

3-3 Viewing-Zone-Angle Expansion of Electronic Holography Reconstruction System

SENOH Takanori, MISHINA Tomoyuki, YAMAMOTO Kenji, OI Ryutaro, and KURITA Taiichiro

Electronic holography is a technology for electronically recording and reconstructing the phase and amplitude of a beam from a three-dimensional object as a diffraction fringes on a reference beam. Since it can reconstruct all information about the beams of an object, electronic holography is an idealistic means of displaying three-dimensional images. However, realizing a wide viewing zone angle requires a display device with a pixel size similar to that of the beam wavelength. Since the pixel sizes of currently available liquid crystal panels and other diffraction fringe display devices are 10 to 20 times the beam wavelength, the angle of beams that can be diffracted with the diffraction fringes displayed is only 2 to 3 degrees, thereby failing to achieve a sufficient viewing zone angle. This paper presents a method of displaying diffraction fringes with different viewing zone angles in parallel, overlapping the reconstructed hologram beams with half mirrors, and realizing a wide viewing zone angle while removing the undesirable beams.

Keywords

Electronic holography, Diffraction fringes, Display device, Pixel size, Viewing zone angle

1 Introduction

Machine-based transportation and communication have been developed as the means of overcoming limited human abilities. Thanks to the development of transportation, human-kind can now not only travel around the world but also into outer space. With regard to communication, it has now become possible to engage in interactive communication not only with speech but also with high-definition, full-color, large-screen imagery, whether around the world or even from outer space. To further enhance this communication capability, studies are being conducted on ultra realistic communication[1]. Ultra realistic communication targets communication with even higher realism based on three-dimensional imagery that combines conventional planar imagery with depth.

Among the means of realizing three-dimen-

sional imagery are: (1) a stereoscopic, three-dimensional imaging system that delivers two separate images with slightly different angles for showing an object to both eyes (right and left), (2) an auto-stereoscopic, three-dimensional imaging system that is an expanded version of the system described in (1) above, and which allows people to observe an object with the naked eye, (3) a volume display system that constructs a three-dimensional image of an object in space including its depth, and (4) a holography system that records and reconstructs the amplitude and phase of beams (i.e., all information about beams emitted from a three-dimensional object) as diffraction fringes on the reference beam[2]. Among the clues for people perceiving three-dimensional objects are: (1) binocular parallax (i.e., slight difference between images projected on the retinas of both eyeballs), (2) changes in the convergence angle

due to the circumnutation of both eyeballs directed toward the object, (3) degree of tension in the ciliary constrictor used to adjust the focus of the eye's crystalline lens, and (4) motion parallax that allows an observer to sense the three-dimensional viewing of an object when the object moves or the observer moves around the object, thereby changing the appearance of the object[3].

There are high expectations for the holography system as an ideal means of three-dimensional display that does not strain the human visual function, because it reproduces all these clues for three-dimensional viewing, and thus reconstructs natural and realistic three-dimensional images[4]. To use this holography as a means of communication, studies have been proactively conducted in recent years on electronic holography for recording and reconstructing holography electronically[5][6].

Electronic holography requires digital data about the diffraction fringes in order to display those diffraction fringes on an electronic display device. The means of acquiring diffraction fringes electronically (aside from using photographic plates) include a method of photographing diffraction fringes directly by using charge coupled devices (CCDs) or other electrical imaging devices[6], and the computer generated hologram (CGH) method, where calculations are performed based on three-dimensional space information about the object[7]. The first method can acquire high-quality diffraction fringes on a real body, but requires a darkroom and a laser beam for taking pictures, making it unsuited for taking pictures of the human body or outdoors. Conversely, the second method can generate diffraction fringes based on calculations. The resultant space information is thus sufficient to enable acquisition of the diffraction fringes of various objects.

In this way, electronic holography can be used to display information about a three-dimensional image as electronic data, which in turn makes it possible to convert holography into motion pictures for transmission over a network. For that reason, expectations run high

for electronic holography as a promising means of realizing ultra realistic communication.

Many challenges remain to be addressed, however, before electronic holography can become a reality. This paper reports on the important challenge of the viewing zone in electronic holography, and the technology developed to expand that viewing zone.

2 Viewing zone of electronic holography

In electronic holography, the phase of spherical waves comprised of beams scattered uniformly from the object are converted and recorded as the diffraction fringes as shown in Fig. 1. When this is reconstructed, a beam is applied to the recorded diffraction fringes, being diffracted in the direction of the object beam at recording, and forming a three-dimensional image of the object. These recorded dif-

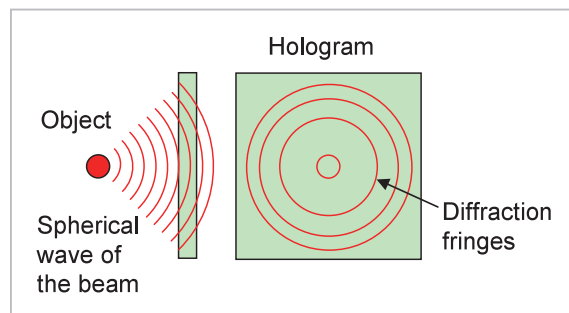


Fig.1 Holography and diffraction fringes

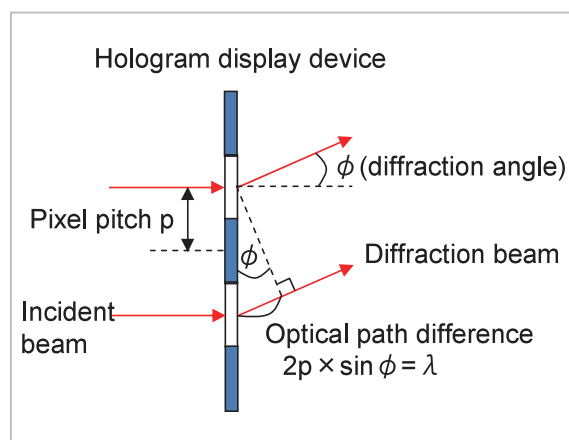


Fig.2 Diffraction angle of hologram reconstructed beam

fraction fringes are called holograms. The red line in the diagram represents the beam phase cycle. The larger the beam's spread angle, the narrower the cycle of peripheral diffraction fringes. To realize a wide viewing zone for the three-dimensional image, it is necessary to record and reconstruct the diffraction fringes of the beam spread over a wide range. This entails the need for a display device that can reconstruct diffraction fringes with very narrow cycles.

