

# **Characterization of Quantum Well Laser Diodes for Application within the AMRDEC HWIL Facilities**

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## **ABSTRACT**

The U.S. Army's Research, Development, and Engineering Command's (RDECOM) Aviation and Missile Research, Development, and Engineering Center (AMRDEC) provides Hardware-in-the-Loop (HWIL) test support to numerous tactical and theatre missile programs. Critical to the successful execution of these tests is the state-of-the-art technologies employed in the visible and infrared scene projector systems. This paper describes the results of characterization tests performed on new mid-wave infrared (MWIR) quantum well laser diodes recently provided to AMRDEC by the Naval Research Labs and Sarnoff Industries. These lasers provide a +10X improvement in MWIR output power over the previous technology of lead-salt laser diodes. Performance data on output power, linearity, and solid-angle coverage are presented. A discussion of the laser packages is also provided.

## **1. INTRODUCTION**

### ***1.1 RDECOM AMRDEC HWIL Facilities***

The Aviation and Missile Research, Engineering, and Development Center (AMRDEC) of the U.S. Army Research, Development, and Engineering Command (RDECOM) on Redstone Arsenal, Huntsville, Alabama, has an extensive history of applying all types of modeling and simulation (M&S) to weapon system development and has been a particularly strong advocate of hardware-in-the-loop (HWIL) simulation and test for many years. The RDECOM AMRDEC has been providing a full range of simulation support to Army Program Executive Officers (PEOs), Project Managers (PMs), other Armed Services agencies, and certain U.S. allies over the past 40 years. In addition, RDECOM AMRDEC has M&S support relationships with the U.S. Army Space and Missile Defense Command (SMDC), and the Redstone Technical Test Center (RTTC).

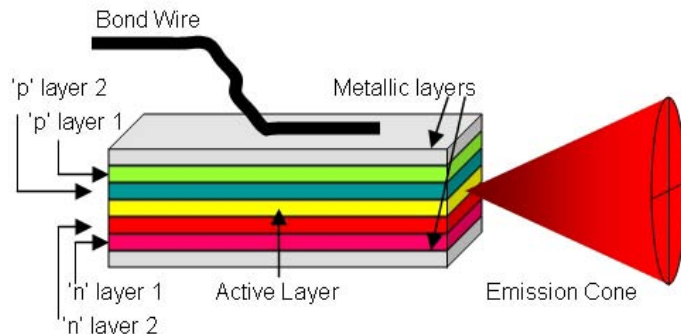
Within the AMRDEC, the Advanced Simulation Center's (ASC) role is to provide a dedicated, government-owned, high fidelity, verified and validated simulation and test tool to assist the project office and prime contractor during missile system development, test, production, and fielding by providing value-added HWIL capabilities. The ASC consists of fourteen (14) HWIL facilities and focuses on the engineering-level simulations that pertain to the missile elements. The ASC is divided into three main areas: Imaging Infrared System Simulation (I<sup>2</sup>RSS), Radio Frequency System Simulation (RFSS), and Multi-Spectral System Simulation (MSSS). The I<sup>2</sup>RSS supports imaging and non-imaging infrared missile programs in both the mid and long wave infrared wavebands and visible waveband. The RFSS supports the X, K, Ka, and W band radio frequency missile. The MSSS supports the common aperture and/or simultaneous imaging infrared, visible, semi-active laser (SAL) and/or millimeter wave (Ka and W band) missile programs.

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## 1.2 Application of IRSP Technologies in HWIL testing

The AMRDEC ASC employs many types of state-of-the-art technologies<sup>1</sup> for the generation of dynamic one- and two-dimensional infrared imagery for presentation to the unit under test (UUT). These technologies include emitter array devices, digital micro-mirror devices (DMD), and infrared laser sources. Each technology provides unique capabilities serving a specific test requirement. The infrared laser sources, specifically, provided high inband power outputs, small packages and very fast response times making them well-suited to the simulation of dynamic, high-intensity objects. Single laser diodes have been successfully employed for simulation of point source objects such as debris, stages, and counter-measures. Integration of multiple lasers has resulted in the successful generation of two-dimensional infrared scene projectors<sup>2</sup>. In each of these cases, the laser diodes employed were of the lead-salt tunable diode laser (TDL) type.

The lead chalcogenides (PbS, PbSe) infrared TDLs have been the workhorse for semiconductor laser sources in the mid-wave and long-wave infrared regions. These sources consist of a double heterostructure (DH) of p-type, n-type and active layer materials sandwiched between metallic contacts. A bond wire to one of the metallic layers provides the input current into the material and emission occurs across the small region of active material between the p-n layers. Figure 1 illustrates the general layout of this DH semiconductor laser. The TDLs implemented at the AMRDEC ASC were operated at cryogenic temperatures (77K) and provided up to 1mW of output power with 0.5A of input current<sup>3</sup>. Response times, limited by the drive electronics, were typically under 100 nsec. While the TDLs have found many useful applications in the simulation community, issues associated with low power and non-linearities have left users within the simulation community desiring greater performance. Recent advances in semiconductor lasers have lead to the development of MWIR quantum well devices offering significant improvements in performance.



