Femtosecond motion picture

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Abstract: We have developed an ultrafast imaging system to record and observe the femtosecond phenomena in air and an optical medium as a form of a temporally continuous motion picture. To obtain the motion picture, the light-in-flight recording by holography using a femtosecond pulsed laser is applied. We demonstrate the recording and observation of femtosecond laser pulse propagating in air and a dispersion prism. The time and spatial behavior of such femtosecond light pulse in the prism and at the boundary between the prism and air is clearly observed. This technology achieves a temporal microscope with more than 1011 magnification.

Keywords: femtosecond technology, femtosecond laser, ultrafast technology, movie, imaging system, ultrafast photonics

Classification: Photonics devices, circuits, and systems

References


1 Introduction
In the frontier of the recent natural science, interests are placed by the ultra high-speed phenomena of the time domain from femtosecond and atosecond. Many researches to discover and elucidate the new phenomena are actively carried out in the fields, such as physics [1, 2, 3, 4, 5], chemistry [6, 7, 8, 9, 10], and biology [11, 12, 13, 14]. In these researches, however, only the relation between the time evolution and other physical quantity, such as energy to time, is discussed. On the other hand, the researches which pursue the space propagation [15, 16, 17], those which pursue time evolution of the intensity accompanying propagation of femtosecond laser light [18, 19] have been carried out, but these researches require not only repetitive femtosecond pulses but also the images are temporally discrete and consist of a few or several frames. Therefore, these researches are quite difficult to apply in the case that the property of each pulse is inhomogeneous among the repetitive pulses. Here we demonstrate the temporally continuous motion picture of a femtosecond light pulse propagating in air and a prism, which is an example of the optical medium, using a light-in-flight holography [20, 21].

2 Light-in-flight recording by holography
Holography is a technique for three-dimensional imaging by recording the interference pattern produced by the light waves scattered from an object and a reference wave [22, 23]. A photographic record of the interference pattern is called as a hologram. When an identical reference beam is used to illuminate the hologram, the original scattered waves are reproduced, resulting in a three-dimensional image of the object. To record the hologram, the light from a laser is divided into two beams. One is used to illuminate the object and the other acts as the reference.

When a continuous beam is used to record a hologram, the image can be reproduced from any position on it because the object wave spreads over the entire hologram and interferes with the reference wave at any point. On the other hand, when an ultrashort light pulse is used, interference on the photographic plate occurs only where the pulse from the object and the pulse from the reference wave arrive at the same time. If the pulse from the reference wave is incident to the plate at an oblique angle, its arrival time varies from point to point on the hologram. This makes it possible to obtain a time resolved recording of the object wave along the transverse axis of the hologram. This is called a light-in-flight recording by holography [20, 21]. When the hologram is illuminated with continuous light wave, each different portion of the hologram reconstructs the image at a different time. Therefore,
it is possible to observe a temporally continuous motion picture of the light propagation by shifting the observed point along the hologram. Although, the experiments for light-in-flight recording have been already carried out using picosecond light pulses [20, 24, 25], observing the femtosecond lasr pulse propagating not only in optical media but also in air has not challenged as a form of the temporally continuous motion picture yet. To apply this technology to the elucidation of an ultra high-speed phenomenon using femtosecond pulsed laser, it is indispensable that the ultra high-speed motion pictures are obtained using the femtosecond pulsed laser itself.

3 Recording and observation of the femtosecond motion picture

Figure 1 shows the basic geometry to record the motion picture of the propagation of femtosecond light pulses. A dispersion prism as the object is illuminated with a collimated light pulse at an oblique angle. A ground glass plate comes in contact with a side surface of the prism. The scattered wave from the surface of the prism is used as the object wave. The reference wave of the collimated light pulse is introduced to a photographic plate at an oblique angle (40° to the plate surface). The distance between the object and the imaging plate is 20 cm.

![Fig. 1. Schematic diagram of the recording arrangement for observing the propagation of femtosecond light pulse. (a) Top view, (b) Bird-eye’s view of a part of the recording arrangement where the prism as the object, the ground glass plate, and the photographic plate are set.](image-url)
To demonstrate the light propagation through a medium, a dispersion prism is set in contact to the ground glass plate. The size of the prism is 40 mm in each side and the angle of the corner is 60°. The pulse was incident to the prism at the minimum deflection angle from right. The collimated light pulse restricted by an aperture is introduced to the prism at the minimum deflection angle from the lower right at a deep angle. The light pulse inside the prism is possible to bring out to outside as the object wave by making the side of the prism facing the ground glass plate to diffusing surface. A mode-locked Ti:S laser (COHERENT Inc. Chameleon system) operated at 720 nm was used for the femtosecond pulsed laser to record the hologram. The duration of the light pulse was 130 fs. Agfa 8E75HD holographic plates were used to record the hologram.

4 Demonstration of the femtosecond motion picture

The propagation of light pulse through the dispersion prism was observed by reconstructing the hologram with a continuous wave He-Ne laser operated at 632.8 nm. Figure 2 shows the dispersion prism and the beam for showing the path of the pulse.

The motion picture digitized from the temporally continuous motion picture that shows the propagation of the light pulse through the prism are shown in Fig. 3. The bright-red straight line indicates the reconstructed image of the light pulse. The triangle shown with a dashed line is overlaid in the picture for clarification of the position of the prism. The reflected pulse at the surface of the prism is also seen at the upper portion. Two or more near lines are seen as the reconstructed images. The weak lines followed by the first one mean that the light pulse that comes out from the laser reflects in

Fig. 2. The dispersion prism and the beam for showing the path of the pulse through the prism. The beam is incident to the prism at the minimum deflection angle from right. The triangle of a dashed line indicates the position of the prism.
Fig. 3. Reconstructed image showing the propagation of femtosecond light pulse through a dispersion prism. The pulse travels from right. The bright straight line shows the reconstructed image of the light pulse. The triangle of a dashed line is inserted in the scene for clarification of the position of the prism. The pulse is in air and has not yet reached the prism and it has partly passed the boundary between the air and the prism. Then the pulse just travels the center of the prism, and it has left partly the prism. Finally the pulse has left the prism completely. The femtosecond pulsed laser is operated at 720 nm with pulse duration of 130 fs. Movie file attached (760 kB).

somewhere and overlaps. Although it seems that the cause is in the inside of the laser oscillator, it is not clarified at present where it is generated. These results suggest that this technology can be used for evaluation of the ultra high-speed characteristic of a laser oscillator. Of interest is the behavior of the pulse at the boundary and inside the prism. It is observed that the direction of the pulse changes due to refraction and its speed decreases in the prism. The direction of the observed pulse front image depends on the direction of the light propagation and the reference beam, and also the position of observation, so the precise analysis is necessary to decide the actual direction of the propagation.

5 Conclusion

We have developed an ultrafast imaging system to record and observe the femtosecond phenomena in air and an optical medium as a form of a temporally continuous motion picture. We demonstrate recording and observation of a femtosecond laser pulse propagating in air and a dispersion prism. A frameless, temporally continuous motion picture of the light propagation was obtained. This progress in the observation of femtosecond light pulse
not only enables the analysis of various kinds of ultrafast phenomena and ultrafast photonics, but also will open the possibility of realizing a temporal microscope with more than $10^{11}$ magnification, that is, a temporal femtoscope. More than $10^{11}$ temporal magnification is achieved, in the case that the size of the horizontal size of the hologram is 10 cm, the incident angle of the femtosecond laser pulse is $40^\circ$ to the plate, we take more than 43.5 seconds to observe the hologram from the right side to the left side.

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