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Image Quality Evaluation and Tolerance Analysis for Camera Lenses with Diffractive Element

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A novel image quality evaluation method, which is based on combination of the rigorous grating diffraction theory and the ray-optic method, is proposed. It is applied for design optimization and tolerance analysis of optical imaging systems implementing diffractive optical elements (DOE). The evaluation method can predict the quality and resolution of the image on the image sensor plane through the optical imaging system. Especially, we can simulate the effect of diffraction efficiencies of DOE in the camera lenses module, which is very effective for predicting different color sense and MTF performance. Using this method, we can effectively determine the fabrication tolerances of diffractive and refractive optical elements such as the variations in profile thickness, and the shoulder of the DOE, as well as conventional parameters such as decenter and tilt in optical-surface alignments. A DOE-based 2M-resolution camera lens module designed by the optimization process based on the proposed image quality evaluation method shows ~15% MTF improvement compared with a design without such an optimization.

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I. INTRODUCTION

Diffractive optical elements (DOE) are increasingly implemented in modern optical imaging systems to correct chromatic aberrations as well as to obtain device compactness. Imprecise control of the DOE profiles in fabrication process,however, can cause severe degradations in image quality such as color run or color sense. For example, fabrication errors in DOE profile can cause a color run problem at the image sensor plane due to existing higher-order diffracted rays. The wavelength dependence of diffraction efficiency can, on the other hand, cause problems in color sense. That is, the DOE design is typically optimized for a single wavelength (green, for example) while other wavelength components in the visible spectrum have different diffraction efficiencies such that degradations in color sense can occur.This can be seen in example pictures taken from a resolution chart image from an all-refractive-lens based imaging system and a DOE-based imaging system as shown in Fig. 1.

Imaging systems are typically designed using commercial ray-tracing software such as CODE V$^{\mathrm{TM}}$ [1]. Although such commercial softwares can support diffractive optical elements in the design, their capabilities are limited such that they cannot be used for the tolerance analysis of the DOE structural parameters as well as for the image quality estimation, which is very important in actual fabrication of the imaging lens modules. To obtain high-quality DOE-based imaging system, therefore, an effective method of image quality evaluation is required in the design stage to obtain optimal DOE designs as well as fabrication tolerances. In this paper, a novel image quality evaluation method for DOE-based optical imaging systems is proposed. Design optimization and tolerance analysis results were presented using an example DOE-based 2M-resolution cellular-phone camera module.

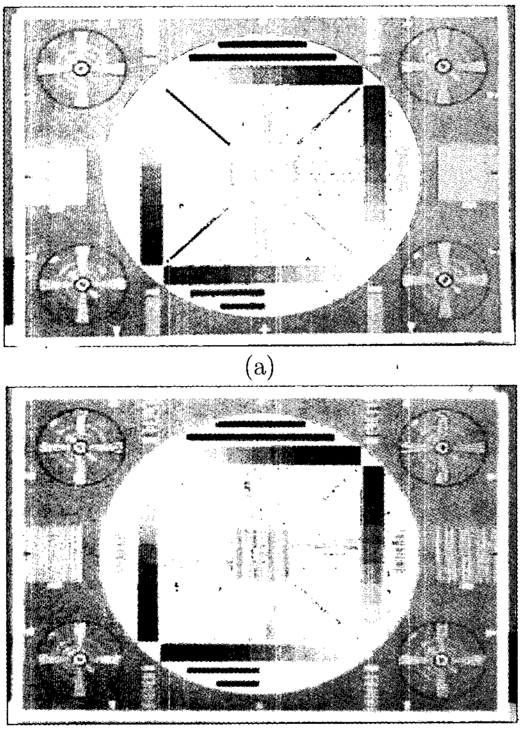
II. LENS MODULE DESIGN

A 2M-resolution cellular-phone camera module was designed, taking into account that it is made by a wafer-scale replication process, as shown in Fig. 2. This lens module is composed of three wafers (Pyrex 7740), each of which has UV-curable polymer lenses on both front- and backsides. One of the wafers [the middle wafer in Fig. 3] includes a DOE lens made by dual-replication process. That is, a diffractive lens was first replicated on the surface of the wafer and the secondrefractive lens was replicated on top of the first replicated diffractive lens as shown in Fig 3. The DOE surface is, then, defined by the optical interface profile between the DOE material (refractive index of n_1= 1.590) and the refractive lens material (refractive index of n_2=1.403).