**Figure 1: DH TDL Illustration**

## 2. Quantum Well (QW) Lasers

### 2.1 Quantum Well Laser Background

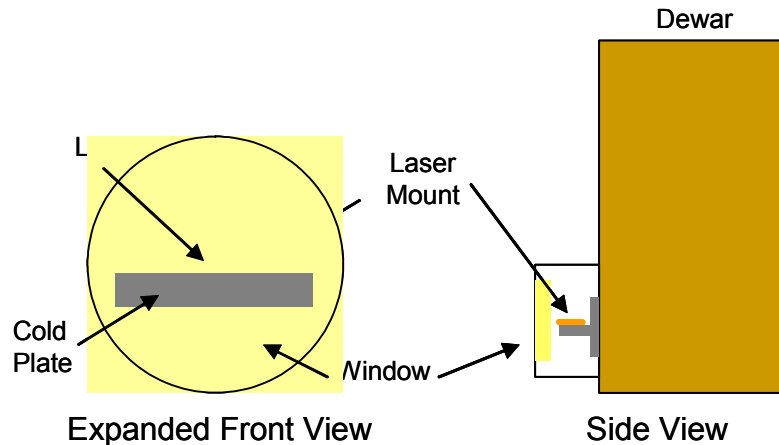
Following the same general principles for semiconductor lasers, the quantum well laser was developed by reducing the active material height to a level consistent with the electron transitory energy levels. By restricting the three dimensional space available for recombination, more precise control of the light emission process is acquired. Placement of multiple 'wells' in series within the laser diode structure provides additional gain amplification. Benefits of the quantum well approach, as compared to the previous double heterostructure design, include the ability to tune the wavelength by varying the active material thickness rather than changing material, lower threshold currents, and higher powers<sup>4,5</sup>.

### 2.2 Quantum Well Laser Manufacturer

The QW diode lasers reported on here were designed and manufactured through the efforts of the Sarnoff Corporation and the Naval Research Laboratory. The lasers were designed to provide maximum continuous output at a 3.3  $\mu\text{m}$  wavelength when operated at 77 degrees K. The active region of these lasers consists of five W-quantum wells that provide the optical gain. The W-QW lasers have cavity lengths of 1 mm and a rectangular aperture size of 100 $\mu\text{m}$  by <1  $\mu\text{m}$ . Reflectance coatings of 30% and 95% were applied to the front and rear facets, respectively. Lastly, the laser diodes were indium-soldered onto the copper mounts.

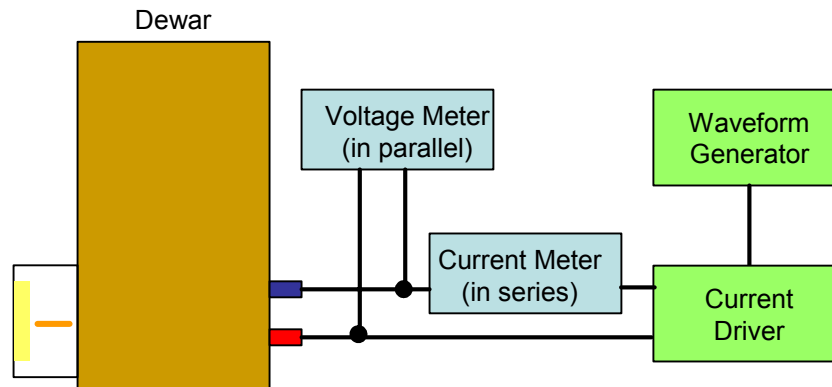
### 2.3 Quantum Well Laser Testing at AMRDEC

The AMRDEC ASC procured five W-quantum well mid-wave infrared (MWIR) diode lasers from the Sarnoff Corporation. The lasers were packaged by Sarnoff onto individual mounts as shown in Figure 2. Two selected laser packages were mounted, one at a time, into a test dewar configuration also shown in Figure 2.



**Figure 2: QW Laser Mounting in Test Dewar**

The test dewar was integrated with the appropriate drive electronics for operating and monitoring the required current and voltage levels. This operational configuration was employed for each of the tests discussed within this paper. Figure 3 below provides a representative block diagram of this configuration.



**Figure 3: QW Laser Test Hardware Configuration**

Each of the two tested lasers was measured for power output, linearity, and emission profile. All measurements were taken while operating the array in a vacuum and at cryogenic (77K) temperatures. Section 3 presents the results of these performance tests. Section 4 provides an in-depth review of the laser packages and packaging issues.

