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Theoretical and experimental studies on single tiled grating pulse compressor

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ABSTRACT

A tiled grating pulse compressor in a single grating configuration has been investigated. Since it is a folded geometry, there are several geometrical constraints that restrict hard-clip-free recompression of positively chirped pulses. Therefore, the parametric space allowed by the geometrical constraints has been worked out for three geometries. In contrast to other pulse compressor designs, owing to the fact that it involves only one tiled optical surface, the present design has advantages of compact geometry, reduced cost, ease of alignment, and easier maintenance for long term stability. Compression of positively chirped laser pulses of ~250 ps duration to 350 fs has been experimentally demonstrated.

1. Introduction

There has been a great interest in generation of high energy, high power, ultra-short pulse laser beams [1,2] for a variety of scientific and industrial applications. Chirped pulse amplification (CPA) [3–6], wherein an ultra-short pulse is first stretched in time, amplified, and then recompressed, has been the key in generation of high energy, ultra-short laser pulses, either using the standard multi-pass laser amplifiers or using optical parametric chirped pulse amplification (OPCPA) [7–10]. A pulse compressor [11] is a crucial part of any CPA or OPCPA based laser system, and is used to recompress the amplified stretched pulse back to the minimum achievable pulse duration limit. For the recompression of high energy laser pulses, one needs a large aperture compressor [12,13], to avoid damage of the compressor gratings. Since the size and the damage threshold of a compression grating are limited, high energy pulse compression remain a practical challenge in any pulse amplification technique. Typical gold coated pulse compressor gratings have a damage threshold in the range 200–300 mJ/cm^2 and the size is limited to approximately 50 cm. The use of large size monolithic compression grating may be avoided in segmented or tiled array of smaller size gratings [14–17]. In a segmented or tiled grating compressor system, gratings with smaller dimensions are coherently tiled together with sub-wavelength accuracies, to mimic a large size monolithic grating. However, there remains a practical challenge to align the tiled optical surfaces and keep them aligned to sub-wavelength accuracies. This is due to the large number of degrees of freedom of motion (translational and rotational) in the system and the corresponding phase errors result in poor temporal pulse compression and focused beam quality [18]. Classically, a high energy pulse compressor deploys two parallel gratings in single [19] or double pass [20] geometry. In literature, several pulse compressor designs have been reported such as (a) single grating pulse compressor [21,22], (b) double grating compressor in diamond geometry [23], (c) triple grating pulse compressor in triangular geometry [24], and (d) unfolded four grating pulse compressor in linear geometry [19]. Each design has its own advantages and disadvantages in terms of design parameters and their performance characteristics. For instance, a compressor design involving more number of gratings poses a technological challenge for their alignment. It would be interesting, if one could use only one tiled surface in a compressor, to have reduced cost, size, and easier maintenance of the compressor. Single grating pulse compressor geometry may provide an alternative solution. However, due to its folded design, it might be difficult to use it for compression of laser pulses of larger beam size and compression factor, due to physical clipping of the laser beam by various optical elements of the single grating compressor.

In this paper, we report theoretical and experimental investigations on tiled single grating pulse compressor. The allowed parametric space, i.e. beam sizes and corresponding compression lengths for given grating and pulse parameters, have been calculated for three different geometries of single grating pulse compressor. Experimental demonstration has been carried out to compress ~250 ps positively chirped laser pulses from Nd:fluorophosphate femtosecond laser oscillator-Martinez pulse stretcher combination down to ~350 fs.

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2. Formulation for parametric space for single grating pulse compressor

In this section, we present formulation for three different geometries of single grating based pulse compressor as depicted in Fig. 1. These are referred to as GI, GII and GIII. In general, any pulse compressor design shall have minimum and maximum geometrical length responsible to add dispersion to incident pulse and shall be governed by grating size and geometrical arrangement of gratings and other optical elements if any, for a given beam size. While conventional two parallel grating pair compressor shall have more range on compression length, the folded geometries shall have more restriction on allowed range on compression length mainly due to folded configuration. We formulate simple geometrical expression for compression length for above three geometries i.e. GI, GII and GIII. These expressions are also valid even in the case of multi-segmented gratings.