A commercial lens design tool, CODE V^{TM}, was used to design such a lens module. To maximize the diffraction efficiency of the DOE lens, the DOE profile depth (d) was first chosen by

$$d=\frac{\lambda_0}{n_1(\lambda_0)-n_2(\lambda_0)}, \tag{1}$$

where λ_0 is the design wavelength and n_1 (λ_0) and n_2 (λ_0) are refractive indices of the DOE lens and the surrounding refractive lens material, respectively. In our design, for example, the required DOE thickness was found to be ~3.2 μm, for a reference wavelength of 587.6 nm and refractive indices are n_1=1.590 and n_2=1.403. The smallest pitch of the implemented DOE is ~30 μm. The imaging performance of the designed camera module is shown in Fig. 4, showing 30% in MTF at 150lp/mm resolution.



(a)

(b)

FIG. 1. Pictures taken from the lens modules which have (a) only refractive lenses and (b) DOE and refractive lenses.

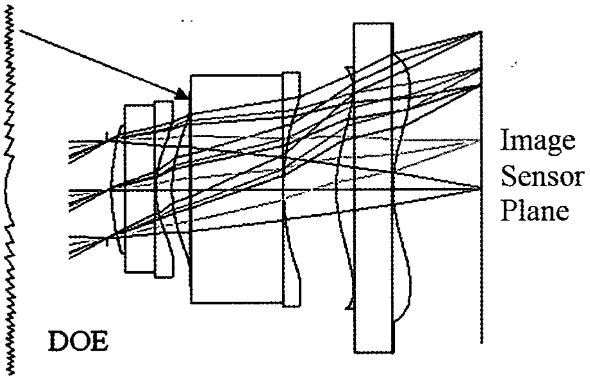


FIG. 2. Schematics of a wafer-scale lens having a DOE surface.

The DOE profile thickness chosenin Eq. (1) is to maximize the diffraction efficiency for a fixed wavelength (i.e. green wavelength). As the diffraction efficiency is wavelength dependent, the DOE profile depth should be optimized to cover the whole visible wavelength range. That is, inorder to achieve proper color sense, the DOE profile depth should be optimized to have similar optimum high efficiency of the first diffracted order for red, green, and blue wavelengths. Additionally the higher-order diffraction efficiency for whole visible wavelength should be optimally minimized to avoid color run.

The efficiency (η_i) of the i-th diffracted order from the DOE lens may be obtained by

$$\eta_i=\frac{2\pi\sum_{m=1}^{N} r_m \Delta r_m \eta_{m,i}}{A}, \tag{2}$$

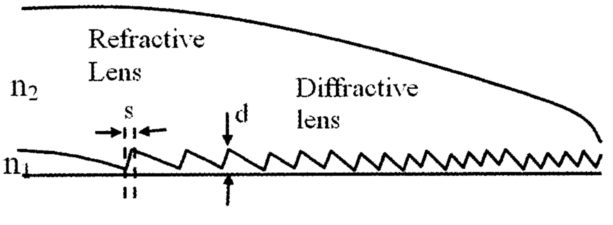


FIG. 3. dual-replicated hybrid diffractive-refractive lens.

where r_m and Δr_m are the radius and the length of the m-th zone of the DOE lens, respectively, $\eta_{m,i}$ is the i-th (i=···-2,-1,0,1,2,···) order diffraction efficiency of the m-th (m=0,1,2,···) zone of the DOE lens, and A is the total area of the DOE lens. Although a scalar diffraction theory can be used for this low-spatial-frequency grating structure [2,3], we applied an electromagnetic diffraction analysis based on rigorous coupled-wave analysis [4] to obtain better estimation of the local-zone diffraction efficiency, $\eta_{m,i}$, of the DOE lens. The first-order diffraction efficiency ($\eta_{1,1}$) of the DOE for various profile depth (d=2.5~3.7 μm) for the red (656 nm), green (687 nm), and blue (487 nm) as a function of the angle of incidence is shown in Fig. 4. For the designed wavelength of 687 nm (green) maximum first-order diffraction efficiency is given for a profile thickness of ~3.2 μm at normal incidence and is decreased as the profile depth and the incidence angle move away from the 3.2 μm and 0°, respectively. The maximum diffraction was achieved for the red and blue wavelength at normal incidence for profile depths of 2.6 μm and 3.5 μm, respectively. This can be expected from the maximum-efficiency depth requirement of Eq. (1). The degradation of diffraction efficiency is shown to be most severe for the blue wavelength as it is the shortest wavelength.

