

CHARACTERIZATION OF CHIRPED VOLUME BRAGG GRATINGS - COMPACT LASER PULSE COMPRESSORS

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Increase in energy of ultrashort (picosecond, femtosecond) laser pulses is typically based on chirped pulse amplification (CPA) method. The nanojoule energy pulses are temporally stretched by several orders of magnitude prior amplification. The peak power is significantly decreased and the gain saturation and detrimental nonlinear optical effects, leading to the beam degradation, are avoided. Amplified pulses are compressed close to the initial pulse duration. Pulse stretching and compression requires special optical devices. In this work, we tested novel compact pulse compressors based on chirped volume Bragg gratings (CVBG), a piece of glass of few cm³ in volume with continuously changing refractive index modulation period. Four CVBGs were analysed by a continuous-wave narrow-bandwidth laser tunable in wavelength between 1028 and 1032 nm, i.e. the bandwidth of our high-power picosecond lasers having active gain medium of ytterbium doped yttrium aluminium garnet (Yb:YAG). Spectrally resolved diffraction efficiency, beam quality, and angular chirp were measured on a beam reflected by the CVBGs.

KEYWORDS

Chirped volume Bragg grating, chirped pulse amplification, pulse compressor, tunable laser, diffraction efficiency, beam quality, angular chirp

1 INTRODUCTION

Increasing the laser pulse peak power has been a challenge for research facilities and laser technologies since the invention of the laser. Q-switching and mode-locking techniques connected with shortening of pulse duration are able to create pulses' peak power in MW and GW range. Progress in development of high-power ultra-short (picosecond, femtosecond) laser pulses has been achieved when chirped pulse amplification (CPA) technique was introduced by Donna Strickland and Gérard Mourou in 1985 [Strickland 1985]. CPA has enabled mitigation of problems with gain saturation and detrimental nonlinear effects in the active medium of amplifiers (self-focusing, self-phase modulation), and facilitated obtaining pulses of TW and PW peak powers.

This progress in ultrafast laser technology has been shown to be very attractive for the laser micromachining of various materials. An appropriate choice of laser parameters (pulse energy, pulse duration, wavelength, and repetition rate) leads to successful surface and volume processing. Ultrashort laser pulses offer high intensities and allow to concentrate high energy into specific locations of the materials where spot sizes in the order of micrometers are needed. Laser micromachining enables material modifications like cutting, drilling, welding, and ablating.

With long pulses, the target surface is firstly heated and the material melted, while the vaporization starts afterwards. Minimal thermal load of the target when using ultrashort pulses allow selective, precise and clean evaporation without affecting the direct surroundings. The reason is that the material does not have time to transfer heat from the affected zone to its surroundings. It enables processing of heat-sensitive and thin materials, a task difficult or impossible to realize with long-pulsed or continuous-wave lasers. Beside the reduced heat-affected zone, the advantages of using laser over traditional machining tools consist in its simplicity, speed and automated control. It is contactless and eliminates tool wear. Materials, which are impossible to machine with tools, can be processed with lasers without inflicting damage to matter surrounding the working area.

The idea behind CPA lies in manipulating the temporal characteristics of ultrashort lasers pulses. The pulse duration is increased in order to avoid very high peak powers in the laser amplifier stages. This is accomplished using a stretcher, which introduces well-characterized dispersion to the pulse. Each spectral component of the pulse is delayed in time in relation to the others. The dispersive elements used for pulse compression are typically diffraction gratings or prisms. For example, the stretcher developed by Martinez [Martinez 1984] contains two diffraction gratings in the antiparallel arrangement and a telescope. When the pulse passes such system, the red spectral component (longer wavelength) travels shorter optical path than blue spectral component (shorter wavelength), i.e. positive dispersion is applied to the pulse, which results in its chirping. By increasing the pulse duration by many orders of magnitude (from fs to hundreds of ps), the peak power is efficiently reduced and the intensity remains under the damage threshold of the active medium. Then the chirped pulse undergoes amplification to high energy levels. Reverse process that shortens the pulse uses the technique of pulse compression. Very often a system developed by Treacy [Treacy 1969] is used. Here two gratings in parallel arrangement are used. The compressor works on the same principle as the stretcher, but produces dispersion with opposite sign. Unfortunately, these systems have considerable disadvantages. When precise complex alignment is necessary, they have limited long-term stability. Large separation distance between the gratings, when large amount of dispersion, is needed. For high-power lasers, gratings with large apertures are required. A suitable alternative for a compact and easily adjustable compressor, which overcomes limitations of prisms or diffraction-grating-based compressors, has been found. Chirped volume Bragg gratings (CVBGs) written inside photo-thermo-refractive (PTR) glass [Glebov 2004] offer an interesting alternative. CVBG is a device with gradually variable period of refractive index modulation (typically around 0.3 μm for 1 μm lasers [Glebov 2004]) in the direction of beam propagation. This structure, holographically written inside the PTR glass, results in reflecting different spectral components from different planes. Time delay between spectral components of the beam is created. If the same beam enters the CVBG from the opposite side, the spectral components are delayed in opposite way, i.e. the dispersion have inverse sign. Thanks to this property, CVBGs can be used for both stretching and compression, and their reciprocity allows to overcome problems with dispersion mismatch. CVBGs' high laser damage threshold, ability to