When a pixel pitch (p) of the device used for displaying the diffraction fringes and a beam wavelength (λ) are given, the maximum diffraction angle (ϕ) of the beam that can be reconstructed with that device is given as shown in Fig. 2 below. The minimum cycle of diffraction fringes that can be displayed on a display device with pixel pitch p is one cycle for two pixels as shown in Fig. 2. In this way, when a portion through which a beam passes is parallel with a portion that blocks the beam for each pixel, then the beam entering a small clearance (p) becomes the point source of light with the same wavelength based on the Huygens-Fresnel principle. These beams intensify each other when having the same phase as the beam emitted from the neighboring pixels, and become weakened in other cases. As a result, the incident beam bends in a certain direction. At that time, angle ϕ between the incident beam and outgoing beam can be expressed by the following equation:

$$\phi = \sin^{-1}\left(\frac{\lambda}{2p}\right) \quad (1)$$

To reconstruct a beam with a diffraction angle smaller than ϕ , it suffices to widen the cycle of diffraction fringes by using many pixels.

As shown in Fig. 3, the diffraction beam is bent on the opposite side as well. The spread range of the beam that can be reconstructed on a display device having pixel pitch p consequently becomes 2ϕ . This is the viewing zone angle of electronic holography that can be displayed on a display device.

The outgoing beams also intensify one another when the optical path difference is an integral multiple of wavelength λ . As a result, diffraction beams are also emitted in the direction of an almost integral multiple of angle ϕ obtained from Equation(1), and these beams are called high-order diffraction beams that become beams based on folded basic diffraction beams, with no new information being indicated.

Hologram display devices currently available include liquid crystal display devices and micro-mirror arrays. The pixel sizes of these display devices are about 10 to 20 times beam wavelength λ (about 5–10 μm). Consequently, the viewing zone angle (2ϕ) of electronic holography that can be displayed on these display devices is about 3 to 6 degrees.

3 Viewing zone angle expansion in electronic holography

3.1 Generating a hologram having an expanded viewing zone angle

To expand the viewing zone angle in electronic holography, a lens-based method that produces small images has been proposed[8]. As shown in Fig. 4, we propose to divide the viewing zone of the object beam, generating each hologram composed of different diffraction fringes (each having a different viewing zone), and to overlap the reconstructed beams. The holograms considered here are those that record the diffraction fringes obtained due to

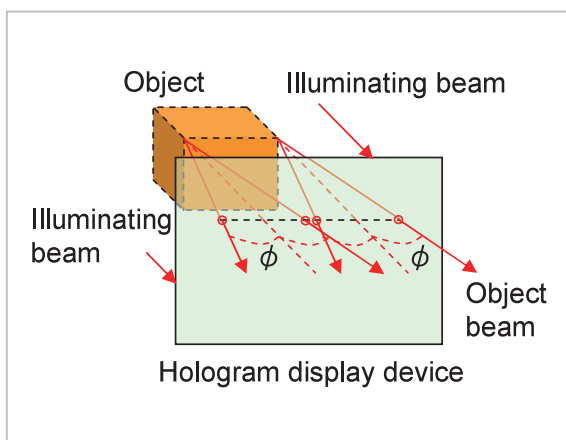


Fig.3 Viewing zone angle 2ϕ of holography

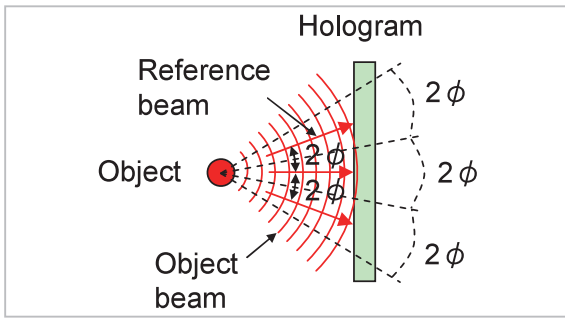


Fig.4 Expanding the viewing zone angle of holography

the overlapping of parallel beams having flat wave surfaces on the object beams that scatter uniformly as spherical waves. One hologram can only reconstruct a viewing zone of 2ϕ , so that the reference beam of a hologram in the viewing zone in the middle of Fig. 4 is sufficient when applied perpendicularly to the hologram surface, but obtaining a hologram with an upper and a lower viewing zone requires that the reference beam be inclined to $+2\phi$ and -2ϕ , respectively.

In this way, a hologram generated by applying a reference beam to the hologram surface at right angles is called an inline hologram. And a hologram generated by applying a reference beam obliquely is called an off-axis hologram. Using an off-axis hologram reduces the difference in inclination between the reference beam and object beam, resulting in wider cycle of diffraction fringes, so that an object beam with a large incident angle relative to the hologram surface can be recorded and reconstructed without folding[9]. There is another method that involves generating diffraction fringes without inclining the reference beam, sampling those fringes at a wider display pixel interval than the width of diffraction fringes, generating diffraction fringes folded in the low region, and reconstructing the original object beam obtained as a high-order diffraction beam from that reconstructed beam[10][11].

