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Verification of Polarization Matching on the Hologram Recording Plane for the Implementation of an Optimized Digital Hologram Printing System

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Conventional studies on digital hologram printer have mainly been conducted on image generation and reconstruction such as multi-view image generation method, computer-generated hologram (CGH) and a method of displaying a wave-front for a 3D object. However, There should be a criterion to evaluate the quality of the reconstructed image because hologram printer use photosensitive recording interference patterns in holographic material. For this reason, The evaluation method of the completed hologram using a digital hologram printer is focused on how well it came out without aberration or how high intensity of light has been reconstructed. However polarization has an effect on hologram regeneration efficiency because holography uses a laser that generates electromagnetic waves. Hologram recording method is usually to match linear polarization in the same direction. but digital hologram printer composed of complex optical components that causes a phase shifting due to a setup error. it will be a problem for resulting in unwanted polarization at the final recording plane. In this paper, we analyzed the possible polarization changes and analyze the optimal polarization matching status using values from hologram results and use them as a study to improve the efficiency of hologram result from holographic printer.

Keywords: polarization, holographic printer, holographic optical elements, diffraction efficiency, photo-polymer

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1 INTRODUCTION

Recently, many studies have been conducted on stereo printing technology that generates and records a three-dimensional multi-view image using holography and wave-front printing technology that reproduces wave-front using CGH in the field of optical information processing [1–8]. these are all about generation and reconstruction 3D image by interference patterns of objective beam and reference beam using holography. And there are various evaluation factors such as the size of the result, field of view at the observer's point and wavelength selectivity for reconstructed light. However, the most important evaluation factor in holography is optical diffraction efficiency because all display are made to see clear brightness and high resolution with human eyes. In holography, two coherent laser lights of an objective beam and a signal light interfere for recording an interference pattern in holographic material. And the reference beam is illuminating to the same light as the initial condition of record to measure efficiency. The measurement method is divided into a relative diffraction efficiency measurement and an absolute diffraction efficiency measurement [9, 10]. The analog hologram recording method which is a traditional optical hologram uses uniform light of a wide distribution [11]. Therefore light is illuminated for few seconds to several tens of seconds or more to record interference patterns in holographic material [12, 13]. But, the holographic printing mostly uses a digital holographic method. Thus, this optical system composes the entire plane like dot printing using small hologram unit within 1 mm size of square and we call it holographic element (Hogel) [14]. And these hogels are so small that they are recorded in several micro seconds. In some research, Hogel sizes ranging from 0.25 to 0.5 mm based on stereo holographic printers are currently being printed [15]. In order to record a hologram of about A4 size with this type of digital hologram printer, printing is required approximately 250,000 times in 0.25 mm hogel size and 1,000,000 times in 0.5 mm size. Therefore, in order to use high intensity of lighting, digital hologram printer can be high diffraction efficiency optical system capable of fast recording. In addition, it is possible to generate a holographic interference pattern with high resolution by minimizing the influence of vibration. For this reason, most holographic printing systems use high light-power lasers and optical components also maintain horizontal and vertical alignment for linear polarization in the same direction when interfering with holographic material and optical components transmittance. However, in digital hologram printer case, white light is synthesized using lasers for full-color implementation and many optical components are involved for matching the coherence length. If the direction is not exactly perpendicular way to incident plane, The polarization will be disturbed by an angle error of mirror reflection or transmission causing the phase shift [16–22]. This is no longer maintained as linear polarization and changed to elliptical polarization with random phase. Polarization in holography has been studied in various fields such as storage systems [23, 24] and digital imaging holograms [25, 26]. Those are studied an ideal polarization method for basic holographic recording or evaluating of data storage capacity according to the polarization direction. But, digital holographic printing case, various optical elements are reflected, passed and filtered by laser and printing speed at least over 20 Hz. In this process, it is necessary to verify an optimized environment rather than an ideal method for saving time and cost. And second critical issue is that there is a limit to implementing a system that is perfectly vertically and horizontally aligned by hand and eyes even if we use polarization measuring and alignment equipment. Those reason can cause changing polarization as we explained above. For this reason, it is to quantitatively analyze the impact of polarization that can change in various ways in a digital hologram printing system and create an optimal environment. This study figures out changes at holographic recording plane and analyzes the polarization combining and compare and analyze the differences between the reconstructed results from Holographic optical element (HOE) on the surface recorded along with the results.

