Letter

160 ps Yb:YAG/Cr:YAG microchip laser

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Abstract

By cryogenically cooling the Yb:YAG/Cr:YAG medium, one can break through the damage limit of Yb:YAG/Cr:YAG passively Q-switched microchip lasers at room temperature and thus achieve a shorter minimum pulse duration. In the proof of principle experiment we carried out, a 160.6 ps pulse duration was obtained. To the best of our knowledge, this is the first realization of sub-200 ps pulse operation for an Yb:YAG/Cr:YAG microchip laser.

Keywords: Q-switched laser, picosecond laser, cryogenically cooled Yb:YAG laser

(Some figures may appear in colour only in the online journal)

1. Introduction

Picosecond lasers are desirable for applications such as industrial micro-material fabrication processes. Currently, the typical method to generate such picosecond pulses is using a mode-locked oscillator. However, such oscillators are complex, which makes them expensive to purchase and maintain. In addition, the output pulse energy is low, which limits their application. Usually, passively Q-switched (PQS) lasers are used for generating nanosecond pulses. However, the duration of a PQS laser pulse is proportional to the cavity length, so it is possible to use a very short cavity length to achieve picosecond pulse operation. Therefore, PQS microchip lasers have been proposed [1]. PQS microchip lasers are monolithic solid-state lasers in which the gain medium and saturable absorber are in direct contact or bonded, and the cavity mirrors are in direct contact with, or deposited on, the laser medium. The microchip laser cavity length is in the millimeter or even submillimeter range. Compared with the mode-locked oscillator, the PQS microchip laser is simple, cost-effective, near alignment-free, allows energy scaling and needs less maintenance.

For just over two decades, Nd:YVO4/semiconductor saturable absorber mirrors (SESAMs) and Nd:YAG/Cr:YAG-based microchip lasers have been widely investigated. Nd:YVO4/SESAM microchip lasers with a sub-millimeter cavity length can generate sub 100 ps laser pulses [2–5], and the recent record is 16 ps [5]. However, the output energy is typically below 1 µJ, which limits their application. Nd:YAG/Cr:YAG microchip lasers can deliver over 1 µJ, or even 1 mJ, pulse energy [1, 6–10]. However, the absorption cross section of Nd:YAG is much lower than that of Nd:YVO4. If the Nd:YAG thickness is too thin, the transmitted high-intensity pump will bleach the Cr:YAG absorber and broaden the pulse duration [6]. In addition, unlike SESAMs, which act as a mirror and do not contribute to the length of the cavity, the thickness of Cr:YAG is not to be neglected. All of these limit the minimum Nd:YAG/Cr:YAG microchip laser cavity length. Therefore, the shortest pulse duration obtained directly from a Nd:YAG/Cr:YAG microchip laser is limited to 148 ps [6] and the typical pulse durations are over 250 ps [1, 9, 10], as shown in figure 1.

Yb:YAG is an attractive candidate for microchip lasers. Compared with Nd:YAG, Yb:YAG has a much higher doping concentration. One can apply a heavily doped Yb:YAG to avoid the pump-induced bleaching effect. Thus, the Yb:YAG/Cr:YAG microchip laser has the potential to achieve a shorter pulse duration than Nd:YAG/Cr:YAG microchip lasers. In addition, the Yb:YAG/Cr:YAG microchip laser can also support high energy, similar to Nd:YAG/Cr:YAG microchip lasers. Furthermore, compared with Nd:YVO4 and Nd:YAG, Yb:YAG also has the advantages of a much longer storage
lifetime and a much broader absorption bandwidth, which reduces requirements for the diode pump (peak power, bandwidth, etc.). However, the saturation fluence of Yb:YAG is as high as ~9 J cm\(^{-2}\) at room temperature. The generated laser fluence is positively related to the saturation fluence of the gain medium. So with picosecond pulse duration, Yb:YAG microchip lasers face inevitable damage problems. For this reason, at room temperature, the shortest Yb:YAG/Cr:YAG microchip laser duration is limited to 237 ps \[11\], and typically the pulse durations are over 250 ps \[12–16\], as shown in figure 1.

