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Direct diode-pumped laser operation of Cr$^{3+}$-doped LiInGeO$_4$ crystals

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Abstract: Quasi-continuous wave (cw) laser action has been demonstrated by direct diode pumping of a new extremely broadband Cr$^{3+}$-doped crystal. In contrast to previous works, where large-frame pump lasers have been employed, we have shown that low-power direct diode pumping of LiInGeO$_4$ is feasible, opening up the way for realizing compact and efficient laser sources for telecommunication applications.

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References and links

1. Introduction

Cr:LiInGeO$_4$ is a relatively new laser active medium, belonging to the olivine group of crystals. However, in contrast to the better known materials like Cr$^{4+}$-doped forsterite (Mg$_2$SiO$_4$)$_2$ and cunyite (Ca$_2$GeO$_4$)$_3$, emission has been assigned to Cr$^{3+}$ in distorted octahedral sites in the case of Cr:LiInGeO$_4$. It features an extremely broad emission spectrum starting at around 900 nm and stretching to 1700 nm, making it a very promising candidate for the generation of ultrashort laser pulses in the far optical telecommunications important near-infrared wavelength range.

So far, laser action in Cr:LiInGeO$_4$ has only been achieved using a complex setup consisting of a 9 mJ Q-switched Nd:YAG laser plus a gain-switched Ti:Sapphire as a pump
source\textsuperscript{4}. However, the absorption spectrum of Cr:LiInGeO\textsubscript{4} shows a high peak at around 800 nm for pump light with a polarization parallel to the longest crystal axis of Cr:LiInGeO\textsubscript{4}. Since efficient, reliable and powerful laser diodes do exist at this wavelength, direct-diode pumping would be highly desirable, as this would open up the possibility to develop compact laser sources with low power consumption, an indispensable requirement for telecommunication applications.

In this work we present direct diode pumped operation of Cr:LiInGeO\textsubscript{4} laser crystals for the first time to our knowledge. We show the dynamic behavior of the laser oscillator and elucidate the challenges one will have to face in the future, which are mainly connected to the unfavorable thermal properties of the material.

2. Experimental setup

Figure 1 shows the setup used in our experiments. The laser crystal is a 0.89 mm thick LiInGeO\textsubscript{4} plate which was placed at Brewster’s angle between two dichroic focusing mirrors with a radius of curvature (ROC) of -50 mm.

During crystal growing, the chromium content in the flux was about 2 weight percent of Cr\textsubscript{2}O\textsubscript{3}. However, we cannot make a conclusion on the concentration of trivalent centers in the crystal based solely on this data because the ratio of trivalent and tetravalent chromium centers in the crystal is unknown and, moreover, the distribution coefficient of chromium in the flux and the crystal is unknown. The measurement of the concentration of Cr\textsuperscript{3+} centers in the crystal and an estimation of the absorption and emission cross-sections will be a subject of our future research.

As a pump source, we used two high brightness fiber-coupled diode laser modules (JUM2500/50/20\textsubscript{808}, unique-mode GmbH, Jena, Germany) with a maximum output power of 2.5 W each. In order to maintain the linear polarization state of the pump radiation, we cut down the delivery fiber which is connected to the diode (50 \textmum core diameter, NA 0.22), to a length of only 5 cm. This resulted in a power ratio of 10:1 between the two perpendicular polarization directions. Two lenses (aspheric doublets with a diameter of 50.8 mm) are used to image the fiber end facet onto the crystal to a 1/e\textsuperscript{2}-diameter of 120 \textmum, as determined by a knife-edge measurement. The standard z-cavity was completed by a plane output coupler with a reflection of R = 97.5\% and a second plane end mirror with 100\% reflectivity, respectively.

3. Results

Due to the relatively low transmission of M1 at the pump wavelength of 808 nm (78\%) and the very thin crystal, less than half of the pump light gets actually absorbed in the Cr:LiInGeO\textsubscript{4} crystal. Of the maximum available pump power per diode of 2.5 W, only 1.1 W is absorbed in the gain medium. Moreover, as we did not use aggressive cooling in our setup, we have noticed that the amplified spontaneous emission (ASE) signal emitted from the oscillator below lasing threshold is increasing for increasing cw pump power only up to an absorbed pump power of about 100 mW and is in fact decreasing for high pump power levels.
This is a clear indication of the strong temperature quenching of the Cr$^{3+}$ centers$^5$, a problem that we will address later.

To avoid the need of a sophisticated cooling geometry, we pumped the oscillator in a quasi-cw mode with pump pulses between 50 $\mu$s and 1 ms in duration and with a repetition rate of 20 Hz, resulting in a relatively low duty cycle. For short pump pulses, the oscillator starts lasing at an absorbed peak pump power of 880 mW.

