Chirped pulse amplification: review and prospective from diffractive optics [Invited]

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It is well-known that the chirped pulse amplification (CPA) technique won the award for the 2018 Nobel Prize in Physics to Mourou and Strickland. The compression and stretching using gratings is the essence of the CPA technique for amplifying femtosecond laser pulses. It seems the public is less aware that there are also other structures for compression and stretching of femtosecond laser pulses using other diffractive gratings, such as doubled-density gratings and deep-etched gratings. Therefore, from the view of diffractive optics, the CPA technique is reviewed with different approaches and experimental implementations that are not only useful for a more comprehensive retrospective overview of CPA, but also for the prospective of the CPA technique, which might lead us to new areas of picometer and femtometer optics in the future.

Keywords: chirped pulse amplification; femtosecond; diffractive gratings.
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1. INTRODUCTION

Since the release of the half-prize of the 2018 Nobel Prize in Physics given to Mourou and Strickland, there have been lots of articles to elucidate on the chirped pulse amplification (CPA) technique from other laser physicists. Laser physicists applauded the CPA for winning the Nobel Prize, since the world's most powerful femtosecond laser systems are built based on the CPA technique.

What is the CPA technique? The CPA technique means a short pulse from oscillator will first be stretched using a grating to a longer pulse extended in time, then the longer pulse will be amplified through a solid-state amplifier, and finally the amplified longer pulse will be compressed back to a short pulse in time by another grating; therefore, its intensity might be amplified to be extremely high, as shown in Fig. 1. Without the CPA technique, amplified femtosecond laser pulses could easily damage solid devices due to their extremely high power and energy.

It is well-known that most articles explaining the CPA technique as the 2018 Nobel Prize work of Strickland and Mourou cited their publication that was in *Optics Communications* in 1985[1]. But, few have noticed their work from the view of diffractive optics, i.e., how CPA is using gratings for compression and stretch, which has been mentioned in this paper: "The stretched pulse is amplified and then compressed by a double grating compressor[2]." In fact, it is Treacy's paper[3] that states clearly that a double grating compressor has been reported to compress the stretched pulse before.

It is no doubt that Mourou and Strickland are recognized as the inventor of the CPA technique. Here, we would like to know more about the CPA technique for a more complete overview from diffractive optics. It should be noted that Treacy[3] made a statement in his 1969 paper, "the grating pair can thus be used to compress optical chirped pulses or to generate chirped pulses out of unchirped pulse." Thus, we know, before Mourou and Strickland's invention of CPA in 1985, from a diffractive optics view, a pair of gratings was introduced to compress the optical chirped pulse in 1969. This is a more complete review to elucidate on the CPA technique to the public.

In fact, there are more approaches and structures developed for stretching and compression of the femtosecond laser pulse[2,4]. A few other approaches, such as using Dammann gratings, deep-etched gratings, and doubled-density gratings, have not been summarized before. It is the aim of this paper to review CPA from the view from Dammann gratings, doubled-density gratings, and deep-etched

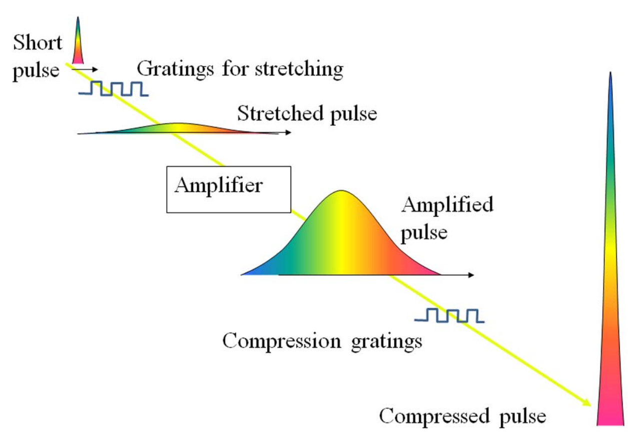

Fig. 1. CPA technique using a pair of gratings to stretch and compress the femtosecond laser pulses between them that are amplified; then, the extremely high laser pulses are obtained after being compressed.

gratings to illustrate other stretching and compression works related with the CPA technique.

Here, we would like to summarize a few other approaches related with the CPA above: (1) Dammann grating pairs for splitting femtosecond laser pulses[5]; (2) doubled-density grating pairs for compression of femtosecond laser pulses[6]; (3) deep-etched gratings for compression of femtosecond laser pulses[7]. In addition to using gratings, there are also other approaches for splitting, multiple pulse generation, and measurement[8] of femtosecond laser pulses.