## 3. AMRDEC QW Laser Measurements

### 3.1 Maximum Output Power

A measurement of the maximum laser diode output power was made using a Molectron PM3 power meter head placed immediately in front of the dewar window. The 0.75 inch diameter collecting surface of the power meter was located immediately in front of the dewar in order to collect as much of the full 3-D emission cone of the laser diode as possible. With an ~1 inch spacing between the detector and the laser diode, a cone angle of approximately  $\pm 20$  degrees could be collected.

During measurement of the laser power, the laser diode was driven using an 80/20 duty cycle at a frequency of 0.01 Hz (80 seconds on / 20 seconds off). Figure 4 below shows the measured test results for laser #3 and #4 of the five

provided to AMRDEC. For comparison, the data provided by Sarnoff at the time of delivery is also included. The values for laser #3 agree well, with an ~15% difference across most of the input current levels. The output power profile for laser #4 was significantly below that measured by Sarnoff. The discrepancy is most likely due to differences in the test setup, specifically the solid angle over which data was collected. Based on measurements of the emission cone (see section 3.3), a small change in either the separation between the detector and laser, or in the detector size would account for this disagreement. Details of the Sarnoff test setup were not known.

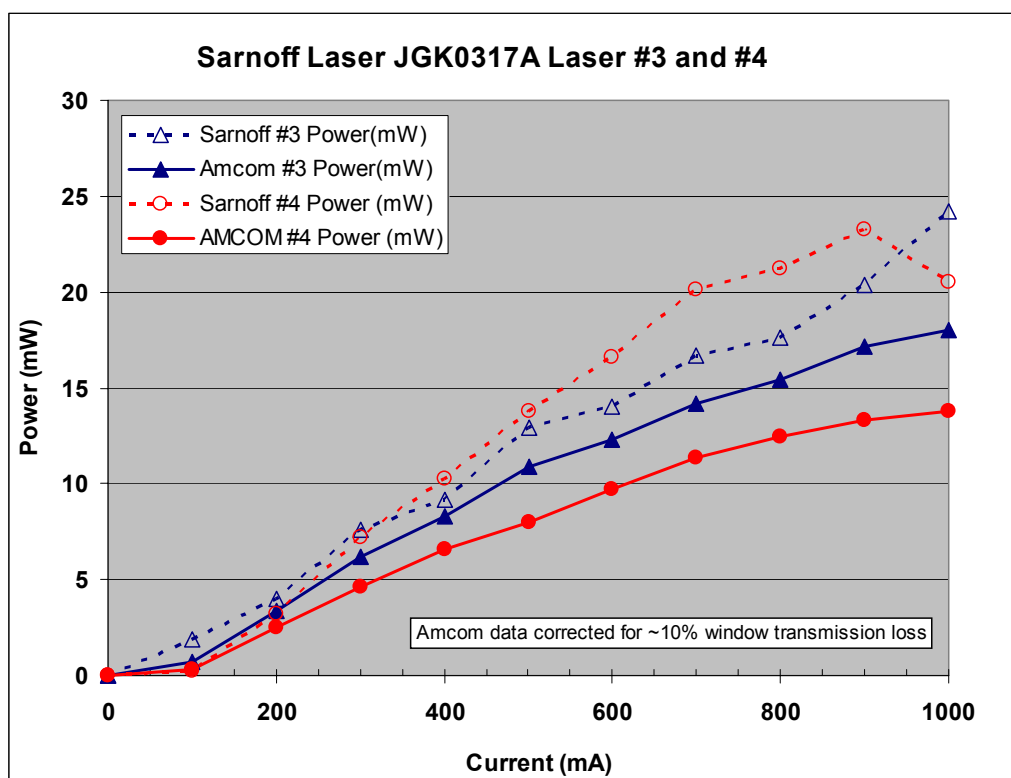


Figure 4: Input Current versus Output Power

For the two lasers tested, the maximum measured output powers at an input current level of 1A were 18mW and 13 mW over the collection solid angle discussed above. As compared to the previously employed lead-salt TDLs, these QW laser diodes provided 10-20X more power out.

### 3.2 Linearity

A mapping of the laser diode output power as a function of input current was made using a Molelectron PM3 power meter head placed immediately in front of the dewar window. The 0.75 inch diameter collecting surface of the power meter was located immediately in front of the dewar in order to collect as much of the full 3-D emission cone of the laser diode as possible. With an ~1 inch spacing between the detector and the laser diode, a cone angle of  $\pm 20$  degrees could be collected.

During measurement of the laser power, the laser diode was driven using an 80/20 duty cycle at a frequency of 0.01 Hz (80 seconds on / 20 seconds off).

Linear curve fitting to the full 100-1000 mA input range and a 300-700 mA subset range were performed. Figure 5 below provides a comparison of these linear curves to the actual data.

