



# Characterizing Lasers that Emit Widely Diverging Radiation

by Richard L. Tober

ARL-TR-4536

August 2008

## **NOTICES**

### **Disclaimers**

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

# **Army Research Laboratory**

Adelphi, MD 20783-1197

---

**ARL-TR-4536**

**August 2008**

---

## **Characterizing Lasers that Emit Widely Diverging Radiation**

**Richard L. Tober**  
**Sensors and Electron Devices Directorate, ARL**

# REPORT DOCUMENTATION PAGE

*Form Approved*  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

|  |                             |                                |  |   |  |
|--|-----------------------------|--------------------------------|--|---|--|
| <b>1. REPORT DATE (DD-MM-YYYY)</b><br>August 2008  |                             | <b>2. REPORT TYPE</b><br>Final |  | <b>3. DATES COVERED (From - To)</b><br>January 1, 2008 to June 20, 2008 |  |
| <b>4. TITLE AND SUBTITLE</b><br>Characterizing Lasers that Emit Widely Diverging Radiation   |                             |                                |  | <b>5a. CONTRACT NUMBER</b>  |  |
|  |                             |                                |  | <b>5b. GRANT NUMBER</b>   |  |
|  |                             |                                |  | <b>5c. PROGRAM ELEMENT NUMBER</b>                                       |  |
| <b>6. AUTHOR(S)</b><br>Richard L. Tober  |                             |                                |  | <b>5d. PROJECT NUMBER</b>   |  |
|  |                             |                                |  | <b>5e. TASK NUMBER</b>  |  |
|  |                             |                                |  | <b>5f. WORK UNIT NUMBER</b>   |  |
| <b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b><br>U.S. Army Research Laboratory<br>ATTN: AMSRD-ARL-SE-EE<br>2800 Powder Mill Road<br>Adelphi, MD 20783-1197   |                             |                                |  | <b>8. PERFORMING ORGANIZATION REPORT NUMBER</b><br><br>ARL-TR-4536      |  |
| <b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>   |                             |                                |  | <b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>                                 |  |
|  |                             |                                |  | <b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>                           |  |
| <b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b><br>Approved for public release; distribution unlimited.   |                             |                                |  |   |  |
| <b>13. SUPPLEMENTARY NOTES</b>   |                             |                                |  |   |  |
| <b>14. ABSTRACT</b><br>It is often difficult to accurately measure the power emitted from mid- and long-wave IR lasers because their inherently large radiation divergence. This is simply due to the fact that experimental geometry limits the solid angle of the emitted radiation that the sensitive area of a power meter can capture. However, one can confidently estimate the total power emerging from a widely diverging laser by integrating the power of an elliptically symmetric Gaussian beam that is incident on the meter's sensitive surface |                             |                                |  |   |  |
| <b>15. SUBJECT TERMS</b><br>Cascade laser, quantum cascade laser, IR laser   |                             |                                |  |   |  |
| <b>16. SECURITY CLASSIFICATION OF:</b>   |                             |                                | <b>17. LIMITATION OF ABSTRACT</b><br><br>SAR | <b>18. NUMBER OF PAGES</b><br><br>14                                    | <b>19a. NAME OF RESPONSIBLE PERSON</b><br>Richard L. Tober       |
| <b>a. REPORT</b><br><br>U  | <b>b. ABSTRACT</b><br><br>U | <b>c. THIS PAGE</b><br><br>U   |  |   | <b>19b. TELEPHONE NUMBER (Include area code)</b><br>301-394-5756 |

---

## Contents

---

|                               |           |
|-------------------------------|-----------|
| <b>List of Figures</b>        | <b>iv</b> |
| <b>List of Tables</b>         | <b>iv</b> |
| <b>Introduction</b>           | <b>1</b>  |
| <b>Experimental</b>           | <b>2</b>  |
| <b>Analysis</b>               | <b>5</b>  |
| <b>Results and Discussion</b> | <b>6</b>  |
| <b>References</b>             | <b>7</b>  |
| <b>Distribution List</b>      | <b>8</b>  |

