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Diffraction Efficiency Analysis of Silver Halide Film for Color Holography Recording

Sung Chul Park[1], Sang Il Kim[1], Kwang Chul Son[1], Soon Chul Kwon[1], and Seung Hyun Lee[1]*

[1]**Graduate School of Holography 3D Contents, Kwangwoon University, 20 Kwangwoon-ro, Nowon-gu, Seoul, Korea*
hangyo1@hangyo97.co.kr, nan31@sbs.co.kr, {ksc0226, kcson, *shlee}@kw.ac.kr

Abstract

Holography technology which was developed by Dennis Gabor (1900~1979) in 1948 is a technology to record wave planes of actual 3D objects. It is known as the only technology which can express 3D information most perfectly close to human-friendly. Holography technology is widely used in advertisement, architecture and arts as well as science technology areas. Especially, digital holographic print which is an applied area is greatly used in military map, architecture map and cultural asset restoration by printing and reproducing 3D information. Holography is realized by recording and reproducing the amplitude and phase information on high resolution film using coherent light like laser. Recording materials for digital holographic printer are silver halide, photoresist and photopolymer. Because the materials have different diffraction efficiency according to film characteristics of each manufacturer, appropriate guide lines should be suggested through efficiency analysis of each film. This paper suggests appropriate guide lines through the diffraction efficiency measurement of silver halide which is a holographic printer recording medium. And the objective of this study is to suggest appropriate guide lines through diffraction efficiency analysis of Ultimate 08-C and PFG-03C which are commercially used. The experiment was prepared by self-diffraction efficiency system which measures the strength with the defector by penetrating RGB recording medium and concentrating diffracted beams through collimating lens. The experiment showed Geola's PFG-03C which is a silver halide for full color has price/performance advantage in optical hologram recording, but recording angles and reproduction angles are irregular for digital holographic printer recording. Ultimate's Ultimate08-C for full color shows its diffraction efficiency is relatively stable and high according to recording angles and laser wavelength.

Keywords: *Holography, Silver Halide Film, Digital Holographic Printer*

1. Introduction

Holography technology which was developed by Dennis Gabor (1900~1979) in 1948 is a technology to record wave planes of actual 3D objects and express hologram through optical restoration[1]. Holography technology is widely used in advertisement, architecture and arts as well as science technology areas. It is used in interferometry, optical elements, optical information processing, holographic memory, security and

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Corresponding Author: shlee@kw.ac.kr
Tel: +82-2-940-5098, Fax: +82-2-918-5683
Graduate School of Holography 3D Contents, Kwangwoon University

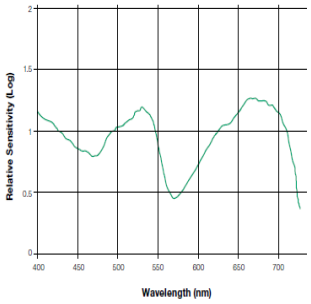
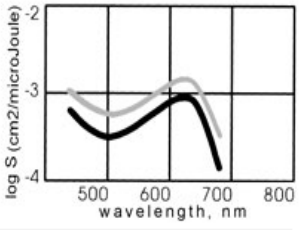
holographic display. Digital holographic print in major applied areas is greatly used in military map, architecture map and cultural asset restoration by printing and reproducing 3D information[2]. Recording materials for digital holographic printer are silver halide, photoresist and photopolymer[4-6]. Because the materials have different diffraction efficiency according to film characteristics of each manufacturer, appropriate guide lines should be suggested through efficiency analysis of each film.

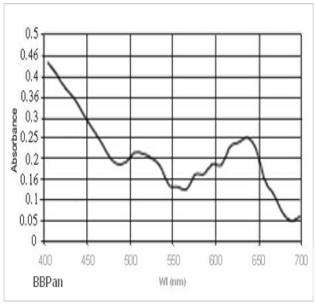
Therefore, in this study, the medium is limited only to silver halide film among the hologram recording media and objective of this study is to suggest proper guide lines through diffraction efficiency analysis of Ultimate 08-C and PFG-03C which are commercially used.