Figure 5 shows the first-order diffraction efficiency of the DOE lens for the red, green, and blue wavelengths. In these calculations, the effect of shoulder error, which is an additional structural profile error defined in Fig. 1 (b), was also considered. The maximum diffraction efficiency occurs at longer (shorter) profile depth for the red (blue) compared with the reference profile depth of 3.2 μm (for green). As the shoulder length increases, the maximum- efficiency profile depth is decreased. In our design, we choose the optimum DOE profile depth to be ~3 μm, where the diffraction efficiency of the blue and red wavelength is nearly the same (~85%) and that of the green wavelength is nearly maximum to be ~94% from the Fig. 5 (a).

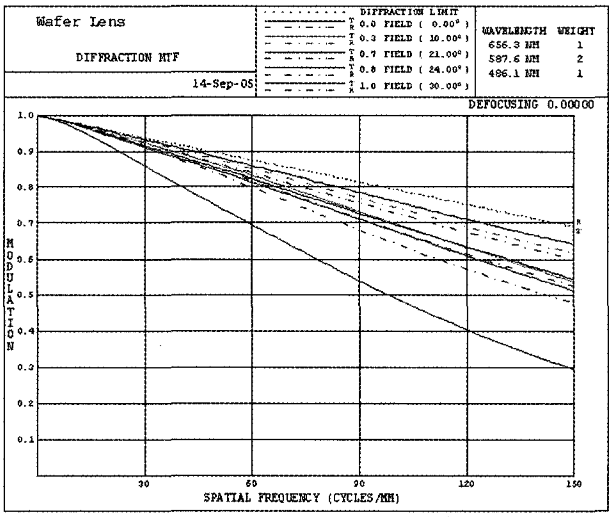
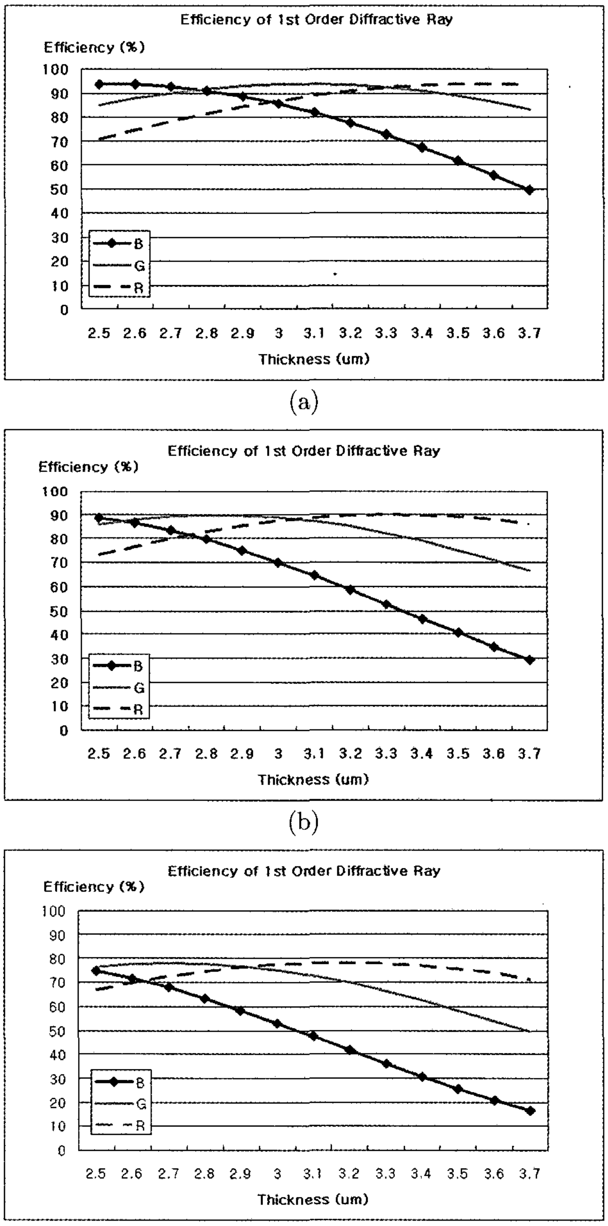


FIG. 4. The imaging performance of the designed camera module.

