Wavelength-multiplexing diffractive phase elements: design, fabrication, and performance evaluation

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We report on the wavelength-multiplexing diffractive phase element (WMDPE) capable of generating independent spot patterns for different wavelengths. The iterative method proposed by Bengtsson [Appl. Opt. **37**, 1998] for designing a kinoform that produces different patterns for two wavelengths is extended to the WMDPE for multiple wavelengths (more than two wavelengths). Effectiveness of the design algorithm is verified by design and computer simulations on the WMDPE's for four and nine wavelengths. The WMDPE for three wavelengths (441.6, 543.5, and 633 nm) is designed with five phase levels and is fabricated by electron-beam lithography. We observed that the individual spot patterns are reconstructed for the design wavelengths correctly. Performance of the WMDPE is evaluated by computer simulations on the uniformity error, the light efficiency, and the contrast. On the basis of the results, the characteristics of the WMDPE's are discussed in terms of various conditions of fabrication and usage.

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1. INTRODUCTION

A diffractive phase element (DPE) is attractive for various optical applications because of its versatility in function and inherent compactness of form. Because of its flexibility in controlling the wave front of light, the DPE is useful in implementing various optical functions with a few elements that are otherwise impossible to implement or require complicated configuration. Some applications of the DPE are the microlens array,[1] the spot-array generator,[2] the beam-shaping element,[3] and the mode former.[4]

To obtain a specific functional DPE, the phase distribution for the function is calculated and fabricated as an optical element. The Gerchberg–Saxton algorithm[5] and the simulated annealing (SA) algorithm[6] are the most popular methods for designing the DPE. For example, these algorithms can be applied to a beam-shaping element[7] and a pattern-classification filter.[6] Microfabrication techniques such as lithography and etching processes enable us to make the optical elements that generate the phase distribution.

The DPE has the characteristics for large dispersion of a wavelength. This comes from the fact that the DPE utilizes the diffraction phenomenon to achieve functionalities. As a result, most of the DPE is specialized for a particular wavelength, and the phase distribution is optimized for the wavelength. Such a DPE does not guarantee the correct function for a wavelength different from the design one. However, if the characteristics of the dispersion are taken into account during the design, we can obtain a DPE for multiple wavelengths. A color-separation element[8] and an achromatic lens[9] are good examples of DPE's.

Wavelength multiplexing is an effective technique to increase information density for high-speed data communication. This technique is expected to be useful in various optical systems in the future. Thus it is important to develop an effective design method for the wavelength-multiplexing diffractive phase elements (WMDPE's) and to study their characteristics. The DPE that generates focus lines at different positions corresponding to wavelengths,[10] and a computer-generated hologram capable of delivering the diffracted light according to wavelengths[11] has already been presented. For the WMDPE, the design method is important because complicated and precise control of the phase distribution is required. The design method for the WMDPE requires high speed, stability, flexibility, high convergence for various target functions, performance uniformity for different wavelengths, and so on. The Gerchberg–Saxton and SA algorithms, which are useful in designing the DPE for a single wavelength, cannot be applied to the WMDPE directly. Yang *et al.*[12–14] and Bengtsson[15] have proposed design methods of the DPE for multiple wavelengths. However, the former requires a large amount of computation and does not take into account performance uniformity over wavelengths; the latter is specified for two wavelengths. Therefore a fast design algorithm is re-

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quired by which we can determine the phase distribution of the WMDPE with high-performance uniformity for multiple wavelengths.

In this paper, the WMDPE capable of generating individual spot patterns for multiple wavelengths is studied. An iterative algorithm based on the optimal rotation angle (ORA) method to design the WMDPE for two wavelengths by Bengtsson[15,16] is extended to the design for multiple wavelengths. The purposes of this study are (1) to investigate the extended design method of the WMDPE for multiple wavelengths, (2) to demonstrate the function of the WMDPE by optical experiments, and (3) to evaluate the performance of the WMDPE for various conditions by computer simulations. Effectiveness of the design method is verified by the WMDPE's for four and nine wavelengths. The WMDPE for three wavelengths is designed with five phase levels and is fabricated. The correct function of the WMDPE is demonstrated experimentally. Performance dependence of the WMDPE on the number of output spots and the number of multiplexed wavelengths is evaluated by the uniformity error, the light efficiency, and the contrast. Performance variations by the distance between the WMDPE and the output plane, the maximum phase modulation, and the wavelength resolutions under several conditions are also discussed.