2. Digital holographic printer recording medium

Medium which can record the hologram is divided largely into silver halide, photoresist and photopolymer. Photoresist is a material used for semiconductor circuit formation and is a recording medium that selectively removes the sensitized parts and no-sensitized parts in development process and subsequently creates texturing process on the surface and finally records the hologram. Despite low diffraction efficiency and resolution which are the most important characteristics in hologram recording, it is an advantageous process for mass production capability with reasonable prices and it is widely used in hologram areas. Photopolymer is an optimized medium in recording hologram and has higher than 90% diffraction efficiency. And it can be applied real-time just with simple bleaching(post exposure or heating) process after recording[5-7].

Table 1. Comparison of silver halide emulsion characteristics of each manufacturer

Company	Product	Grain size	Resolution	Spectral Sensitivity
Fuji film	F HL	35nm	3,000 lines/mm	
Geola	PFG-03C	10nm	5,000 lines/mm	 Figure1: Spectral sensitivity curve for PFG-03C (gray) and PFG-03M (black)
Ultimate Holography	Ultimate 08-C	8nm	10,000 lines/mm	Red : 610~660 Green : 440~540 Blue : 440~480

Color holographic	BB Pan	25nm	5,000 lines/mm	

Currently, Dupont and Bayer's photopolymers are being studied as recording materials for digital holographic printer and Dupont's photopolymer is being restrictedly provided to some research institutes and companies. Especially, Zebra imaging uses Dupont's photoresist as digital holographic printer recording material[4][8].

Bayer is also upgrading polymer characteristics with restricted supply according to co-research agreement. Additionally, it is an appropriate recording medium as a material for HOE (Holographic Optical Elements) and security materials as well as for holographic printer recording. Silver halide which can be generally purchased and handled most easily has been used in hologram area for a long time and recently, there are many ongoing researches also in digital holographic printer area. As the silver halide which has diffraction efficiency and resolution close to photopolymer has been developed by the manufacturers, its use value becomes more bigger[8].

Current silver halide manufacturing companies are Fuji film, Geola, Ultimate holography and Color holographic at large. In case of Fuji film, they don't produce the products any more after the exhaustion of stock since 2012 and the products are not currently available. And, Color holographic's BB pan is excluded in this paper because of manufacturer's no quality assurance notice and home and abroad trading difficulty due to the containment of hazardous materials.

Geola's PFG-03C receives the silver halide film and plate from Slavich and it has good performance compared with reasonable prices due to its variety of product line-up and mass production facilities among silver halide manufacturers. The product which has the best diffraction efficiency and resolution among silver halide products is Ultimate's Ultimate08-C. But, this has a disadvantage of very high product price because of no mass production facility even though it has excellent characteristics close to Photopolymer. Ultimate08-C is also applied as a medium for Ultimate's DHP. Table 1 shows simple product characteristics of each manufacturer[9-11].

3. Diffraction efficiency measurement system

Objective of this study is to analyze the diffraction efficiency which is most important to hologram recording among optical characteristics of silver halide. Diffraction efficiency measurement equipment which is selected in this study is designed by upgrading the diffraction efficiency system of DuPont, and diagram 1 and 2 show the structural diagram and system pictures[6][12].

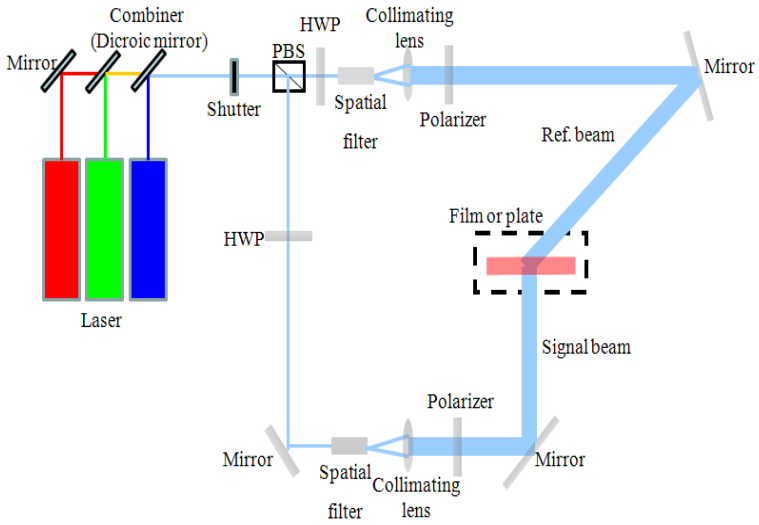


Figure 1. Structural diagram of interference pattern recording system (reflection type)

