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Spatio-temporal characterization of laser pulses by spatially resolved spectral interferometry

Caracterización espacio-temporal de pulsos láser por interferometría espectral resuelta espacialmente

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ABSTRACT:

We have implemented a Mach-Zehnder interferometer scheme to characterize the spatio-temporal amplitude and phase of ultrashort laser pulses. We perform spatially resolved spectral interferometry using a homogeneous plane beam as reference that is achieved after spatially filtering a replica of the test beam. We have tested our system and reconstruction algorithm with simulations and experiments. We study the limits of spectral interferometry in our system and, as an example, we reconstruct a linearly tilted beam. This method is expected to be used to characterize pulses with more complex spatio-temporal structure.

Key words: Spectral Interferometry, Laser Beam Characterization, Spatio-Temporal.

RESUMEN:

Se ha implementado un esquema usando un interferómetro Mach-Zehnder para la caracterización espacio-temporal de la amplitud y fase de pulsos láser ultracortos. Se ha llevado a cabo interferometría espectral resuelta espacialmente utilizando un haz plano homogéneo como referencia, obtenido después de filtrar espacialmente una réplica del haz a caracterizar. Hemos probado nuestro sistema y el algoritmo de reconstrucción por medio de simulaciones y experimentos. Se han estudiado los límites de la interferometría espectral en nuestro sistema y, como ejemplo, se reconstruye un haz con inclinación lineal. Se espera que este método se pueda usar para caracterizar pulsos con estructura espacio-temporal más compleja.

Palabras clave: Interferometría Espectral, Caracterización de Haz Láser, Espacio-Temporal.

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1. Introduction

The field of ultrashort laser beams characterization has achieved important advances during last years and it is very active due to the importance of the complete knowledge of the laser beam before or after a certain experiment. Nowadays, the pulses can be fully known in temporal domain by using current standard techniques such as spectral interferometry (SI) [1], Frequency Resolved Optical Gating (FROG) [2] or Spectral Phase Interferometry for Direct Electric-field Reconstruction (SPIDER) [3]. In spatial domain, the amplitude and phase (wave-front) can also be characterized with well-known techniques [4,5]. However, the coupled measurement in space and time still remains an open field. Some approaches have been done with spatially resolved spectral interferometry but only to characterize the difference of phase introduced by an optic system or other processes and not to obtain the spatio-temporal intensity reconstruction [6,7]. To our best knowledge, the first complete reconstruction was performed by Diddams et al. [8] using a Mach-Zehnder interferometer but neglecting the phase of the reference beam. The same idea was applied by Amir et al. [9] who also assumed constant spatio-spectral phase of the reference and characterized it on axis.

During the last years, some novel schemes have been introduced to study the spatio-temporal structure of laser beams. For example, spatially-resolved temporal autocorrelation has been applied by Trull et al. to measure complex pulses produced by nonlinear propagation [10] whereas amplitude and phase reconstructions have been made with SEA TADPOLE [11]. Other developed methods are based on holographic techniques as STRIPED FISH [12], two dimensional spatio-spectral shearing [13] or Hartmann-Shack sensor [14].

The aim of our work is to implement a system for spatio-temporal amplitude and phase characterization of laser beams based on spatially-resolved spectral interferometry using a Mach-Zehnder interferometer and involving a homogeneous reference beam. The motivation of this work is to characterize complex spatio-temporal structures such as those arising from nonlinear processes (e.g. in filamentation), or special beams as solitons or vortices. We do not regard polarization thus only measuring linearly polarized beams.

