3D Projection Screen using Advanced Volume Holography

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Abstract

The authors introduce 3D display systems developed in our laboratories for recent ten years. Those are mainly realized by several technologies in holography: electro-holography, holographic stereogram, holographic optical elements (HOE) and hologram screen. We are currently focusing the development of 3D projection screen without glasses. Powerful directionality of the light beam is required for 3D projection screen unlike 2D type. We succeeded in achieving the superior diffractive efficiency of hologram screen that is based on the advanced volume holography. This technology is extensively useful to retrieve the Bragg condition of volume hologram in the three-dimensional space. Owing to this technology we could establish the principle of multi-view projection screen and have confirmed the case of 4 viewing points.

1. Introduction

1.1 History of researches

Laboratories of Image Information Science and Technology (LIST) were organized about ten years ago. They are supported by the capital of several large companies in the west regional area in Japan. The innovational technologies are expected for providing them new business chances in the near future. The group of the authors has been developing various progressive 3D display systems.

We first started on the research of electro-holography. The synthesis of electro-holography and optical holography was realized [1]. We could express dynamic image generated by a parallel computer on the still background of optical hologram. This display was very amazing because of the full parallax. However the size of image was very small in spite of the cost of this system.

Holographic stereogram was available for the display with horizontal parallax. We studied stereogram systems using the combination of hologram panel and liquid crystal display (LCD) panel [2][3]. In these systems the maximum number of viewing points could reach 32 areas. This technology needed extremely fine resolution of display panel.

In binocular systems like a head mounted display (HMD), 3D displays could be made of very simple configuration using HOE. We developed a HMD that provided the bright Maxwellian view [4][5]. In the case of the Maxwellian view crystalline lens became like a pinhole camera and free from accommodation.

On the other hand we continued to improve the quality of display hologram [6]-[8]. We developed several techniques of holography: color conversion by a single laser, achromatic volume hologram and three-dimensional Bragg diffraction. Using these techniques we could produce multi-view projection screen easy to generate the objective diffracted beam.

1.2 Principle of multi-view screen

The typical multi-view screen is shown in Figure 1. Each illumination from m numbers of projectors A_m is projected to the hologram screen and forms diffracted beam focusing on the viewing point a_m. It was initially understood that such a multiple reconstructed hologram could be easily produced by multiple exposure [9]. It is the truth that brightness of the diffracted beam is degraded to 1/N or $1/N^2$ (N means the number of exposures) [10].