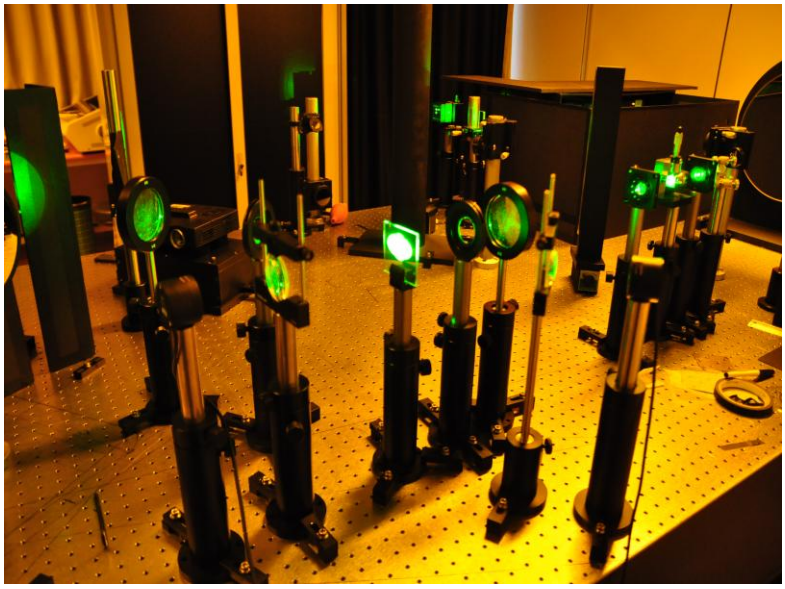


Figure 2. Diffraction efficiency measurement system

Total 3 lasers are used for diffraction efficiency analysis about full color recording medium and each wavelength and characteristics are shown at table 2. Beams from RGB laser are progressed through the mirror and combiner (dicroic mirror) and the exposure is controlled by controlling electrical shutter open and close time. Because PBS(polarizing beams splitter) has HWP(half wave plate) at the front and back of the cube, the strength of the beams which are divided into two can be adjusted. And, extra HWP is installed and is changed to p-polarization because the beams which passes through PBS has s-polarization. Spatial filter is composed of objective lens (x10) and pinhole (25μm) and it diffuses beams and plays a filtering role. Diffused beams are changed to parallel beams through collimating lens and catch polarized lights once again while passing through the polarizer.

Table 2. Comparison of RGB laser characteristics used in the system

Laser color	Manufacturer	Wavelength	Type	Max. output
Red	Cobolt	660±0.6nm	DPSS	~400mW
Green	Coherent	532±3nm	DPSS	~2,000mW
Blue	Coherent	460±3nm	DPSS	~1,000mW

In this study, interference patterns with 3cm diameter were recorded on silver halide medium and output percentage of recorded beams was set as 1:1 where the maximum refraction modulation occurs in general. Slope of the recording was designed as 45°/0° and 56.5°/0°. Reproduction after recording hologram interference patterns was measured by blocking signal beams (0°) in the recording device in diagram 1 and measuring the penetrated beams and strength of diffracted beams. Diagram 3 shows the structural diagram of reproduction and diffraction efficiency measurement system.

