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An Octave-Spanning, Kerr-Lens Mode-Locked Ti:sapphire Oscillator with Double-Chirped Mirrors and BaF_2 *

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We demonstrate an octave-spanning Kerr-lens mode-locked Ti:sapphire laser with double-chirped mirrors (DCMs), BaF_2 wedges and plate, which generates laser pulses in the spectrum range from 600 nm to 1200 nm at −45 dB below the maximum and the duration of 8.5 fs at the repetition rate of 80 MHz. The average output power is 100 mW under 5 W pump power. By carefully adjusting the insertion of BaF_2 wedges and the optimization position of Ti:sapphire crystal in the cavity, we can obtain the smooth swings in the interferometric autocorrelation trace due to good third-order dispersion compensation.

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Kerr-lens mode-locked Ti:sapphire lasers have revolutionized the frequency metrology,[1,2] attosecond generation,[3,4] and fundamental constant measurement[5,6] since the invention of frequency combs in 2000.[7,8] A standard Ti:sapphire frequency comb consists of a 20–30 fs oscillator and a piece of photonic crystal fiber (PCF)[9,10] which generates a supercontinuum spectrum for f–$2f$ measurement on the carrier-envelope phase offset (CEO) frequency between adjacent pulses. The PCF is a special kind of highly nonlinear fiber with a small solid core diameter of 1–2 µm, surrounded by a number of honeycomb-like hollow holes arranged neatly in cladding. Such a structure in PCF can cause strong nonlinear effects such as self-phase modulation (SPM), four-wave mixing, and self-steeping, which extend the spectrum range of the input laser to more than one octave. The PCF played an important role for the Ti:sapphire frequency comb in the early stages, but it also brings some disadvantages. Firstly, it is very difficult to couple the light into the fiber core because of the small diameter, which leads to two problems: low coupling efficiency and high sensitivity to the light pointing. With the usual 40–50% coupling efficiency, half of the laser power is lost, and a small deviation of the light pointing will make the system unstable. Secondly, shining with the strong focused laser the end facets of PCF are apt to be damaged once a speck of dust has contaminated them. Moreover, additional amplitude-to-phase noise might be brought due to the ultrashort pulses propagating in a long PCF.[11,12] Therefore, it is necessary to construct compact and stable femtosecond frequency combs based on the wide spectrum oscillator, which can directly produce laser pulses with spectral range of more than one optical octave without using the PCF.

Owing to the advent of chirped-mirrors and high-order dispersion compensation techniques,[13] ultrabroad frequency combs directly generated from Ti:sapphire oscillators became feasible in recent years.[14−16] The key breakthrough was shown in Ref. [15], in which a direct ultrabroad femtosecond Ti:sapphire frequency comb with more than one optical octave was demonstrated at the repetition rate of 1 GHz based on double chirped mirrors(DCMs) dispersion compensation technique. Compared to the operation time of less than one hour for traditional Ti:sapphire combs with PCF, the direct comb's operation time is dramatically increased. The stable running time can be extended to approximately ten hours or even more. With these long time stable direct Ti:sapphire frequency combs, absolute optical frequency measurement experiments and astro-frequency combs have been successfully demonstrated.[17]

In this Letter, we report an octave-spanning kerr-lens mode-locked Ti:sapphire oscillator at the repetition rate of 80 MHz by using DCM intra-cavity for wide spectral dispersion compensation. By precisely controlling the dispersion and optimizing the SPM, an octave-spanning spectrum, from 600 to 1200 nm, has been obtained directly from the oscillator. It is free from complicated alignment of PCF and has the potential to operate at an even higher repetition rate, which will be an ideal source as frequency combs.

The experimental setup is shown in Fig. 1. It consists of eight mirror astigmatic compensated Z-folded cavities, in which a plate of BaF_2 in the short arm and a pair of BaF_2 wedges in the long arm are placed with Brewster angle for dispersion fine-tuning. The Ti:sapphire crystal is 2 mm in thickness, two-side

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Brewster cut, which is pumped by an all-solid state double frequency Nd:YVO_4 laser with the power of 5 W at 532 nm (Coherent Verdi V5). The lens L with a focal length of about 60 mm is used to focus the pump laser into the Ti:sapphire crystal. In this cavity, M_2–M_7 all are broadband DCMs, which are designed to provide smooth group-delay dispersion (GDD) in pairs. Simultaneously the reflectivity is as high as 99.9% over an octave range. M_3 and M_4 are a pair of concave mirrors with radius of curvature (ROC) of 100 mm. As the end mirror in the short arm, M_1 is a broadband high reflective mirror. The output coupler (OC) is a plane mirror with thickness 2 mm and the transmission of 1% in a broadband spectrum range.

