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Dual integrated laser interferometer for fringe projection techniques

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Abstract. An integrated optical system being the basis of proposed solution of dual laser interferometer composed of two integrated Michelson's interferometers is presented and shortly discussed. Such an integrated system is designed for obtaining simultaneously two sets of plane parallel fringes. These two, in general different-colour sets of fringes, are projected in a mutually orthogonal way onto the surface of the object tested. Alternatively, the fringes can be generated by using two independent aperture masks. Using, simultaneously, such two orthogonal, distinguishable sets of projected fringes enables to perform mapping of dynamically changed surfaces and deformations of objects under investigation with a similar resolution in both orthogonal directions. The picture of resulting dual-colour grating is recorded with a digital colour camera in one shot, and can be used for obtaining these, changing in time, maps and deformations after suitable digital processing applied to each colour component extracted from the recorded picture, separately.

Keywords: laser interferometry, Moiré fringes, gratings, displacements, deformations, Michelson interferometer, double interferometry.

INTRODUCTION

Orthogonal polarization and multi-wavelength sources being applied in laser interferometry are known for many years. The methods using two different wavelength or polychromatic light were used to obtain multi-wavelength interference patterns for the needs of multi-wavelength interferometry [1].

Pedrini at al. [2] demonstrated that two slightly different red wavelengths of pulsed ruby laser can be used to determine the shape of one object, as the phase difference between such two wave fronts may be obtained by recording two digital holograms, each with a different wavelength.

Pedrini, Tiziani and Gusev [3] described also simultaneous application of two different wavelengths separated by significant gap of spectrum (e.g. one red and the other ultraviolet) to a digital holography. When applying Fourier or Fresnel transform to the intensity of recorded in such a way two-wavelength holograms, one can obtain two primary reconstructions: The larger obtained with the shorter wavelength, and the smaller one with the longer wavelength. The first may be used to investigate the parts of object with smaller deformations. This increases the sensitivity range of digital holographic interferometry.

In shearography, Siebert and Schmitz [4] pointed at the necessity of simultaneous measurement of two shear directions. A number of separate laser devices working at different wavelength were used for simultaneous illumination of tested specimens in multi-wavelength speckle-pattern shearography for measurement of two-dimensional strain distributions. Kastle et al. ([5], [6]) used three laser diodes (810, 830 and 850 nm) for illumination from different directions. In the aftermath, a single-shearing interferometer was used for specimen imaging with the use of three separate CCD cameras with narrow-bandpass filters. Two orthogonally polarized laser beams were used for switching between two shearing configurations by Groves and Tatam [7]. The change of polarization was achieved by change of linearly polarized laser light wavelength (its modulation) on the input of linearly birefringent optical fiber, for which orthogonal polarization eigenmodes are equally distributed in the resulting beam. A change of phase between the two modes occurred while changing incoming wavelength. In principle, the fast modulation (sequential switching) between two shearing configurations enables measuring of much slower dynamical changes of the specimen. In such a solution the fast switching between two different wavelengths was used to avoid necessary change of measuring system configuration or simultaneously use of two separate sets of shearing interferometers. In 2001, Groves, James and Tatam applied shadow Moire method (SMM) in three-dimensional shearography for determination of a source position [8]. The SMM method is generally used for determination of contour or deformations of object in macro scale of projected fringe spacing while shearography is suitable for micro scale of wavelengths.

The presented solution of dual laser interferometer was first proposed for needs of SMM in 2003 [9]. It was composed of two integrated Michelson's interferometers with mirrors separated by significant distances. In the solution described in the present paper, the mirrors were integrated with beamsplitters forming more compact and reliable device, with generally much better characteristics of crossed different-color beams of laser fringes. The latter may be simultaneously projected on a specimen, approximately from the same direction. Each beam is of different laser wavelength and this enables to separate the resulting pictures of fringes by different CCD cameras with wide-bandpass filters or aftermath by filtering of two resulting color components from simultaneously registered two-wavelength interferograms.

