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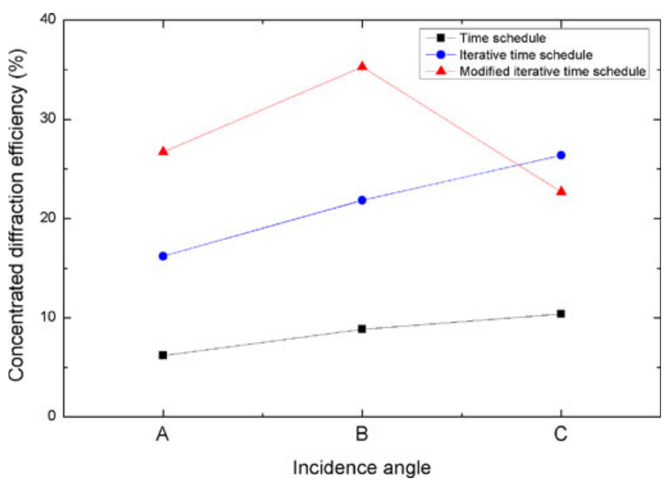

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Holographic Solar Energy Concentrator Using Angular Multiplexed and Iterative Recording Method

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Abstract: Holographic optical elements can be fabricated to concentrate the solar energy with no sun tracking system. Concentrated diffraction efficiency (CDE) for the holographic solar concentrator is suggested as a new efficiency calculation method. The exposure response of a monochromatic hologram recorded in photopolymer film is presented. The iterative exposure schedules at three different angles are chosen to optimize the uniformity of the CDE using angular multiplexed technique. The experimental results confirm that the angular multiplexing method and newly proposed iterative recording scheduling are appropriate for fabricating the holographic solar concentrator.

Index Terms: Holographic optical elements, multiplex holography, solar energy, concentrators.

1. Introduction

The photovoltaic (PV) system, which converts solar energy to electrical energy, has been in the spotlight as an alternative energy source. This is because the PV system provides infinite green energy. Compared to other sources of green energy, solar energy system is the most economic to setup and maintain. However, the PV system has some problems related to a low energy conversion efficiency and high cost. Hence, in order to improve the PV conversion efficiency and reduce the cost of solar PV systems, the concentrated photovoltaic (CPV) system has been studied for which not only the number or size of the solar cells could be reduced, but the energy conversion efficiency could also be increased. The most common solar concentrator for the CPV used in commercial systems is the Fresnel lenses [1]. The Fresnel lens has a relatively higher concentration ratio than other optical mechanisms to reduce the amount of expensive PV materials. On the other hand, the Fresnel lens requires a cooling system because the high concentration ratio of Fresnel lens can cause the overheating of PV cells. In addition, it also requires a sun tracking system and complex optical mechanisms. These drawbacks tend to raise the cost of the PV system.

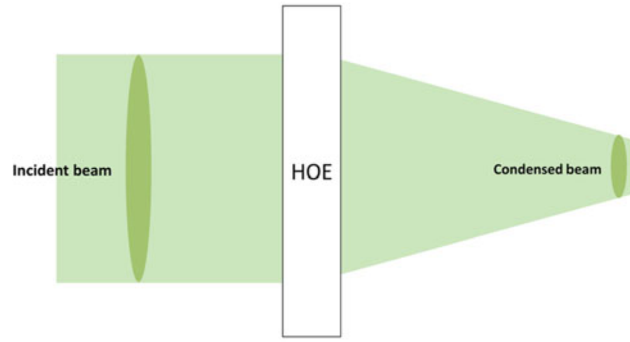

Fig. 1. Schematic diagram of ECR.

