Optical Concepts, Inc.

27 January 1995

Contract # N00014-94-C-0173

Progress Report

UV, Blue and Green Vertical Cavity Lasers

Author: Frank H. Peters

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1. Introduction

Vertical cavity surface emitting lasers (VCSELs) have improved rapidly during the last few months. Workers at Sandia National Laboratories have demonstrated VCSELs with wall plug efficiencies as high as 50%. All improvements such as these, contribute to the development of UV, blue and green VCSELs, since the basic infra-red VCSEL is fundamental to our doubling scheme. These new structures have larger optical field densities then any existing VCSELs, due to reduced mirror resistances and reduced optical losses.

During the last two months of this phase I investigation, we have included the most recent Sandia inventions into our proposed device designs, and have proceeded with our experiments.

2. Technical Progress

The technical report that was submitted in November, 1994 outlined our objectives, recognizing that a completed device is beyond the scope of the Phase I 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 1 shows an example cavity with dielectric DBR mirrors deposited on each side of the non-linear material.

The cavity was 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.

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At present we have designed and received a GaAs wafer with epitaxy grown for this purpose. The wafer design is shown in Figure 1b and the theoretical and measured reflectivity of the wafer is shown in Figure 2. Since the technical report was written we have received the wafer with the dielectric mirror, and have proceeded with the optical pumping experiment. The wafer was in resonance at 1000 nm in the center, and at 955 nm at the very edge of the wafer. This tendency can be seen in Figure 2. As shown on the figure the design wavelength at wafer center was 930 nm. As a result, we have spent considerable time attempting to coax the Ti-Sapphire laser out to at least 960 nm. This has not been successful during the last few months.

To solve this problem, and proceed with the optical pumping experiment, we are proceeding in two parallel directions. First we are acquiring another GaAs wafer to be centered at 930 nm, and second we will attempt to increase the tuning capabilities of the Ti-Sapphire laser by installing a longer wavelength output coupler. Thus, during the final two months of Phase I we will finish this optical pumping experiment to demonstrate the frequency doubling of the GaAs based materials.

2.2 Evaluate Fabrication Methods

The major technological hurdle in the fabrication is to align the polarization of the optical field for maximum second harmonic generation. During the last two months of the Phase I investigation we have made some conclusions as to the capabilities of some of our proposed fabrications. Initially our possible fabrication solutions were:

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.

It is our conclusion that the first fabrication alternative will not be successful. Non-circular VCSELs have shown polarization selection, however in a laser only a very small polarization sensitivity is necessary for polarization selection. This means that the non-linear element will act as a much better polarization control then will the non-circular fabrication. We mentioned in our technical report that 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. This question has not yet been answered since Optical Concepts does not produce laser grown with these orientations. Our interaction with Sandia shows that such lasers do indeed have strong polarization selection, however we have not yet found out what the polarization of these lasers is in relation to the crystallographic orientation. This will let us know if the polarization is selected because of the potential non-linear effects, or if it is due the inherent gain of the quantum wells.

Optical Concepts has developed a wafer fusion technology for their long wavelength VCL research. Using this technology, a (111) AlGaAs non-linear layer would be fused to a (111) VCSEL structure before the fabrication and dielectric mirror deposition. This will result in a polarization-dependent non linear conversion as shown in Figure 3. This procedure will then make polarization control irrelevant. This is the only solution that we know will result in successful blue/green lasers in Phase II.

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 VCSEL 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 was outlined in our technical report, and is shown below:

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 4 shows a visual description of equation 5.8 as a function of the thickness of the nonlinear material (AlGaAs) for the fabrication design outlined 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

Because of the Sandia improvements using a native oxide, our ideas on the device designs have changed considerably. Figure 5 shows a schematic of the new frequency doubling design using the oxide. The oxide procedure has the immediate advantage that the optical losses are greatly reduced. This is highly significant for doubling structures, since it is the optical power density that is important, not the optical power. Reducing the optical losses results in a tremendous improvement in the optical efficiency of small VCSELs, which tend to have the highest optical power densities. For example, before using the native oxide approach the best efficiency of a 8 μm diameter VCSEL was about 10%. Using the native oxide 50% has been achieved.

