# Temperature Dependence of the Wavelength Spectrum of a Resonantly Pumped W-OPIC Laser

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***Abstract*—Developing efficient semiconductor lasers capable of operating in the mid-infrared spectrum at a temperature reasonably close to room temperature requires further characterization and study of these semiconductors. The emitted wavelength of a semiconductor laser exhibits a parabolic temperature dependence, with values increasing as temperature increases. Additionally, when Fourier transformed infrared spectra of a W-optical pumping injection cavity laser are taken with sufficient resolution, a fine structure is observed within the central peak. By studying the location of this large peak and the separation between the fine peaks of this structure, a change in the index of refraction can be determined. This value could provide insight into the optical pumping dependence of the gain. The emitted wavelength varied from 2.8 µm at 78 K to 3.3 µm at 325 K. Pump wavelengths varied across the temperature range to maximize the signal produced by the sample, and both the pump wavelength and emitted wavelength exhibit a parabolic relationship with temperature. Future research is necessary to determine the cause of this parabolic dependence and how it relates to a possible change in index of refraction.**

***Index Terms*—Semiconductor lasers, FTIR spectroscopy, mid-infrared, optical pumping, refractive index, temperature tuning**

## I. Introduction

THE efficient generation of mid-infrared radiation at near-room temperature could greatly expand the accessibility of a more precise and sensitive means of chemical detection [1]. If semiconductor lasers are to be applied in these fields, it is necessary to promote practical, portable operation by reducing the necessary cooling to that provided by a thermoelectric device.

Optical pumping injection cavity (OPIC) lasers show great promise in this field, as they have exhibited higher temperature operation than electronically injected varieties [2,3]. The semiconductor studied is a W-type laser, named after the shape of the quantum wells [4]. The placement of distributed Bragg reflector (DBR) mirrors on either side of the active region allows maximum absorption of photons by the quantum wells, resulting in increased efficiency [1,5]. Another method of maximizing output for a given input is to pump the laser at etalon resonance. While earlier approaches involved growing the sample such that the resonance corresponded to the available pump wavelength, an optical parametric oscillator (OPO) can tune the wavelength of the beam striking the sample. This becomes particularly significant as temperature is varied; the resonance wavelength shifts as temperature is increased, and the input beam wavelength must be tuned accordingly. Pumping at resonance both improves efficiency and reduces the threshold intensity for lasing behavior to begin [5].

By varying temperature, the characteristics of a mid-infrared OPIC laser can be better understood. Previous studies have shown a linear relationship between the emitted wavelength and temperature of a laser diode [6]. When studying Fourier transformed infrared (FTIR) spectra, this emitted wavelength is given by the center of the peak in the spectra. This broad envelope consists of a series of smaller peaks indicative of a modal structure. While the center of the peak remains the overall emitted wavelength, the distance between the peaks of the longitudinal modes can be used to determine how the index of refraction, $n$, of the laser varies using Eqn. (1) [7]. The center wavelength and peak separations, $k$ and $\Delta k$ respectively, are both determined from the FTIR spectra. Fitting the broad peak with a Gaussian gives an x-center value corresponding to $k$, while fitting each modal peak with a Gaussian, recording the center wave numbers, and subtracting the values for adjacent peaks gives values that are then averaged to find $\Delta k$. Eqn. (1) can be used to solve for either $\Delta n$ or $n$; however, if solving for $\Delta n$, an estimate of $n$ is required to complete the calculation. Estimating $n$ is done by determining $n$ for each element and weighting these values according to the layer thickness of that element in the sample.

$$\Delta n = -n\frac{\Delta k}{k} + \frac{1}{2Lk} \qquad (1)$$

The refractive index is known to depend on wavelength, temperature, and the gain of the medium. While wavelength and temperature can be controlled as elements of an

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experiment, optical pumping alters the gain of the laser. Calculating a value for $\Delta n$ allows this change in gain to be quantified. We want to determine the relative contributions of temperature shift vs. gain-induced changes in refractive index due to the higher optical pumping intensities required at higher temperatures. We seek to do this by studying both temperature dependence and intensity dependence to quantify differences in $\Delta k$ and $\Delta n$