Recently, holographic optical elements (HOEs) have been studied for use in various solar applications to substitute optical mechanisms in solar concentrators [2]–[4]. The recording material of HOEs is usually flat and thin to replace Fresnel lenses for condensing solar energy [5]. Moreover, HOEs have the ability to diffract the light in a specific direction, and they also have the potential to provide angular or wavelength multiplexing [6]. By applying the angular multiplexing method [7] to the HOEs recording, the angular multiplexing-based HOEs could act as the sun tracker. The HOEs that operate at specific wavelengths are able to diffract the desired specific wavelengths and remove other unwanted wavelengths, such as UV rays. Therefore, the problem of overheating solar cells could be solved [8]. However, HOEs have certain constraints on the multiplexing method due to the angular and wavelength dependence of the diffraction efficiency properties of holographic gratings. Usually, the multiplexed holograms have low diffraction efficiencies [9], and therefore, sun tracking by HOEs might be inefficient. We propose the angular multiplexed HOE lenses with enhanced diffraction efficiency using the iterative recording method [10], [11].

In this paper, holographic angular multiplexed lenses are studied to solve the drawbacks of conventional solar concentrators. In order to combine the solar concentrator and sun tracking functions in a single photopolymer, a convex lens was used as a recording object while multiplexing the incident beams of three angles. In the experiment, the iterative recording method is utilized to compensate the low efficiency of the angular multiplexed holograms. We used a monochromatic light to prove the proposed method with the optical experiment. We mainly focus on the application of the angular multiplexed HOE using iterative recording in the field of solar energy.

2. Design HOE for Solar Concentrator

2.1 Concentrated Diffraction Efficiency

Generally, the performance of a HOE is determined by the diffraction efficiency. The diffraction efficiency is defined as the ratio of the intensity of the diffraction beam to the sum of the intensity of diffraction beam and transmission beam. However, it is difficult for the diffraction efficiency to evaluate the performance of the HOE as a solar concentrator [12].

Effective concentration rate (ECR) is a metric measure that is already proposed for measuring the concentration rate of the solar concentrator [13]. This concept is usually applied in solar concentrators in case of Fresnel lenses. Fig. 1 shows the schematic diagrams of ECR. The ECR was calculated from the equation

$$\text{ECR} = \eta_{opt} \times R_c \tag{1}$$

where η_{opt} is the optical efficiency which is the ratio of condensed light intensity to incident light intensity, and R_c is the geometric concentration rate which is the ratio of area of incident beam and condensed beam. Therefore, we newly suggest the concentrated diffraction efficiency (CDE) calculation method that uses an ECR. The CDE, i.e., η_c, is defined by ECR_h of HOE and ECR_l of

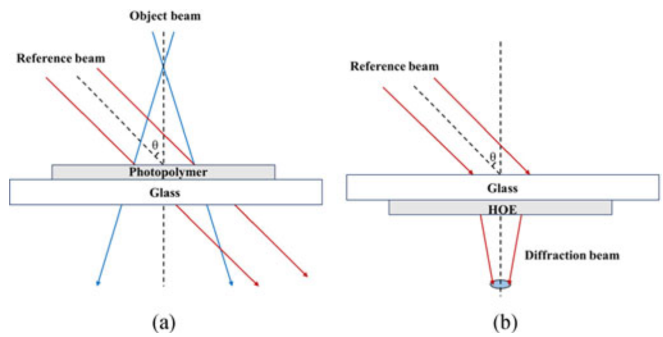

Fig. 2. Schematic diagrams of the transmission hologram for the HOE solar concentrator on the photopolymer film. (a) Recording. (b) Reconstruction.

the convex lens as follows:

$$\eta_c = ECR_h / ECR_l \times 100\,(\%), \tag{2}$$

Equation (2) shows the actual performance of the recorded HOE as a solar concentrator. Here, it can be seen that the CDE is more effective than ECR to demonstrate the concentration efficiency of solar energy. Actually, the two concepts are very similar to each other, and the CDE gets a high value when the DE also gets higher. The difference between the two concepts is that the CDE expresses the similarity of HOE with the hologram recording object. The advantage of the CDE-based method is that the CDE can figure out the direct similarity of the HOE and convex lens. The HOE with a higher CDE is more similar characteristic to conventional convex lenses. In other words, the HOE of 100% CDE has completely the same performance as the lens. We only considered monochromatic light at 532 nm wavelength, and the effect of other wavelengths was not considered in CDE calculation.