---

## List of Figures

---

|   |   |
|---|---|
| Figure 1. Schematic of experimental apparatus. The sample was separated from the power meter's sensitive area by 20 mm. The meter captured radiation in a solid angle of 50.8°..... | 1 |
| Figure 2. Spectra obtained from the sample QCL 07-562 at 288 K and 2 different bias values. ....  | 3 |
| Figure 3. Peak bias versus peak current.....  | 3 |
| Figure 4. Peak power versus peak current. ....  | 4 |
| Figure 5. Power conversion efficiency versus input power.....   | 4 |

---

## List of Tables

---

|   |   |
|---|---|
| Table 1. QCL 07-562 operating characteristics @ 288 K. .... | 2 |
|---|---|

---

## Introduction

---

Electrically pumped quantum cascade lasers (QC lasers) and interband cascade lasers (IC lasers) are currently being developed for a wide variety of commercial and defense applications (*1 through 6*). Of course, rapid development requires precise characterization so that feedback can be provided for improving not only laser designs but growth techniques as well.

Characterizing cascade laser device current and bias parameters is fairly straightforward. However, power measurements are often difficult as their emitted radiation is widely diverging. The large divergence is due to QC and IC laser emission wavelengths and structure geometry (7,8). The situation is further exacerbated by mechanical isolation if the laser needs to be operated at low temperatures.

Figure 1 shows a schematic of the experimental apparatus. The QC laser is mounted on the cold finger of a cryostat in such a way that it is separated from the power meter's sensitive area by 20 mm. The meter can only capture laser radiation within a solid angle of  $50.8^\circ$ . The radiation from this laser has a fast axis ( $1/e^2$ ) divergence of  $106^\circ$  and a slow axis ( $1/e^2$ ) divergence of  $57^\circ$ . Thus, the sensitive area of the power meter captures only a fraction of the emitted radiation.

This report documents the results of laser experiments and theoretical calculations performed to determine a method to characterize the specific operating parameters of widely diverging lasers. Specifically, it shows how the total power emerging from a widely diverging laser can be confidently determined.

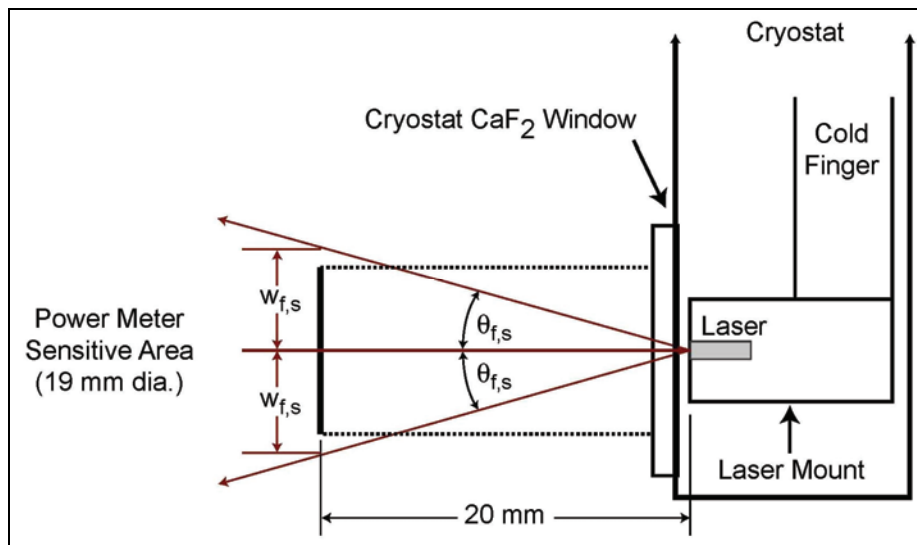


Figure 1. Schematic of experimental apparatus. The sample was separated from the power meter's sensitive area by 20 mm. The meter captured radiation in a solid angle of  $50.8^\circ$ .

---

## Experimental

---

A quantum cascade laser (QCL 07-562) was mounted in a Janis ST-100 cryostat so that it could be maintained at 288 K. Power was applied to the laser using an Avtech current pulser, the peak current and peak bias were measured using a LeCroy digital oscilloscope, and the power was measured using a Molelectron power meter. Spectra were acquired using a McPherson 2/3 meter monochromator. All results and measurement parameters are listed in table 1 and data are shown in figures 2 through 5.