2. DESIGN METHOD

Figure 1 shows the model assumed in the design procedure. The plane of the WMDPE is partitioned into rectangular pixels. The amplitude and the phase of the illuminating light at the pixel l on the WMDPE plane are assumed to be constant, and the central coordinate $(x_l, y_l, 0)$ is used to represent the pixel. The output spot m can be set at an arbitrary position (u_m, v_m, L) on the output plane. Wavelengths assigning to the output spots are expressed as $\lambda_A, \lambda_B, \lambda_C, \ldots$, which are called design wavelengths. The set of the spots assigned to a specific wavelength λ_X is expressed as M_X. In Fig. 1, L is the distance between the WMDPE and the output planes, which is called output distance; $\mathbf{k}$ is the wave vector of the light just behind the WMDPE ($|\mathbf{k}| \equiv k = 2\pi/\lambda$; λ is wavelength). Hereafter, the term "pixel" is used for the WMDPE, whereas "spot" is for the output.

The field amplitude of the light incident upon the pixel l is expressed as $U_{ol}[\equiv A_{ol}\exp(j\varphi_{ol})]$, and the field amplitude U_{lm} of the spot m coming from the pixel l is expressed as follows:

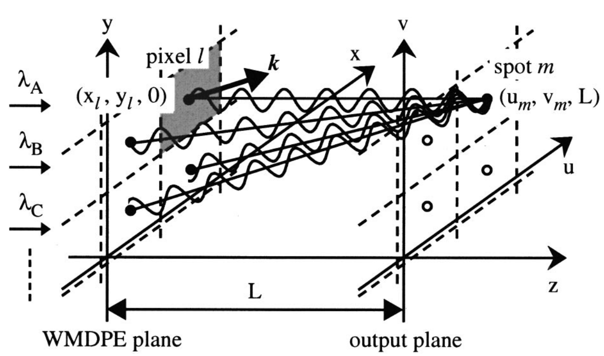

Fig. 1. Model of the WMDPE in design.

$$U_{lm} = U_{ol}\exp(j\Delta\varphi_l)A_{lm}\exp(j\varphi_{lm}), \quad (1)$$

where $\Delta\varphi_l$ is the phase modulation of the pixel l. $A_{lm}\exp(j\varphi_{lm})$ denotes the modification of the field amplitude of the light propagating from the pixel l to the spot m, which is called transfer function in this paper. By the Fresnel approximation, the transfer function is calculated by the following equation:

$$A_{lm}\exp(j\varphi_{lm}) = \frac{1}{\lambda L}\exp\left\{\frac{jk}{2L}[(u_m - x_l)^2 + (v_m - y_l)^2]\right\}. \quad (2)$$

We extend the ORA method proposed by Bengtsson[15,16] to optimize the phase modulation of the pixels for multiple wavelengths. The transfer function for a design wavelength is calculated by Eq. (2). The phase modulation for λ_A is described as $\Delta\varphi_l^{(A)}$, which can be treated as an independent variable. Then the phase modulation for the other wavelength $\lambda_Y (Y = B, C, \ldots)$, $\Delta\varphi_l^{(Y)}$, is expressed as follows:

$$\Delta\varphi_l^{(Y)} = \frac{\lambda_A}{\lambda_Y}\Delta\varphi_l^{(A)}. \quad (3)$$

The field amplitude U_m at the spot $m (m \in M_A)$ is expressed by superposition of the light propagating from all the pixels.

$$U_m \equiv A_m\exp(j\varphi_m) = \sum_l U_{lm} = \sum_l A_{ol}A_{lm}\exp(j\varphi_{lm})\exp\{j[\varphi_{ol} + \Delta\varphi_l^{(A)}]\}. \quad (4)$$

When $\Delta\varphi_l^{(A)}$ is changed into $\Delta\varphi_l^{(A)} + \delta\varphi_l^{(A)}$, the difference of $|U_m|$ is expressed as ΔU_m. The condition $|U_m| \gg |U_{lm}|$ is satisfied for each spot, so that

$$\Delta U_m \cong A_{lm}\cos[\phi_{lm} - \delta\varphi_l^{(A)}] - A_{lm}\cos\phi_{lm}, \quad (5)$$

where

$$\phi_{lm} = \varphi_m - [\varphi_{lm} + \varphi_{ol} + \Delta\varphi_l^{(A)}]. \quad (6)$$

This difference occurs not only at the spot m but also at all the spots corresponding to the design wavelengths.