2. Spectral interferometry

The SI is a method for ultrashort laser pulses characterization that needs the previous knowledge of a reference pulse. It consists in measuring the spectral interferences of two delayed collinear pulses, test and reference. The total spectrum is the sum of each pulse spectrum and an interferential term oscillating with period inverse to the delay τ (see Fig. 1) and codifying the phase difference of the pulses, as expressed in the equation

$$S = S_{ref} + S_{test} + \\ + 2\sqrt{S_{ref} S_{test}} \cos(\phi_{test} - \phi_{ref} - \omega\tau), \quad (1)$$

where S and ϕ represent the spectrum and the phase as a function of the angular frequency ω (or equivalently the wavelength λ). The sign criterion corresponds to reference always traveling before the test pulse. The reference spectrum must be at least as large as the test spectrum in order to obtain phase information for the whole test spectrum. The amplitude of test and reference pulse should be similar to have well contrasted fringes.

The test pulse phase is retrieved by Fourier-Transform Spectral Interferometry (FTSI) algorithm [15]. First, an inverse Fourier-transform is applied to the interferential spectrum thus in time domain yielding three peaks. One peak is centered in t=0 corresponding to the continuum contribution of each pulse spectrum, and the other two centered at $t=\pm\tau$, coming from the interferential term. The test and reference spectra can be subtracted before this step to get rid of the central peak. Then, one lateral peak is filtered with a numerical gate. By Fourier-transform, the pulses phase difference $\phi_{test}-\phi_{ref}$ is directly obtained in frequency domain. Thus, if the reference pulse is characterized, the test pulse phase is retrieved, so the amplitude and phase (complete information) of the test pulse is known if also measuring the test spectrum. Any error in the reference phase characterization would be translated to the test phase retrieved and thus to the pulse reconstruction. The delay τ is limited below because of separation of the peaks in time domain and above because of spectrometer resolution due to the period of the fringes.

The one dimensional SI described above can be extended to spatial domain by measuring the spectral interferences of delayed test and reference beams (see Fig. 2) across the transverse dimensions $S(\omega,\vec{r})$. The FTSI algorithm is applied to each spatial point and thus the phase difference between the arms is obtained as a function of the wavelength and the transverse dimensions. In order to know the reference spectral phase $\phi_{ref}(\omega,\vec{r})$, a homogeneous plane wave can be used as reference beam assuming that the phase is not dependent on the spatial position $\vec{r}$ and characterize it in a single point (on axis) with standard device for ultrashort pulses measurements as FROG or SPIDER.

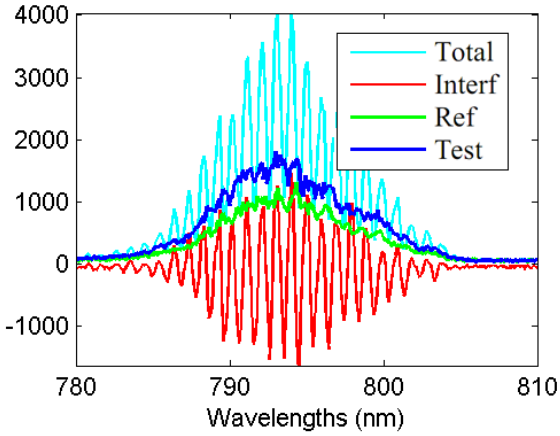

Fig. 1. Experimental spectra in spectral interferometry: total (cyan), reference (green), test (blue) and interferential term after continuum subtraction (red).

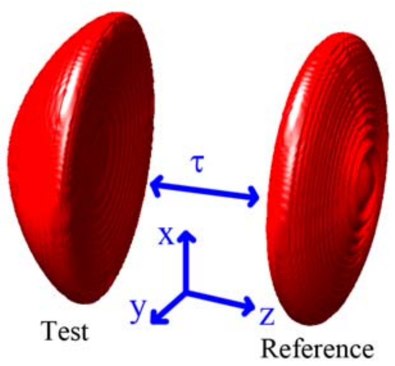

Fig. 2. Scheme of spatially resolved spectral interferometry. A homogeneous beam is used as a reference for each transverse position.

In our experiments and simulations, we will restrict ourselves to study one transverse dimension x. This scan provides enough information when characterizing beams with cylindrical symmetry.

