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ZERO-DISTANCE PULSE FRONTS OF STRETCHER AND ITS OPTICAL SYSTEM

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Zero-distance Pulse Fronts of a Stretcher and its Optical System

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Abstract

A two-grating stretcher is a dispersion delay line that is widely used in chirped pulse amplification for ultrafast laser pulses. If the stretcher consists of two reflecting diffraction gratings with a perfectly reflective optical system between them, its dispersion can be calculated by using the concept of a ‘‘zero-distance pulse front.” We introduce the concept of a ‘‘zero-distance pulse front” of the real optical system, which characterizes its aberrations. The similarity of these zero-distance pulse fronts allows us to study the influence of aberrations in an optical system on the dispersion of a stretcher.

1. Introduction

It is known that the shorter the light pulse is the greater is the influence of the dispersion on its duration. Therefore, the optics of ultrashort pulses (USPs) has a specific field of research, namely dispersion delay lines (DDLs), which allow managing the duration of the pulses in a reversible fashion [1].

DDL is characterized by the group delay τ of the wavelength λ. If the function $\tau(\lambda)$ is strictly increasing, then dispersion is negative and the corresponding DDL is a compressor [2,3]. If the function $\tau(\lambda)$ is strictly decreasing, then dispersion is positive and the corresponding DDL is a stretcher [4,5].

The damage threshold for reflective optical elements is much greater than that for optical media. Therefore, DDLs for super-powered USPs are usually made from only reflective optical elements, such as mirrors and reflection diffraction gratings. If DDL is made from only reflective optical elements then inside of it all monochromatic wave components and the USP as a whole run in free space with the same speed, the speed of light in vacuum c. Therefore, its group delay $\tau(\lambda)$ equals its phase delay $T(\lambda)$ which is directly proportional to the path length p of the corresponding monochromatic ray:

$$T(\lambda) = p(\lambda)/c.$$

In future, instead of the phase or the group delay of reflection DDL, we will simply speak about its time delay. In „natural“ system of units c = 1, so the time delay is just the path length:

$$T(\lambda) = p(\lambda).$$

2. Technique of the zero-distance front

In free space light rays travel along straight lines but optical elements fold the paths of the light rays. A straight line is the simplest geometrical curve. There are a lot of different unfolding techniques, e.g. the technique of the zero-distance front.

2.1. Zero-distance pulse front of compressor

Treacy’s system consists of a pair of identical reflection gratings arranged parallel [2,3]. The first grating splits an incident polychromatic ray into a diverging homocentric beam of spectrally colored rays. According to the reversibility principle the second grating transforms this beam into a parallel beam of rays, the so-called “spatial chirp” of Treacy’s system. The position of a monochromatic ray in the spatial chirp depends on its wavelength, so the cross section of the spatial chirp can be used as a natural non-uniform wavelengths scale $\Delta\xi(\lambda)$.

A ray of the spatial chirp can be continued in its reverse direction to a point F^*, where points F^* and F are equidistant from point M:

$$|F^*M| = |MF|.$$

The set of points $\{F^*\}$ is a “zero-distance pulse front of Treacy’s system” [6] (Fig.1).

Let the reference plane of Treacy’s system be a plane passing through point F and perpendicular to the input ray. The time delay T^{Tr} of Treacy’s system for the monochromatic component is equal to the path length from point F^* to point $M_\perp$ of the reference plane:

$$T^{\mathrm{Tr}} \equiv |F^*M_\perp| .$$

The “zero-distance pulse front” in the “coordinate system of the time delay T^{Tr} vs the displacement $\Delta\xi(\lambda)$” is the natural characteristic of Treacy’s system. This characteristic is a strictly increasing function. Therefore, Treacy's system has a negative dispersion.

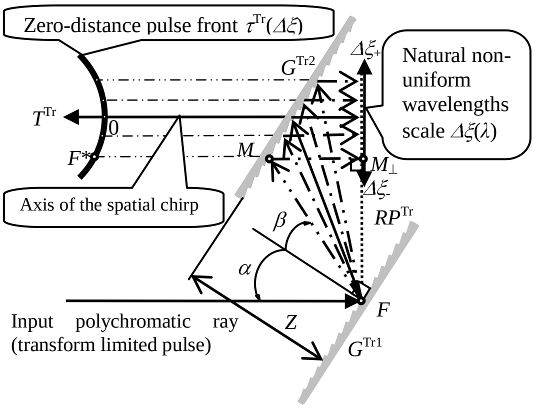

Fig. 1. Treacy's system and its zero-distance pulse front $T^{Tr}(\Delta\xi)$ in the "coordinate system of the time delay T^{Tr} vs the displacement $\Delta\xi(\lambda)$". The red ray is shown by the double dash-and-dot line and the blue ray is shown by the dash-and-dot line.

