Reprinted from Applied Optics, Vol. *24*, page 2021, July 1, 1985

Femtosecond laser pulse compression using volume phase transmission holograms

Tsung-Yuan Yang, Ping-Pei Ho, Alvin Katz, R. R. Alfano, and Ronald A. Ferrante

Combining holographic and femtosecond laser pulse compression technology, gigawatt peak power and 85-fsec bandwidth-limited laser pulses were obtained. Pulse compression was achieved using a pair of high diffraction efficiency volume phase transmission holographic gratings.

Pulse compression[1–5] is a useful tool to reduce the pulse duration of ultrashort lasers down to the bandwidth-limited region. At the same time, this increases obtainable pulse peak power for ultrafast laser spectroscopy. In the past, reflection gratings have been used to compress successfully laser pulses to bandwidth-limited durations.[1–7] A typical ruled blazed reflection grating has ~60% absolute diffraction efficiency per grating at the wavelength used. Its diffraction efficiency also depends on the laser polarization direction, incidence angle, and wavelength. The overall efficiency for a pair is 36%. With the advent of holographic technology,[8–11] high efficiency and high damage threshold volume phase transmission holograms recorded in dichromated gelatin have achieved over 90% absolute diffraction efficiency. In a cw laser experiment, damage threshold for a gelatin film was ~3000 W/cm^2 for a 60-sec exposure.[12] In this paper, we report for the first time the adaptation of a high-efficiency transmission holographic grating pair and the extension of Treacy's pulse compression concept[1] into the 85-fsec bandwidth-limited region with overall efficiency of over 60% at gigawatt laser pulse power.

The transmission gratings used in this experiment are high diffraction efficiency volume phase dichromated gelatin holograms derived from Kodak 131 photographic plates.[8–11] Two types of transmission grating were fabricated from different optical arrangements. An argon laser operating at 488-nm wavelength was used to generate two collimated beams as the reference and object beams to make simple holographic gratings. The first type of transmission grating has unslanted fringes formed in the 8 ± 0.5-μm gelatin film (measured by a Tencol profilemeter) when both the reference and object beams are incident to the recording plate at 17.4 and, −17.4°, respectively, during the exposure. The surface spatial frequency of this grating is ~1220 lines/mm. The second kind of holographic grating has slanted fringes. The incidence angle of the reference and the object beams are 0 and 33.5°, respectively. The surface spatial frequency of this type of hologram is ~1130 lines/mm. The hologram developing processes are described in Refs. 8–11. The finished holograms were sealed with a 1-mm thick glass cover plate for environmental protection. The absolute diffraction efficiency ($= I_{\text{output}}/I_{\text{input}}$) of all holograms used in this study was in the 76–85% range at the 625-nm laser wavelength. The zeroth-order undiffracted beam varied from 0 to 6%. Other losses from these holograms are surface reflection and recording material scattering. After a month long exposure to the GW/cm^2 incident peak power density of the femtosecond laser pulse, these holograms did not show any damage. This may be accounted for by the low hologram absorption and the low input laser energy (~mJ/cm^2).

The experimental arrangement of the laser pulse compression technique is shown in Fig. 1. The generation of femtosecond laser pulses from a mode-locked colliding pulse ring dye laser with a four-stage dye amplifier, has been described elsewhere.[13,14] After the four-stage amplifier, the output laser pulse at 625-nm wavelength has ~2-GW peak power and 450-fsec pulse duration. A typical KDP second harmonic generation autocorrelation laser pulse duration measured curve is shown in Fig. 2(a). The measured spectral bandwidth of the dye laser before and after the four-stage amplifier was ~40 Å under both conditions. The widened laser pulse is mainly due to the dispersion of the laser pulse as it travels through over 25-cm long dye solutions in the amplification process.[6]

Ronald Ferrante is with NCR Corporation, Scanners and Peripherals Development Department, Cambridge, Ohio 43725; the other authors are with City College of New York, Institute for Ultrafast Spectroscopy and Lasers, New York, New York 10031.

