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A 515-nm laser-pumped idler-resonant femtosecond BiB_3O_6 optical parametric oscillator

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We report on an idler-resonant femtosecond optical parametrical oscillator (OPO) based on BiB_3O_6 (BiBO) crystal, synchronously pumped by a frequency-doubled, mode-locked Yb:KGW laser at 515 nm. The idler wavelengths of OPO can be tuned from 1100 nm to 1540 nm. At a repetition rate of 75.5 MHz, the OPO generates as much as 400 mW of idler power with 3.1 W of pump power, the corresponding pulse duration is 80 fs, which is 1.04 times of Fourier transform-limited (FTL) pulse duration at 1305 nm. In addition, the OPO exhibits excellent beam quality with $M^2 < 1.8$ at 1150 nm. To the best of our knowledge, this is the first idler-resonant femtosecond OPO pumped by 515 nm.

Keywords: nonlinear frequency conversion, 515-nm laser pumped femtosecond optical parametric oscillator, BiB_3O_6 nonlinear crystal

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1. Introduction

The ultrafast laser sources in the region of 1100 nm–1600 nm have enormous application potential in various fields, such as optical coherence tomography, multiphoton microscopy, and coherent anti-Stokes Raman scattering (CARS).[1–4] In particular, the ultrashort pulses at 1300 nm are very suitable for optical communication due to zero dispersion and low loss during propagation. The optical parametric oscillator (OPO) provides one of the most effective methods to obtain the above laser sources due to its extremely broad spectral coverage, high signal-to-noise ratio, and high coherence.[5–7] In the past, the OPOs in near-infrared region (NIR) were mainly pumped by Kerr-lens mode-locked Ti:sapphire laser. However, such OPOs are limited to low output power, high cost, and complex operating systems.[8–15] Recently, the development of high power Yb-doped all-solid-state laser and fiber amplifier have overcome the limitation of Ti:sapphire pump technology.[16–18] The wavelengths of Yb-doped laser pumped OPOs are generally longer than 1300 nm, while the OPOs pumped by green laser could cover visible (VIS)–near infrared pulses simultaneously,[19] and the short wavelength of idler pulses can cover the spectrum over 1100 nm–1300 nm.

However, the green laser-pumped OPOs were mainly focused on the signal-resonant configuration before,[20–27] where idler pulses emitted after only a single pass through the crystal, resulting in low powers and poor beam quality. There are two ways to solve the above difficulty. One way is to improve the pump power, the other way is to allow idler pulses to resonate in a cavity. For the former way, there have been many reports on signal-resonant femtosecond OPOs based on high power pump sources. In 2011, Cleff *et al.* reported a signal-resonant LiB_3O_5 (LBO) femtosecond OPO pumped by a frequency-doubled Yb-fiber amplifier. The OPO generated more than 300 mW of idler pulses with spectrum tunable across 1630 nm–1190 nm with pump power of 2.3 W.[3] Based on a frequency-doubled mode-locked Yb:KGW oscillator as pump source, Meng *et al.* demonstrated a 515-nm pumped signal-resonant femtosecond OPO tunable across 1100 nm–2000 nm. With 3.75-W pump power, the maximum power of the idler was 408 mW.[24] Though the idler power has been increased by higher pump power, poor beam quality is still an issue, which limits the practical applications. However, the idler-resonant configuration can not only scale the output power but also optimize the beam quality. In fact, there are many reports about 1-μm pumped idler-resonant OPOs. The method of "idler-resonant" was firstly used in a nanosecond OPO pumped by the Q-switched Nd:YAG laser based on periodically poled MgO-doped congruent $LiNbO_3$ (PP-MgO:CLN), average output powers of 16.7 W at 3.84 μm and 46 W at 1.47 μm were obtained. The M^2 factors at

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3.84 μm were measured to be 2.03 and 5.89 in the horizonal and vertical directions, respectively.[28] Then, Parsa *et al.* demonstrated a high-power idler-resonant picosecond OPO. The OPO generated 3.5 W of idler power and exhibited excellent beam quality ($M^2 < 1.8$) in a spectrum coverage from 4028 nm to 2198 nm.[29] In 2014, an idler-resonant femtosecond MgO:PPLN OPO pumped by Yb-doped fiber amplifier was demonstrated, which generated 600 mW of idler pulses with high beam quality ($M^2 - 1.05$) at 2.2 μm–2.6 μm.[30] Though the output power and beam quality could both satisfy the needs of applications, the output wavelength could not reach around 1.3 μm. Using green laser as pumping source could easily overcome this problem, however, there are few reports about idler-resonant femtosecond OPOs pumped by green laser.