3. Summary and Conclusion

During the last two months we have encountered some technical problems related to equipment and outside sources. since the Phase I effort is relatively short, our effort has doubled to ensure a successful completion of our experiments during the final two months. Improvements in the basic VCSEL technologies that have appeared recently, point to the eventual success of the frequency doubling approach. During the final two months we plan to complete our optical pumping experiment, finish our modeling work, and propose final device designs that will be achievable during a Phase II investigation.

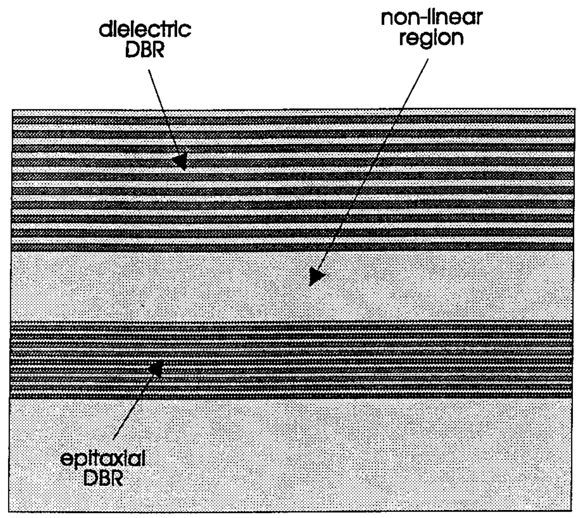

Figure 1a

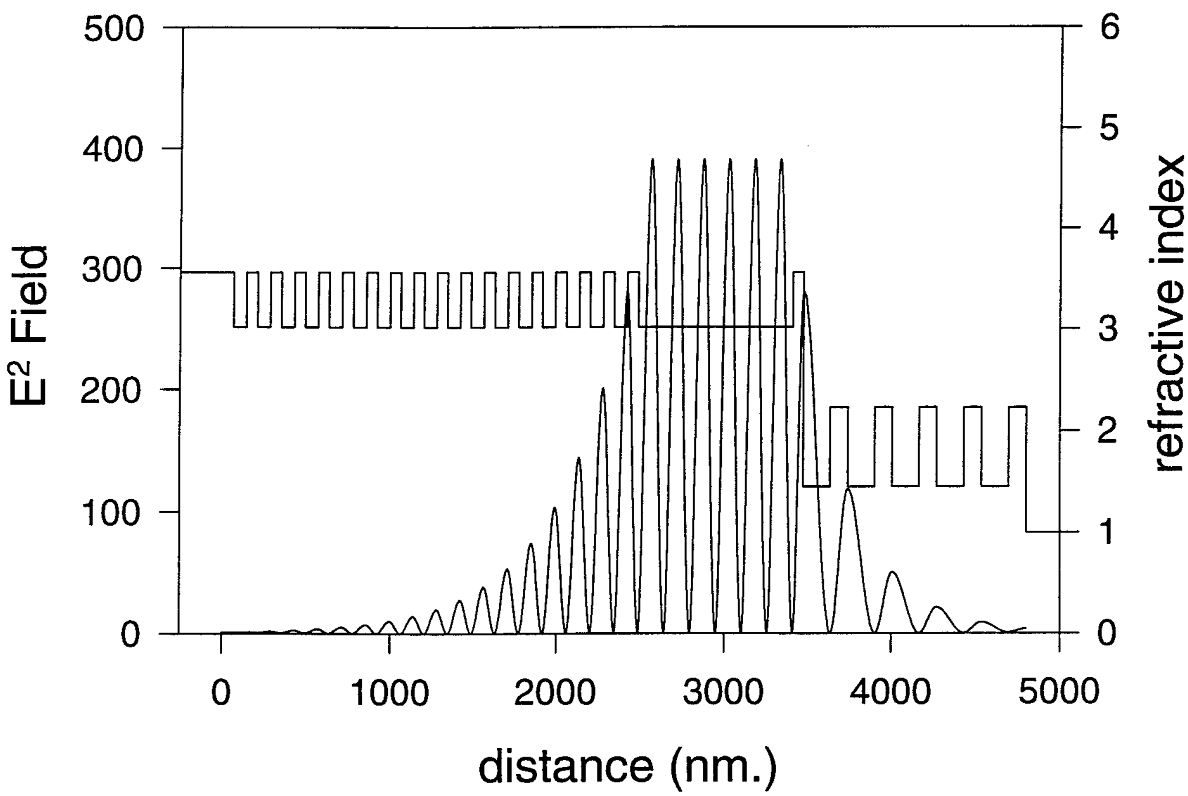

Figure 1b

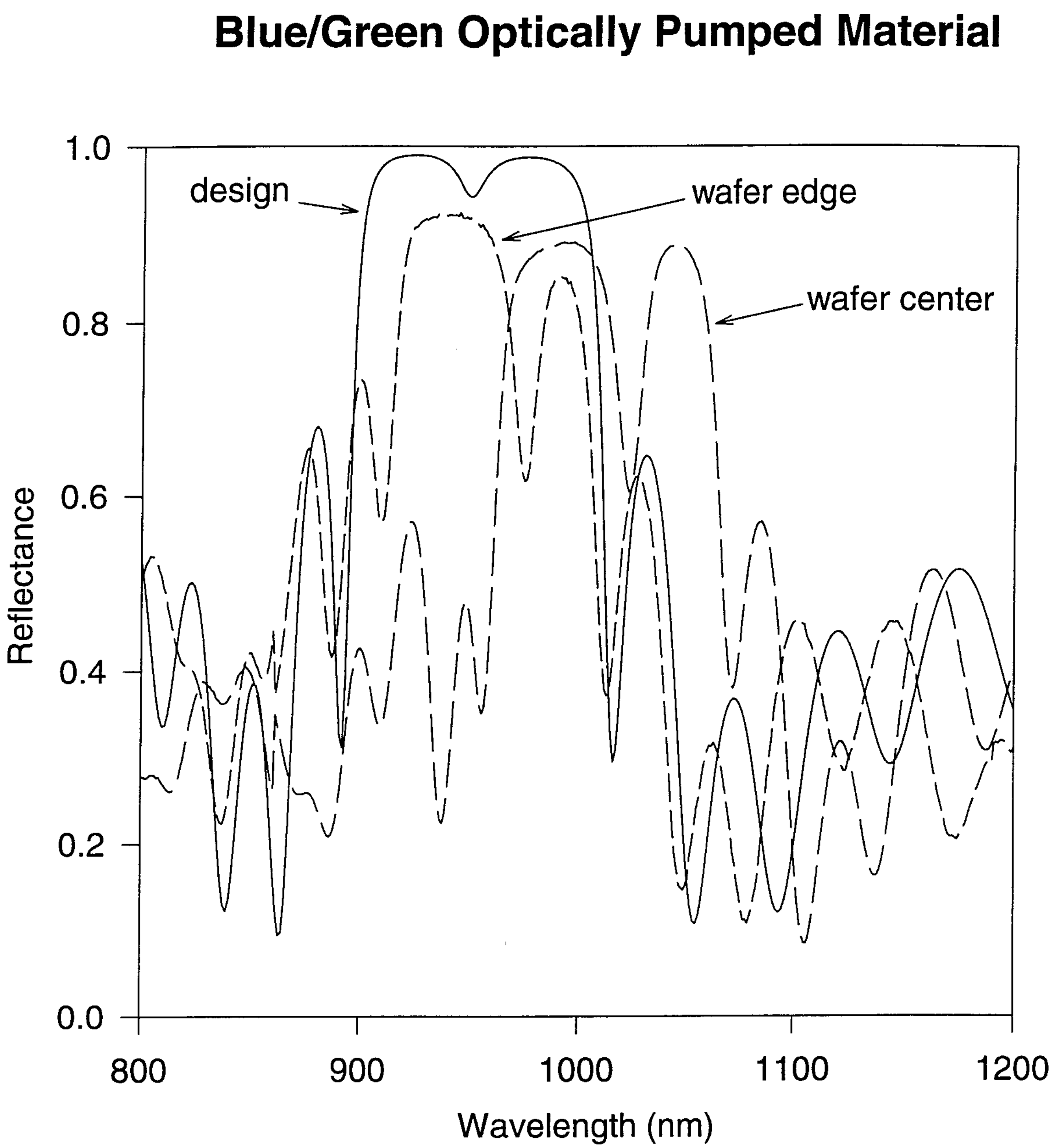
Blue/Green Optically Pumped Material
design
wafer edge
wafer center
Reflectance
1.0
0.8
0.6
0.4
0.2
0.0
800
900
1000
1100
1200
Wavelength (nm)

