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# Dispersion and compensation of temporal pulse width for femtosecond pulse laser ranging

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ABSTRACT

We built an atmosphere dispersion model of femtosecond laser pulses that can calculate temporal pulse width travelling in air. The initial pulse duration of 100 fs can be broadened to 60 ps when propagating 200 km in the atmosphere. An experimental system has been established to compensate the large dispersion propagating 200 km in the atmosphere. The single model fiber (SMF) and the prism pairs were, respectively, used for coarse and fine compensation in the system. The pulse duration was consistently regulated 150 fs by moving the distance of prism pairs. This method can reach submicron resolution for a long distance by means of time of flight measurement.



## 1. Introduction

The significant developments of compactness, portability, and stability of femtosecond pulse lasers have led to the advancement of optical distance metrology in several respects [1–5]. Ultrashort femtosecond pulses have shorter pulse duration than moderate pulses in the picosecond and nanosecond regime, and therefore, femtosecond pulse laser has higher range accuracy than them. Several of the most notable techniques for measuring absolute distances are synthetic wavelength interferometry, operating with a sequence of RF harmonics of the pulse repetition rate [6], a frequency-modulated continuous wave method [7], multiple wavelength interferometry [8], dispersive interferometry by means of spectral spreading of a femtosecond pulse [9], and time-of-flight measurement with the balanced optical cross-cross-correlation technique [10]. These techniques have different range of distance from several microns to beyond $10^6$ m and accuracy from nanometer to micron.

According to the uncertainty principle, pulse duration is inversely proportional to spectral range. Thus, femtosecond pulse laser has wider spectral range than nanosecond and picoseconds pulse lasers [11]. Femtosecond light 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 while propagating over a long path travel in air due to different propagating velocity of these spectra. The broadened pulses will effect ranging accuracy. It is therefore essential to devise a suitable method to compress the broadened pulses. In this paper, we use single-mode fiber and prism pairs to compress the broadened pulses.

## 2. Atmosphere dispersion model

The spectral range of Fourier transform-limited Gaussian pulse is calculated by

$$\Delta\lambda = \frac{0.4412 n\lambda^2}{c\Delta t} \tag{1}$$

Here, $n$ is the refractive index of air at wavelength $\lambda$, $c$ is the light velocity in vacuum, and $\triangle t$ is the pulse duration.

There is an exemplary case in which the spectral range of four Fourier transform-limited Gaussian pulses of 10 fs, 100 fs, 1 ps, and 1 ns temporal pulse width are 353, 35, 3.5, and $3.5 \times 10^{-4}$ nm at a 1550 nm wavelength, respectively. Thus, the shorter the pulse duration, the wider the spectral range.

The pulse duration $T(z)$ while propagating the distance $z$ in dispersive medium can be derived by the wave differential equation:

$$T(z) = T_0\left[(1 + C(t)\beta_2 z)^2 + \left(\frac{4\ \ln 2\beta_2 z}{{T_0}^2}\right)^2\right]^{1/2} \tag{2}$$

Here, $T_0$ is the initial pulse duration, $C(t)$ is the chirp coefficient, and $\beta_2$ is the group velocity dispersion (GVD). The pulse is known as the Fourier transform-limited pulse when $C(t)$ is zero.

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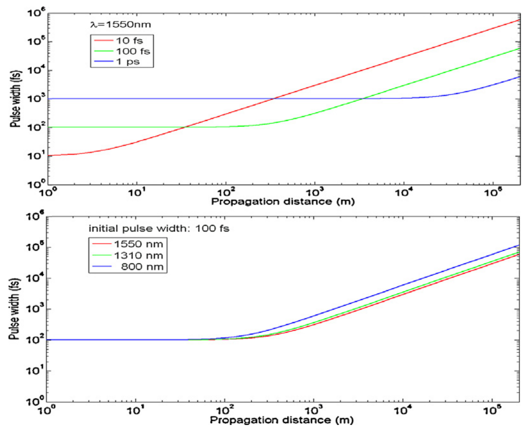


**Fig. 1.** Computation of temporal broadening of pulses while propagating in air with the standard environmental conditions of 15 °C, 1 atm, and relative humidity of 70%. (a) Example of pulse broadening for three different temporal pulse widths with the same wavelength. (b) Example of pulse broadening for three different wavelengths with the same temporal pulse width.

The GVD is related by

$$\beta_2 = \left(\frac{\lambda^3}{2\pi c^2}\right)\left(\frac{d^2 n}{d\lambda^2}\right) \tag{3}$$

In the Marini–Murray model [12], the refractive index $n$ of air can be expressed as the form of

$$n = 1 + 10^{-6}\left[\left(287.604 + \frac{1.6288}{\lambda^2} + \frac{0.0136}{\lambda^4}\right) \times \left(\frac{P}{1013.25}\right)\left(\frac{1}{1+0.003661 t_{\mathrm{atm}}}\right) - 0.055\left(\frac{760}{1013.25}\right)\left(\frac{e}{1+0.00366 t_{\mathrm{atm}}}\right)\right] \tag{4}$$

Here, $P$ is the atmospheric pressure in millibar, $e$ is the partial water vapor pressure in millibar, and $t_{\mathrm{atm}}$ is the temperature in degrees Celsius. In Eq. (4), the relation between the refractive index of air and the wavelength of light is given.