From Figs. 5 (b) and (c), we can see that the effect of shoulder for the color combination is very important, in addition to the profile depth, such that it should be tightly controlled in the fabrication process to obtain a good image quality lens module. The efficiencies of the higher diffracted orders were also calculated. As the profile depth moves away from the reference wavelength, the efficiency of the first diffracted order decreases and that of the second diffracted order mainly is increased, which can cause color run.



(a)

(b)

(c)

FIG. 5. Diffraction efficiency of the 1st diffracted order of DOE with (a) no shoulder error (b) shoulder error of 3 μm (c) shoulder error of 6 μm, respectively.

III. IMAGE QUALITY EVALUATION METHOD

As was shown in the previous section, the DOE profile depth and the shoulder are the main parameters to be precisely controlled in the fabrication stage to obtain a high-quality imaging module with proper color combination and negligible color run. For that purpose, we need to evaluate the image quality of the DOE-based imaging system and tolerance analysis on the main structural parameters. The commercial software COVE V^{TM} can provide image-quality evaluation (such as MTF analysis) only for the ideal DOE lens with a first diffracted order and cannot provide the effect of higher diffracted orders. The existing higher-diffracted orders cause color run such that image degradation occurs. Therefore a new image- quality evaluation method for the DOE-based imaging system that can include all higher diffracted orders is called for. We performed the image quality analysis on our DOE-based imaging module as follows. Firstly a virtual resolution chart, which can be used as an illumination beam pattern in the CODE V^{TM}, is generated and located at the image field of interest as shown in Fig. 6. Then, the CODE V^{TM} can generate the output images for various diffracted orders separately.

Figure 7 shows the simulated output pattern results for each diffracted orders for the green wavelength. Except for the first diffracted orders [Fig. 7 (c)], all higher-order images are blurred. The final output pattern fora green wavelength can be obtained by the summation of all intensity patterns from diffracted orders weighted by their diffraction efficiencies. To see the color run effect, we repeated the above-mentioned process for the red and blue wavelengths. The final color output pattern image was obtained by summation of red, green, and blue patterns. Figure 8 shows an example output image of a resolution chart. We can see a slight color run in the high spatial frequency region. The color run becomes more severe if the fabrication errors in DOE profile depth and the shoulder exist. Note that, the CODE V^{TM}, does not provide combined image simulation that includes all diffracted orders in a DOE-based imaging system.

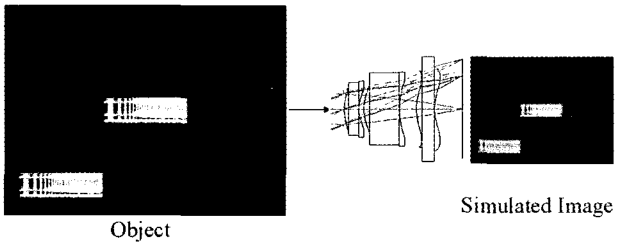


FIG. 6. Virtual resolution chart (object) and the simulatedimage through the imaging system.

The performance of the imaging system can be represented by the modulation transferfunctions (MTF) as shown in Fig. 3. We obtained the MTF of the DOE-based imaging module by analyzing the final image pattern of the resolution chart. That is, the intensity pattern across the resolution chart is first obtained. The MTF can be calculated from the intensity pattern by