Cryogenically cooled Yb:YAG has been applied in both continuous wave and pulsed laser systems \[17–21\]. Recently, some efforts have been made to produce liquid nitrogen (LN) cryogenically cooled Yb:YAG/Cr:YAG PQS microchip lasers \[22–24\]. However, in previous cryogenically cooled Yb:YAG lasers, attention was paid to reducing the threshold pump power and improving the output average power, energy, efficiency and repetition rate. In this letter, we first propose that by cryogenically cooling the Yb:YAG/Cr:YAG medium, one can break through the damage limit of Yb:YAG/Cr:YAG microchip lasers at room temperature and thus achieve a shorter minimum pulse duration. This is based on the fact that at LN temperature (77 K) the Yb:YAG saturation fluence is approximately five times lower than at room temperature. Since the material-supported damage fluence is nearly proportional to the square root of the pulse duration, if we assume 237 ps is the damage-limited pulse duration for an Yb:YAG/Cr:YAG medium, one can break through the damage limit of Yb:YAG/Cr:YAG microchip lasers at room temperature and thus achieve a shorter minimum pulse duration. This is based on the fact that at LN temperature (77 K) the Yb:YAG saturation fluence is approximately five times lower than at room temperature. Since the material-supported damage fluence is nearly proportional to the square root of the pulse duration, if we assume 237 ps is the damage-limited pulse duration for an Yb:YAG/Cr:YAG microchip laser at room temperature, the damage-limited pulse duration will be reduced to 9.5 ps at LN temperature. A proof of principle experiment was carried out. We used a 1.1 mm Yb:YAG/Cr:YAG microchip crystal cryogenically cooled by LN, and 160.6 ps (full width at half maximum, FWHM) was obtained. To the best of our knowledge, this is the shortest pulse duration for an Yb:YAG/Cr:YAG microchip laser, as shown in figure 1. By further reducing the Yb:YAG/Cr:YAG thickness and increasing the doping concentration, it is possible to obtain sub-100 ps pulses.

2. Experimental setup

Figure 2 shows a schematic diagram of the microchip laser. An Yb:YAG/Cr:YAG composite crystal fabricated with thermal bonding technology (Cryslaser Inc.) was used in the experiment. The thicknesses of the Yb:YAG and Cr:YAG layers were 0.7 mm and 0.4 mm, respectively. Thus, the total thickness of this microchip crystal was 1.1 mm. The aperture of this microchip crystal was a square with 5 mm sides. Yb:YAG and Cr:YAG were [1 1 1] and [1 1 0] cut, respectively. The doping concentration of the Yb ions was 20 at.% and the initial transmission of the Cr:YAG was 75%. The calculated pump absorption was ~70% with a pump wavelength of 936 nm. The Yb:YAG surface was coated with a film that is highly reflective (HR, \(R > 99.8\%\)) at 1030 nm and a film that is anti-reflective (AR, \(R < 5\%\)) at 940 nm, which worked as an input cavity mirror. The Cr:YAG surface was coated with partially reflective (PR) film with \(R = 40\%\) at 1030 nm, which worked as an output coupler. The surface flatness of the coated cavity surfaces was \(\lambda/8\) (\(\lambda = 633\) nm). The microchip crystal was mounted on thermally conductive copper plates. Thin indium foils were used between the crystal and copper contact surfaces to obtain high thermal conduction and relieve the stress from the mismatch between the coefficients of thermal
expansion of YAG and copper. The copper heat sink was cooled in a vacuum by LN to a temperature of 77 K.

A fiber-coupled water-cooled 936 nm laser diode (BWT Inc.) was used as the pump source. The core diameter of the fiber was 135 µm with a numerical aperture of 0.22. The laser diode worked in quasi-continuous wave (QCW) mode. The pump pulse duration was set to 1 ms and the repetition rate was set to 10 Hz. The pump light from the fiber was coupled to the microchip crystal with a 44 µm (FWHM) diameter by a pair of lenses.

The laser output energy was measured with an energy meter (QE8SP-B-MT, Gentec-EO). The emission spectra of the laser were measured with a spectrometer (HR4000, Ocean Optics). The laser pulse characteristics were detected with a fast photodiode (<25 ps rise time, ET-3500, Electro-optics Technology) and recorded with a 12 GHz bandwidth oscilloscope (Infinium DSO81204B, Agilent). The beam profile was measured using a charge-coupled device (DMK51BU02. WG, The Imaging Source, GmbH).