2.1. Geometry GI and GII

A finite beam size (beam diameter of D_b) is allowed to incident on one extreme end of grating, which diffracts on to one of the mirror of horizontal retro reflector (HRR) as shown in Fig. 2. The diffracted beam in horizontal plane, eventually diverted back on other extremity of the grating with the help of second mirror (kept at 90° to first mirror) of the horizontal retro reflector. In present case, the angle of incidence on first hit at grating is considered to be α, while the diffraction angle is β. The angle of diffraction becomes angle of incidence on the second hit on the grating. And hence the diffracted beam on second hit becomes a collimated beam with spatial chirp. The spatial chirp of the laser beam is avoided by traversing the grating-horizontal retro mirror again using an additional vertical retro mirror as shown in Fig. 1. The grating is considered to have a width of W and height H. The angular dispersion $\delta\beta$ can be determined using simple grating equation $\sin\alpha+\sin\beta=N\times\lambda$, where N is the groove density and λ is the wavelength of laser radiation. This optical arrangement is same as that in the case of conventional two parallel gratings compressor but the use of horizontal retro reflector is avoided in conventional compressor as second hit appears on a second grating, which is kept parallel to the first one. The dispersion characteristic of the single grating pulse compressor is therefore similar to the parallel grating pulse compressor. Hence, the stretching or compression defined as stretched pulse duration divided by the product of spectral bandwidth and stretching/compression length (sec/m^2) for a stretcher or compressor geometry may be given as

$$\frac{d\tau}{d\lambda}=\frac{2N^2\lambda_0 L}{c\cos^2\beta} \tag{1}$$

where λ_0 is the central wavelength, c is speed of light and L is effective single pass compression length and defined as path traveled by the laser beam between first and second hit on the grating. Corresponding to Fig. 2, L equals to sum of various path segments AB, BC, CD, DE and EF. From simple geometry, one may estimate the effective beam size (D'_b) along dispersion plane after the second hit on grating as

$$D'_b=D_b+\frac{\cos\alpha}{\cos\beta}L\delta\beta \tag{2}$$

In order to allow a clip-free propagation of the laser beam through the compressor, the grating size (width and height) should be large enough to accommodate two hits of the beam. These constraints may be expressed as

$$\frac{(D_b+D'_b)}{\cos\alpha}\le W \tag{3}$$

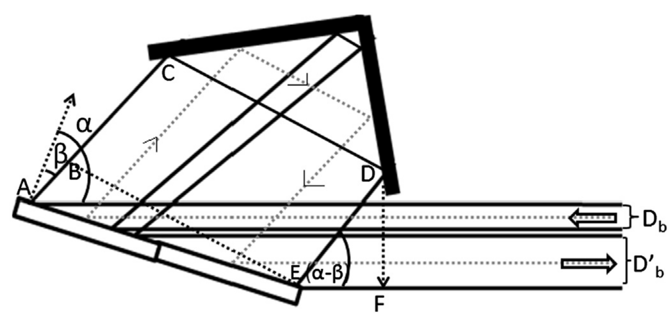

Fig. 2. Geometrical description for compressor geometries GI and GII.

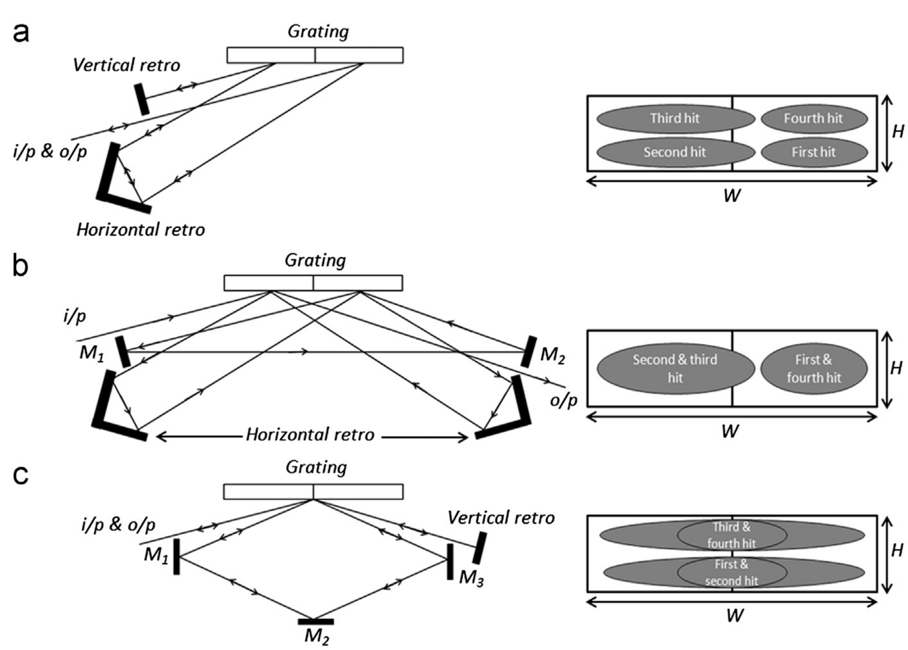

Fig. 1. Compressor geometries of single grating pulse compressor: (a) Geometry GI, (b) Geometry GII, and (c) Geometry GIII. Various laser beam hits are also depicted in respective geometries.