Experimental arrangement for a Two-Dimensional Thermo-Optical Phase Shaper

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Abstract

This report describes the setup and the characteristics of a two-dimensional phase modulator applicable for ultrashort laser pulse manipulation. The thermo-optical modulator is based on a change of the refractive index of a liquid layer with temperature. The temperature change in the liquid layer is generated by projection of an illumination pattern into the liquid layer containing a suitable absorber. Illumination is performed with a commercially available video projector.

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CONTENTS

I. INTRODUCTION

Programmable spectral phase modulation is a technique that is widely used in ultra fast optics [1]. There is a number of spatial light modulators (SLM) such as liquid crystal arrays, acousto optical devices and deformable mirrors that allow controlling almost all degrees of freedom of light. Another technique for SLM is thermo-optical phase modulation [2–4]. It is based on the variation of the optical path length due to a thermal modification of the refractive index. The thermal modification is reached by local absorption of light and thus heating of the medium. For heating the emission of a video projector is used. Heating results in a smooth spatial distribution of the refractive index. The ability of such a thermo optical phase modulator for ultra short pulse shaping has been successfully demonstrated by re-compressing a dispersion broadened femtosecond pulse [5]. By application of sinusoidal spectral phase modulations also multiple pulses have been generated. These experiments have been performed by placing the thermo optical phase modulator in the Fourier plane of a 4f zero dispersion stretcher that produces a line focus. With the line focus only modulations in one dimension have been possible.

There is, however, no restriction to use the ability of the device for modulation in two dimensions, too [4]. By lining up multiple spectra in the second dimension each of them can be manipulated individually. The superposition of this independent manipulated spectra offer more freedom in tailoring pulses than phase manipulation only.

In our report the experimental arrangement for two-dimensional modulations are described. Further on there are different improvements of the apparatus. The thermo optical phase modulator has been optimized in terms of stability and lower distortions. The set up has been adapted for two-dimensional use and a single shot FROG (Frequency Resolved Optical Gating) for characterization of the pulses has been constructed.

II. PRINCIPLE OF THE CELL

A. Temperature dependence of the refractive index of H_20

The refractive index of water varies significantly with temperature. The average thermal dispersion between 20C and 70C is about $-1.510^{-4}K^{-1}$ for a wavelength of 808nm [5]. This implies that the optical path length $L_{\mathrm{opt}} = L_{\mathrm{geom}}\ n$, given by the geometric path length L_{geom} multiplied with the refractive index n varies as a function of temperature. If there is a transversal temperature gradient in the liquid the phase of a transmitted laser pulse varies spatially.