In this paper, a high-power, idler-resonant femtosecond OPO pumped by 515 nm at a repetition rate of 75.5 MHz is demonstrated based on BiBO crystal. To the best of our knowledge, this is the first 515-nm pumped idler-resonant femtosecond OPO. Based on a 1.5-mm-long BiBO nonlinear crystal, a widely tunable spectrum from 1100 nm to 1540 nm (idler) is realized by adjusting the crystal angle and cavity length. Using a 10% output coupler, average output power of 400 mW is obtained at 1305 nm with pump power of 3.1 W, the corresponding pulse duration is 80 fs. In addition, the beam quality factors are measured to be 1.659 and 1.796 in the horizontal and vertical directions, respectively.

2. Experimental setup

The experimental configuration of idler-resonant femtosecond OPO is shown in Fig. 1. The OPO is synchronously pumped by a frequency-doubled mode-locked Yb:KGW oscillator (Light Conversion, FLINT6.0) delivering 90-fs pulses centered at 1030 nm with 7 W of average power at a repetition frequency of 75.5 MHz. A 2.5-mm long LBO crystal is used for frequency doubling. In order to realize type I ($\mathrm{o} \rightarrow \mathrm{e}+\mathrm{e}$) phase matching for LBO, the first half wave plate (HWP1) is used to convert p-polarized laser of Yb:KGW oscillator to s-polarization. A lens L1 ($f = 75$ mm), anti-reflection (AR) coated at 1030 nm is used to focus pump laser into the LBO crystal to obtain 515-nm laser. Then, the green laser is collimated by the second lens L2 ($f = 150$ mm). Two dichroic mirrors (DM1, DM2) are AR coated for 1030 nm and high-reflectivity (HR) coated for 515 nm, thus 515-nm laser is extracted to pump the OPO. The second half-wave plate (HWP2) combined with polarization beam splitter (PBS) can be used to attenuate power at 515 nm. Finally, we obtain 3.1 W of green laser after PBS. The third half wave plate (HWP3) can change the polarization of the 515-nm laser from the s-polarized state to the p-polarized state, thus satisfying the polarization of gain crystal.

In femtosecond OPOs, it is also vital to choose the suitable nonlinear crystal. The BiBO crystal can excel other nonlinear crystals (LBO, BBO, *etc.*) due to the larger effective nonlinear coefficients (2.86 pm/V), the wide transparency of 280 nm–2700 nm, inertness with respect to moisture.[9,20,31] Especially, its nonlinear coefficient is 3.5–4 times higher than that of LBO, 1.5–2 times higher than that of BBO. In this experiment, the 1.5-mm thick BiBO is used as gain crystal and placed in room temperature. As a biaxial crystal, BiBO can realize angle tuning in the large scale. It is cut at $\theta = 168.3^\circ$, $\varphi = 90^\circ$ for type I (I ($\mathrm{o} \rightarrow \mathrm{e}+\mathrm{e}$) phase matching and coated AR for the pump laser (510 nm–520 nm), the signal and the idler (650 nm–1600 nm). The pump laser at 515 nm is focused into the BiBO crystal by the lens L3 with a focus length of 100 mm. The idler-resonant cavity used in this experiment includes two concave mirrors, resulting the beam waist diameter of 41 μm inside BiBO, five plane mirrors and one output coupler. It is important to choose the appropriate focusing spot size of pump laser to improve the nonlinear frequency conversion efficiency. The "M1" and "M2" represent dichroic concave mirrors ($R = 100$ mm) coated AR for 515 nm and HR across 1100 nm–1600 nm. A 10% of transmission output coupler is mounted on a micrometer driven translation stage to adjust finely the cavity length. The others are plane mirrors coated HR across 1100 nm–1600 nm. In order to synchronize with the pump laser at a repetition frequency of 75.5 MHz, the total cavity length of the OPO is around 1986 mm.