2.2 Optical Characteristics of the Photopolymer

The recording material affects the performance of HOE which is the most important factor for holographic experiments. In this paper, the photopolymer is used as a recording material [14], due to the features of the multiplexing method and its high diffraction efficiency. In addition, the photopolymer requires no post processing after holographic exposure, and it provides a high angular Bragg selectivity and an excellent signal-to-noise ratio.

The photopolymer used in this paper is a Bayfol HX photopolymer, provided from Bayer Material Science AG [15], [16]. The photopolymer layer has a thickness of 16.8 μm with substrate that has a thickness of 175 μm. The average refractive index of photopolymer is 1.58. Fig. 2 shows the schematic diagrams of the hologram recording for the solar concentrator. In this experiment, holograms are recorded by transmission geometry because it is advantageous for the HOE solar concentrator. To optimize the performance of the photopolymer, several exposure conditions are considered, like the exposure energy, angles, and energy ratio of two beams with 532 nm (green laser) and a convex lens (focal length = 200 mm).

Through the experiment analysis of the photopolymer, the conditions for the optimized HOE lens are studied. It is possible to extract the experimental conditions for a maximum CDE over several tests. Fig. 3 shows the experimental results corresponding to the different exposure energy, ratio of reference beam to object beam, and incidence angle in Green laser. According to the results in the graphs, the optimized conditions for the multiplexing experiments can be selected as in Table 1.

Fig. 4 shows the condensing performance of the holographic lens fabricated with the optimized recording conditions which shown in Table 1. The area of the incident beam and condensed beam is 3 cm^2 and 0.2 cm^2, respectively. It shows that the fabricated holographic lens condenses the

