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Development of a computer generation holography for generating square matrix light spots applied to the laser patterning system

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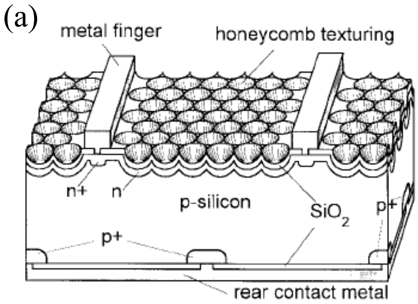
Abstract. A computer generation holography (CGH) is proposed herein to synthesize square-matrix light spots. Such a design of CGH is possible by reducing the 2-D problem to two 1-D problems. The both 1-D CGHs are designed with the conjugate-gradient method and verified with the Fresnel-Kirchhoff diffraction theory. This quantized 8-levels CGH is fabricated by using optical contact lithography and reactive-ion etching techniques. Measurement demonstrates that the fabricated CGH has the desired optical function, i.e., it forms square-matrix light spots in the image plane at a distance of 40 mm from the CGH. The developed CGH can be applied to the laser patterning system by optical projection and direct etching.

Introduction

Multicrystalline silicon solar cells have a high market share in the production volume of solar cells because of its low cost combined with the high energy conversion efficiency. One of the essential tasks for cell fabrication is the surface texturing to reduce the reflection loss of silicon solar cells in the interface of the silicon material and surrounding materials [1]. As shown in Fig. 1(a), the contact photolithography process is used to fabricate honeycomb cell structure on silicon solar cell with improved light trapping. Patterning the interface surfaces of solar cell with the laser technique has the advantage of noncontact processing and is already well- established in the industrial solar-cell processes [2,3]. However, it is time-consuming to generate a 2-D pattern on the surface of silicon wafer point by point using the laser technique.

Computer generation holography (CGH) is now more and more widely used to process light wave-front for performing desired optical functions, such as fan-out elements or colour separation [4-6]. The fabrication of CGH has reached a satisfying maturity and can proceed with multi-level structures providing high diffraction efficiency. In this paper, we develop the CGH that can implement the optical function of square-matrix light spots. In a high powe laser system, the CGH can be applied to the laser patterning system by optical projection and direct etching. As shown in Fig. 1(b), the square-matrix light spots can texture the surfaces of the silicon solar cell. In order to design the CGH with high diffraction efficiency, we simplified the complicated 2-D problem as two 1-D problems. The algorithm that we used to design two 1-D CGHs is the conjugate gradient method [7]. This is a basic principle to minimize the derivation of the reconstructed wave fields from the desired light field distributions. Then, the standard semiconductor process wase used to fabricated the desired CGH. The optical performance of fabricated CGH was also measured and analyzed.



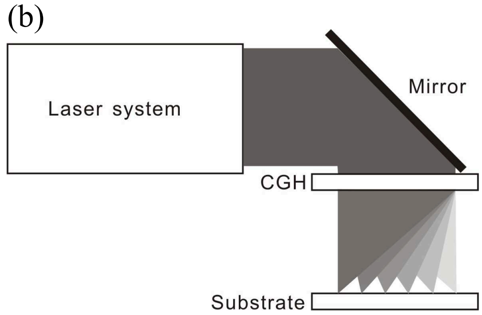


Fig.1 (a) Honeycomb cell structure on silicon solar cell with improved light trapping.[3] (b) Laser patterning system by optical projection and direct etching.

Design method and results

In particular, when the output light field $U_2(x_2,y_2)$ is a separable function of x_2 and y_2, that is, $U_2(x_2,y_2)=U_2(x_2)U_2(y_2)$, the input optical field $U_1(x_1,y_1)$ is also a separable function and the design problem of the 2-D CGH can be reduced to two design functions of 1-D CGHs. Then, the both 1-D CGHs can be designed with the conjugate gradient method. Based on the optical superposition theory, the 2-D CGH can be formed with the two designed 1-D CGHs.