3.2 Preparing an inline hologram

When preparing an inline hologram on a computer, since phase ϕ_R of reference beam $R = r \exp(-j\phi_R)$ with amplitude r that strikes the hologram surface at right angles as shown

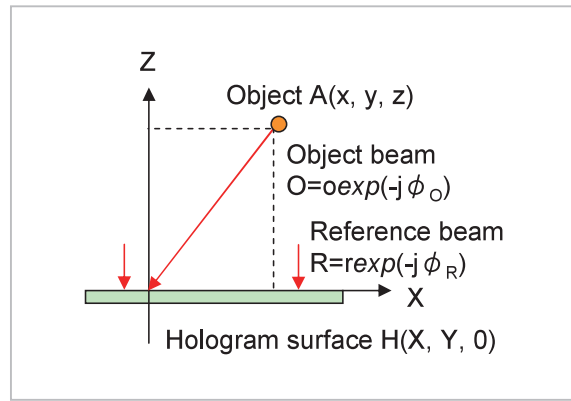


Fig.5 Inline hologram

in Fig. 5 is constant regardless of location, the following equation holds:

$$\phi_R = 0 \quad (2)$$

Phase ϕ_o on the hologram surface of object beam $O = o \exp(-j\phi_o)$ with amplitude o and initial phase 0 (zero) emitted from the object is determined by the distance from object point A (x,y,z) to a point (X,Y,0) on the hologram surface. And this can be expressed by the equation shown below. Here, λ denotes the beam wavelength.

$$\phi_o = 2\pi \frac{\sqrt{(x-X)^2 + (y-Y)^2 + z^2}}{\lambda} \quad (3)$$

This equation can be approximated as shown in the equation below when there is a sufficiently small scattering angle of the object beam as in electronic holography. Here, $k = 2\pi/\lambda$.

$$\phi_o \cong k(z + \frac{\sqrt{(x-X)^2 + (y-Y)^2}}{2z}) \quad (4)$$

In fact, the initial phase of the object beam is indefinite. For the value of diffraction fringes indicated in Equation(5), however, the object beam's initial phase only changes the initial phase of diffraction fringes (i.e., phase where the object beam strikes the hologram surface at right angles) and does not change the width of diffraction fringes. The beam used to reconstruct the object beam is therefore diffracted in the same direction regardless of the object

beam's initial phase. Here, for the sake of simplification, the initial phase of the object beam was set to 0.

From another viewpoint, this shows that one can safely regard the phase difference from the reference beam having the same initial phase as the object beam recorded on the hologram surface as diffraction fringes. When the reference beam's initial phase is not 0, only the initial phase of diffraction fringes will change, with the cycle of diffraction fringes remaining unchanged, so that the same reconstructed beam can be obtained.

Diffraction fringe H is a recording of the intensity of interference of the beam produced when object beam $O = o \exp(-j\phi_o)$ and reference beam $R = r \exp(-j\phi_R)$ are irradiated simultaneously on the hologram surface, as a striped pattern of different density levels. This can be expressed by the equation below. Here, * denotes complex conjugation.

$$\begin{aligned}
 H(X, Y, 0) &= |O + R|^2 = (O + R)(O^* + R^*) \\
 &= |O|^2 + |R|^2 + OR^* + O^*R \\
 &= o^2 + r^2 + or \exp(-j\phi_o + j\phi_R) \\
 &\quad + or \exp(j\phi_o - j\phi_R) \\
 &= (o^2 + r^2) + or[\exp\{-j(\phi_o - \phi_R)\} \\
 &\quad + \exp\{j(\phi_o - \phi_R)\}] \\
 &= (o^2 + r^2) + 2or \cos(\phi_o - \phi_R)
 \end{aligned} \tag{5}$$

In this equation, the first term (o^2) and second term (r^2) are uniform values proportionate with the respective power of the object and reference beams, and become offset values for the diffraction fringe level. The third term is proportionate with amplitude o of the object beam. In case of an inline hologram, $\phi_R = \text{constant}$. From the foregoing discussion, we know that one can produce the equation: $\phi_R = 0$. Therefore, the value will be the result of converting phase ϕ_o of the object beam into cosine and turning it into a pattern repeated with a cycle of 2π . This cycle produces ring-shaped diffraction fringes as shown in Fig. 2. When diffraction fringes are to be directly recorded, one cannot delete the first and second terms, with higher contrast in the diffraction fringes not being possible. However, in CGH where holograms

are generated on a computer, the first and second terms can be deleted. It therefore suffices to record the value indicated in the following equation as diffraction fringes of the inline hologram, so that a highly contrasted hologram can be generated.

$$H(X, Y, 0) = 2or \cos \phi_o \tag{6}$$

When this is recorded, the offset value is added to Equation(6) and recorded, in order to prevent the value of H from becoming negative.

3.3 Generating an off-axis hologram

For off-axis holograms (as shown in Fig. 6), the reference beam is inclined by $\theta = 2\phi$ in the direction of the X axis. Phase ϕ_R therefore varies with the location $(X, Y, 0)$ on the hologram surface and can be expressed by the following equation:

$$\phi_R = \frac{2\pi}{\lambda} X \sin \theta = kX \sin \theta \tag{7}$$

Phase ϕ_o of the object beam can conversely be expressed by Equation(4) similarly to inline holograms. The value H of the diffraction fringe generated by the interference of both beams, as the result of deleting the offset terms (first and second terms) from Equation(5), is given as follows:

$$H(X, Y, 0) = 2or \cos(\phi_o - kX \sin \theta) \tag{8}$$

The reference point of $X = 0$ in that case can be taken anywhere. However, the same reference