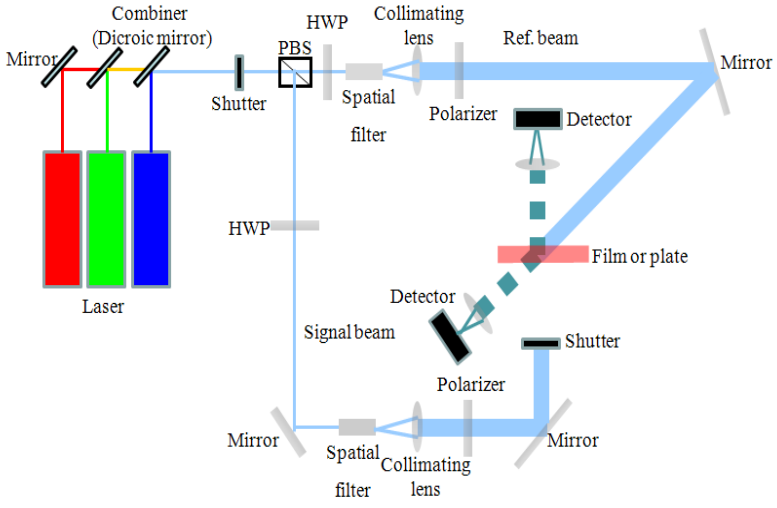


Figure 3. Structural diagram of diffraction efficiency measurement system

Like equation 1, regarding the diffraction efficiency, the strength was measured with the detector by concentrating penetrated and diffracted beams of the RGB recording medium through collimating lens[5][6][13].

$$DE = \frac{\text{Strength of diffracted beams}}{(\text{Strength of penetrated beams} + \text{Strength of diffracted beams})} \times 100$$

4. Experiment

Regarding the subjects for diffraction efficiency measurement analysis, Geola's PFG-03C and Ultimate's ultimate08-C glass plate were selected among 4 kinds of full color silver halide which were mentioned at the introduction. Regarding the size of specimens, negative plate (300X400mm) was used by cutting into smaller size plate with 60X65mm, and interference patterns were recorded by changing the exposure from 0 to 10,000μJ/cm2. Diagram 4 shows recorded images of the samples. Diffraction efficiency was measured with

the recording angles of 45°/0°, 56.5°/0°. Table 3 and 4 showed the working process in each test.

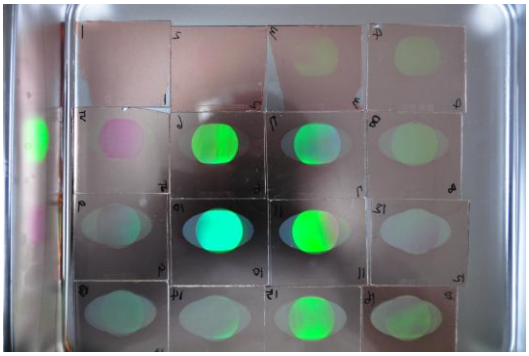


Figure 4. Silver halide plate samples where the interference patterns are recorded

Table 3. Test working process

Recorded medium	Recorded angles (R/S)	Recorded laser	Exposure (μJ/cm^2)	Post-Process
PFG-03C	45°/0°	R	0~6.000	hardening 6min → washing 2min → CW-C2 development 3min → washing 2min → PBU-amidol bleach 6min → washing 5min → stop bath 2min → photoflo 1min → drying
		G		
		B		
	56.5°/0°	R		
		G		
		B		
U08-C	45°/0°	R	0~10.000	ultimate development 6min → washing 2min → ultimate bleach 4min → washing 2min → photoflo 1min → drying
		G		
		B		
	56.5°/0°	R		
		G		
		B		

Table 4. Manufacturing process of developing solution and bleaching solution

	Hardener	CW-C2	PBU-amidol	Stop bath
Chemistry	Formalin 37% 10ml Potassium bromide 2g Sodium carbonate 5g Distilled water 1L	Solution A : Catechol 20g Ascorbic acid 10g Sodium sulfite(anhydrous) 5g Urea 60g Distilled water 1L Solution B : Sodium carbonate 60g Distilled water 1L	Potassium persulphate 10g Citric acid 50g Cupric bromide 1g Potassium bromide 20g Amidol 1g Distilled water 1L	Acetic acid 20g Distilled water 1L

5. Experiment results

Each samples was recorded with each condition (angles, laser, color, exposure) and was manufactured through post-processes like phenomenon and bleaching, and the diffraction efficiency of each samples was reproduced and calculated by the diffraction efficiency measurement system in diagram 3.