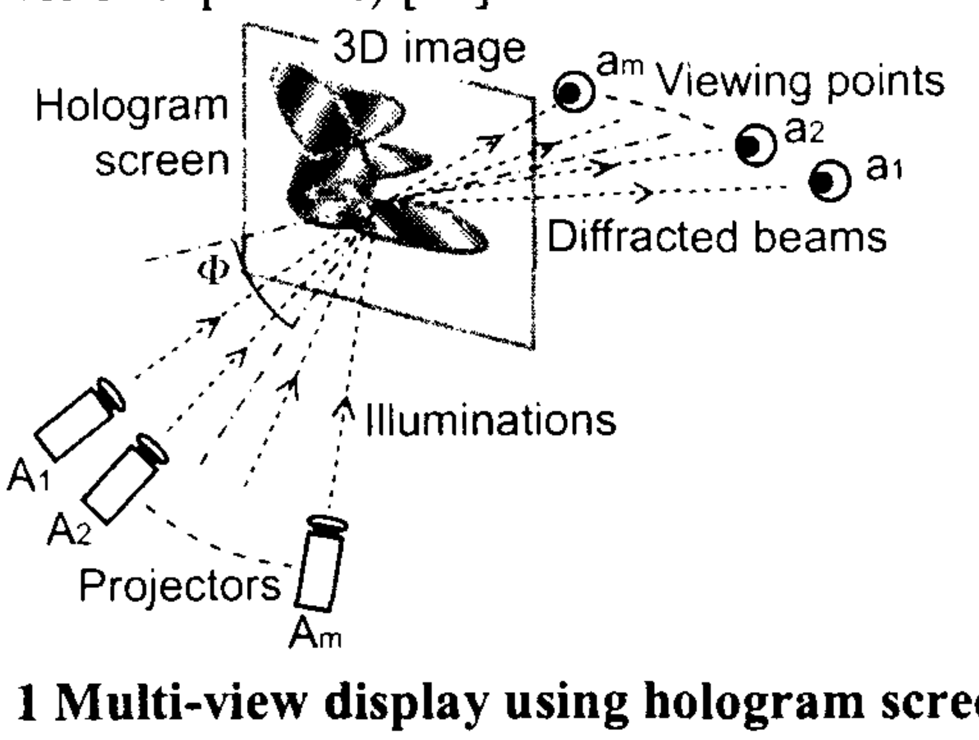

Figure 1 Multi-view display using hologram screen.

Many researchers directed their schemes toward the development of grating panels like our system using holographic stereogram [11]-[13].

We pointed out that even single recorded hologram could be multiple reconstructed by the illuminations near the Bragg angle [14]. This projection screen was effective among the angular selectivity of hologram. Thus we really achieved multi-view hologram screen.

Though the first version had narrow viewing zone because of the angular selectivity, the second version could be given wide viewing zone by the advanced volume holography that is capable of retrieving the Bragg diffraction in the three-dimensional space.

In this paper we explain the advanced volume holography: color control by a single laser and three-dimensional Bragg diffraction. Then we introduce a multi-view projection display without glasses.

2. Advanced volume holography

2.1 Color hologram by a single laser

Figure 2 illustrates the relation between recording and replay of color volume hologram. Each circle shows the Ewald sphere in the reciprocal space of crystal optics [7][15]. The upper side (a) expresses the conventional style. The radius of each Ewald sphere shows the inverse of wavelength λ_j. Here suffix j means color: red (R), green (G) or blue (B). The parameter n is the refractive index of hologram.

The grating vector $\mathbf{r}_{Kj}$ is the vector that subtracts the vector of illumination $\mathbf{r}_{Cj}$ from the vector of reconstructed beam $\mathbf{r}_{Ij}$. That is expressed by