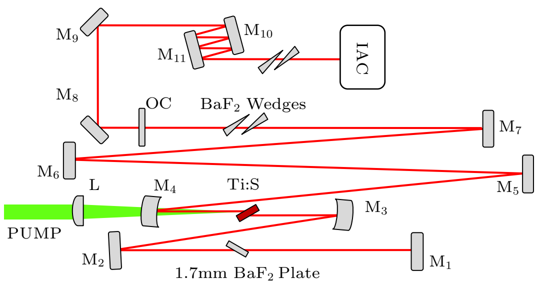

Fig. 1. Schematic of the octave-spanning Ti:sapphire oscillator.

In experiment, each pair of DCMs can supply anomalous GDD of $-120\,\mathrm{fs}^2$ around the central wavelength of 800 nm (DCM7, VENTEON). Therefore the total GDD of three pairs is $-360\,\mathrm{fs}^2$ which can cancel all the normal dispersion induced by air and the other components in the cavity. In order to adjust the dispersion precisely and to improve intra-cavity dispersion map, a small angle BaF_2 wedge pairs are inserted into the light path of the long arm. Meanwhile, a BaF_2 plate with a thickness of 1.7 mm is also used in the short arm to balance the dispersion. Compared with the other materials, BaF_2 can bring much less third-order dispersion (TOD) because of the lower ratio of third- to second- order dispersion (see Fig. 2). The TOD in BaF_2 is about $18\,\mathrm{fs}^2/\mathrm{mm}$, much less than those of the other materials for ultrashort laser pulse with a central wavelength of 800 nm (see Fig. 3). This is very important for the generation of laser pulses with the ultrabroad spectrum, since the extra TOD will bring a serious broadening effect in the time domain. In addition, the slope of dispersion is similar to that in air, implying that the length of the cavity for this laser oscillator can be reduced by inserting BaF_2 with suitable thickness, which will increase the repetition rate of output pulses. Lastly, the output coupler is made of the MgF_2-ZnSe material rather than traditional fused silica. With a higher index contrast, MgF_2-ZnSe can support a high transmission in much broader spectral bandwidth from 650 nm to 1100 nm. Considering the "roll-off" effect, the output spectrum could span over one octave bandwidth.

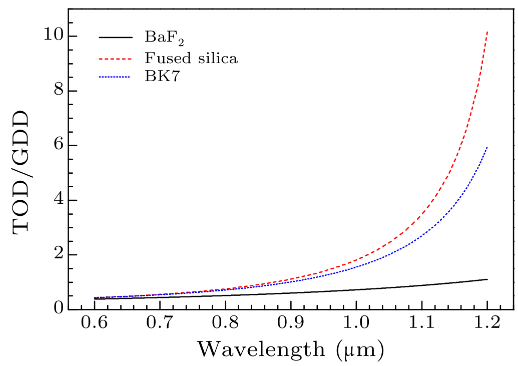

Fig. 2. The comparison of the ratio TOD/GDD for BaF_2, fused silica and BK7.

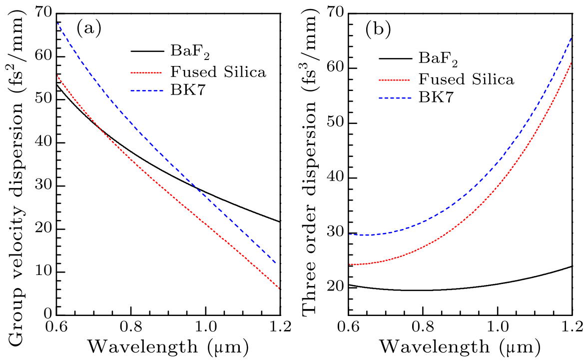

Fig. 3. Group velocity dispersion and three-order dispersion of BaF_2, fused silica and BK7.

