Distortion free pulse stretching and compression by chirped volume holographic gratings

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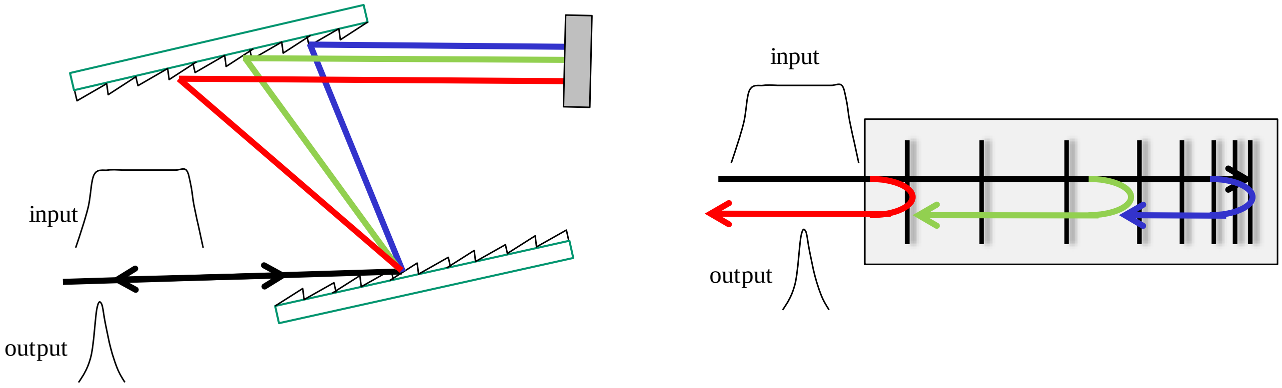
ABSTRACT

We have developed a novel method to correct the spatial distortion resulting from temporally stretching/compressing optical pulses with a chirped volume holographic grating (CVHG) in glass. We show that the inherent spatial beam distortion can be corrected to produce a distortion-free round beam output. We fabricated a 30 mm long CVHG with 9 nm bandwidth, 300 ps delay at 1031nm exhibiting a smooth round spatial Gaussian profile after compression. Coupling efficiencies for the compressed pulse exceeds 75% into a single mode fiber. The spatial profile is maintained over a wide temperature range from 10 to 60 degrees Celsius. We believe that the spatial beam profile improvements of CVHG demonstrate herein enables the practical realization of ultra-compact and efficient chirped pulse amplification laser systems.

Keywords: ultra-fast, lasers, chirped volume grating, pulse, efficient, compact, compression, stretching.chirped pulse amplification

INTRODUCTION

Chirped pulse amplification is the dominant method to produce the highest peak power pulsed lasers [1-2]. A short optical pulse (less than 1ps) from a low power oscillator is first temporally stretched in time by typically 3 orders of magnitude before optical amplification. Because the damage threshold of amplifier materials is approximately inversely proportional to the square root of the pulse duration, a one nanosecond pulse can be amplified by 9 orders of magnitude more than a one picosecond pulse. After optical amplification, the pulse is temporally compressed back to its original pulse duration, a process resulting in a high peak power pulse (peak power is the energy of the pulse divided by the pulse duration).



(a)

(b)

Figure 1: technologies for compressing/stretching the duration of optical pulses (a) dispersive grating pair (b) chirped volume holographic grating (CVHG).

There are several technologies to temporally stretch or compress pulses of light. The most ubiquitous is a technique based on pairs of dispersive diffraction gratings. Figure 1a illustrates the concept. The first grating angularly disperses the different wavelengths forming the short pulse while a second grating parallel to the first one collimates the different wavelengths. This double diffraction provides a path difference between the spectral components forming the pulse. A mirror reflects the collimated beam back onto itself, doubling the path difference in the process and resulting in a temporally compressed or stretched pulse. This method involves 4 passes through the dispersive gratings. High end dispersive gratings have optimized diffraction efficiency in the first order reaching 90% per pass. The maximum effective efficiency of a pulse stretcher/compressor with a pair of gratings is consequently approximately 65%. The footprint of such a system is several hundreds of square centimeters. Fine angular alignment on each grating pair and mirror is required and is tedious.

