Power Performance of a Continuous-Wave Cr^{2+}:ZnSe Laser at 2.47 μm

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Abstract: Continuous-wave power performance of a Cr^{2+}:ZnSe laser was investigated at 2.474 μm. End pumped by a 1.583-μm NaCl:OH^- laser, the resonator with a 3% transmitting output coupler produced as high as 250 mW of output power with a slope efficiency of 24.2%. Analysis of the laser efficiency data shows that the magnitude of the excited-state absorption cross section is less than 5% of the emission cross section in agreement with spectroscopic results. Numerical calculations further predict the optimum crystal length and absorption coefficient to be 2.5 cm and 0.49 cm^{-1}, respectively, for continuous-wave operation.

OCIS Codes: (140.3580) Lasers, solid-state; (140.3600) Lasers, tunable; (140.5680) Rare earth and transition metal solid-state lasers; (160.6990) Transition metal-doped materials.

Introduction

Recently, thorough spectroscopic studies have been carried out to investigate the quantum electronic properties and to assess the mid-infrared lasing potential of several zinc chalcogenide hosts doped with different transition metal ions [1]. In particular, chromium-doped zinc selenide (Cr^{2+}:ZnSe) was found to possess several favorable spectroscopic properties as a mid-infrared solid-state laser material. These include strong emission between 2 and 3 μm, low level of non-radiative decay at room temperature, and weak excited-state absorption. Another attractive feature is the presence of a strong absorption band between 1500 and 2000 nm, ideal for the construction of compact mid-infrared laser sources with InGaAs pump diodes. To date, pulsed [2] and continuous-wave (cw) [3] lasing have been demonstrated in Cr^{2+}:ZnSe. In pulsed pumping experiments, a tuning range extending from 2150 to 2800 nm was demonstrated with output energies close to 1 mJ [2]. In cw experiments, as high as 250 mW of output power was obtained with continuous tuning between 2138 and 2700 nm [3]. In addition to lasing experiments, Cr^{2+}:ZnSe has also been used as a passive Q switch in pulsed 1.54-μm Er:glass lasers [4].

In this study, we investigate the cw power performance of a Cr^{2+}:ZnSe laser pumped by a NaCl:OH^- color-center laser at 1.583 μm. In lasing experiments, the resonator with a 3% transmitting output coupler produced as high as 250 mW of output power at 2.474 μm with a slope efficiency (absorbed power) of 24.2%. Experimental pump absorption saturation and lasing efficiency data were analyzed to determine the values of the absorption (σ_a), emission (σ_e) and excited-state absorption (σ_{esa}) cross sections. Best-fit values of σ_a and σ_e were determined to be 0.76×10^{-19} cm^2 and 1.63×10^{-19} cm^2, respectively. In addition, the model predicted the magnitude of the excited-state absorption cross section to be less than 5% of the emission cross-section, thereby supporting the spectroscopic findings about weak or non-existent excited-state absorption. By using the best-fit values of the cross sections, the dependence of the output power was investigated numerically as a function of the absorption coefficient

and crystal length. Results indicate that optimum power performance should be obtained with a 2.5-cm-long crystal which has a small-signal differential absorption coefficient of 0.49 cm^{-1}.

