Active compensation of large dispersion of femtosecond pulses for precision laser ranging

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Abstract: We describe an active way of compensation for large dispersion induced in the femtosecond light pulses travelling in air for laser ranging. The pulse duration is consistently regulated at 250 fs by dispersion control, allowing sub-micrometer resolution in measuring long distances by means of time-of-flight measurement. This method could facilitate more reliable applications of femtosecond pulses for satellite laser ranging, laser altimetry and active LIDAR applications.

OCIS codes: (280.3400) Laser range finder; (230.2035) Dispersion compensation devices; (010.3640) Lidar; (120.3930) Metrological instrumentation.

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1. Introduction

Satellite laser ranging (SLR) is to determine the distance to a satellite from the ground station by means of time-of-flight measurement of light pulses [1]. Its ranging precision depends on the pulse duration of the laser transmitter employed as the light source. Early SLR systems relied on Q-switched ruby lasers with pulse duration of several tens of nanoseconds to obtain precision to a few meters. Later Q-switched Nd:YAG lasers with pulse duration of less than 10 nanoseconds began to be employed to reduce random ranging errors. Modern SLR systems tend to adopt mode-locked picosecond Nd:YVO$_4$ and Nd:YAG lasers to remove unwanted temporal biases generated due to the multi-mode nature of Q-switched lasers [2]. Even though the state-of-the-art SLR technology has already provided precision to a few millimeters, continued improvement needs to be made for the near-future missions planned to understand our planet better about the tectonic plate motion, polar wobble, variation in the Earth's rotation rate and length variation of a day [3,4]. The very start of the improvement would begin with the employment of ultrashort femtosecond (fs) pulse lasers for SLR along with the development of faster single photon avalanche photo-diodes and also accurate event timers [5].

The advent of ultrafast femtosecond pulse lasers has led to the advance of many fields of optical metrology including not only frequency/time measurements but also laser ranging [6–8]. Precision ranging using femtosecond pulses was firstly demonstrated with a scheme of synthetic wavelength interferometry in which a sequence of radio frequency harmonics of the pulse repetition rate was extracted to achieve precision to several micrometers over a distance of 240 m [9]. Following was a proposition of time-of-flight measurement using femtosecond pulses based on coherent interferometry, which claimed the possibility of attaining sub-μm precision at distances beyond 10^6 meters for next-generation space missions [10,11]. Later an advanced concept of spectrally resolved interferometry was introduced to determine long distances by analyzing the femtosecond interference signal using a diffraction grating [12,13]. This was further refined by adopting the multi-heterodyne principle combined with time-of-flight measurement using a pair of femtosecond lasers to achieve sub-micrometer precision over a 1.14 km delay length of optical fiber [14]. Recently the authors demonstrated a method of precision time-of-flight measurement using femtosecond pulses with the aid of the balanced optical cross-correlation technique, which offered an unprecedented precision level of 7 nm in measuring a distance of 0.7 km in air [15]. All these results established during the last decade are persuasive enough to validate the necessity of femtosecond lasers for long-distance laser ranging for SLR, laser altimetry and active LIDAR systems. Further, the first mobile version of femtosecond-terawatt (10^{15} W) laser, Teramobile, has proven to be able to send ultrashort pulses to an altitude of more than 20 km in the atmosphere [16], showing the availability of high power femtosecond laser sources for long-distance ranging applications.

Femtosecond light pulses used for laser ranging go through a significant pulse broadening while propagating over a long path travel in air. This pulse broadening was not a significant issue when using nanosecond or picosecond pulses. This is why atmospheric models such as Marini-Murray model generally regarded pulses as a light source of single wavelength or two-color combination [17–20]. However, in dealing with the problem of laser ranging using femtosecond pulses, these simple approaches would not be sufficient. Femtosecond pulses are usually a mode-locked combination of several hundreds of thousands of optical components spanning over a broad spectral range, resulting in a severe pulse broadening due to dispersion. This is particularly the case when a long distance is measured in the troposphere. It is therefore essential to devise a suitable means of removing or compensating for the dispersion effect precisely to take the advantage of exploiting femtosecond pulses for laser ranging. Here, in this paper, we describe an active way of compensating for large dispersion by combining a sequence of single-mode fibers along with active control of a prism pair.