Table 1. QCL 07-562 operating characteristics @ 288 K.

| Operating Characteristic           | Symbol           | Value           | Unit        | Comments  |
|------------------------------------|------------------|-----------------|-------------|---|
| Temperature                        | $T_{op}$         | $288 \pm 1$     | K           | Heat Sink Temperature   |
| Threshold Current                  | $I_{th}$         | $0.96 \pm 2\%$  | Amps (peak) | 500 nsec pulses<br>10 kHz rep. rate   |
| Maximum (tested) Operating Current | $I_{max}$        | $2.33 \pm 2\%$  | Amps        | 500 nsec pulses<br>10 kHz rep. rate   |
| Maximum (tested) Operating Voltage | $V_{max}$        | $13.42 \pm 2\%$ | Volts       | 500 nsec pulses<br>10 kHz rep. rate   |
| Maximum 2-Facet Output Power       | $P_{2-f}$        | $664 \pm 3\%$   | mW          | 2- facet peak power, $T_{op} = 288$ K,<br>$V_{op} = 12.44$ V and $I_{op} = 1.83$ Amps |
| Slope Efficiency                   | $\eta$           | $1.2 \pm 4\%$   | W/A         | $I > I_{th}$ , $\delta P_{2-f} / \delta I$  |
| Central Wavelength                 | $\lambda_{cent}$ | $5.83 \pm 0.02$ | $\mu m$     | $V = 11.83$ , $I = 1.54$ Amps   |
| Fast Axis Divergence               | $\theta_f$       | $106^\circ$     | degrees     | $1/e^2$   |
| Slow Axis Divergence               | $\theta_s$       | $57^\circ$      | degrees     | $1/e^2$   |



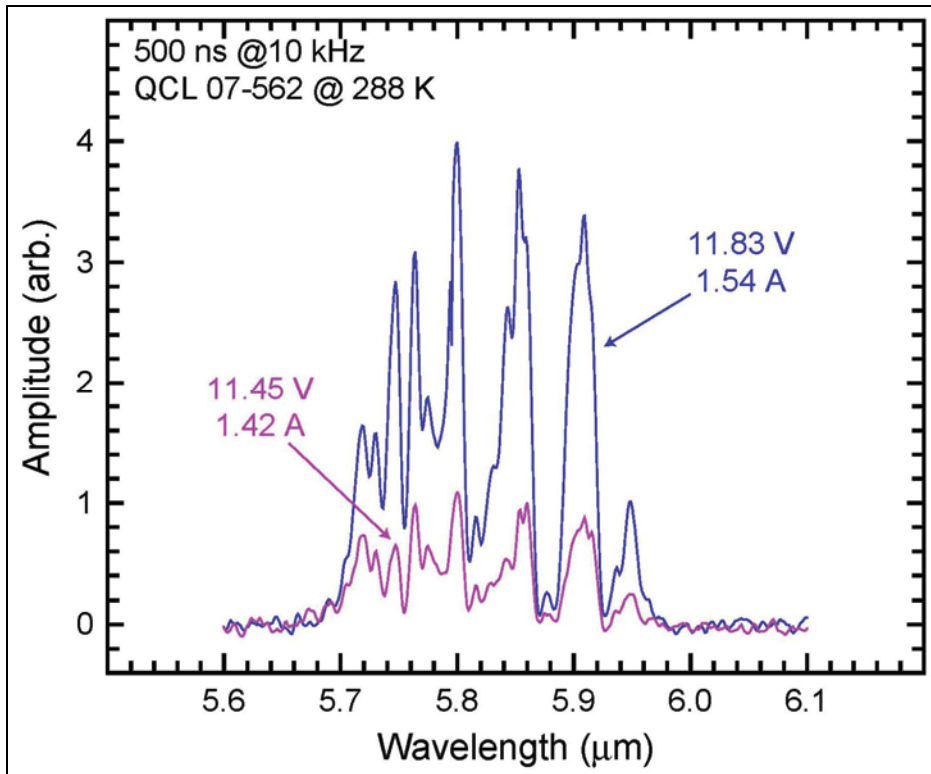


Figure 2. Spectra obtained from the sample QCL 07-562 at 288 K and 2 different bias values.