The parameters used in the design of CGH are as follows. The size of incident planar-wave beam is 7.5 mm x 7.5 mm, and the wavelength of incident beam is 532 nm. The predicted numbers of square-matrix light spots inside a output area of 2 mm x2 mm is 52 x 52. The distance between the CGH and output plane is 40 mm. It is also called the focal length of CGH. From our simulation, we find that the numbers of sampling points of 1-D CGH and its corresponding output pattern play impotant roles in the optimization process. There are restrictions on the two numbers of sampling points. For instrance, the minimum feature size permitted for the fabrication process determines the upper limit of the number of sampling points of 1-D CGH. To ensure convergence for the algorithm, we relax the restriction of inition condition. In the beginning calculation, we strat with a smaller number of sampling points of output pattern. Then, we use more sampling points and substitute the result that is calculated before as initial phase of optical field U_1 in the next calculation process. Finally, the number of the sampling points of output pattern is increased to 2500 in the last calculation. As shown in Fig. 2, the designed CGH is a similar symmetry surface structure after optimization. The clear window of the designed CGH is 7.5 mm x 7.5 mm, and its minimum feature size is 3μm x 3μm. In order to evaluate the optical performance of designed CGH, the output illuminance of CGH is reconstructed by using the Fresnel-Kirchhoff diffraction theory. The reconstructed x-axis illuminance distribution of square matrix ligh spots is showed in Fig. 3. It shows that the output illuminance distribution has the predicted optical properties. The number of light spots in the x-axis inside the region [-1 mm, 1 mm] is 52. The distance between each light spot is 38.8 μm. The average full width of the light spot is 4.1μm at the point of 13.6% peak value.

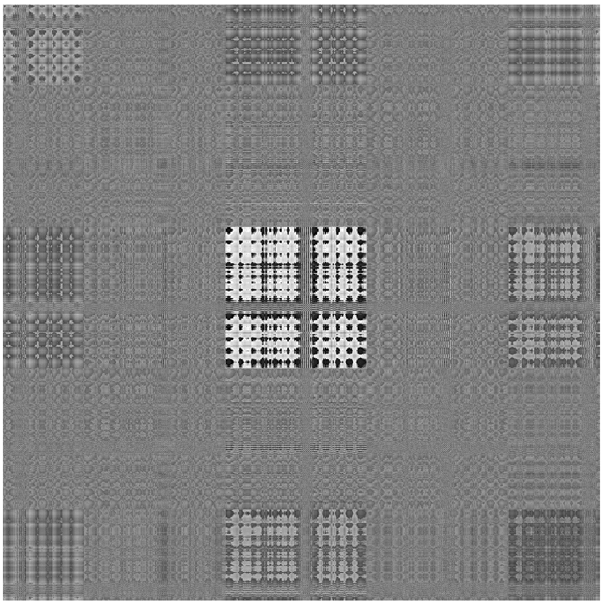


Fig.2 Phase distribution of the designed CGH that can generate square-matrix ligh spots inside the area of 2 mm x 2 mm at a distance of 40mm from the CGH.

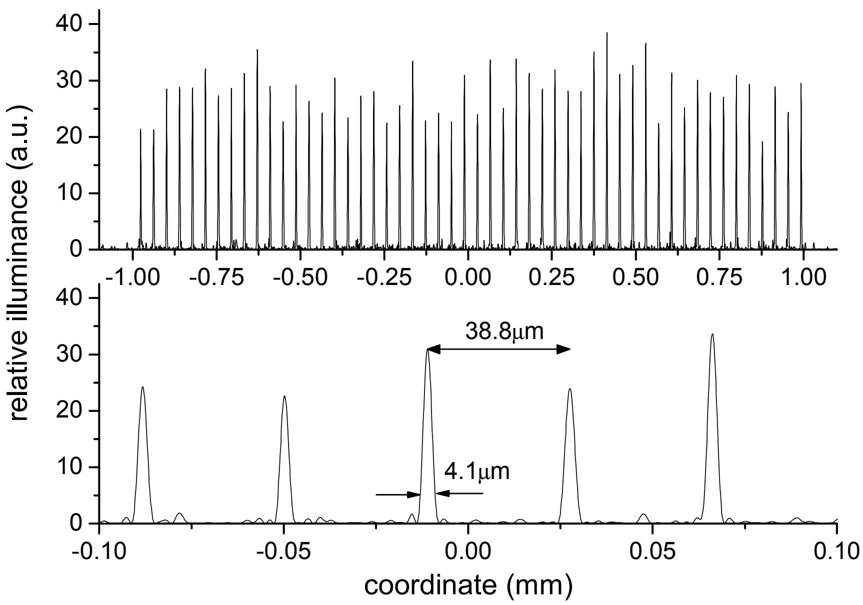


Fig. 3 Reconstructed illuminance distribution of output pattern in the x-axis. Below figure is the enlarged curve of the output region [-0.1mm, 0.1mm].