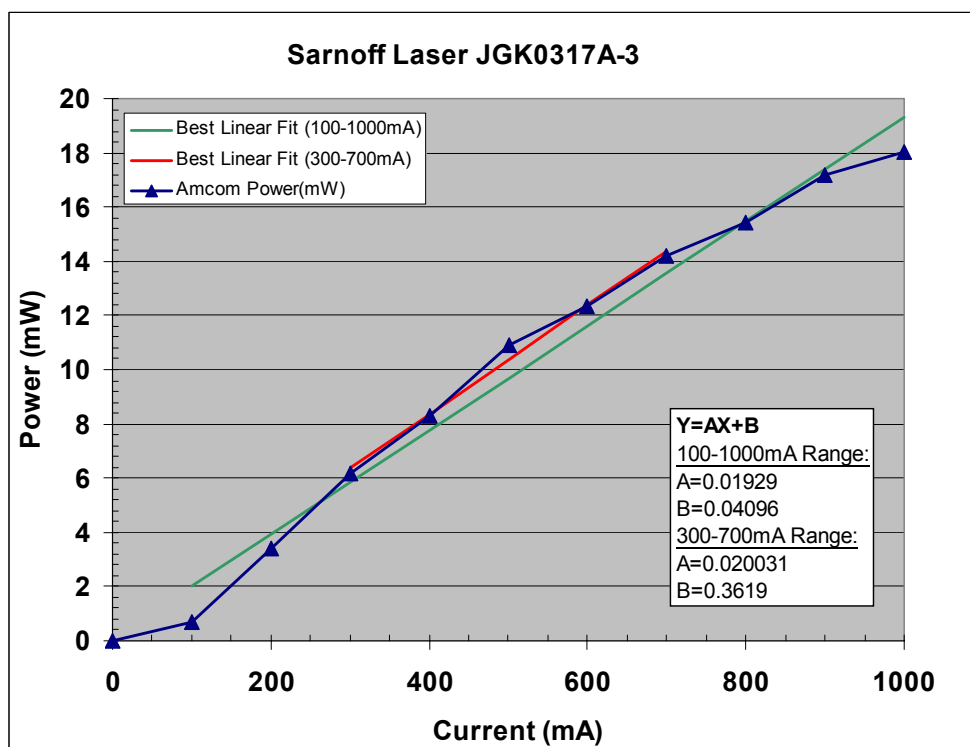


Figure 5: Response Linearity of Sarnoff QW Laser #3

As can be seen from the figure above, the QW laser exhibited good linearity over much of its operational range. Over the smaller sub-range, covering approximately half of the overall operational range, the linearity is excellent. Previously implemented lead-salt TDLs exhibited many non-linearities and required burdensome look-up tables for characterization and operation. A linear response system significantly simplifies the overall calibration and control process while reducing costly hardware memory requirements. The Sarnoff QW laser #4 exhibited similar linearity in its response.

### 3.3 Emission Profile

Inherent in semiconductor performance is the elliptical and non-uniform emission cone of the output optical energy (see Figure 1). Knowledge of the maximum output power alone is not sufficient for determining the expected performance of the diode laser when coupled to a unique optical system. Information pertaining to the energy available within a given F-cone of the associated optics is required for accurately estimating the simulated level in radiometric terms (apparent temperature, for example). AMRDEC performed a mapping of the QW diode output through sampling of horizontal and vertical slices across the emission cone. Data was collected over  $\pm 40$  degrees in the vertical (large spread) direction and  $\pm 20$  degrees over the horizontal direction. Figure 6 below shows the data collected from these two slices for laser #3. The elevation scan, along the 100um length of the laser, exhibits good symmetry over a spread of  $\sim \pm 10$  degrees. The azimuth scan, along the narrow length of the laser, reveals a 30 degree spread in one direction and an unusual and broad spread in energy in the opposite direction.