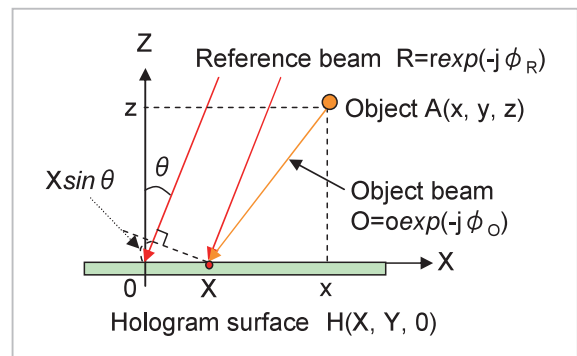


Fig.6 Off-axis hologram

point must be used in all diffraction fringes produced by scattered beams emitted from a single object point. The diffraction fringes given in Equations (6) and (8) take positive and negative values, but the hologram display device cannot display negative amplitudes, so that a value with an added offset value will be recorded to prevent the value obtained in Equation (8) from becoming negative.

4 Reconstructing holography with expanded viewing zone

4.1 Reconstructing an inline hologram

Holograms are reconstructed by applying the same illuminating beam $R = r \exp(-j\phi_R)$ as the reference beam to a display device that displays diffraction fringe H in Equation (8). The beam reconstructed at that time can be expressed by the following equation:

$$\begin{aligned} RH &= r \exp(-j\phi_R) \times 2or \{1 + \cos(\phi_O - \phi_R)\} \\ &= 2or^2 \exp(-j\phi_R) + or^2 \exp(-j\phi_R) \\ &\quad [\exp\{-j(\phi_O - \phi_R)\} + \exp\{j(\phi_O - \phi_R)\}] \quad (9) \\ &= 2or^2 \exp(-j\phi_R) + or^2 \exp(-j\phi_O) \\ &\quad + or^2 \exp\{j(\phi_O - 2\phi_R)\} \end{aligned}$$

The first term of Equation (9) is an undesirable beam based on the transmission of an illuminating beam. The second term is a beam with the amplitude of the object beam multiplied by r^2 . However, since it forms the original object image, it is called a reconstructed beam. The third term is another undesirable beam (called the conjugate beam) having a conjugate phase relative to the reconstructed beam based on a phase double that of the illuminating beam.

In reconstructing an inline hologram, one can consider that $\phi_R = 0$, in order to produce the following equation:

$$\begin{aligned} RH &= or^2 + or^2 \exp(-j\phi_O) \\ &\quad + or^2 \exp(j\phi_O) \quad (10) \end{aligned}$$

In all that, the only thing necessary is the reconstructed beam of the second term; the other beams are unnecessary. Figure 7 shows these

beams, which overlap the reconstructed beam and may hamper the observation of holography images.

4.2 Removing undesirable beams

As shown in Fig. 7, in inline holograms, an undesirable beam overlaps a reconstructed beam, thereby hampering observation of the reconstructed image. Such a beam must be removed. The reconstructed and undesirable beams emitted from one point of a diffraction fringe have different beam angles, which can be used to remove the undesirable beam. To that end, a convex lens is placed at a location separated from the hologram by its focal point distance (f). When things are arranged that way (as shown in Fig. 8), the beams emitted from the hologram converge at different points on the focal plane after the lens. A spatial filter can therefore be placed there to remove only the undesirable beams. This is known as the single sideband method [11].

Although this arrangement can certainly reconstruct an object beam scattered upward in the horizontal direction as viewed from the hologram surface, the spatial filter blocks any beams scattered downward. Conversely, the conjugate beam of the object beam scattered downward is generated upward, passes through the spatial filter, and then overlaps the reconstructed beam. As shown in Fig. 9, beams scattered from an object when generating a hologram are therefore limited to those scattered upward from the horizontal level, thereby generating a hologram. This method is called the

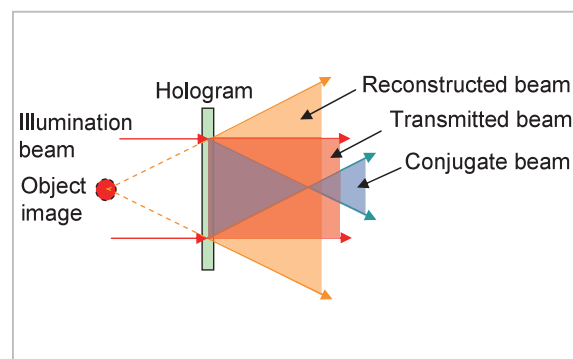


Fig. 7 Reconstructed beam of an inline hologram

half-zone plate method[12]. In this method, the perpendicular viewing zone is reduced to half. The object beams scattered on both sides (right and left) can be used in the horizontal direction, however, thereby resulting in the same horizontal viewing zone.

By applying the removal of undesirable beams in Fig. 8 to a hologram generated in this

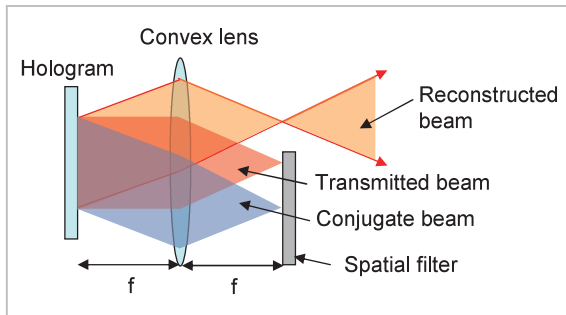


Fig.8 Removing undesirable beams with a lens and spatial filter

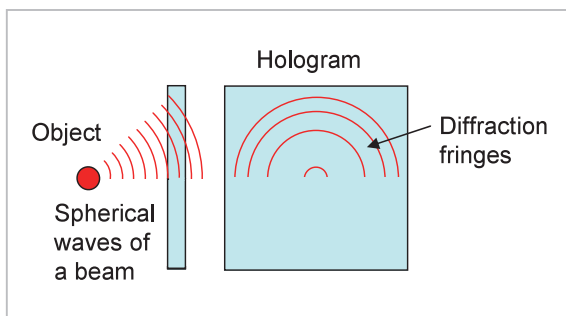


Fig.9 Hologram based on half-zone plate method

way, such beams can be removed by being regarded as conjugate beams[12], because no object beams come downward from the hologram. Moreover, as no reconstructed beams are emitted downward from the diffraction fringes, there are no conjugate beams emitted upward either. This makes it possible to remove undesirable beams, but reconstructed beams are Fourier-transformed by a convex lens, and must be restored.

