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A Wide Spaced Femtosecond Ti:Sapphire Frequency Comb at 15 GHz by a Fabry–Pérot Filter Cavity *

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We realize a wide spaced frequency comb by using an external low-fineness Fabry–Pérot (F-P) cavity to filter few-cycle laser pulses from a Kerr-lens mode-locked Ti:sapphire laser at the fundamental repetition rate of 350 MHz. Mode spacing as wide as 15 GHz with spectrum covered from 690 nm to 710 nm is demonstrated, corresponding to a filter multiple of about 43. The scanning transmission peaks after the F-P cavity with cavity lengths are also simulated numerically, and the results are in agreement with the experiment.

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The optical frequency comb with wide mode spacing, or high repetition rate, has wide applications in many fields. In particular, those of 15–20 GHz mode spacing, used as wavelength calibration sources of high-resolution astrospectrometers, will enable us to improve increasingly the precision of radial velocity,[1−3] which may lead to considerable progress in search for the terrestrial mass planets in earth-like orbits,[4−6] measurement of the cosmic expansion velocity[7−9] and observation of temporal variation in fundamental constants.[10−12] However, most of the frequency combs usually have mode spacing of the order of hundreds MHz or several GHz. It would be insufficient to distinguish individual comb lines if such frequency combs have been used directly in calibrating the existing astronomical spectrographs whose resolution is about 15 GHz at present.[13] Therefore, we have to utilize other methods to increase the repetition rate of normal frequency combs.

The mode-filtering scheme by external Fabry–Pérot (F-P) cavity is a valid way to broaden the mode spacing of the frequency comb, which was first proposed for generating an astronomical frequency comb in 2007.[14,15] Compared to the inherent 10 GHz frequency comb derived from the Kerr-lens mode-locked femtosecond laser oscillator,[16,17] the F-P filter cavity technique has an obvious advantage in that it does not need a complicated optical cavity consisting of a piece of gain medium and some high reflectivity mirrors, and hence, it does not need strong nonlinear effects like self-phase modulation (SPM) and Kerr-lens to excite mode-locking among amounts of longitudinal modes. However, the output power of a wide mode-spaced frequency comb transmitted from the F-P cavity will suffer a large loss because of the filter function, which limits the feasible application. For example, for femtosecond laser pulses with the average power of 100 mW at repetition rate of 1 GHz, the output power will be decreased to 10 mW when the repetition rate is increased to 10 GHz by the F-P filter cavity. To solve this problem, Wilken *et al.* used a fiber laser amplifier to raise the power following the filter cavity.[18] In this case a fiber frequency comb was generally employed as the seed to match the fiber amplifier. More recently, Wilken *et al.* further enhanced the frequency comb power up to 300 mW at repetition rate of 18 GHz by cascaded fiber laser amplifiers.[19] It has been well used to explore the radial velocity of the earth-like planet as an astro-comb.

In this Letter, we present a wide spaced frequency comb based on a Kerr-lens mode-locked (KLM) Ti:sapphire laser comb at repetition rate of 350 MHz.[20] By using an external low-fineness Fabry–Pérot (F-P) cavity as the filter, the repetition rate of the comb source is raised to 15 GHz within a spectral bandwidth of about 40 nm. To understand in depth the filtering mechanism of F-P cavity and to verify the experimental results, we simulate the transmission peak distribution when scanning the length of F-P cavity. The results show that they are consistent with the signals recorded by the oscilloscope in the experiment.

The 350 MHz frequency comb is based on our homemade KLM Ti:sapphire femtosecond oscillator with few-cycle duration and an ultrabroadband spectrum. With an improved scheme for optimizing the different-frequency generation between high and low frequency components in the same femtosecond laser pulse, the signal-to-noise ratio of the carrier-envelope phase offset frequency between adjacent laser pulses was obtained to be as high as 50 dB, which greatly enhanced the stability and robustness of the frequency comb in a long term operation.[20] Here it is selected as the stable comb source for generating the wide-spaced

