Efficient femtosecond optical parametric oscillator pumped by all solid-state mode-locking Yb:YCOB laser

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We experimentally demonstrate a femtosecond optical parametric oscillator (OPO) synchronously pumped by a home-made solid-state mode-locking Yb:YCOB laser, which is capable of laser pulse as short as 102 fs and average power of 620 mW at the central wavelength of 1052 nm. By using a periodically poled lithium niobate with tuning of the grating periods from 28.5 to 31.5 μm as the nonlinear gain crystal, tunable femtosecond pulses from 1444 to 1683 nm are realized by conveniently adjusting the OPO cavity length with 76.8 MHz repetition rate. The maximum average output power is 152 mW at 1568 nm, corresponding to an idler power of 75 mW at 3197 nm as well as 36.6% total extraction efficiency.

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Synchronously pumped femtosecond optical parametric oscillators (OPOs) in the visible and mid-infrared (IR) range have attracted increasing interests as efficient tunable sources for various applications including optical communication[1], terahertz generation[2], time-resolved spectroscopy[3], and mid-IR frequency comb[4]. Due to the much larger nonlinear coefficient and allowing for non-critical phase matching without walk-off effect, periodically poled crystals based on the quasi-phase-matching technique[5] such as periodically poled KTiOPO$_4$, periodically poled stoichiometric lithium tantalate, and periodically poled lithium niobate (PPLN) are widely used in femtosecond OPOs. In the past years, many investigations were mainly focused on Ti:sapphire laser-pumped OPOs[6–11] as well as OPOs pumped by a Yb-doped fiber laser with a master oscillator power amplifier stage[12–16]. For instance, Xu *et al.* reported an efficient femtosecond OPO with dual-wavelength operation, which was synchronously pumped by a Kerr-lens mode-locked Ti:sapphire laser in 2012[8]. High average power, widely tunable femtosecond laser source from red to mid-IR was realized from a Yb fiber laser pumped femtosecond OPO[12]. Diode-pumped Yb-doped solid-state lasers are also promising alternative as pump sources for femtosecond OPO due to their compact and cost-effective features as well as high output power without additional power amplification. Till now, PPLT OPOs pumped by a femtosecond Yb:YAG thin disc laser with up to 19 W signal power have been reported[17]. In 2011, two-color femtosecond OPO pumped by a 7.4 W Yb:KGW bulk laser delivering 1.7 W output power was also demonstrated[18].

In this letter, we experimentally demonstrate an efficient femtosecond OPO using a PPLN as the nonlinear gain material pumped by a Yb:YCOB solid-state laser. Tunable femtosecond pulses from 1444 to 1683 nm are realized by conveniently adjusting the OPO cavity length in combination with tuning of the grating periods from 28.5 to 31.5 μm. A maximum average output power of 152 mW at 1568 nm is obtained, corresponding to an idler power of 75 mW at 3197 nm as well as 36.6% total extraction efficiency. Our measurement shows a temporal duration of 465 fs for the signal pulses at 1514 nm assuming a sech^2 pulse profile.

The schematic of our experimental setup is shown in Fig. 1. The pump source is a home-made Yb:YCOB solid-state femtosecond laser delivering up to 620 mW pulses at 1052 nm with a pulse duration of 102 fs and a repetition rate of 76.8 MHz. During the OPO experiment, our pump laser was operating at the maximum power to maintain stable output characteristics. A half-wave plate (HWP) was used to control the polarization for phase matching in the nonlinear crystal. To ensure optimum overlap between the pump beam and the resonant signal inside the crystal, a quartz lens with 100 mm

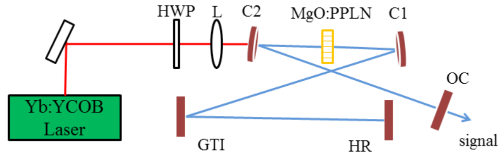

Fig. 1. Experimental setup for Yb:YCOB laser-pumped femtosecond OPO. L, lens with $f = 100$ mm; HR, high reflective mirror.