To that end, the same convex lens is placed at a location separated even further from the spatial filter by focal point distance f as shown in Fig. 10. When things are arranged this way, the two lenses constitute a relay lens. Wherever the object may be placed, its image will be produced with the same magnification at a location advanced from the original object location by a distance four times the focal point distance of the lens[13]. The location and size of the image reconstructed by the single sideband method in Fig. 10 can be derived from the equation below. First, object A at a height of Y standing on the optical axis of the lens at a location separated from convex lens 1 by a distance of D to the left produces an inverted image of height y at distance d to the right of lens 1. At that time, the beam parallel with the optical axis emitted from the object passes through the right-hand focus of the lens, and the beam coming from the object and passing through the lens center

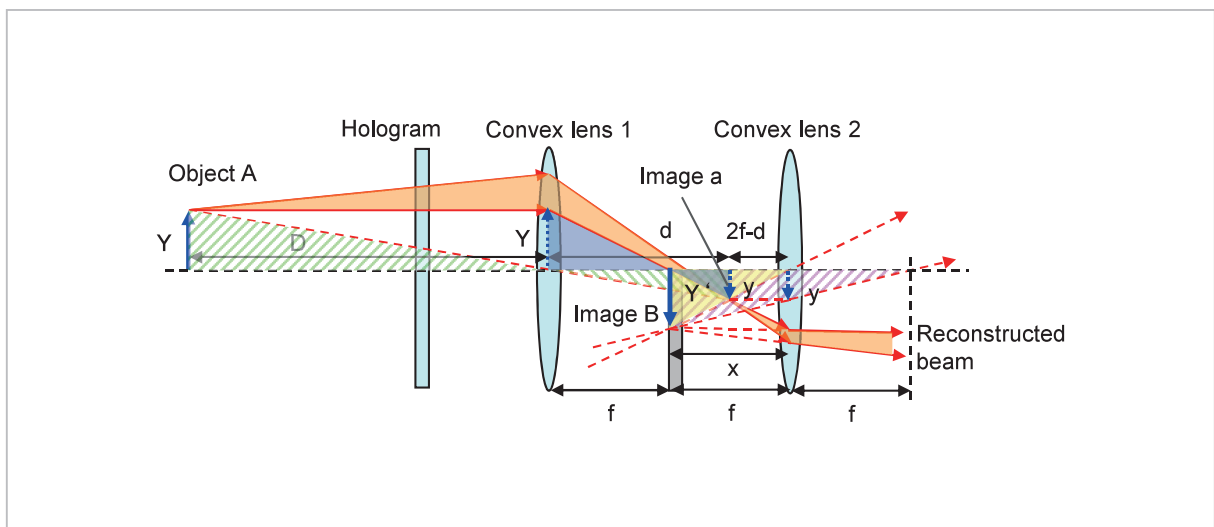


Fig.10 Optical system for removing undesirable beams by using single sideband method and a relay lens

goes straight, so that the two triangles with a green hatch composed of both beams become similar figures, and the following equation holds:

$$\frac{y}{Y} = \frac{d}{D} \quad (11)$$

Moreover, the two blue triangles also become similar figures. Therefore, the following holds:

$$\frac{y}{Y} = \frac{d-f}{f} \quad (12)$$

From these two equations, d can be determined as follows:

$$d = \frac{Df}{D-f} \quad (13)$$

From this and from Equation(11), height y of the image a becomes as follows:

$$\frac{y}{Y} = \frac{d}{D} \quad (14)$$

Next, lens 2 produces a virtual image (B) of this inverted image a at the location with distance x from lens 2 at height Y' . At that time, inverted image a is located at a distance $(2f-d)$ from lens 2. Both triangles in the pink hatch and both triangles in the yellow-colored portion are mutually similar figures, however, so that the following equation holds:

$$\frac{y}{Y'} = \frac{f}{x+f} = \frac{2f-d}{x} \quad (15)$$

From this,

$$x = \frac{f(2f-d)}{d-f} \quad (16)$$

$$Y' = \frac{yx}{2f-d} = \frac{yf}{d-f}$$

Thus, location x and height Y' of output image B are determined. Entering location d and height y of inverted image a given in Equations(13) and (14) into this equation results in the following:

$$x = D - 2f \quad (17)$$

$$Y' = y \frac{(D-f)}{f} = \frac{fY}{D-f} \frac{D-f}{f} = Y$$

This allows one to see that an image with the same magnification can be produced.

From Fig. 10, the distance between object A to image B can be determined by subtracting distance $x = D - 2f$ from lens 2 to image B from the distance $(D + 2f)$ from object A to lens 2. It therefore becomes as follows:

$$(D+2f) - x = (D+2f) - (D-2f) = 4f \quad (18)$$

One can therefore see that image B will be produced at the location advanced from object A by a distance four times focal point distance f of the lens. This relay lens is therefore also known as the $4f$ optical system.