Received 21 February 1985.
0003-6935/85/132021-03$02.00/0.

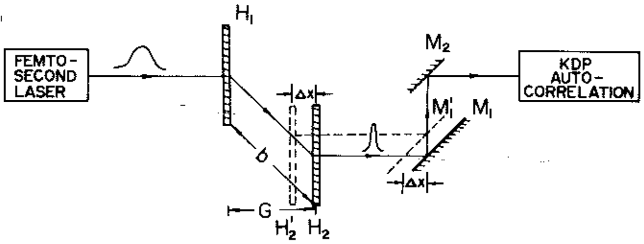

Fig. 1. Schematic diagram of femtosecond laser pulse compressor using the transmission grating pairs: b, slant distance; G, separation distance between the parallel holograms; θ, the diffracted angle; and $r = 0$, incident angle. M_1' and H_2' are the new locations of mirror M_1 and hologram H_2, respectively, when the separation distance between the hologram pair is changed by Δx.

The chirped 450-fsec laser pulse was then sent through a pair of parallel transmission gratings. The outgoing compressed laser pulse was directed into a KDP autocorrelator to determine the pulse duration. To achieve the optimum pulse compression, the separation distance of this paired gratings was adjusted. To avoid the optical beam direction deviation during the change of the distance of the paired gratings, the first grating H_2 in Fig. 1 was attached to a mirror M_1 on a translational stage. The mirror was set at a 45° incidence angle with respect to the laser propagation direction. In this manner, when the grating pair separation distance was varied, H_2 and M_1 were moved together, and the outgoing beam after M_2 was propagated along the same optical path. This arrangement avoids the realignment procedure of the autocorrelation pulse duration measurement. A compressed laser pulse duration of ~85 fsec is shown in Fig. 2(b).

In Treacy's analysis of pulse compression using a pair of reflection gratings, the variation of group delay with wavelength is expressed as[1]

$$\frac{\Delta\tau}{\Delta\lambda} = \frac{b(\lambda/d)}{cd[1 - (\sin r - \lambda/d)^2]}, \tag{1}$$

where b is the slant distance d is the grating constant, c is the speed of light, λ is the laser wavelength, r is the laser incidence angle, and $(r - \theta)$ is the diffracted angle. Following his approach, an identical result of the pulse compression factor with the use of a pair of transmission gratings is obtained from the geometry of Fig. 1 with θ as the diffracted angle (see Appendix).

Following the geometry of Fig. 1, the incident angle $r = 0$, the diffracted angle $\theta = 45°$, the spatial frequency of hologram $1/d = 1130$ lines/mm, and $b = G\sec\theta = 18$ mm, the calculated dispersive delay parameter $\Delta\tau/\Delta\lambda$ from Eq. (1) is ~92 fsec/nm. The measured $\Delta\lambda$ was ~4 nm. This calculated value is in good agreement with the measured compressed pulse duration in Fig. 2(b). Using a (sech)^2 temporal pulse envelope function, the bandwidth-limited pulse duration is ~85 fsec.

We have also tested the pulse compression technique using a pair of reflection gratings for comparative study. Using Eq. (1), when $r = 0$, $1/d = 600$ lines/mm, and $b = 60$ mm, the calculated dispersive parameter is ~45 fsec/nm. This calculation is also in good agreement with our experimental results. Equation (1) provides a good guideline for a pulse compression experiment to select the proper spatial frequency of the grating and the separation distance arrangement when the desired $\Delta\tau/\Delta\lambda$ is determined. The angular bandwidth (FWFM) $\Delta\theta$ and the spectral bandwidth (FWFM) $\Delta\lambda$ inside the medium of a volume phase transmission hologram can be approximate to be[15]

$$\Delta\theta \approx 2(d/t), \tag{2}$$

$$\Delta\lambda \approx 2(d/t), \tag{3}$$

where t is the thickness of the gelatin layer, and d is the spatial separation between the grating fringe. For holograms used in this experiment, d is ~0.8–0.9 μm, and t is ~8 μm. The angular bandwidth calculated from Eq. (2) is ~11.5°, and the spectral bandwidth calculated from Eq. (13) is ~1200 Å. In comparison to the laser output characteristics of this experiment, $\Delta\lambda_L = 40$ Å and $\Delta\theta_L \approx 0.2°$. The Bragg condition of high diffraction efficiency is assured from this combination.

