Large Size of Real-Time Bi₁₂SiO₂₀ Hologram Device Made with Inexpensive Wafer Cutting Method

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The large real-time hologram device made by the previous Bi₁₂SiO₂₀ single crystal wafer cutting method poses several problems such as a large residue of material hinders the practical use. A study was carried out to fabricate a real-time hologram device using inexpensive laterally cut circular (1 0 0) Bi₁₂SiO₂₀ single crystal wafers which would be suitable for practical use for 3-dimensional display. An angle incident on a (1 0 0) wafer is applicable to the real-time hologram. An optimal electrode design for a device with uniform diffraction efficiency was considered, and the device properties were experimentally investigated.

Key words: hologram, photorefractive, 3-dimensional display, Bi₁₂SiO₂₀, diffraction

1. Introduction

The 3-dimensional display is a promising application of holograms. Unlike photosensitive materials used in photography, a real-time hologram (RH) device with photorefractive material can make a 3-dimensional display practical because no chemical processing is necessary. Applications on 3-dimensional displays require that a Fresnel hologram have a horizontal length greater than the distance between human eyes (about 50 mm), because human stereoscopic recognition depends primarily on parallax vision. Using Bi₁₂SiO₂₀ single-crystals (BSO), we have manufactured a large-area RH device useful for 3-dimensional displays permitting observation with both eyes simultaneously and have checked its functions.¹ A large BSO crystal rod about 80 mm in dia. and 100 mm long was grown by the Czochralski method. The pulling axis of the crystal was the ⟨1 0 0⟩ axis because BSO can be grown relatively easily by this axis.² This crystal was used for the device. Figure 1(a) shows the method used to cut the BSO wafers to make the large-area RH device. The technique allows (0 1 1) wafers and ⟨0 1 1⟩ orientation electric field applied wafers to be obtained. Although it further allows orientation of wafers to be oriented to yield the highest diffraction efficiency, several problems are involved such as the complexity of the cutting process, a large residue of material and the difficulty in producing large numbers of the same size wafers. These drawbacks raise the cost of the device and hinder its practical use. A wafer cut by an inexpensive and easy method is needed for practical application of a large RH device. This paper discusses and shows test results of the design and manufacture of large-area RH devices with permit observation with both eyes and are made from BSO wafers produced by an efficient, waste-free and practical cutting method.

2. Device Design

There are three items to consider in designing the device: the wafer cutting orientation, an estimate of the diffraction efficiency and the electrode design. First, the wafer cutting orientation is described. For the cutting, a lateral method is needed to obtain inexpensive wafers. A crystal rod was cut vertically to its center axis for yield laterally cut (1 0 0) wafers. This technique offers practical advantages over the previous method (Fig. 1(a)): the cutting process is simple and does not produce much material waste, and the cutting orientation is the same as for BSO wafers used in other devices such as the BSO spatial light modulator.³ The inexpensive lateral cutting method is shown in Fig. 1(b), and we tried produced a large-area RH device with BSO wafers, which were laterally cut out.

The next, we discuss a method for obtaining a valid photorefractive effect in laterally cut wafers. The generation process of the photorefractive effect can be understood by the charge-transport model.⁴ The photorefractive effect of BSO originates as follows: a space-charge field is generated by non-uniform light illumination and changes the refractive index by means of the Pockels effect. A saturated space-charge field \(E_{sc}\) with adequate exposure is given by

\[
E_{sc} = m \left( \frac{E_{ex}^2 + E_{dr}^2}{(1 + E_{ex}/E_{dr})^2 + (E_{ex}/E_{dr})^2} \right)^{1/2},
\]

where \(m\) is a contrast ratio of the exposed fringe, \(E_{ex}\) diffusion electric field, \(E_{dr}\) external applied electric field and \(E_{sc}\) limited space-charge field.⁵ The limited space-charge field is given by

\[
E_{sc} = m e N_t / \varepsilon_0 \kappa,
\]

where \(e\) is the elementary electric charge, \(N_t\) the trapping center density, \(\varepsilon_0\) relative dielectric constant and \(\kappa\) dielectric constant of free space. As stared, the space-charge field \(E_{sc}\) changes the refractive index. The refractive index amplitude \(\Delta n\) is proportional to the electric field in the crystal as,

\[
\Delta n = \alpha E_{sc},
\]

where \(\alpha\) is a proportional constant indicating the efficiency of the Pockels effect. \(\alpha\) depends on the orientation of the crystal and the direction of the electric field.

