Design optimization of highly efficient spectrum-splitting and beam-concentrating diffractive optical element for lateral multijunction solar cells*

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Two improved algorithms are proposed to extend a diffractive optical element (DOE) to work under the broad spectrum of sunlight. An optimum design has been found for the DOE, with a weighted average optical efficiency of about 6.8% better than that of the previous design. The optimization of designing high optical efficiency DOEs will pave the way for future designs of high-efficiency, low-cost lateral multijunction solar cells based on such a DOE.

Keywords: thickness optimization, solar cell, split, concentration, diffractive optical element

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1. Introduction

Today's solar cell market has revealed an urgent need for cost effective solar cells. Increasing the photovoltaic efficiency and decreasing the cost are the two ways to meet the demand. Tandem multijunction solar cells have been proven to be an effective way to increase photovoltaic efficiency[1–6] through absorbing different spectral bands of sunlight with different solar cells. Based on the same principle, photovoltaic efficiency can also be promoted by integrating solar cells with a spectrum-splitting optical element, such as a dichroic mirror.[4,6,7] In addition, concentration is applied to decrease the cost by dramatically reducing the area of solar cells needed for absorption. In order to realize spectrum splitting and beam concentrating simultaneously, holographic systems have been proposed by researchers.[7–10] A holographic element is implemented by recording the interference pattern of laser beams. However, high diffractive efficiency over wide spectral regions is hard to achieve, and doubly exposed holograms for extending the band width limit, the effectiveness and replication of the devices.[7–11] A single prismatic structure that splits and concentrates light based on the dispersive behavior of the employed material has been proposed.[11] However, its performance relies heavily on the dispersive nature of the material, which may result in non-uniform wavelengths spreading on the output plane. For example, the refractive index of fused silica, widely used in optics, changes from 1.494 at wavelength 280 nm to 1.456 at wavelength 600 nm, but at wavelength 1500 nm it changes only slightly to 1.445. In our previous work we proposed a thin planar diffractive optical element (DOE) that increases the photovoltaic efficiency by splitting sunlight and decreases the cost by concentration, and we developed a thickness optimization algorithm to design such a DOE for lateral multijunction solar cells.[12,13] The design and testing of DOE were mainly restricted to several wavelengths in the visible region, while the entire visible region accounts for only about 50% of the energy of sunlight. In order to realize the application of DOEs in solar cells systems, the design of DOEs to operate under a continuous spectrum of sunlight has to be discussed and the algorithm has to be improved.

In this paper, we propose two new thickness optimization algorithms in Section 2. In Section 3, the influence of algorithms and design parameters on the optical efficiencies of the DOE under sunlight are discussed. The prospect of integrating DOEs and solar cells is also presented. Section 4 concludes the paper.

2. Design of a thin spectrum-splitting and beam concentrating DOE with thickness optimization algorithms

2.1. Initial thickness optimization algorithm

In our previous work,[13] a thickness distribution was proposed to describe the surface-relief structure of a DOE that can implement the functions of spectrum splitting and beam con-

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centrating simultaneously:

$$h_0(x_1) = \frac{x_{1\mathrm{m}}^2/4 - x_1^2}{2(n-1)f} + \mathrm{mod}\left[\left(x_1 + \frac{x_{1\mathrm{m}}}{2}\right)\tan(\beta), \frac{\lambda_0}{n-1}\right], \quad (1)$$

where the first term describes a focus lens with focal length f, and the second term describes a blazed grating which diffracts nearly all the energy of wavelength λ_0 to its first diffraction order; $x_{1\mathrm{m}}$ is the size of the DOE in the X direction, x_1 is a coordinate which ranges from $-x_{1\mathrm{m}}/2$ to $x_{1\mathrm{m}}/2$ with $x_1 = 0$ at the center of the DOE, n is the refractive index of the DOE, whose dispersive effect is ignored, f is the focal length of the lens, λ_0 is a chosen parameter for the central wavelength, β is the blazed angle of the refractive blazed grating, and d is the grating period which equals $\lambda_0 \cot(\beta)$; $\mathrm{mod}\,[a,b]$ is the modulus function and its value lies between 0 and b for any positive real numbers a and b.