An alternative technique for altering the pulse duration is based on chirped VHGs. The attractive features of a CVHG solution over the grating pair solution described above are that (1) it provides higher compression/stretching efficiency (typically 85% vs 65%) and (2) it is extremely compact (footprint of several cm^2 vs several 100 cm^2) which increases pointing stability. The CVHG solution, illustrated in figure 1b, is the free space analog to CVHG in waveguides [3] and was recently implemented in high power laser systems [4]. A bulk volume grating is recorded in such a way that the period of the grating varies continuously along the length of the device. A collimated short pulse incident on the CVHG is either compressed (or stretched) by providing a delay in the spectral component of the pulse: e.g the “red” component of the pulse spectrum is diffracted at the beginning of the CVHG and the “blue” component is diffracted near the end of the length of the CVHG. For example a 30mm long glass-based CVHG transforms a short bandwidth limited pulse to a 0.3 ns long pulse (2*length*refractive index / speed of light).

Although this technique was introduced almost two decades ago, there has not been any practical demonstration nor commercial implementation using this technology until recently. This is about to change for two reasons: (1) improvements in low loss holographic glass with high damage threshold (170MJ/cm^2 in the nanosecond regime) and (2) the dramatic improvement in beam quality outlined in this paper.

2. SPATIAL CHIRP

Photothermal holographic glasses exhibit a DC refractive index change upon exposure with ultra-violet illumination. The higher the exposure (mJ/cm^2), the larger the refractive index change. This process saturates when the index change reaches approximately 10^{-3}. During fabrication, a bulk photosensitive glass wafer several millimeters thick is exposed, throughout its thickness, to record a grating. Due to the intrinsic absorption of the illuminating ultra-violet beams (necessary to record the grating), the exposure decays throughout the thickness of the glass wafer: exposure is the highest at the top and decay towards the bottom. Consequently, the DC refractive index changes monotonically across the thickness of the wafer, thus creating a graded refractive index profile in the direction along the thickness. Figure 2 illustrates the effect.

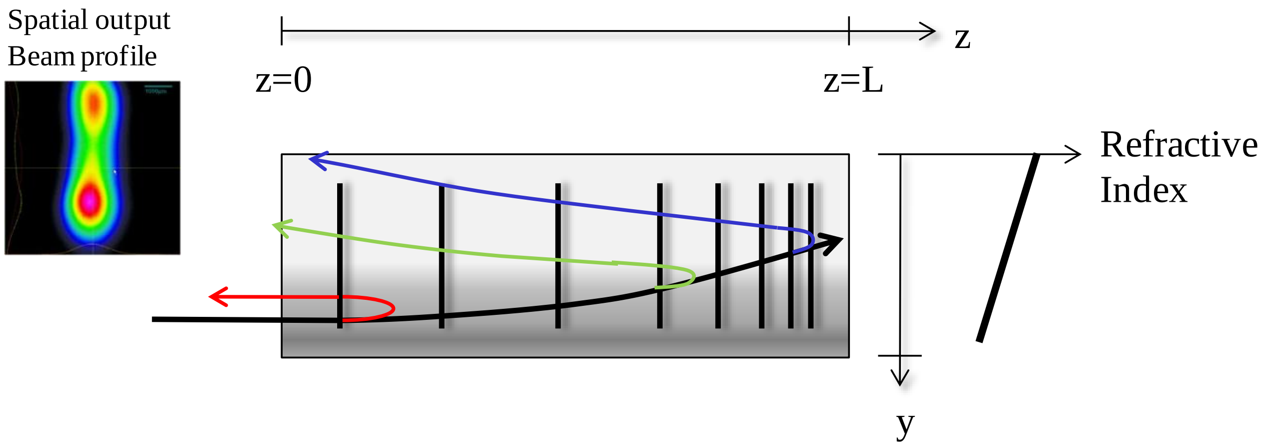


Figure 2: beam propagation in a graded index chirped VHG that results in an elongated spatial output beam profile.