A single two-coloured interferogram may be recorded by a single CCD camera. However, to get the best sensitivity in both directions, two such cameras may be applied for simultaneous recording of dynamically evolving interferogram, from the two orthogonal directions. It is essential that both the cameras, as well as the dual integrated laser interferometer used for fringe projection, shall not be moved during the whole recording process.

INTERFEROGRAM SENSITIVITY

After illumination of XY plane from the top with a beam of interference fringes parallel to Y axis, the following intensity distribution of light in this plane is obtained [10] (Figure 1):

$$I = I_0 [\, 1 + \cos (2\pi x s^{-1})] \tag{1}$$

where

I_0 – peak intensity for bright fringe

s – fringe spacing at XY-plane.

When the interference pattern is observed at an angle θ to Z axis, fringe spacing is equal to:

$$d = s \cdot \cos(\theta) \tag{2}$$

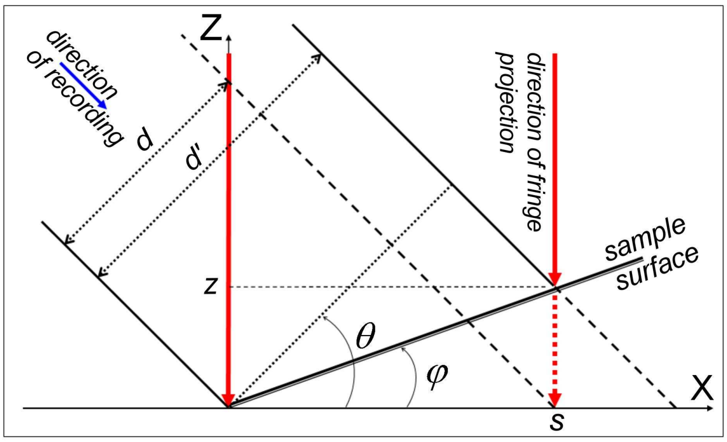

FIGURE 1. Space layout of fringe projection onto plane sample surface.

Consider the simple test object as a plane, initially orthogonal to XZ plane and tilted to XY plane at an angle φ. Let initially the Y axis lay in this plane.

The observed fringe spacing changes with increasing φ from d to:

$$d' = d + z \cdot \sin(\theta) \tag{3}$$

where z is the local height of object's surface.

Without lost of general character of presented considerations, a specific fringe projection layout can be assumed, for which $\theta = \pi/2$. The result of such simplification is d=0 and d'=z. It means that d' increases rapidly with increasing angle φ of rotation of the test object plane around Y axis.

Consider now another similar layout, which differs from the previous one in that that the X axis lays in the test object's plane orthogonal to YZ plane and tilted to XY plane at an angle φ. No change may now be observed of fringes distribution on the surface of this sample object with rotation around X axis on the angle φ, while the plane is observed along X axis, because only the edge of the plane is visible (Figure 2a).

Moreover, while observing this process along Y-axis, no changes of d are detected (Figure 2a). It means that the method is not sensible at all to tested surface rotation around the axis perpendicular to the direction of observation, when initially (for $\varphi = 0$) fringes are parallel to this observation direction.

However, when we change the initial direction of fringes, as in the Figure 2b, to the orthogonal one, they become parallel to X axis, and again the increase of fringes spacing from d=0 to d'=z may be observed with increasing rotation angle φ.