Fabricated and measured results

To meet the requirement of our fabrication process, the obtained optimum continuous surface profile must be quantized in the multilevel structure. In our case, the continuous surface profile of designed CGH is quamtized in 8 levels. The fabrication process of the CGH is as follows. First, three photographic masks were generated by a laser beam pattern generator. Then optical contact lithography and reactive-ion etching processes were used to fabricate the surface relief structures of the CGH on a flat quartz substrate. The quartz material is selected as the CGH substrate due to avoid the surface structure damaged under the condition of high power laser beam incidence. The refractive index of quartz material is 1.49 at the wavelength of 532 nm. The maximum depth of the surface relief structure is 1.085 μm. Figure 4 shows a photograph of the fabricated CGH. The thickness of the CGH substrate is 2 mm. Figure 5 shows a part of the enlarged surface structure of the fabricated CGH. To verify the optical performance of the fabricated CGH, we measured the illuminance distributions of the output pattern. A collimated laser beam passes through the fabricated CGH and forms square matrix light spots on the image plane. A CCD camera was placed on the optical bench and moved to the image plane to record the output image. A part of measured output illuminance distribution of is shown in Fig.6. The output spot is similar Gaussian distribution. The average diameter of those light spots is about 4.3 μm at the point of 13.6% peak value. In order to analyze the tolerance over which the image plane can be displaced while the light spots remain in acceptablely shap focus, the spot size of light spot is measured near the focus position. Figure 7 shows the normalized peak value of measured output light spot as a function of the displacement of focus position. This analyzed results illustrate that the depth of focus of this CGH is 80 μm at the 90% peak value of light spot.

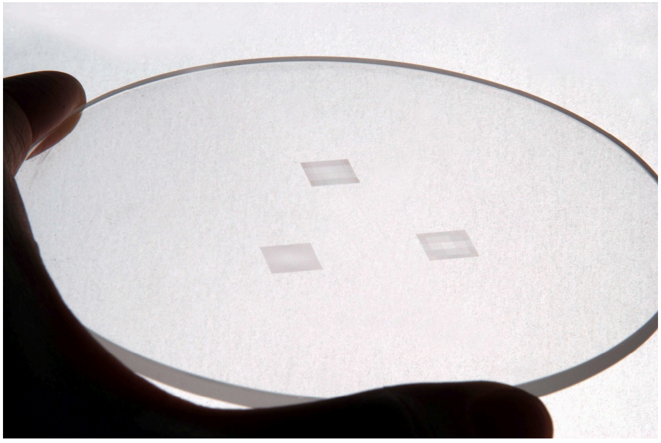


Fig. 4 Photography of the quantized 8-levels CGH. The maximum depth of the surface relief structure is 1.085 μm. The thickness of used quartz substrate is 2 mm.

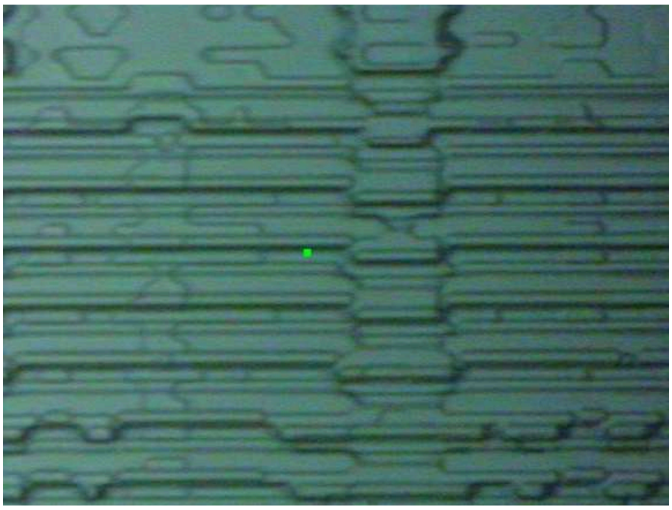


Fig. 5 Photography of the enlarged surface structure of the quantized 8-level CGH. The minimum feature size of structure is 3μm x 3μm.