B. Construction of the Cell

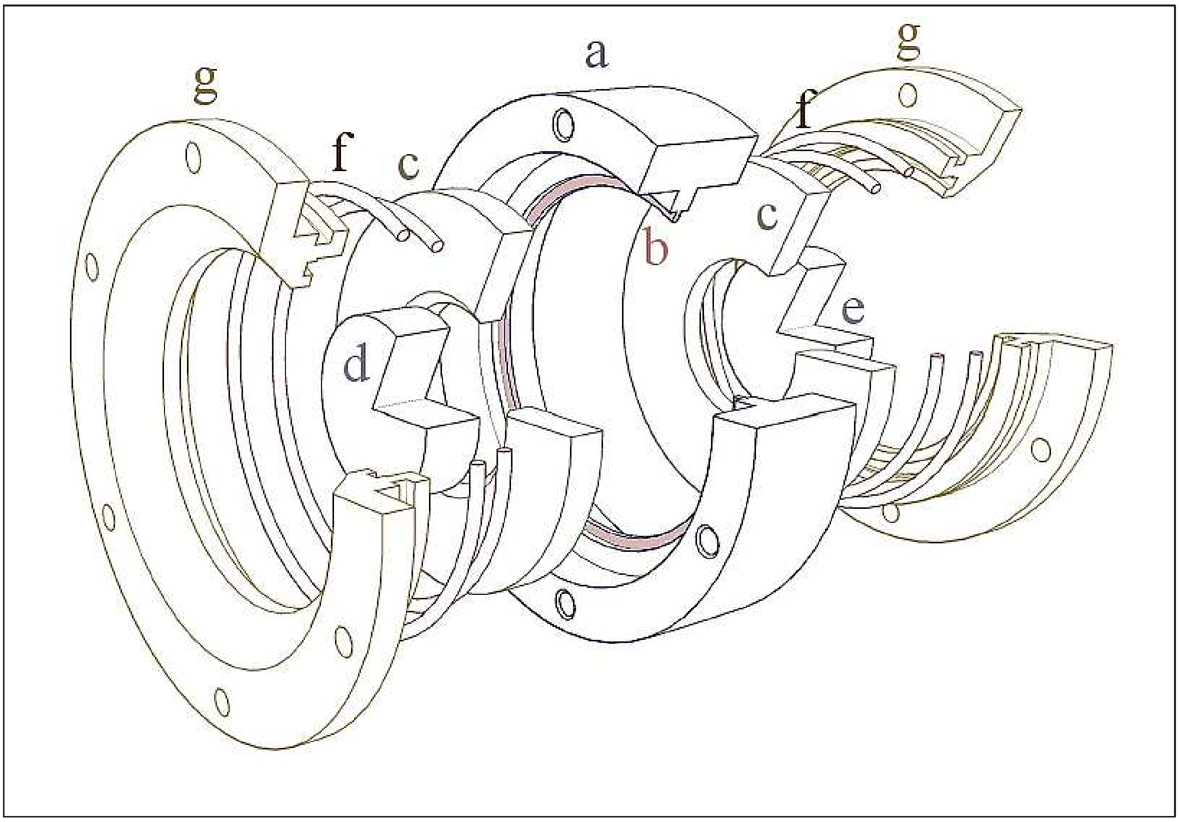


FIG. 1. Schematics of the phase modulator cell, it consists of the main body (a), window holders (c) with window/mirror (d, e), O-rings of viton to seal the cell (f) and the cover part (g). The spacer (b, red) defines the thickness of the liquid layer. The cell is hold together with six M6 screws on both sides.

We built a cell that consists of a water layer between a window and a mirror. This liquid is heated by illuminating with a video projector. The local intensity of the illumination pattern is controlled by gray scale values. For better absorption Rhodamine B is resolved in the water in a concentration of 14 mM. Transmission and absorption curves of the mirror, window and aqueous Rhodamine B solution can be found in [4]. In figure 1 the construction of the cell is shown. There is a main body (a) with a spacer (b, red) that defines the thickness of the liquid layer. In our current configuration the thickness of spacer and aqueous Rhodamine B solution is $1mm$ The window (d) and mirror (e), made of BK7 and polished to a flatness of $\frac{\lambda}{20}$, are glued stress-free into holder plates (c). Finally these plates are positioned between a cover part (g) and the main body (a) and sealed by two O-rings of Viton (f) on both sides. The cell is assembled with M6 screws. The fine control of parallelism of window and mirror can be adjusted by the tightness of these screws. The mounting point of the cell is exactly below the mirror surface. This is important with respect to long term stability of the phase modulator. It avoids changes of the mirror position and thus the phase due to heat expansion.

C. The Illumination Unit

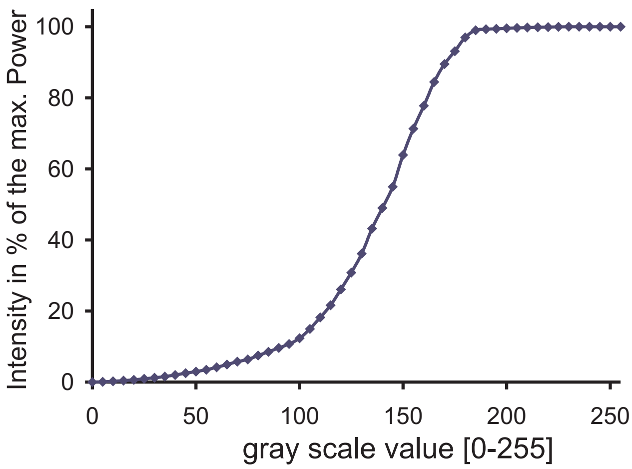


FIG. 2. Calibration curve for the irradiated power as a function of gray scale value

The illumination unit of the phase modulator is a commercial video projector (Acer PD725P) with partly removed internal optics. The primary picture produced by the projector is imaged into the liquid cell with a $f = 117mm$ lens of $120mm$ diameter. The size of the image is $12mm \times 16mm$. The maximum intensity at the image plane is $2.15\frac{W}{cm^2}$, it scales nonlinearly with gray scale values. A calibration curve to control the irradiated power is shown in fig 2. In the projector the light is generated by a $300W$ lamp that needs cooling by a fan. To suppress vibration transfer to the optical set up the projector is mounted on vibration damping buffers.