4.3 Reconstructing an off-axis hologram

An off-axis hologram can be reconstructed by applying an illuminating beam to an off-axis hologram (as shown in Fig. 6) at an inclination to the left or right, and at an angle of $\theta = 2\phi$. The beam reconstructed at that time is expressed by Equation(9) and includes undesirable beams (transmitted beam and conjugate beam). These beams are emitted in the same perpendicular direction as the inline hologram shown in Fig. 8. These beams can therefore be removed with the $4f$ optical system similarly to inline holograms. The only difference from inline holograms is that the location of the window opened in the spatial filter is positioned to the left or right according to the horizontal direction of the reconstructed beam. Figure 8 shows the amount of window movement. When the hologram is displayed on the focal plane to the left of the lens with focal point distance f , the off-axis reference beam with angle $\theta = 2\phi$ reaching the lens converges at the location deviated by $f \tan \theta$ in the peripheral direction of the lens and by $f \tan \theta$ from the center of the lens on the focal plane to the right of the lens. The reconstructed beam from the hologram is then

spread around this location, so that the center location of the window need only be deviated by $f \tan \theta$ from the center of the lens. The window can be set to the same size because the spread range of the reconstructed beam is the same as that of inline holograms.

4.4 Optical system with expanded viewing zone

To expand the viewing zone, it is necessary to reconstruct the off-axis holograms produced on both sides of the inline hologram as well. As shown in Fig. 4, if the object is a dot, then it suffices to display an inline hologram and an off-axis hologram side by side. If the object is spread, however, an off-axis hologram and an inline hologram must overlap (one on top of the other) as shown in Fig. 11.

Displaying holograms requires specific display panels. It is therefore necessary to display holograms in time series or optically overlap beams emitted from the hologram display panel arranged at spatially separate locations. In time series display, the time for displaying the entire viewing zone will increase, resulting in a lower frame rate for displaying motion pictures. We will therefore consider a method of spatially divided display here.

Figure 12 shows the configuration of the

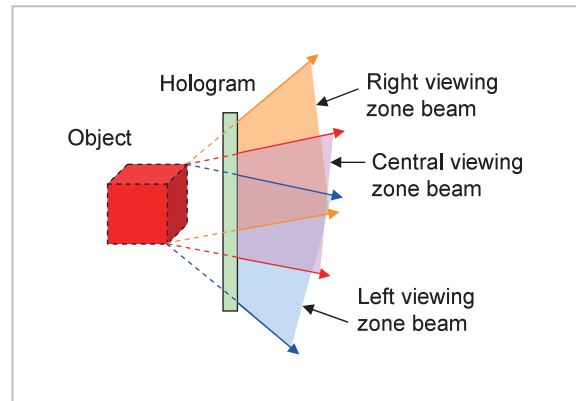


Fig.11 Overlapping of the viewing zones

optical system enlarged three times with the viewing zone spatially divided. Each hologram display panel shows an inline hologram and right and left off-axis holograms, and is equipped with a half mirror so as to overlap output images of the $4f$ optical system for removing undesirable beams. For the $4f$ optical system, the spatial filter is located at a different location depending on the viewing zone, so that it is arranged in each viewing zone. The output lens of the $4f$ optical system is shared in the entire viewing zone.

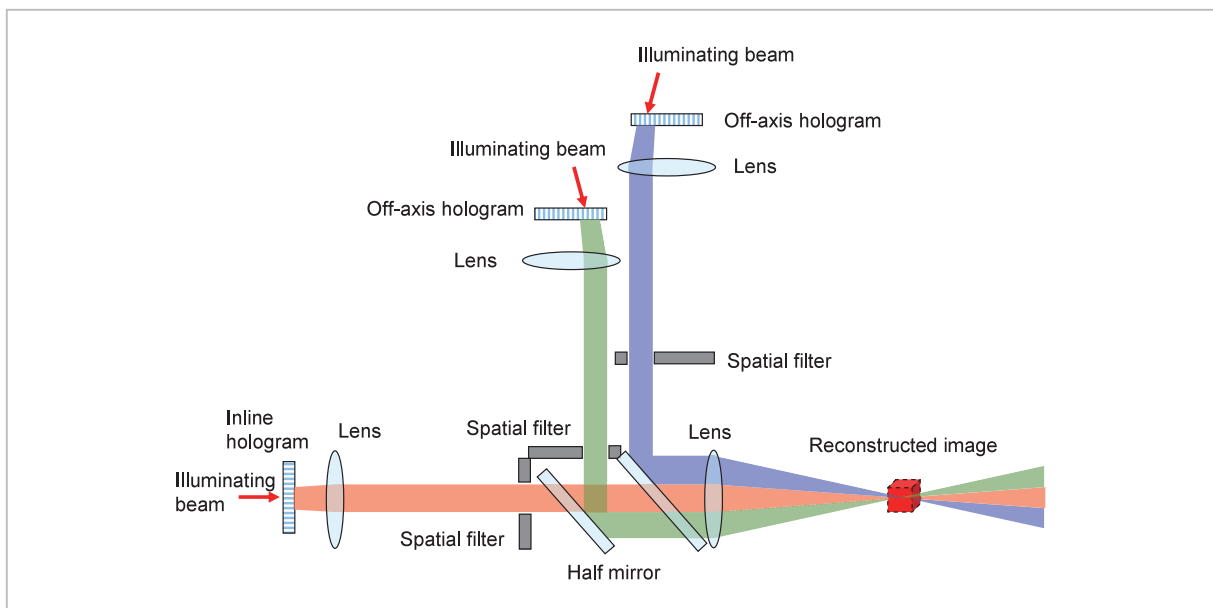


Fig.12 Configuration of an optical system with expanded viewing zone angle

5 Optical experiments

We applied the above findings to prototype an electronic holography reconstructor with its viewing zone expanded by three times, and conducted reconstruction experiments on hologram images. The results are described below[9].