A collimated beam propagating in a graded refractive index medium is deflected. For constant refractive index gradients ($\partial n/\partial y$) perpendicular to the beam path small deflection angles α can be approximated to $\alpha \approx (\partial n/\partial y)\, z/n$, where z is the length of the beam path and n the average refractive index of the medium. The angular divergence $\Delta\Theta$ between the beams diffracted at the entrance and exit facets of a chirped VHG is:

$$\Delta\Theta \approx 2\,(\partial n/\partial y)\cdot L, \qquad (1)$$

where L is the grating length. Equation (1) takes into account that both, incident beams and diffracted beams are bending towards the refractive index gradient and that the divergence is measured outside the medium. For example, the expected angular divergence is $\Delta\Theta = 5$ mrad in the case of a CVHG with an index gradient of $0.83\cdot10^{-4}$ /mm, length of 30 mm and average index of 1.5.Although the index change is small, the angular deflection is several times the diffraction limited angular spread of a 1 mm collimated beam (1 mrad).

The output beam diffracted off the CVHG exhibits an angular spread wherein for each angle corresponds a spectral component of the input pulse. The output beam is elongated in one direction and thus exhibits a spatial chirp (i.e wavelength depends on position in the output beam).

3. SPATIAL CHIRP CORRECTION

The spatial chirp occurs only in one dimension, therefore a method for chirp compensation is only needed in that dimension. Because the grating is continuously chirped along the z direction , the magnitude of the grating vector $K(z)$ depends on the position z along the length of the CVHG: $K(z) = 2\pi/\ \Lambda(z))$, where $\Lambda(z)$ is the grating period at position z. Let us assume a CVHG having a grating vector $K(z)$ pointing in the same direction i.e independent of position z. Figure 3a illustrates the case. The gradient refractive index deflects the collimated pulse beam upon propagation through the CVHG. As a result, the angle α between the pulse propagation direction and the local grating vector grows from zero at the entrance of the CVHG to its maximum value at the exit (z=L).

The spatial chirp compensation method consists of curving the local grating vector to match the pulse propagation direction [5]. This is achieved in one of two ways:

3.1 Mechanical

This method consists of mechanically bending the CVHG by applying a force on one end of the grating. Figure 3b shows the CVHG held firmly on one side and bended by applying a force on the other end so as to orient the local grating vector in the same direction as the local beam propagation direction. The drawing exaggerates greatly the deformation only for purposes of illustration. A deflection angle of 5 mrad corresponds to a displacement of 75 μm at the end of a 30 mm CVHG.

3.2 Curved Grating

This method consists of recording a “curved” grating in such a way that the grating vector direction depends on the position. Figure 3c illustrates the method. This can be achieved by using mismatched divergent beams in the holographic recording process.

For manufacturability reasons, the mechanical correction is preferred because this method is adjustable during packaging (by changing the stress applied) to obtain the best possible output beam profile. We show experimental results below.