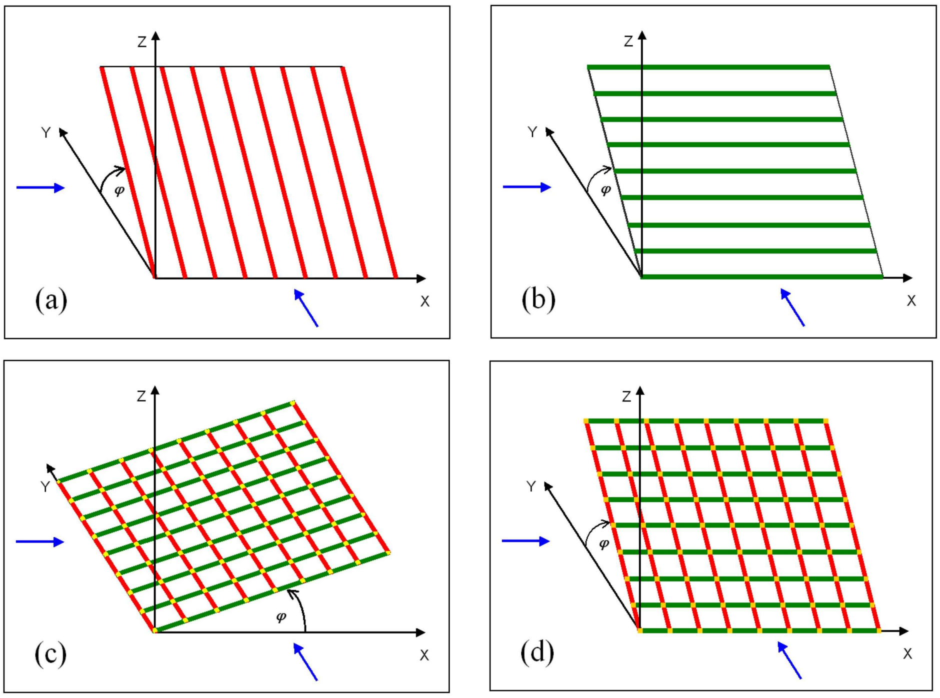

FIGURE 2. Different space layout configurations of fringe projection onto dynamically changing plane sample surface. Arrows represent the directions of interferogram recording. The fringes are projected from the top.

While the plane tilted around X axis is observed along the same axis, only the edge of a sample plane can be seen (Figure 2).

Also, while it is observed in direction of Y axis, only red fringes of constant spacing are visible. The spacing does not change with increasing φ (Figure 2a).

Changing orientation of fringes (from red to green) causes rapid change of fringe spacing from 0 to infinity, when φ changes from 0 to $\pi/2$ (Figure 2b).

For crossed fringes, despite of the direction of sample plane tilt, there is always a set of parallel fringes, for which the spacing changes rapidly with rotation angle, when observed at one of orthogonal directions.

Figure 2c presents the set of red fringes observed in the direction of X axis. In Figure 2d there is the set of green fringes observed in the direction of Y axis.

Usually, we don't know *a priori* in which direction the sample surface tilts. As a result, we also can not predict the most effective measuring configuration for single-wave interferometer. In particular, the significant sample changes may occur, which are reflected in minor only changes of fringes space frequency in comparison with another possible (orthogonal) configuration of fringes set.

That is the best recommendation for applying simultaneously two orthogonal sets of fringes for interferogram recording. Consequently, these sets of fringes should be separated and processing in parallel.

They may be projected onto sample surface from two different orthogonal directions with the use of two separate laser interferometers and recorded by CCD camera, but the process may also be reversed, i.e. one can use two cameras recording, from two different orthogonal directions, the picture of crossed fringes projected from another, suitably chosen, single direction. The resulting sensitivity will be very similar. Moreover, for the latter case, one can restrict the measurement by applying for recording the interferogram a single camera tilted along the diagonal of elementary rectangles of interference pattern. In such a case, the sensitivity for both orthogonal directions also remains similar because of similar starting fringe spacing recorded by the camera for both color sets.

Using simultaneously such two orthogonal, distinguishable sets of projected fringes enables to make mapping of dynamically changed surfaces and deformations of objects under investigation with a similar resolution in both orthogonal directions.

INTEGRATED DUAL LASER INTERFEROMETER

One of possible schematic of double integrated interferometer for generation of such two different-colour, mutually orthogonal sets of parallel fringes is presented in Figure 3 below.