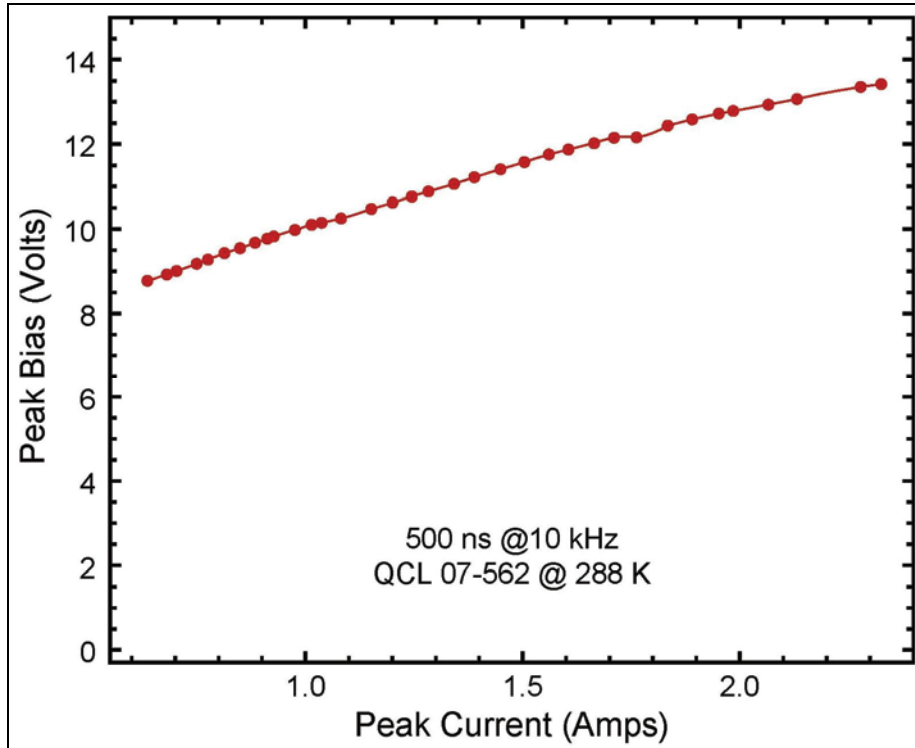


Figure 3. Peak bias versus peak current.

