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Devrelis, Vladimyros; O'Connor, Martin; Munch, Jesper.

Coherence length of single laser pulses as measured by CCD interferometry, *Applied Optics*, 1995; 34 (24):5386-5389.

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17th December 2010

<http://hdl.handle.net/2440/12383>

Coherence length of single laser pulses as measured by CCD interferometry

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A novel interferometric method for the direct, real-time measurement of the complete temporal coherence function of a pulsed laser is presented. A Michelson interferometer is modified by replacing one mirror with an inclined diffraction grating to observe interference fringes as a function of path-length difference on a single pulse. Computerized data acquisition and methods of extending the range of wavelengths to the infrared are discussed.

Key words: Coherence length, interferometry.

1. Introduction

In some experiments it is necessary to measure the complete coherence function of a single laser pulse. Until now, the only method available was the holographic approach we discussed in Ref. 1. In that approach, a hologram of an inclined plane is recorded with the laser to be diagnosed. When the resulting hologram is reconstructed, the intensity distribution of the resulting image of the inclined plane can be used to determine the complete coherence properties of the single laser pulse. Although this method works well, it is limited to parts of the spectrum where holographic emulsions function, and it is not convenient, real time, or suitable for modern experiments in which lasers operate at high-pulse-repetition rates with computerized data-acquisition systems.

In this Note we discuss a novel approach that solves all the limitations of the holographic method while retaining the fundamental measurement capability. As we show, the new method is an interferometric method that records in digital form the direct interference fringes for all path-length differences on a single laser pulse, as well as the transverse intensity distributions of the individual interfering beams. Although the optical layout has many similarities with the holographic method of Ref. 1, the new method differs significantly in its direct measurement of the fringe visibility as opposed to the holographic method, in which the coherence function was re-

trieved from the brightness distribution of the reconstructed image.

The present interferometer was developed as a diagnostic instrument for experiments on optical phase conjugation by the use of stimulated Brillouin scattering. The experiments are a continuation of those described in Ref. 2, which at that time led to the development of the holographic approach. The present experiments investigate the effect of intermediate coherence lengths on simulated Brillouin scattering with a pulsed Nd:YAG laser operating at 1.06 μm and a pulse-repetition rate of 10 Hz. At this wavelength, conventional holograms are difficult to make. Furthermore, for intermediate values, the coherence length is rarely exactly reproduced from pulse to pulse, because of the weak axial mode control used. We thus need a new, convenient method to measure the complete coherence function for each laser pulse at infrared wavelengths, and the present method satisfies all these requirements. There are other methods for measuring coherence length, including the original Michelson approach,³ étalons,⁴ and phase conjugate interferometers.⁵ None of these methods can yield the complete coherence function on a single laser pulse, and they are only suited for use on cw lasers where path lengths or étalon spacings can be scanned as a function of time. An additional method often used for single pulses is the temporal pulse shape, but this method is not reliable, as discussed in Ref. 1.

2. Approach

The temporal coherence function of a source is usually determined from an observation of the visibility of the interference fringes formed as a function of path-length difference when two parts of the source

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Received 26 July 1994; revised manuscript received 3 April 1995.
0003-6935/95/245386-04\$06.00/0.

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are made to interfere with each other.⁴ Thus, for two beams of intensity I_1 and I_2 interfering with each other with a path-length difference l , the normalized interference pattern $I_N(l)$ can yield the visibility $V(l)$ and hence the mutual coherence function of the two beams, $\gamma_{12}(l)$, from

$$I_N(l) = \frac{I_1 + I_2 + 2\gamma_{12}(l)\sqrt{I_1 I_2} \cos kx}{I_1 + I_2}$$

$$= 1 + V(l)\cos kx,$$

with

$$V(l) = \frac{2\gamma_{12}(l)\sqrt{I_1 I_2}}{I_1 + I_2},$$

where all intensities are functions of the transverse coordinates (x, y) and k describes the interference pattern in one dimension (fringes are parallel to the y axis in this case).

This measurement is usually done for a continuous source by measurement of $V(l)$, I_1 , and I_2 for different values of l in a Michelson interferometer. The challenge for a pulsed source is to include all possible values of l in a single pulse. This was accomplished in the holographic method by using a diffuse inclined plane. In an interferometer we need an inclined specular reflector of good optical quality to produce recognizable interferometric fringes. Small strips of mirror placed at different values of l could be used to produce a discontinuous sample of the coherence function. We chose a better method, making use of a blazed diffraction grating in a Littrow mount. The grating is a high-quality optical element that can produce interference fringes that are observable with a CCD camera.