## II. Materials and Methods

### *A. Experimental Setup*

The OPIC laser studied was part of the ITV-1108 wafer grown by Sarnoff Corporation and used in T. C. McAlpine's thesis [8]. This sample was grown via molecular beam epitaxy on a GaSb substrate. The W-well active region (10 periods of 21 Å InAs/34 Å GaSb/21 Å InAs/40 Å AlSb) was topped with a strain balance layer of 40 Å AlSb. This was surrounded on each side by 100 Å hole-blocking layers made of $AlAs_{0.08}Sb_{0.92}$. The top and bottom quarter wave stacks consisted of 10 and 18 periods, respectively, of 1451 Å GaSb and 1758 Å $AlAs_{0.08}Sb_{0.92}$. The sample of this material was cleaved to a cavity length of 1780 μm and mounted on a heat sink made of copper to ensure good thermal contact for temperature regulation. The third harmonic of a Spectra-Physics Quanta-Ray Pro-250 Nd: yttrium-aluminum-garnet (YAG) laser set to Q-Switch mode with 10 Hz frequency pumped a Spectra-Physics Quanta-Ray MOPO-PO (optical parametric oscillator.) The OPO allowed the wavelength with which the sample was pumped to be tuned, providing a means of pumping the sample at resonance. The sample was mounted in a cryostat and cooled to temperatures as low as 78 K using liquid nitrogen. A mechanical pump reduced the ambient pressure to <5 mTorr. After the pressure was initially brought down, a sorption pump was used to maintain a vacuum, preventing condensation of contaminants on the sample surface. $CaF_2$ lenses were used for focusing the beam to avoid beam absorption. The intensity of the beam striking the sample was controlled in two ways.

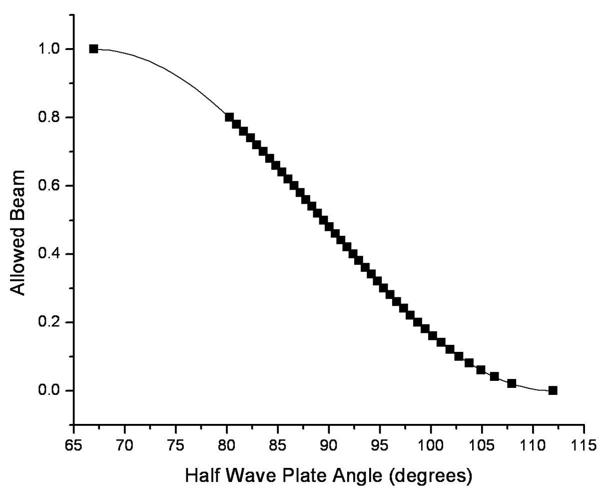


**Fig. 1. Permitted pump beam as a function of the half wave plate angle. Adjusting the half wave plate controlled the intensity of the beam striking the sample.**

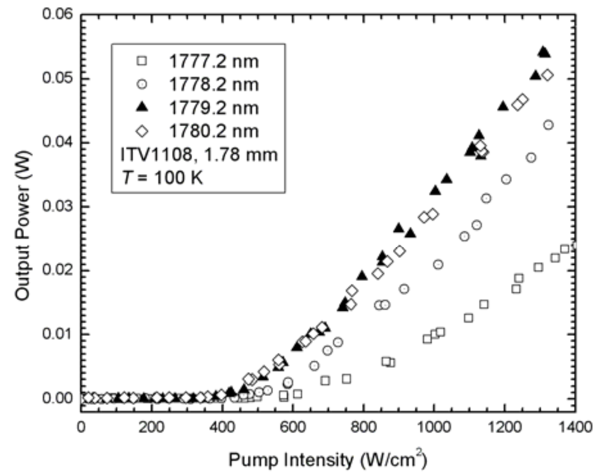


**Fig. 2. Light-light curves. The point at which the lines begin rising give the threshold intensities, or minimum intensity for which lasing will occur at that wavelength. The resonant wavelength gives the set of points with the steepest slope, indicating the greatest increase in output for a given change in input.**

A polarizing cube of constant orientation was used in conjunction with a half wave plate to filter out a percentage of the signal; changing the half wave plate rotated the polarization of the input beam, allowing the polarizing cube to filter out a portion of the beam. The relationship between the half wave plate angle and the beam transmitted by the polarizing cube is shown in Fig. 1. A series of neutral density optical filters were used for additional reduction of intensity.