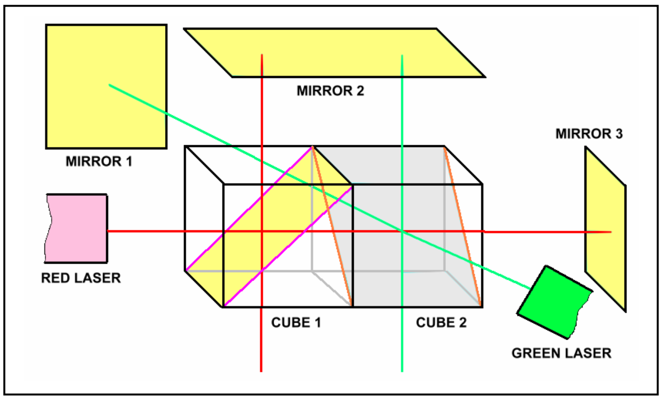

FIGURE 3. Space layout of the main part of the integrated system of double laser interferometer. It is based on two separate cube beamsplitters. It should be noticed that Cube 1 and Cube 2 may be replaced one with another without changing the essential solution; one should only remember about translation of Green Laser and Mirror 1 in parallel with the Cube 2. Cube 1 and Cube 2 comprise the integrated optical set of four roof prisms interlayed with two beamsplitting layers. The two laser beams are leaving the interferometer (at the bottom) and are directed toward the set of lenses expanding them into two corresponding conical beams.

Its early, introductory version from Figure 4 was presented and discussed elsewhere [9].

However, the fully usable experimental model of dual integrated interferometer was realised and promptly tested during last few years. It was realised in accordance with the scheme from Figure 3 and is presented in Figure 5 and Figure 6 during action.

The two laser beams from integrated double laser interferometer are projected via the set of lenses expanding them into two corresponding conical beams. In such a form they are suitable for projection onto object's surface (Figure 5). The two different lasers (one of wavelength 632 nm and the other of 532 nm wavelength; i.e. red and green) were used (Figure 6).

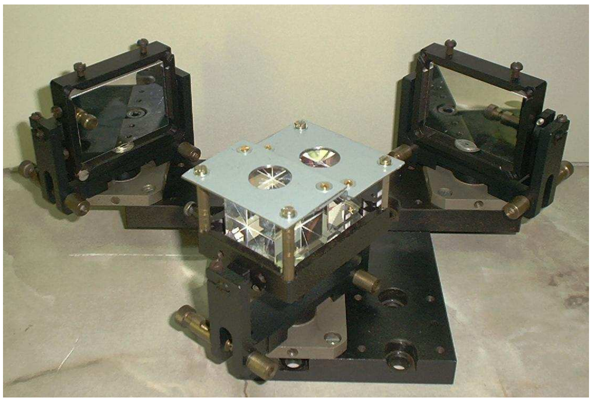

FIGURE 4. Early, introductory version of dual integrated interferometer model. The two different sets of orthogonal sets of fringes were obtained from beams coming from the top section of this device.

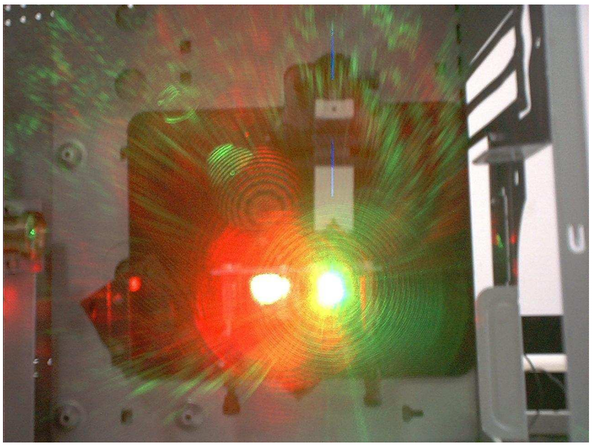

FIGURE 5. Integrated dual laser interferometer using two orthogonal beams (red and green) and sets of parallel fringes.