2 MATERIALS AND METHODS

2.1 Principle of Linear Polarization, Circular Polarization and Elliptical Polarization

The factor that determines the direction of polarization is related to a solution of two plane waves consisting of electric fields denoted by $\vec{E}$ and magnetic fields denoted by $\vec{B}$ from the Maxwell equation. $\vec{E}$ is interpreted as $\overrightarrow{E_o}e^{i(\vec{k}\cdot\vec{x}-wt)}$ and is interpreted as $\overrightarrow{B_o}e^{i(\vec{k}\cdot\vec{x}-wt)}$, and these two components are called polarization vectors. These are the vectors in the three directions of the complex, the wave vector $\vec{k}$ and the angular frequency ω are real and are associated with $\omega = c|\vec{k}|$ in the vacuum state. This relationship means that the electromagnetic wave velocity is independent of the speed of light. In addition, we can obtain a parallel wave called $\overrightarrow{B_0} = \frac{1}{\omega}(\vec{k} \times \overrightarrow{E_0})$. This equation means that the magnetic field of the plane wave is completely determined by the electromagnetic field and is related to $|\overrightarrow{E_0}| = c|\overrightarrow{B_0}|$ and is $\vec{k}\cdot\overrightarrow{E_0} = 0$, $\vec{k}\cdot\overrightarrow{B_0} = 0$, $\overrightarrow{E_0}\cdot\overrightarrow{B_0} = 0$.That is the polarization vector of the electron, the polarization vector of the magnetic field and the direction $\vec{k}$ in which the plane wave propagate are all orthogonal. Since we put hat on the vector to indicate the direction, that is, $\hat{z} = (0, 0, 1)$, the electric field can be written as $\vec{E} = \overrightarrow{E_0}e^{iw(\frac{z}{c}-t)}$, which moves in the z direction at the speed of light. Complex numbers E_x and E_y are used to represent $\overrightarrow{E_0} = (E_x, E_y, 0)$ because $\overrightarrow{E_0}$ and $\vec{k}$ are orthogonal. The two complex amplitude E_x and E_y have respective sizes and phase, so polarization vectors can be defined by $\vec{E} = E_x\hat{x}\cos(kz - wt + \phi_x) + E_y\hat{y}\cos(kz - wt + \phi_y)$[27, 28]. If there is no phase difference between E_x and E_y, it means that the electric and magnetic fields are linearly polarized and as shown in **Figure 1A**, the synthesized linear polarization of the two waves proceeds at constant amplitudes and phases in the 45° rotation direction. Although the amplitude is the same, the phase is shifted by a quarter of a wavelength, so we can represent $\phi_x - \phi_y = -\frac{\pi}{2}$ and it will cause a right-handed circularized light and is shown in **Figure 1B**. On the other way, if the phase difference becomes $\phi_x - \phi_y = \frac{\pi}{2}$, it becomes left-handled circularly polarized light. And if phase ϕ is not zero, the shape of polarization changes as the x-y plane rotates which is called elliptical polarization. In addition if E_x and E_y are different, elliptical polarization varies in amplitude in time division [29, 30]. Therefore, linear polarization is a condition to be $\phi = 0$, and circular polarization is the same as E_x and E_y, and it is a condition to be $\phi \pm \frac{\pi}{2}$ and all elements outside these two conditions are considered elliptical polarization and represented as shown in **Figure 1C**. This polarization takes place in a situation where the amplitude of the electric and magnetic fields is the same, and the angle of the two waves in the X-Y plane is exactly 90°. but, In the case of digital hologram printer, It is difficult to environment an ideal situation as above. Full-color displays composed in holographic printers use red, green and blue lasers. The light output from each laser is separately making ray by a beam splitter and illuminates even the spatial light modulator (SLM) as and objective beam to synthesize the full color and the light modulated by SLM illuminates one side of the hologram medium. And