According to the reversibility principle if two Treacy's systems are arranged back-to-back (Fig. 2a) then this system turns an input polychromatic ray caring a transform-limited pulse into an output polychromatic ray caring a pulse with a negative dispersion, the so-called "down-chirp". This system is a compressor. Its relative time delay is a double relative time delay of a single Theacy's system. Because of the mirror symmetry this compressor is equal to a single Theacy's system with a retro-mirror (Fig. 2b).

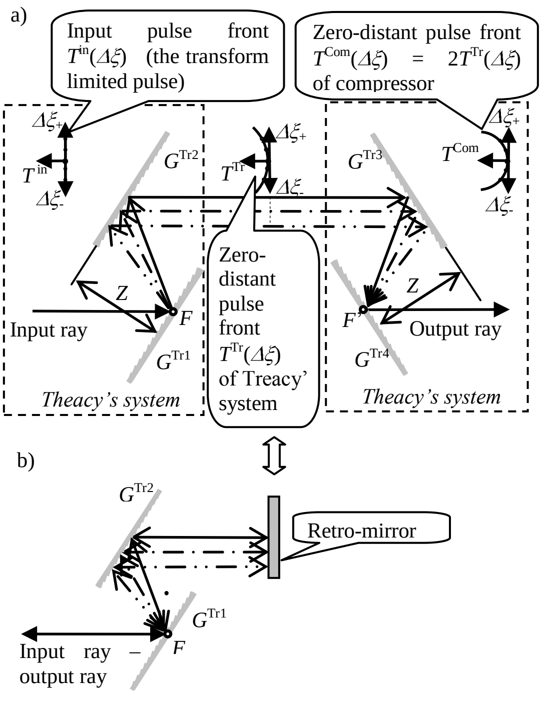

Fig. 2. Four-grating compressor a). Two-grating compressor with the retro mirror b).

2.2. Zero-distance pulse front of stretcher with perfect optical system

Martinez's system consists of a pair of identical reflection gratings and a mirror optical system with unit magnification between them (Fig. 3a) [4,5]. Let points *Q* and *Q*' be optical conjugate on-axis points of the optical system. The first grating G^{Mar1} splits an input polychromatic ray into a diverging homocentric beam of spectrally colored rays. The perfect optical system turns this beam into a mirror symmetrical converging homocentric beam. According to the principle of reversibility, the second grating G^{Mar2} turns the convergence beam into an output polychromatic ray which is mirror symmetrical to the input polychromatic ray [7,8].

Let us shift the second grating G^{Mar2} along the optical axis (Fig. 3b). The incident angle β is preserved, so the second grating G^{Mar2} transforms the converging homocentric beam into a parallel beam of monochromatic rays, the so-called "spatial chirp" of Martinez's system. The position of the monochromatic ray in this spatial chirp depends on its wavelength, so the cross section of the spatial chirp $\Delta\xi\,(\lambda)$ can be used as a natural non-uniform wavelengths scale λ.

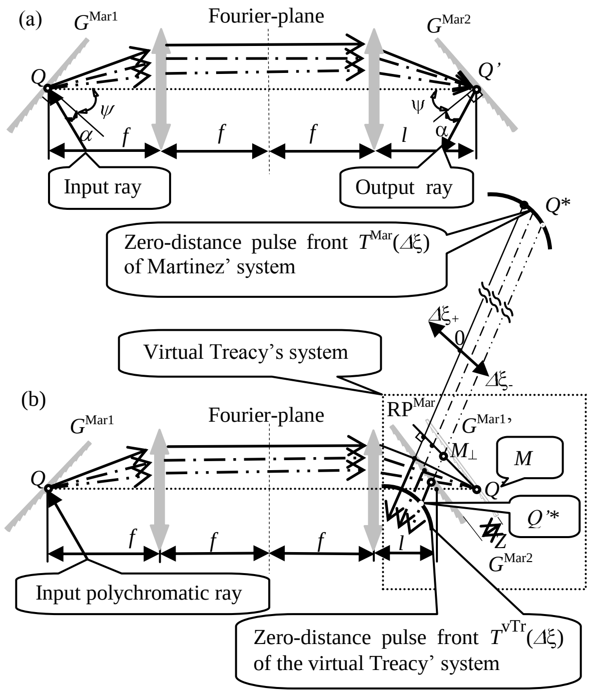

Fig. 3. Mirror-symmetric optical system ($l = f$) (a), Martinez's system as an imaging perfect optical system with a minus unit linear magnification ($l < f$) and its zero-distance pulse front (b).