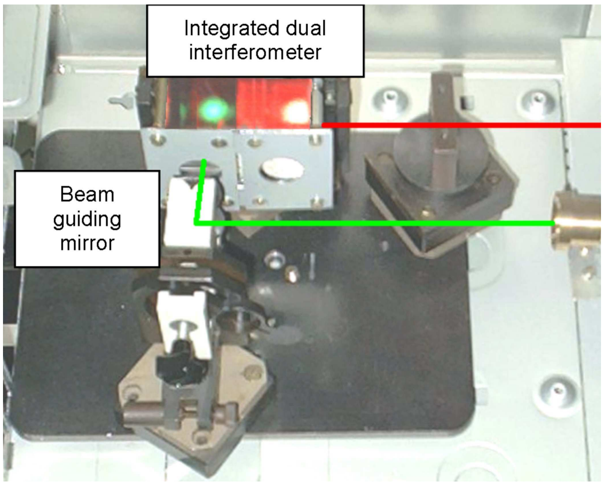

FIGURE 6. The layout of dual laser interferometer emitting two orthogonal sets of parallel fringes.

The examples of illumination of model objects with such two orthogonal sets of fringes were presented in the next paragraph. The two different sets of laser interference fringes crossing at the surface of the tested objects had been obtained.

TWO-COLOURED INTERFERENCE PATTERNS FROM DUAL LASER INTERFEROMETER

Below, the examples of registered with the use of simple color camera two-colored laser interference patterns, simultaneously projected from dual laser interferometer onto plane surface (Figure 7) and spatial object (Figure 8) are presented.

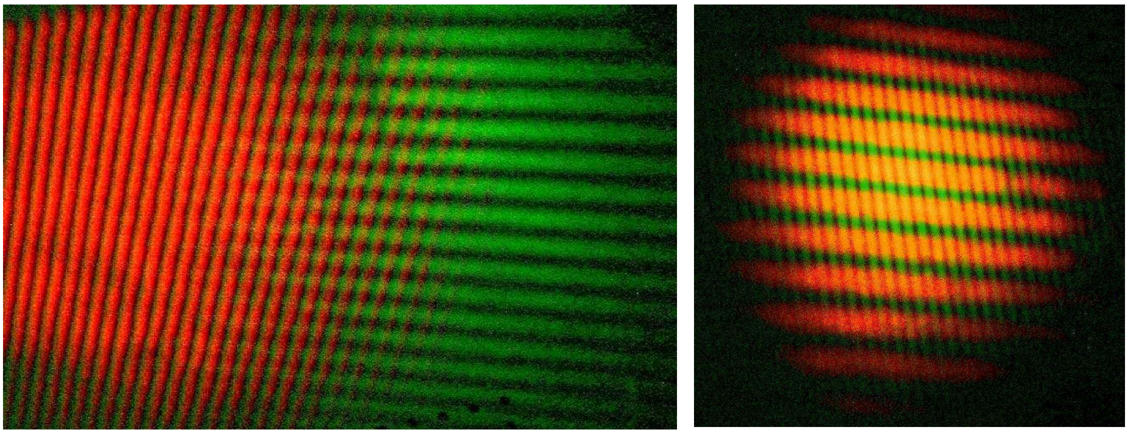

FIGURE 7. The examples of two laser beams containing fringes with different spacing, obtained with the use of integrated dual laser interferometer, projected onto plane surfaces.