provide a large amount of dispersion [Liao 2007] and high efficiency make it suitable for different laser systems. Besides their easy alignment and compactness (typical volume in order of several cm³), it is resistant to shocks [Sun 2016] and independent of polarization. In laboratory environment, CVBGs are chemically stable.

On the other hand, demanding production of CVBGs causes inaccuracies that significantly affect the output temporal and spatial characteristics. To record the Bragg grating inside, a piece of PTR glass is illuminated by an interference pattern of UV beams. As a result of the intrinsic absorption of the illuminating UV beams, the exposure changes from the top towards the bottom of the glass and a graded refractive index profile is created. A beam propagating across this structure is deviated and a spatial chirp is formed between input and diffracted beams. Additionally, the recording process of refractive index modulation causes some additional absorption and scattering that affects the diffraction efficiency. Material dispersion together with imperfect hologram structure can cause an additional delay of the different spectral components. The total dispersion is then expressed by polynomial function and represents higher orders of dispersion [Moser 2010] resulting in worse pulse compression.

A bandwidth of the CVBG is given by refractive index modulation in the PTR glass. An increase in the bandwidth requires higher refractive index modulation. This is compensated by the corresponding thickness of the CVBG. The reflectance of CVBG is from units of percent up to 99 % depending on its thickness and on the refractive index modulation. CVBG should contain at least several thousands of refractive index modulation periods and simultaneously large differences between its minimum and maximum refractive index should be achieved. After that, the CVBG is capable of higher compression ratio, but due to missing tuning mechanism of the CVBG, dispersion is fixed.

As a result of the demanding recording process and its errors, each spectral component could be reflected at a slightly different angle and contributes to the introduction of an angular chirp. Angular chirp causes problems with focusing of the beam during application experiments which need high intensities. Moreover, due to this significant shift of spectral components the output beam is spatially chirped and affects deterioration of the beam quality factor M^2 .

For quantification of the behavior of spectral components, we used a narrow-bandwidth laser tunable over a wavelength range wider than the bandwidth of the CVBG. In this work, we characterize the amount of angular chirp, beam quality of diffracted spectral components, and diffraction efficiency of the CVBGs.

2 METHODS

We tested four CVBGs of different properties by a continuous-wave narrow-bandwidth (~0.04 nm) semiconductor laser. Tuning of the wavelength is performed by adjusting the position of a diffraction grating and a birefringent filter inside the cavity of the laser. The polarized output beam reaches a power of 1 mW.

A schematic layout of the setup for characterization of the angular chirp, M^2 parameter and efficiency in dependence on wavelength is shown in Fig. 1.

A small portion of the laser output beam, controlled by a half-wave plate and polarization beam splitter (PBS), enters into the spectrometer Micro Spectra (Resolution Spectra Systems) for monitoring the wavelength. The rest of the beam is directed through a polarization beam splitter (PBS) and a quarter-wave plate into the CVBG under test. The beam is collimated inside the CVBG and the CVBG is placed perpendicularly to the beam. The beam reflected by the CVBG propagates to the device measuring the M^2 parameter with a CCD camera placed on the motorized translation stage (Laser Laboratorium Göttingen). The camera measures beam diameters in dependence on camera position, which is used for calculation of the M^2 parameter. The quality of the beam was measured in accordance with the ISO 11146-1: 2004 standard. Additionally, for reference measurement of the M^2 , i.e. M^2 of the input beam, a removable reflective flat mirror was placed in front of the CVBG and guided the beam into the same direction. Angular chirp caused movement of the profile on the CCD camera in the far field position while the wavelength was being tuned. From the position change of the beam centroid, we were able to calculate the amount of angular chirp.