2. DAMMANN GRATINGS FOR SPLITTING

Let us first review the splitting of femtosecond laser pulses using Dammann gratings and its compensation gratings[5]. The Dammann grating is a binary phase grating whose phase transitional points are modulated to generate multiple equal-intensity spots in the far field. If one Dammann grating is used, the femtosecond laser pulse will be split into multiple spots with equal intensity; however, each diffractive order will have different angular dispersions, so that the diffractive spots split by a Dammann grating will become more elliptical when it travels a longer distance. One simple way to compensate this angular dispersion is to use another compensation grating to collimate the diffractive beam into a circular beam without angular dispersion, which is shown in Fig. 2. We can also say that each diffractive-order beam with angular dispersion compensated by another corresponding compensation grating can be regarded as one CPA beam with a grating pair, different diffractive-order angular dispersion requires different-density compensation gratings, in this way, all diffractive-order beams can be compensated, and parallel circular multiple beams can be obtained.

3. DOUBLED-LINE DENSITY GRATINGS

Another way to compress the femtosecond laser pulse is to use doubled-density gratings[6], as shown in Fig. 3.

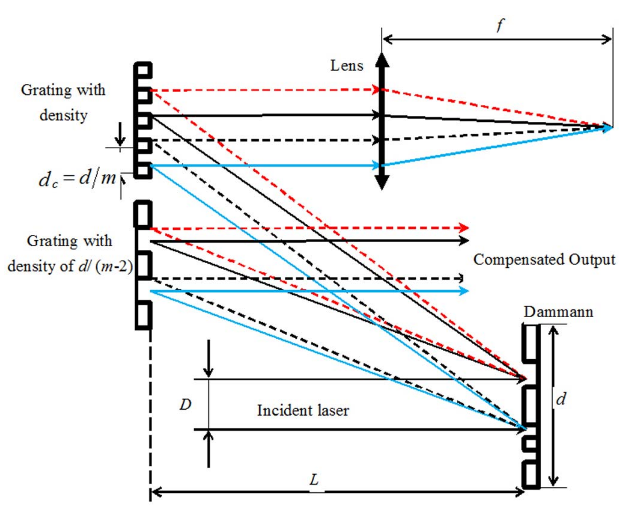

Fig. 2. Dammann grating can split the input femtosecond laser into multiple beams with compensation gratings for each diffractive order.

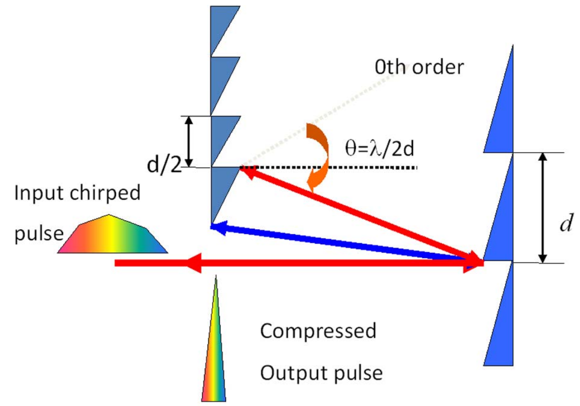

Fig. 3. Doubled-density gratings for compression of femtosecond laser pulses.

Here, the doubled-density gratings mean that the second grating with a marked period of $d/2$ has a doubled density compared with the first diffractive grating with period of d, and both of the gratings stand in parallel. The first grating will diffract the incident laser beam into the diffractive order, which will touch on the second grating. Since the second grating's density is doubled compared with the first grating, the diffraction angle by the second grating will be doubled, because the diffraction angle is reverse to the line density of grating. Therefore, the diffracted beam from the second grating will return back to the first grating, and the returned beam will be diffracted again by the first grating back as the output beam. If the incident beam has positive chirped dispersion, and these doubled-density gratings provide negative dispersion, then the reflected output beam will be a compressed pulse, as shown in Fig. 3.

4. DEEP-ETCHED GRATINGS

We can also use a pair of deep-etched gratings[7] for compression of femtosecond laser pulses. Here, deep-etched gratings mean that the depth of the etched grooves of a high-density grating has an optimized value so that the etched grating has a high efficiency at the −1 diffractive order. Normally, deep-etched gratings have a high density so that they have a strong capability of large angular dispersion. Therefore, a small-sized, deep-etched-gratings compressor can compress the chirped pulses, as compared to the prism compressor, as shown in Fig. 4. For example, the laser pulse from one commercial oscillator can be compressed by using a normal prism-pair compressor with size of 55 cm in Fig. 4. When the doubled-line density grating pair in Fig. 4 is used, its size might be reduced to 250 mm, roughly half the size compared with the oscillator of the prism pair at the top of Fig. 4. If deep-etched fused silica gratings are used, its size will be reduced to be smaller than 5 mm, which means roughly 100-times smaller than the prism compressor at the top of Fig. 4.