Experimental

The experimental set-up is shown in Fig. 1. A cryogenic NaCl:OH^- laser, pumped by a 1064-nm Nd:YAG laser was used to excite the Cr^{2+}:ZnSe laser at a wavelength of 1.583 μm. The astigmatically compensated z-cavity housed a 2.3-mm-thick Cr^{2+}:ZnSe crystal which had a small-signal differential absorption coefficient of 7.98 cm^{-1}. The crystal was oriented at Brewster incidence and positioned between two curved high reflectors (M1 and M2) each with a radius of curvature of 10 cm. The total cavity length (between M3 and M4) was 183 cm. The crystal was held between two copper plates which were at approximately 26 ^{0}C. The pump beam was focused by the input lens (L1) through the input mirror (M1) to an estimated 40-μm waist inside the Cr^{2+}:ZnSe crystal. The amount of pump power could be continuously adjusted by using a half-wave plate (W1) and a polarizing beam splitter (PBS). The maximum available pump power before the focusing lens L1 was 1.7W. Lasing of the free-running cavity was obtained at 2.474 μm. By measuring the incident threshold pump power as a function of output coupler transmission, the round-trip crystal loss was estimated to be 5%. The resulting crystal figure of merit *FOM* ($FOM=\alpha_{1583}/\alpha_{2474}$, α_λ =small-signal differential absorption coefficient at the wavelength λ) was determined to be 80. Laser efficiency data were collected with a 3% transmitting output coupler. In addition, the variation of the crystal transmission was measured as a function of the incident pump power at 26 ^{0}C.

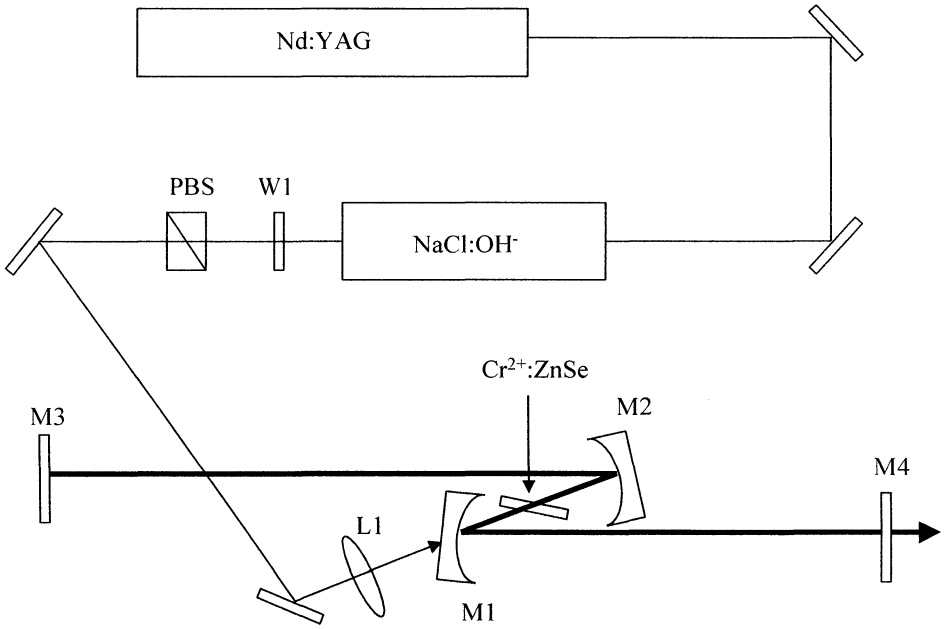
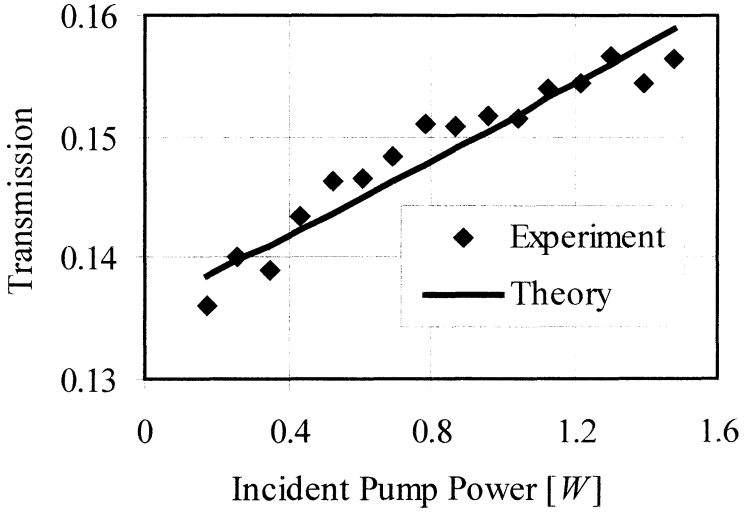


Fig. 1. Schematic of the experimental set-up.