1) Diffraction efficiency analysis about Geola's PFG-03C

Diffraction efficiency measurement results about PFG-03C showed diffract beams occurred at different angles regardless of recording angles (45°, 56.5°). Diagram 5 to 7 show the diffraction efficiency of recorded samples with 45°/0°. In case of Red 45° samples, diffract beams were not almost generated at 45° recording angle. Examined results of reproduction angles with strong diffracted beams showed the diffracted beams could be observed at 10~20° reproduction angles, but in this case, beams strength could not be measured. Diagram 6 shows diffraction efficiency measurement results of Green 45° samples. Maximum diffraction efficiency is obtained about 80% at 4,000~5,000μJ/cm2 exposure, but at some points, maximum diffracted beams could be observed at the angles which are different from reproduction angles. And, even though Blue 45° samples in diagram 7 also show consistent 80% level of diffraction efficiency, reproducing angles are identified to be distorted.

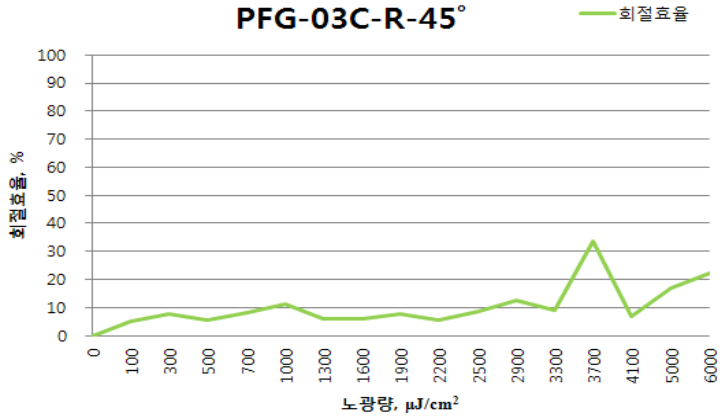


Figure 5. PFG-03C Red 45° samples diffraction efficiency measurement graph

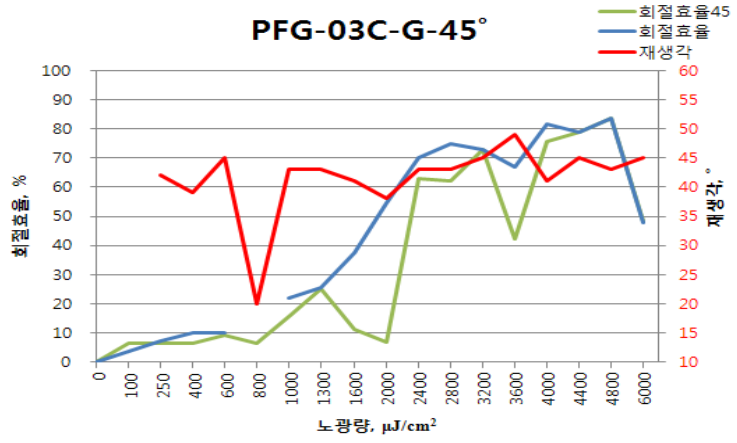


Figure 6. Diffraction efficiency measurement graph of PFG-03C Green 45° samples

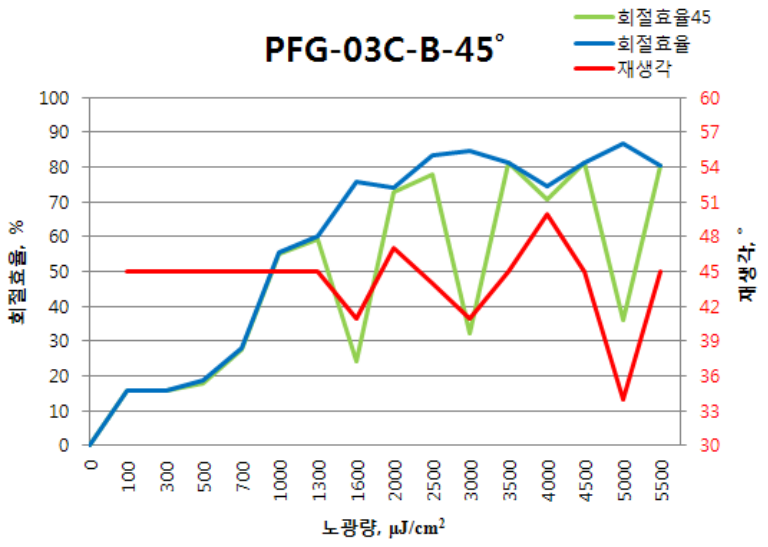


Figure 7. Diffraction efficiency measurement graph of PFG-03C Blue 45° samples