The concept is illustrated in Fig. 1, which shows a Michelson interferometer with the inclined grating in one arm. There is a line on the grating marked D for which the path lengths of the interferometer arms

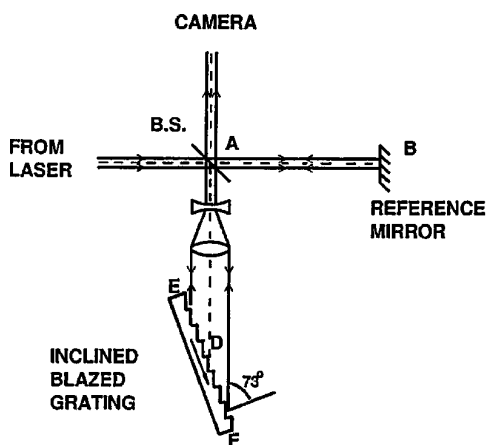
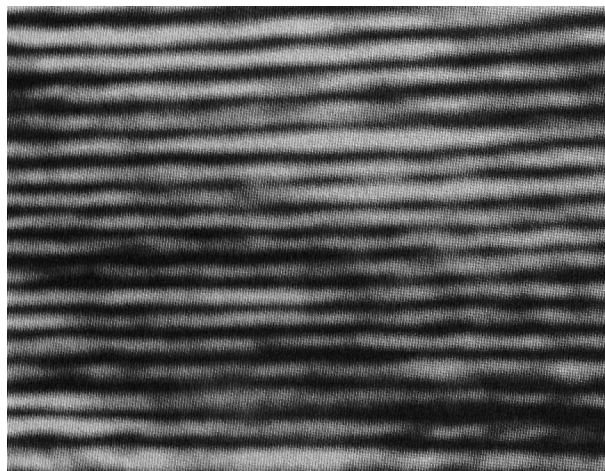
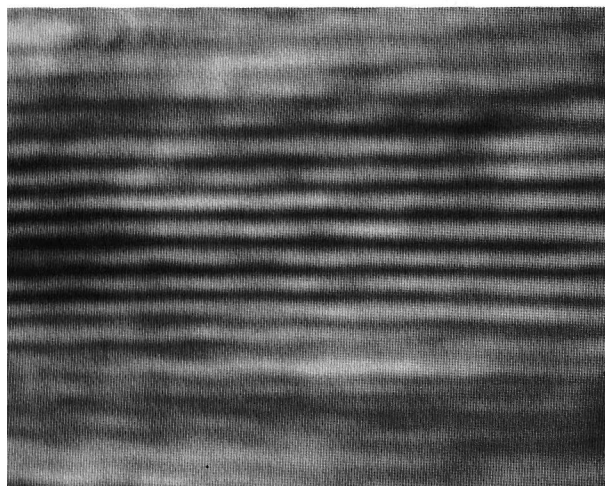


Fig. 1. Michelson interferometer with a blazed diffraction grating as one of the reflectors. The optical path lengths AB and AD are equal. Interference produced from lines E and F corresponds to shorter and longer path-length differences, respectively. B.S., beam splitter.

are equal. Excellent fringe visibility will result from light reflected from this part of the grating. Light from other parts (E and F) on the inclined grating will take shorter or longer times to reach the interference plane on the CCD camera. The visibility of the interference fringes from these parts will therefore depend on the coherence length of the laser. The instantaneous, complete coherence function can thus be observed as the visibility of the fringes along the grating as seen on the TV monitor for each pulse. This direct observation of the coherence function is especially useful when one is adjusting intracavity étalons in the laser resonator to produce intermediate coherence lengths. When permanent data are required, the computer can grab and store the fringe pattern. When appropriate masks are used to cover parts of the reflectors, independent measurements of slices of the intensity distribution of each of the interfering beams together with the interference pattern can be obtained on a single frame. Cross-



(a)



(b)

Fig. 2. Typical interference patterns observed on the TV monitor: (a) long coherence length, (b) short coherence length. The horizontal center line on each figure corresponds to path-matched interference. Above the center line corresponds to shorter paths (region E in Fig. 1), and below the center line corresponds to longer paths.

sectional intensity profiles of the interfering beams and the interference pattern are obtained from columns of the digitized frame, and from these data the complete coherence function can be calculated.

The grating used was 210 mm long, with 600 lines/mm, and blazed at 17°. We needed an inclined plane as long as possible along the beam and made use of the fact that for the 90° groove shape often used on gratings, the diffraction efficiency is high at both the blaze angle and its complement. The grating was thus reversed and used with an angle of incidence of 73°, as shown in Fig. 1. A telescope was used to expand the beam to fill the grating. The closest and furthest points on the grating along the direction of the laser beam were separated by 200 mm, allowing coherence lengths of up to 400 mm to be measured with the setup shown.