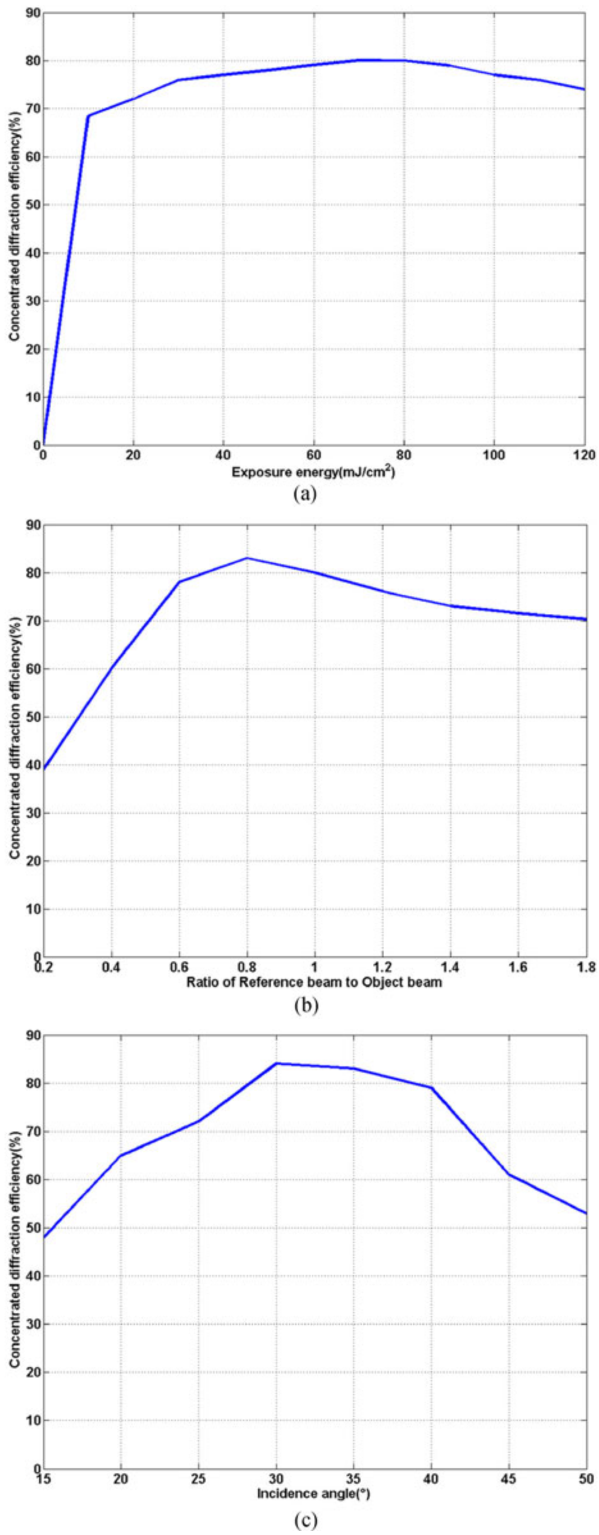

Fig. 3. Experiment results of CDE curves according to (a) exposure energy, (b) ratio of reference and object beam, and (c) incidence angle.

TABLE 1
Optimized Recording Conditions for HOE Solar Concentrator

Experimental Condition	Condition Value
Exposure energy (mJ/cm^2)	60–80
Reference beam: Object beam	0.8
Incidence angle $\theta(°)$	30–40

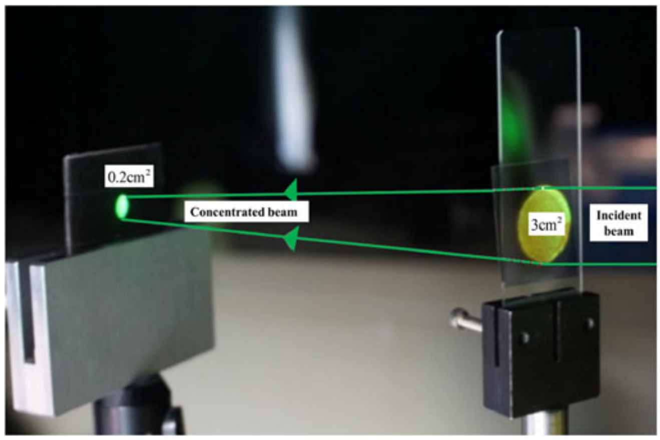

Fig. 4. Optical setup for measuring the concentration rate of HOE.

wide input light into a small area. It can also be observed directly that the condensed light of the fabricated sample is brighter than the incident beam.

3. Iterative Exposure Schedule for Angular Multiplexing

3.1 Theoretical Model for Multiplexed Recording with Iterative Exposure

In a single grating formation, the photopolymer receives an illumination of holographic spatial distribution $I(x)$

$$I(x) = I_0 (1 + m \cos Kx) \tag{3}$$

where I_0 is the total exposure intensity, K is the grating vector, and m is the modulation of holographic pattern. For the hologram, the first-order Fourier coefficient $\Delta n(t)$, which is identical to the refractive index modulation of the hologram grating, at each time t can be written:

$$\Delta n(t) = \Delta n_{sat} \cdot \left\{1 + \tau_D/\tau_p \exp\left[-\left(1/\tau_p + 1/\tau_D\right) t\right] - \left(1 + \tau_D/\tau_p\right) \exp\left(t/\tau_p\right)\right\} \tag{4}$$

where t is the recording time, $\tau_p = 1/\kappa\sqrt{I_0}$ indicates the polymerization time constant (κ is the polymerization coefficient that is assumed to be constant), $\tau_D = 1/DK^2$ is the diffusion time constant (D is the constant diffusion coefficient of monomer), and Δn_{sat} is the saturation index modulation, which is related to the initial monomer concentration [17].

The formation of refractive index modulation of a holographic grating can be divided into two procedures in the multiplexing process; first, the index modulation grows up until the next grating

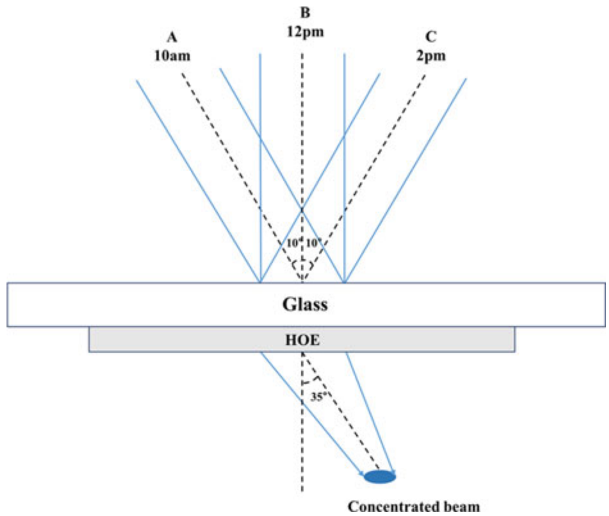

Fig. 5. Schematic diagram for angular multiplexed holographic solar concentrator.

