Theoretical investigation of high temperature IV–VI compound continuous wave midinfrared vertical cavity surface emitting lasers

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Theoretical investigations on the optically pumped IV–VI mid-infrared vertical-cavity surface emitting lasers were made. Key parameters such as Auger recombination and heat dissipation were identified and maximum operating temperature, peak output power, and threshold pumping power were simulated. Unlike other band-to-band mid-IR laser materials, Auger recombination does not limit IV–VI diode lasers to operate at room temperature in continuous wave (cw) mode. However, insufficient heat dissipation is the dominant factor in preventing laser operation at room temperature. The calculated maximum cw operation temperature for a simple active layer design was 282 K and could be further improved for more advanced structures such as quantum well lasers. These results indicate that such lasers are promising for thermoelectrically cooled spectroscopic systems. © 2001 American Institute of Physics. [DOI: 10.1063/1.1337626]

The main application for midinfrared semiconductor diode lasers is ultrahigh-sensitivity chemical detection. Laser performance requirements that are not yet available include continuous wave (cw) operation at room temperature (or at least the thermolectric cooling range of $T\approx 240$ K), spectral purity and reasonable output power (≥1 mW) with good beam quality. Currently, IV–VI lead salts, quantum cascade, and type-II quantum well (QW) diode lasers, are leading approaches being pursued to meet these application needs.

Auger recombination is the main loss channel for all band-to-band mid-IR laser materials at high temperature. Auger coefficients of IV–VI materials are typically an order of magnitude smaller than those in type-II QW lasers. These, in turn, are significantly suppressed relative to other III-V and II-VI semiconductors with the same energy gaps. This is perhaps the greatest advantage of IV–VI laser materials for high-temperature and long-wavelength operation. The major drawback of IV–VI materials is low thermal conductivity. Recently, we have reported optically pumped IV–VI mid-IR vertical-cavity surface emitting lasers (VCSELs) that operated at 289 K in pulse mode. Lead salt VCSELs may overcome many of the main limitations of IV–VI edge-emitters as described in Ref. 15. Once optimized, this should provide an attractive high-temperature, single-mode cw source for spectroscopy and other mid-IR applications. Theoretical investigations on such lasers will be of great interest to help understand the impact of Auger recombination and heat dissipation.

The core of simulation presented here is the simultaneous solution of the coupled rate Eqs. (1)–(3) given by

$$\frac{dN}{dt} = \frac{P}{A\hbar \omega_{\text{pump}}} - \gamma_3(T_i)N^3 - \frac{N}{\tau_{\text{SR}}} - \sum_m \Gamma_m \frac{g(h \omega, N, T_i)}{A}$$

$$\frac{dS_m}{dt} = \beta AR_{\text{sp}}(N, T_i) + \frac{c}{n_m} \left( \Gamma_m g - (1 - \Gamma_m) \alpha_{\text{clad}} - \Gamma_m \sigma_f N + \frac{\ln(R_i R_2)}{2L_{\text{cav}}} - \frac{1}{\alpha_{\text{clad}}(N)} \right) S_m,$$

$$T_l = T_0 + \frac{P}{Adh\omega_{\text{pump}}} + d \gamma_3 N^3 E_3$$

where $N$ is carrier concentration density, $P$ is pumping power, $d$ is the active region thickness, $\hbar \omega_{\text{pump}}$ is photon energy of the pump, $T_l$ is lattice temperature, $\gamma_3$ is the Auger coefficient taken from reference, $R_{\text{sp}}$ is spontaneous radiation rate estimated from the typical measured spontaneous power of PbSe DH lasers, and $\tau_{\text{SR}}$ (10 ns) is the Shockley–Read lifetime, $A$ is the effective active region area (i.e., circular opening with radius $\approx 30 \mu m$), $m$ (throughout the calculation, single mode operation is assumed. i.e., $m=1$), mode refractive index $n_m$, $g$ is the gain based on the expression provided by Ref. 18. $R_1$ and $R_2$ are the bottom and top mirror reflectivity with $R_1=0.994, R_2=0.93$. The reflectivity was calculated for a three-pair bottom mirror and a two-pair top mirror described in Ref. 15. In Eq. (2), only free carrier absorption is considered as a loss term. Other possible losses such as interface recombination were ignored. Note that Joule heating in Eq. (3) is eliminated due to optical pumping.