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The refractive index is given by the length of the principal axes of the ellipse on the cross section in a parallel plane to the transmitted light wavefront passing through the center of the index ellipsoid. When the light enters the (1 0 0) wafer vertically, the cross-section is circular because \( x_1 = 0 \) was put in Eq. (11), by

\[
x_3^2/n_0^2 + x_2^2/n_0^2 = 1
\]

(12)

which shows \( \Delta n_0 = 0 \). Thus, the photorefractive effect cannot be observed.

The following assumes that the light is incident on the crystal surface at an oblique angle. Two designs are investigated: in design A the incident plane is parallel to the \( x_1 - x_3 \) plane (Fig. 2(a)), in design B parallel to the plane containing the \( x_1 \) axis and the \( <0 10> \) axis (Fig. 2(b)). The angle between the optical axis and the \( <0 10> \) axis in the crystal is written as \( \theta \) and that between the electric field and the \( <0 10> \) axis as \( \phi \). Transforming the index ellipsoid obtained in Eq. (11) into the \( X_1X_2X_3 \) coordinate system in which the \( X_1 \) axis is parallel to the optical axis, in design A we obtain

\[
\frac{(X_1 \cos \theta + X_3 \sin \theta)^2}{n_0^2} + \frac{X_2^2}{n_0^2} = \frac{(X_1 \cos \theta - X_3 \sin \theta)^2}{n_0^2} + 2rE_x \sin \phi (X_1 \cos \theta - X_3 \sin \theta)(X_1 \cos \theta + X_3 \sin \theta)
\]

(13)

The elliptical cross-section due to the wave front is obtained by putting \( X_1 = 0 \) in Eq. (13). From the length of the principal axis of this ellipse, refractive index \( n \) is obtained by

\[
n = \frac{n_0^2 + rE_x \sin \phi \sin \theta \cos \theta}{\pm rE_x \sin \theta (\sin^2 \phi \cos^2 \theta + \sin^2 \phi)^{1/2}}
\]

(14)

Because \( \Delta n_0/n \ll 1 \), in general, from Eq. (14) index variation \( \Delta n \) is given as

\[
\Delta n = -(1/2)n_0^2 rE_x (\sin \phi \sin \theta \cos \theta + \sin \theta (\sin^2 \phi \cos^2 \theta + \sin^2 \phi)^{1/2})^{1/2}
\]

(15)

This shows that the refractive is changed proportionally to the strength of the applied electric field by the Pockels effect. Existence of the valid photorefractive effect can be understood from Eq. (8).

From the well-known formula of the diffraction efficiency of the volume hologram, when circularly polarized light enters, diffraction efficiency by the photorefractive effect \( \eta \) in a holographic recording is given by

\[
\eta = c(\Delta n_{c1}^2 + \Delta n_{c2}^2)
\]

(16)

with the naturally rotatory polarization of BSO discounted, where \( c \) is a proportional constant and \( n_{c1} \) and \( n_{c2} \) the index variations along each principal axis. Using Eq. (15), diffraction efficiency in the case of design A is obtained by

\[
\eta = c(1/4)n_0^2 r^2 E_x^2 (\sin^2 \phi \sin^2 \theta \cos^2 \theta + \sin^2 \theta \sin^2 \phi \cos^2 \theta)^{1/2}
\]

(17)
In design B, the index ellipsoid in the $X_1X_2X_3$ coordinate system is similarly given by

$$X_1^2/n_{1}^2 + X_2^2/n_{2}^2 + X_3^2/n_{3}^2 + 2rE_0\sin\phi(-X_1\sin\theta - X_2\cos\theta)(X_1\cos\theta + X_3\sin\theta)/\sqrt{2} + 2rE_0\cos\phi(X_1\cos\theta + X_3\sin\theta)(-X_1\sin\theta + X_2\cos\theta)/\sqrt{2} = 1$$