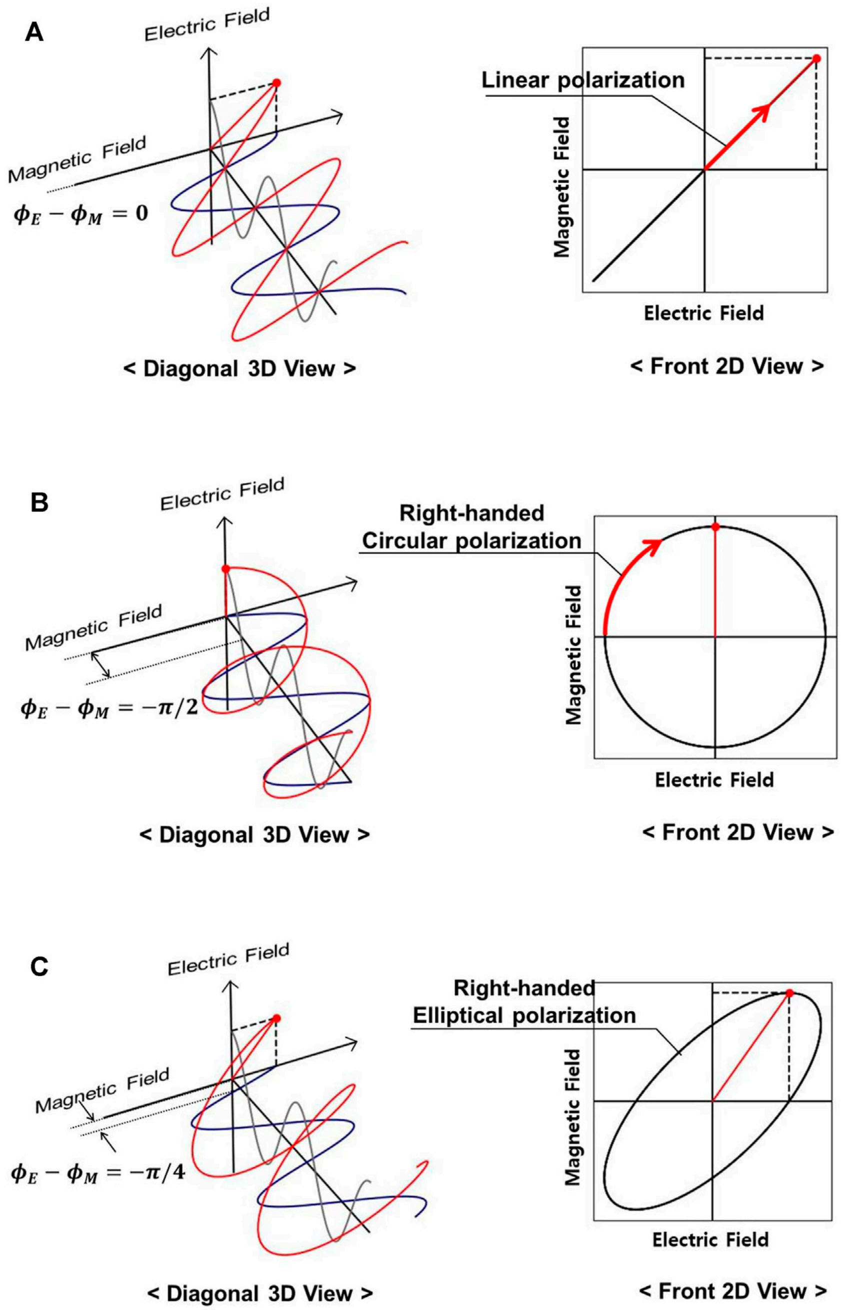

FIGURE 1 | Polarization that occurs depending on the phase difference. **(A)** Linear polarization **(B)** Circular polarization **(C)** Elliptical polarization.

another separated light is regarded as a reference beam and reference beam turns to the opposite side of the hologram medium and matches exactly the same position of the objective beam to create holography interference patterns. In this process, various optical elements such as a beam splitter, mirror, lens, and filter are passed. And since most systems are implemented by optical engineer themselves. It can be a reason it cannot be guaranteed that the reflection angle is completely different from initial design. Finally, since the condition of the optical elements is not permanently preserved there is a part that needs to be checked from time to time before hologram printing. If we setup a geometrically completely parallel ray and reflect it to be exactly vertical direction we can accurately match the polarization of the objective beam and the reference beam. but it is practically impossible. Therefore, quantifying the qualitative evaluation of holograms reproduced according to the polarization of the two beams recorded on the final hologram plane will create a