$$\mathbf{r}_{Kj} = \mathbf{r}_{Ij} - \mathbf{r}_{Cj}. \qquad (1)$$

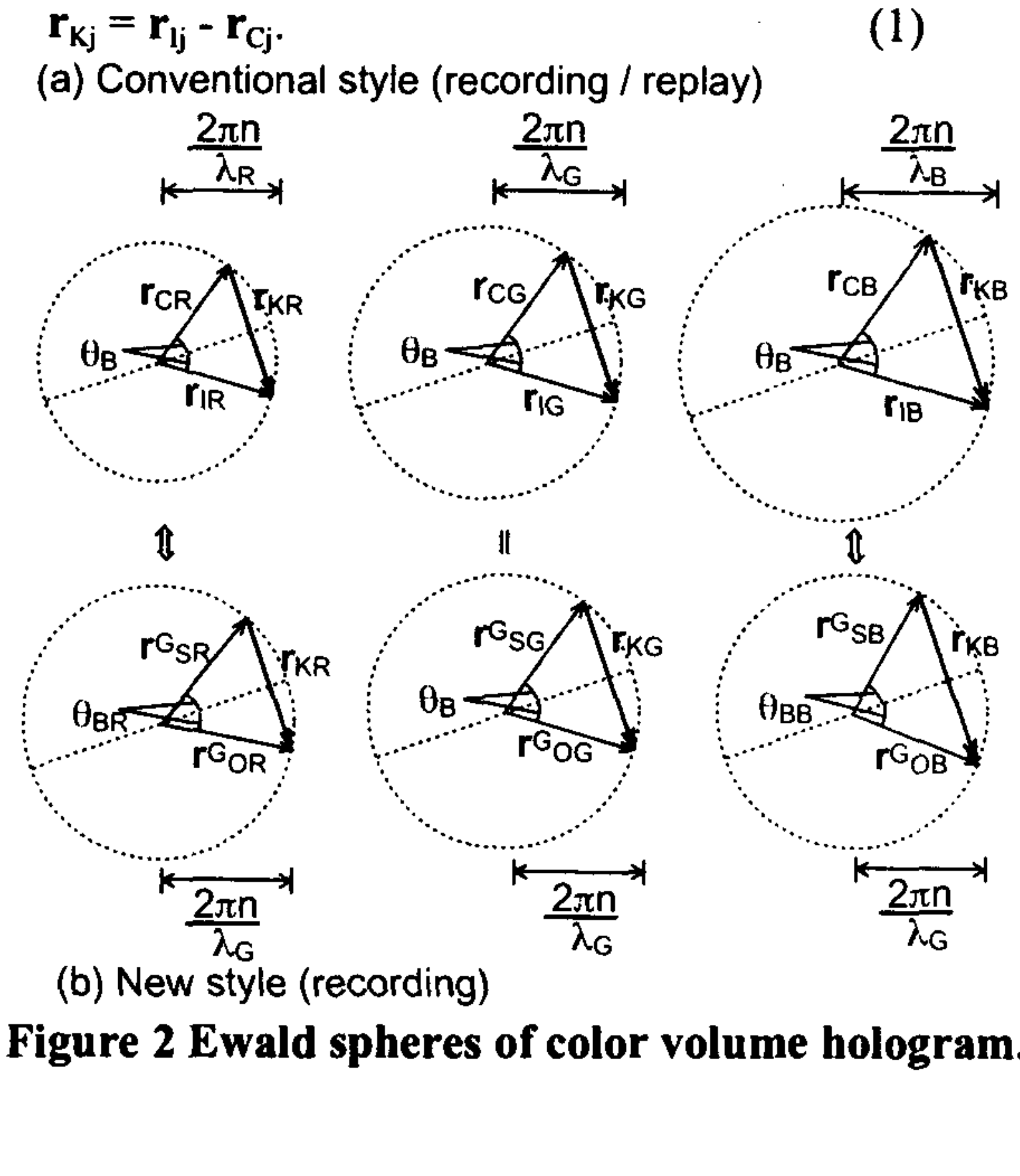

Figure 2 Ewald spheres of color volume hologram.

θ_B shows the Bragg angle that becomes same in the color hologram. The Bragg condition is expressed by

$$(2\pi n/\lambda_j) \sin(\theta_B) = \pi/\Lambda_j, \qquad (2)$$

where Λ_j is the grating period [10]. Each direction of grating vectors $\mathbf{r}_{Kj}$ is equal to the others in the color volume hologram. This hologram is usually exposed in the same incident angle between two interfering lights by three times: red, green and blue. Then 3 lasers have to be used in the conventional case.

In our case the Bragg angle θ_B is changed instead of the wavelength λ_j of Eq. (2). The lower side (b) of Figure 2 shows the idea that a color volume hologram can be made by a single laser. However the size of every Ewald sphere is same, the length of each grating vector is different. The equality of the grating vector $\mathbf{r}_{Kj}$ between the upper and lower Ewald spheres should be noticed in each color case. We could convert the color of hologram to any wavelength by changing the Bragg angle between recording and replay. Only one laser had to be needed.

Our new procedure differs from the method of pseudocolor hologram recorded by the technique of rainbow hologram. Pseudocolor hologram is classified into plane hologram like rainbow hologram. Each direction of the grating vectors among 3 colors may be delicately shifted, where the diffraction efficiency is degraded and the reappearance of color is not so good. As our new color hologram belongs to volume hologram, we can achieve superior diffraction efficiency and good reappearance of color.

2.2 Distinction between volume hologram and plane hologram

There is a well-known criterion Q to decide the type of hologram [10][16][17]. It is expressed by

$$Q = 2\pi\lambda s/n\Lambda^2, \qquad (3)$$

where s is the length of illumination path through the hologram. Small values of Q (Q<1) correspond to plane holograms. Large values of Q (Q>10) correspond to volume holograms.

