Femtosecond Yb:YAG Laser Mode-Locked using Intracavity SHG

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Abstract: $\chi^{(2)}$-lens mode-locking of an Yb:YAG laser is demonstrated using intracavity SHG in LBO crystal. Stable operation is achieved with pulse duration of 560 fs, output power of 0.8 W at repetition rate of 110 MHz.
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1. Introduction

Diode-pumped solid-state lasers, emitting picosecond or femtosecond pulses with high average power (>1 W), have attracted significant attention because of their applications in material processing, nonlinear frequency conversion and time-resolved spectroscopy. Currently, mode-locking operation of these lasers is based mainly on two mode-locking techniques: semiconductor saturable absorber mirrors (SESAMs) and Kerr lens mode-locking (KLM). Although SESAMs are well established devices for lasers emitting around 1 µm, their residual absorption is an intrinsic drawback that limits the mode-locking reliability and power scaling. KLM is based on the third order nonlinearity and is widely applied for mode-locking of lasers with broad and smooth amplification bandwidth. However the value and the sign of such nonlinearity are fixed, which limits the flexibility of the cavity design.

An alternative mode-locking technique is based on $\chi^{(2)}$-lens formation in a crystal for second harmonic generation (SHG). It can be applied in any spectral range, where efficient laser media and SHG crystals are available. SHG crystals possess higher damage threshold and lower residual absorption in comparison with SESAMs. Therefore stable operation at high average power can be achieved [1–3]. $\chi^{(2)}$-lens mode-locking technique is similar to KLM, but it utilizes second order nonlinearity, whose sign and magnitude are easily controlled by the phase matching conditions of the SHG crystal [4]. Moreover, this technique can benefit from soliton-like pulse shaping without any dispersion compensating elements, due to the intra-cavity self-phase modulation, introduced by phase mismatched SHG. This effect has been recently exploited in a SESAM mode-locked laser emitting transform-limitted pulses with duration of 114 fs [5]. Nevertheless, $\chi^{(2)}$-lens mode-locking was demonstrated only with picosecond lasers so far.

In this work we report $\chi^{(2)}$-lens mode-locking of an Yb:YAG laser using a LBO as an intracavity SHG crystal. The laser generates 560 fs pulses with output power of 0.8 W at repetition rate of 110 MHz. To our knowledge, this is the first demonstration of femtosecond pulse generation using $\chi^{(2)}$-lens mode-locking technique.

2. Experimental set-up

The linear Z-shaped cavity is 1.4 m long (fig. 1). The active element is a 6 mm long 5 at. % doped Yb:YAG crystal antireflection coated for the laser and the pump wavelengths. It is mounted in a copper holder maintained at temperature of 20 °C by circulating water. The active element is end pumped by a 970 nm laser diode (LD), coupled in an optical fiber (OF) with core diameter of 100 µm. Two aspherical lenses (L1 and L2) ensure pump waist diameter of 120 µm in the active element.

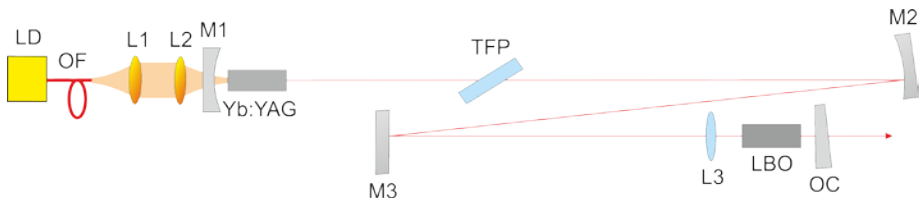

Fig. 1. Laser cavity layout. M1, M2, M3: highly reflective at 1030 nm; M1: highly transmitting at 970 nm, RC=150 mm (radius of curvature); M2: RC=600 mm; M3: flat mirror; L3: focusing lens (f3=50 mm).