In most cases, the DOE is too thick to be fabricated with modern photolithography technology, thus the thickness of the DOE should be confined in a reasonable range. It is well known in physical optics that adding or removing the 2π phase does not change the performance of the optical element. As a result, the DOE may be attenuated to a much thinner one by removing several 2π phases. An equivalent thickness $h_i = h_i(x_1, \lambda_i)$ for wavelength λ_i is therefore given by

$$h_i = \mathrm{mod}\,[h_0(x_1), \Delta h_i], \quad (2)$$

where $h_i = \lambda_i/(n-1)$ corresponds to a phase change of 2π for wavelength λ_i ($i = 1,2,3,\ldots,N$). According to Eq. (2), N equivalent thicknesses can be obtained for N waves, respectively. For the solar cells where the incident sunlight contains multiple wavelengths, we have to design a DOE to meet the requirement of multiple wavelengths. In our previous work we proposed a thickness optimization algorithm to design such a DOE.[12,13] The main idea of that algorithm is to choose several typical wavelengths from the wide spectrum of sunlight and find a common thickness from their equivalent thicknesses $h_{\mathrm{e}i}$, which is given by

$$h_{\mathrm{e}i} = h_i + m\Delta h_i, \quad m = 0,1,2,\ldots. \quad (3)$$

All $h_{\mathrm{e}i}$ are restricted to a finite thickness $h_{\max}$, which is determined by the lithographic technology. If not specified particularly, $h_{\max} = 9\lambda_0/(n-1)$ is selected in this paper, where $\lambda_0 = 0.60$ μm and $h_{\max}$ correspond to a maximum phase modulation of 18π for λ_0. The common thickness $h_{\mathrm{c}1}$ is defined as the mean value of the equivalent thicknesses, namely

$$h_{\mathrm{c}1} = \frac{1}{N}\sum h_{\mathrm{e}i}, \quad (4)$$

where $h_{\mathrm{e}i}$ is the definite thickness for wavelength λ_i that minimizes the error function, and is defined as

$$\Delta = \sum_i \sum_{j\neq i} \left|h_{\mathrm{e}i} - h_{\mathrm{e}j}\right|. \quad (5)$$

Consequently, the field distribution on the input plane (P_1) $U_1(x_1, y_1, \lambda_i)$ is given by

$$U_1(x_1,y_1,\lambda_i) = \rho_1(x_1,y_1,\lambda_i)\exp[\mathrm{i}k\cdot(n-1)\cdot h(x_1,y_1)], \quad (6)$$

where $k = 2\pi/\lambda_i$ is the wave vector, $\rho_1(x_1, y_1, \lambda_i)$ is the amplitude of the input light of wavelength λ_i, and $h(x_1, y_1) = h_{\mathrm{c}1}$ is the common thickness specified by Eq. (4). The intensity $|\rho_1(x_1,y_1,\lambda_i)|^2$ could be an energy flux or a photon flux. If we consider the incidence of uniformly distributed sunlight on the input plane (P_1), $\rho_1(x_1, y_1, \lambda_i)$ is simplified as $\rho_1(\lambda_i)$. The field distribution $U_2(x_2,y_2,\lambda_i)$ on the output plane (P_2) can be calculated by[14]

$$U_2(x_2,y_2,\lambda_i) = \int_{-x_{1\mathrm{m}}/2}^{x_{1\mathrm{m}}/2}\int_{-y_{1\mathrm{m}}/2}^{y_{1\mathrm{m}}/2} G(x_1,y_1;x_2,y_2;f,\lambda_i) \times U_1(x_1,y_1,\lambda_i)\,\mathrm{d}x_1\,\mathrm{d}y_1, \quad (7)$$