$$MTF=(I_{max}-I_{min})/(I_{max}+I_{min}), \qquad (3)$$

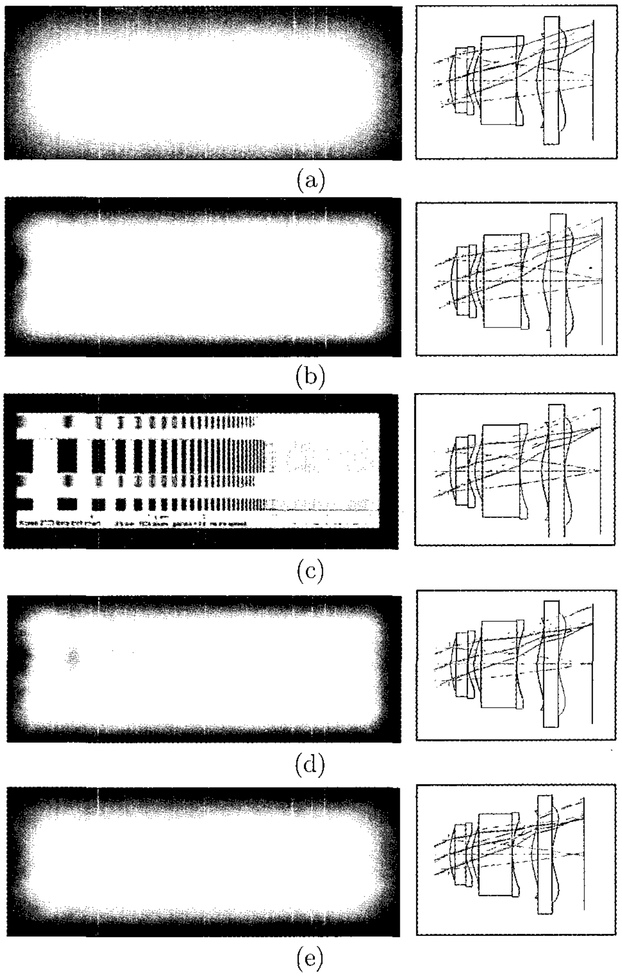


FIG. 7. Center region of simulated images for (a) -1st (b) 0th, (c) 1st (d) 2nd (e) 3rd diffracted rays for the green wavelength.

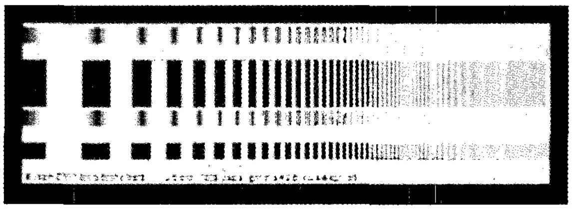


FIG. 8. Final Image obtained by weighted summation of all diffracted order images for RG & B wavelength.

where I$_{max}$ and I$_{min}$ are maximum and minimum intensity for a spatial frequency of the image. Figure 9 shows an example of MTF estimations. As the object image has a finite region in the image sensor, calculated MTF shows difference from the designed value (at 0.7 field). Taking into account the image sensor resolution, we used the reference MTF value to be at 150 lp/mm for the thickness optimization and the tolerance analysis.

IV. TOLERANCE ANALYSIS

1. Effect of thickness error

One of the most important structural parameters that can affect the quality of the DOE-based imaging system is the thickness of the DOE as shown in section 2. That is, improper profile thickness of the DOE results in image blurring as the diffraction efficiencies for higher-order noise rays, which have focal length different from that of the first order ray, grow. Additionally, diffraction efficiency depends on the wavelength.

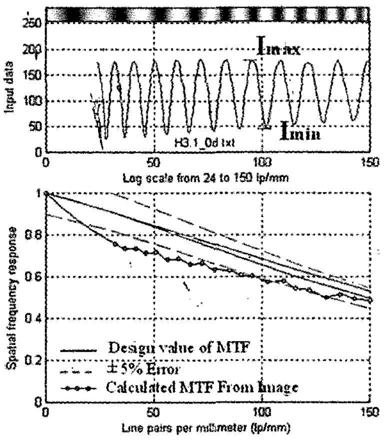
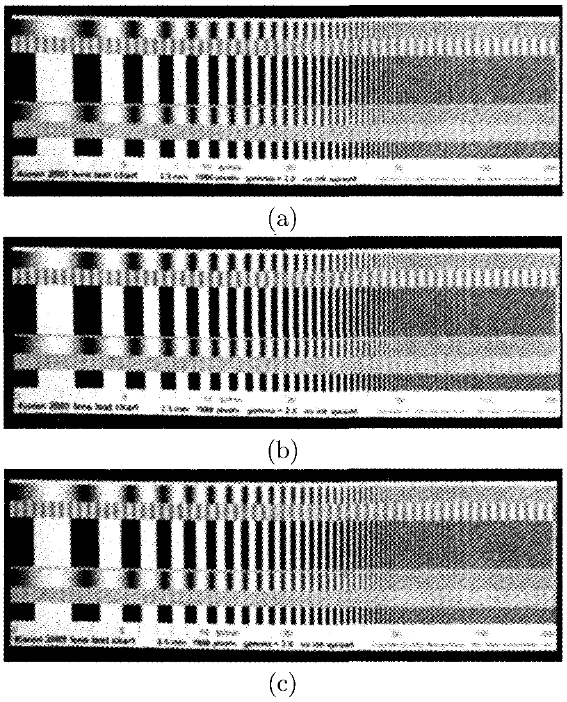


FIG. 9. Modulation transfer function obtained by the final image, Calculated from the outer resolution chart of the object.