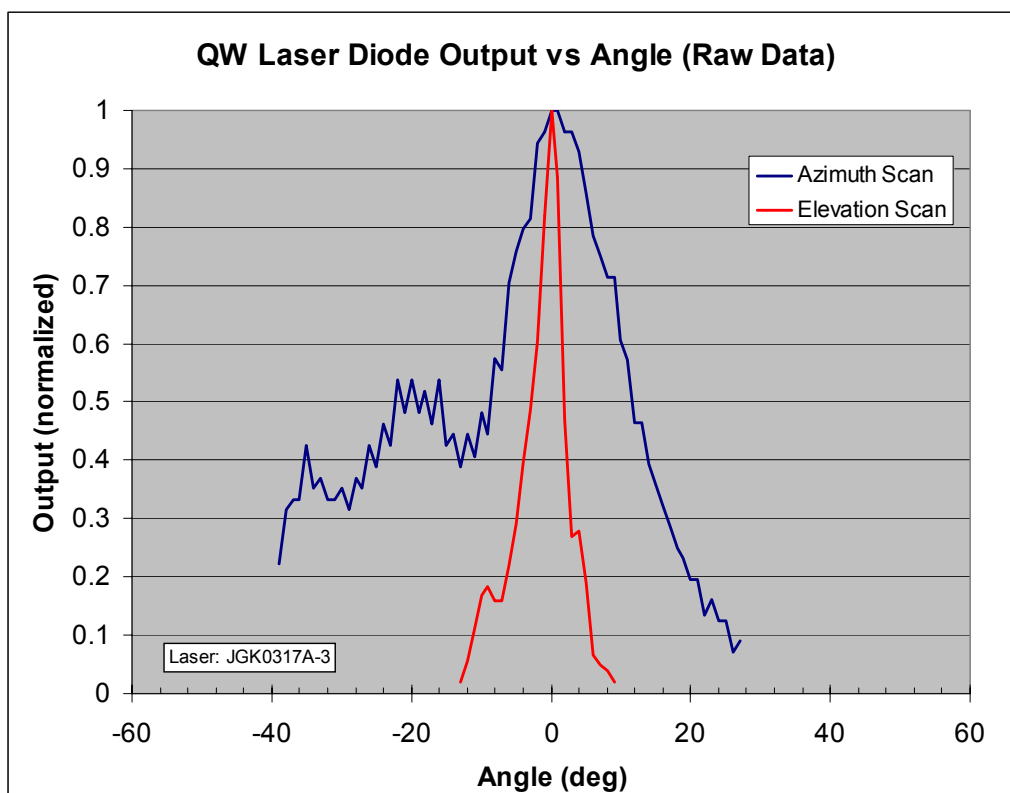


Figure 6: Profile Slices of QW Laser Diode Emission

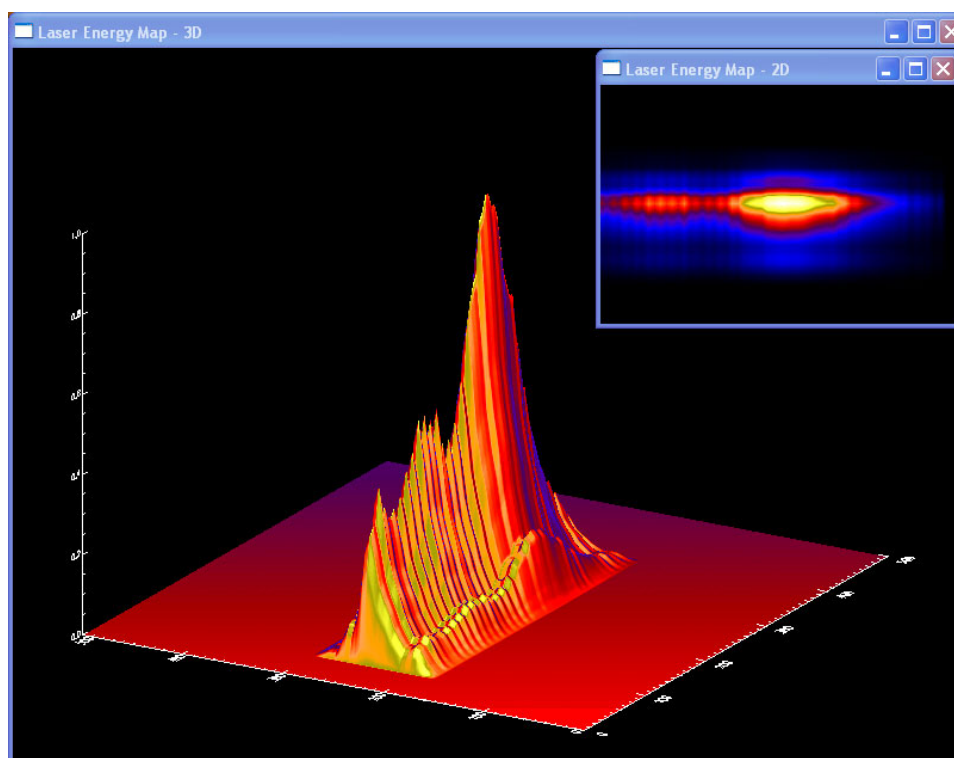


Figure 7: 2D and 3D Map of QW Emission Profile

Based on these two profile measurements, a three dimensional profile was generated. This 3-D profile is plotted in two forms in Figure 7. The elliptical nature of the emission, along with the anomalous behavior along one axis, is clearly evident. Based on this 3-D profile, a calculation of the percentage of total energy within any given cone can be made. Table 2 below shows these values for full cone angles from 10 to 80 degrees, at 10 degree intervals. It can be seen that the collection of a significant portion of the energy emitted by the laser diode (>50%) requires a ‘fast’ optical system (<F/3).