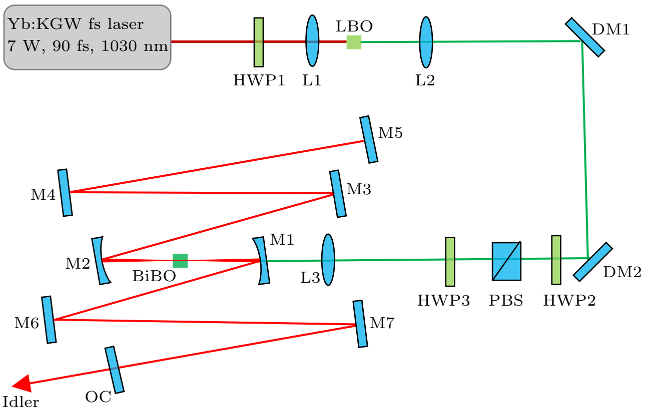

Fig. 1. The experimental setup of 515-nm pumped idler-resonant femtosecond OPO based on BiBO. HWP: half wave plate; L1, L2, L3: lens with a focal length of 75 mm, 150 mm, 100 mm, respectively; PBS: polarization beam splitter; DM1, DM2: dichroic mirrors; LBO: $\mathrm{LiB_3O_5}$; BiBO: $\mathrm{BiB_3O_6}$; M1, M2: concave mirrors with the radius of curvature of 100 mm; M3, M4, M5, M6, M7: high reflecting mirrors, OC: output coupler.

3. Results and discussion

Firstly, the idler spectrum measurements are taken with a spectrometer (AQ-6315A ANDO, Japan), as displayed in Fig. 2. The continuously tunable wavelength ranges are from 1100 nm to 1540 nm by rotating the crystal angle and precisely adjusting the cavity length. The FWHM spectral bandwidth ranges from 8 nm to 29 nm. The spectrum at 1305 nm is characterized by the blank curve, corresponding to an FWHM spectral bandwidth of 23 nm. Furthermore, the cavity detuning characteristic of OPO is also researched. The output coupler is mounted on translation stage, and it is adjusted finely to change cavity length to realize different wavelength on a smaller scale.

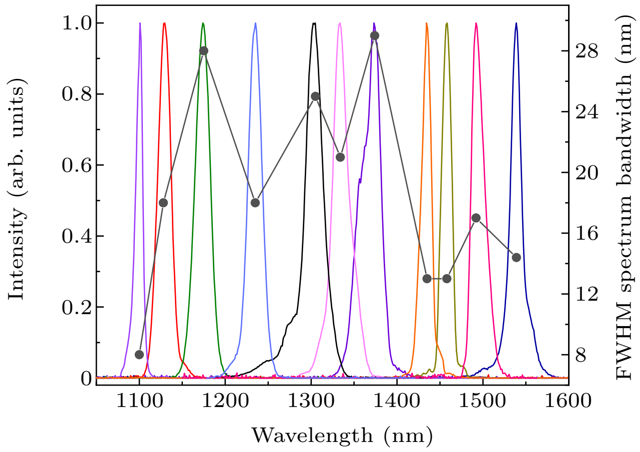

Fig. 2. The continuously tunable wavelength ranges of idler-resonant femtosecond OPO.