3. Experimental results

In the experiment, we applied the QCW mode and only one PQS laser pulse for the LD pump duration. Figure 3 is the measured oscilloscope trace with a photo diode. The blue line is the measured LD waveform (also the oscilloscope’s trigger) and the red line is the PQS laser pulse. It is obvious that there is only one laser pulse in one pump pulse.

After that, we measured the PQS pulse duration, and found it to be dependent on the pump focus spot position on the crystal, as shown in figure 4(a). The focus position of zero corresponds to the position that results in the lowest threshold pump power. Under this condition, the output laser pulse duration was as long as 182 ps. Then, we moved the pump focus spot away from the saturate absorber and the pulse duration was reduced to 172 ps. There was an opposite effect if we moved the focus spot in the opposite direction. This effect was due to the pump-induced bleaching of the saturable absorber. Since the microchip laser crystal is thin, the transmitted pump light from Yb:YAG is strong and will partially bleach the saturable absorber, which reduces the saturable loss for the formation of the PQS pulse and increases the minimum pulse duration. Moving the focus spot away from the saturable absorber increases the pump intensity on the gain medium and decreases it on the saturable absorber, so pump-induced bleaching decreases. As a result, the output pulse duration decreases. Zayhowski et al [6] have made a detailed analysis of this effect both theoretically and experimentally.

To further reduce the pump-induced bleaching effect and get a shorter pulse duration, we also tilt the microchip crystal. As shown in the insert in figure 4(b), the pump light is incident to the crystal surface at an angle (~5.2°) to the normal.
In this layout, the pump-induced bleaching area in the saturable absorber is angled away from the direction of the generated laser beam. Thus, we weaken the effects on the formation of the PQS pulse from pump-induced bleaching. By tilting the microchip crystal, we achieved a pulse duration as short as 160.6 ps (FWHM), which was very close to the 147.2 ps calculated from the rate equations. Figure 4(b) shows the measured pulse profile.

The output pulse energy is 6.3 µJ. With a 160.6 ps pulse duration, the resulting peak power is as high as 39 kW. It is easy to enlarge the pump beam diameter, and the output pulse energy can increase to over 100 µJ. However, in the experiment, with a larger pump beam diameter, the output pulse duration increased, even though we tried to move the pump focus spot away from the saturable absorber. The reason for this is that a larger pump beam diameter will result in a longer pump beam Rayleigh length, so the pump beam diameters on the gain medium and saturable absorber are almost the same. As a result, we cannot sufficiently reduce pump-induced bleaching. We think this problem can be solved by tuning the pump wavelength to match the Yb:YAG peak absorption wavelength exactly and by increasing the Yb:YAG doping concentration. Figure 5(a) shows the stability of the experimental output energy over a 10 min period. The root mean square variability is as small as 0.9%. This high stability can be attributed to the simple microchip structure.

Figure 5(b) shows the measured beam radius as a function of the beam propagation position. The fitted beam propagation factor $M^2$ is 1.02 and 1.01 in the horizontal and vertical directions, respectively. The inset figure is the laser focus spot. The output beam quality is quite high, which is beneficial for applications such as nonlinear frequency conversion.

We measured the laser output spectrum, as shown in figure 6(a). The center wavelength was 1029.4 nm with a 0.13 nm bandwidth (FWHM). The bandwidth is near the limit of the spectrometer’s resolution. The narrow bandwidth is one of the advantages of the microchip laser. Since linear polarization is important for many applications, we measured the laser polarization using a polarizer. Figure 6(b) shows the experimental (solid circles) and calculated (solid line) output laser intensities after a polarizer at different angles. We can see that laser polarization is purely linear in the vertical direction.

4. Conclusions

In conclusion, we have developed a diode-pumped cryogenically cooled Yb:YAG/Cr:YAG microchip laser, and a pulse duration as short as 160.6 ps was obtained. Cryogenically cooled Yb:YAG/Cr:YAG microchip lasers are, therefore, a promising method for generating high-energy ultrashort picosecond laser pulses.

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