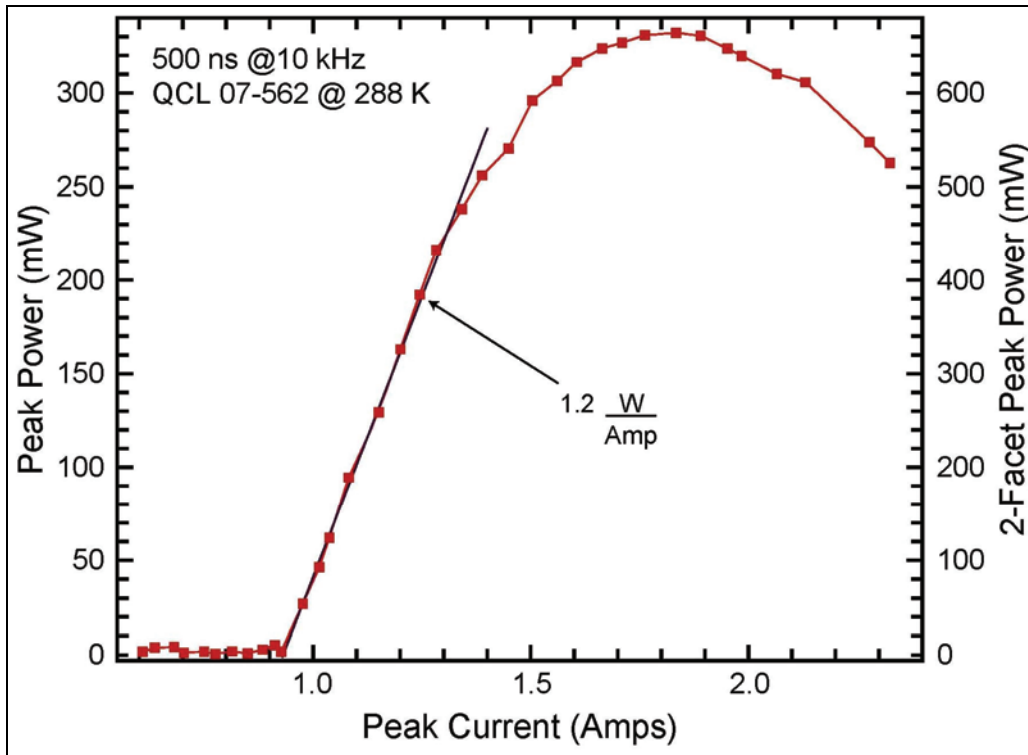


Figure 4. Peak power versus peak current.

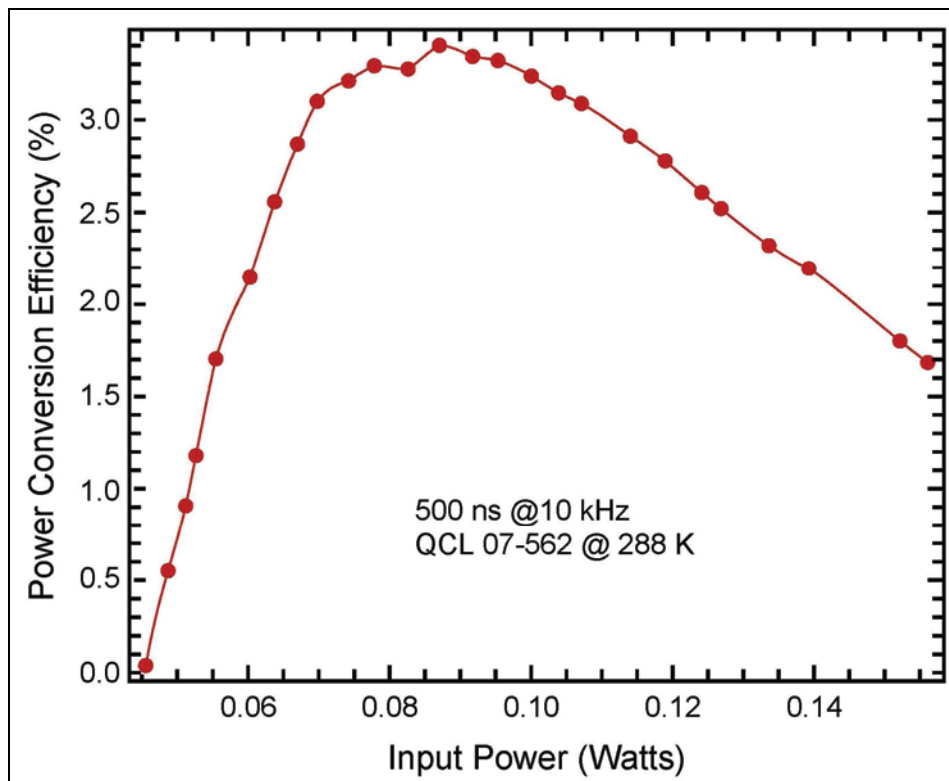


Figure 5. Power conversion efficiency versus input power.

This QC laser was operated in an evacuated cryostat and was, therefore, separated from the power meter's sensitive area by a CaF<sub>2</sub> window and a distance of 20 mm.

First, spectra were obtained in the spectral range between 5.6 and 6.1 μm using 500 ns pulses at 10 kHz, and at 1.42 and 1.54 amps (peak). The emission had multiple longitudinal modes at both currents commensurate with the 3 mm long mesa waveguide (see figure 2). The radiation over filled the collection optics, but posed no problem for determining the emission spectra.

Next, a bias was applied to the sample so that power, current, and voltages could be simultaneously measured. Figure 3 shows the voltage across the mesa as a function of the applied current. Similarly, figure 4 has power plotted as a function of the applied current. The raw power data was adjusted for the 92% window transmission and multiplied by a power adjustment factor commensurate with the amount of radiation actually captured by the power meter (see figure 1 and the analysis described below). Note that the vertical axes indicated the peak power as measured and the peak power as if equal amounts exited both facets (the facets were uncoated).