Let us consider summation of ΔU_m for all the spots by introducing two weight factors. The first is the weight factor w_m to control the intensity ratio among all the spots $m \in M_X$ for a specific wavelength λ_X, and the second is W_X to control the ratio of the total spot power among all the design wavelengths. These factors work to decrease the intensity of the spots brighter than the others and to increase that of the darker spots. Summation of ΔU_m, including the two weight factors, $f[\delta\varphi_l^{(A)}]$, is expressed as follows:

$$f[\delta\varphi_l^{(A)}] = \sum_X W_X S_X \cos\left[\frac{\lambda_A}{\lambda_X}\delta\varphi_l^{(A)} - \alpha_l^{(X)}\right] + \text{const.}, \quad (7)$$

where

$$S_X = \mathrm{sgn}(S_{1X})\,(S_{1X}^2 + S_{2X}^2)^{1/2},$$

$$S_{1X} = \sum_{m \in M_X} w_m A_{lm} \cos \phi_{lm},$$

$$S_{2X} = \sum_{m \in M_X} w_m A_{lm} \sin \phi_{lm},$$

$$\alpha_l^{(X)} = \arctan\left(\frac{S_{2X}}{S_{1X}}\right), \tag{8}$$

where sgn(x) is the signum function for a variable x. By updating $\Delta\varphi_l^{(A)}$ with the value $\delta\varphi_l^{(A)}$, which maximizes $f[\delta\varphi_l^{(A)}]$, the total light power of all the spots can be increased by suppressing intensity variations among the spots. This procedure is applied to each pixel sequentially.

After computation for all the pixels, the obtained phase modulations are substituted into Eq. (4) to calculate U_m. On the basis of the results, w_m and W_Y are updated according to the following expressions:

$$w_m = w_m^{\mathrm{old}}\left(\frac{I_X^{\mathrm{ave}}}{I_m}\right)^p,$$

$$W_A = 1,$$

$$W_Y = W_Y^{\mathrm{old}}\left(\frac{I_A^{\mathrm{ave}}}{\beta_Y I_Y^{\mathrm{ave}}}\right)^q, \tag{9}$$

where w_m^{old} and W_Y^{old} are the weight factors of the last iteration, $I_m (= |U_m|^2)$ is the intensity of the spot m, I_X^{ave} is the average of the intensity of all the spots for wavelength λ_X, and β_Y is the compensating parameter to equalize the spot powers for the wavelengths of λ_A and λ_Y. The exponents p and q are both set to 0.2 experimentally. In the calculation of w_m, the reference intensity I_X^{ave} to the intensity I_m of each spot for a specific wavelength λ_X is updated in each iteration. This makes it possible to find w_m by adjusting to the intermediate results so that the intensity variation among the spots $m \in M_X$ is suppressed effectively. Also in the calculation of W_Y, the reference averaged intensity I_A^{ave} to the averaged intensity I_Y^{ave} for wavelength λ_Y is updated in each iteration. As a result, the difference of light efficiencies for all design wavelengths can be reduced in the progress of the iteration.

In this paper, the target pattern is assumed to be composed of multiple spots with equivalent intensity. Note that the spot diameter obtained at the output plane is in proportion to the wavelength because of diffraction. Therefore we set

$$\beta_X = (\lambda_X/\lambda_A)^2. \tag{10}$$

With use of β_X, the total power of the all spots for each wavelength can almost be equalized. The initial values for the designs in this study are

$$\Delta\varphi_l^{(A)} = \forall \gamma \in \Gamma,$$

$$(\Gamma = \{\gamma | 0 \leqslant \gamma \leqslant (\text{maximum phase modulation})\}),$$