3. Simulations

We have implemented spatially resolved SI simulations to study the FTSI limitations and also to test our reconstruction algorithm. We generate the interferential, test and reference spectra and express them in the same form than the data acquired in the experiment, that is, with the same resolution than the spectrometer limit. Then, we apply the same reconstruction algorithm we use with the experimental measurements.

First, we have done parametric studies of SI varying the delay, the reference spectral bandwidth, the test chirp and the relative amplitude. We have found that the delay can be chosen between a wide range from few hundred femtosecond (limited by the pulse width) to several picoseconds because our spectrometer resolution of Δλ=0.1 nm gives information up to t_{max}=10.8 ps. The test chirp was studied through negative and positive group delay dispersion (GDD) up to 80000 fs^2 (it corresponds to a pulse stretching of $FWHM$ = 2 ps) and we did not find limit in that range. Obviously, when the reference spectrum is narrower than the test spectrum it produces wrong reconstructions.

As an example, we show the simulation of the reconstruction of a very positively chirped pulse of 100-fs duration but also with much smaller spectral amplitude than the reference. The pulse used to generate the simulation is represented in blue in Fig. 3, whereas the FTSI retrieved pulse is represented in red (the red curve almost overlays the blue one due to the good agreement). We represent the intensity that is retrieved perfectly as well as the instantaneous wavelength calculated as the derivative of the temporal phase, observing slight differences for the extreme wavelengths where the fringes are less contrasted.

In order to test spatio-temporal non trivial beams, we simulate a test beam being the spatio-temporal interference of a plane and a spherical wave of 100-fs duration each. In Fig. 4(a), we represent the interferential spectrum between the reference beam (2-ps delayed) and the test beam. We represent it as a function of one spatial dimension varying from the center of the beam to the periphery. The fast oscillations in the wavelength dimension are due to the spectral interferences with the reference beam. These interferences have two types of evolution respect to the position, a quadratic one due to the spherical wave and a constant one due to the plane wave. The fringes in the position dimension are caused by the spatial interference of the plane and spherical wave. In Fig. 4(b), we show the test beam intensity FTSI reconstruction (we have checked that it matches the beam used to generate the simulation). The spatial interferences are observed, verifying that the maxima and minima get closer in the periphery as expected due to quadratic variation of the spherical wave, i.e. slower change in the center of the beam (the contrary effect for the fastest variation is due to the resolution in position).

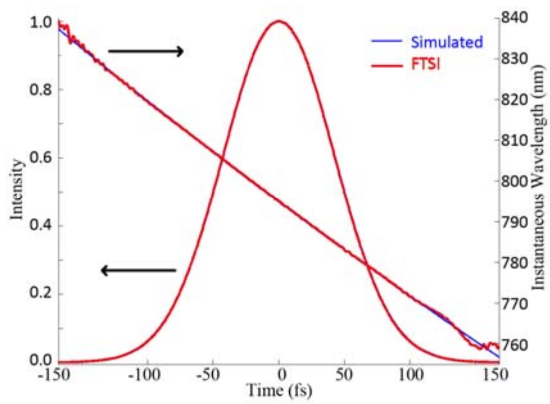

Fig. 3. Intensity and instantaneous wavelength of strongly chirped pulse simulated (blue) and FTSI retrieved (red).