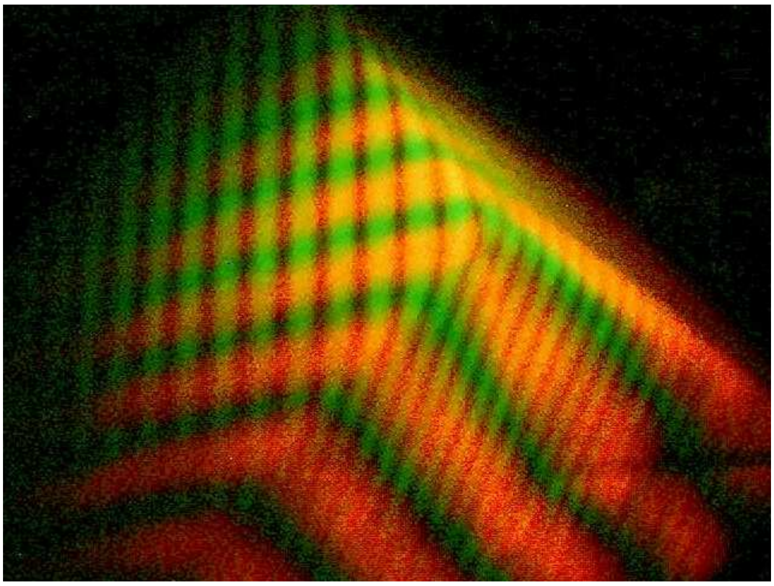

FIGURE 8. Interference pattern projected on a model surface object with the use of experimental model of integrated dual laser interferometer.

The picture of resulting two-colour grating is recorded with the use of simple digital colour camera in one shot, and can be used for obtaining the time-varying contour maps of sample surfaces, after suitable digital processing applied to each colour component extracted from the recorded picture, separately. The sequential interferograms have to be recorded to obtain information of possible dynamical surface deformations. The best for this need would be cameras with at least two different CCD matrices having filters enabling independent and simultaneous recording of each of two orthogonal components of different colour.

But also, the digital processing of each colour picture may separate these sets of fringes in two independent pictures (Figure 9) suitable for further analyses, e.g. fringes tracing (Figure 10).

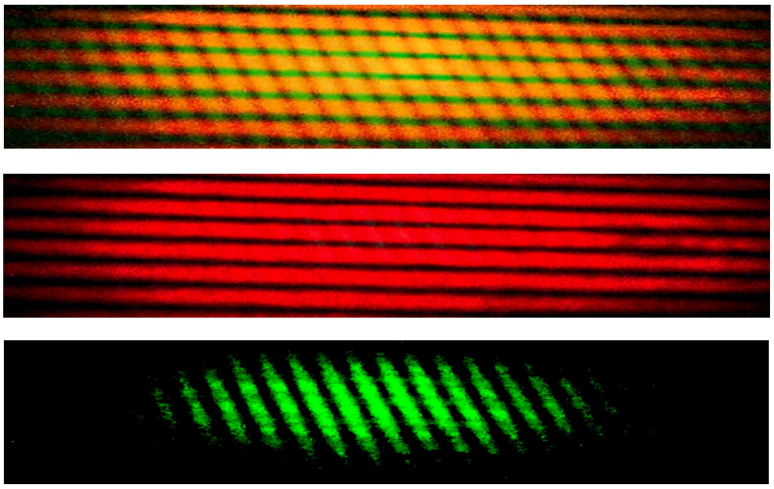

FIGURE 9. An example of separation of two-colour interference pattern (top) into red only part (middle) and green only part (bottom picture).

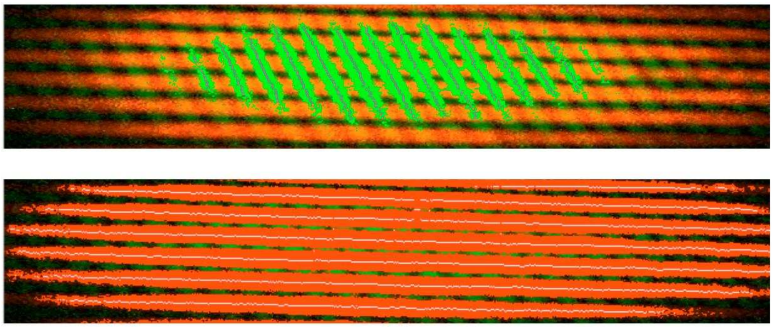

FIGURE 10. Fringes tracing of two-colour interference pattern into green only part (top) and red only part (bottom).

CONCLUSIONS

Both operational modes of double integrated interferometer have been demonstrated, as well as the possibility of digital separation of different colour fringe patterns was experimentally verified.

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