is recorded, and second, the grating will continue to grow until the index modulation reaches the level set in advance around time t. The first procedure accords with the model for writing single grating. The second procedure cannot be depicted with the single grating model, which means the writing procedure of all gratings after nth grating will significantly influence the growth of the previous n gratings. Considering the multiplexing mechanism, the refractive index modulation of the nth hologram in the multiplexing process will be

$$n \cdot \Delta n_0 = \Delta n_{sat} \cdot \left\{1 - \exp\left(t_n/t_p\right) - \tau_D/\tau_p \exp\left[-\left(1/\tau_p + 1/\tau_D\right) t\right] \cdot \left[\exp\left(t/\tau_p\right) - 1\right]\right\} \quad (5)$$

where Δn_0 is assumed to be the final value of the refractive index modulation of every grating. It is possible to solve this equation for exposure time required to realize multiplexed holograms of uniform diffraction efficiency in photopolymer.

3.2 Experimental Schematic for Angular Multiplexing

In solar concentrator systems, the sun tracking systems are necessary owing to the movement of the planet. In order to realize the effective sun tracking system, an interval within 10 am to 2 pm is widely used, as shown in Fig. 5. This scheme shows the schematic diagram that condenses the light coming from three different angles to a fixed single point. Note that the interval degrees between each angle are decided as 10 degrees because it matches the movement interval of the sun at 10 am to 2 pm. Also, according to the simulations by Bragg's law, 10 degrees' interval can avoid the crosstalk [18].

For a HOE-based solar concentrator, the diffraction efficiencies of multiplexed holograms have to be uniform, but in this paper, we need to equalize the CDE. In the first angular multiplexing experiment, the CDE of three holograms needed to have uniformity and similar lens function. If the holograms are multiplexed with equal exposure time without considering the saturation time, the CDE and its uniformity would have a low value. Therefore, an appropriate exposure schedule is needed to achieve uniform CDEs.

The exposure schedules during the recording of the hologram using the angular multiplexing technique are related to the CDE at the three angles. The CDE test results show in Table 2. All the CDEs from the three incidence angle A, B, and C are extremely low. Therefore, it is difficult to apply the solar concentrator. To optimize the exposure schedule to obtain similar CDE for the three angle,

TABLE 2
Experiment Results Using Time Schedule

	Incidence angle	ECR_h of HOE	CDE η_c(%)
ECR_l of the Convex lens = 101.4	A	5.9	5.82
	B	8.5	8.38
	C	10.2	10.06

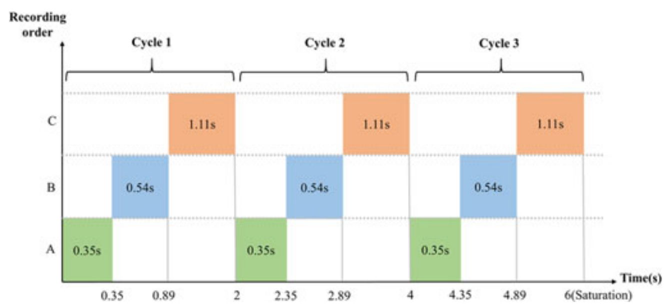

Fig. 6. Exposure time schedule using iterative recording method.

the effect of a sequential recording on an existing HOE must be considered. The solution for these kinds of problems is to record with a series of short exposures. Therefore, we apply the iterative recording time schedule to enhance the CDE.