III. PULSE SHAPING SET UP IN A 4F STRETCHER

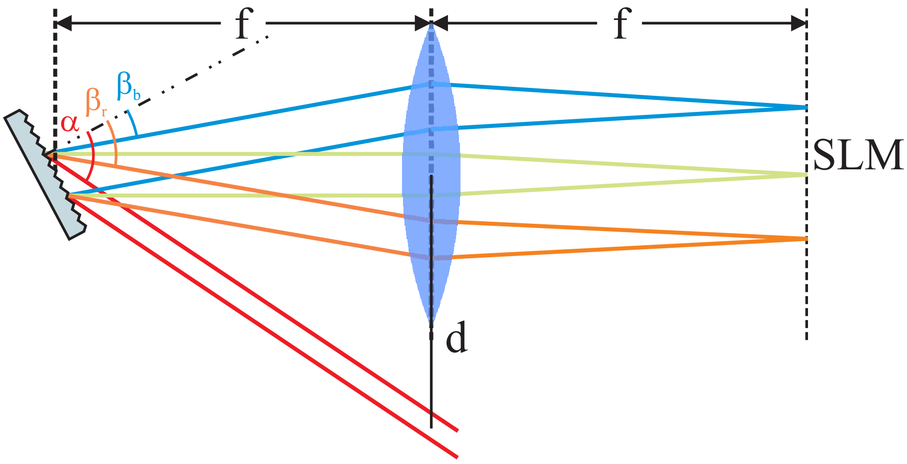


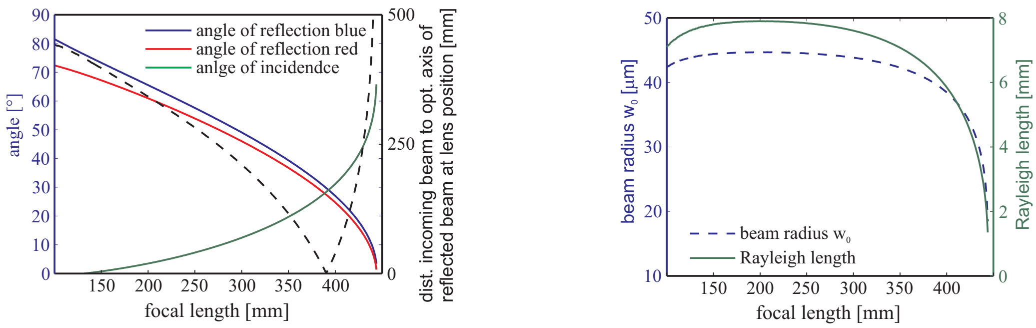
FIG. 3. A 4f stretcher in reflection, M marks the SLM

The principle of phase shaping of ultrashort pulses is based on individual manipulation of every single frequency in the spectrum of a pulse. Therefore a spatial spectral separation is needed. This is commonly done with a 4f stretcher where a grating or a prism serves as dispersive element. After the grating distinct wavelengths are diffracted with different angles and then focused by a lens. In the Fourier plane of this lens is a spatial map of the focused spectrum. Placing a phase modulator in this plane allows manipulating the different wave lengths individually.

A. The Choice of Grating and Lens

For the 4f stretcher the grating and the lens have to be chosen to fit the parameters of the laser system. We are working with $200fs$ pulses with a spectral bandwidth of $\Delta\omega = 10nm$

FWHM at a central wavelength of $794nm$. The width of the spectrum in the Fourier plane has to fit to the width of the shaping area that in our case measures $16mm$. If $3\Delta\omega$ is imaged on the modulator, 99.96% of the specral intensity is covered. Furthermore the Rayleigh range should be so large, that within the modulator the wavefronts can be considered as plane waves. The spot diameter gives the maximum of possible different wavelength points that can be modulated. In figure 4(a) the incident and reflection angles for a grating with $1200\frac{l}{mm}$ are plotted. The distance of the incident beam to the optical axis at the beam position shows if the configuration is possible without the lens blocking the incident beam. in figure 4(b) the focal radii and Rayleigh lengths for an incoming beam diameter of $5mm$ are shown.



