Pulsed digital holography for recording ultra-fast events*

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In this paper, spatially angular multiplexing technique in pulsed digital holography and an optical system based on this technique are introduced. Optical simulation and calculating analysis show that the designed system can be employed to record ultra-fast events of a time resolution in nanosecond.

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Thanks to the rapid development of the technique in ultra-short pulsed laser and Charge Coupled Device (CCD) during the latest decades, pulsed digital holography has shown its superiorities in recording and reconstructing ultra-fast processing[1,2]. Psaltis and his colleagues have reported some of their results in ultra-short pulsed digital holography recording and reconstructing ultra-fast processing, where angular multiplexing technique is employed to record a sequence of sub-holograms in a single CCD frame, and each of the sub-holograms can be independently reconstructed through digital spatial filtering and reversed Fourier transformation[3].

It is noticed, however, that by the conventional angular multiplexing recording, the angles included between object beams and reference beams have to be strictly limited due to the restriction of the CCD pixel size[4,5], therefore the spectra of the sub-holograms are along a line on their Fourier plane, resulting in a difficult spatial filtering.

In this paper, a spatially angular multiplexing technique for ultra-short pulsed digital holography is reported, whereby the spatial orientation of each of the reference beam can be differently adjusted while keeping the value of the angle included between the object and the reference unchanged, so that the spectra of the sub-holograms are clearly separated within the whole Fourier plane and can be easily separated with a higher quality during the following spatial filtering process of the reconstruction, and more sub-holograms can be recorded in a single frame of a CCD consequently.

Our optical simulation and calculating analysis show that the designed system can be employed to record ultra-fast events of a time resolution in nanosecond.

Fig. 1 shows the principle of the spatially angular multiplexing technique, where the x-y plane is the hologram plane, O is an object beam propagating along the z axis, R_1 and R_2 refer to the reference beams with different spatial orientations, namely in x-z plane and y-z plane, respectively, α and β is the angle included between the object O and the references, R_1 and R_2, respectively. The angles of α and β are so adjusted that, in width, any single interference fringe period will cover at least two CCD pixels, to fit the requirement of the Nyquist sampling theorem and to ensure that all the interference fringes and the 0'th and the $\pm$1'est order of the Fourier transform can be clearly separated.

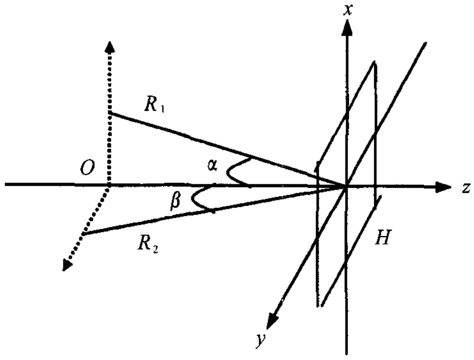

Fig. 1 Schematic diagram of spatially angular multiplexing

Fig. 2 is a schematic of the Fourier spectra of the sub-holograms recorded with the spatially angular multiplexing technique shown in Fig. 1, where k_1 and k_2 is the position of the 1'est order of the Fourier transform of the sub-hologram determined by the angle α and β, respectively, and $f_{x\max}$ and $f_{y\max}$ is the maximum bandwidth of that in x and in y direction, respectively. As it can be seen from Fig. 2 that all the spectra of the object, as well as that of different orders can be clearly separated, which will ensure a high quality of the following digital frequency filtering and reconstruction.

To examine the effect of the spatially angular multiplexing technique, a simulation experiment with CW laser light is carried out, in which two transparent objects, as shown in Fig. 3 and Fig. 4, are positioned respectively at the optical path of R_1 and R_2, and keep the path of O

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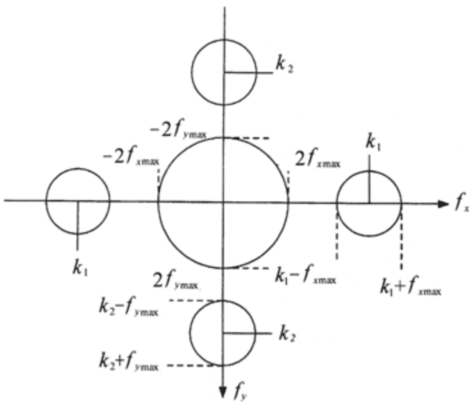

Fig. 2 Fourier spectra of the sub-holograms recorded with spatially angular multiplexing

free from any object, to obtain a hologram with two sub-holograms overlapped as shown in Fig. 5. Fig. 6 shows the Fourier transform of the hologram in Fig. 5. After the spatial frequency filtering, the digitally reconstructed image of Fig. 3 and Fig. 4 is obtained as shown in Fig. 7 and Fig. 8, respectively. It is confirmed by analyzing the simulation results that, with the spatially angular multiplexing technique, more spatial freedom of adjusting the angles included between the object and the references can be obtained while keeping the angles between the object and the references big enough to fit the requirement of the Nyquist sampling theorem, which ensures a higher quality of the reconstructed images.

An optical system employing the spatially angular multiplexing technique is designed to record a series of ultra-fast events as shown in Fig. 9, in which a single ultra-short pulse from a amplify system is amplitude-divided by a polarizing beam splitter into two parts, the horizontal for the reference and the vertical for the object, and two specially designed cavities, Object cavity and Reference cavity, are positioned in the respective optical paths to generate sub-pulse trains, for object and reference, respectively. It is noticed that the sub-pulse trains from the object cavity will illuminate the fast even at the same direction while that from the reference cavity will change its direction from sub-pulse to sub-pulse, to record a series of sub-holograms with the angular multiplexing technique.