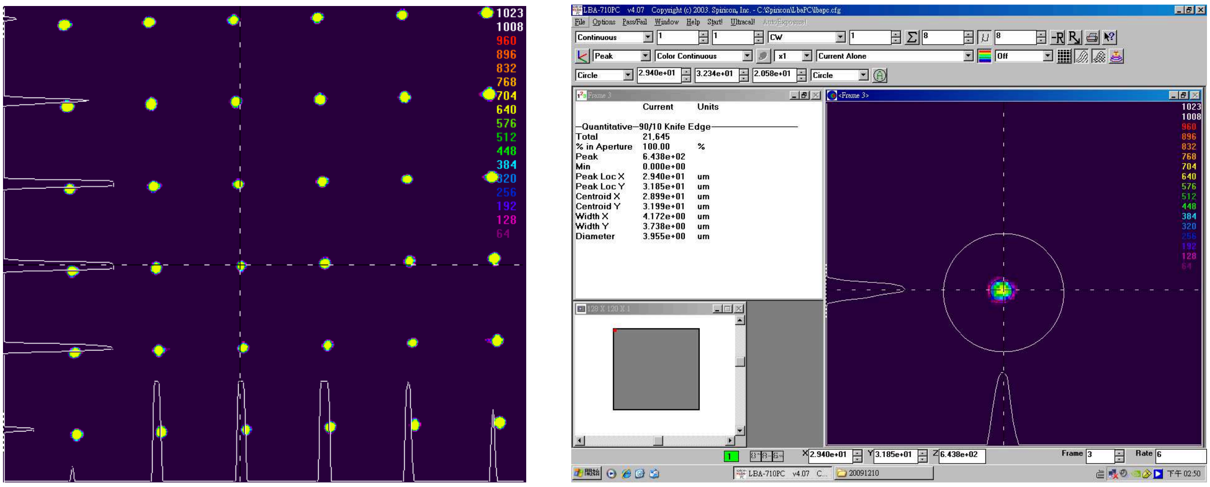


Fig. 6 Part of the measered output illuminance distribution of spot patten. Right figure shows the measured results of spot size. The output spot is similar Gaussian distribution. The average diameter of those light spots is about 4.3 μm at the point of 13.6% peak value.

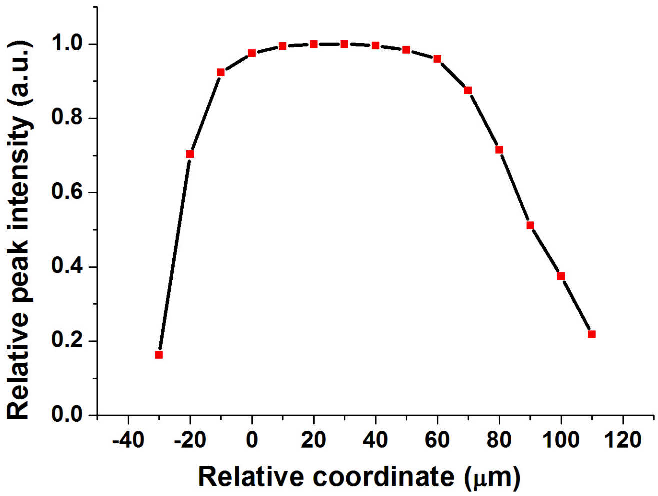


Fig. 7 Normalized peak value of light spot as a function of the optical axis. The zero position of x coordinate denotes the focus position. The focal depth of fabricated CGH is 80μm.

Summary

We developed a CGH that can synthesize square-matrix light spots pattern in the image plane. It can be apply to the laser patterning system by optical projection and direct etching. In order to design the CGH with high diffraction efficiency, the complicated 2-D problem is simplified to two 1-D problems. Then, the 1-D CGHs can be designed efficiently with the conjugate-gradient numerical algorithm and verified with the Fresnel-Kirchhoff diffraction theory. The target square-matrix light spots pattern has the spot spacing of 38.8 μm and 52 x 52 spots within the output area of 2mm x 2mm. A standard semiconductor process was used to fabricate the desired CGH. Measurement demostrates that the average diameter of light spots is 4.3 μm at the point of 13.6% peak value. The focal depth of fabricated CGH is 80μm at the 90% peak value of light spot. Those results show that the output illuminance distribution of fabricated CGH has the desired optical function.

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