(a) (b)

FIG. 4. (a) shows the combination of angle of incidence/reflectance together with the focal length for the spectrum to fit on the shaping area. The blue and red line correspond to β_b and βr in figure 3, the angle of incidence to α. The grating constant is $1200\frac{l}{mm}$. The dashed curve shows the distance from the incident beam to the optical axis of the reflected beam at the lens position (d in figure 3). In (b) the Rayleigh length as well as the beam radius in the focal plane are shown as function of focal length of the lens. The diameter of the beam before the grating is 5mm

B. Transfer function

The effects of a pulse propagation through different elements as well as the manipulation by a spatial light modulator can be described by Fourier optics where the effect of every element is given by its transfer function [6, 7]. These functions can be evaluated subsequently to express the pulse at a specific position. This chapter follows the steps in [6] In the setup of a zero dispersion 4f stretcher the input laser pulse just before the grating is describe by $\mathcal{E}(x;t)$ and its Fourier transformed field in the frequency domain by $\tilde{\mathcal{E}}(x;\Omega)$. Ω is the relative frequency $\Omega = \omega - \omega_c$ with respect to the central frequency. The direction of propagation is the z axis. For simplicity all elements are considered in a transmission mode, this means a transmission grating is assumed and the pulses are considered to transmit the modulator. Further on no tilt is introduced by the grating. The y-direction is chosen to be perpendicular to the table and is the axis parallel to the grating lines and the direction where the cylindric lens has no curvature. Therefore the y-components of the fields are not affected by the elements and in a first set are neglected. The transfer function of the first element, the grating, is characterized by

$$\mathcal{E}_{out} = \sqrt{b}\mathcal{E}_{in}(bx;\Omega)\exp(i\gamma\Omega x). \tag{1}$$

where $b = \frac{\alpha}{\beta_c}$ describes the change of the beam diameter as a function of the angle of incidence α and the diffraction angle of the central wavelength β_c. $\gamma = \frac{2\pi M}{\omega_c G\cos\beta_c}$ with the diffraction order M and the grating constant G. In our setup $M = 1$. After the grating the pulse propagates over a distance f. Propagation along f is described by

$$\tilde{\mathcal{E}}_{out}(k_x;\Omega) = \tilde{\mathcal{E}}_{in}(k_x;\Omega)\exp\left(-ikz + i\frac{f}{2k}k_x^2\right), \tag{2}$$

with k and k_x the wave vector and its x-component. An ideal cylindric lens with focal length f effects the field like

$$\tilde{\mathcal{E}}_{out}(x;\Omega) = \tilde{\mathcal{E}}_{in}(x;\Omega)\exp\left(\frac{ik}{2f}x^2\right). \tag{3}$$

With these three transfer functions the effect of the 4f stretcher can be evaluated. Spectral manipulation in the Fourier plane is described by a function $M(x)$. For the nonpixelated thermo-optical phase modulator this is simply a continuous function with specific phase for the transverse x position

$$M(x) = \exp(-i\Phi(x)). \tag{4}$$

Using eqs. (1)-(4) the field after the pulse shaper is given by

$$\tilde{\mathcal{E}}_{out}(x,\Omega) = \frac{ik_c}{bf}\, e^{4ik_c f} \int_{-\infty}^{\infty} dx'\, \tilde{\mathcal{E}}_{in}(x';\Omega)\, \tilde{M}\left(-\frac{k_c}{bf}(x-x')\right)\, e^{i\frac{\gamma\Omega(x-x')}{b}}, \tag{5}$$

or

$$\mathcal{E}_{out}(x,t) = \frac{ik_c}{bf}\, e^{4ik_c f} \int_{-\infty}^{\infty} dx'\, \mathcal{E}_{in}\left(x'; t+\frac{\gamma}{b}(x-x')\right)\, \tilde{M}\left(-\frac{k_c}{bf}(x-x')\right), \tag{6}$$

k_c is defined as $k \approx k_c = k(\omega_c)$ and $\tilde{M}(k_x)$ the Fourier transform of $M(x)$. For this transfer function the evolution of the y component has been regarded as free space propagation, i.e. the field does not vary in this direction. The ability of the thermo-optical phase shaper for manipulation in two dimensions allows for every value of y within the resolution to apply a different phase modulation function $M_y(x)$.