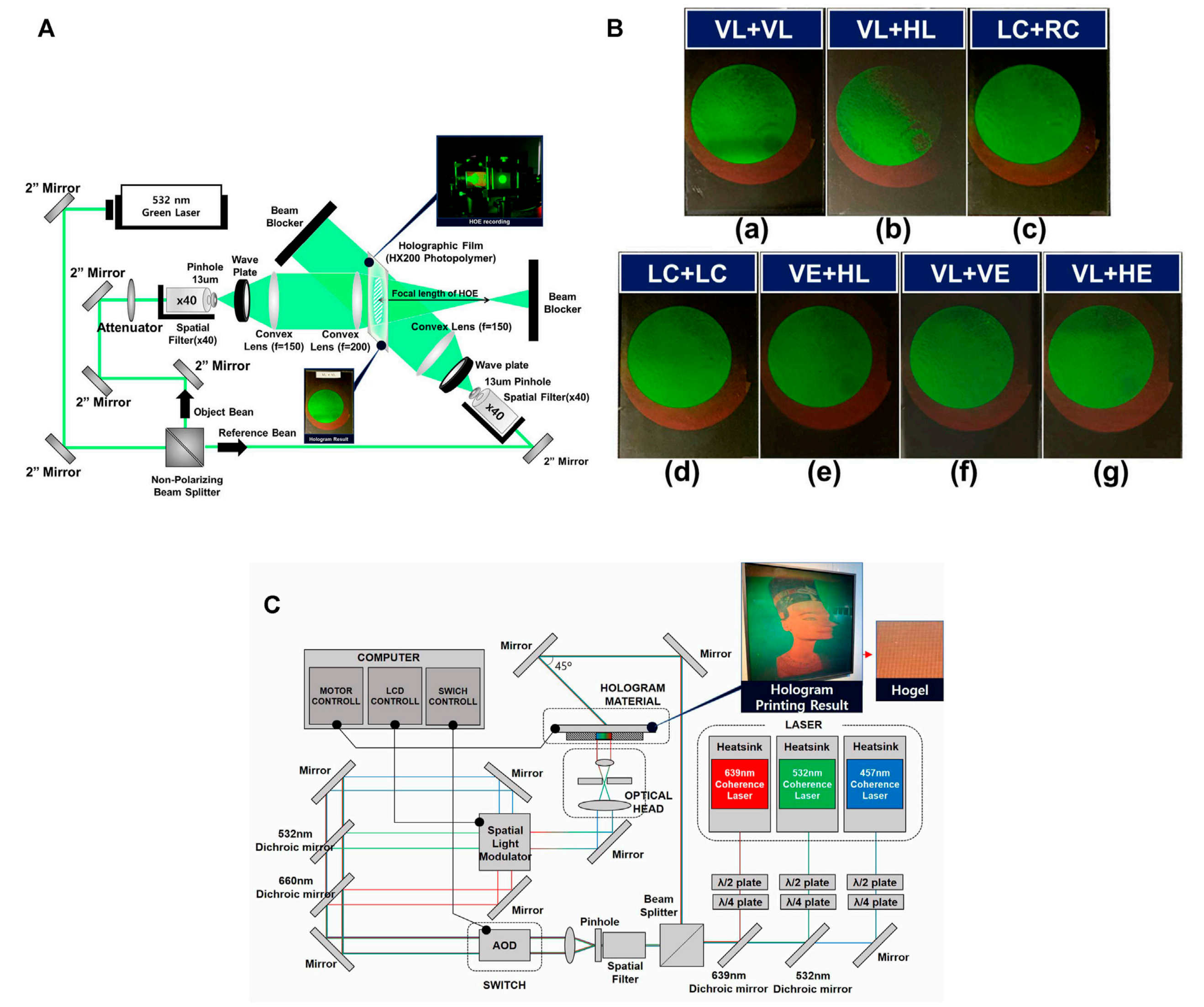

FIGURE 2 | Fabrication of holographic optical elements with focal length of 200 mm using different polarization. **(A)** Schematic of optical system **(B)** HOE results from polarization matching.

criterion for satisfying the ideal level of content. if they are not ideally perfect.

2.2 Fabrication of HOE for Polarization Analysis

Holograms produced by digital holographic printing consist of the synthesis of images reconstructed from hogels less than 1 mm. Reconstructed image from a focal plane has an similar interference area with single hogel because HOE operates like a lens. Therefore, HOE is fabricated and the analysis on the focal plane can be applied to the analysis of hogel recorded by digital holographic printing. This HOE constructed by off-axis holographic techniques using object of single lens. HOE has the lens function. Then amplitude is 1, phase is zero and incident angle is θ. Reference beam has the following equation on the hologram plan given in **Eq. 1**.