Figure 2

Polarization vs. Relative SHG for (111) Orientation

plus wafer fused (111) with 90° rotation

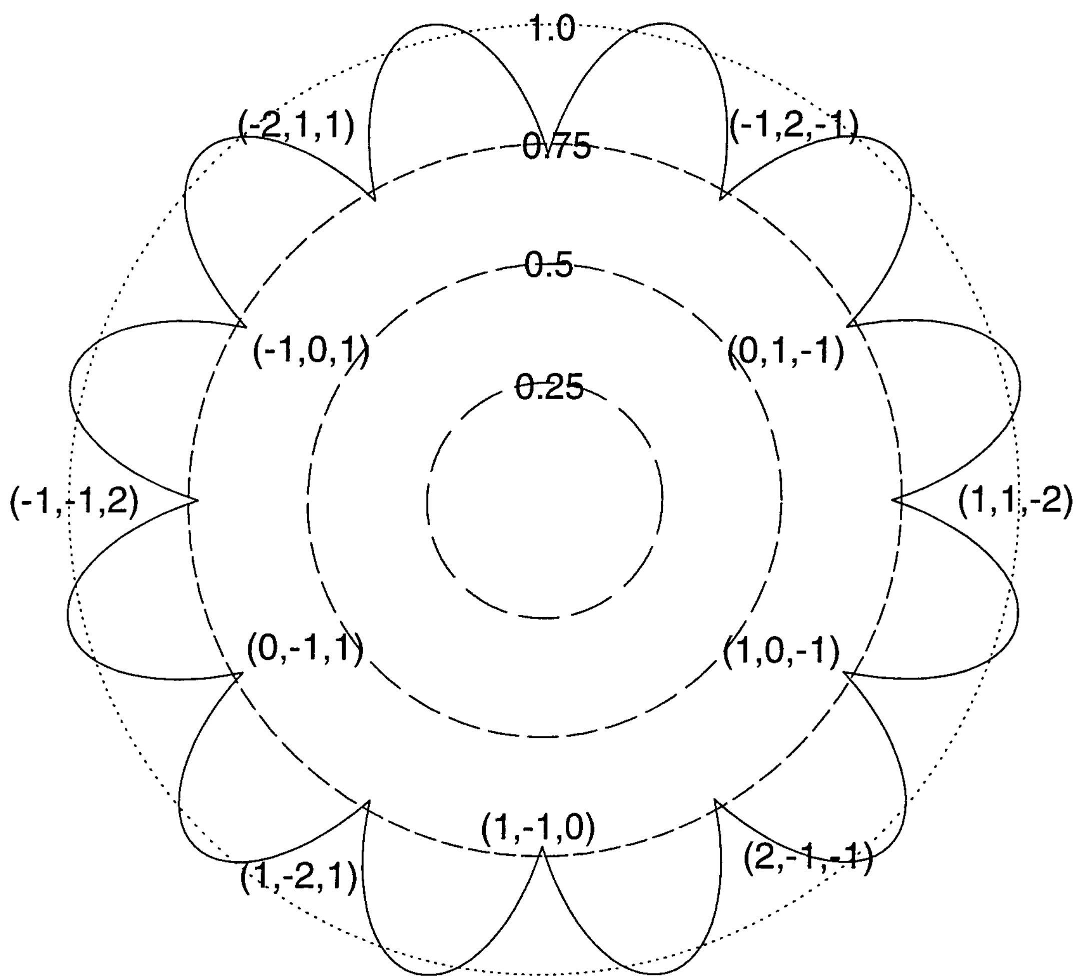

Figure 3

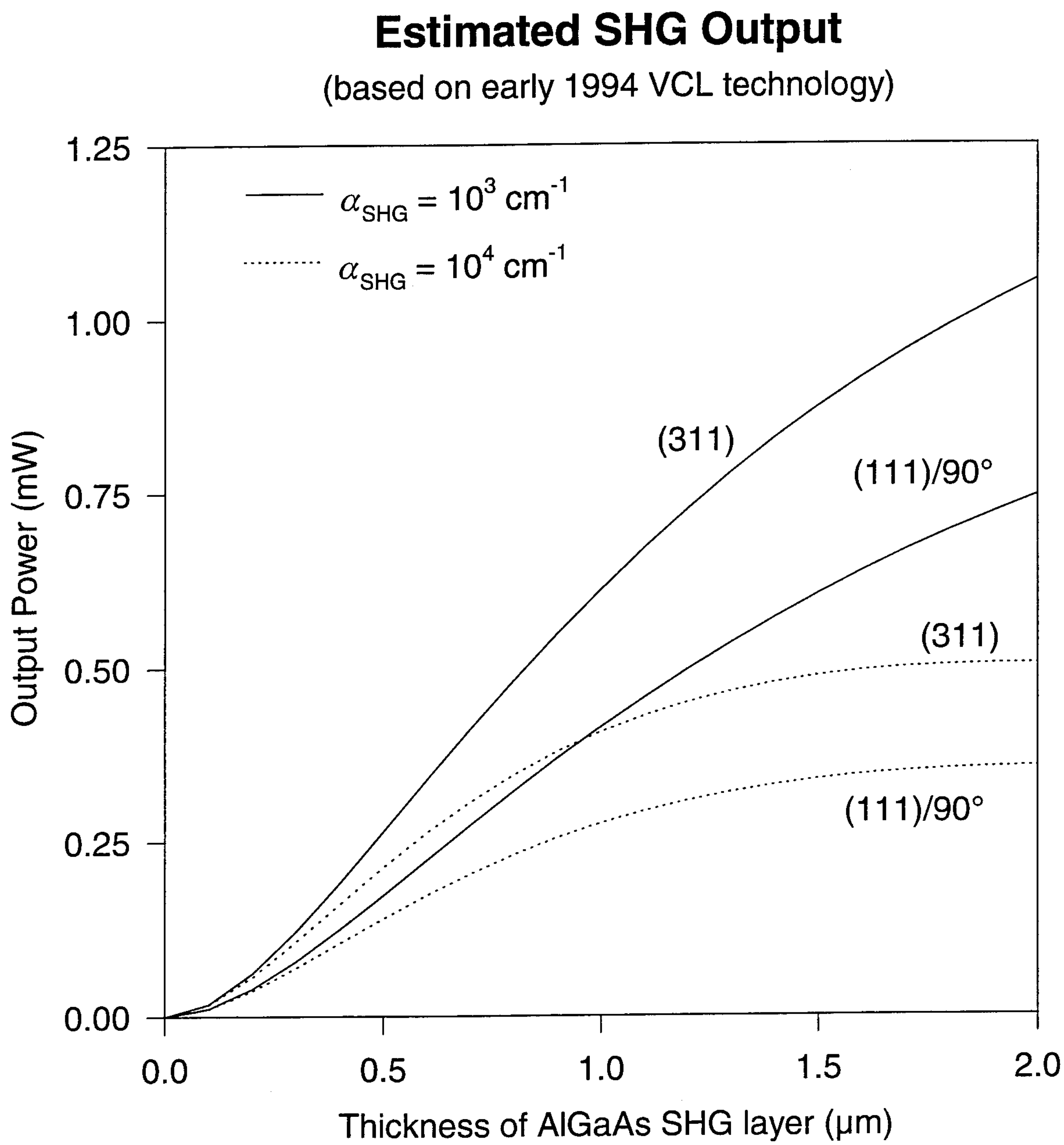
Estimated SHG Output
(based on early 1994 VCL technology)
$\alpha_{SHG} = 10^3$ cm^{-1}
$\alpha_{SHG} = 10^4$ cm^{-1}
Output Power (mW)
1.25
1.00
0.75
0.50
0.25
0.00
0.0
0.5
1.0
1.5
2.0
(311)
(111)/90°
(311)
(111)/90°
Thickness of AlGaAs SHG layer (μm)