Figure 3 shows the cross section of hologram that is a model of layers about interference fringes [18]. In Fig. 3 AE expresses the length s of illumination path through the hologram and CD expresses the length of illumination path between two neighboring fringes.

The ratio q of AE to CD is expressed by

$$q = s/(\Lambda/\sin(\theta_B)) = (t \sin(\theta_B))/(\Lambda \cos(\phi)), \qquad (4)$$

where t is the thickness of hologram and ϕ is the angle of illumination in the hologram.

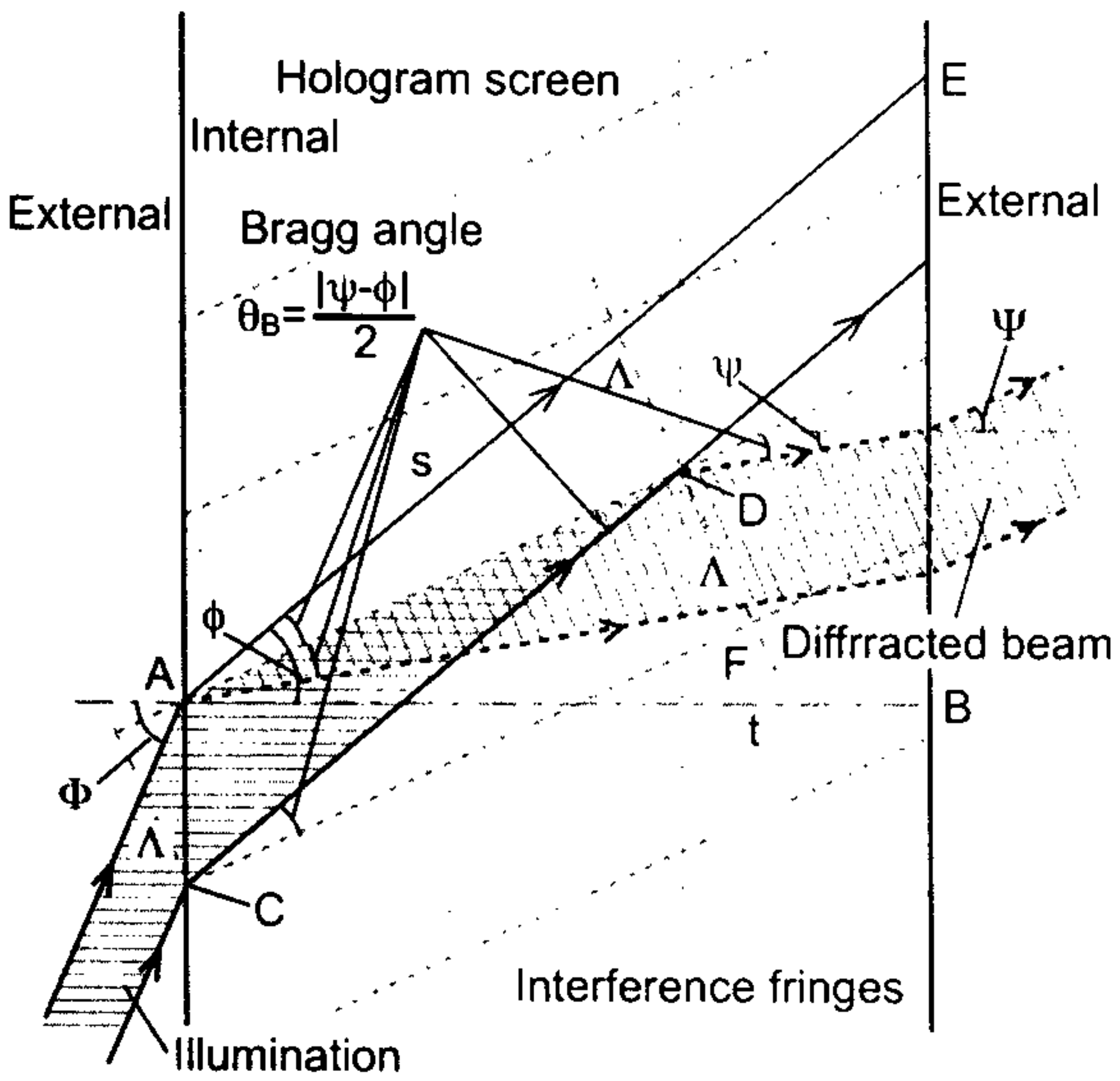

Figure 3 Cross section of volume hologram.