The output power ranges of the idler at different wavelengths are illustrated in Fig. 3. The idler threshold of OPO across entire tunable wavelength is observed in the ranges from 1.5 W to 2 W of pump power at 515 nm. The average output power varies from 80 mW to 400 mW in the 1100 nm–1540 nm spectral ranges. However, most of generated signal pulses at 774 nm–968 nm pass through the concave mirror M2 and mix with residual pump laser, while there is still small amount of signal pulses and other sum frequency pulses could be seen behind each cavity mirror and output coupler. Thusly, a longpass filter with cut-on wavelength of 1100 nm (FEL1100, Thorlabs) is placed behind the output coupler to separate the idle pulses from others. The transmission loss per round-trip is also not negligible due to the HR-coating defects of cavity mirrors and AR-coating defects of the nonlinear crystal. When the wavelength ranges from 1100 nm to 1305 nm, the output power increases continuously. With 3.1 W of incident pump power at 515 nm, the maximum output power is 400 mW at 1305 nm. When the wavelength is longer than 1305 nm, the output power drops sharply. The minimum average output power is 80 mW at 1540 nm. The reason for the low output power at long wave is as follows: the BiBO nonlinear crystal needs rotating larger angle to obtain long wavelength pulses, and the relatively obvious refraction phenomenon makes the overlaps in space between idler and pump laser worse. Then, the shorter effective interaction length between the pump and idler laser in the long wavelength reduces the optical–optical conversion efficiency of the pump and idler pulses. The above phenomenon may be mitigated by using shorter crystal and choosing the appropriate cut-angle of crystal that is close to phase matching angle of long wave. In order to further increase output power, it is necessary to use the optimized transmission of the output coupler and scale the pump power. We believe that higher nonlinear frequency conversion efficiency can be realized by trying the output mirrors with various transmittance and nonlinear crystals with different thicknesses, and reducing intracavity loss by using higher quality HR/AR-coating for cavity mirrors and gain crystal.

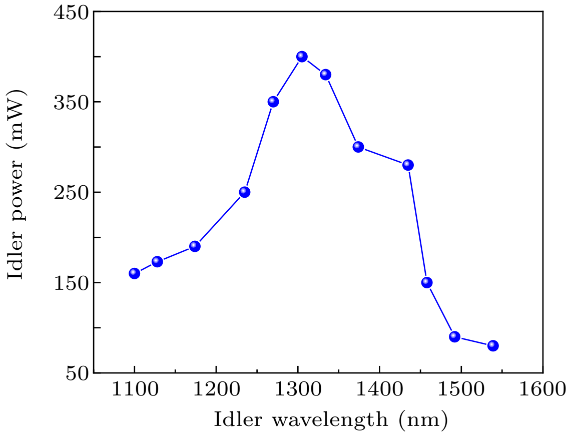

Fig. 3. The output power ranges of the idler at different wavelengths with 3.1-W pump power.

Figure 4 shows that the corresponding Fourier-limited pulse durations vary from 72 fs to 173 fs, and the measured pulse durations are in the ranges of 80 fs–248 fs over the entire wavelength tuning ranges from 1100 nm to 1540 nm. This is due to the introduced group delay dispersion (GDD) by cavity mirrors and nonlinear crystal. It can be seen that the corresponding red and blue data points at other wavelengths are separated by some distance, and the measured pulse durations are longer than the limited ones, which are to be expected due to no dispersion compensation in the cavity.

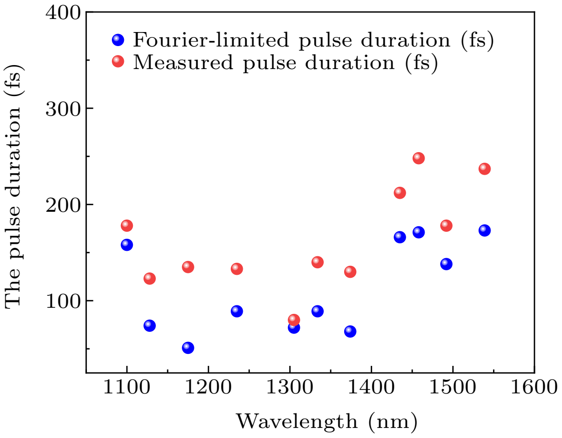

Fig. 4. The Fourier-limited pulse durations and the measured pulse duration across the entire tunable wavelength.