focal length was utilized to focus the pump laser in the nonlinear crystal with a beam waist radius of 34 μm, matching the waist radius of 28.5 μm for signal beam in the OPO cavity with special design. The nonlinear crystal used here is a 3 mm long, 1 mm thick, 5 mol% MgO-doped PPLN with seven grating periods from 28.5 to 31.5 μm, in steps of 0.5 μm. It is anti-reflective coated around 1020–1080 and 1200–2100 nm on both surfaces. Doping with 5 mol% MgO significantly increases the photorefractive damage threshold of PPLN, so the OPO can be operated at room temperature. To protect the pump source from the feedback of the OPO, the PPLN crystal was slightly tilted. The signal resonance oscillator is a simple X-fold cavity consisting of five mirrors. Both C1 and C2 were dichroic mirrors with radius of curvature of 100 mm which were coated with high reflection in the range of 1400–1800 nm and high transmission at 1000–1100 nm. A Gires–Tournois interferometer (GTI) mirror was used for dispersion compensation which is able to introduce a group velocity dispersion of -500 fs^2 per bounce within the 1480–1530 nm range. An output coupler (OC) with 1.5% transmission across 1400–1800 nm was mounted on a translation stage for cavity length tuning. Using a flat mirror with high reflectivity over 1400–1800 nm as the end mirror, the cavity has a total length of about 976 mm corresponding to the repetition rate of 153.6 MHz, which is twice of the repetition rate of the pump source.

By conveniently adjusting the OPO cavity length in combination with tuning of the grating periods from 28.5 to 31.5 μm, broad tunable signal cover 1444–1683 nm corresponding to 239 nm tuning range was achieved (Fig. 2). Calculated from the energy conservation, the corresponding tunable idler wavelength was over 2806–3875 nm with a tuning range of 1071 nm. The tunable signal range was limited by the coating of the cavity mirrors in the short wavelength (1400 nm) as well as the limited measurement range of the spectrometer (AQ6370C, YOKOGAWA, wavelength range from 600 to 1700 nm) used.

Under the maximum pump power of 620 mW, the signal output power can reach 152 mW at 1568 nm. According to the conservation of photon number, we calculated the corresponding idler power of 75 mW centered at 3197 nm. The maximum total extraction efficiency is 36.6%. The overall threshold of the femtosecond OPO system was measured to be 300 mW. The output power depending on the tuning signal wavelengths is recorded in Fig. 3. As evident from Fig. 3, the power is above 80 mW for 78% of the tuning signal wavelengths. Figure 4 depicts the power stability at the maximum power characterized in 1 min, it reveals the root mean square (RMS) of power stability less than 0.2%. However, within longer time operation, the power becomes unstable and drops due to the ambient temperature fluctuation, air flow, and mechanical vibration. By slightly adjusting the end mirror or OC, the OPO can be recovered for operation. To enhance the stability for long-term running, housing the OPO inside a box for resisting the air flow and preventing from the mechanical vibration as well as using an electronic loop for controlling the OPO cavity length are necessary. Presently, this work is under process, we believe more stable operation is possible with a laser house and an electronic loop.

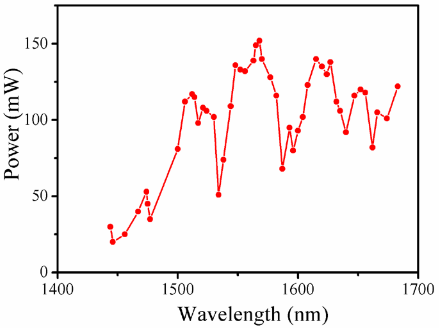

Fig. 3. Output power across the tuning range of the femtosecond OPO.