Figure 10 shows the simulated images of resolution chart for several DOE profile thicknesses. As can be seen in Fig. 5, if the thickness of the DOE gets thinner than the reference thickness, the efficiency of the blue wavelength gets higher. Figure 10. (a) clearly shows the blue background color instead of white. In opposite case, when the DOE thickness is thicker than the reference thickness, red appears as the background color as shown in Fig. 10. (c). Thickness error of DOE is clearly shown to make the final image with different color sense from the original image and causes degradation of MTF performance. If we assume 20% of thickness error of the DOE, the MTF has 8% lower value for the spatial frequency of 150 lp/mm comparing with the maximum value of MTF as shown in Fig. 11. Additionally, if the DOE thickness error exists,



(a)

(b)

(c)

FIG. 10. Simulated Images of resolution chart in case of (a) d=2.5 μm (b) d=3.1 μm (c) d=3.7 μm, respectively.

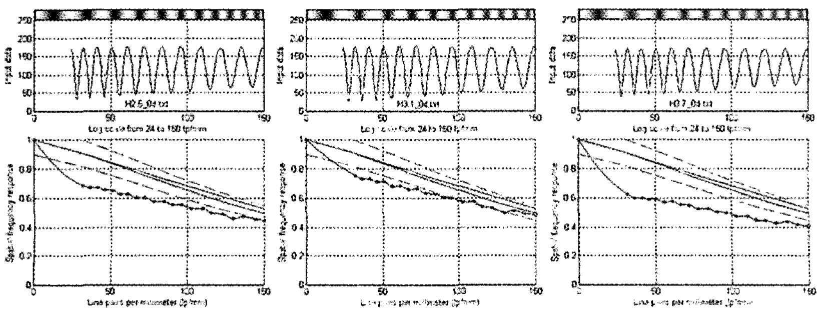


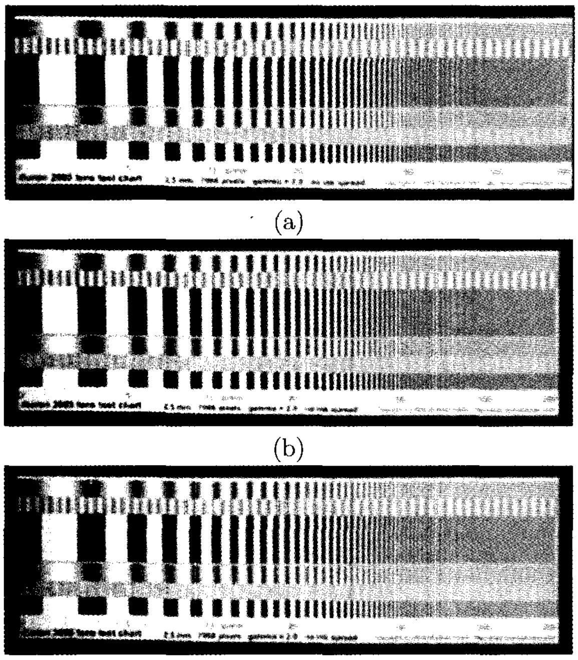
FIG. 11. MTF calculations in case of (a) d=2.5 μm (b) d=3.1 μm (c) d=3.7 μm, respectively.

the 2nd diffracted order efficiency grows such that the MTF performance is also degraded.

Therefore, the DOE thickness should be optimized and well-controlled in the fabrication stage to suppress higher-order rays as well as to obtain similar first-order diffraction efficiencies over the whole visible spectrum.

2. Effect of shoulder error

Another important parameter that can affect the image quality for DOE lens in imaging system is the shoulder (the length of abrupt profile change between two zones). Similar image simulations and MTF analyses were performed for a DOE-based imaging system allowing shoulder errors as shown in Figs. 12 and 13. Imaging performance degradation is shown to be evident as the shoulder error increases. The final images show that the shoulder error causes color run at the images. The proposed image quality evaluation method can be applied to obtain fabrication tolerance of the shoulder. The analysis result shows 12% degradation in MTF for the spatial frequency of 150 lp/mm with a 6 μm shoulder length for the example DOE-based camera lens module.


(a)

(b)

(c)

FIG. 12. Simulated images of resolution chart from a DOE-based lens module in case of (a) s=0 (b) s=3 μm (c) s=6 μm.