A portion of the data, just above threshold, was fit to a straight line. The slope yielded the internal quantum efficiency (1.2 W/Amp), the x-axis intercept indicated the 0.96 Amp threshold current (both values are listed in table 1). The slope of the power versus current curve decreased after about 1.4 amps and became negative at 1.56 Amps. This reduction in slope was due to the decreasing efficiency that accompanied the current induced temperature increases.

The power conversion efficiency (*PCE*, see figure 5) was calculated by assuming equal amounts of radiation was emitted from each facet, then dividing twice power (as measured with the power meter) by the average current-voltage product.

$$PCE = \frac{2 \times P_{meas}}{(I \times V)_{ave}}$$

---

## Analysis

---

Since the power meter had a limited field of view, a power adjustment factor (PAF) was used to adjust the measured data to a value commensurate with the total laser power emitted. The PAF was calculated as a ratio of the total power contained in an elliptically symmetric Gaussian to that captured by the surface area of the power meter.

The procedure follows from the fact that the power contained in a Gaussian beam can be determined as follows:

$$P_{Total} = \int I_{x,y} dA = I_0 \int_{-\infty}^{+\infty} e^{-\frac{2x}{w_x}} dx \int_{-\infty}^{+\infty} e^{-\frac{2y}{w_y}} dy \quad (1)$$

where  $I_0$  is the beam intensity,  $I_{x,y}$  is the Gaussian intensity profile;  $dA$  is the cross section of the laser beam at the position of the power meter's sensitive surface;  $w_x$  and  $w_y$  are the beam waists in the x and y-directions, respectively;  $w_{x,y} = z \tan \theta_{f,s}$  where  $\theta_{f,s}$  are the  $1/e^2$  half angle beam divergences for the fast and slow axes;  $z$  is the position of the power meter; and the limits of integration extend to infinity.

The total power captured by the power meter can be calculated using:

$$P_{meas} = I_0 \int_0^{r_{x,y}} e^{-\frac{2x}{w_x}} dx \int_0^{r_{x,y}} e^{-\frac{2y}{w_y}} dy \quad (2)$$

where the limits of integration now extend only over the surface area of the power meter's sensitive area. Equation 2 must be integrated numerically in its present form. However, if you approximate the power meter's circular surface with a square having the same area ( $4s^2 = \pi r^2$ ) then the integral can be readily evaluated using error functions. The PAF can then be written as:

$$PAF = \frac{P_{Total}}{P_{meas}} = \frac{\int_{-\infty}^{+\infty} e^{-\frac{2x}{w_x}} dx \int_{-\infty}^{+\infty} e^{-\frac{2y}{w_y}} dy}{\int_{-s}^{+s} e^{-\frac{2x}{w_x}} dx \int_{-s}^{+s} e^{-\frac{2y}{w_y}} dy} \quad (3)$$

## Results and Discussion

Table 1 shows performance details of the quantum cascade laser QCL 07-562. Experimental uncertainty and conditions have been included as well. Of note is the fact that the power determined as discussed above agrees, within in the experimental error, with values obtained using an integrating sphere capable of capturing all the emitted radiation (9). Further, additional independent studies (10) using well calibrated visible lasers have verified that the techniques described do provide a credible method for determining the total power emitted from widely diverging lasers.