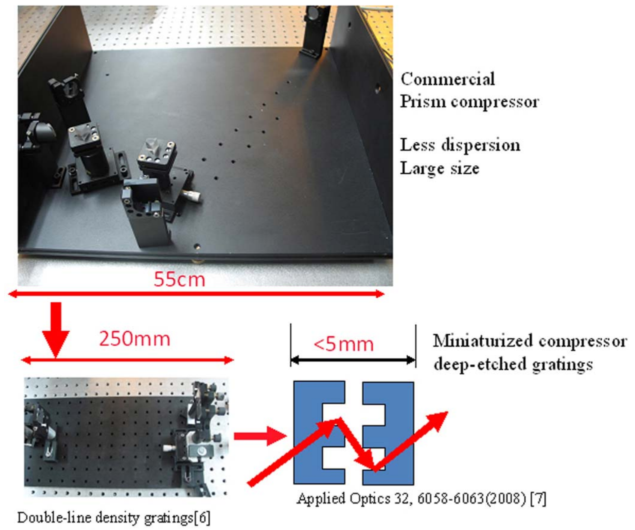

Fig. 4. Deep-etched gratings for compression of femtosecond laser pulses.

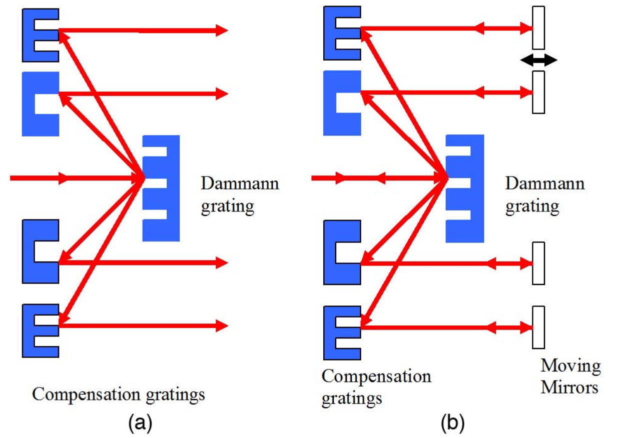

Fig. 6. Multipulse generation using a Dammann grating and compensation gratings.

5. APPLICATIONS

There are a variety of structures using Dammann gratings for compression of femtosecond laser pulses, as shown in Figs. 5(a)–5(c). Figure 5(a) is in fact equivalent to what is shown in Fig. 4. Figure 5(b) shows a 1×2 Dammann grating and two compensation gratings with double-line density for ± 1 diffractive orders that are used to generate two separated pulses, or one compressed pulse when two doubled-line density gratings are mounted a short distance between each other in one reflective plane and perfectively overlapped in one reflective plane. Figure 5(c) shows a general structure where a Dammann grating and the respective compensation gratings are adopted for generation of adaptive multiple reflective pulses or a single pulse when all compensation gratings are in different planes or in the same plane.

Figure 6 shows that the general working principle is similar to that in Fig. 2, i.e., the compensation gratings have the line density equivalent to or multiple times (up to the diffractive orders) to that of the original first-order Dammann grating. Figure 6(a) is the scheme for multiple-pulse generation, which might be useful for multiple laser micromachining, and Fig. 6(b) is another structure for generation of reflective multiple pulses.

Using gratings, we can also build a structure for measurement of the femtosecond laser pulse[8]. Figure 7(a) shows that one reflective arm generated from the Dammann grating will be changed by using a reflective mirror in a moving stage. Figure 7(b) shows that one reflective grating compensating for the angular dispersion of the Dammann grating in one arm will be moved slightly for tunable temporal overlapping of two pulses for autocorrelation of two femtosecond laser pulses using a frequency resolved optical grating (FROG) for measurement of femtosecond laser pulses. Since the femtosecond laser pulse to be measured is supposed to be short in the femtosecond level, the moving distance for such a measurement should be shorter than several millimeters. If the two arms of this structure are long, e.g., hundreds of millimeters, the slight moving distance compared with the long structure has less effect on the femtosecond pulse; therefore, we could use this structure to measure the femtosecond laser pulse.

There are other optical structures to generate multiple femtosecond laser pulses using diffractive gratings, for example, two gratings whose period is larger than the wavelength of femtosecond laser pulses but shorter than two times the wavelength of femtosecond laser pulses, the first grating is used to generate 1×3 diffractive-order beams, and the second is used to combine the two ± 1 diffractive

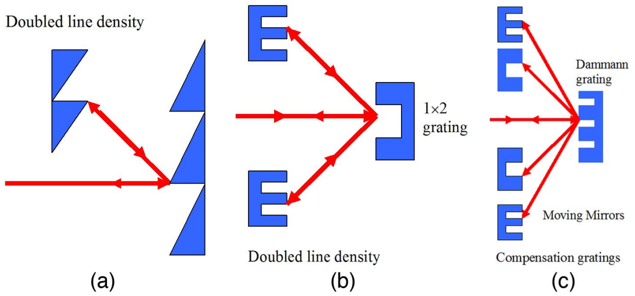

Fig. 5. Structures using a Dammann grating and compensation gratings for compression of femtosecond laser pulses.