It is understood that all the illumination generates the Bragg diffraction when q>1. Only some part of the illumination generates the Bragg diffraction when q<1. As the Bragg angle is expressed by Eq. (2), q becomes

$$q = \lambda s/(2n\Lambda^2) = \lambda t/(2n\Lambda^2 \cos(\phi)), \qquad (5)$$

for an arbitrary wavelength λ. Comparing Eqs. (3) and (5), it is cleared that the relation between Q and q is

$$Q = 2\pi(2q). \qquad (6)$$

This indicates that Q is nearly equal to 12q. Then q>1 is more adequate than Q>10 for estimating volume hologram. From Eq. (5) it is calculated that the minimum of incident angle Φ with the illumination is about 35 degrees outside the hologram where the angle of the diffracted beam Ψ is 0.

2.3 Three-dimensional Bragg diffraction

The Bragg diffraction is usually analyzed in two-dimensional plane like Fig. 3. That procedure is proper in the case where the common plane containing both illumination and reconstructed beam is perpendicular to the hologram screen. When the common plane is not perpendicular, we must consider the state of diffraction in the three-dimensional space.

Figure 4 shows an example of three-dimensional Bragg diffraction where the refractive index n is assumed constant. The interference fringes are corresponding to the illumination from projector A_1 and the diffracted beam for viewing point a_1.

When the pair of A_1 and a_1 is rotated by ω around the grating vector, an arbitrary pair of A_m and a_m also