(18)

and diffraction efficiency is given by

$$\eta = c(1/2)n_0^6r^2E_0^2(\sin^2\theta\cos^2\theta(\cos\phi + \sin\phi)^2 + \sin^2\theta(\cos\phi - \sin\phi)^2)/2.$$  

(19)

Equations (17) and (19) suggest that an angle incident on a wafer makes even (100) wafers usable in RH devices.

The largest diffraction efficiency is given by a (0 1 1) wafer by application of the electric field parallel to the (0 1 1) axis. In this case the index ellipsoid is given by

$$X_1^2/n_{1}^2 + X_2^2/n_{2}^2 + X_3^2/n_{3}^2 - 2rE_0X_3X_1 = 1.$$  

(20)

The diffraction efficiency is obtained by

$$\eta = c(1/2)n_0^6r^2E_0^2.$$  

(21)

From this formula, the diffraction efficiency of design A with $\phi = 90^\circ$ and $\theta = 45^\circ$ is expected to become a quarter of that of the most efficient design.

The last item to be considered is the design of electrodes. To apply a laterally cut (100) wafer to an RH device while retaining its large area, it is preferable to use only a wafer with polished (100) surfaces, that is to say, an overall cylindrical crystal shape. In ordinary RH devices, the electric field in the crystal is made uniform by parallel flat electrodes to apply the external electric field. However, when electrodes are formed at the periphery of
a circular wafer, they make a non-uniform electric field in the wafer, and the diffraction efficiency becomes non-uniform. Electrodes must therefore be formed so that non-uniformity of the diffraction efficiency is as small as possible. An investigation was carried out using numerical calculations with the finite element method to determine the optimal location and size of electrodes to ensure a large and primarily uniform diffraction efficiency. Assuming a symmetrical electrode layout, the Laplace equations were solved and a potential distribution due to the voltage applied between electrodes was obtained. Calculations were performed on the layouts for designs A and B shown in Fig. 3, where the electrodes have a central angle of $2\theta$ and are located as shown in the figure. Some of the calculated results are shown in Fig. 4. These were calculated under a not-graded light intensity exposed condition. When the exposed light is graded, the potential changes because of the conductivity distribution.

From these results, the distributions of diffraction efficiency were obtained using Eqs. (17) and (19).

Application of a Fresnel hologram is assumed here. The object light must be diffused so that a speckle pattern is exposed on the device. In this case, the exposed light intensity is not uniform along any direction on the device surface. All components of the electric field form the charge distribution and influence the photorefractive effect.

When the parallel fringe is exposed, only the components of the applied electric field perpendicular to the fringe affect the photorefractive effect because the content of the electric field along the uniform light intensity direction does not form a charge distribution. In such case, Eqs. (17) and (19) must be modified because these equations include the effect of all components.

The circularly polarized readout beam was incident on the wafer at the incident angle $\theta=60'$. This incident angle corresponds to $\theta=20'$ because of the refraction at the BSO surface. Examples of the calculation are shown in Fig. 5. These were obtained using the potential distribution shown in Fig. 4 and device design A. The levels and uniformity of diffraction efficiency for both designs A and

![Image](image_url)

Fig. 6. Characteristic curves of the level of diffraction efficiency and its uniformity versus $\rho$, respectively. The level indicates the mean value of the diffraction efficiency in the wafer using an arbitrary unit. The uniformity $U$ was defined as value Eq. (14). A relatively large and uniform diffraction efficiency is obtained by design A with $\rho=45'$.