3. Results

Typical examples of long- (injection-seeded) and short- (no axial mode control) coherence-length fringe patterns are shown in Fig. 2. The uneven intensity distribution is due to transverse variations in the intensity of the two interfering beams, $I_1(x, y)$ and $I_2(x, y)$. By recording I_1 and I_2 separately, one can still obtain the mutual coherence function $\gamma_{12}(l)$ as discussed above. This unevenness, together with the high contrast of Fig. 2, tends to mask the envelope of the interference fringes used for real-time observa-

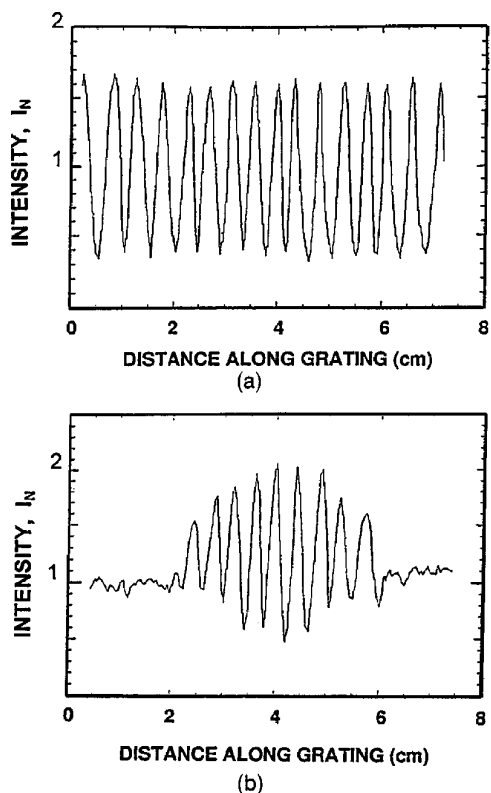


Fig. 3. Plot of the normalized intensity distribution obtained from a single column of the digitized frame showing the resulting fringe visibility as a function of path-length difference along the grating for the interferograms shown in Fig. 2. (a) long coherence length, (b) short coherence length.

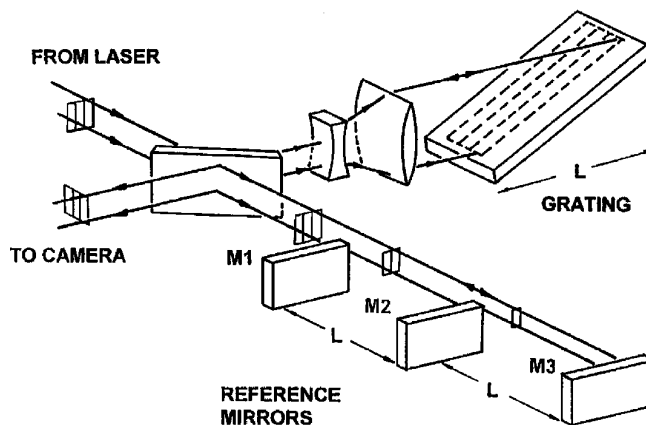


Fig. 4. Experimental arrangement with multiple reference mirrors (M1, M2, M3), used to extend the effective range of the coherence lengths measurable with a single grating. For a continuous coherence function, the separation of the mirrors should be L , the length of the grating along the beam.

tion of the coherence length, but on a TV monitor, it was readily observable. Plots of the normalized interference pattern, $1 + V/I \cos kx$, for the data shown in Fig. 2 are shown in Fig. 3. In Fig. 3 the envelope of the interference pattern is the mutual coherence function, and the coherence length is defined as the path-length difference required for reduction of the visibility by a factor of 2 as compared with the path-matched condition.^{3,4} From Fig. 3 the coherence length of the multimode pulse can be seen to be 17 mm, and the coherence length of the injection-seeded pulse exceeded the maximum length measurable (>0.4 m). In a separate experiment the long coherence length was determined to be 3 m (see below). The noise and the lack of symmetry of the fringes shown are believed to be the result of imperfections in the normalizing procedure and variations in the intensity from pulse to pulse. For our purposes, this is not considered a limitation and can be improved by recording all intensities required on each pulse, as suggested above, and by improving the statistics by averaging adjacent pixel columns.

The coherence length measurable in the system shown is limited by the length of the grating. This limitation can easily be overcome by additional reference mirrors arranged in such a way as to create narrow slices of the grating, each slice representing further samples of path-length difference, as shown in Fig. 4. These slices can form a continuous coherence function by separating the mirrors by the grating length as shown or can yield piecemeal samples in the case of very long (e.g., 3 m) coherence lengths.

4. Concluding Remarks

Using components found in most modern optics laboratories, we have assembled and demonstrated a simple diagnostic tool that can record the complete coherence function of a single laser pulse. The method permits real-time observations of the whole visibility pattern and is capable of producing near-real-time coherence functions, which are limited by the

speed and the capacity of the computer frame grabber. The method is useful over the whole range of visible and infrared wavelengths in which CCD cameras and other imaging arrays function.

This work was supported in part by research grants from the Australian Research Council and the Defence Science Technology Organization.

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