Assuming a sech^2-pulse shape, as short as 80-fs pulses centered at 1305 nm are measured by the intensity autocorrelator (Pulse check, A.P.E.), as shown in Fig. 5. It has an FWHM spectrum bandwidth of 23 nm, which is close to the

Fourier transform-limited (FTL) pulse duration of 77 fs. The actual time-bandwidth product of 0.324 is close to the Fourier transform limitation for a sech^2-pulse shape (0.315). This may be due to dispersion balance each other at 1305 nm, and the optimized interaction between the pump and idler laser. Finally, the beam quality of idler-resonant femtosecond OPO is measured by a commercial M^2 factor meter (Spiricon M^2-200 s), as displayed in Fig. 6. At the center wavelength of 1150 nm, the M^2 factors are 1.659 and 1.796 in the horizontal and vertical directions, respectively. The multiple round trips of the idler in the cavity and the spatial walk-off in the BiBO crystal make the beam quality factors far from the diffraction limited.[16]

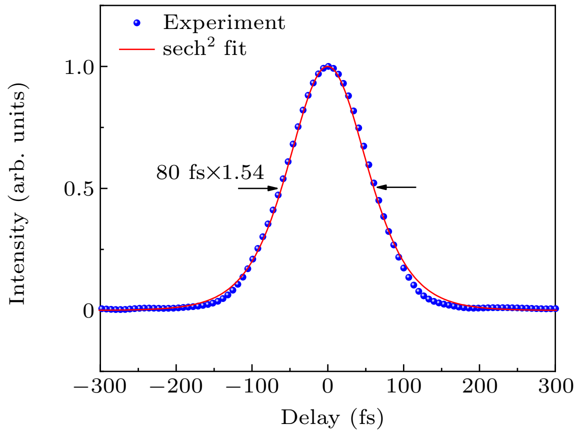

Fig. 5. Assuming a sech^2-pulse shape, the intensity autocorrelation trace of idler-resonant femtosecond BiBO OPO at 1305 nm.

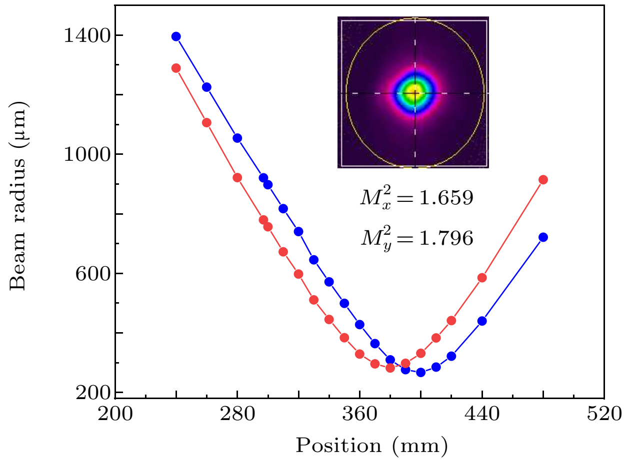

Fig. 6. The beam quality of BiBO femtosecond OPO at the center wavelength of 1150 nm.

4. Conclusion

In conclusion, we report on a widely tunable, idler-resonant femtosecond OPO pumped by second harmonic Yb:KGW mode-locked oscillator. Based on BiBO crystal, we generate 400 mW of average output power from a synchronously-pumped femtosecond OPO at the center wavelength of 1305 nm. The measured idler pulse duration of 80 fs is close to transform-limited pulse duration of 77 fs. Over 440 nm of broadly tunable bandwidth is readily realized from 1100 nm to 1540 nm for idler pulses. At a repetition frequency of 75.5 MHz, we infer that the peak power is 66 kW. Moreover, the beam quality of output laser at 1150 nm is characterized with $M^2 < 1.8$.

A potential approach to obtain high power as well as good beam quality laser for femtosecond OPOs at NIR wavelength is the idler-resonant in optical cavity. The idler-resonant method has only been used for the 1-μm pumped OPOs before, and we have demonstrated that this method can also be applied in 515-nm pumped OPOs to obtain high power and high beam quality laser with a spectrum coverage of 1.1 μm–1.6 μm. We believe that such laser sources will play an increasingly important role in various fields such as optical communication.

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