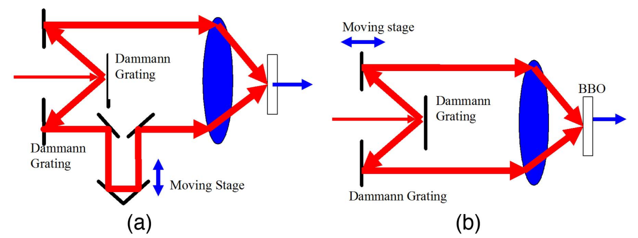

Fig. 7. Measurement using a Dammann grating and compensation gratings[8].

orders into one single pulse or to generate one single pulse by switching the second grating with a quarter of the period. It is also a novel optical structure for switching the femtosecond laser pulses from one single pulse to two pulses[9].

Using a femtosecond laser, we can also build an optical system for observation of femtosecond laser interaction with matter using both transmission holography and reflective holography simultaneously[10]. We can observe the effect of femtosecond laser pulses on the heating of chromium film, which seems interesting for further investigation of femtosecond laser pulses with matter. It seems interesting that a single-groove grating can produce one-to-five splitting[11], and a grating with double pass can be used for spectral combining of a laser array[12]. A book of Dammann gratings and applications can be found in Ref. [13].

6. PERSPECTIVE

A. Picometer Optics

Now there are different optical systems or structures developed for compensation of both spatial and angular dispersion for compression, stretching, and splitting of femtosecond laser pulses from the view of diffractive optics. One approach to obtain a higher laser pulse is to use a larger-sized grating compared with smaller-sized gratings for a CPA laser, supposing that the laser damage threshold has a limit on a grating. Therefore, meter-sized gratings have been proposed. This requirement of an over meter-sized grating pushes the measurement of the grating period in the picometer level in an averaged sense. For example, supposing the grating for the CPA has a line density of 1480 lines/mm, if there is one picometer error in a single period, for 1 m grating, the total error would be accumulated to be 1.48 μm, which is far larger than the central wavelength (800 nm or 900 nm) of the femtosecond laser. It means that if such a grating without control of pitch error in picometers is used it would deteriorate the performance of the whole grating. Therefore, we need to measure the period of such a grating in the picometer level. We have built an optical system for measurement of a period in the picometer level, which has been measured with a standard deviation of 1.5 pm[14].

For making a large-sized grating for the CPA laser, we need to develop the picometer optical measurement technique[15,16]. Although this picometer accuracy of period is an averaged value, it is our motivation to develop picometer optics from gratings[17] and holography[18]. When we can try to make two gratings with their periods in picometer difference, such a picometer-differential optical element is called a picometer comb[19]. We have made such a picometer comb for three-dimensional measurement[20], which implied that picometer optics can be developed from a picometer comb[21].

B. Femtometer Comb and Femtometer Optics

In an academic view, we will invent a new femtometer comb[21], similar to a picometer comb[19], and then we might establish a new branch of femtometer optics using the femtometer comb[21] to handle the related femtometer measurement. There are three prerequisites for femtometer optics. One is that we could make nanogratings with tunable mechanisms for femtometer modulation, which might be realized by changing the angle of two short waves, such as X-rays, similar to what we have done for picometer measurement[15]. The second is that such a tunable femtometer modulation should be uniform over at least one thousand periods, similar to what we have done for the picometer comb[19]. The third is that we should have established picometer metrology; based on picometer metrology, we can go into femtometer optics. It should be noted that femtometer (or picometer) simply means only the length in mathematical representation. From the metrology view, femtometer metrology, by itself, does not relate to any concrete atoms or molecules or their internal structures and properties. There are enough challenging extremes of picometer optics and femtometer optics for us to explore in the future.

We are concerned with how to open the doors of these unexplored areas in optics. Since the concept of the picometer comb is general in physical principle, the femtometer comb can also be developed from the same methodology as the picometer comb. When the femtometer comb is developed as a solid base, it is quite possible to develop femtometer metrology, femtometer measurement, and femtometer optics.

In conclusion, from the diffractive optics view of the CPA technique, we reviewed the past achievements of other gratings, which can also stretch and compress the femtosecond laser pulses. For perspective, we might foresee whole new branches of picometer optics[21] and femtometer optics in the coming years.

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