Diagram 8 is the diffraction efficiency measurement graph of Red 56.5° samples. Even though approximately 60% of diffraction efficiency is identified around 56.5° recording angle, severe distortion was observed that reproducing angles modulation has been changed to 26° at the exposure above 4,500μJ/cm2. Diagram 9 is the diffraction efficiency measurement graph of Green 56.5° samples. Even though the diffraction efficiency was not uniformly observed at 56.5° recording angle, 70~80% of diffraction efficiency could be obtained around 45° reproducing angle with 2,300μJ/cm2 of exposure. Finally, diagram 10 is the graph of Blue 56.5° samples. Like Green 56.5° samples, diffraction efficiency was not uniformly observed at original angles and 70~80% of diffraction efficiency could be obtained around 45° reproducing angle with 2,500μJ/cm2 of exposure as well. And, looking at the graph of 56.5° samples, the graph which were reproduced at recording angles and the graph where maximum diffraction efficiency was obtained at different angles showed the reversal each other.

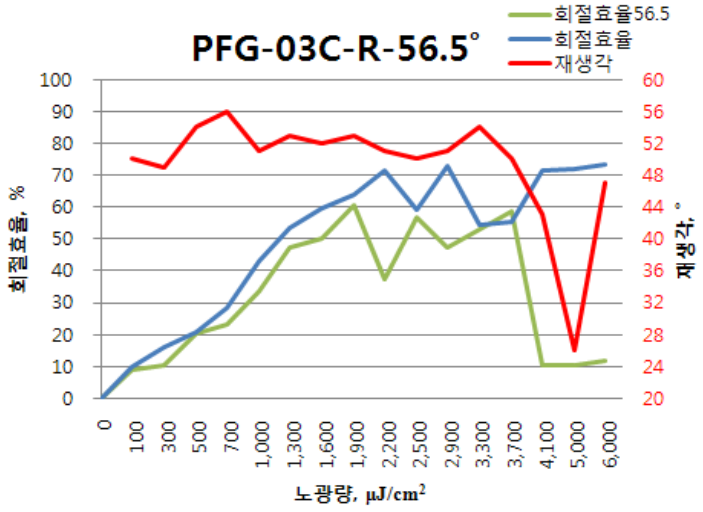


Figure 8. Diffraction efficiency measurement graph of PFG-03C Red 56.5° samples

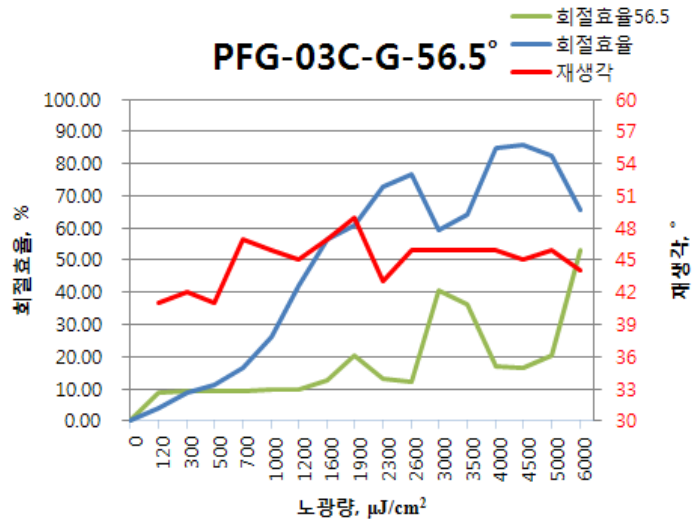


Figure 9. Diffraction efficiency measurement graph of PFG-03C Green 56.5° samples