$$w_m = 1,$$

$$W_X = 1. \tag{11}$$

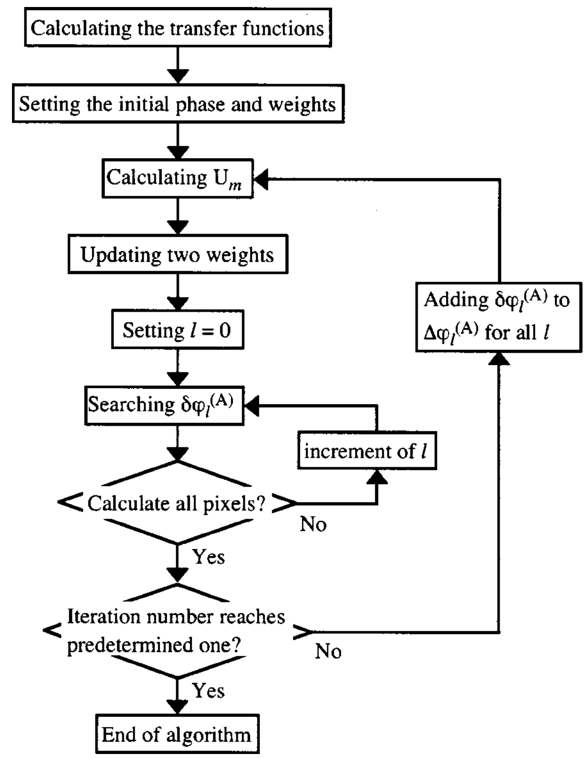

Fig. 2. Flowchart of design algorithm.

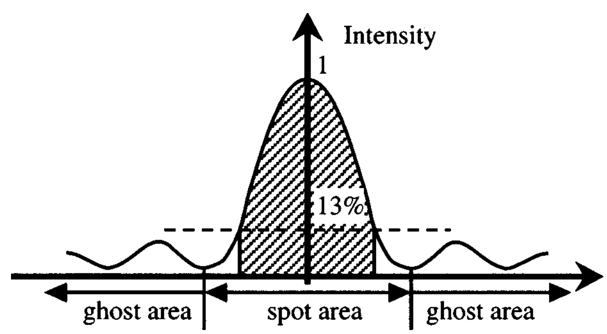

Fig. 3. Definition of the areas of spot and ghost.

The flowchart of the design algorithm is shown in Fig. 2. According to the algorithm, the phase modulation of the WMDPE that generates the target spot patterns for the design wavelengths is obtained. A preliminary experiment shows that the algorithm almost converges within 30 iterations; thus we execute 40 iterations in the design, to add a safety margin. The light incident to the WMDPE is assumed as a unit-amplitude normal plane wave.

Performance of the designed WMDPE is evaluated by the uniformity error, the light efficiency, and the contrast. These performance measures are defined as follows:

Uniformity error. The uniformity error is defined as Eq. (12) to evaluate uniformity over the intensities of all the spots for a specific wavelength λ_X. If this value is small, variation of the spot intensities is small for the wavelength.

$$\text{Unif. Err.} = \frac{\max_{\lambda_X}(I_m) - \min_{\lambda_X}(I_m)}{\max_{\lambda_X}(I_m) + \min_{\lambda_X}(I_m)}, \qquad (12)$$

where $\max_{\lambda_X}(I_m)$ and $\min_{\lambda_X}(I_m)$ denote the maximum and the minimum spot intensities for λ_X, respectively.

Light efficiency. The light efficiency is defined as the following expression, which evaluates light efficiency for a specific wavelength:

$$\text{Light. Eff.} = \frac{\text{(summation of power within all spots for one wavelength)}}{\text{(total power of illuminating light for one wavelength)}}. \qquad (13)$$

The power of the spot is defined as the intensity integrated over the area whose intensity is larger than $13\% (\cong 1/e^2)$ of the peak intensity around the spot (shaded area in Fig. 3).

Contrast. The contrast is defined as the following expression, which shows the contrast of the output spot-array pattern:

$$\text{Contrast} = \frac{\min_{\lambda_X}(I_m) - \max_{\lambda_X}(I^{\text{ghost}})}{\min_{\lambda_X}(I_m) + \max_{\lambda_X}(I^{\text{ghost}})}, \qquad (14)$$

where $\max_{\lambda_X}(I^{\text{ghost}})$ denotes the maximum intensity of the ghost of the output pattern for the wavelength λ_X. The ghost is defined as the pattern that appeared outside the spot area, as shown in Fig. 3.