Thus, the temporal pulse width while propagating a certain distance in dispersive medium can be calculated by Eqs. (2)–(4).

From Eq. (2), the temporal pulse width is found to be mainly affected by the group delay dispersion (GDD).

Fig. 1a shows an exemplary case in which three pulses of 10 fs, 100 fs, and 1 ps temporal pulse width with the same 1550 nm wavelength were compared by simulation based on Eqs. (1)–(3). Fig. 1b shows an exemplary case in which three pulses of 1550, 1310, and 800 nm wavelength with the same 100 fs temporal pulse width were compared. The pulse width of the shortest pulse would exceed those of two other longer pulses after propagating a certain distance as its wider spectrum leads a larger amount of dispersion, thus the shorter the pulse width, the larger the dispersion, and femtosecond pulses are no longer in the femtosecond regime after propagating at the most several kilometers in air (Fig. 1a). The shorter the laser wavelength, the larger the dispersion, thus the longer wavelength laser is first considered as the actual application (Fig. 1b).

## 3. Scheme of dispersive compensation

The femtosecond fiber laser (PolarOnyx) is used to produce ultrashort pulses of 100 fs pulse width with the pulse repetition rate of 100 MHz and the maximum output power of 100 mW at a 1550 nm wavelength. It is very difficult to achieve a long air propagation (about 200 km) in the laboratory, so we use the dispersion compensation fiber (DCF) with a positive GVD to simulate the positive atmosphere GDD about 200 km long air path. Then the SMF of the negative GVD is used to compensate the positive atmosphere GDD. This led to a substantial reduction in the pulse duration. The length of SMF is selected based on the propagating distance of femtosecond pulses in the atmosphere. Then the dispersion amount can be finely adjusted within a smaller range by moving the step motor along the connecting line between the apexes of the prisms with the prism (P2). After SMF and prism pairs compensating the dispersion, the autocorrelation curve is measured by the autocorrelator. The voltage signal of autocorrelation data is obtained by the data acquisition card and send to the computer, and the peak number of half-width of autocorrelator curve is calculated by the computer in real time, and then the pulse width $T$ is worked out as $T = (n-1)\lambda/ck$, where $n$ is the peak number of half-width of autocorrelator and $k$ is the autocorrelator coefficient (see Fig. 2). The key question is how to control the distance that the step motor moves to reach the pre-assigned target pulse width value (150 fs). Here Eq. (2) is changed as

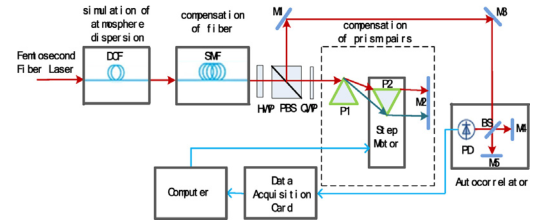


**Fig. 2.** Scheme of compensation of dispersion with the real-time capabilities.

$$T_r = T_0\left[\left(1 + C(t)(\beta_{\mathrm{DCF}} z_{\mathrm{DCF}} + \beta_{\mathrm{SMF}} z_{\mathrm{SMF}} + \beta_{\mathrm{P}} z_{\mathrm{P}})\right)^2 + \left(\frac{4\ \ln 2(\beta_{\mathrm{DCF}} z_{\mathrm{DCF}} + \beta_{\mathrm{SMF}} z_{\mathrm{SMF}} + \mathrm{GDD_P})}{{T_0}^2}\right)^2\right]^{1/2} \tag{5}$$

$$T_d = T_0\left[\left(1 + C(t)(\beta_{\mathrm{DCF}} z_{\mathrm{DCF}} + \beta_{\mathrm{SMF}} z_{\mathrm{SMF}} + \beta_{\mathrm{P}} z'_{\mathrm{P}})\right)^2 + \left(\frac{4\ \ln 2(\beta_{\mathrm{DCF}} z_{\mathrm{DCF}} + \beta_{\mathrm{SMF}} z_{\mathrm{SMF}} + \mathrm{GDD'_P})}{{T_0}^2}\right)^2\right]^{1/2} \tag{6}$$

where $T_r$ is the real-time pulse width that is calculated by the computer, $T_d$ is the pre-assigned target pulse width, and $T_0$ is the initial pulse width of laser.$\beta_{\mathrm{DCF}}$ and $\beta_{\mathrm{SMF}}$ are, respectively, the GVD of DCF and SMF. $z_{\mathrm{DCF}}$ and $z_{\mathrm{SMF}}$ are, respectively, the length of DCF and SMF.$\mathrm{GDD_P}$ and $\mathrm{GDD'_P}$ are, respectively, the group velocity dispersion before moving the prism pairs and after moving it.

According to Fork's approximation about prism pairs dispersion [13]:

$$\mathrm{GDD_P} \approx \frac{\lambda^3}{2\pi c^2}[1.0354 - z_{\mathrm{P}}(7.48\times10^{-3})], \quad \text{and}$$

$$\mathrm{GDD'_P} \approx \frac{\lambda^3}{2\pi c^2}[1.0354 - z'_{\mathrm{P}}(7.48\times10^{-3})]$$

where $z_{\mathrm{P}}$ is the distance of the connecting line between the apexes of the prisms before the step motor moving. $z'_{\mathrm{P}}$ is the distance of the connecting line between the apexes of the prisms after the step motor moving.