IV. DETECTION

A. Principle of a FROG

For controlling femtosecond pulses a diagnostics unit is necessary to measure the temporal and spectral properties of the pulses. There are different tools to do this (FROG [8], SPIDER[10], GRENOUILLE[9], TADPOLE[11]), we choose a single shot FROG (Frequency Resolved Optical Gating). In a FROG a spectrally resolved autocorrelation is measured. From the spectrogram the spectral/temporal phase is obtained. In our system we measure the second harmonic generated (SHG) in a non linear optical crystal. The pulse is split in two before and overlaps under an angle in the crystal, cf. figure 5. The advantages of a single shot frog is the absence of movable parts and the possibility of measuring in real time.

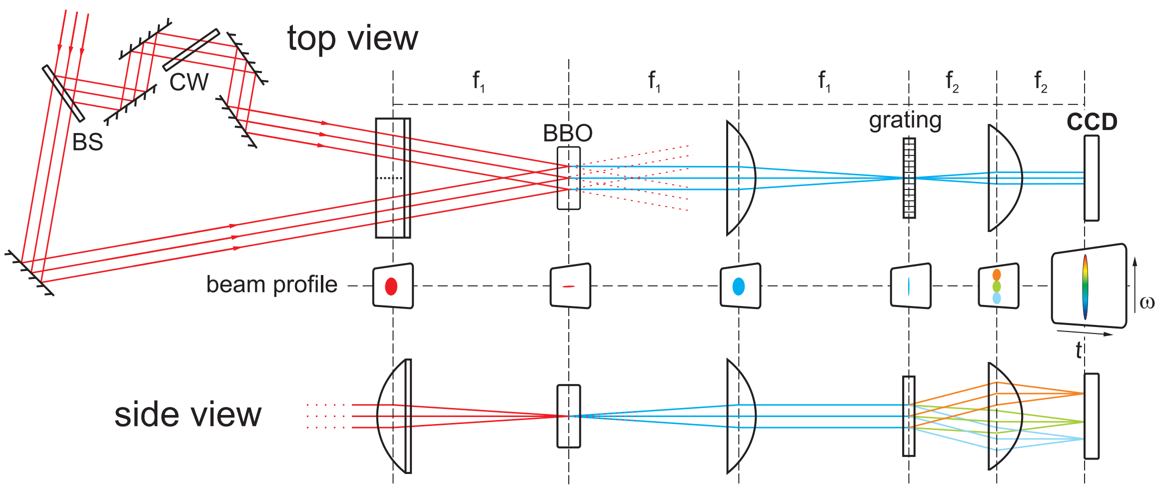


FIG. 5. Schematic set up of a single shot FROG. The beam is divided into two beams at a 50 : 50 beam splitter (BS). A compensation window (CW) assures that in both paths the same amount of dispersion is added. The pulses are focused by a cylindric lens into a non linear Beta-Bariumborat crystal (BBO). The horizontal axis (parallel to the table) of the SHG signal (top view) corresponds to the temporal axis and is imaged by a 4f image onto a CCD camera. In the vertical part (side view) of the SHG signal the spectral components are separated at a grating and focused onto the CCD camera.

B. System Parameters of Single Shot FROG

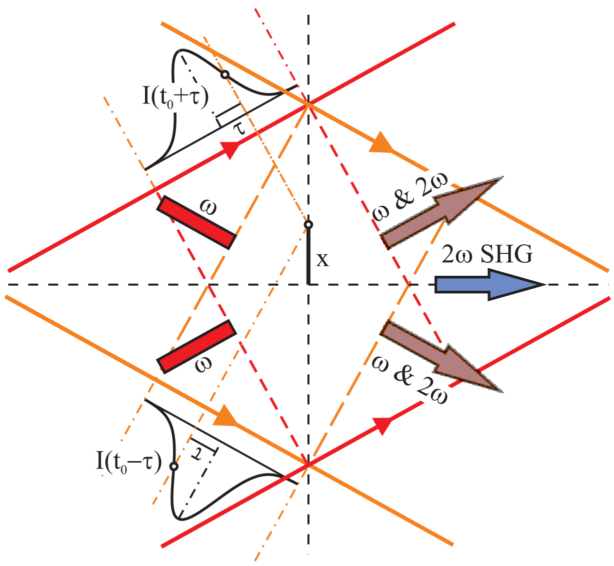


FIG. 6. Interaction of two pulses crossing in an SHG crystal. At a position x offset of the center the lower pulse arrives earlier than the upper one. The signal generated at this position is proportional to $I(t + \tau)I(t - \tau)$ with a delay τ depending on the x position.