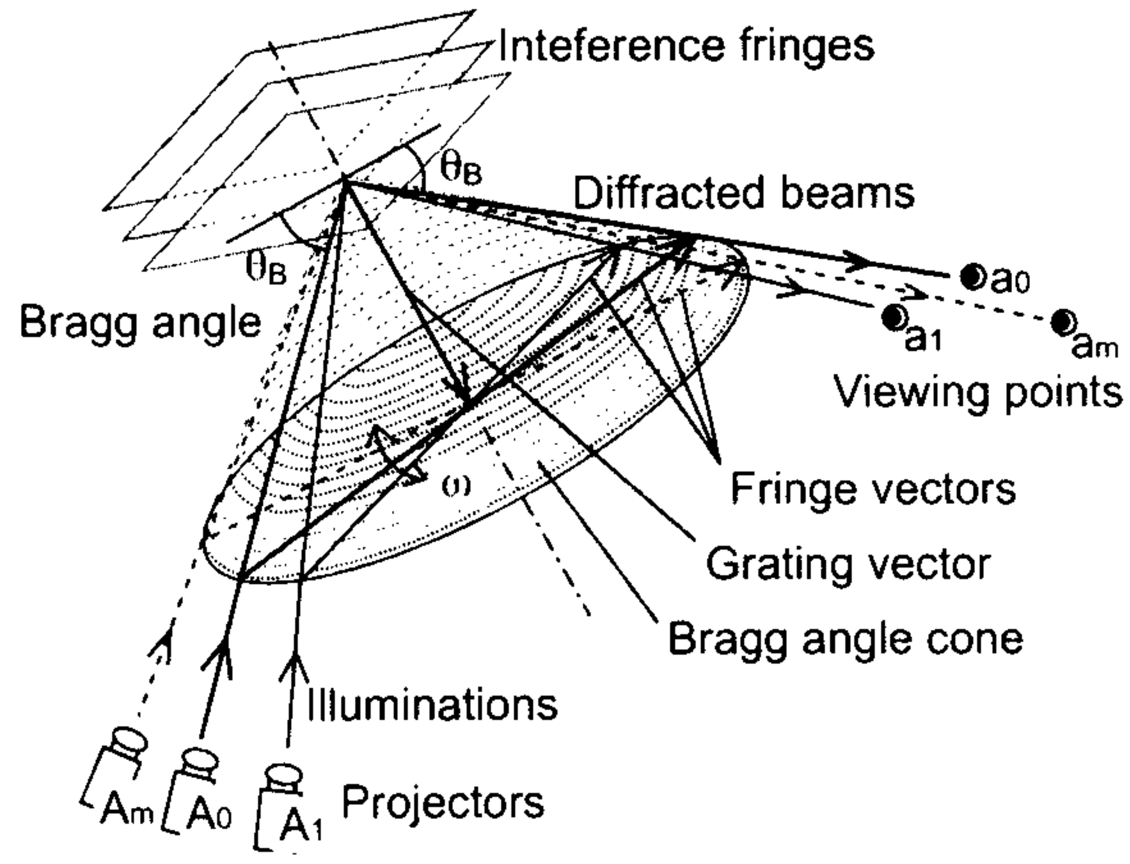

Figure 4 Multiple reconstructions on fringes of the once recorded volume hologram.

satisfies the same Bragg condition. It is because the diffraction angle of the new pair is equal to that of the original pair.

Three-dimensional Bragg condition is simply expressed by the notation of unit vectors **p** as follows;

$$(\mathbf{p}_i-\mathbf{p}_c)/(2\sin(\theta_B)) = (\mathbf{p}_{i\omega}-\mathbf{p}_{c\omega})/(2\sin(\theta_B)), \qquad (7)$$

$$(\mathbf{p}_i+\mathbf{p}_c)(\mathbf{p}_{i\omega}+\mathbf{p}_{c\omega})/(4\cos^2(\theta_B)) = \cos(\omega), \qquad (8)$$

where each suffix (i, c, iω or cω) means the illumination before rotation, the reconstructed beam before rotation, the illumination after rotation or the reconstructed beam after rotation. Eq. (7) is related to the direction of grating vector and Eq. (8) is related to the plane parallel to the fringes. The components of each vector can be mutually converted between the internal and the external of hologram by Snell's law.

3. Multi-view hologram screen

We designed a hologram screen for multi-view display without glasses by the above advanced volume holography. We decided the angle of illumination 20 degrees and that of the diffracted beam -15 degrees in order that the distortion of 3D image becomes as little as possible. Each distance of projectors is -250cm (negative for incident beam) to the hologram screen and each distance of viewing points is 100cm.

Figure 5 shows the calculated orbits of diffracted beam and illumination. These are on the nearly horizontal circles whose centers are at the vertical axis of the hologram. Marks of the diffracted beam are illustrated by 6.5cm and marks of the illumination corresponding to them are illustrated in the same way. Each radius of orbits from the *x*-axis on the center of hologram screen is 97cm about the diffracted beam or -235cm about the illumination.