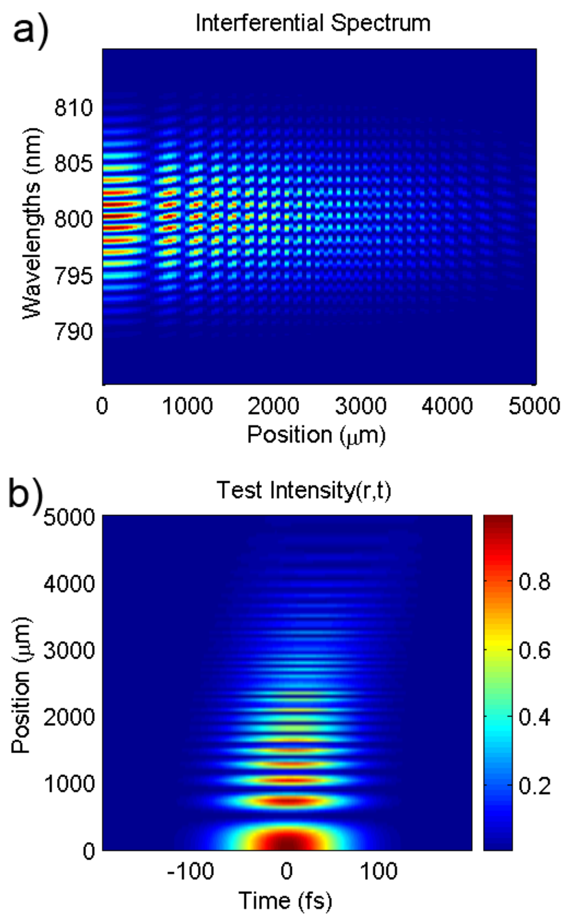

Fig. 4. Simulation of the spatio-temporal interference between a plane and a spherical wave: interferential spectra (a) and FTSI retrieved test intensity (b).

4. Experimental setup

For the experiments we have used a Ti:Sapphire CPA laser system (Spectra Physics) delivering 120-fs pulses centered at 795 nm with a repetition rate of 10 Hz. The temporal characterization of the reference beam has been done with a GRENOUILLE device (single-shot FROG, Swamp Optics). The spectrum has been measured with a standard spectrometer (AVANTES). A multi-wave interferometry device has been used to characterize the wave-front (PHASICS). If the delay is appropriately chosen as discussed before, the SI gives the full phase difference and the error in the measurement is given by the reference calibration precision.

The experimental setup scheme is presented in Fig. 5. We use a standard Mach-Zehnder type interferometer. The unknown beam to be characterized is split into two arms. A delay stage in the test arm controls the relative delay between test and reference. The reference arm is spatially filtered in order to have homogeneous reference beam. Then, both beams are aligned and sent collinearly to the detection devices. We check the filtered reference wave-front flatness and measure the required temporal phase of the reference. The spatially resolved spectrum is measured using a motorized stage in small steps at the same time of acquiring the spectrum. We measure the test, reference and interferential spectrum as a function of the spatial position.

The spatial filter consists in a system of two lenses 2-f separated and a pinhole in the intermediate focus that filters the beam profile. In Fig. 6(a) and (b), we represent the spatial profile of the reference beam without and with filter respectively, showing the beam cleaning done by the pinhole. We also have characterized the reference wave-front without and with the filter and found that is flat enough for our requirements when the spatial filter is used (Fig. 6(c) and (d) respectively). Notice the improvement in the wave-front flatness (the color scale is different in Fig. 6(c) and (d)). However, the use of a spatial filter is not an easy issue at all. There are some problems arising from different concerns. For example, the high intensity at the focus can produce nonlinear effects. Moreover, the diameter of the pinhole has to be adapted for each beam and sometimes the position of the second lens has to be changed to correct for some convergence or divergence. Finally, we have also observed that certain beams coming from nonlinear processes have a very complex structure that cannot be perfectly filtered out with this scheme. Notice that we use as reference beam a filtered replica of the test beam because when characterizing nonlinear processes we need a reference with the same spectrum.