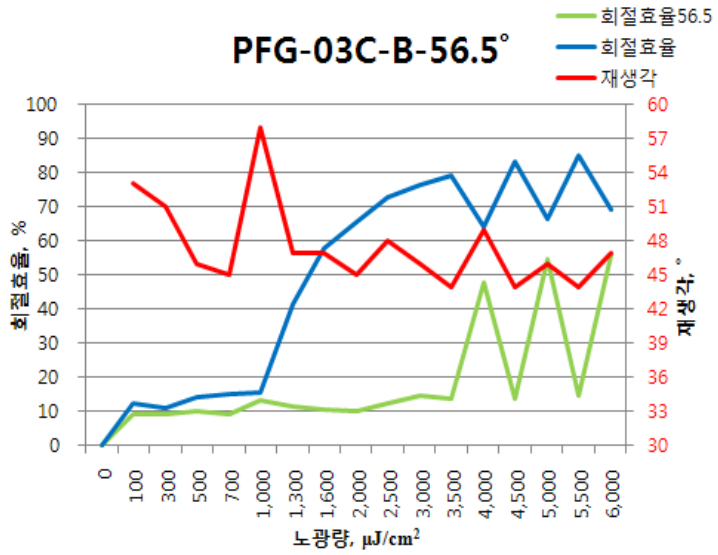


Figure 10. Diffraction efficiency measurement graph of PFG-03C Blue 56.5° samples

2) Diffraction efficiency analysis of Ultimate's Ultimate08-C

Different from PFG-03C, diffraction efficiency analysis results of Ultimate08-C didn't show changed reproduction angles and maximum diffraction efficiency in recording angles. Diagram 11 is a diffraction efficiency measurement graph of U08-C 45° samples. Red samples showed 70~80% diffraction efficiency at above 1,700~6,000μJ/cm2 of exposure level and Green samples showed 80~90% of high diffraction efficiency at 800~1,700μJ/cm2 of exposure level. Blue samples could obtain 95% of stable and high diffraction efficiency at 700~5,000μJ/cm2 of exposure level. RGB samples showed sharply decreasing diffraction efficiency phenomenon at 7,000μJ/cm2 of high exposure level.

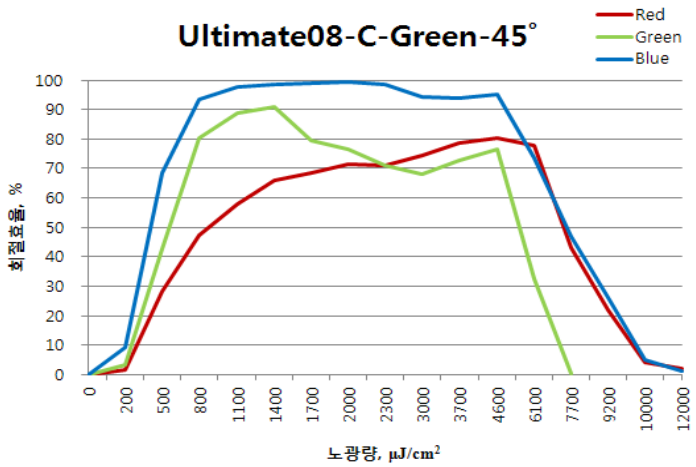


Figure 11. Diffraction efficiency measurement graph of Ultimate08-C 45° samples

Diagram shows the diffraction efficiency measurement graph of Ultimate08-C samples which is recorded at 56.5°. RGB samples could obtain stable and high diffraction efficiency. First, Red samples showed 80~90% of high diffraction efficiency at 1,500~6,000μJ/cm2 section and this showed almost same exposure section with 45° samples, but the diffraction efficiency was higher more than 10%. Green samples showed 80~95% of high diffraction efficiency at 900~4,000μJ/cm2 of exposure level. These results also showed maximum diffraction efficiency at the similar exposure section with 45° samples, but 56.5° samples showed a little higher diffraction efficiency. Finally, Blue samples showed 95% of high diffraction efficiency at 500~5,000μJ/cm2 exposure section, and these are the same results with 45° samples in exposure section and diffraction efficiency. And, all RGB samples show sharply decreasing diffraction efficiency at above 7,000μJ/cm2 exposure. This is an identically occurred phenomenon in 45° samples and 56.5° samples. And, these are the results caused by excessive exposure.