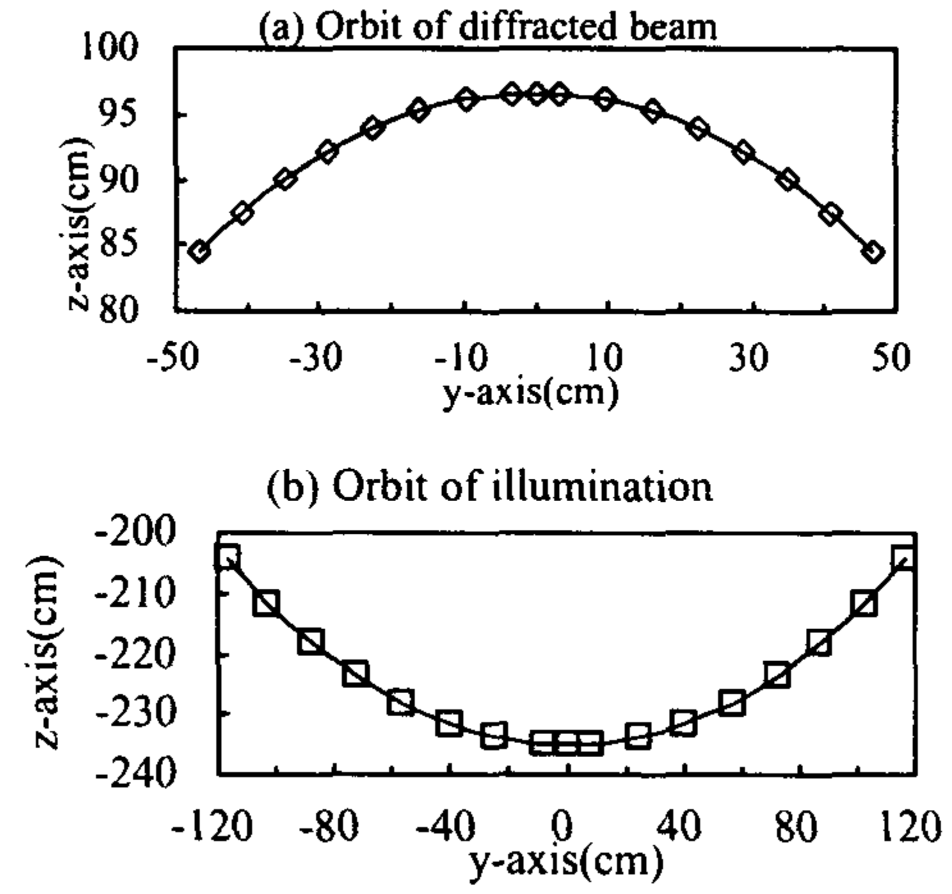

Figure 5 Horizontal orbits of multi-view screen.

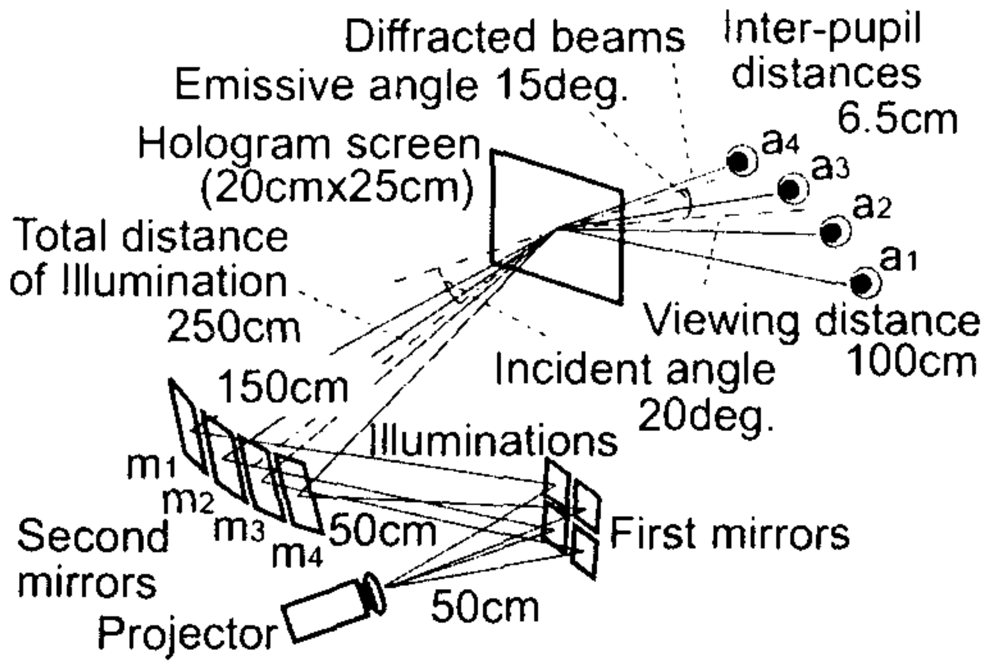

Figure 6 Configuration of 4 viewpoints' display.