By properly antireflection coating the air–glass surfaces, the absolute throughput from this transmission holographic grating pair compression arrangement can be >80%. Since we chose a simple transmission grating, there is little restriction on the wavelength used in the experiment as long as the wavelength is in the visible and near IR, which is outside the absorption region of the hologram. The alignment procedure is simpler than reflection gratings, and the damage threshold is higher. Using the hologram–mirror–translational stage arrangement, the pulse compression system can be inserted into our gigawatt femtosecond laser output and can be adjusted to the optimum grating separation distance when a shorter pulse duration is required.

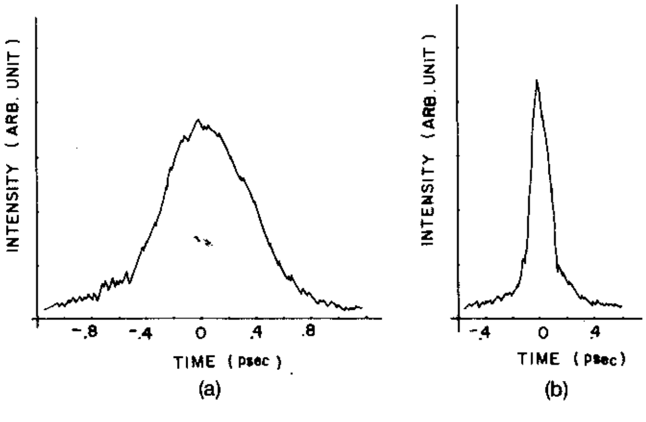

Fig. 2. Typical femtosecond laser pulse duration measured by a 0.3-mm thickness KDP second harmonic generation autocorrelator: (a) laser pulse duration with compression ($\lambda_L \approx 450$ fsec); (b) compressed laser pulse with a transmission grating pair separated by 12.5 mm. The spatial frequency of these two identical holograms is 1130 lines/mm. The pulse duration is ~85 fsec. The calculated pulse duration from the autocorrelation measurement is derived by fitting the second harmonic generation data with a (sech)^2 pulse envelope function.

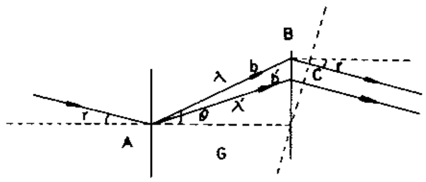

Fig. 3. Geometrical arrangement of the transmission grating pair pulse compression: G, separation distance between holograms; b, b', slant distance; r, incident and outgoing angle; θ, diffracted angle.

In conclusion, we have successfully demonstrated use of a volume phase transmission grating pair to compress femtosecond laser pulses. The dispersed gigawatt femtosecond laser pulse duration has been reduced to the bandwidth-limited value of 85 fsec. The dispersive parameter of the transmission grating pair based on the Treacy reflection grating pair approach is a good guideline for practical parameter adjustment. The use of high diffraction efficiency (80% absolute diffraction efficiency at the wavelength used), high damage threshold (GW/cm^2 peak power density), minimum optical alignment constraint, and low cost volume phase dichromated gelatin transmission holographic gratings can be integrated to the femtosecond laser technology for future photonic devices and other ultrafast laser spectroscopy applications.