**Table 2: Laser #3 Percent Energy versus Cone Angle**

Cone Angle Collected (deg)	F/#	% of Total Energy
10 ( $\pm 5$ )	5.7	25
20 ( $\pm 10$ )	2.8	49
30 ( $\pm 15$ )	1.9	64
40 ( $\pm 20$ )	1.4	75
50 ( $\pm 25$ )	1.1	85
60 ( $\pm 30$ )	0.87	91
70 ( $\pm 35$ )	0.71	96
80 ( $\pm 40$ )	0.60	100

## 4. QW Laser Package

### 4.1 Package Requirements

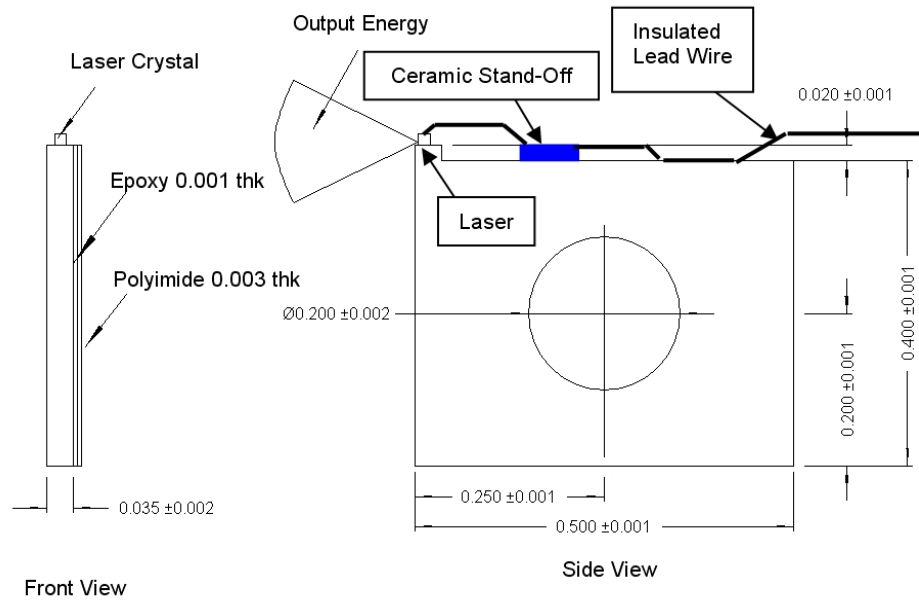
The performance of the laser diode becomes a moot point if adequate packaging is not supplied. Poor mechanical, electrical, or thermal performance of the package may render the diode useless in practice. Package requirements must be understood well, with respect to the given application, to insure optimal performance of the laser diode can be attained.

The laser package in general provides accommodation for the mechanical mounting, electrical power, and thermal control. The mechanical mount requirements address the physical placement and attachment of the laser diode to the package, as well as the attachment of the package to a test apparatus (often a cold finger inside a cryogenic, vacuum dewar). If operation of multiple diodes is desired, as is the case for some AMRDEC applications, the package must also support the need for placement of other diodes in close proximity. The electrical requirements address the supply of current to the top of the laser diode and grounding of the laser diode to the package. Lastly, the thermal requirements address the need for removing the heat generated during operation and maintaining a stable operational temperature for the laser diode. The following sections describe the initial package design, package shortcomings, and proposed changes.

### 4.2 QW Laser Diode Packaging

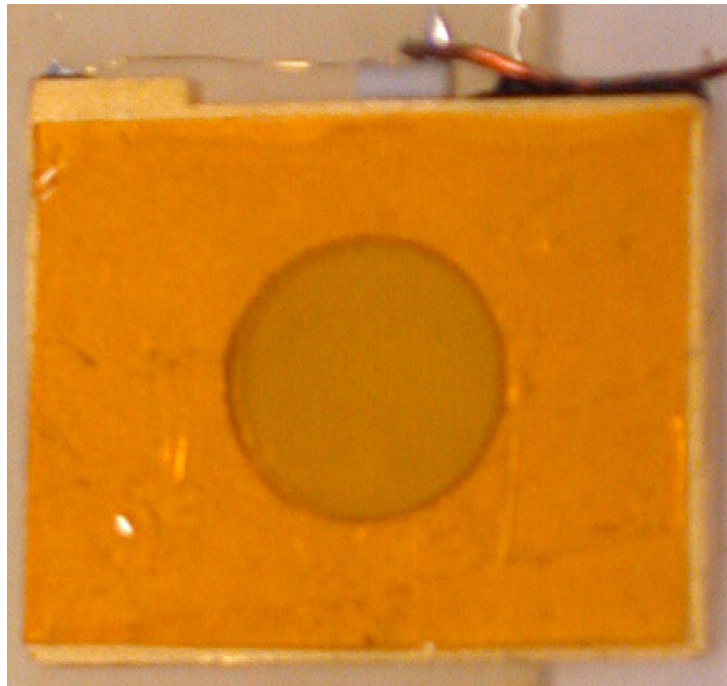
Laser Analytics Corporation had originally manufactured the lead-salt TDLs Laser packages previously implemented at the AMRDEC ASC. These packages supported the mounting of multiple lasers into a linear array for use within the AMRDEC Laser Diode Array Projectors. The laser packages were a second generation “slimline” mount in which many issues with the laser mounting, thermal insulation, and handling had been resolved. Unfortunately, Laser Analytics was unable to provide similar mounts for the five quantum well laser diodes discussed in this paper. Sarnoff Corporation, therefore, manufactured the packages for these five lasers. The schematic for these laser packages is shown in Figure 8 below.