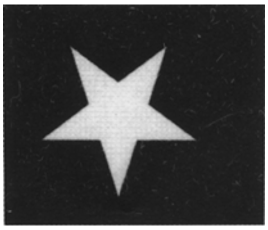

Fig. 3 Image of a pentacle

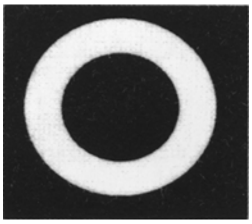

Fig. 4 Image of a ring

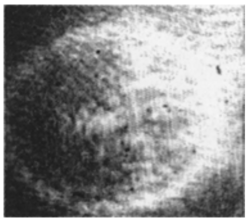

Fig. 5 Partial holograms

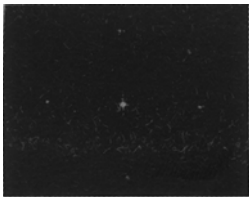

Fig. 6 Frequency spectrum of the holograms

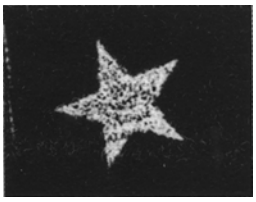

Fig. 7 Digital reconstruction of the holograms of the pentacle

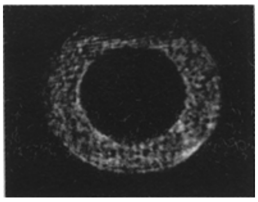

Fig. 8 Digital reconstruction of the holograms of the ring

In the reference cavity, the incident pulse enters the cavity via a coupling mirror M_1, and travels in cyclically in the cavity between the two mirrors, M_2 and partial mirror, where the mirror M_2 is so adjusted that each of the sub-pulses amplitude-split from the cavity will travel at a different smaller spatial angle to the axis of the cavity, as required by the spatially angular multiplexing technique. The time separation of the sub-pulses output from the cavity depends on the cavity length, which can be adjusted of the order of nanosecond. In the optical path of the object, the vertically polarized incident pulse will pass through a time delayer before being coupled into the cavity, to optimize the arrival time at the hologram plane. In the object cavity, a Pockels cell is timed to behave like a temporary $\lambda/4$ wave plate to rotate the polarization of the pulse trapped inside the cavity, and a series of sub-pulses will be amplitude-divided and output

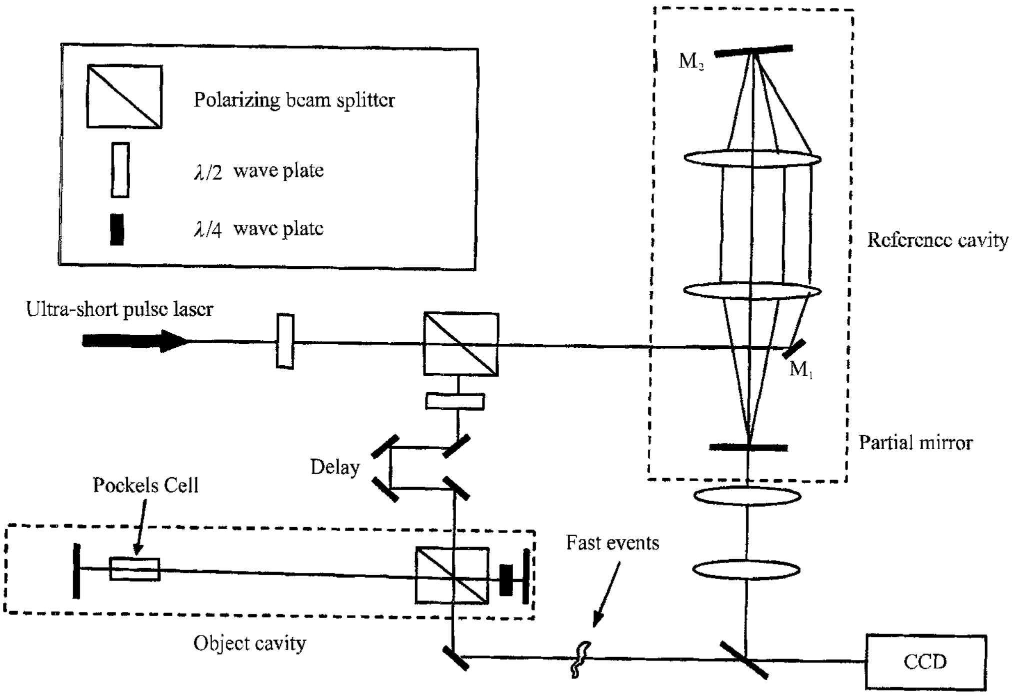

Fig. 9 Optical system recording pulsed digital holography with spatially angular multiplexing

by the polarizing beam splitter. The time separation of the sub-pulses from the cavity can be adjusted of the order of nanosecond, by easily changing the cavity length.

In conclusions, we have introduced the principle of the spatially angular multiplexing technique for the pulsed digital holography recording ultra-fast events, and the validity of this approach has been proven by the simulation experimental results. Our analysis confirms that this optical system employing the spatially angular multiplexing technique can be used to record a series of ultra-fast events of the order of nanosecond.

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