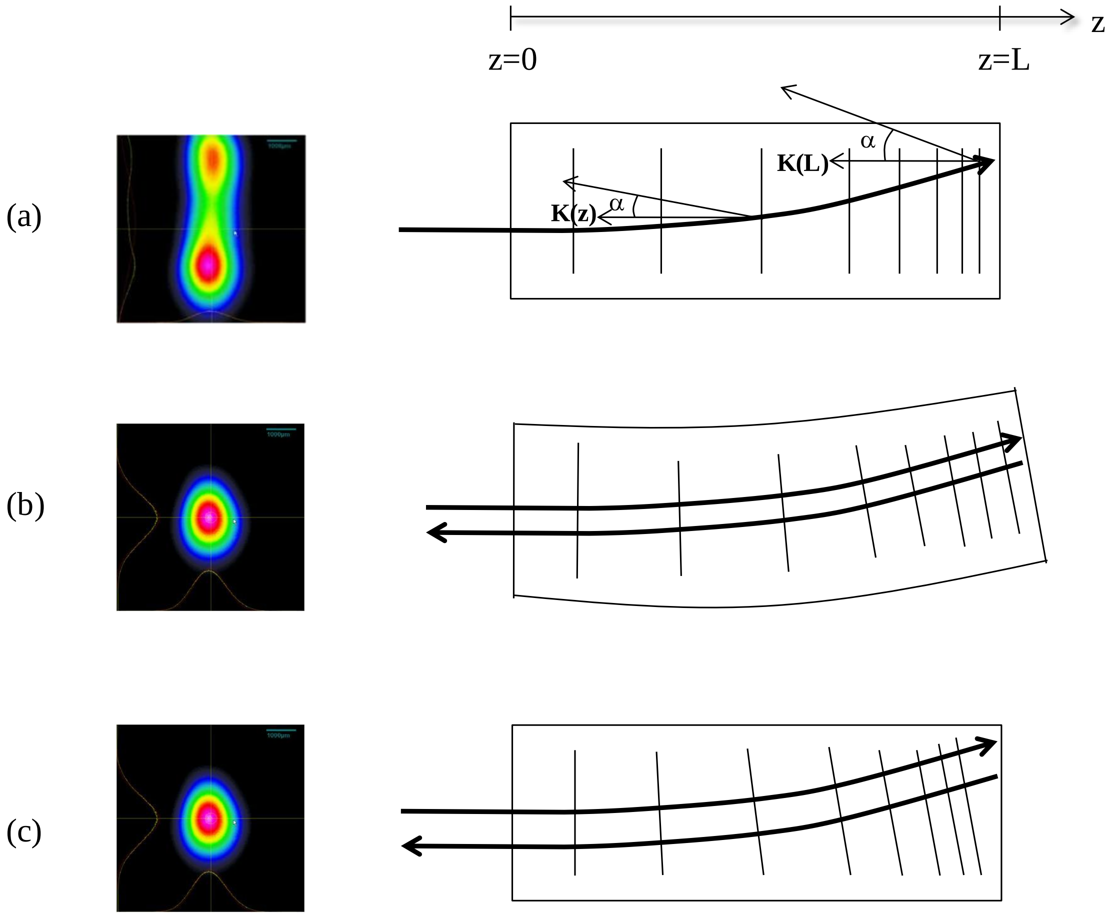
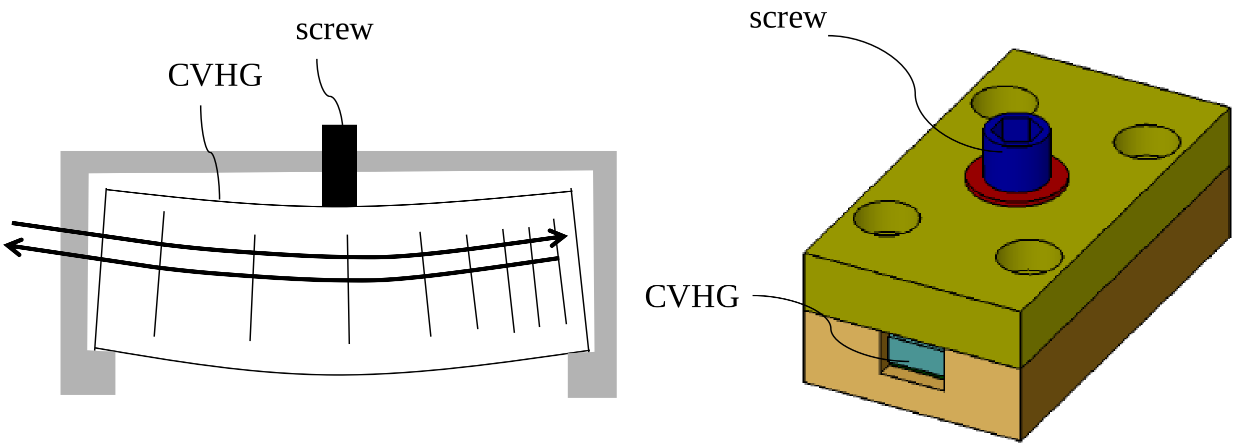


