made possible in a vertical cavity laser structure for two major reasons. First the structures can be made with near 100% reflectors so that the photon density is extremely high inside the cavity, and second the mirrors inherently transmit at the second harmonic.

Previously, green emission has been demonstrated using second harmonic generation inside specially designed solid state cavities using diode lasers as pump sources. This approach works well and is commercially available. The difficulty with this approach is that it cannot be mass produced at low cost. Presently the least expensive source costs around five thousand dollars, and it is expected that the cost will eventually be reduced by an order of magnitude. Although this may initially sound successful, these devices will be too expensive to reach most of the potential markets for short wavelength sources.

For a short wavelength source to be inexpensive it needs to be a completely integrated source made with minimal packaging. At present there are two potential competing technologies. The first is lasers made using II-VI materials. As mentioned above, these devices have been somewhat successful in the past year, however this is the result of many years of extensive development. It is unclear whether II-VI based visible lasers will ever be reliable enough for commercial applications. The second potential source of low cost visible lasers is gallium nitride based lasers. At present, very efficient blue emitting LEDs have been made using GaN, and a great deal of global funding has been put into developing lasers using this material system. GaN based devices may well be the ultimate source of short wavelength lasers however that technology has some significant technical problems to solve before low cost, reliable lasers are available.

2. Technical Approach

The approach under investigation in this contract is an entirely new approach suggested by Optical Concepts. The fundamental GaAs technology is mature, and the capabilities of vertical cavity lasers (VCL) are rapidly improving. Single mode VCLs produce a few milliwatts of optical power using a few milliamps of current, with internal photon densities of MW/cm^2. By increasing the reflectivity of the mirrors the internal photon density can be increased by another order of magnitude or more depending on the internal optical losses of the device.

Figure 1 shows a schematic of the proposed device. A GaAs based vertical cavity laser is made using a (311) oriented wafer and a top dielectric mirror. Inside the optical cavity is an AlGaAs layer used for the second harmonic conversion. The resulting non linear conversion will be highly polarization dependent, as shown in Figure 2, and as a result the primary challenge in the contract will ultimately be polarization control of the VCL. Assuming polarization control is achievable, a second harmonic emitting VCL should be able to produce in the order of a milliwatt of second harmonic power based on current VCL performance.

A completed device is beyond the scope of the Phase I effort. Thus the fundamental technologies will be investigated and demonstrated in order to better design an achievable device for a Phase II effort. Our stated objectives were:

1. Demonstrate enhanced second harmonic generation resulting from a resonant cavity.

2. Evaluate methods of integrating the nonlinear material with the GaAs based system.

3. Develop device models for second harmonic generation in GaAs based vertical cavity lasers.

4. Design vertical cavity laser structures optimized for second harmonic generation and predict the ultimate performance of the devices.

2.1 Demonstrate Enhanced Second Harmonic Generation

We proposed to examine the effect of resonant cavities on second harmonic generation. The resonant cavity is designed to increase the optical field strength for improved second harmonic generation. Figure 3 shows an example cavity with dielectric DBR mirrors deposited on each side of the non-linear material.

The cavity will be designed to be resonant at the fundamental frequency and transparent to the second harmonic. The resulting optical field strength can be increased using this method by about three orders of magnitude. This is the principle used to make short wavelength VCLs operational. By increasing the intensity of the optical field at the non-linear element, the conversion efficiency of the second harmonic can be greatly increased for a given interaction length.

The fundamental problem with this method is in matching the input laser radiation with the resonant cavity. This will be done by using a tunable Ti-Sapphire laser to ensure matching. This resonant cavity approach is only an interim approach to characterize the non-linear material, check the feasibility of growing dielectric mirrors on a non-linear material and to demonstrate enhanced second harmonic generation.

At present we have designed and received a GaAs wafer with epitaxy grown for this purpose. The wafer design is shown in Figure 3b and the theoretical and measured reflectivity of the wafer is shown in Figure 4. The wafer is now waiting for dielectric mirror deposition before the optical pumping experiment can be made.

2.2 Evaluate Fabrication Methods

We have considered a number of fabrication methods for the creation of a second harmonic generating VCL. As stated earlier the major technological hurdle is to align the polarization of the optical field for maximum second harmonic generation. We are currently investigating three methods to achieve this:

1. Use (311) AlGaAs as nonlinear material and create non-circular VCLs for polarization control.

2. Use wafer fused (111) AlGaAs material oriented 90° to original (111) grown material for uniform non-linear conversion.

3. Use barium titanate epitaxially grown on GaAs with the axis oriented for uniform non-linear conversion.

Research performed at Sandia National Laboratories has shown that non-circular implantations for current constriction in VCLs will result in polarization control of the VCL. This approach breaks the symmetry of the structure so that the losses of one polarization are greater than the crossed polarization. It is not yet clear how effectively this method can be used for polarization control of a second harmonic generating VCL, and this will be a subject of investigation. Once a VCL is made using a (111) or (311) GaAs wafer, there may be a strong polarization dependence due to the quantum well grown on the substrate. It is possible, though not likely, that the polarization preference of the quantum well may be useful in creating an efficient second harmonic generating VCL. To better understand this problem, we will investigate the polarization dependence of vertical cavity lasers and LEDs grown on (311) substrates. The result of this investigation will be critical in assessing the best device designs.

Optical Concepts has developed a wafer fusion technology for their long wavelength VCL research. Using this technology, an AlGaAs non-linear layer would be fused to the proposed structure before the fabrication and dielectric mirror deposition. This will result in a polarization-dependent non linear conversion as shown in Figure 5. This procedure will then make polarization control irrelevant, although the additional fabrication procedures will increase the cost of the final product. Also the additional material will result in increased internal losses which will decrease the potential performance of the device.