![Image](image_url)

Fig. 7. Calculated diffraction efficiency distribution of the optimal design (design A with $\rho=45'$). The dispersion is smaller than those shown in Fig. 5.
B are summarized in Fig. 6. The uniformity \( U \) was estimated with the following definition:

\[
U = \frac{S_i}{S_o} \times 100(\%)
\]  \hspace{1cm} (22)

where \( S_o \) is the area of the whole wafer and \( S_i \) the area where the diffraction efficiency becomes within the range of \( \pm 20\% \) of the average efficiency over the whole wafer. In short, \( U \) means the area size in which diffraction efficiency is almost the same. The results here suggest that the electrode design achieving relatively large diffraction efficiency and with uniformity is design A with \( \rho = 45\% \). The diffraction efficiency distribution shown in Fig. 7 is relatively uniform at the center of the wafer, and suggests that the wafer is suitable for an RH device for display applications.

3. Experimental Results and Discussion

To confirm the discussion in the previous section about the relation between \( E_n \) and \( E_s \), characteristic curves of diffraction efficiency versus applied electric field are measured. A (0 1 1) BSO wafer is used and the electric field is applied along the (0 1 1) axis. As shown in Fig. 8, the diffraction efficiency is proportional to the square of the electric field. This tendency agrees with Eq. (21), and suggests the appropriateness of Eq. (7).

The large RH device thus fabricated had a (1 0 0) BSO wafer 80 mm in diameter and 2 mm thick. The electrodes were made of conductive resin according to optimal design A with \( \rho = 45\% \). The device was mounted on a holder made of Teflon to avoid electric discharge. The external applied voltage between the electrodes was 40 kV dc. Holographic recording and reconstruction was attempted using the device. In the recording process, an object and a reference beams with a wavelength of 488 nm were incident on the

Fig. 9. Reconstructed images from the large BSO RH.

Fig. 8. Characteristic curves of diffraction efficiency of the BSO RH versus applied electric field. Symbols ● and ○ show the efficiency under the exposure energy 2 mJ/cm² and 4 mJ/cm², respectively. The diffraction efficiency is proportional to the square of electric field.

Fig. 10. Characteristic curves of the diffraction efficiency level and intensity refraction efficiency of circularly polarized light versus \( \theta \) and incident angle.
RH device at an angle of 60' (θ=20'), and the mean value of interference fringes was about 130 fringes per mm. A reconstruction beam with wavelength 633 nm was incident on the recorded device satisfying Bragg diffraction conditions. The measured diffraction efficiency was 0.2% at the center of the device. A picture drawn on a transmission film sheet 60×60 mm² in size was irradiated and recorded by a coherent diffused light with wavelength 488 nm. The reconstructed image is shown in Fig. 9. Its brightness showed no prominent unevenness. The image could be observed by the naked eyes and depths corresponding to the counterparts in the original were observed.

For various practical applications, the diffraction efficiency of the device and the brightness of reconstructed images must be increased. The diffraction efficiency varies with angle θ between the ⟨1 0 0⟩ axis in the wafer and the optical axis. Their relation is shown in Fig. 10. An incident angle of 60', which is the RH device with the optimal design, corresponds to θ=20'. The diffraction efficiency becomes maximum when θ=45' (Fig. 9). The maximum value of the diffraction efficiency is about three times the value with θ=20', which leaves room for improvement in the diffraction efficiency. However, adjustment of the incident angle by tilting the RH device fails to meet the condition θ=45', because of refraction at the BSO wafer surface. Further increasing the incident angle will invite such problems as increasing loss of the readout beam due to Fresnel refraction at the wafer surface, and decrease in the effective area of the device. Such difficulties can be eliminated by taking effective measures to control the optical axis such as by attaching a prism or diffraction grating on the BSO wafer surface; this requires further study. Increasing the external applied voltage will be effective in raising diffraction efficiency. This necessitates a study on an element structure that can prevent discharges and allows a high applied voltage. Raising diffraction efficiency through such improvements is expected to advance the development of large RH units for practical use.

4. Conclusions

Application of laterally cut BSO (1 0 0) wafers on a real-time volume hologram device was first considered and an optimal design of the RH device was described. A large RH device was fabricated based on this design and 3-dimensional images were reconstructed which were observable by the naked eyes. Measures for increasing the diffraction efficiency of the device were discussed. Useful large and inexpensive RH devices can be made by the proposed cutting method and device structure.

References