Figure 3: (a) diffraction from an uncorrected CVHG produces spatial chirp that distorts the spatial beam profile (b) corrected spatial beam profile by mechanical stress (c) corrected spatial beam profile by recording a CVHG with curved (slanted) grating vectors

4. EXPERIMENTAL RESULTS

A 30 mm long CVHG was holographically recorded with a chirp rate of 0.3 nm /mm. The resulting FWHM bandwidth was 9 nm and 80% absolute efficiency with an aperture of 5mm x 2 mm. The CVHG was supported on both ends and a force was applied near the center of the CVHG to apply a curvature to the grating vector. Figure 4a shows the schematic and figure 4b shows the package. Mechanical stress was adjusted with a screw to tune the curvature of the CVHG's grating vector.



(a) (b)

Figure 4: (a) schematic of the arrangement for providing mechanical stress to apply a curvature to the grating vector (b) 3-dimensional view of the package.

The measurement test method is illustrated in figure 5. A fiber coupled cw broadband source (Superlum, SLD-531) was collimated to produce a beam with a $1/e^2$ diameter of 1 mm. The CVHG package was mounted on a temperature controlled plate, which was then mounted on a 5 axis stage for angular and spatial adjustments. A beam-splitter deflected the diffracted beam onto a beam profiler camera (Thorlabs, BC106-VIS) placed 1.5 meters away.

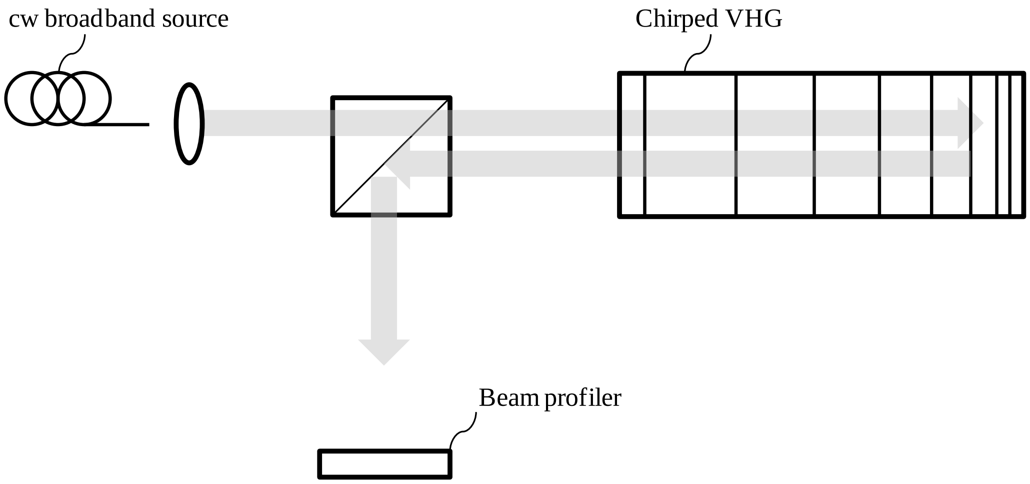
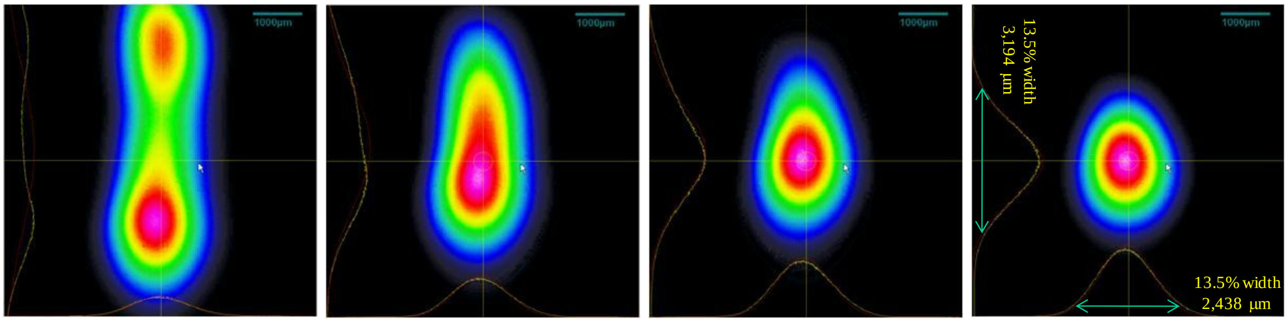