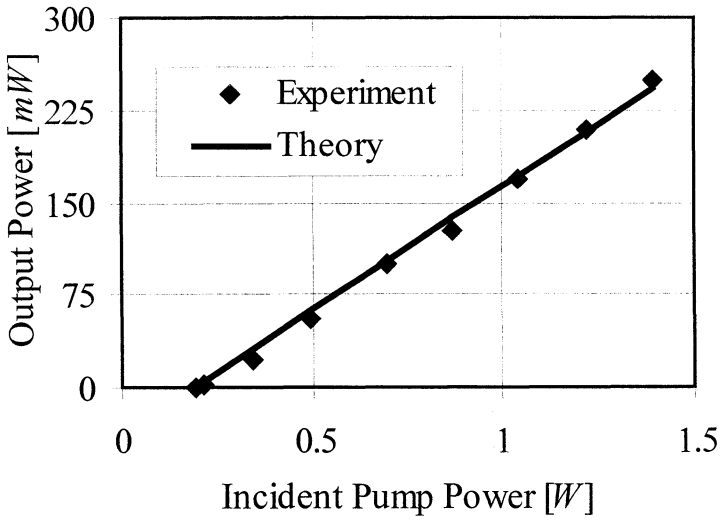
Results and Analysis

A numerical model was used to analyze the experimentally acquired pump absorption saturation and laser efficiency data and to determine the best-fit values of σ_a, σ_e, and σ_{esa}. As described in detail earlier [5], this model calculates the continuous-wave output power of a solid-state laser by accounting for the

absorption saturation at the pump wavelength, pump-induced heating inside the gain medium, the temperature dependence of the fluorescence lifetime, excited-state absorption at the lasing wavelength, and laser induced gain saturation. According to the results of the spectroscopic studies [1-2], Cr^{2+}:ZnSe exhibits an unusual lifetime-temperature dependence. As opposed to a monotonically decreasing trend, the fluorescence lifetime peaks around room temperature. Since the measurements presented here were done near room temperature, the temperature dependence of the fluorescence lifetime and pump-induced heating inside the crystal were neglected in the calculations.



(a)



(b)

Fig. 2. (a) Measured and calculated crystal transmission as a function of incident pump power and (b) measured and calculated efficiency curves with a 3% transmitting output coupler.

The relevant parameters of the Cr^{2+}:ZnSe medium which were used in the calculations are listed in Table 1. Among these, the locations of the pump and laser beam waists (z_{fp} and z_{fL}) were estimated by searching for the configuration that gives the best overlap between the pump and the laser beams inside

the crystal. In particular, z_{fp} and z_{fL} were varied in order to maximize the average value of the mode matching function $\eta(z)$, defined according to [6]

$$\eta(z) = \frac{4\omega_p^2(z)\omega_L^2(z)}{\left(\omega_p^2(z) + \omega_L^2(z)\right)^2}. \quad (1)$$

Here, $\omega_p(z)$ and $\omega_L(z)$ are the respective pump and laser spot-size functions and $\eta(z)$ is averaged over the crystal length L. By using the beam waists and wavelengths given in Table 1, z_{fp} and z_{fL} were determined to be 0.17 cm and 0.25 cm, respectively.

Table 1. Parameters of the Cr^{2+}:ZnSe gain medium.