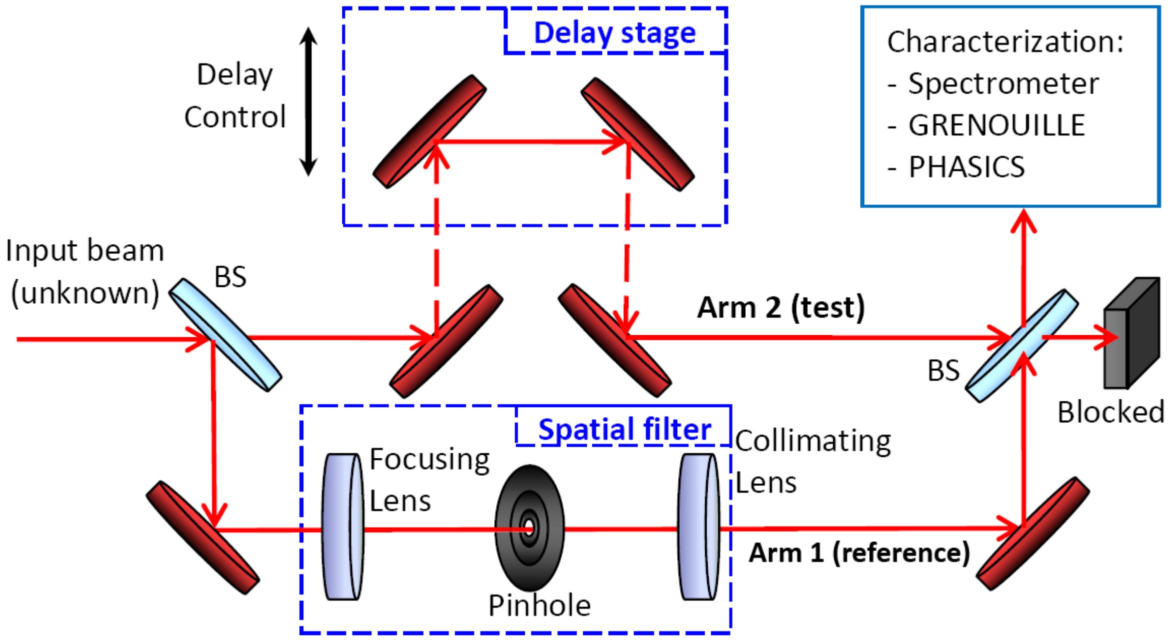

Fig. 5. Experimental setup for spectral interferometry. The unknown beam is divided and recombined in a Mach-Zehnder type interferometer. The reference beam is spatially filtered and the relative delay is controlled. BS = Beam splitter.

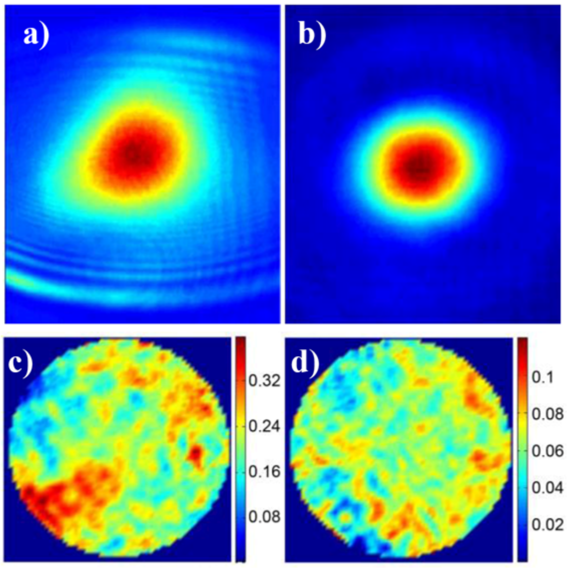

Fig. 6. Spatial profile of the reference beam without (a) and with (b) filter. Wave-front of the reference beam without (c) and with (d) filter: color scale is phase (rad).

5. Experimental measurements

The range of application of the system depends on the spectrometer resolution and spectral bandwidth of the test pulse. As sais before, our spectrometer resolution is $\Delta\lambda$=0.1 nm (that corresponds to t_{max}=10.8 ps after Fourier-transform). In this case, the upper limit for unchirped gaussian pulses is 1 ps duration (FWHM) because longer pulses would have very narrow spectrum preventing enough resolved fringes regardless of the delay. Longer pulses could be measured with better spectral resolutions. The lower limit for pulse duration is given by the spectral bandwidth of operation of the spectrometer and the optics, and the reference characterization.