Figure 5: set-up for measuring the spatial beam profile of the beam diffracted from the chirped VHG

When no force is applied to the CVHG, the output beam exhibits an oblong shape in one direction caused by spatial chirp (see figure 6a). The beam measures 7 mm in the spatial chirp direction. This elongation corresponds to a divergence angle of 4.6 mrad in good agreement with the estimated 5 mrad computed in the prior example.

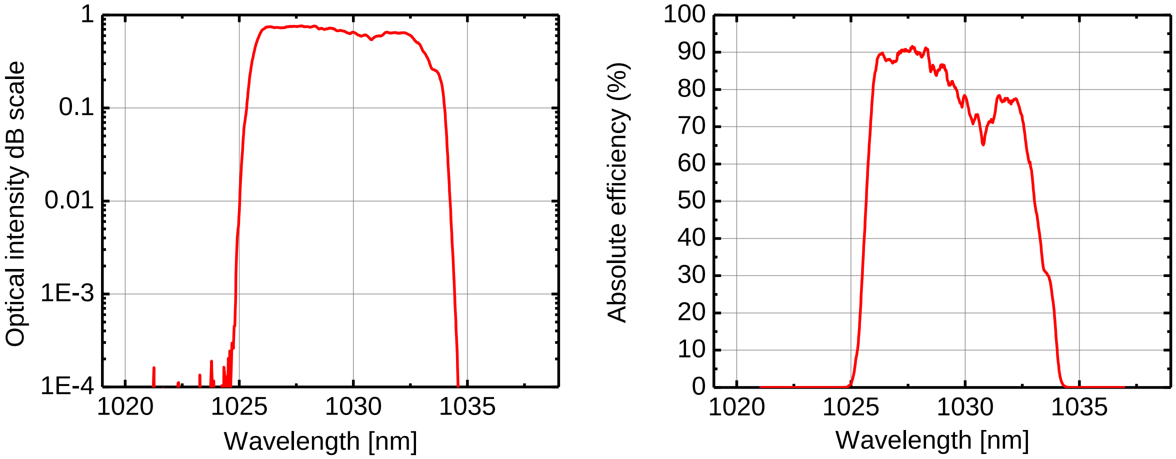
Figures 6b through figure 6d show the spatial beam quality improving as stress is applied onto the CVHG by turning the screw on the package. The spatial beam shape in figure 8d is 76% circular as measured at the 13.5% ($1/e^2$) point. The improvement in spatial beam quality between figure 6a and 6d is dramatic.



(a) (b) (c) (d)

Figure 6: output spatial beam profile after diffraction of a round Gaussian beam from a CVHG (a) without spatial chirp compensation and (b-d) with spatial chirp compensation by applying increasing mechanical stress.

The spectrum of the diffracted beam was measured by an OSA by coupling the round output beam (figure 6d) into a single mode fiber. More than 75% absolute coupling efficiency was achieved. Figure 7a shows the spectral shape in logarithmic scale. The side modes were below the noise detection level at –40dB. The linear scale (7b) shows the spectral efficiency uniformity. The absolute efficiency (diffracted output power/incident input power) was 80% with a ripple of +/- 10%.



(a) (b)

Figure 7: spectral profile after diffraction from a CVHG and single mode fiber coupling (a) logarithmic scale (b) linear scale.

The spatial beam profile was measured as a function of ambient temperature (Figure 8). The CVHG package temperature was varied from 10^{o}C to 60^{o}C. The result was less than 2% change in beam width in both X and Y axis.