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2. Temporal broadening of femtosecond pulses in air

Ultrashort femtosecond pulses tend to broaden faster and may become even longer than moderate pulses in the pico- and nano-second regime when travelling a long distance in air. Figure 1(a) shows an exemplary case in which three pulses of 10 fs, 60 fs and 1 ps temporal pulse width were compared by simulation based on the Marini-Murray model [17]. All the three pulses were assumed Fourier-transform-limited with their spectral width being 353 nm, 59 nm and 3.5 nm centered at a 1550 nm wavelength, respectively. The pulse width of the shortest pulse soon exceeds those of two other longer pulses as it experiences a larger amount of dispersion due to its wider spectrum. Femtosecond pulses are consequently no longer in the femtosecond regime soon after propagating at the most several kilometers in air. Furthermore, for SLR systems operating in the troposphere, the group delay dispersion (GDD) is found to be significantly affected by temperature and pressure as shown in Fig. 1(b) and 1(c). All these observations justify the necessity of active compensation of pulse broadening particularly when femtosecond pulses are to be employed for precision long distance measurements in air.

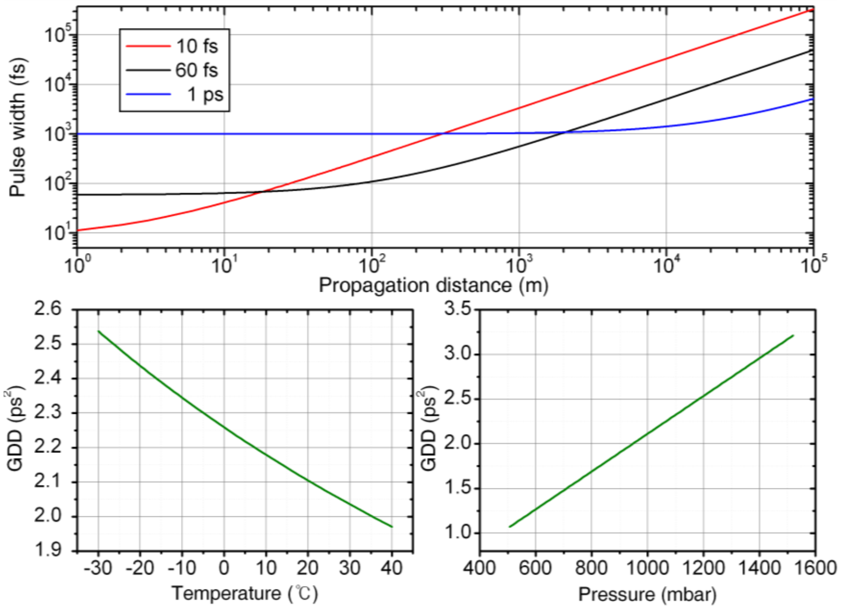

Fig. 1. Computation of temporal broadening of femtosecond pulses while propagating in air. (a) Example of pulse broadening for three different pulses. The Marini-Murray model was used with the standard environmental conditions of 15 °C, 1 atm and relative humidity of 70%. (b) Temperature-dependency of group delay dispersion (GDD). (c) Pressure-dependency of GDD.

3. Active compensation of large dispersion in femtosecond pulses

Figure 2 shows the hardware system configured to measure distances by incorporating the active control scheme devised in this investigation for compensation of large dispersion. An Er-doped femtosecond fiber oscillator (MenloSystems GmbH, C-Fiber) is used to produce ultrashort pulses of **100 fs** temporal duration. The output spectrum of the generated pulses is centered at a 1550 nm wavelength with a bandwidth of 60 nm. The pulse repetition rate is fixed at a nominal value of 100 MHz with a tunable range of ± 200 kHz. The output power is amplified to 240 mW using a home-built Er-doped fiber amplifier (EDFA). The output pulse train is collimated and passed through the dispersion management unit before being directed to the retro-reflector located at a remote distance. The returning pulse train is delivered to the autocorrelator detecting the pulse broadening induced by dispersion in the given air path. The interferometric autocorrelator measures the pulse width up to a maximum of 6 ps at an update rate of 4 Hz. Finally, the time-of-flight of the returning pulses is determined by monitoring the timing difference between the photo-detector signals of PD_{REF} and PD_{MEA} using a high resolution interval timer referenced to the Rb atomic clock. To improve the timing resolution to a sub-fs level, the balanced optical cross-correlation technique **is** utilized as described in Ref [15].