Figure 4

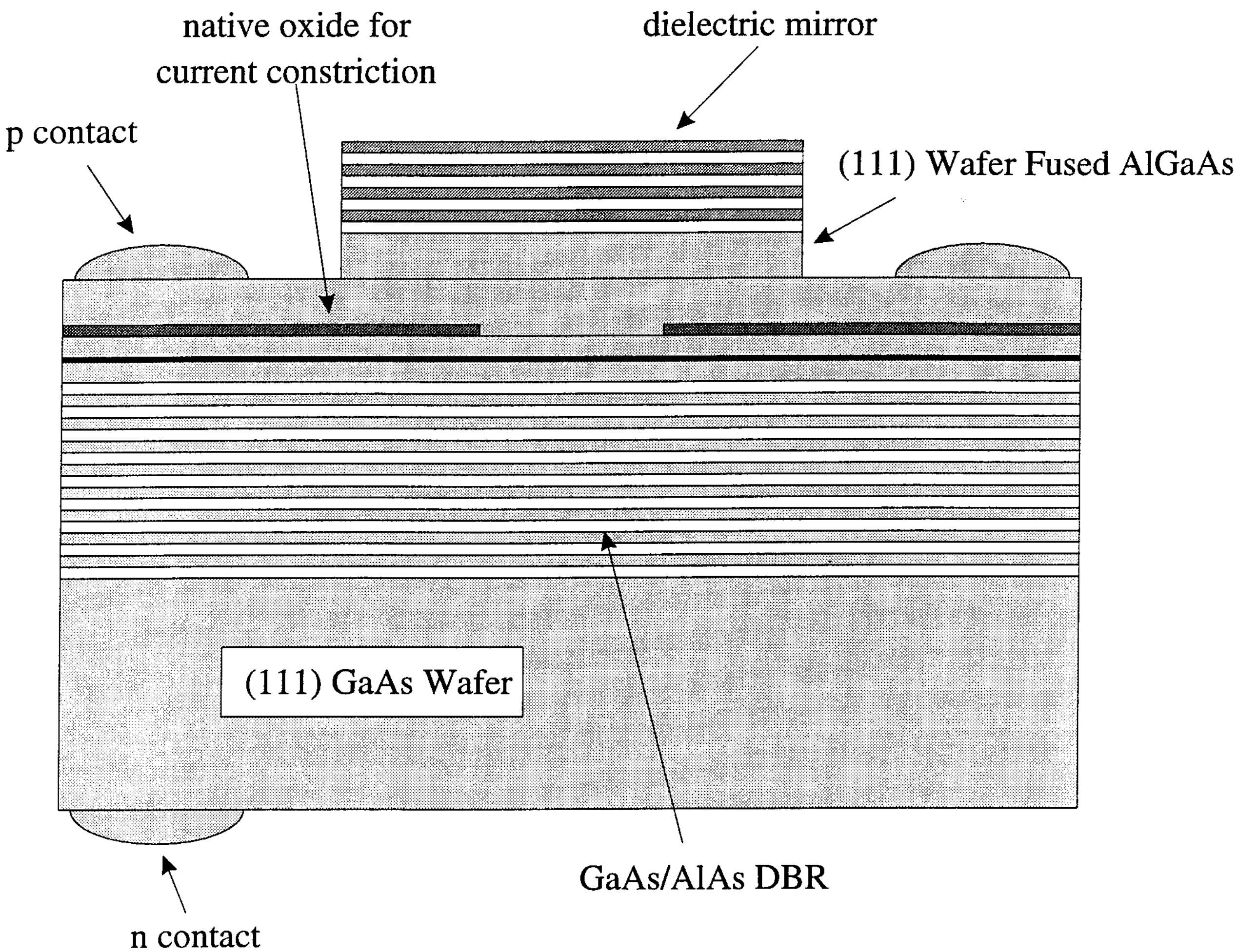
native oxide for
current constriction
dielectric mirror
p contact
(111) Wafer Fused AlGaAs
(111) GaAs Wafer
GaAs/AlAs DBR
n contact

Figure 5