3. DESIGN EXAMPLES OF THE WAVELENGTH-MULTIPLEXING DIFFRACTIVE PHASE ELEMENTS

Two kinds of the WMDPE's for multiple wavelengths (more than two wavelengths) are presented here and are designed by the method described in Section 2. To demonstrate capability for a large number of wavelength multiplexing, the WMDPE for nine wavelengths [identification number 1 (#1)] is designed. To investigate the effect of the distance to the output plane, the WMDPE for four wavelengths [identification number 2 (#2)] is studied. The parameters used in these designs are summarized in Table 1.

First we describe the design of the WMDPE #1. The design wavelengths are determined by the following rule:

$$\frac{1}{\lambda_A} - \frac{1}{\lambda_B} = \frac{1}{\lambda_B} - \frac{1}{\lambda_C} = \cdots, \qquad (15)$$

where $\lambda_X (X = A, B, \ldots)$ is ordered in wavelength. The target spot patterns of the WMDPE for the individual wavelengths are the composing letters of "OSAKA UNIV." Each letter is placed inside a rectangle area $0.4\,\text{mm} \times 0.6\,\text{mm}$ on the output plane. The distribution of the phase modulation and the calculated output patterns of the designed WMDPE are shown in Fig. 4. The output patterns are normalized by the maximum intensity among the spots for all wavelengths. These results show that the target patterns are obtained in the output plane with little ghost pattern. Dependences of the peak intensity and the area on the parameter β_X are shown in Fig. 5 for the maximum-intensity spot for the given β_X. Note that if we specify the base wavelength λ_A, β_X corresponds to a wavelength as seen from Eq. (10). The base wavelength λ_A is set as the longest design wavelength 933 nm. The peak intensity and the spot area are normalized by these values for wavelength 400 nm and 933 nm, respectively. These results show that the peak intensity is in inverse proportion to β_X, and the spot area is in proportion to β_X. This property indicates that the power in the spots $m \in M_X$ for all wavelengths λ_X is balanced by the weight factor W_X in Eq. (7) and that stable performance for all design wavelengths is obtained.

The performance measures, i.e., the uniformity error, the light efficiency, and the contrast, of WMDPE #1 are listed in the first column of Table 2. In Table 2 the evaluated values are calculated by averaging over the all de-

Table 1. Parameters of the Designed WMDPE's

Parameters	Identification Number 1	2	3
Number of wavelengths	9	4	3
Output distance (cm)	10	5–20	20
Pixel number in WMDPE plane	256 × 256	256 × 256	512 × 512
Pixel pitch in WMDPE plane (μm)	10	10	10
Pixel number in output plane	101 × 101	65 × 65	129 × 129
Pixel pitch in output plane (μm)	20	20	40
Wavelength (nm)	400, 431, 467, 509, 560, 622, 700, 800, 933	500, 622, 700, 800	442, 543.5, 633
Maximum phase modulation	4π (for 933 nm)	2π (for 800 nm)	2π (for 633 nm)