We have performed experimental measurements to test the spatio-temporal reconstruction system. First, we have done a scan varying the delay between the reference and the test pulse from −5.7 to +9.0 ps. In Fig.7(a) we show the interferential spectrum as a function of this delay seeing how the period of the fringes varies (it is proportional to the inverse of the delay). The interferential beating is faster for the highest delays and around zero delay the fringes vanish. In Fig. 7(b), we show the magnitude of the delay retrieved by FTSI (red marks) depending on the introduced delay and compare to the expected value (blue line). We find excellent agreement except for the zero delay because in this case the side peaks and the central peaks overlap in time domain after Fourier-transform. We have also proved the pulse reconstruction for the different delays.

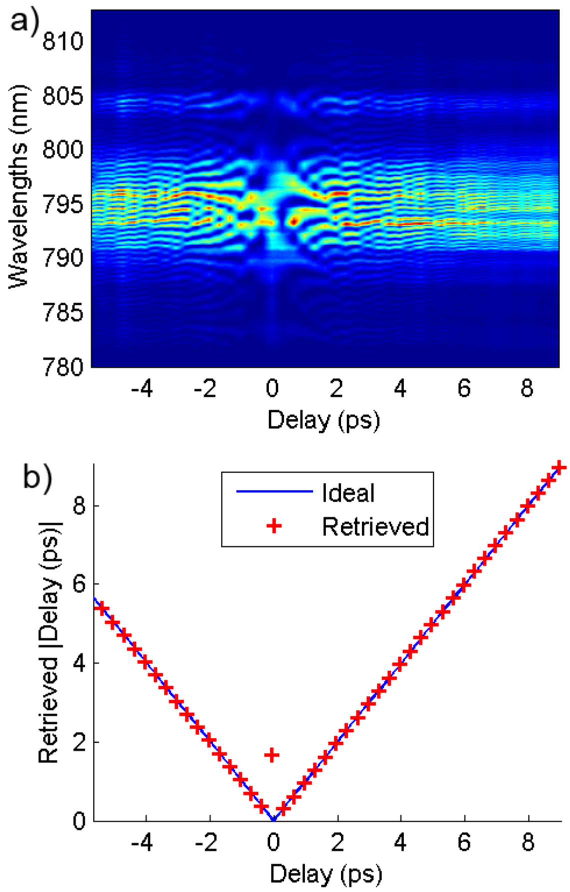

Fig. 7. Delay scan experiment: interferential spectrum (a) and retrieved delay (b) as function of the introduced delay.

In a second experiment, we make the test beam pass through a half-beam plate what represents that half beam is delayed respect to the part that does not go through the plate as illustrated in Fig. 8(a). The difference of delay $\Delta\tau$=1671 fs introduced by the plate is calculated from $(n-1)L = c\cdot\Delta\tau$ where L=1.1 mm is the thickness of the plate and n=1.454 is the refractive index of the fused silica at wavelength λ=795 nm. In Fig. 8(b) we show the interferences as a function of the scanned transverse position seeing the variation of the fringes period in the two regions. In Fig. 8(c), the FTSI retrieved delay is represented giving clear proof of the delay jump. The mean of the delays obtained by FTSI in each region is respectively τ_1=1757 fs and τ_2=3453 fs. Thus, the experimental difference of delays between the two regions is $\Delta\tau$=1696 fs, that is in good agreement with our estimation with the plate characteristics.