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frequency comb by the technique of external F-P cavity. The whole experimental setup is shown in Fig. 1. The F–P cavity consists of two identical concave mirrors with the radius of curvature (ROC) of 400 mm and the reflectivity of 99% coated in the range from 600 nm to 800 nm separated by the distance of 10 mm. Both concave mirrors are mounted separately on two piezoelectric transducers (PZT), one is modulated by the frequency of 20 kHz provided by a function generator, the other is feedback controlled by the phase-locked-loop electronics to stabilize the F-P cavity to the comb source. A small part of the transmitted light from the F-P cavity is received by a photo detector (PD) and demodulated with a mixer referenced to the modulation frequency of 20 kHz. In this way, a dipolar error signal will be generated and then be transformed to a control signal by the loop filter. This control signal is input into the feedback PZT and keeps the F-P cavity on resonance. Such dither locking technique offers stable and longtime operation for the F-P cavity without frequency shift. A cw diode laser with the wavelength of 780 nm is used to provide a reference for determining the mode number of the wide-spaced comb filtered by the F-P cavity. To make the F-P cavity work efficiently, a ∼50-cm-long single-mode fiber is used to optimize the beam quality of the light emitted directly from the comb source and two lenses are aligned to ensure good mode-matching between the comb source and the F-P cavity.

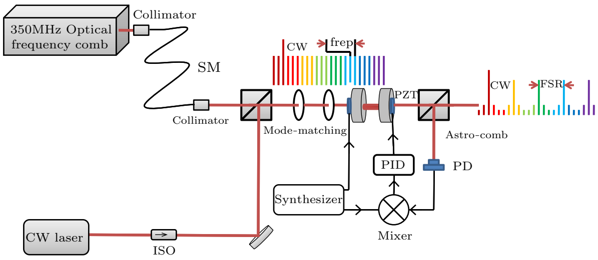

Fig. 1. The experimental setup of the F-P filtering cavity.

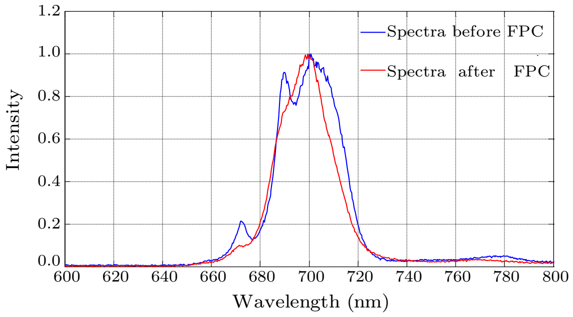

Fig. 2. The spectral envelope of comb before (blue) and after (red) the Fabry–Pérot cavity (FPC).

The spectral envelopes of original comb and astro-comb (before and after the F–P cavity) are shown in Fig. 2. Limited by the bandwidth of the single mode fiber, the spectral width of the original comb has been narrowed to a rather small coverage from 690 nm to 710 nm (blue line) when it entered into the F-P cavity. For F-P filter cavities, there is a conflicting station in the choice of their fineness, where two important specifications of the astro-comb, both the bandwidth and the side-mode suppression ratio are determined by the fineness of the F-P cavity in the diametric opposition. The changes of these two factors are demonstrated in Fig. 3, the higher the fineness, the narrower the bandwidth and the better the side-mode suppression ratio. Thus, the achievement of the wide band astro-comb is inevitably at the cost of the performance of the side-mode suppression when filtered by the F-P cavity. Using two or more cascaded low fineness F-P cavities solves this problem and makes the system more stable at the same time.[19] Here the fineness of the F-P cavity with 99% reflectivity is about 300, which allows the astro-comb with 180 nm bandwidth. Therefore, compared with the original comb, we find that there is no significant narrowing effect occurring on the astro-comb whose mode-spacing has been multiplied to 15 GHz (red line), corresponding to the filtering ratio of 43.