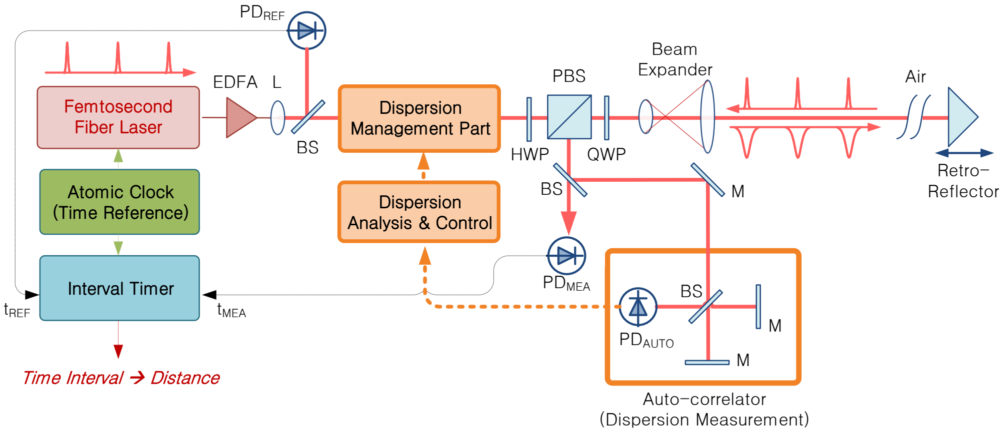

Fig. 2. Overall system configuration to measure absolute distance with active compensation of large dispersion induced in femtosecond pulses travelling a long air path.

There are several dispersion-compensation methods available for femtosecond pulses. A pair of diffraction gratings or prisms may be used for the purpose. A single chirped mirror can also perform the same function by reflecting different wavelengths from different mirror depths. However, the well-known methods offer a limited amount of dispersion compensation, being found not adequate for pulses propagated through a long path in air. Here we propose a composite scheme of dispersion management that incorporates a sequence of single-mode fibers for coarse dispersion control together with a pair of prisms for fine control as shown in Fig. 3. The material dispersion of a single-mode fiber is $-21\ ps^2/km$ (SMF, Corning, SMF-28) in the wavelength range around 1550 nm, yielding a negative chirp to compensate for the air-induced dispersion. The prism pair used here enables fine dispersion compensation in the negative direction with an amount of $0.031\ ps^2/m$ by changing the separation gap between the prisms. A motorized stage with 50 nm positioning resolution is used to control the prism gap. A large amount of dispersion is firstly compensated at a multi-channel fiber-based dispersion compensator being composed of a one-by-N optical switch, a set of single-mode optical fibers of different lengths, and an N-by-one coupler as shown in Fig. 3. The pulse train to be compensated is passed through the prism pair and reflected at a long dielectric mirror of 170 mm length. One prism moves along the connecting line between the apexes of the prisms, offering varied dispersion compensation as required. The prisms are made of SF10 and the size of the second prism (P2) is selected as large as possible to extend the amount of angular dispersion created in the current design. The incidence angle to the first prism (P1) is set at 50° with the second prism (P2) mounted on the stage to move from a nominal position of 400 mm apart from P1. The movement of P2 causes a path delay in the measurement arm, so it is traced in real time continuously through the linear- position sensor installed on the stage. Then the caused path delay would be corrected in the measured distance by time-of-flight through a lookup table that can be precisely established through a calibration process.