---

## References

---

1. Faist, J.; Capasso, F.; Sivco, D. L.; Sirtori, C.; Hutchinson, A. L.; Cho, A. Y. *Science* **264**,553, 1994.
2. Lin, C.-H.; Yang, R. Q.; Zhang, D.; Murry, S. J.; Pei, S. S.; Allerma, A. A.; Kurtz, S. R. *Electron. Lett.* **1997**, *33*, 598.
3. Useful reviews of the recent state-of-the-art and applications are available for both the QC lasers and IC lasers in *IEEE J. Quantum Electron.* **2002**, *38* (6), 509–602.
4. Vurgaftman, Meyer, J. R.; Ram-Mohan, L. R. *IEEE Photo. Tech. Lett.* **1997**, *9*, 170-172, and references cited therein.
5. Yang, R. Q.; Bradshaw, J. L.; Bruno, J. D.; Pham, J. P.; Wortman, D. E.; Tober, R. L. *Appl. Phys. Lett.* **2002**, *81*, 397.
6. Faist, J.; Capasso, F.; Sitori, C.; Sivco, D. L.; Hutchinson, A. L.; Cho, A. Y. *Appl. Phys. Lett.* **1995**, *67*, 3057.
7. Sirtori, Carlo; Page, Hideaki; Becker, Cyrille; Ortiz, Valentin. *IEEE Journal of Quantum Electronics* **June 2002**, *38* (6).
8. Wienold, M.; Semtsiv, M. P.; Bayrakli, I.; Masselink, W. T.; Ziegler, M.; Kennedy, K.; Hogg R. *J. Appl. Phys.* **2008**, *103*, 083113.
9. Anish Goyal, private communication.
10. Tober, Richard L. Independent verification.

| <u>No. of Copies</u> | <u>Organization</u>  | <u>No. of Copies</u>             | <u>Organization</u>  |
|----------------------|--|----------------------------------|--|
| 1<br>ELEC            | ADMNSTR<br>DEFNS TECHL INFO CTR<br>ATTN DTIC OCP<br>8725 JOHN J KINGMAN RD STE 0944<br>FT BELVOIR VA 22060-6218  | 1                                | COMMANDER<br>US ARMY RDECOM<br>ATTN AMSRD AMR<br>W C MCCORKLE<br>5400 FOWLER RD<br>REDSTONE ARSENAL AL 35898-5000  |
| 1                    | DARPA<br>ATTN IXO S WELBY<br>3701 N FAIRFAX DR<br>ARLINGTON VA 22203-1714  | 1                                | US GOVERNMENT PRINT OFF<br>DEPOSITORY RECEIVING SECTION<br>ATTN MAIL STOP IDAD J TATE<br>732 NORTH CAPITOL ST NW<br>WASHINGTON DC 20402  |
| 1 CD                 | OFC OF THE SECY OF DEFNS<br>ATTN ODDRE (R&AT)<br>THE PENTAGON<br>WASHINGTON DC 20301-3080  | 1                                | US ARMY RSRCH LAB<br>ATTN AMSRD ARL CI OK TP<br>TECHL LIB T LANDFRIED<br>BLDG 4600<br>ABERDEEN PROVING GROUND MD<br>21005-5066   |
| 1                    | US ARMY RSRCH DEV AND ENGRG<br>CMND<br>ARMAMENT RSRCH DEV AND<br>ENGRG CTR<br>ARMAMENT ENGRG AND<br>TECHNLGY CTR<br>ATTN AMSRD AAR AEF T J MATTS<br>BLDG 305<br>ABERDEEN PROVING GROUND MD<br>21005-5001 | 1                                | DIRECTOR<br>US ARMY RSRCH LAB<br>ATTN AMSRD ARL RO EV<br>W D BACH<br>PO BOX 12211<br>RESEARCH TRIANGLE PARK NC<br>27709  |
| 1                    | US ARMY TRADOC<br>BATTLE LAB INTEGRATION &<br>TECHL DIRCTRT<br>ATTN ATCD B<br>10 WHISTLER LANE<br>FT MONROE VA 23651-5850  | 13                               | US ARMY RSRCH LAB<br>ATTN AMSRD ARL SE EE R TOBER<br>(10 COPIES)<br>ATTN AMSRD ARL CI OK T<br>TECHL PUB<br>ATTN AMSRD ARL CI OK TL<br>TECHL LIB<br>ATTN IMNE ALC IMS<br>MAIL & RECORDS MGMT<br>ADELPHI MD 20783-1197 |
| 1                    | PM TIMS, PROFILER (MMS-P)<br>AN/TMQ-52<br>ATTN B GRIFFIES<br>BUILDING 563<br>FT MONMOUTH NJ 07703  |                                  |  |
| 1                    | US ARMY INFO SYS ENGRG CMND<br>ATTN AMSEL IE TD F JENIA<br>FT HUACHUCA AZ 85613-5300   |                                  |  |
|                      |  | TOTAL: 24 (1 ELEC, 1 CD, 22 HCS) |  |