The setup for the single shot FROG is shown in figure 5. The incoming pulse is divided in two parts by a 50 : 50 beam splitter of $2mm$ BK7 glass. Both parts are then horizontally focused with a $200mm$ cylindric lens into a BBO crystal of $50\mu m$ length. The two linefocii of about $8mm$ length overlap under an angle of 12 degrees. This corresponds to an internal angle in the BBO of 7.2 degrees. Two pulses crossing at a large angle lead to a transversely varying time delay due to the tilted wave fronts as illustrated in figure 6. The time window of our setup is approximately $3.3ps$. In one of the two paths is a delay stage for precision synchronisation. A compensation window of $2mm$ BK7 glass makes sure the same amount of dispersion is present in both paths. After the Beta-Bariumborat crystal (BBO) the horizontal axis (parallel to the table surface cf. figure 5 ,top view) of the generated second harmonic signal that corresponds to the time axis is imaged with a 4f image of a 200mm and a 100mm lens onto a CCD camera. In between there is grating with the grating lines aligned to act as a mirror for this orientation. The vertical axis (perpendicular to the table surface cf. figure 5, side view) of the second harmonic signal is recollimated by the first lens, then spectrally decomposed at a grating of $1800l/mm$. The individual wavelengths are

focused by the second lens onto the CCD camera.
For practical reasons, to keep the beam parallel to the table surface, there is a 90 degree beam rotator in front of the grating. This beam rotator is not shown in figure 5.

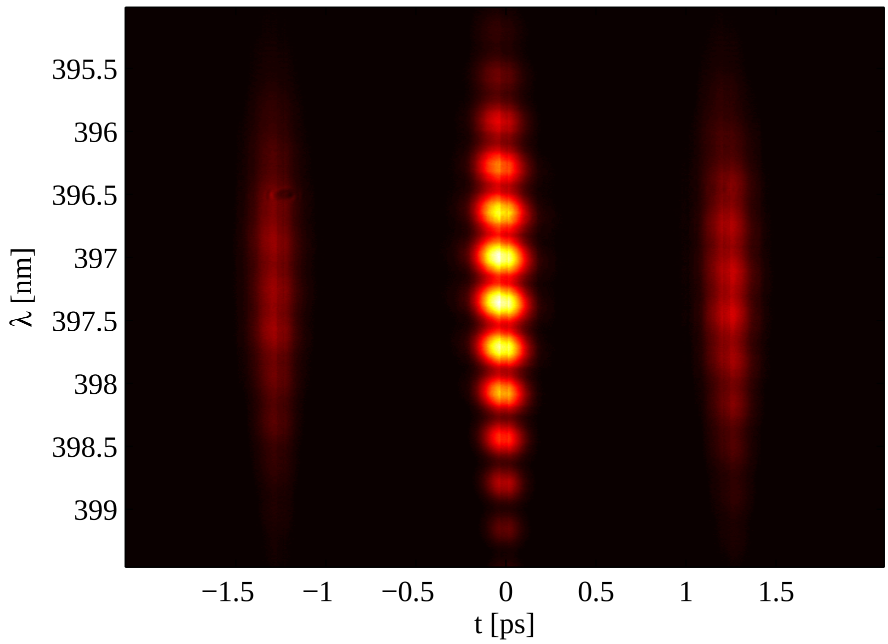


FIG. 7. FROG trace

A frog trace recorded for calibration purpose with a double pulse from the front and back surface reflection of a 150 nm glass plate is shown in figure 7. The two pulses are temporally seperated by $1.27ps$ and the temporal FWHM is $173fs$ the spectral FWHM $4.9nm$.

ACKNOWLEDGMENTS

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