where $G(x_1,y_1;x_2,y_2;f,\lambda_i)$ is the well-known transform kernel of light travelling in free space. In the Fresnel diffraction system where paraxial approximation is applied, it has the form[15]

$$G(x_1,y_1;x_2,y_2;f,\lambda_i) = \frac{-\mathrm{i}}{\lambda_i f}\exp(\mathrm{i}kf)\exp\left\{\frac{\mathrm{i}k}{2f}\left[(x_1-x_2)^2 + (y_1-y_2)^2\right]\right\}. \quad (8)$$

The intensity $I_2(x_2,y_2,\lambda_i) = |U_2(x_2,y_2,\lambda_i)|^2$ is calculated accordingly. To evaluate the concentration performance of the DOE for wavelength λ_i, an optical efficiency function $\eta(\lambda_i)$ is defined as

$$\eta(\lambda_i) = \frac{\int_{x_{2\mathrm{f}}-w/2}^{x_{2\mathrm{f}}+w/2} |U_2(x_2,\lambda_i)|^2\,\mathrm{d}x_2}{\int |U_1(x_1,\lambda_i)|^2\,\mathrm{d}x_1} \times 100\%, \quad (9)$$

where $x_{2\mathrm{f}}$ represents the focal position for wavelength λ_i on P_2 and $w/2$ is the half width of the focal region. The optical efficiency $\eta(\lambda_i)$ represents the percent of energy in the given region $[x_{2\mathrm{f}} - w/2, x_{2\mathrm{f}} + w/2]$ on P_2 compared to the total energy which impinges upon the DOE at wavelength λ_i; $x_{2\mathrm{f}}$ has the form

$$x_{2\mathrm{f}} = -f\cdot\tan\left\{\arcsin\left[\frac{\lambda_i}{\lambda_0}(n-1)\tan(\beta)\right]\right\}. \quad (10)$$

2.2. Improved thickness optimization algorithm

By using several wavelengths as design parameters, an efficient spectrum-splitting and beam-concentrating DOE that works for the broad spectrum was implemented. However, only three wavelengths in the visible region ($\lambda_i = 450$ nm, 550 nm, 650 nm) were used as the design parameters in the aforementioned thickness optimization algorithm in our previous work. A systematic study of the choice of design wavelengths and thickness optimization algorithm was needed to

obtain a possibly better result. In this section, we discuss two improved algorithms based on analyses of basic principles of physics and mathematics.

If we suppose a small variation of thickness in Eq. (6), for instance, a same deviation of δh at all sampling points, the change of the complex amplitude is $\delta U_2 = U_2 \times [\pi(n-1)\delta h/\lambda] = U_2 \times \delta\phi$. The equation shows that a given variation of thickness causes different variations of the complex amplitude for different wavelengths, i.e., shorter wavelengths will have larger changes. Therefore, in applying thickness optimization to acquire a common thickness from several equivalent thicknesses, we propose another error function

$$\Delta_2 = \sum_i (\Delta\phi_i)^2 = \sum_i \left[\frac{2\pi(n-1)}{\lambda_i}\right]^2 (h_i - h)^2, \qquad (11)$$

thus changing the problem into finding an appropriate h to minimize Δ_2. Solving $\partial\Delta_2/\partial h = 0$ provides us with the following expression for common thickness h (rewritten as h_{c2})

$$h_{c2} = \frac{\sum_i h_i/\lambda_i^2}{\sum_i 1/\lambda_i^2}. \qquad (12)$$

It should be noted that the energy distribution of sunlight is not uniform at different wavelengths, thus the total optical efficiency should be an averaged one where the weighting factor of the energy distribution is considered. The total optical efficiency is thus defined as

$$\eta_{\text{total}} = \frac{\sum \eta(\lambda_i) f(\lambda_i)}{\sum f(\lambda_i)}, \qquad (13)$$