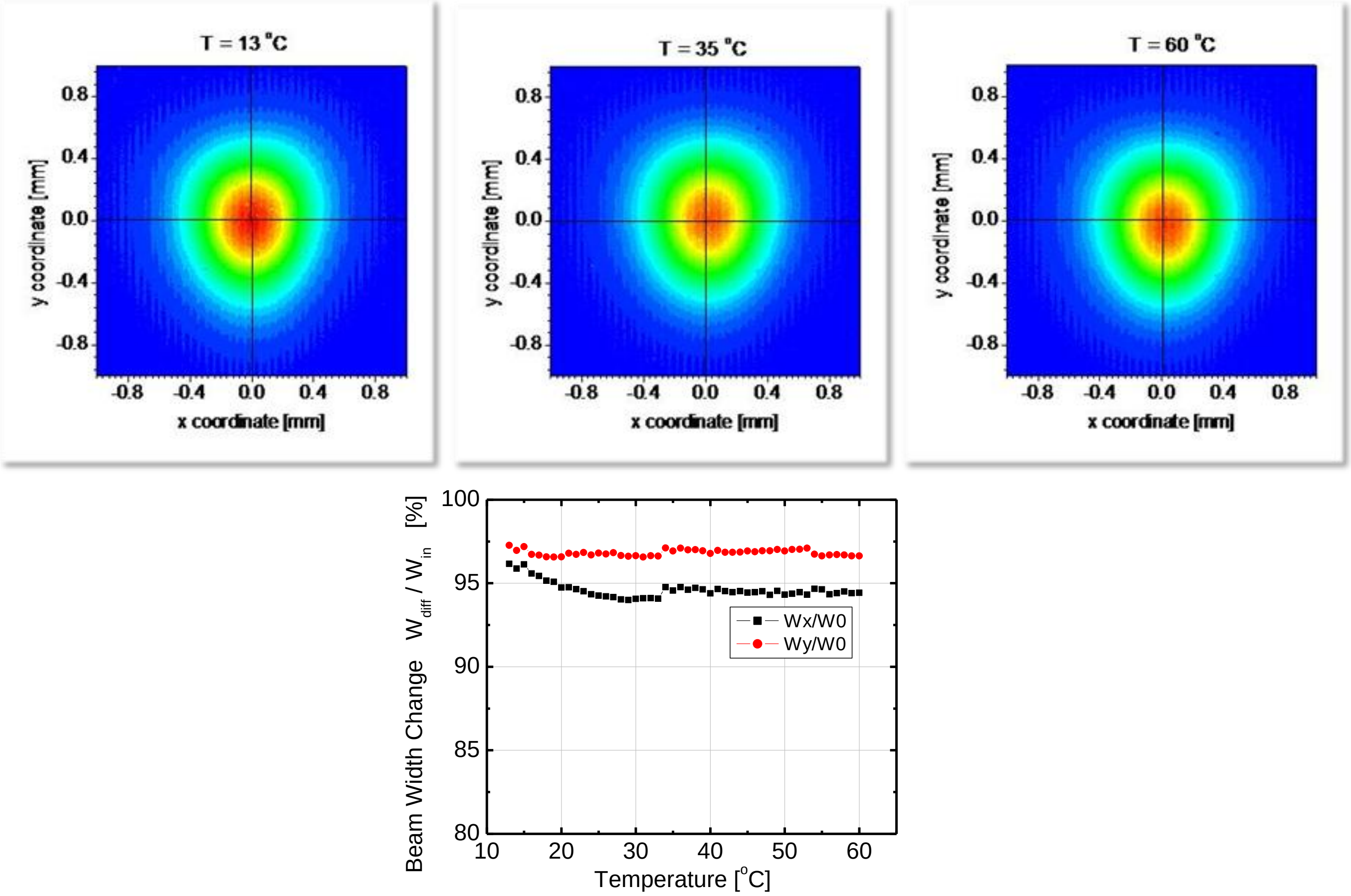


Figure 8: spatial beam profile of the output beam diffracted from a CVHG as a function of package temperature. Less than 2% variation in spatial beam profile was observed over a 50 degree range.