The ray of the spatial chirp can be continued in its reverse direction to a point *Q**, where points Q and $Q*$ are equidistant from point M (Fig. 3b):

$$|Q{*}M| = |QM|.$$

The set of points $\{Q*\}$ can be called a "zero-distance pulse front" of Martinez's system [9].

In the image space of a perfect optical system the second grating G^{Mar2} and the image of the first grating $G^{\prime Mar1}$ form a virtual Treacy's system with the reference plane RP^{vTr}, the zero-distant pulse front, and the time delay which is the path length from the point $Q'*$ to the point $M_\perp$ of the reference plane (Fig. 3b):

$$T^{vTr} \equiv |Q'{*}M_\perp| .$$

If the reference plane of the virtual Treacy's system is accepted for a reference plane RP^{Mar} of Martinez's system, then the time delay of Martinez's system T^{Mar} is directly proportional to the path length $|Q{*}\,M_\perp|)$. The "zero-distance pulse front" in the coordinate system of the time delay T^{Mar} vs. the displacement $\Delta\xi(\lambda)$ is the natural characteristic of Martinez's system. Note that the time delay of Martinez's system T^{Mar} is equal to the time delay of the perfect optical system $T_o=R/c$ minus the time delay of the virtual Treacy's system $T^{vTr.}(\Delta\xi)$ (the path length $|Q'{*}M_\perp|$) [9]:

$$T^{Mar}(\Delta\xi) = T_o - T^{vTr.}(\Delta\xi).$$

So Martinez's system has a positive dispersion.

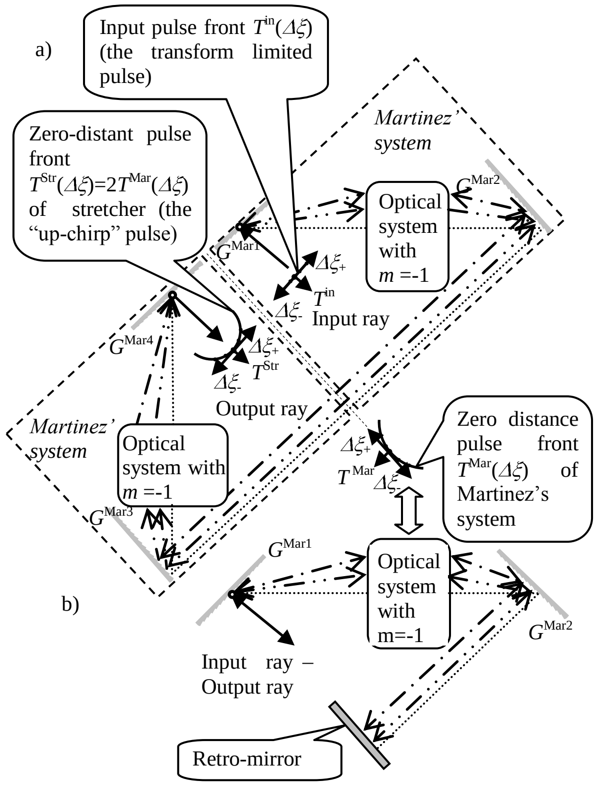

Fig. 4. Four-grating stretcher a). Two-grating stretcher with the retro mirror b).

According to the reversibility principle if two Martinez's systems are arranged back-to-back (Fig. 4a) then this system turns an input polychromatic ray caring a transform-limited pulse into an output polychromatic ray caring a pulse with a positive dispersion, the so-called "up-chirp". This system is a stretcher. Its relative time delay is a double relative time delay of a single Martinez's system. Because of the mirror symmetry this stretcher is equal to a single Martinez's system with a retro-mirror (Fig. 4b).

2.3. Zero-distance pulse front of a real optical system of a stretcher

Let us consider a real optical system (Fig.5). The real optical system transforms a broad diverging homocentric beam of rays from the object point Q into a converging non-homocentric beam having a "break-shaped" envelope with the top at the image point Q'. Continue the straight ray from a point A of the caustic in its reverse direction to the point $q^{\#}$, where points Q and $q^{\#}$ are equidistant from the point A (Fig. 5a):

$$[q^{\#}, M](u') = \mathrm{OPL}[Q,A](u').$$

The set of points $\{q^{\#}\}$ is a "zero-distance phase front of the optical system". Note that the "zero-distance phase front of a perfect optical system" $\{Q^o\}$ is a circle with the radius $R = cT_o$, the so-called a "reference sphere".