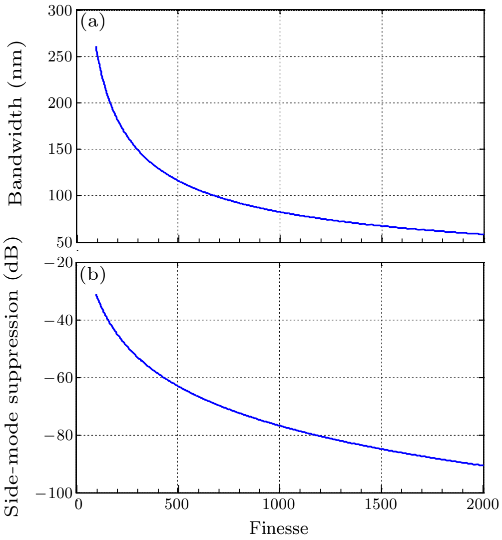

Fig. 3. The bandwidth and side-mode suppression rate as a function of fineness at 15 GHz FSR of filter cavity based on 350 MHz repetition rate of comb.

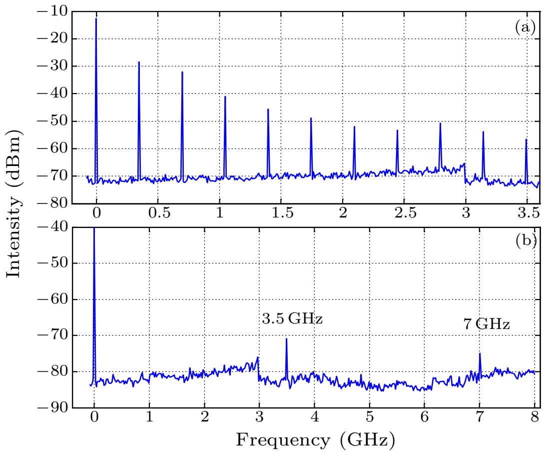

Fig. 4. The rf spectrum of (a) the comb source at 350 MHz, (b) the filtered comb at 3.5 GHz.

Since the resolution of the optical spectrum analyzer in our lab is only 0.1 nm around the central wavelength of Ti:sapphire comb, it cannot resolve the single comb line with the mode spacing lower than 20 GHz. Therefore, we used an rf spectrum analyzer (E4407B, Agilent Inc.) to measure the mode spacing of the transmitted laser pulse train. Figure 4 presents the repetition rates and their harmonics of the astro-comb in the microwave frequency domain. We can see that there are a lot of high order harmonics, aside from the 350 MHz fundamental repetition rate, which are the heterodyne beat frequencies between each mode and another one apart from two, three or several modes in the optical frequency comb. Some of the modes will be destined to become unwanted lines in the process of increasing the spacing of the mode, in other words, they will be canceled, or filtered by the F-P cavity. The filtered mode nearest to the main transmitted mode has usually the lowest suppression ratio with respect to the other unwanted ones. Therefore, the rf distribution of the transmitted laser pulse train after the F-P cavity carries information of the mode-spacing as well as the side-mode suppression. This is also an indirect approach of measuring the side-mode suppression of the filtered comb. Figure 4(b) illustrates the rf spectrum of the transmitted light at 3.5 GHz detected with a 25 GHz fast photo detector (1437, New Focus Inc.). This signal of 3.5 GHz and its second-order harmonic of 7 GHz appearing in Fig. 4(b) are very low. In fact, they are completely submerged in the noise of fundamental repetition rate and their harmonics before we extracted them by placing a narrow band interference filter to decrease the noise background below 80 dBm. The main reason for this case is that the power of the filtered comb at 3.5 GHz has been damped to about 2 mW, which is not enough for supporting good rf signal. The same situation happens for measurement of the filtered comb with larger mode spacing than 4 GHz. Thus we recorded the transmitted signals of the filtered combs with an oscilloscope as shown in Fig. 5. Numerical simulation is also made to verify this experimental result.

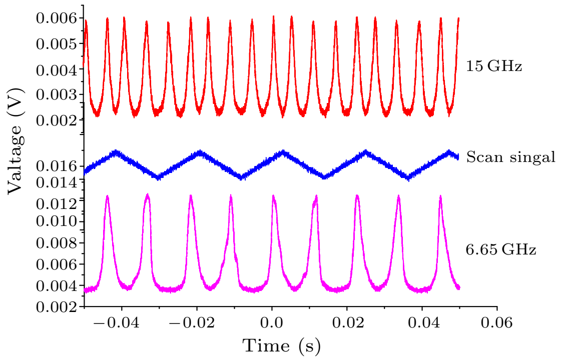

Fig. 5. The transmission signal of the filtered comb, at 15 GHz (upper, red line), at 6.65 GHz (lower, pink line) with the same reference of scanning zigzag wave (middle, blue line).