3.3 Time Schedule Using Iterative Recording Cycle

In order to build up a model for multiple holographic grating in photopolymer, the effect of an iterative recording on an existing grating must be considered. The iterative method is applied to make holograms through repetitive exposure in one photopolymer that each of the N holograms is recorded with a series of short exposure time within the material's saturation time.

This approach was introduced in area of neural network applications, in which multiple short exposures in random order are used to store and update the multiplexed holograms [19], especially on holographic storage system [20]–[21]. We investigated an incremental recording method using photorefractive materials that it considered the erasure effect to calculate the recording cycles and scheduled recording. In this paper, the incremental recording technique for calculating recording cycles in photopolymer is applied to effectively stabilize the reaction of the monomer to reduce the difference of CDE between each angle and to obtain a high efficiency. According to the theoretical model, we decided the sequence of recording and calculated the recording cycles to make holograms repetitively in each angle within saturation time. Fig. 6 shows the exposure time schedule using the iterative recording method and three of the sequential recording cycles.

Fig. 7 shows the optical system for angular multiplexing in a photopolymer that uses 532 nm laser illumination. The beam is split into two beams using a polarizing beam splitter (PBS). To adjust the intensity ratio of reference beam and object beam, a half wave plate (HWP) and a polarizing beam splitter are used. A convex lens with 200 mm focal length is used as an object for recording the characteristics of the lens. In the recording of three different lenses, the beams reflected from three mirrors are concentrated at a single photopolymer. The intensity of incident beam is 1.5 mW/cm^2.

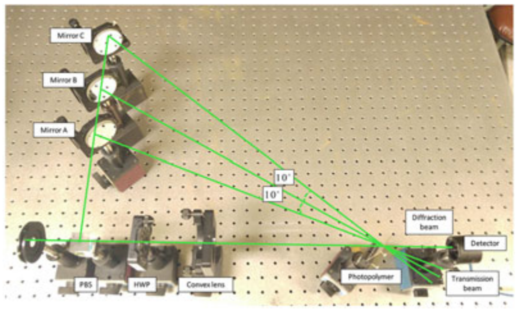

Fig. 7. Experimental set up for angular multiplexing: PBS, polarizing beam splitter; HWP, half wave plate.

TABLE 3
Experiment Results Using Iterative Time Schedule

	Incidence angle	ECR_h of HOE	CDE η_c(%)
ECR_l of the Convex lens = 101.4	A	16.8	16.57
	B	22.1	21.79
	C	26.9	26.53

In Table 3, the experimental results show that the iterative recording method compensates the low efficiency of the multiplexed holograms, but the intensity of the concentrated beam from incidence angle A is a little low than other angles. In addition, the uniformity of CDE for each angle and the intensity of the beam are not large enough to use as a solar concentrator. Therefore, a new recording method that combines other recording conditions is needed to a solar concentrator for real applications.

3.4 Experimental Result Using Modified Iterative Recording Method

To search for a recording method that can carry a higher CDE, we suggest another variations of exposure time duration for each recording angle and the recording order to realize multiplexed holograms with uniform CDEs on the photopolymer. These factors may affect the CDE of HOE. The CDEs for each angle are measured as approximately 71.14%, 73.95%, and 69.02%, respectively, at the corresponding incidence angle of A, B, and C. In order to avoid the confusion with the other values, they are denoted as a, b, and c. Therefore, the redistribution of exposure energy is used to obtain a more equalized efficiency. Using the CDE from the three angles, the intensity ratio of each angle is defined as follows:

$$a : b : c = 71 : 74 : 69. \tag{6}$$

Considering this ratio, the exposure time is adjusted for uniformed CDEs. Additionally, the influences of recording order and cycle pattern are considered, because, the first hologram has the highest CDE. The cause for the difference of CDEs on each hologram is identified as the order of recording. Therefore, the sequential order of recording is changed in a cyclical order like $A \rightarrow B \rightarrow C \rightarrow C \rightarrow B \rightarrow A$. The cycle of iteration recording is another valuable factor. In order to subdivide the cyclical recording order, four cycles are carried out. We also set the exposure time difference based on each cycle, that is, a new exposure time schedule, as shown in Fig. 8.