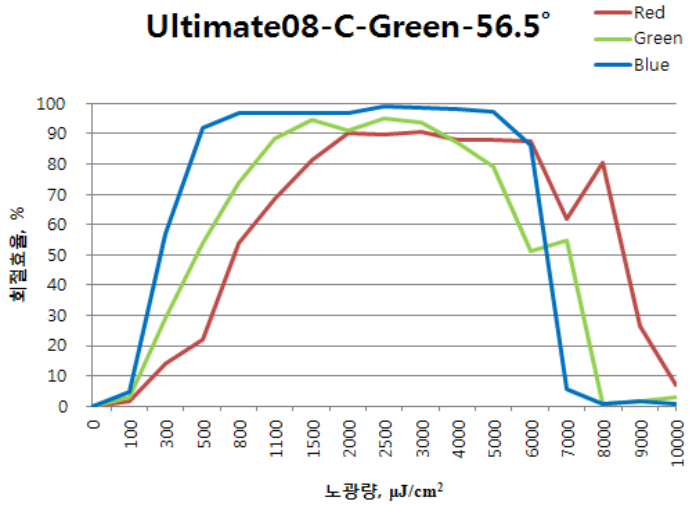


Figure 12. Diffraction efficiency measurement graph of Ultimate08-C 56.5° samples

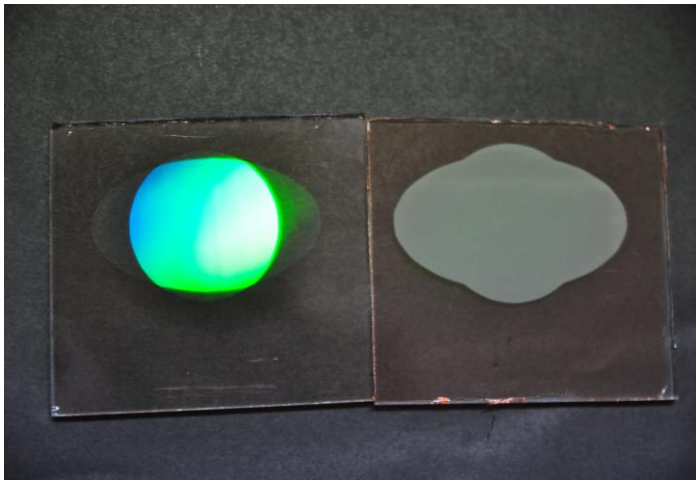


Figure 13. Alteration cause by excessive exposure (left: appropriate exposure, right: excessive exposure)

6. Result study

This paper suggests appropriate guide lines through the diffraction efficiency measurement of silver halide which is a holographic printer recording medium. PFG-03C which is Geola's silver halide for full color generally has the price performance advantage in analog hologram recording. But, its recording angles and reproduction angles are irregular to be used for DHP recording which is recorded with dot method, due to the reflective index moderation reason which is caused by medium's contraction after recording hologram. Post-processes are also complicated compared with other silver halide media.

Ultimate's Ultimate08-C for full color has 10% of difference in laser wavelength in diffraction efficiency, but it shows relatively stable and high diffract efficiency. (Red 70~80%, Green 80~90%, Blue higher than 90%). Therefore, when recording full color hologram with Ultimate08-C, excellent diffraction efficiency could be obtained if laser output is adjusted with RGB color combination of 2.1 : 1 : 0.9 at 45°/0° and 1.7 : 1 : 0.6 at 56.5°/0°.

7. Conclusion

This paper analyzed the diffraction efficiency of silver halide which is one of digital holographic printer recording media. Regarding the analyzed full color silver halide film, Geola's PFG-03C and Ultimate's Ultimate08-C are targeted which are commercially being used. Additionally, guide lines were suggested which could maximize the diffraction efficiency according to measurement results when recording holographic print. Relevant results are expected to be applied when recording full color hologram as well as holographic printer recording.

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