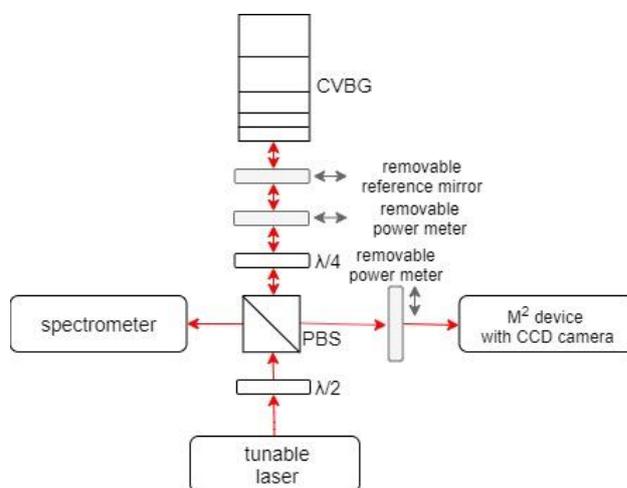


Figure 1. Experimental setup for characterization of the M^2 , spatial chirp, and diffraction efficiency of the CVBGs using a wavelength tunable laser. PBS-polarization beam splitter, $\lambda/2$ half-wave plate, $\lambda/4$ quarter-wave plate.

Incident and diffracted power was measured with a power probe (Ophir). The probe was inserted in front of the CVBG for measurement of incident power. Diffracted power was recorded in the diagnostics arm with the M^2 device.

Complete characteristics of the CVBGs were measured at both ends of the gratings. When the beam enters the CVBG where the grating period is larger, this end is referred to as the 'red end'. In contrast, the 'blue end' is when the beam enters through the face where the grating period is the smallest.

3 RESULTS

With the above described setup, properties of the chirped volume Bragg gratings were investigated. Here we present results obtained during testing one of the samples of CVBGs.

3.1 Diffraction efficiency

The CVBG is designed to have efficiencies higher than 70 % in the bandwidth for which the CVBG is designed. Wavelengths out of this range should be transmitted. We have experimentally confirmed this assumption.

Fig. 2 shows measurement of the dependency of diffraction efficiency on wavelength of sample 1. Values of 1028.75 nm

and 1031.05 nm specify the bandwidth at full width at half maximum of the CVBG. Within the most of the bandwidth of the CVBG the diffraction efficiency does not drop below 80 %. Maximum diffraction efficiency reaches almost 96 %. Behind these limits, the diffraction efficiency falls to few units of percent. The diffraction efficiency of the CVBG increases with wavelength when the beam enters the red end while for the opposite direction it decreases. Because spectral components propagating longer path through the CVBG have higher losses, this phenomenon occurs.

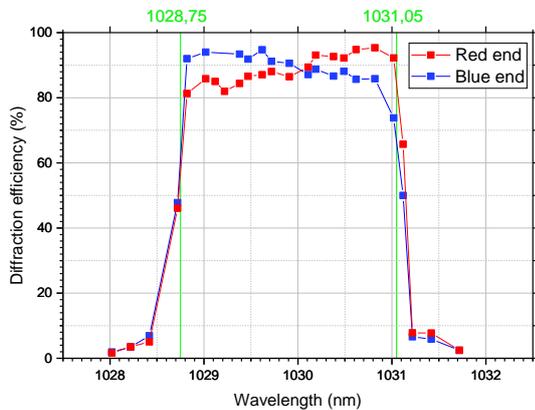


Figure 2. Diffraction efficiency of the CVBG vs. wavelength when the beam enters the CVBG from the red end (red curve) and the blue end (blue curve).

3.2 Beam quality parameter M^2

Beam quality represented by the M^2 parameter vs. wavelength is in the Fig. 3. This figure shows the M^2 for beam entering the red and the blue end of the CVBG together with the dependency in the horizontal and vertical plane.

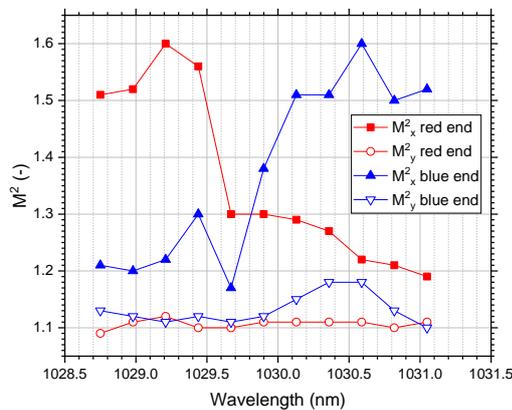


Figure 3. M^2 dependence on wavelength for beam entering the red and the blue end of the CVBG in horizontal (solid markers) and vertical axis (hollow markers).