$$R(x,y) = A_R(x,y)\exp(ikx\sin\theta) = \exp(ikx\sin\theta) \tag{1}$$

Therefore, HOE can be expressed given in **Eq. 2**

$$\begin{aligned} I(x,y) &= |O(x,y) + R(x,y)|^2 \\ &= |O(x,y)|^2 + 1 + O(x,y)\exp(-ikx\sin\theta) + O^*(x,y)\exp(i2kx\sin\theta) \end{aligned} \tag{2}$$

If the reference beam is illuminated as recorded in this off-axis hologram, the image is reconstructed as shown given in **Eq. 3**

$$\begin{aligned} I(x,y)\times R(x,y) = &\left(|O(x,y)|^2 + 1\right)\exp(ikx\sin\theta) \\ &+ O(x,y) + O^*(x,y)\exp(i2kx\sin\theta) \end{aligned} \tag{3}$$

The first term is direct light as DC term. The second term is object light that the case of HOE is light that functions as a lens. The third term is the conjugate light which is proceeds approximately in 2θ direction. Because of $\exp(i2kx\sin\theta) \approx \exp(ikx\sin 2\theta)$. Therefore, HOE is equivalent to applying the refractive function of a lens. In this paper, HOE with a focal length of 200 mm was produced to analyze the hologram product according to polarization as shown in **Figure 2A** and the result was analyzed. In front of the object beam and reference beam, quarter wave plate and half wave plate were properly arranged to create the desired polarization and holograms were recorded using difference phase. The NBK-7 convex lens was placed 200 mm in front of the holographic medium. The finally recorded HOE was designed to have a focal length approximately 200 mm. For analysis, HOE was produced using a total of 7 different type of polarization as shown in **Figure 2B**. We denote Linear polarization in the vertical direction as **VL**, linear polarization in the horizontal direction as **HL**, right-handed circular polarization rotating in the clockwise direction as **RC**, left-handed circular polarization rotating in the opposite clockwise direction as **LC**, elliptical polarization in the vertical direction as **VE** and elliptical polarization in the horizontal direction as **HE**. Various combinations can be created using more diverse amplitude and phase-shifting. but since this produces an infinite combination, the amplitude of objective beam and reference beam gives default values and uses a fixed ratio by adjusting the intensity of the laser so that the light of objective beam and reference beam can be recorded at a intensity ratio of 1:1. For hologram reconstruction images were analysis in the focal plane of HOE, the beam from the laser was expanded to use collimation beam and illuminate same angle as initial conditions used for hologram recording.

3 RESULTS AND DISCUSSION

3.1 Polarization for Hologram Recording

The polarization combination used above can be combined into quarter-wave plate and half-wave plate. If you want to change only θ using half-wave plate, you only need to adjust θ of the rotation stage. If we want to change the rotation direction in circular polarization, we can place half-wave plate. In circular polarization, if quarter-wave plate is adjusted to $\theta = 45$ in linear polarization, right-handled rotation can be obtained, and if set up to $\theta = -45$, left-handled rotation can be obtained. Elliptic polarization can be obtained from all angles except $\theta = 45$ in Linear polarization. In this case, there are unlimited combinations we can make. we presuppose that the elliptical polarization will proceed with the experiment with only two types, vertical and parallel in the $\theta = 67.5$ shifted. The optical component was minimized by placing quarter-wave plate and half-wave plate at the location before the objective beam and signal light finally passed through the lens. In this study, we start with two prerequisites. The first is that the magnetic file amplitude from the laser and the electric field amplitude come out with a strength of 1:1, and the intensity of the pick to pick of linear, circular, and elastic polarization is the same. When most holograms are recorded, interference patterns occur in the section where objective beams and reference beams overlap, and the higher the beam intensity, the higher the efficiency. Therefore, it is a prerequisite that efficiency is matched only with three types of polarization and recorded with the same intensity in order to see only the determined effects related to polarization type. Second, the elliptical polarization is limited to one type. There may be countless cases because elliptical polarization occurs in all phase differences other than 45° in phase differences. Therefore, we need to define the elliptical polarization and conduct an experiment. When elliptical polarization is closer the phase difference is to 0°, it will be more linear polarization and when elliptical polarization is closer to 90°, it will be the closer to circular polarization. To make a difference from the two polarization, we use the most neutral angle which has a representative value for the phase difference of 67.5°.