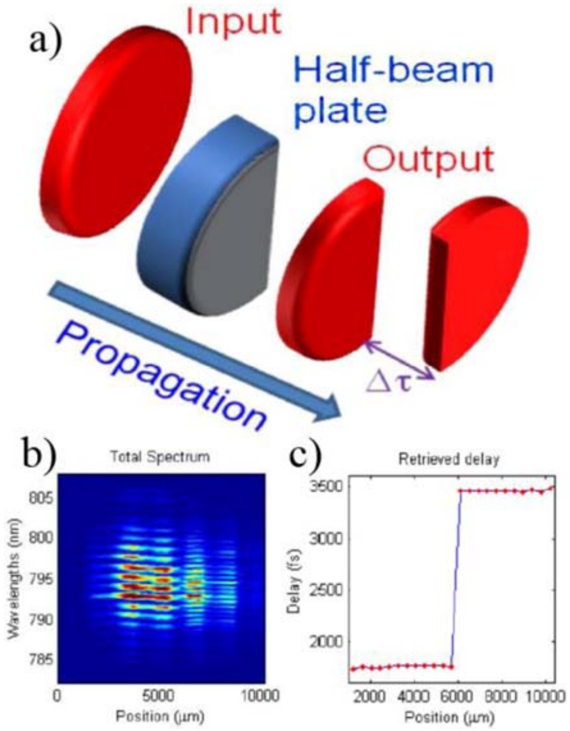

Fig. 8. Half beam plate experiment: a plate that delays half test beam (a). Interferential spectrum (b) and retrieved delay (c) as a function of the position.

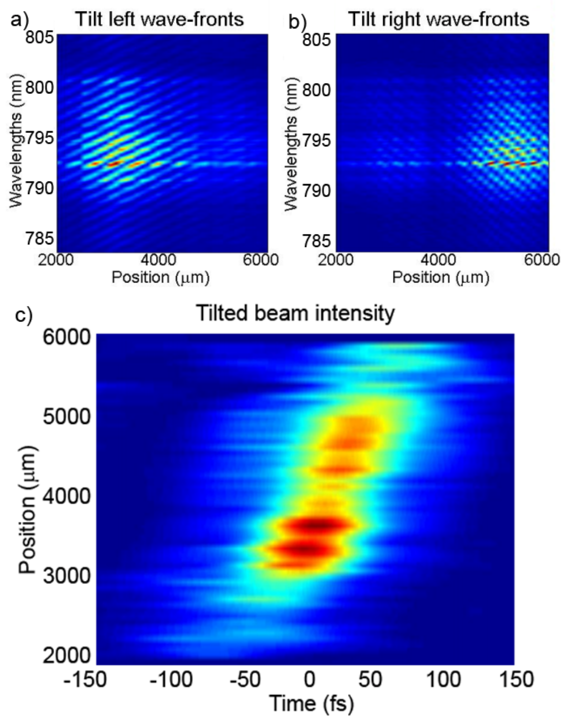

Fig. 9. Experimental spectral interferences for different side, (a) and (b), linearly tilted test beams. Spatio-temporal intensity reconstruction of a tilted test beam (c).

We have measured a test beam linearly tilted (just crossing at an angle) respect to the reference beam. The interferential spectrum traces for two opposite tilt cases are shown in Fig. 9(a) and (b), presenting the expected fringes variation with the position. In Fig. 9(c), we show the spatio-temporal intensity reconstruction of the tilt case corresponding to Fig. 9(a). We have checked that the retrieved tilt is in agreement with the introduced tilt (calibrated from the spatial interferences with the reference in zero delay) and the fringes tilt in the spectral trace.

We have also measured convergent and divergent beams and found their opposite quadratic variation of the fringes with the position scan in agreement with our simulations.

The typical temporal duration of a spatial scan is one minute, depending on the number of points. The algorithm of reconstruction can be done in situ and also takes around one minute.

6. Conclusions

We have developed an interferometric device (Mach-Zehnder) to perform spatially resolved spectral interferometry. This system allows us to measure spatio-temporal amplitude and phase of ultrashort laser beams.

We have shown our system and reconstruction algorithm through simulations and experiments. We expect this method to be used to characterize more complex spatio-temporal coupled beams.

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