where $f(\lambda_i)$ is the energy flux at wavelength λ_i, and experimental data of AM1.5G spectrum is adopted in this paper.[16] Further improvement can be made by assuming a special case, that $f(\lambda_1) = 1$ and $f(\lambda_2) = 0.01$. It is obvious that the optical efficiency $\eta(\lambda_2)$ contributes much less to η_{total} compared to $\eta(\lambda_1)$. As a result, the weighting factor $f(\lambda_i)$ should also be added in the thickness optimization algorithm. In other words, equations (11) and (12) become

$$\Delta_3 = \sum_i f(\lambda_i)(\Delta\phi_i)^2 = \sum_i f(\lambda_i)\left[\frac{2\pi(n-1)}{\lambda_i}\right]^2 (h_i - h)^2, \qquad (14)$$

and the common thickness h is written as

$$h_{c3} = \frac{\sum_i f(\lambda_i) h_i/\lambda_i^2}{\sum_i f(\lambda_i)/\lambda_i^2}. \qquad (15)$$

3. Results and discussion

3.1. Comparison of the three algorithms

The following parameters are used in this paper: $\beta = \pi/160$ radian, $\lambda = 0.6$ μm, $f = 80.0$ cm, $n = 1.46$ (fused silica whose dispersive effect is ignored), $x_{1m} = 22.17$ mm, and the default max phase is 18π, which corresponds to phase modulation of the DOE for wavelength λ (i.e. max phase $= 2\pi(n-1)h_{\max}/\lambda$); $N = 3$; and wavelengths $\lambda_i = 450$, 650, 850 nm were selected as the parameters to design the DOE. Wavelengths in the first column (Table 1) were chosen to evaluate the performance of the DOE for the broad spectrum of sunlight. The total optical efficiency η_{total} is defined as the weighted average of optical efficiencies of the wavelengths from 400 nm to 1300 nm, with an equal interval of 20 nm, as tabulated in Table 1. Symbols D1, D2, and D3 correspond to the different thickness optimization algorithms for minimizing Δ, Δ_2, and Δ_3, respectively, and 'original' represents the original thickness given by Eq. (1) (i.e. before applying the thickness optimization algorithm); $f(\lambda_i) = 1.5595$, 1.3594, and 0.8937 ($i = 1,2,3$) are used as weighting factors for wavelength λ_i ($i = 1,2,3$), which are extracted from the energy flux from AM1.5G spectrum.[16] The parameters used in our previous work[13] are $\lambda_i = 450$, 550, and 650 nm ($i = 1,2,3$) with the definition of D1, and that configuration is defined as D1_{ref} in this paper. Comparisons of the optical efficiencies for the three aforementioned definitions are presented in Table 1 in sequence. The following results are obtained: first, the total optical efficiency of D1_{ref} is smaller than D1, indicating that optimization of the design wavelengths is needed; second, the optical efficiencies for the design wavelengths ($\lambda_i = 450$, 650, 850 nm, $i = 1,2,3$) exhibit behavior as expected. D1 has sharply decreased optical efficiency for short wavelengths ($\lambda_1 = 450$ nm) compared to the 'original' one, D2 has optical efficiencies between D1 and D3 at the three wavelengths, and D3 has the largest optical efficiency at $\lambda_1 = 450$ nm, which has the biggest weighting factor, while λ_3, with the smallest weighting factor $f(\lambda_3)$, obtains the lowest optical efficiency among D1, D2, and D3. This result is closely related to the definition of D1, D2, and D3, which favors different wavelengths when trying to find a common thickness for each sample point. For example, under D1, long wavelengths are favored, so higher optical efficiency is obtained for $\lambda_i = 850$ nm. However, under the definitions of Δ_2 and Δ_3, total optical efficiencies are higher, indicating that the improvement of the algorithms is effective. Since η_{total} of Δ_2 is higher than Δ_3 and the equation of Δ_2 is simpler, we adopted Δ_2 for further analysis and calculation.