To understand the temporal character of the femtosecond OPO, we measured the pulse duration with a commercial intensity autocorrelator (FR-103XL, Femtochrome Research, Inc.). Typical result for signal wavelength at 1514 nm is shown in Fig. 5(a). The measurement implied that the pulse duration is 465 fs if a sech^2-pulse shape was assumed. The spectrum at 1514 nm is recorded in Fig. 5(b) with a full-width at half-maximum of 12 nm, resulting in a time-bandwidth product (TBP)

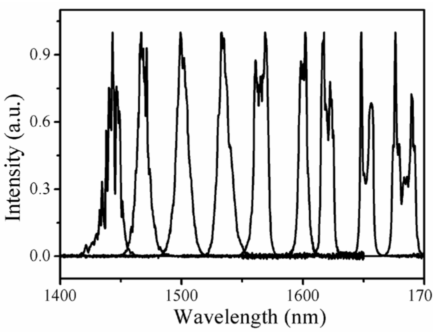

Fig. 2. Signal wavelength tuning range of the femtosecond OPO.

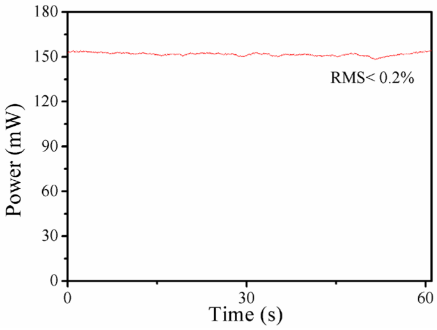

Fig. 4. Power stability of the femtosecond OPO measured in 1 min.

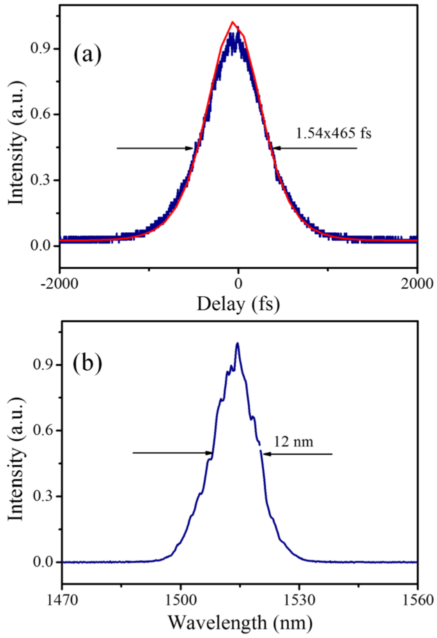

Fig. 5. (a) Intensity autocorrelation trace of the femtosecond OPO at 1514 nm: experimental data and the sech^2-fitting curve are shown by the blue curve and the red curve, respectively and (b) corresponding signal spectrum.

of 0.73. The TBP is twice of the transform limit of a sech^2-pulse shape (0.315) due to the 3 mm length of the PPLN crystal we choose, resulting in a big group velocity mismatching (GVM) between the pump and the signal. The GVM through the whole crystal was calculated to be 287 fs. Near transform limited pulse duration is expected by using thinner PPLN crystal such as 1 mm thick and better intracavity dispersion compensation.

In conclusion, we demonstrate a Yb:YCOB laser pumped femtosecond OPO. Tunable signal from 1444 to 1683 nm and idler wavelength over 2806–3875 nm (calculated from the energy conservation) are achieved. A maximum average output power of 152 mW at 1568 nm is obtained, corresponding to an idler power of 75 mW at 3197 nm (calculated form the conservation of photon number) as well as 36.6% total extraction efficiency. We believe that higher power should be possible by optimizing the OC's transmission and improving the pump power. The OPO operating at the maximum power shows a good power stability (RMS < 0.2%) in a short time (1 min). Due to the big GVM in the 3 mm long PPLN, the pulse duration measured at 1514 nm is 465 fs. Shorter pulse close to transform limit is possible by using a thinner crystal combined with more careful dispersion compensation.

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