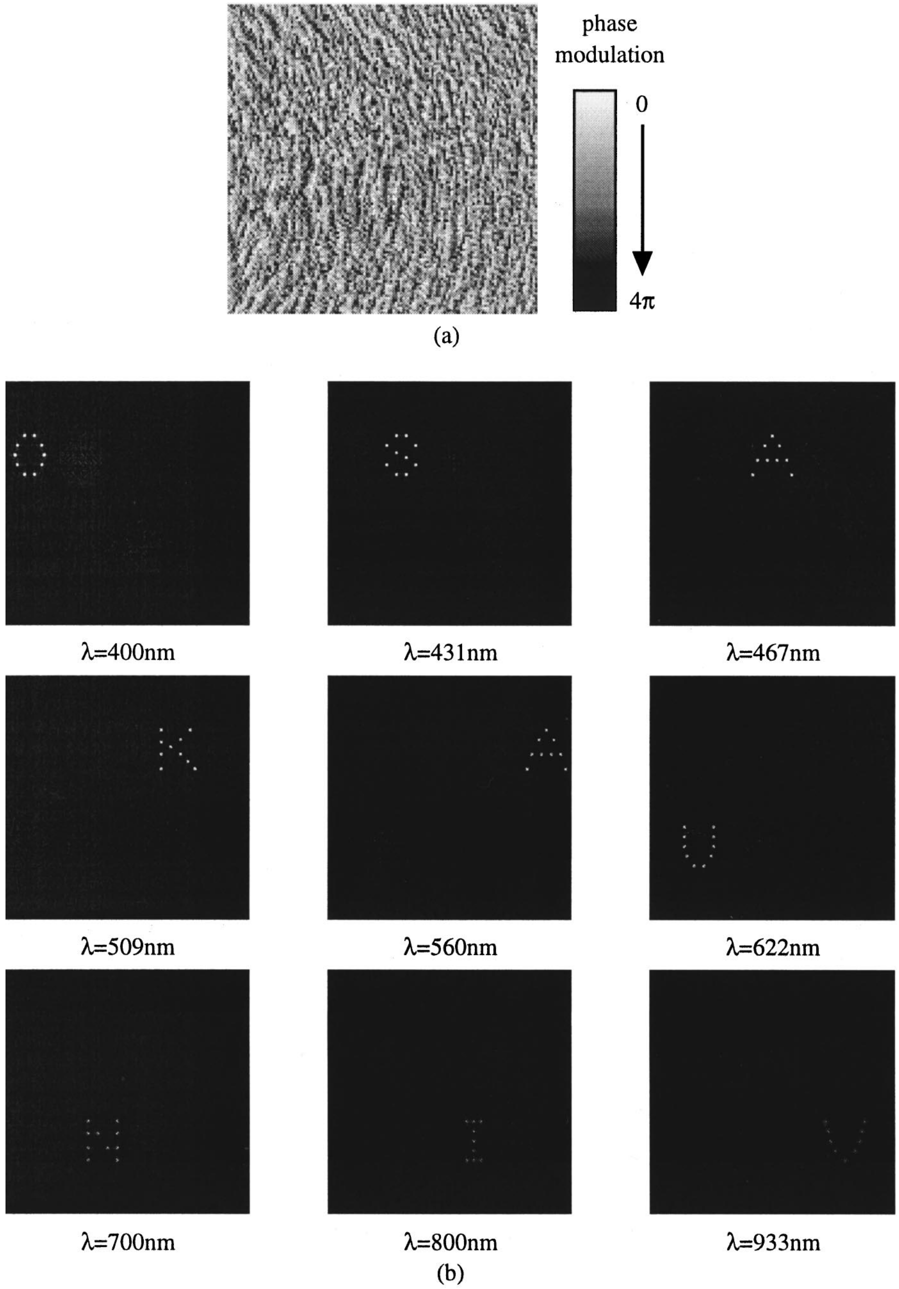

Fig. 4. Design results of the WMDPE for nine wavelengths; (a) distribution of phase modulation and (b) calculated output patterns.

sign wavelengths. A high-contrast value of about 0.8 is obtained, which shows that the designed WMDPE has good capability for separating the output spot patterns for nine wavelengths. The light efficiency is less than 20%, but this can be improved by increasing the maximum phase modulation of the WMDPE and the other conditions as shown in Section 5.

Next WMDPE #2, which generates spot patterns on the different output planes corresponding to four wavelengths, is designed. The target patterns are "5," "10," "15," and "20" on the output planes of 5, 10, 15, and 20 cm distance, respectively, from the WMDPE. The distribution of the phase modulation and the calculated output patterns of the designed WMDPE are shown in Fig. 6. The correct patterns are obtained on the different output planes corresponding to the wavelengths. The performance measures for WMDPE #2 are summarized in the second column of Table 2. Performance can be improved by optimizing the design parameters. Consequently, it is

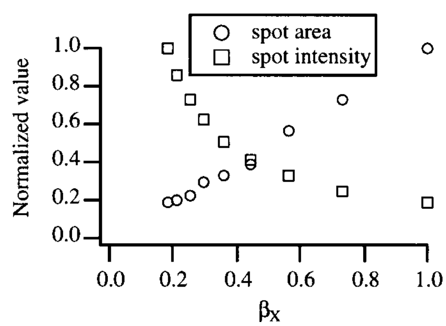

Fig. 5. Dependence of peak spot intensity and spot area on β_X.