Table 1. Comparisons of the optical efficiencies resulting from thickness optimization algorithms.

Wavelength/nm	D1 $\eta(\lambda)/\%$	D2 $\eta(\lambda)/\%$	D3 $\eta(\lambda)/\%$	Original $\eta(\lambda)/\%$	D1_{ref} $\eta(\lambda)/\%$
450	57.19	63.17	63.60	64.86	–
650	92.00	88.89	88.43	94.29	–
850	67.70	63.83	62.54	72.07	–
η_{total} (%)	57.03	58.38	58.36	76.19	54.16

3.2. Investigation of design wavelengths to design the DOE

As can be seen from Table 1, D1 has an optical efficiency 3% higher than that of $D1_{ref}$, indicating that the selected design wavelengths influence the optical efficiency of the DOE. There are three factors of the design wavelengths: first, the number of design wavelengths; second, the coverage range of the design wavelengths; third, the intervals between the design wavelengths. We will study the influence of the three factors on the optical efficiencies in sequence in the following part. First, we use a different number of wavelengths ($N = 3,4,5,6,7,8$) to design parameters to design the DOE, and the results are listed in Table 2. MP stands for minimal phase algorithm defined by Δ_2, and MPN5 stands for the minimum phase algorithms defined by Δ_2 with 5 design wavelengths. It is seen from Table 2 that MPN5 yields the highest total optical efficiency among all these configurations, and using more wavelengths to design the DOE does not lead to a higher total optical efficiency; secondly, $N = 5$ is used to study the second factor. The 5 design wavelengths are evenly distributed in the range between 450 nm and λ_{max}, where λ_{max} varies from 650 nm to 1150 nm. Table 3 lists the detailed configurations and their optical efficiencies. Table 3 shows that a larger wavelength does unnecessarily yield a higher total optical efficiency, and the configuration MPN5c has the highest total optical efficiency. The result may be related to the fact that long wavelengths account for a small part of the solar spectrum, while extending the range would thus lower the optical efficiencies for short wavelengths. Table 4 presents the results of increasing the number of design wavelengths and coverage range simultaneously. Still, MPN5c yields the highest optical efficiency. Figure 1 presents the light intensity distribution of the DOE designed by the MPN5c compared with that of previous work ($D1_{ref}$). Figure 2 shows the optical efficiencies of DOE designed by MPN5c and $D1_{ref}$. It is seen that wavelengths from 400 nm to 1300 nm are better split and concentrated on P_2 and almost all the wavelengths have higher optical efficiencies (about $0 \sim 15\%$ higher) when DOE is designed by MPN5c compared to $D1_{ref}$. It should be noted that there are infinite combinations of design parameters and we have only discussed the aforementioned typical combinations. Nevertheless, through the improvement of the thickness optimization algorithm and optimization of design wavelengths, a DOE with a much better performance of sunlight splitting and concentrating has been obtained.

Table 2. Optical efficiencies of the DOE for different numbers of design wavelengths.

Symbols	N	λ_i (nm), $i = 1,2,\ldots,N$	$\eta_{total}/\%$
MPN3	3	450, 650, 850	58.38
MPN4	4	450, 583, 713, 850	60.78
MPN5	5	450, 550, 650, 750, 850	60.94
MPN6	6	450, 530, 610, 690, 770, 850	55.40
MPN7	7	450, 517, 583, 650, 717, 783, 850	58.42
MPN8	8	450, 507, 564, 621, 679, 736, 793, 850	57.77

Table 3. Optical efficiencies of the DOE for different intervals of design wavelengths.