3. Tolerance analysis of DOE

According to theimage simulation and calculation of the MTF, thickness deviation and shoulder error of the DOE profile causes degradation in color sense and color run near the edge of the resolution chart pattern. If there is no shoulder error in DOE, the optimum thickness of DOE can be 3.1 μm as shown in Fig. 14. However, it is impossible to make such perfect DOE features in practice. If we assume that the controllable shoulder size is 3 μm, the thickness of the DOE should be controlled 2.9 μm +/- 200 nm for the 40% of the MTF value at 150 lp/mm. Although the MTF specification for the camera lens module is 30%, 10% margin remains for other fabrication and assembling tolerances.

A DOE-based 2M-resolution camera lens module designed by the optimization process based on the proposed image quality evaluation method shows ~15% MTF improvement compared with a design through CODE V^{TM} without such an optimization. It is because the CODE V^{TM} does not support the tolerance analysis of DOE fabrication. The MTF estimation from the proposed method was found to agree within ~5% to that from the direct MTF analysis from the CODE V^{TM} for an imaging system.

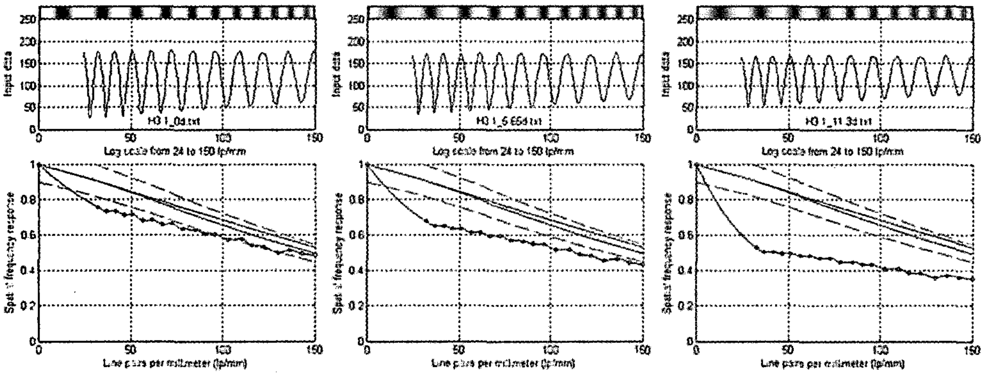


FIG. 13. MTF calculations in case of (a) s=0 (b) s=3 μm (c) s=6 μm.

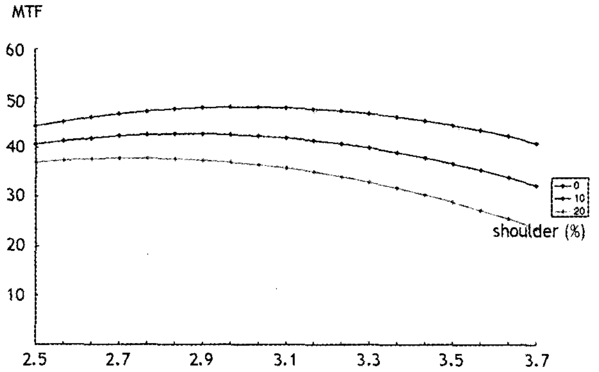


FIG. 14. Calculated MTF of the resolution chart images from the DOE-based imaging system having DOE profile errors.

V. CONCLUSIONS

A novel image quality evaluation method is proposed and is applied for design optimization and tolerance analysis of DOE-based optical imaging systems. Although, we can analyzethe typical fabrication tolerances of the lens module such as decenter and tilt using commercial software such as the CODE V^{TM}, we cannot evaluate the image quality parameter such as the MTF when the fabrication error of the DOE lens is involved. The proposed image quality evaluation method is based on combination of the rigorous grating diffraction theory and the ray-optic method. Diffraction efficiencies of DOE lens for various diffracted orders were calculated for red, green, and blue wavelengths. And then, a virtual resolution chart is generated to form an object and the output images through the imaging system were obtained by the CODE V^{TM} for each diffracted rays and for each red, green, and blue wavelengths. The final image is obtained by summation of all images obtained above weighted by their diffraction efficiencies. The performance of the lens module is estimated with the modulation transfer function (MTF) obtained by analyzing the final image of the resolution chart. Optimum thickness of DOE and fabrication tolerance limit are determined by analyzing the MTF. Test image shows that this method can be effectively applied to the image evaluation of DOE-based optical imaging systems.

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