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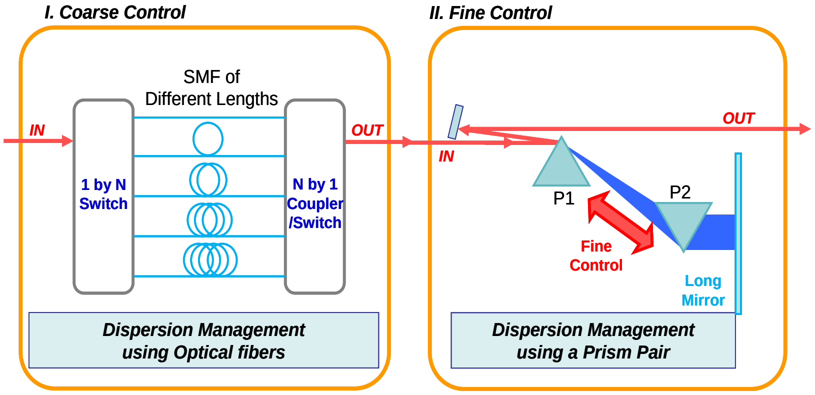

Fig. 3. Composite control scheme for compensation of large dispersion caused by air. The material dispersion of single mode fibers is used for coarse control, while the wavelength-dependent delay in a prism pair is used for fine control.

4. Experimental verification and discussions

Active dispersion compensation is to maintain the pulse duration at a pre-assigned target value consistently during time-of-flight measurement. Figure 4 shows an exemplary time trace of the controlled pulse duration over a period of 1,200 seconds with the target value set to 540 fs. Only the fine control procedure using the prism pair was activated with a control bandwidth of 5 seconds. The control bandwidth was selected in consideration of the 4 Hz sampling update rate of the autocorrelator set to measure the pulse duration. With the fine control turned on, the standard deviation of the temporal fluctuation of the measured pulse width was monitored to be 7.21 fs with a good level of reproducibility when there was no drastic disturbance in the room temperature condition.

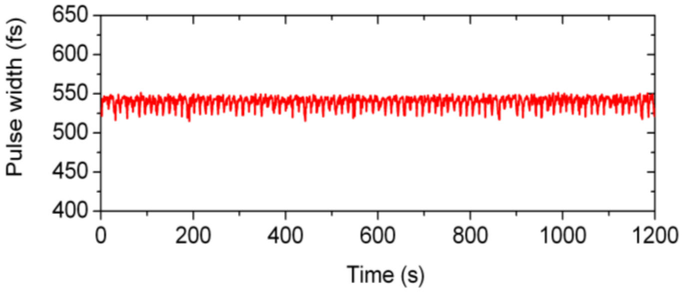

Fig. 4. Test result of active dispersion compensation obtained by controlling the separation gap of a prism pair.

Figure 5(a) shows a test result of the control locking stability obtained against a series of step-like abrupt disturbances deliberately given by inserting a glass block repeatedly in the measurement path. The glass block was made of BK7 of 1.44 refractive index with a 40 mm thickness. The amount of GDD dispersion caused by the glass insertion was measured 935 fs^2. Incoming pulses have a negative dispersion from air and the glass block tends to compensate the pulse duration, from 400 fs to 362 fs. Control of the separation gap of the prism pair stabilized the pulse duration within a fluctuation of 8.4 fs to a target value of 400 fs. At the moments of insertion and extraction of the glass block, overshoots were observed due to the limited control bandwidth due to the slow update rate of the autocorrelator. The current level of control bandwidth was however found sufficient for most cases when there are no abrupt changes of dispersion. If required, the update rate of the autocorrelator may be enhanced to several kHz simply by reducing the measurement range of the pulse duration.

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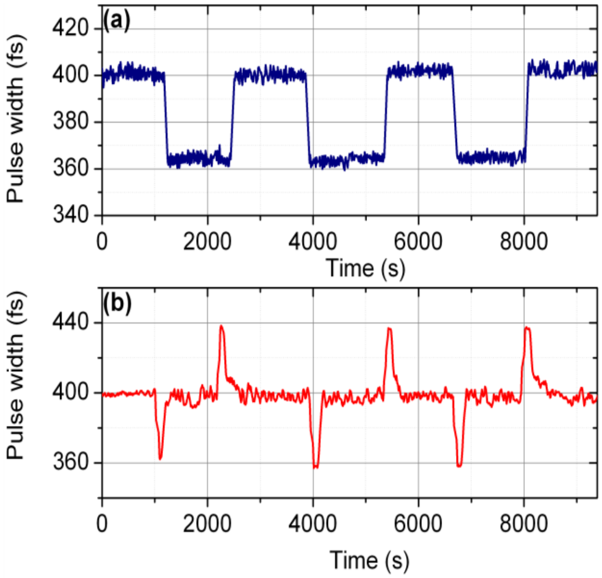