### *B. Determining resonance using light-light curves*

The sample beam was directed into a Judson liquid-nitrogen-cooled InSB detector, which measured the power of the sample beam. Plotting this power against the input intensity for a variety of OPO wavelengths generated a light-light curve, shown in Fig. 2. The line with the steepest slope, indicating the greatest external differential quantum efficiency, represents the resonant wavelength [4]. The resonant wavelength also has the lowest threshold intensity, given by the point at which there is a steep change in slope.

### *C. Fourier Transformed Infrared Wavelength Spectra*

The spectra were taken by a Varian FTIR Spectrometer, controlled with the Varian Resolutions-Pro software. The signal was received by a liquid-nitrogen-cooled HgCdTe detector. Step-scan nanosecond time-resolved spectroscopy (TRS) was selected as the scan mode. For each time step, a plot of response as a function of wave number was available. The signal reached the FTIR between 174.5 and 174.7 μs after the laser was triggered. To reach this time, 69 2.5 μs steps were taken, followed by 4 500 ns steps, providing rough spectra of the first 174.5 μs. To ensure sufficiently precise measurement of the signal of interest, 20 10 ns steps covered the range from 174.5 to 174.7 μs. The time-step at which this peak was maximized was saved and exported to Origin 7.5 software for analysis. The overall peak was fit with a Gaussian to find the center wave number (and as such wavelength) of this multi-mode peak. In cases with sufficient resolution (0.25 $cm^{-1}$) each peak within the longitudinal

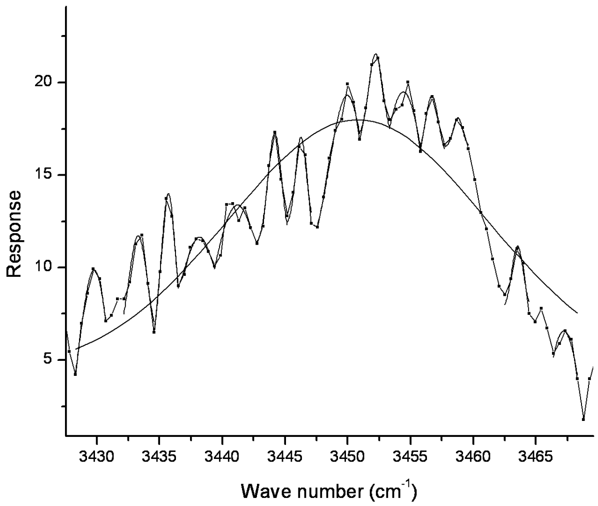


**Fig. 3 Wavelength spectra of the area of interest. With the wave numbers shown on the horizontal axis limited to those containing the broad peak, the broad peak is fit with a Gaussian (the overall line) as well as the individual modal peaks.**

structure was also fit with a Gaussian to determine its center. Examples of these fits are shown in Fig. 3, which highlights the modal peaks as well as the shape of the broader envelope. The difference between the peaks was calculated to allow determination of the change in index of refraction using Eqn. (1). This required an estimate of the effective index of refraction, $n_{eff}$.