Appendix: Derivation of Eq. (1) for a Transmission Grating Pair

The time for a laser pulse to travel the optical path ABC in Fig. 3 can be expressed as

$$\tau = \frac{b + b \sin\theta \sin r}{c}\,. \tag{A1}$$

The variation of pulse delay as a function of incident wavelength can be written as

$$\frac{\Delta\tau}{\Delta\lambda} = \frac{(1 + \sin\theta \sin r)}{c}\frac{\partial b}{\partial\lambda} + \frac{b \cos\theta \sin r}{c}\frac{\partial\theta}{\partial\lambda}\,. \tag{A2}$$

Using the grating equation,

$$\lambda = d(\sin r + \sin\theta), \tag{A3}$$

we can obtain

$$\frac{\partial\theta}{\partial\lambda} = \frac{\sec\theta}{d}\,, \tag{A4}$$

$$\frac{\partial b}{\partial\lambda} = \frac{G \sec^2\theta \tan\theta}{d}\,. \tag{A5}$$

Substituting Eqs. (A4) and (A5) into Eq. (A2), we obtain

$$\frac{\Delta\tau}{\Delta\lambda} = \frac{b(\lambda/d)}{cd(1 - (\lambda/d - \sin r)^2]}\,. \tag{A6}$$

References

1. E. E. Treacy, "Optical Pulse Compression with Diffraction Gratings," IEEE J. Quantum Electron. **QE-5**, 454 (1969).
2. I. P. Ippen and C. V. Shank, "Dynamic Spectroscopy and Subpicosecond Pulse Compression," Appl. Phys. Lett. **28**, 204 (1975).
3. R. H. Lehmberg and J. M. McMahon, "Compression of 100 ps Laser Pulse," Appl. Phys. Lett. **28**, 204 (1976).
4. R. L. Fork, O. E. Martinez, and J. P. Gordon, "Negative Dispersion Using Pairs of Prisms," Opt. Lett. **9**, 153 (1984).
5. D. Grischkowsky and A. C. Balant, "Optical Pulse Compression Based on Enhanced Frequency Chirping," Appl. Phys. Lett. **41**, 1 (1982).
6. C. V. Shank, R. L. Fork, R. Yen, R. H. Stolen, and E. J. Tomlinson, "Compression of Femtosecond Optical Pulse," Appl. Phys. Lett. **40**, 761 (1982); R. L. Fork, C. V. Shank, and R. T. Yen, "Amplification of 70 fs Optical Pulses to Gigawatt Powers," Appl. Phys. Lett. 41, 223 (1982).
7. J. G. Fujimoto, A. M. Weiner, and E. P. Ippen, "Generation and Measurement of Optical Pulses as Short as 16 fs," Appl. Phys. Lett. **44**, 832 (1984).
8. T. A. Shankoff, "Phase Holograms in Dichromated Gelatin," Appl. Opt. **7**, 2101 (1968).
9. S. K. Case, "Hologram Formation and Harmonic Generation in Dichromated-Gelatin Film," J. Opt. Soc. Am. **65**, 1220 (1975).
10. D. Mayerhofer, *Holographic Recording Materials*, H. M. Smith, Ed. (Springer, New York, 1977), Chap. 3.
11. R. A. Ferrante, "Dichromated Gelatin Volume Phase Recording Material," Master Thesis, U. Arizona (1980).
12. W. S. Colburn, R. G. Zech, and L. M. Ralston, "Holographic Optical Elements," Air Force Technical Report AFAL-TR-72-409 (Jan. 1973), p. 61.
13. R. L. Fork, B. I. Greene, and C. V. Shank, "Generation of Optical Pulses Shorter than 0.1 ps by CPM," Appl. Phys. Lett. **38**, 671 (1981).
14. P. P. Ho, A. Katz, R. R. Alfano, and N. H. Schiller, "Time Response of Ultrafast Streak Camera System Using Femtosecond Laser Pulses," Opt. Commun. (in press) **xx**, 000 (1985).
15. R. J. Collier, C. B. Burckhardt, and L. H. Lin, *Optical Holography* (Academic, New York, 1971), p. 252.

This work partially meets the requirement for a Master degree in electrical engineering for T. Yang. We thank Y. Budansky for technical assistance. This research is supported by NSF and AFOSR. A. Katz is supported by the Newport Research Award.