The final method to be examined is to have a non linear material such as barium titanate grown directly on the GaAs. This has been demonstrated. The difficulty with this approach is that barium titanate has a much smaller nonlinear component than AlGaAs, and therefore the predicted performance would be hundreds of microwatts, at best, based on current VCL technology.

2.3 Develop Models for Second Harmonic Generation in VCLs

We have been developing models of the second harmonic output of VCLs. These have been of great use in examining various potential designs. The essential model used for estimating optical power is outlined below. This is just the initial model and is in the process of being expanded for accuracy.

The ideal second harmonic generating device will have an amount of second harmonic generation which is equal to the amount of transmission losses of the device. By using highly over-designed mirrors the transmission loss (T) will be essentially zero, and then the threshold gain will be:

$$G = L_i . \qquad \textbf{(2.1)}$$

Above threshold, the round trip gain will increase to compensate for the second harmonic generation losses:

$$G = L_i + T_{SHG} . \qquad \textbf{(2.2)}$$

In order to calculate T_{SHG} according to equations 2.1 and 2.4, the internal optical power must be estimated. The total optical power produced by a device can be calculated using the external efficiency, that is:

$$P_{out} = P_{tot} \eta_{ext} . \qquad \textbf{(2.3)}$$

Also, the internal power can be calculated using the transmission losses:

$$P_{out} = P_{in} T . \qquad \textbf{(2.4)}$$

Therefore, the internal power:

$$P_{in} = \frac{P_{tot}}{L_i + T + T_{SHG}} , \qquad \textbf{(2.5)}$$

where:

$$T_{SHG} = \frac{P^{(2\omega)}}{P_{in}} = \frac{(L_i + T)\,P^{(2\omega)}}{P_{tot} - P^{(2\omega)}} \,. \qquad \textbf{(2.6)}$$

The maximum internal power achievable will exist with highly over-designed mirrors (T=0).

In the resonant cavity, the standing wave causes the electric field profile to be greatly enhanced at the peak of the standing wave. This in turn creates an enhancement in the second harmonic generation. By integrating over the E^2 profile in the second harmonic material, it can be calculated that there is a factor of four enhancement in second harmonic generation due to the standing wave, such that equation 2.4 becomes:

$$P^{(2\omega)} = 4 \times 10^7 \left[\frac{\omega d l P^{(\omega)}}{\omega_0} \right]^2 , \qquad \textbf{(2.7)}$$

where $P^{(\omega)}$ is the internal power of one of the traveling waves. It is clear from equation 2.7 that the maximum second harmonic power will be produced when the ratio of internal power to spot size is maximized. According to equations 2.5 and 2.7 the amount of second harmonic power generated is related to the internal field which is related back to the losses due to second harmonic generation. By manipulating equations 2.5-2.7 one can produce the quadratic equation describing the total amount of second harmonic generation as a function of the thickness of the nonlinear material:

$$P^{(2\omega)} = \frac{1}{2}\left(2\,P_{tot} + \frac{L_i^2}{A\,l^2} - \frac{L_i^2}{A\,l^2}\sqrt{1 + \frac{4\,P_{tot}\,A\,l^2}{L_i^2}} \right) , \qquad \textbf{(2.8)}$$

where:

$$A = 32\left(\frac{\mu_0}{\varepsilon_0}\right)^{3/2} \frac{\omega^2 d^2}{\pi \omega_0^2 n^3} \approx 10^5\ m^{-2} W^{-1} . \qquad \textbf{(2.9)}$$

The total amount of second harmonic power which will exit the device is dependent on the thickness of the nonlinear material (l) and the internal loss (L_i), which is related to the design of the structure.

Figure 6 shows a visual description of equation 5.8 as a function of the thickness of the nonlinear material for the two fabrication designs outlines in Sections 2.1 and 2.2. It is clear that if polarization control of the VCL can be accomplished the rewards will be significant, in terms of both device performance and cost.

2.4 Design Efficient Second Harmonic Emitting VCLs

Various VCL designs are currently under investigation as shown in Figure 1 and discussed in Section 2.2. The design will not be finalized until the end of the Phase I effort.

3. Summary and Conclusion

Using existing technologies, it is theoretically possible to produce second harmonic generating vertical cavity lasers emitting in the blue and green. All the required processes have been previously demonstrated and published. The ideas discussed here are made possible by joining the fields of nonlinear physics with GaAs device engineering. Fundamentally there is nothing exceptional about the proposed devices, rather the devices use basic ideas from two previously non-convergent fields. The proposed device should be able to produce a few hundreds of μW, if not mW of blue/green CW optical power using existing technology, and much higher powers as the vertical cavity technologies improve. Pulsed operation of the devices should produce many mW of optical power, even with no improvements in basic vertical cavity technology.

Vertical cavity structures are early in their development, and have far to go before they reach maturity. This is very promising for the second harmonic generating devices. Due to the nonlinear nature of the devices, a twofold improvement in the basic vertical cavity laser technology will result in nearly a fourfold improvement in second harmonic generating devices. Eventually, there will be a saturation of the rapid growth of the second harmonic devices, but only after the efficiencies of the second harmonic devices have reached similar levels as standard vertical cavity lasers. In conclusion, blue and green laser are a possibility using existing technologies, and will become more practical as technology improves.

We have begun an in depth investigation into second harmonic emitting VCLs. As outlined in the Technical Approach Section, there are some technical problems to be overcome before a successful device can be produced. If produced however, the payback would be enormous since as yet there are no practical semiconductor lasers at wavelengths shorter than red.