Estimating $n_{eff}$ involved studying the epitaxial structure of the sample and determining the index of refraction of each element with which the incident photons interact – InAs, GaSb, AlSb, and $AlAs_{0.08}Sb_{0.92}$.

$$n_\lambda(T) = n_\lambda(300)e^{\alpha(T-300)} \tag{2}$$

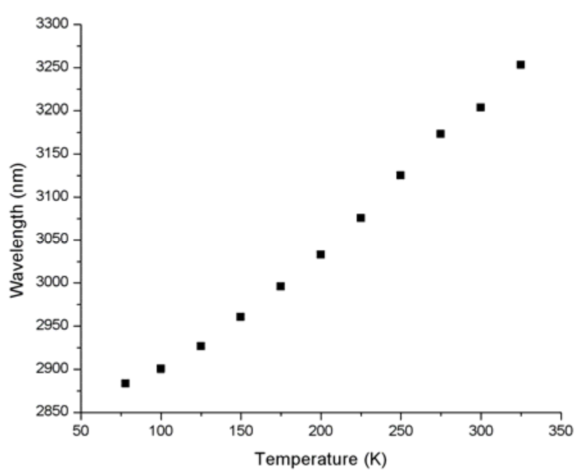


**Fig. 4. Temperature dependence of emitted central wavelength. As the temperature of the sample is increased, the wavelength emitted from the sample cavity increases. Wavelength varies from 2.8µm at 78K to 3.3µm at 325K. The behavior is slightly parabolic, deviating from the expected linear relationship.**

The indices of refraction are dependent on the wavelength and temperature under consideration. Eqn. (2) provides a means of relating $n$ for one wavelength at room temperature to another temperature. The constant α varies for different materials; for InAs and GaSb, $\alpha$=9x10$^{-5}$ K$^{-1}$, and for AlSb and AlAs, $\alpha$=5x10$^{-5}$ K$^{-1}$. Through this process, it became possible to determine $\Delta n$ and begin analyzing the effect of optical pumping on gain.

## III. Results

The emitted wavelength exhibited parabolic behavior with respect to temperature, as shown in Fig. 4, increasing from 2.8 µm at 78 K to 3.3 µm at 325 K. The peak separations, $\Delta k$, are expected to decrease as temperature increases. To resolve the separations predicted by the estimates shown in Fig. 5, a resolution of at least 0.35 cm$^{-1}$ is necessary; thus, the 1 cm$^{-1}$ data was taken with insufficient resolution and can not be used to make an assertion about trends in $\Delta n$. More data at a sufficient resolution are necessary for a decisive relationship to be observed; however, preliminary data, shown in Fig. 5, with the correct resolution (0.25 cm$^{-1}$) shows peak separations on the same order of magnitude as those predicted.

## IV. Discussion

The parabolic behavior of both resonant wavelength and emitted wavelength with respect to temperature does not agree with the expected linear trend. We believe that an explanation for these discrepancies lies in $\Delta n$; however, given the insufficient resolution used for the majority of the collected data, a definitive statement can not be made about possible behaviors of $\Delta n$. Results so far are given in Fig. 6; these values are on the same order of magnitude as the constant α used in Eqn. (2). Knowing that $\alpha$ is used to describe a change in refractive index per degree Kelvin and the relationship being studied is the change in refractive index as a function of

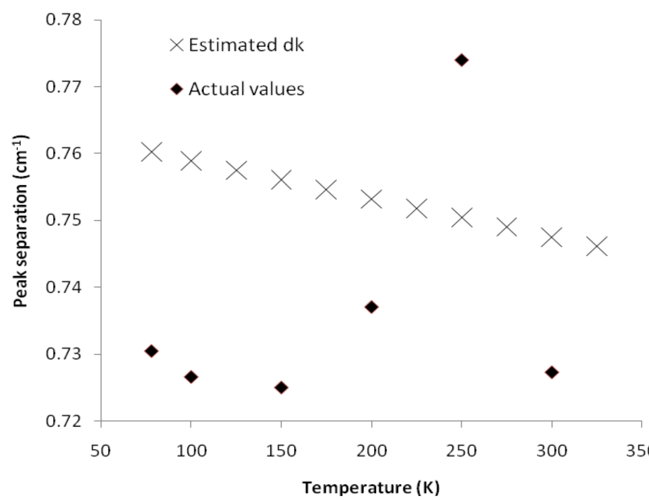


**Fig. 5. Estimated temperature dependence of separation between FTIR peaks (Δk). Using the effective index of refraction and the known cavity length gives an estimate for peak separation values. Actual data accumulated thus far is given by the solid points.**