Figure 2 shows the temporal output of the oscillator for the highest available pump power of 2.2 W absorbed. About 5 $\mu$s after the pump has been switched on, the laser emits a series of relaxation oscillations, which dampen out towards the steady-state cw lasing level. The frequency of the oscillations was measured to be $\omega_{sp} = 1.55 \times 10^6$ s$^{-1}$ and the damping time constant to be $\tau_{sp} = 5.6$ $\mu$s. The relation$^6$

$$\tau_{sp} = \frac{2\tau_a}{r}$$

allows one to determine $\tau_a = \frac{1}{\gamma_a}$ which is the atomic decay time for the upper lasing level. With $r$ being the ratio of the actual pump power to the threshold pump power, which is 2.5 in our case, and, the measured value of 5.6 $\mu$s for $\tau_{sp}$, we get $\tau_a = 7$ $\mu$s, which is in good agreement with our previous measurements at room temperature$^1$. The frequency of the relaxation oscillations allows one to determinate the cavity decay rate $\gamma_c = \tau_c^{-1}$ via the relation$^6$

$$\omega_{sp} = \sqrt{(r-1)\gamma_a \gamma_c \gamma_a - \left(\frac{\gamma_a}{2}\right)^2}.$$  \hspace{1cm} (2)

The resulting cavity decay time of $\tau_c = 89.2$ ns is composed of round-trip cavity losses due to the 2.5% output coupler ($R_{oc} = 0.975$) plus other distributed cavity losses, which we think are resulting from excited state absorption in the laser crystal$^7$ and a non-perfect adjustment of the Brewster angle. With a cavity round trip time of $T = 4.8$ ns we can estimate our additional cavity losses via$^6$

$$\delta_0 = \gamma_c T - \ln(1/R_{oc})$$ \hspace{1cm} (3)

to be 0.028, corresponding to 2.8% additional losses.

The spectrum of the oscillator is shown in Fig. 3 on a logarithmic scale. The radiation is centered at around 1317 nm and has a bandwidth (-10 dB) of 20 nm. This very broadband emission characteristic underlines the potential of Cr:LiInGeO$_4$ to generate femtosecond
pulses in the wavelength range above 1300 nm, which is important for telecommunications applications.\(^8\)

As mentioned before, the unfavorable thermal properties of the laser crystal imply that real cw operation is only possible with a sufficiently advanced thermal management. The exact value for the thermal conductivity of LiInGeO\(_4\) is still unknown, but one can expect it to be similar to Ca\(_2\)GeO\(_4\) crystals where a value of 0.03 W/(cm·K) at 300 K has been determined\(^9\).

As shown in Fig. 4, if the pump is left on for a time as long as 1 ms, excessive heating of the laser crystal occurs in the pumped volume. The strong temperature quenching of the Cr\(^{3+}\) fluorescence results in a rapid decrease of the life time of the meta-stable level in Cr:LiInGeO\(_4\). As the initial temperature rise due to the point-like heat source within the crystal can be assumed to be approximately linear (initial rise in an exponential function) and as the upper state life time decreases almost linearly with a rising temperature\(^1\), the linear decay of the output signal versus time can be explained.

For a fixed duration of the pump pulses of 1 ms, the temperature within the crystal completely recovers to its initial value between two pump pulses only for repetition rates below 20 Hz. Above that, a drop in the value of the initial cw lasing level can be observed. For a repetition rate of 70 Hz we have observed a 25% drop in the initial signal, while for repetition rates above 125 Hz, lasing action stops completely.

However, it should be mentioned that Cr\(^{4+}\):Ca\(_2\)GeO\(_4\) and Cr\(^{4+}\):Mg\(_2\)SiO\(_4\) exhibit similar temperature quenching, nevertheless favorable laser properties have been demonstrated even
under cw pumping conditions. More sophisticated cooling techniques, like cryogenic cooling would certainly improve the laser characteristics, but most important, we believe that we will be able to grow much longer crystals with a reduced dopant concentration in the future, which will drastically reduce the thermal stress. At the moment, we are limited to the use of relatively thin plates as our crystals are severely solvent entrapped but with improvements in the growing technique this issue can certainly be overcome\textsuperscript{10}. We believe that Cr:LiInGeO\textsubscript{4} is a very promising laser material even though strong temperature quenching exists.

An interesting mode of operation occurs if the pump pulse duration is decreased down to approx. 1 \( \mu \text{s} \), i.e. it ends after the first (gain-switched) pulse appeared at the laser output. Then, a train of short pulses is emitted at the repetition rate of the pump. A single of those pulses is shown in Fig.5. This mode imposes a reduced thermal load onto the crystal, so that the repetition rate of the pump pulses can be increased up to 3 kHz until thermal quenching causes a reduction of the output pulse energy. At a repetition rate of 4.5 kHz, the peak power of the pulses decreased by 25\% while only at repetition rates above 5 kHz lasing action stops completely.

![Fig. 5. Single gain-switched laser pulse](image)

3. Conclusions

In conclusion, we have demonstrated for the first time to our knowledge, that direct, low power diode pumping of Chromium doped LiInGeO\textsubscript{4} is feasible. The broad free-running laser spectrum is a clear indication, that the generation of femtosecond laser pulses for telecommunications applications should be possible using this host material. We have also shown that the poor thermal conductivity of the host crystal will be the major challenge to overcome in future developments and that by gain-switching it is possible to generate a train of laser pulses with sub-\( \mu \text{s} \) duration.

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