5.1 Hologram conversion of integral photography

The objects for the experiments were building blocks shaped like the letters “I” and “P” as shown in Fig. 13. Electronic holography is usually photographed in a darkroom by using a laser beam as an illuminating beam. To apply it to ultra realistic communication, real images taken in natural light must be turned into electronic holography. We consequently employed integral photography. We consequently employed integral photography (IP) images[14] that can be taken in a natural illuminating beam to generate holograms. This IP photography was conducted in cooperation with the NHK Science & Technology Research Laboratories[15].

Integral photography is conducted (as shown in Fig. 14) with a lens array of small lenses arranged in a shape like a two-dimensional array in front of a standard camera, which is used to take microscopic images (IP images) produced on the focal plane behind the lens array. The pixels of an image taken (as shown in Fig. 14) correspond to sampling of the directions of beams emitted from each point of the object on the focal plane to the right of the microscopic lens array. This concept can be regarded as the same as that described in the previous section on electronic holography, where the directions of beams emitted from the object are converted and recorded as striped cycles of diffraction fringes. Thus, maintaining and reconstructing the directions of these beams will consequently cause the reconstructed beams to pass through the original object and form a three-dimensional image there. To that end, integral photography involves placing the same lens array as the one used in taking pictures at a location separated from the screen by the focal point distance of the lens, thereby

reproducing the directions of the beams for each pixel.

Three-dimensional images generated with this beam reconstruction method can be taken in natural light. These images can therefore be used to enable the holographic reconstruction of real images.

More specifically, placing a hologram surface on the optical path of reconstructed beams for integral photography and recording the phase of those beams as diffraction fringes with the phase of the reference beam (as shown in Fig. 15) makes it possible to obtain a hologram



Fig.13 Object

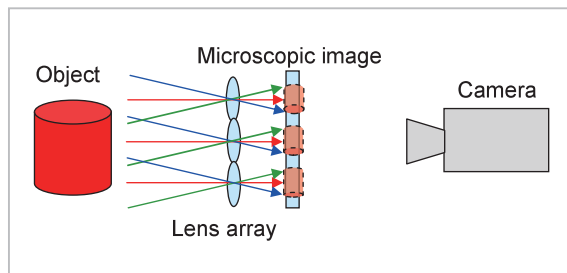


Fig.14 Taking images with integral photography (IP)

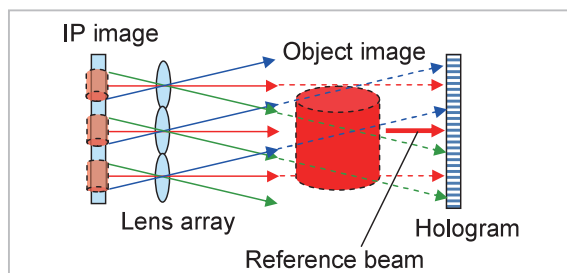


Fig.15 Hologram conversion of an IP image

of images reconstructed with integral photography^[16]. All this processing can be conducted on a computer when an integral photography image is available^[17].

5.2 Expanding the viewing zone angle in integral photography images

The viewing zone angle in integral photography images is expanded as described below. The location of each pixel in IP images corresponds to the beam direction as shown in Figs. 14 and 15. In IP photography, a size (D) and focal point distance f are therefore chosen for the IP lens, so that each image can be taken up to the beam corresponding to the expanded viewing zone angle. For example, when a hologram display device with maximum diffraction angle ϕ is used to expand the viewing zone angle by three times, diameter D and focal point distance f of the IP lens are then determined as shown in Fig. 16 (a) to satisfy the following:

$$\tan(3\phi) = \frac{D/2}{f} \quad (19)$$

As shown in Fig. 16 (b), IP images taken with this IP lens are beams with viewing zone angle $\pm\phi$ taken in the region occupying one-third of the lens center (red portion in the diagram), and beams with viewing zone angle ϕ to 3ϕ are taken in the region 1/3 in the periphery (green or blue portion in the diagram),.

The pixels of an IP image taken this way are divided into those in the central viewing zone and those in the peripheral viewing zone; the pixels in the central viewing zone are used to generate an inline hologram, while pixels in the peripheral viewing zone are used to generate an off-axis hologram. And these pixels are displayed on the optical system's hologram display device for expanding the viewing zone shown in Fig. 12. As shown in Fig. 16, an IP image has equal viewing zones horizontally and vertically. Here, however, only the horizontal viewing zone, which is important for visual characteristics, is expanded by three times, so that the vertical peripheral viewing zone pixels are not used.

5.3 Electronic holography reconstruction experiments

Tables 1 and 2 list the specifications for the IP camera^[15] used in taking pictures and those for the liquid crystal panel used in hologram display. When the depth range of an object is wide, IP photography may involve arranging a convex lens (a depth control lens) between the object and lens array, in order to form a real image of the object on the lens array, and photograph this real image through the IP lens. The depth of the photographed object image is 5 mm (the letter "I") and 28 mm (the letter "P") to the left of the lens array; the image height is 37 mm.