3.2 Analysis of optimal hologram recording environment using HOE

3.2.1 Comparison of Diffraction Efficiency and Intensity of Reconstructed Image

Our experiment used a laser with a single frequency of 532 nm among the samba series manufactured by COBOLT which is a laser manufacturer. A non-polarizing beam splitter was used to set up to go to polarization of the same angle as possible until it was recorded on the holographic material and the angle was adjusted by Quarter-wave plate and half-wave plate just before the objective beam location and reference location beam were incident. A lens with a 200 mm focal length of 2 inches was placed as close as possible to the medium so that the HOE finally recorded could be closest to the focal length of 200 mm. As for the holographic material, we used a photo-polymer called HX200 by COVESTRO. This photo-polymer has a recording dosage that has 30 mJ/cm^2 of energy. **Figure 3A** shows the reaction saturation of the recorded hologram using the HX200. Due to the characteristics of the photo-polymer, since it is saturated without proceeding with the reaction for a certain period of time or longer, we conducted the experiment only until the photo-polymer was all reacted and no longer reacted. All polarization associations can finish holographic records within 100–120 s and recording are already finish around 80 s. **Figure 3B** shows the result of reconstruction of the beam using the same recording conditions after the recording is completed. A reference beam with an intensity of 183.97 umW with a collimated uniform beam was illuminated by HOE under the same conditions as the initial state. As a result, HOE recorded between linear polarization of the same angle had an efficiency of 63% and a diffraction beam with an intensity of 151.9 umW was reconstructed. In addition, HOE recorded as Right-handed circular polarization and Left-handed polarization rotating in the same direction facing the recording medium had an efficiency of 60% and an intensity of 110.38 umW was regenerated.

3.2.2 Optimized Polarization Matching Results

Combinations with the lowest efficiency were vertical linear polarization and horizontal linear polarization. This

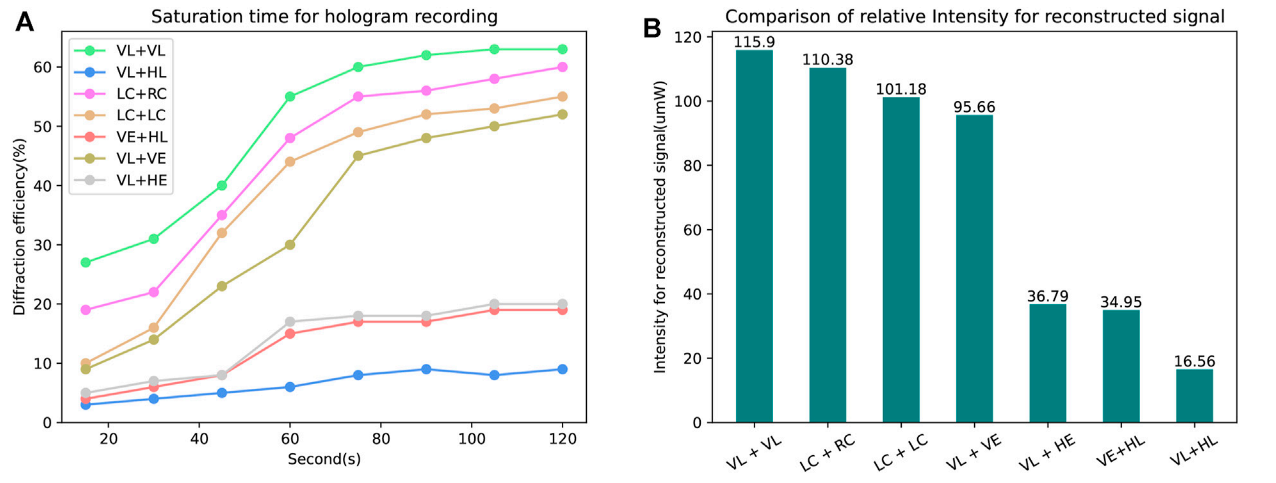

FIGURE 3 | Results for reconstructed holographic image from different polarization. **(A)** Saturation time for hologram recording, **(B)** Comparison of relative intensity for reconstructed signal.