Name	Symbol	Units	Value
Absorption cross-section	σ_a	cm^2	0.76×10^{-19}
Emission cross-section	σ_e	cm^2	1.63×10^{-19}
Normalized strength of excited-state absorption	σ_{esa}/σ_e	1	0.046
Fluorescence lifetime	τ_0	μs	5.09
Thermal gradient of lifetime	τ_T	μs	0
Refractive Index	n_0	1	2.4
Crystal figure of merit	FOM	1	80
Wavelength of the pump beam	λ_p	μm	1.583
Wavelength of the laser beam	λ_L	μm	2.474
Pump beam waist	ω_{p0}	μm	40
Cavity beam waist	ω_{L0}	μm	35
Crystal length	L	cm	0.25
Location of the pump beam waist inside the crystal	z_{fp}	cm	0.17
Location of the laser beam waist inside the crystal	z_{fL}	cm	0.25
Small-signal differential absorption coefficient	α_{1583}	cm^{-1}	7.98
Reflectivity of the output coupler	R_L	1	0.97

Figure 2(a) shows the measured and calculated variation of the crystal transmission as a function of the incident pump power at a crystal boundary temperature of 26 ^{0}C. Note that as the pump is increased from 174 mW to 1.48 W, an increase of approximately 2% occurs in the transmission. In the analysis of the absorption saturation data, laser induced gain saturation was neglected in addition to the assumptions outlined above. As can be seen from Fig. 2(a), the best fit between the measured data and model predictions was obtained for a σ_a value of 0.76×10^{-19} cm^2.

Figure 2(b) shows the laser efficiency data obtained with a 3% transmitting output coupler. At an incident pump power of 1.4W, as high as 250 mW of cw output power was obtained at 2.474 μm. The measured absorbed power slope efficiency was 24.2%. In the calculations, the best fit between the experimental efficiency data and model predictions was obtained for σ_e and σ_{esa}/σ_e values of 1.63×10^{-19} cm^2 and 0.046, respectively. Note that the model predicts a very small amount of excited-state absorption in good agreement with spectroscopic results [1].

Results of Numerical Simulations

By using the best-fit values of the laser cross sections, the model was used to study the variation of the output power as a function of the small-signal pump absorption coefficient α_{1583} at different crystal lengths. In these calculations, the incident pump power and the pump beam waist were assumed to be 2W and 35 μm, respectively. Furthermore, the waist locations of the pump and the laser beams were centered inside the crystal and the crystal figure of merit *FOM* was assumed to be constant (*FOM*=80) as a function of doping concentration. Other fixed parameters are as given in Table 1. As can be seen from Fig. 3, calculations predict that the use of the optimum crystal with a length of 2.5 cm and an absorption coefficient of 0.49 cm^{-1} (total pump absorption = 71%) should lead to significant improvement in the cw power performance of Cr^{2+}:ZnSe lasers.

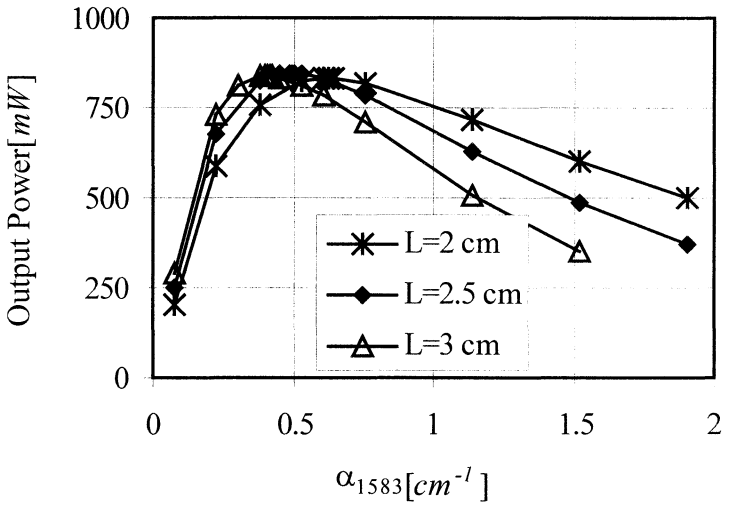


Fig. 3. Calculated variation of the output power as a function of the small-signal absorption coefficient α_{1583} for different values of the crystal length *L*.

Acknowledgments

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