Single transverse mode (TEM_{00}) operation is obtained by overlapping the cavity mode size with the pump waist in the active element. A thin film polarizer (TFP) is inserted ensures linear beam polarization. The SHG crystal is a

20-mm long LiB_3O_5 (LBO) cut at θ=90° and φ=0° in the *x*-y plane for type-I oo-e noncritical phase-matching. Its both faces are AR-coated for the fundamental and the second harmonic wavelengths. The LBO crystal is mounted in an oven, whose temperature controls the phase matching conditions. The output coupler (OC) is a flat mirror with transmission of 5% at 1030 nm.

3. Experimental results

In order to obtain mode-locking operation, the positions of the output coupler and the LBO crystal are optimized. The LBO crystal temperature is 177 °C, detuned from perfect phase-matching condition at 192 °C. The phase mismatch $\Delta kL \approx 50$ rad is calculated, where $\Delta k = 2k_{\omega} - k_{2\omega}$ is the wave vector mismatch. This value is considerably higher than those used in picosecond $\chi^{(2)}$-lens mode-locked lasers. Our calculations show that such a high value of ΔkL corresponds to self-phase modulation, which balances the influence of the group-velocity dispersion on the pulse duration. Therefore, soliton-like pulse shaping effects are supposed to enable the stable $\chi^{(2)}$-lens mode-locking with minimum pulse duration.

The output power in mode-locking operation is 0.8 W at absorbed pump power of 25 W (fig. 2 (a)). The mode-locking operation is observed at the region of input–output characteristics close to the maximum achievable output power in CW operation, when the slope efficiency becomes negative. In this region increasing the absorbed pump power leads to higher thermal lens power, which deteriorates the spatial overlap between the pump waist and cavity waist in the active element (fig. 2 (a) blue line). Then this non-optimum overlap is compensated in mode-locking operation by the $\chi^{(2)}$-lens formation in the LBO crystal.

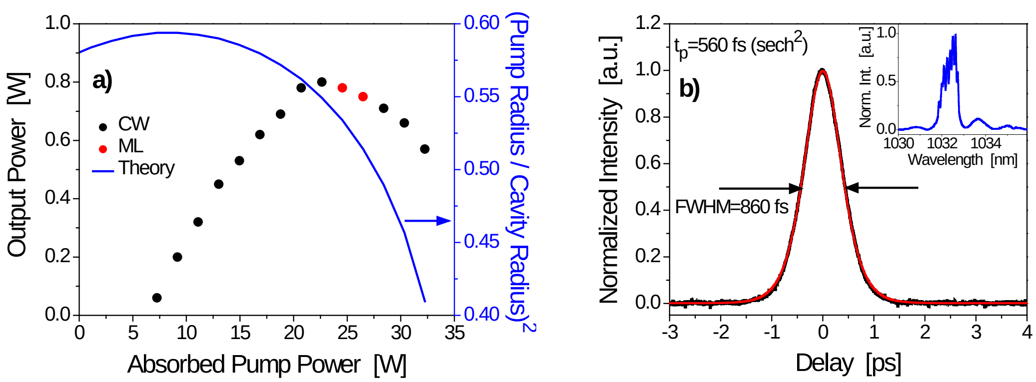

Fig. 2. (a) Input–output characteristics of the Yb:YAG laser in continuous-wave (CW) operation (black dots), mode-locking (ML) operation (red dots) and spatial overlap between pump waist and cavity waist in the position of the active medium (blue line); (b) autocorrelation curve (black), fit assuming $sech^2$ pulse shape (red) and optical spectrum (inset).

The pulse duration is 560 fs assuming $sech^2$ pulse shape (fig. 2 b)). The optical spectrum is centered at 1032.4 nm (fig. 2 b) inset). The pulse repetition rate is 110 MHz, corresponding to a single pulse in the cavity.

4. Conclusion

We demonstrate femtosecond pulse generation based on $\chi^{(2)}$-lens mode-locking of an Yb:YAG laser, for the first time to our knowledge. Phase mismatch values as high as $\Delta kL \approx 50$ rad contribute to soliton-like pulse shaping and enable obtaining stable operation with pulse duration of 560 fs. The output power is 0.8 W at repetition rate of 110 MHz.

5. References

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