Symbols	N	λ_i (nm), $i = 1,2,\ldots,N$	$\eta_{total}/\%$
MPN5a	5	450, 500, 550, 600, 650	57.06
MPN5b	5	450, 525, 600, 675, 750	58.02
MPN5c	5	450, 550, 650, 750, 850	60.94
MPN5d	5	450, 575, 700, 825, 950	59.01
MPN5e	5	450, 600, 750, 900, 1050	59.28
MPN5f	5	450, 625, 800, 975, 1150	58.96

Table 4. Optical efficiencies of the DOE when enlarging the number of design wavelengths and keeping the intervals of design wavelengths.

Symbols	N	λ_i (nm), $i = 1,2,\ldots,N$	$\eta_{total}/\%$
MPN5c	5	450, 550, 650, 750, 850	60.94
MPN6c	6	450, 550, 650, 750, 850, 950	56.88
MPN7c	7	450, 550, 650, 750, 850, 950, 1050	58.79
MPN8c	8	450, 550, 650, 750, 850, 950, 1050, 1150	58.56

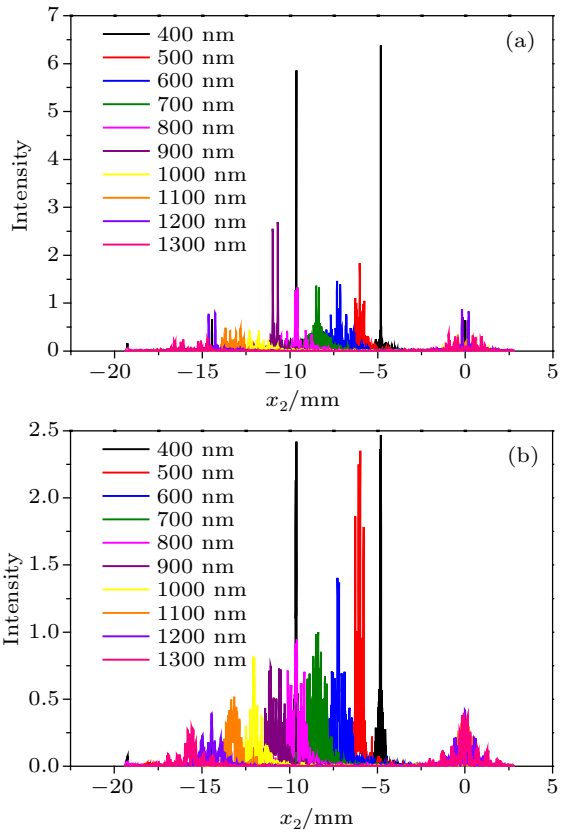


Fig. 1. (color online) Comparisons of intensity distribution on P_2 when the DOE is designed under different configurations (a) $D1_{ref}$ and (b) MPN5c.

Further improvement of the optical efficiency can be realized by increasing h_{max}, i.e., the maximum phase. Figure 3 presents the optical efficiencies under different maximum phases. It is seen that efficiencies with a maximum phase of 50π ($h_{max} = 32.61$ μm) are already close to those of the original, where the DOE with a thickness of 169.57 μm is relatively difficult to fabricate with today's lithographic technology. Figure 4 presents the intensity distribution of the DOE designed with MPN5c with a maximum phase of 50π, where

different wavelengths are well split. Though optical efficiencies of long wavelengths are not high enough near x_{foc} (Fig. 3), calculations show that the other energy mostly lies in the region near $x_2 = 0$, and the sum of optical efficiencies in these two regions is about 90%. Therefore, if we laterally place solar cells with different band gaps in the region where waves are well split and put an appropriate solar cell in the region near $x_2 = 0$, the incident energy can be efficiently utilized, and a high photovoltaic efficiency of such a kind of lateral multi-junction solar cells can be expected.