The size of the IP image taken is about five times that of the liquid crystal panel used for display ($52 \mu\text{m}/10.4 \mu\text{m}$). The size is therefore reduced to a one-fifth when the IP image is reconstructed. At that time, the focal point distance of the reconstruction-use IP lens was set to 1.2 mm so that the spread angle of the recon-

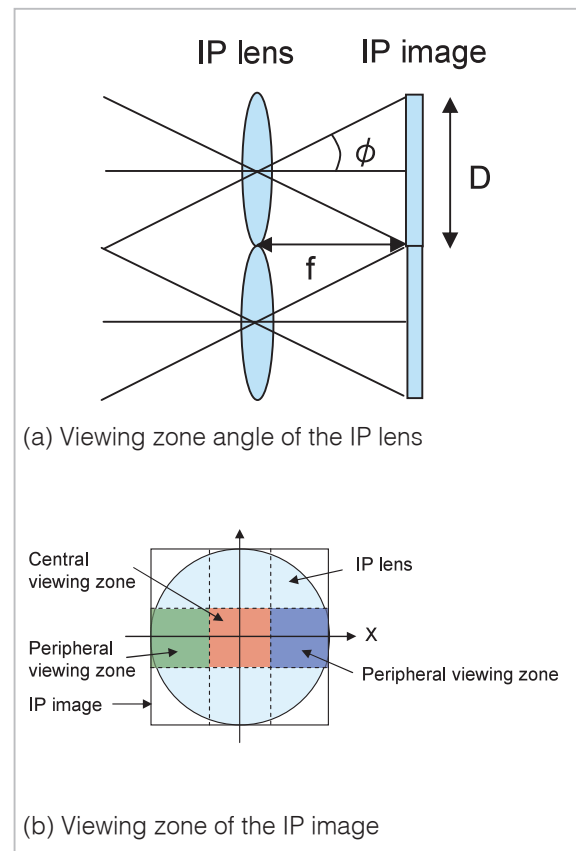


Fig.16 Dividing viewing zone of an IP image

Table 1 Parameters of an IP image

Focal point distance of the IP lens	2.65mm
Number of IP lenses	54(H)×63(V)
Pixels of an IP image	21(H)×21(V)
Pixel size of an IP image	52μm

Table 2 Specifications for the liquid crystal panel

Screen size	0.7 inch diagonal
Number of pixels	1400(H)×1050(V)
Pixel size	10.4μm

structed beam will become a viewing zone angle that can be displayed on the liquid crystal panel ($10.5^\circ = 3 \times 2 \sin^{-1} [632.8 \text{ nm}/(2 \times 10.4 \mu\text{m})]$). For that reason, the longitudinal magnification ($0.45 = 1.2 \text{ mm}/2.65 \text{ mm}$) of the three-dimensional image to be reconstructed will deviate from the transverse magnification ($0.2 = 10.4 \mu\text{m}/52 \mu\text{m}$), resulting in an image with its depth slightly emphasized as being reconstructed. Moreover, the beams to be reconstructed will have an angle of about 0.5° ($10.5^\circ/21$ pixels) between them.

Figures 17 and 18 show reconstructed images of electronic holography used for expanding the reconstructed viewing zone. Figure 17 shows a reconstructed image taken from the left. As the letter “I” is in the foreground on the left side, there are apparently tight clearances between the letters. Figure 18 shows an image taken from the right where there are apparently wide clearances between the letters.

It was observed that, as one changes one’s viewpoint, the letters accordingly look different, and that a space image has been constructed at each depth location. The viewing zone angle was about 8° as measured, and proved to be effective in expanding the viewing zone. The reconstructed image was such that the letter “I” was 3 mm horizontally and 7.5 mm vertically, and constructed at 2 mm behind the liquid crystal panel. The letter “P” was 5 mm horizontally and 6 mm vertically, and constructed at 12 mm behind the liquid crystal panel. The difference (10 mm) in depth be-

**Fig.17** Holographic image taken from left of the viewing zone**Fig.18** Holographic image taken from right of the viewing zone

tween “I” and “P” of the reconstructed image was about 0.43 times the depth difference (23 mm) of the IP image, while the size ratio was 0.2 ($= 7.5 \text{ mm}/38 \text{ mm}$) and correctly reproduced for both longitudinal and transverse magnifications.

The above observations confirmed the effectiveness of the method for expanding the viewing zone angle.

6 Conclusion

We consider three-dimensional imagery based on electronic holography as a leading means of making ultra realistic communication a reality. Electronic holography can reconstruct information about the amplitude and phase of a beam, thereby reproducing the same field of the beam as when we look at a real body in the natural world. For that reason, holography imagery has all of the following clues for three-dimensional viewing: binocular parallax, con-

vergence, accommodation, motion parallax, and pictorial cue. It can thus provide three-dimensional imagery that is natural and not tiring. As currently available holography display devices lack adequate resolution, however, such devices have been disadvantageous in entailing narrow viewing zones and undesirable beams overlapping reconstructed beams. Using the technology for expanding the viewing zone as reported in this paper enables a wide viewing zone to be obtained and removes undesirable beams, thereby achieving high-quality electronic holography images.

The experiments involved the use of a system for converting integral photography into electronic holography, which enables the reconstruction of real images in electronic holography. Using this system makes it possible to transmit motion picture images on a real-time

basis and to reconstruct electronic holography, thereby taking us one step closer to realizing ultra realistic communication.

There are high expectations for realizing full-color electronic holography images with even higher resolution and a wider viewing zone in the future.

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SENOH Takanori, Dr. Eng.
Expert Researcher, 3D Spatial Image and Sound Group, Universal Media Research Center
Electronic Holography, 3D Image Technology



MISHINA Tomoyuki, Dr. Eng.
Guest Expert Researcher, 3D Spatial Image and Sound Group, Universal Media Research Center
Electronic Holography, 3D Image Technology



YAMAMOTO Kenji, Dr. Eng.
Senior Researcher, 3D Spatial Image and Sound Group, Universal Media Research Center
Electronic Holography, 3D Image Technology



OI Ryutaro, Dr. Sci.
Senior Researcher, 3D Spatial Image and Sound Group, Universal Media Research Center
Optical Wave Propagation Analysis, Holography, 3D Imaging Technology, Image Sensor



KURITA Taiichiro, Dr. Eng.
Group Leader, 3D Spatial Image and Sound Group, Universal Media Research Center
Television System, Information Display, 3D Image Technology