**Figure 8: Quantum Well Laser Package**

The laser packages are made from copper and are approximately 12.5mmx10mmx1mm in dimension. Figure 9 below is a photograph of one of the five quantum well laser diodes mounted onto a delivered package.



**Figure 9: Photograph of Example Laser on Package**

A raised platform at the front of the mount provides the location for placement of the laser diode and insures proper clearance is available for the electrical bond wire leading to the diode. A ceramic standoff, in the middle of the top of the package, provides an electrically isolated pad for bonding of the small wire to the insulated lead wire providing the current feed. Attachment of the lead wire to the package is required to minimize mechanical strain on the bond wire

and diode laser. A 5 mm mounting hole was provided in the middle of the package and allows for multiple packages to be securely aligned in a linear fashion using a stainless steel rod. Lastly, an electrical and thermal barrier consisting of polyimide tape was attached to one side of the laser package.

#### 4.3 Package Shortcomings

In the evaluation of the laser packages, several issues arose which posed significant risk to the performance of the quantum well laser diode. These issues, and proposed modifications, are discussed below.

##### 4.3.1 Bond Wire Spacing to Platform

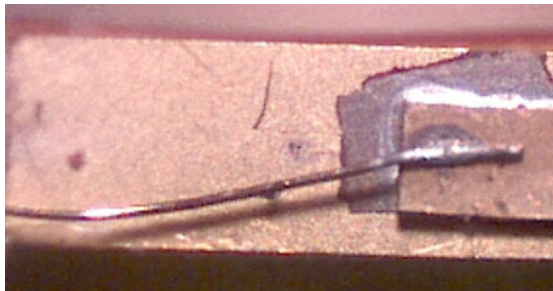
The 'bond' wire provides the electrical interface to the incoming lead wire and the laser diode. The electrical connection with the lead wire is made on top of an electrically isolated ceramic pad. Attachment of the bond wire to the laser diode is made at the top surface of the laser diode. Care must be taken to insure that the bond wire sufficiently clears the surface of the laser diode mounting pad. Bond wires that lie too close may short directly to the mounting pad. Some of the five delivered packages exhibited poor clearance between the bond wire and the mounting pad. Figure 10 shows a photograph of one such package.



**Figure 10: Insufficient Bond Wire Clearance**

Several remedies are available for addressing this packaging issue. Relocation of the ceramic pad to a position closer to the laser platform would shorten the bond wire and reduce the potential for 'sag'. Reduction in the platform length would also reduce the likelihood of the bond wire coming in contact with the platform/package.

##### 4.3.2 Bond Wire Alignment With Package



**Figure 11: Bond Wire Too Close To Edge**

The bond wire must also demonstrate sufficient clearance with the edge of the laser package. Figure 11 shows a package where the bond wire has been placed too close to the edge of the laser package. While sufficient height from the package may exist, allowing the bond wire to be placed this close to the edge risks shorting to the cold finger or neighboring laser package.

As with the previous bond wire issue, reduction in the distance to the ceramic pad will reduce the occurrence of this by shortening the overall bond wire length.

##### 4.3.3 Ceramic Pad

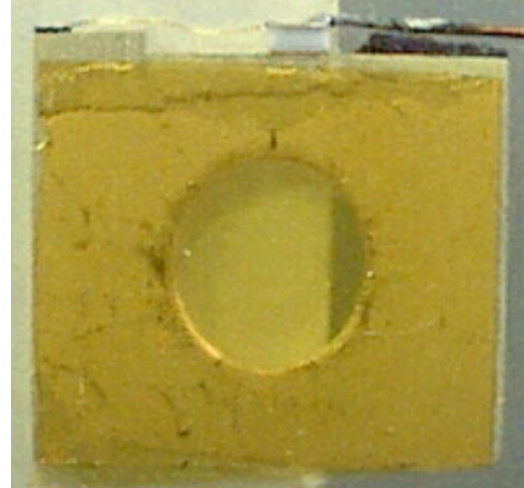
The ceramic pad provides a location, electrically isolated from the copper package, for the attachment of the electrical lead wire and bond wire. As mentioned above, the placement of the ceramic pad should be moved forward to shorten the bond wire and reduce the possibility of issues associated with the bond wire. Figure 12 shows the ceramic pad as viewed from above the copper package. The width of the ceramic pad is comparable to that of the laser package and the potential for shorting to the cold finger or other laser packages is high. Also, the lead and bond wire extend, or nearly extend, beyond the borders of the pad thereby also creating the risk of an electrical short. The ceramic pad width should be reduced and the placement of the lead and bond wire on top of the pad should be such that no overhang occurs.