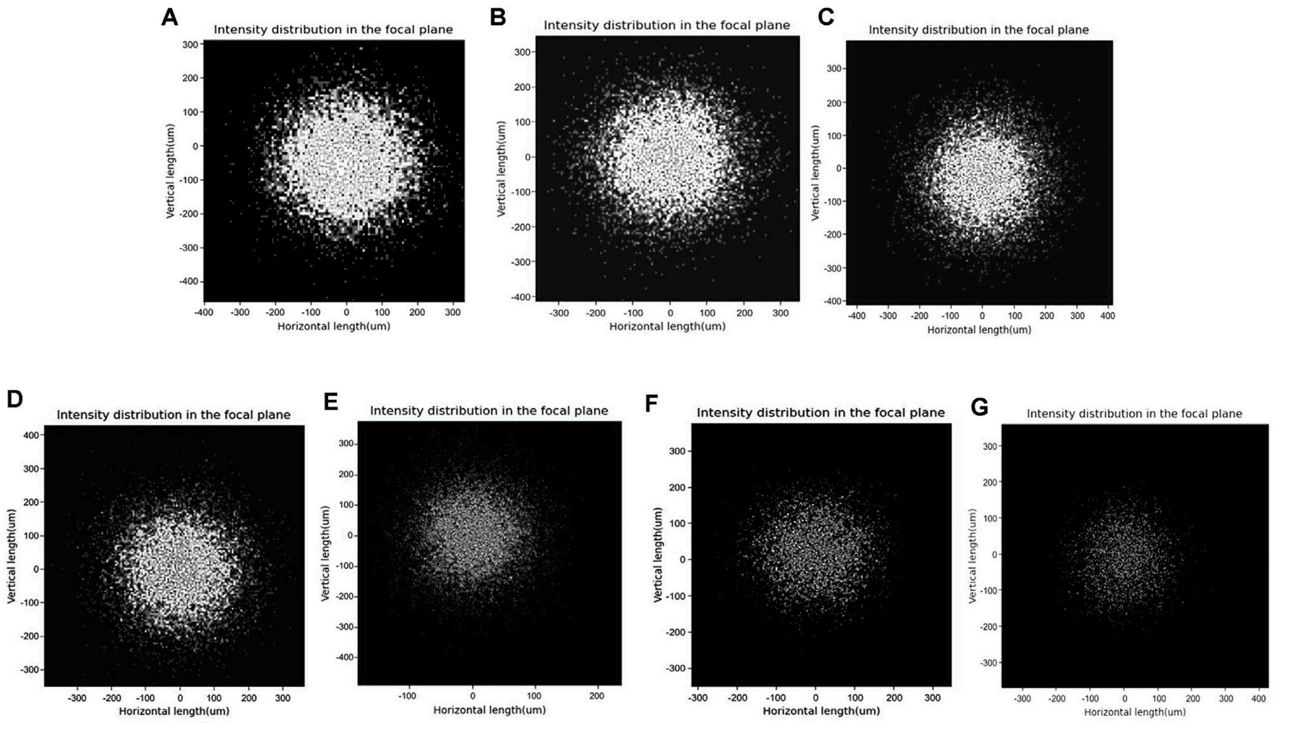

FIGURE 4 | Intensity of the reconstructed image at the focal plane by CCD camera. **(A)** VL + VL **(B)** LC + RC **(C)** LC + LC **(D)** VL + VE **(E)** VL + HE **(F)** VE + HL **(G)** VL + HL.

combination output reconstructed light with an efficiency of less than 10% and an intensity of 16.56umW. In actual holographic records, **VL** and **HL** are not often matched. The reason is that most of the work of matching the intensity of light with the angle of polarization is the most basic process in holographic records. In the case of a simple holographic recording optical system, a vertical polarization beam from the laser is initially used only as a PBS and half-wave plate to align the vertical (or horizontal) linear polarization. In complex optical systems such as digital hologram printer, linear polarizer are used at the end of recording light to accurately align vertical or horizontal direction and holographic material is calculated at appropriate exposed time for optimal recording dosage This complex system inevitably results in optical polarization and circular polarization due to various errors caused by placing optical components on the optical table. **VL + VL, LC + RC,**