Quality of the reference beam remains stable independently on the wavelength in both planes with the value of 1.11 and 1.08 in the horizontal and vertical plane, respectively. In the case of the beam diffracted by the CVBG, different values were measured. As can be seen, the M^2 values for the vertical plane remains almost on the similar level. Only slight increase up to 1.18 is observed. The beam quality in horizontal axis vary between 1.17 and 1.6. An interesting observation is that the M^2 depends on the end through the beam enters the CVBG. As illustrated for beam entering the red end, the M^2 is greater

than 1.5 for wavelengths up to 1029.5 nm and then the M^2 parameter falls to 1.3 at 1029.7 nm. With further increasing wavelength, the M^2 decreases to 1.19. On the other hand, opposite trend when beam enters the blue end, can be observed. Between 1028.7 – 1029.7 nm the M^2 does not exceed 1.3. Above this range of wavelengths, the M^2 increase faster up to 1.56 at 1031.5 nm.

These opposite trends originate from the production process of the CVBG and they stem from the reversed orientation of the CVBG. During manufacturing process, PTR glass is processed above the glass transition temperature. At this temperature, material deformation occurs and after cooling it does not disappear completely, incurring inhomogeneity of the glass which affects the resulting M^2 . The longer path the spectral component travels through the CVBG, the more is the output beam influenced by the inhomogeneity of the CVBG and therefore the M^2 factor increases.

3.3 Angular chirp

A beam propagating across graded refractive index medium is deviated and an angular chirp is formed on diffracted beams. The dependency of the angle of diffraction (AOD) of each spectral component on the wavelength determines the strength of the angular chirp. In the fig. 4 this dependency is shown. Angle of diffraction varies between -0.1 and 0.1 mrad. Angular chirp is the strongest for the horizontal axis at the blue end of the CVBG, 0.2 mrad. In the vertical axis, AOD is in a range of 0.17 mrad. Red end has a smaller range, specifically 0.13 mrad in both axes. As in the previous paragraph, trend for the red-end entry is almost identical as a reversed blue-end trend.

Due to the shift of spectral components, the broad-spectrum output beam is distorted, resulting in a decrease in beam quality.

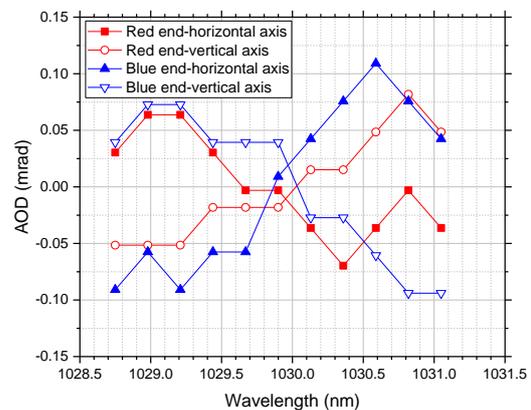


Figure 4. Angle of diffraction of spectral components in horizontal (solid markers) and vertical axis (hollow markers).

4 CONCLUSIONS

In conclusion, we have demonstrated a setup for characterization of a chirped volume Bragg gratings. CVBG, the space-saving, easy-to-align pulse compressor, is a convenient choice for compact CPA systems. The principle of this device is based on time delay between spectral components, which are reflected on different planes of refractive-index modulations. A specific structure of the CVBG enables stretching and compression of pulses, and thus production of the positive or negative dispersion, in dependency on the end through the

beam enters the CVBG. Unfortunately, demanding production of these optical components leads to inaccuracies, which affect diffracted beam. For this reason, CVBGs require detailed characterization of properties such as beam quality, angular chirp and diffraction efficiency, which was done in this work.

In this experiment, 0.04 nm wide spectral components falling into the CVBG's bandwidth are generated by a narrow-bandwidth, wavelength-tunable laser. Behaviour of the spectral components after their reflection from the refractive index modulations is observed. Diffraction efficiency of reaches values above 80% in the bandwidth for which the CVBG is intended and then sharply declines to values of single digits of percent because the majority of the incoming light transmits through the grating. A dependency of M^2 parameter on wavelength was observed and measured. The dependency is flat in the vertical plane and the measured values of M^2 remained around the value of 1.1. However, the M^2 in the horizontal plane increased up to 1.6 at certain wavelengths. Dependence of angle of diffraction on wavelengths indicates the strength of angular chirp of 0.2 mrad. Due to this shift of spectral components and inhomogeneity of the glass, the output beam with broader spectra used in CPA is distorted and causes deterioration of the beam quality.

Our tested samples show similar behaviour. Diffraction efficiency is higher than 60% in the CVBGs' bandwidths. The M^2 factors are higher in horizontal axes for all of the samples and angular chirp reaches up to 0.33 mrad for certain CVBG.

Our results allow to evaluate the quality of each CVBGs and valuable feedback is provided for their producers. Based on our developed methods, it is possible to optimize production process in order to improve the quality of the CVBGs.

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