4. Trial device with 4 viewing points

We developed a trial device with 4 viewing points as is illustrated in Figure 6. Instead of 4 projectors we used a projector and arrays of optical mirrors. The hologram screen is made of a PFG-03C plate and its size is 20cm x 25cm. The recording wavelength is 532nm of Verdi V-2 solid-state laser by Coherent Inc. The designed wavelengths of the diffracted beams are 620nm (red), 532nm (green) and 465nm (blue) [7]. Figure 7 shows a picture of the trial device. Extremely bright 3D image is reconstructed on the hologram screen. The model of LCD projector is LVP-X500 made by Mitsubishi Electric Ltd. The brightness of the projector is 370 lumens. The power is 420 watts.

5. Conclusions

We originally developed the advanced volume holography: color control by a single laser and three-dimensional Bragg diffraction. We also succeeded in developing a multi-view projection display by the advanced volume holography.

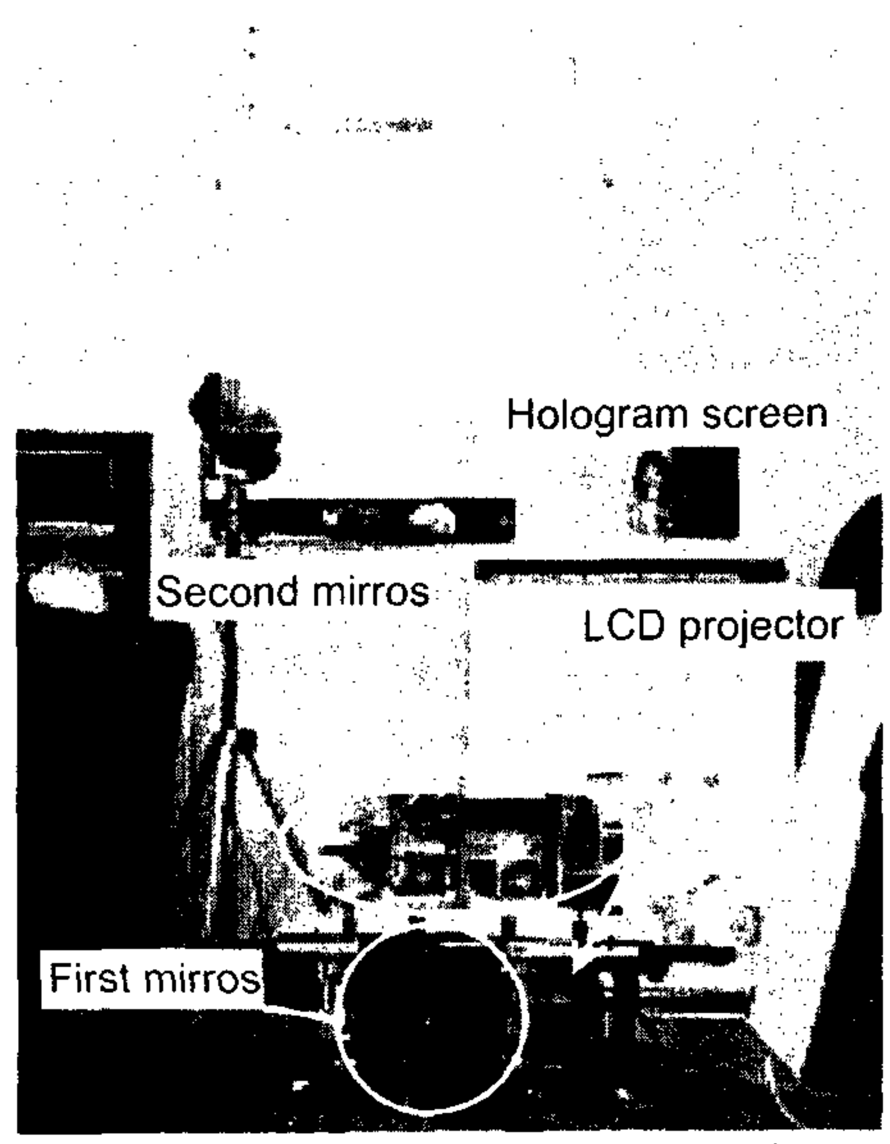

Figure 7 Example of 4 viewpoints' display.

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