**Figure 12: Ceramic Pad on Package Top**

#### 4.3.4 Thermal Barrier

The laser diodes are not efficient light generators and a high percentage of the input current is converted into heat. Stable operation of the laser diodes requires a consistent operating temperature. To remove the generated heat, the lasers are mounted on copper heatsink packages. When multiple lasers, and hence multiple packages, are integrated together, it becomes necessary to insure that the heat generated from one laser diode is not conducted directly to the heatsink of neighboring laser diodes. Likewise, the electrical current driven to one laser diode cannot be allowed to conduct through to other laser diodes via contact of the laser packages. This requires that an electrical and thermal barrier be placed between the laser diode packages. The barrier, however, should not add appreciably to the overall thickness of the laser package. For the initial set of laser packages, an adhesive-backed polyimide tape was applied to one side of the package. Figure 13 shows a picture of one of the laser packages with the polyimide tape applied. The Kapton tape, applied manually, does not provide complete coverage of the package. Small regions around the periphery remain uncovered. Also, sections of the tape extend beyond the package by margins sufficient to inhibit integration of multiple packages into an array. Lastly, the adhesive backed tape did not remain adhered to the package well with peeling visually evident. The tape easily detached from the surface under moderate torque during fastening of the package to the cold finger.



**Figure 13: Barrier Attached to Package**

AMRDEC has recommended that the thermal barrier material be applied in a manner which bonds the barrier to the package. This process should provide better coverage and adhesion than that of the tape material employed on the sample packages.

#### 4.3.5 Lead Wire

Current for operation of the laser diode is brought to the laser package through an insulated electrical 'lead' wire. This wire is soldered to the 'bond' wire running directly to the laser diode. Hence, a direct mechanical attachment is made between the lead wire and laser diode. To insure that handling of the lead wire does not place undue strain on the laser diode, strain relief must be applied to the lead wire. Figure X shows a picture of the attachment point for the lead wire on one of the five quantum well laser diode packages. The strain relief is provided by an epoxy which bonds the insulated lead wire to the package. However, for each of the supplied laser packages, the length of the epoxy region was insufficient for providing acceptable strain relief. One of the packages, shown in the figure, had the lead wire come completely separated from the available strain relief.



**Figure 14: Lead Wire Attachment**

Improvements to the attachment of the lead wire can be made through a series of simple steps. AMRDEC has recommended that the ceramic pad be positioned closer to the laser diode, thereby allowing for a greater length area along the top of the package for strain relief. The epoxy should be extended as far as possible along this length, covering at least half the length of the package. Lastly, the epoxy material should completely encompass the lead wire, insuring a secure attachment to the package.

#### 4.3.6 Package Review Summary

The laser package serves a critical role in the overall performance of the laser diodes. The initial laser packages provided by Sarnoff incorporate all the necessary functionality but require minor modifications for insuring optimal

performance can be attained. Efforts currently underway at Sarnoff are expected to address each of these issues in the next lot of laser diodes provided to the AMRDEC.

## 5. Conclusion and Future Work

The quantum well laser diodes provide a significant advance in the performance of available mid-wave infrared laser diodes. Greater power and improved linearity will enhance and expand the roles these devices have found in the simulation community. Issues associated with packaging, integration into linear arrays, and optical interfacing are being addressed at the AMRDEC.

The AMRDEC ASC is currently planning the integration of the quantum well laser diodes into advanced infrared scene projector systems for use within the HWIL facilities. Testing of these quantum well lasers at near-room temperature conditions is currently planned for the near future. Testing of other quantum well laser diodes, promising higher output powers at near room temperature, are also planned.

## 6. Acknowledgements

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The authors would like to thank the Naval Research Laboratory and the Sarnoff Corporation for their cooperation and support in the testing performed at the AMRDEC.

## 7. References

<sup>1</sup>“Overview of Dynamic Scene Projectors at the U.S. Army Aviation and Missile Command”, SPIE Vol ?, 2002, Daniel A. Saylor, D. Brett Beasley, and Jim Buford

<sup>2</sup>“Current Status of the Laser Diode Array Projector Technology”, SPIE Vol ?, 1998, D. Brett Beasley and Daniel A. Saylor

<sup>3</sup>“Diode laser arrays for dynamic infrared scene projection”, SPIE Vol 1967, 1993, D. Brett Beasley and John B. Cooper

<sup>4</sup>Overview information on quantum well laser diodes, and semiconductor laser diodes in general, can be found at:

[http://www.mtmi.vu.lt/pfk/funkc\\_dariniai/diod/led.htm](http://www.mtmi.vu.lt/pfk/funkc_dariniai/diod/led.htm)

<sup>5</sup>Overview information on quantum well laser diodes, and semiconductor laser diodes in general, can be found at:

<http://britneyspears.ac/physics/fplasers/fplasers.htm>