LC + LC, and **VL + VE** which the reference beam and the objective beam overlap each other have an efficiency of at least 52% to a maximum of 63%. On the other hand, **VL + HE, VE + HL**, and **VL + HL** which are orthogonal to each other represent a minimum of 9% to a maximum of 20%. A recently published digital hologram printer study records holograms at an average speed of 25 Hz. In addition, A short delay in each hogel also causes a problem of recording holograms for a considerably long time considering the overall hologram recording time because of the tiling type printing using one small hogel size within0.4 mm^2. However, if the reference beam and objective beam are perfectly matched using several linear polarizer at the end of the reference beam for maximum efficiency, it takes as long as 4 because the amount of light is reduced by 75% in the reference beam caused by the physical transmittance of the polarizer. However, according to the results of the experiment below, when comparing the efficiency difference between **VL + VL** and **VL + VE** in the most ideal form, there is only a relatively 18% difference. For this reason, when printing in dot form in a holographic printing system, adjusting the polarization angle by adjusting the polarization angle by considering the rotation direction is more important than accurately aligning the polarization with a vertical linear or horizontal linear. **Figure 4** is an reconstruction image from the focal plane of the HOE using a CCD camera. When recording a hologram, an objective beam and a reference beam interfere to form a grating on holographic material and interference pattern is recorded. This is a picture taken after matching the image levels of reconstructed from the HOE at focal plane. **Figure 4A** is reconstructed image using **VL + VL** and it can be verified that the efficiency of the reconstructed image decreases as it goes toward **Figure 4G**. When viewed from the order of high to low diffraction efficiency, it was confirmed that the reconstructed image from **VL + VE** was similarly displayed to high brightness. However, in the case of **VL + HE**, **VE + HL**, and **VL + HL**, in which polarization was recorded orthogonally, intensity from reconstructed image was not enough to be difficult to see. Since it is extremely subjective when a person feels a reconstructed holographic image, there is no standard value on how much efficiency should be higher or lower. However, hologram traditionally results with diffraction efficiency of 60–70% or more have no discomfort or awkwardness when people feel them. Therefore, there is no need to use optical components more than necessary or increase the overall volume of the system by using expensive lasers or adding unnecessary optical paths to compensate for the reduced amount of light to match polarization after an accurate hologram recording optical setup. The error caused by the phase shift occurs due to superposition in the optical components. It proved that there is no need that there must be align circular polarization and elastic polarization to change linear polarization. At the front end of the beam separation, it was confirmed that the most effective way is to configure the system with the shortest path within the range where the polarization of the objective beam and the reference beam can be matched with the coherence length.

4 CONCLUSION

The paper has conducted a study on a polarization matching method which may have high diffraction efficiency in a system that forms an entire hologram using a unit hologram as hogel. In a conventional method, angle adjustment for making the strongest intensity using a wave plate has been prioritized at the front part of the polarization type and angle. This is a process focused only on using high intensity power. However, regardless of the intensity power, a review of the effect of polarization recorded as an interference pattern in actual holographic media as conducted in this study. The study was divided into two parts. One is that through linear polarization, circular polarization, and elliptical polarization, the difference in diffraction efficiency according to the type of polarization was quantified. Second pert is that we analyzed it from the obtained results and set a appropriate standard for polarization matching that can create an optimal environment for holographic printing. As expected, **VL + VL** method which is a method of recording holograms showed the highest efficiency and **VL + HL** method showed the lowest diffraction efficiency. This proved the hypothesis that the more overlapping the amplitude distribution constituting laser polarization for the higher the efficiency. For this reason, **VL + VE** in the same direction showed 11% lower efficiency than **VL + VL** which is exactly matched and **VL + VE** showed 32% lower results than **VL + HE**. When we record the hologram, we do optical set-up so that objective beam and reference beam can just meet at the same area. this can cause the problem that we cannot determine how the polarization direction meets. The above results show from an experiment that even if the holographic material can be completely interfered with using the same area, diffraction efficiency of hologram can be depending on the amplitude size of the electric and electromagnetic fields. Printing systems for digital hologram recording such as stereographic hologram printing and wave-front holographic printing are undergoing various studies such as high angle of view, fast recording speed and image processing for the observation of three-dimensional reconstructed light but few studies for high efficiency hologram results. The conventional analog hologram recording method has used qualitative and know-how recording methods of engineers such as holographers rather than quantitative analysis by scientists and digital holograms have focused on the synthesis method and quality of images. However, the holography we use refers to film-type product that records interference patterns that reproduce three-dimensional images in holographic material. Therefore, in applications that directly use holographic material, digital holographic printing, the most representative of which research is needed on how well holographic interference patterns are recorded. This study analyzed the recording condition and efficiency that various environment depending on the polarization state of the light divided into objective beam and reference beam in the digital printing system. And this can be that this will not only help positive results for future research on constructing digital holograms by configuring printing systems but also be the starting point for various preliminary studies to improve the quality of results for holographic printing.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All the authors have made substantial contributions regarding the conception and design of the work, and the acquisition, analysis and interpretation of the data. Specifically, conceptualization, LH and JJ; methodology, SK and JJ; formal analysis, PG; validation, CY and SL All authors have read and agreed to the published version of the manuscript.

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