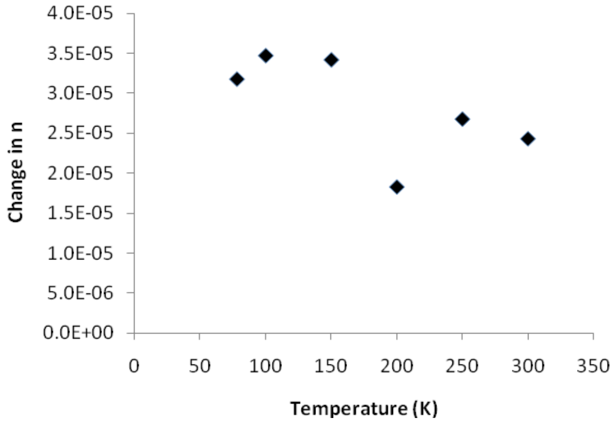


**Fig. 6 Change in n for a range of temperatures. While the data do not show a strong trend, 78 K is the only temperature at which multiple spectra were analyzed, and a greater pool of data is expected to provide clearer results.**

temperature, this level of agreement is encouraging. Currently, the only point representing more than a single spectrum is that for 78 K. Ideally, after a greater number of spectra have been analyzed, a more definite trend will be observed.

The estimates of $\Delta k$ shown in Fig. 5, while on the same expected order of magnitude, do not follow the trend indicated by Eqn. (3).

$$\Delta k = \frac{1}{2nL} \tag{3}$$

This prediction assumes that $\Delta n$=0. However, the primary means of explaining the parabolic dependences of resonant and pump wavelengths on temperature appears to lie in a positive definite value of $\Delta n$. While the values of $\Delta n$ are expected to be low enough to involve $\Delta k$ values on the same order of magnitude as these estimates, the values themselves should be less than those shown in Fig. 5.

Finding accurate values for $\Delta k$ and $k$ from analyzing spectra will help us understand the gain dependence of $\Delta n$. Referring to the quantities listed in Eqn. (1), the cavity length and $n$ vary linearly with temperature, while $k$ varies parabolically with temperature. More data collection and analysis are required to determine the trend in $\Delta k$. While these values are known to change with temperature, $n$ is a gain-dependent quantity, and optical pumping is known to increase gain by increasing the absorption of photons. This gain change leads to an additional change in $\Delta n$, as a greater portion of the pump beam must be allowed at higher temperatures to continue measuring the laser output. Increasing the optical intensity also increases the heating that takes place as the sample receives the input beam. We aim to use the data to determine the overall shift in gain and the relative contribution of temperature-dependence, allowing better assessment of the gain-induced changes in lasing behavior.

## V. Conclusion

The emitted wavelength of a W-OPIC laser is a temperature-dependent quantity, increasing as temperature increases. This is in agreement with prior studies and calculated expectations. The relationship is parabolic, and by studying peak separations and analyzing $n$ and $\Delta n$ the cause of this parabolic relationship could be determined. The expected change in peak separation also exhibits temperature dependence. While our current data do not reflect the expected trend in $\Delta k$, the values are within .04 $cm^{-1}$ of the prediction. The use of FTIR spectroscopy to analyze the signal emitted from an OPIC laser is a new technique in this lab, and this degree of accuracy bodes well for the continued analysis of these peak separations.

An immediate area of expansion on this study is further collection of data with the corrected resolution. Gathering more data will clarify the current information involving $\Delta n$. Future research could involve studying the time evolution of the FTIR pulses and how this changes as a function of temperature. Additionally, studying the effect of sub-threshold input intensities on these relationships utilizing the Hakki-Paoli method may also lead to greater understanding of OPIC semiconductor lasers and these observed longitudinal modes.

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