Standard Runge–Kutta method with $10^{-4}$ relative error was used. The steady-state values for the carrier density, photo density, and lattice temperature are obtained once transient relaxation oscillations have faded out. Lattice temperature instead of electron temperature at steady states in Eqs. (1) and (2) was used since there is only a minute difference between the two. Equation (3) is basically the linear approximation of thermal conductivity. In order to couple Eq. (3) to the others, its first time derivative was calculated as our time

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dependent lattice temperature equation. This simplifies Eq. (3) and gives slower and smoother temperature variation without losing the accuracy of the equations.

The VCSEL structure used for our calculation is shown in Fig. 1. The cavity thickness was chosen so that the maximum overlap of the cavity mode with the gain peak would occur at a desired temperature. The design of the top DBR mirror was intended to place the pump wavelength of 2.098 μm in a low-ripple region of the reflectivity interference fringes. We note that the energy gap of the Pb0.85Sr0.15Se on the top DBR is larger than the pump photon energy. Our simulation of top mirror reflectivity at 2.098 μm for 37° incident light showed that about 80% of the pumping energy would be absorbed in the active region.

Based on thermo-electrical cooling limit (i.e., 250 K) and thermal runaway predicted by our simulation for T > 255 K, an optimized thickness for T = 250 K was obtained through the following procedure. Gain equation was first solved for several different values of carrier concentration density N. Maximum gain was then calculated for the average asymptotic value of N. So hω and consequently λ and d were obtained (λ = n_d, d). Finally the thickness d (0.8911 μm) was used to calculate the threshold and efficiency over a range of temperatures starting at 180 K. Figure 2 plots the dependencies of both the threshold pump intensity and the optical power conversion efficiency on temperature. In this plot, each individual data point is produced by separate simulation.

Figure 3 shows the light–light curves at the series of temperatures. We will have lower output and higher threshold for T < 250 K or T > 250 K due to our optimization for T = 250 K. Although the output power and efficiency are higher than their experimental values, the locations of the threshold pumping and the shape of temperature dependent efficiency agree well with the reported experimental data.13–15. The reason for higher simulated output power might be due to the fact that all other loss terms such as interface recombination in Eq. (2) were not included. We note that more loss terms in Eq. (2), or even shorter Shockley–Read lifetime in Eq. (1), will reduce the efficiency and the output power but they do not prevent the VCSEL from lasing. The dominating loss term here is the fast Auger recombination process.

To investigate the impact of Auger recombination and the heat dissipation separately, Eq. (3) was ignored in order...
to prevent thermal runaway. Thickness $d$ was also optimized through the previous procedure for 300 K. The simulation in Fig. 4 clearly shows that the Auger recombination does not prevent the IV-VI VCSELs from operating at room temperature in cw mode if the generated heat can be removed efficiently from the active region. Auger recombination is the dominating loss channel and determines the heat generation for all IV-VI diode lasers. Therefore, this result can also be applied to all IV-VI diode lasers, which have a similar gain and loss ratio including the edge emitting laser.

Our simulation showed that reduction of Auger recombination $\gamma_3 N^3$ by an order of magnitude either by reducing the Auger coefficient $\gamma_3$ or by reducing threshold carrier concentration $N$ (note that the effect is $\propto N^3$) will allow room temperature cw operation of the same VCSEL structure even with heat dissipation. Since the threshold carrier concentration in PbSe QW laser structures could be reduced and likely Auger coefficient as well, PbSe QW VCSELs should be able to operate at room temperature in cw mode.

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