A pair of CVHGs were then used as a stretcher and compressor in a chirped pulse amplification (CPA) ultra-fast laser system. Figure 9 illustrates the arrangement. Details of the laser parameters cannot be revealed however the amplified and compressed output beam exhibited a round spatial shape with a pulse duration of 650 femtoseconds. To the authors' knowledge, this represents the first successful demonstration of a high quality output beam profile of CPA laser using CVHG technology.

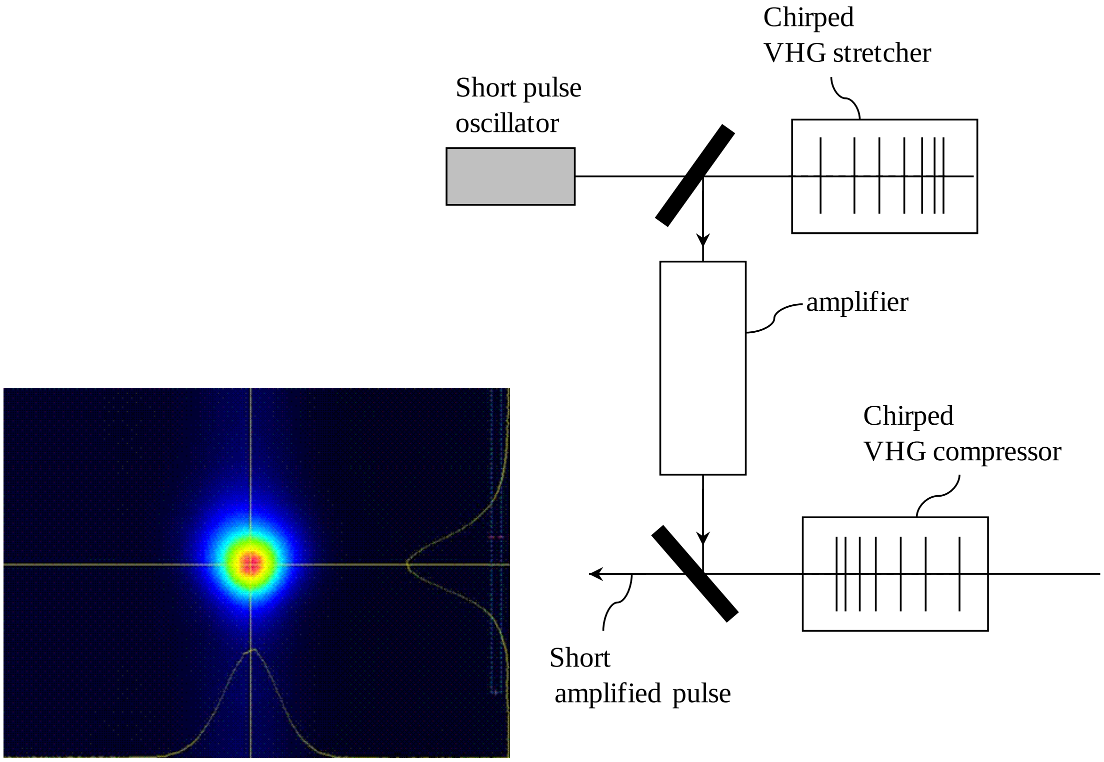


Figure 9: First successful demonstration of high quality output beam from a CPA system using a pair of chirped VHG for pulse stretching and compressing.

5. CONCLUSIONS

A technique has been demonstrated for correcting the inherent spatial beam profile distortion of the output beam diffracted by chirped volume holographic gratings in glass. The resulting output beam quality is a smooth nearly circular Gaussian beam profile. The beam correction method was tested in a chirp pulse amplification laser system. The result was a circular laser output beam profile after compression exhibiting 650 femtosecond pulses.

For pulse durations above approximately 400 femtoseconds, the CPA-CVHG technology offer superior performance over the traditional CPA-dispersive grating pair technology. Specifically, the optical efficiency is increased by 25% and results in a more rugged laser system because of the compact footprint and athermal performance. The compactness of a CPA laser system using CVHG beam correction technology is very attractive for industrial micro-machining and medical applications in which a tightly focused beam with perfect beam quality is required.

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