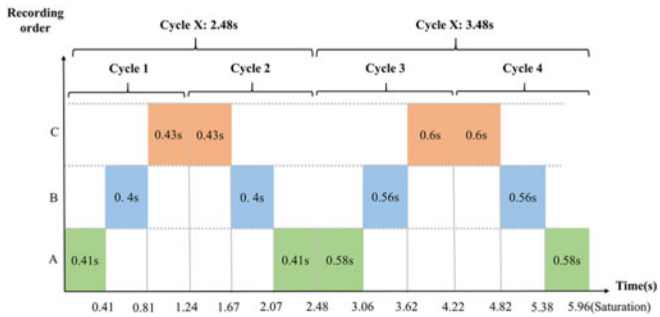

Fig. 8. Exposure time schedule using modified iterative recording method.

TABLE 4

Experiment Results Using Modified Iterative Time Schedule

	Incidence angle	ECR_h of HOE	CDE η_c(%)
ECR_l of the Convex lens = 101.4	A	27.1	26.73
	B	35.8	35.31
	C	23.1	22.78

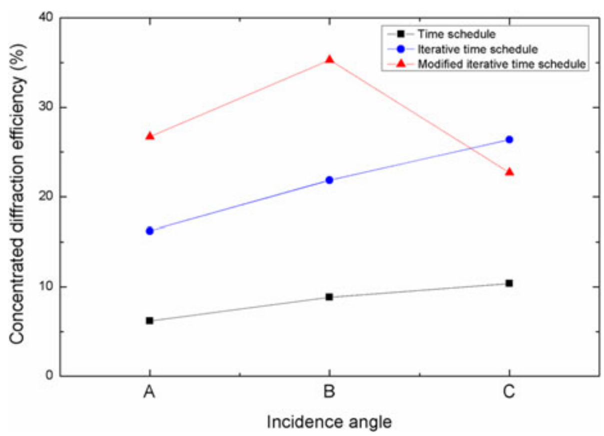

Fig. 9. CDE comparison graph based on each recording methods.

As a result, when the intensity of incident beam is 1.5 mW/cm^2, the light energy from the three incidence angles is successfully concentrated as 2.71 mW/cm^2, 3.58 mW/cm^2, and 2.3 mW/cm^2. The calculated CDEs of three angles are presented in Table 4. Through this exposure time schedule, the utility of the angular multiplexed holographic solar concentrator is demonstrated.

The condensing performances from the three recording techniques are presented in Fig. 9. The time schedule recording method for CDEs is marked with a square shape. In this case, the results are relatively low, which means that this method could not concentrate the solar energy effectively. The iterative time schedule recording method for CDEs is marked with a circle shape. Here, the results are higher more than two times than previous method, but it is not efficient enough to be applied to a solar concentrator. The modified iterative time schedule recording method for CDEs is marked with a triangle shape. Based on the previous work, the final proposed method finds an appropriate time schedule to condense the light with much higher efficiency. Therefore, the experimental results from the exposure time schedule using a modified iterative recording method are very useful and remarkable for solar concentrators.

4. Conclusion

In order to fabricate a holographic solar concentrator, an angular multiplexed HOE is produced using a photopolymer. A convex lens is considered as a recording object to condense the lights. The new efficiency calculation method, i.e., CDE, could express similar performance for the actual optical element as a solar concentrator. Through the characteristic analysis of the photopolymer, the optimized recording conditions for the HOE lens are carried out. Also, the most suitable recording method for an angular multiplexed HOE solar concentrator is studied. Using the iterative recording method, the low efficiency of multiplexed holograms is compensated. Furthermore, we suggest a new recording schedule calculation with a modified iterative recording method. As a result, the fabricated holographic solar concentrator that uses the proposed method from this paper has ideal results. The performance of the fabricated holographic solar concentrator has CDEs of 26.73%, 35.31%, and 22.78%, respectively, from incidence angles A, B, and C. The fabricated HOE has a more appropriate concentration rate and CDE than the previous method. Therefore, we can conclude that the fabricated HOE that uses the modified iterative recording method is suitable for applications of angular multiplexed solar concentrators.

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