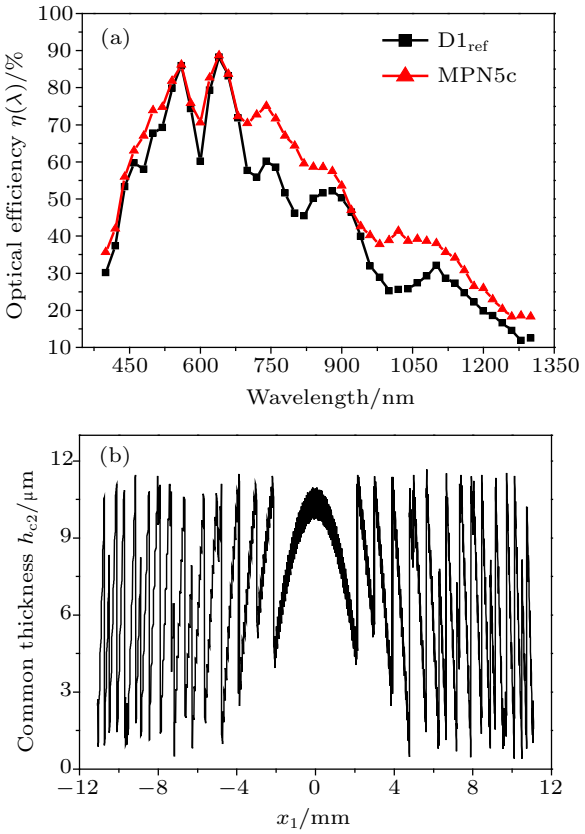


Fig. 2. (color online) (a) Comparison of optical efficiencies when the DOE is designed under different configurations. (b) Thickness distribution of DOE designed with configuration MPN5c.

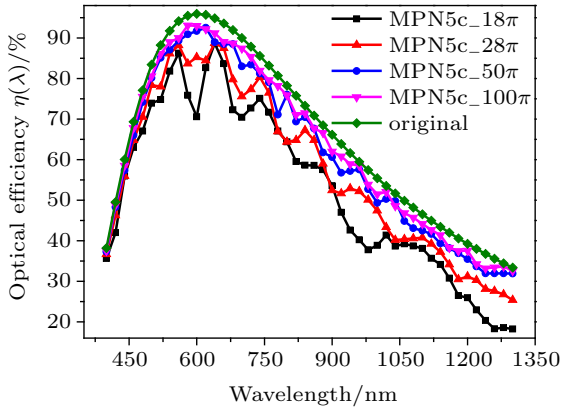


Fig. 3. (color online) Optical efficiency comparison of DOEs designed with MPN5c for different maximum phases.

In our present work, reflection loss is neglected since an antireflection layer can be employed to reduce reflection loss to almost zero.

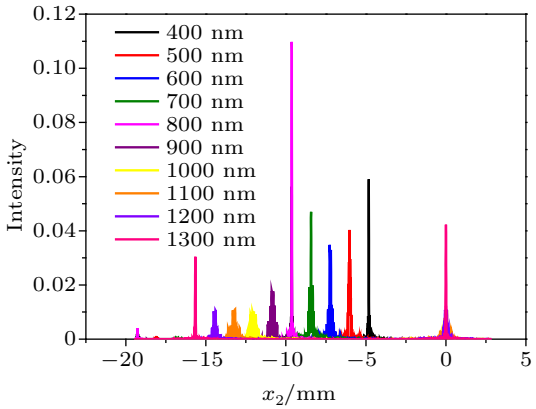


Fig. 4. (color online) Intensity distribution of DOEs designed by MPN5c with a maximum phase of 50π.

4. Conclusions

By improving the algorithms and optimizing the design parameters, better spectrum-splitting and beam-concentrating performance of the DOE has been achieved across the full spectrum of sunlight. Optical efficiencies are increased by $0 \sim 15\%$ across the full spectrum, and the total optical efficiency is increased about 6.8% compared with the previously designed DOE, under the same limit of maximum thickness.[13] Calculations also show that increasing thickness yields a higher optical efficiency. Since optical efficiency directly affects the overall photovoltaic efficiency, the improvement of optical efficiency is fairly helpful and will provide a basis for future work.

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