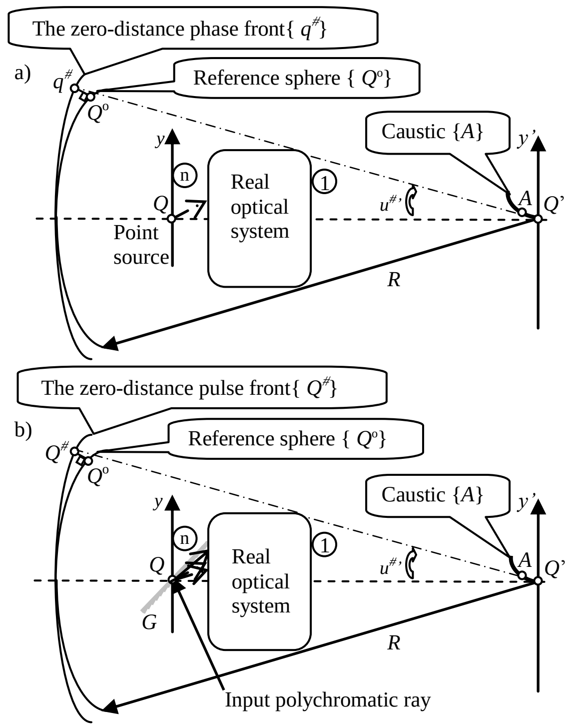

Fig. 5. (a) The zero-distance phase front of an optical system $\{q^{\#}\}$ and its wave aberration $|Q^o q^{\#}| \approx |q^{\#}Q'| - R$. (b) The correspondent zero-distance pulse of the optical system $\{Q^{\#}\}$ and its wave aberration $|Q^o Q^{\#}| \approx |Q^{\#}Q'| - R$.

The difference between the zero-distance phase front of the real optical system and the reference sphere is its wave aberrations function $W(u')$:

$$W(u') \equiv [q^{\#}, A](u') - R.$$

Note that a diffraction grating G illuminated by a thin polychromatic light ray can act as a point source of radiation (Fig. 5b), but diffracted rays of this point source are not coherent and have different frequencies, so they cannot interfere. In this case, the term "zero-distance phase front of the optical system" $\{q^{\#}\}$ should be replaced with the term "zero-distance pulse front of the optical system" $\{Q^{\#}\}$. In a reflective optical system, the zero-distant pulse front and the zero-distant phase front are the same.

2.4. *Zero-distance pulse front of stretcher with real optical system*

Note that a real optical system of the stretcher can be replaced by its zero-distance phase front (Fig. 6). The time delay of Martinez's system T^{Mar} (the path length $|Q^{\#} M_{\perp}|$) is equal to the time delay of the perfect optical system $T_o=R/c$ plus the wave aberration function of the real optical system $W(\Delta\xi)/c$ minus the time delay of the virtual Treacy's system $T^{vTr.}$ $(\Delta\xi)$ (the path length $|Q'^{*}M_{\perp}|$):

$$T^{Mar}(\Delta\xi) = T_o + W(\Delta\xi)/c - T^{vTr.}(\Delta\xi) .$$

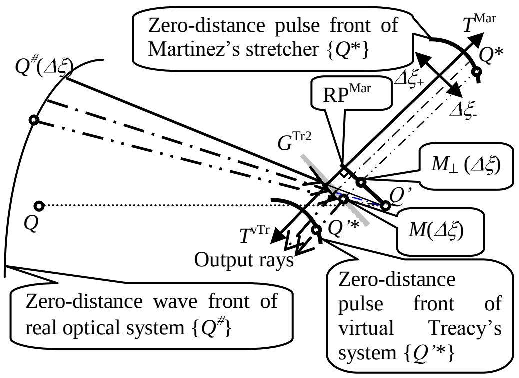

Fig. 6. Relationship between the zero-distance pulse front of Martinez's system $\{Q^*\}$, the zero-distance pulse front of its optical system $\{Q^{\#}\}$, and the zero-distance pulse front of virtual Treacy's system $\{Q'^*\}$

.Conclusion

-The concept of ''zero-distance pulse front" provides a new way of representing the dispersion of compressor, stretcher and the aberrations of the stretcher optical system in a pictorial manner.

-The similarity of the zero-distance pulse fronts of the stretcher and its optical system allows us to take into account the aberrations of the optical system while calculating the dispersion of the stretcher.

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