Fig. 5. Test result of the locking capability against a repeated abrupt dispersion variation introduced by inserting a glass block. (a) Step-like change of the pulse duration caused by inserting a glass block in the measurement path. (b) Controlled pulse duration to a target value of 400 fs.

Finally the whole composite control strategy to compensate for large dispersion was tested following the two-step procedure illustrated in Fig. 3. For this experimental verification, a large amount of dispersion usually encountered in a long air path was simulated by installing an optical fiber (DCF, OFS, 6801-LLWBDK) of 10 m length in the measurement arm, which was equivalent to a ~200 km long air path. Then, the course of coarse compensation was taken by selecting a single-mode fiber within the multi-channel dispersion compensator. This led to a substantial reduction in the pulse duration from ~100 ps to ~600 fs. Then the fine control of the prism gap was conducted to suppress the remaining amount of dispersion that is subject to a peak-to-valley fluctuation of 350 fs in the pulse duration due to the environmental change during 300 seconds even in the room temperature condition as shown in Fig. 6. The fine control results in a further reduction of the pulse duration to 250 fs and the standard deviation of the pulse duration was stabilized to 11 fs. This level of dispersion control suffices for enabling sub-μm precision ranging by measuring the time-of-flight of femtosecond pulses using the balanced detection of the optical cross-correlation signal [15].

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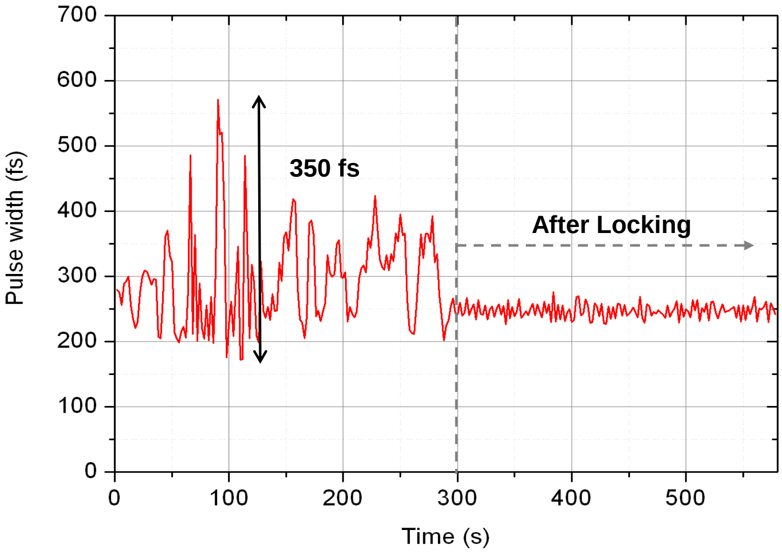

Fig. 6. Active compensation of a large amount of dispersion by combining coarse and fine adjustment. A dispersion corresponding to a 200 km propagation in air is simulated here. Firstly, a large amount of dispersion is coarsely compensated by using a single-mode fiber of ~100 m. The prism pair is then controlled to remove the rest of the dispersion in a fine manner with a target value of 250 fs.

5. Conclusions

Our active compensation scheme is effective in suppressing large dispersion of femtosecond pulses induced in air, regulating the pulse duration to be ~250 fs with a standard deviation of 11 fs. Further reduction of the pulse duration with improved stabilization could be achieved by enhancing the control bandwidth in the proposed compensation scheme of adjusting the separation gap of the prism pair. Nonetheless, the current level of dispersion compensation and active control is sufficient in attaining sub-micrometer precision in laser ranging of long distances using femtosecond pulses. This method could be applied for satellite laser ranging, laser altimetry and active LIDAR applications in the near future.

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