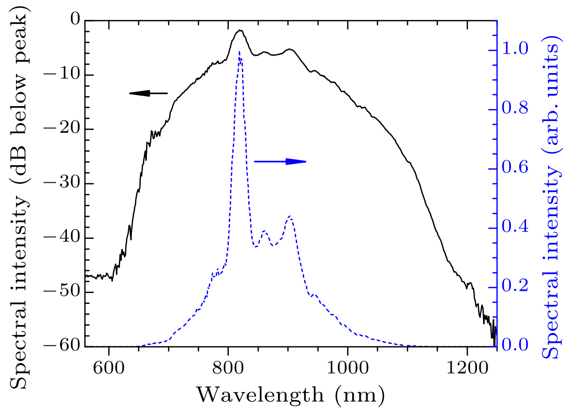

Fig. 4. Output spectrum on a logarithmic and on a linear scale.

The stable kerr-lens mode-lock was obtained by changing the position of concave mirrors and adjusting the insertion of BaF_2 wedge pairs. An average output power over 200 mW was realized at the pump power of 5 W, but it was hard to keep the mode-lock in the octave-spanning spectrum range. This largely depends on the balance of dispersion compensation and SPM inside the cavity. Actually, the spectral bandwidth of the ultrashort pulses was mainly determined by the SPM in the cavity. For typical Ti:sapphire oscillator configuration, SPM supplied by the focused light with two concave mirrors is so weak that it cannot support more spectral components to resonate in the cavity. In 2001, Ell *et al.*[14] introduced a BK7 plate into the cavity to solve this problem, by producing another focus area to enhance the SPM effect. They successfully obtained 5 fs laser pulses with the spectrum from 600 nm to 1200 nm. To simplify the laser structure and to make the alignment easier, we designed a suitable configuration of the z-fold cavity in this experiment and the SPM effect strengthened by adjusting the position between concave mirrors and gain crystal precisely.

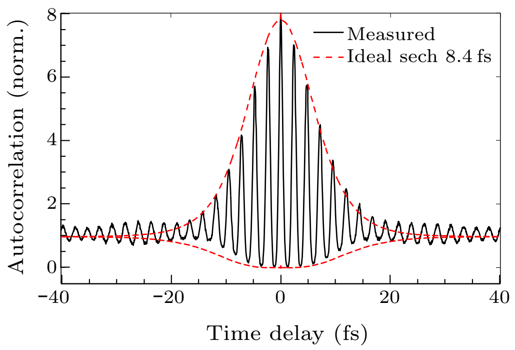

Fig. 5. Interferometric autocorrelation trace of the laser pulses after extracavity compensation.

Figure 4 shows the typical spectrum of the few-cycle femtosecond laser we observed. Just as the logarithmic scale displays, the spectrum spans from 600 nm to 1200 nm with about −45 dB level from the maximum intensity at the wavelength of 820 nm (ANDO AQ6315E). It is almost smooth over the whole spectral range. However, as shown from the curve of spectrum in absolute intensity scale, it is obvious that the laser got a higher gain in the long wavelength than in the short one, especially at the wavelength of around 600 nm. This is probably because of the low transmission of output coupler below 650 nm. Under the stable octave-spanning operation, the average output power is about 100 mW. Meanwhile, we measured the pulse duration with a commercial second-order autocorrelator (FEMTOMERER PC-DAQ). To get the narrowest pulse duration, we utilized two chirped mirrors M_8 and M_9 outside the cavity to compensate for the dispersion induced by output coupler. Assuming a sech^2 pulse shape, we measured the interferometric trace shown in Fig. 5, and evaluated a pulse duration of 8.4 fs, which comprises about three optical cycles. The dashed envelope of interferometric fringe is a theoretical curve of the ideal sech^2-shape pulse as a reference. Both wings in the interferometric trace are smooth due to good third-order dispersion compression by BaF_2.

In summary, we have implemented an octave-spanning Ti:sapphire Kerr-lens mode-locked laser oscillator by using DCMs, intra-cavity BaF_2 plate and wedge pairs to fine balance the dispersion. By precisely optimizing the second- and high-order dispersion and the SPM, the pulse duration as short as 8.4 fs and spectrum extending from 600 to 1200 nm has been achieved. The mode-locked operation can be maintained well for a few hours at the repetition rate of 80 MHz. In view of the ultrabroad spectrum and compact alignment, this octave-spanning laser oscillator will be an ideal source for the optical parametric amplification, metrology and other scientific fields.

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