Our simulation of the transmitted signal for the filtered comb is under the condition of scanning the length of the F-P cavity by adding a zigzag wave to the PZT which was glued to one of the mirrors. When the F-P cavity resonates around a fixed length corresponding to a free spectral range (FSR) that is of integer multiples of the free spectral range of the comb source, the signal of current intensity received by the fast PD will reaches the highest. For off-resonance of the F-P cavity, the signal is nearly zero. Thus the transmitted peaks will change on the oscilloscope as the F-P length is scanned. The simulation model is based on the theory of multi-beam interferences of F-P cavity. With this model, we can get the intensity transmission function of the filtering cavity, and then combine the condition of resonance and the responding convolution of PD; the simulated peaks for the femtosecond laser pulses with bandwidth of 10 nm at the central wavelength of 780 nm in the cases of 6.65 GHz and 15 GHz are shown in Fig. 6, which are in agreement with the experimental results demonstrated in Fig. 5.

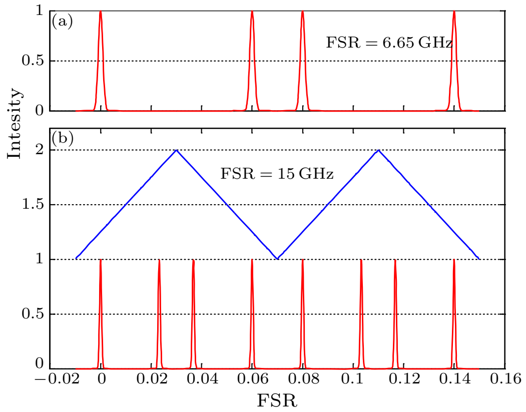

Fig. 6. The simulated transmission peaks by scanning Fabry–Pérot cavity at 6.65 GHz and at 15 GHz.

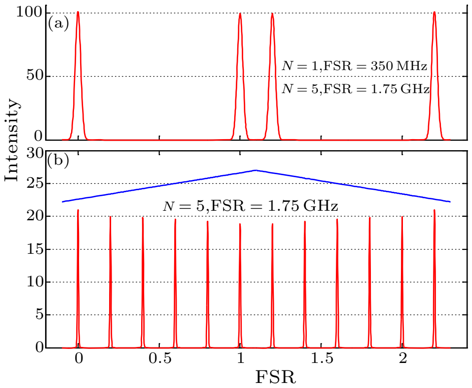

Fig. 7. The simulated transmission peaks by scanning Fabry–Pérot cavity at 350 MHz and 1.75 GHz.

Defining N as the ratio of the length of comb source and that of the F–P cavity, we can find that the number of the transmitted peaks become more as N becomes larger in the fixed scanning voltage added to the PZT, and has the relationship with the filtering ratio. For example, 15 GHz is about 2 times of 6.65 GHz, then there are two peaks in the filtered comb of 15 GHz while one peak in 6.65 GHz for the same scanning range; and it is similar for 350 MHz and 1.75 GHz, 1.75 GHz is 5 times of 350 MHz, then there are five peaks in the filtered comb of 1.75 GHz while one peak in 350 MHz for the same scanning range as Fig. 7. According to these results, we can estimate the mode-spacing of the filtered comb by counting the number of the scanning transmitted peaks observed in the oscilloscope.

In conclusion, we have demonstrated the generation of a wide spaced frequency comb by using an F–P cavity to filter the unnecessary mode lines and locking it to our homemade 350 MHz Ti:sapphire laser frequency comb. A comb with the mode-spacing from 3.5 GHz up to 15 GHz has been achieved. Our experiment shows that higher power of the filtered comb can be further obtained by using a fiber laser amplifier.

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