Table 2. Performance Measures of the Designed WMDPE's

	Identification Number			
Performance Measures	1	2	3	3 (after quantization)
Uniformity error (%)	1.22	2.14	0.76	3.08
Light efficiency (%)	15.6	22.4	27.6	21.3
Contrast	0.784	0.754	0.958	0.938

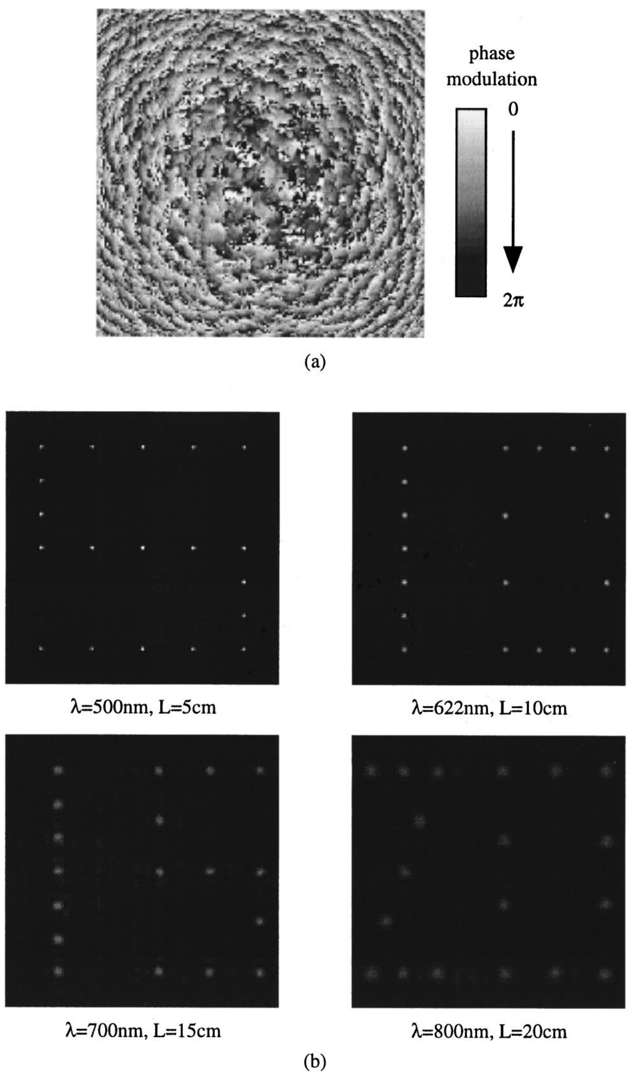

Fig. 6. Design results of the WMDPE for four wavelengths; (a) distribution of phase modulation and (b) calculated output patterns.

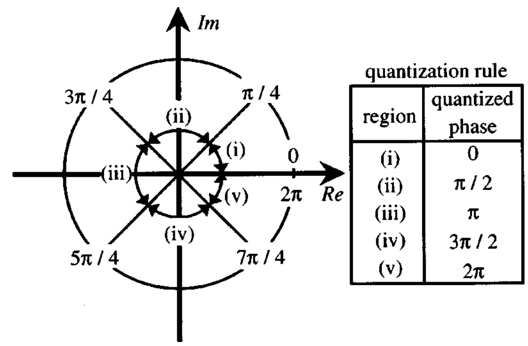

Fig. 7. Method of phase quantization.

confirmed that the WMDPE capable of generating individual patterns on the different planes corresponding to wavelengths can be obtained by the proposed method.

4. EXPERIMENTAL VERIFICATION OF THE FABRICATED WAVELENGTH-MULTIPLEXING DIFFRACTIVE PHASE ELEMENT

In this section, experimental results of the fabrication and the verification of the WMDPE are presented. The WMDPE for three wavelengths is fabricated in the experiment. The target pattern of the WMDPE is a flower composed of a blue stem (422 nm), green leaves (543.5 nm), and red petals (633 nm). The WMDPE is designed by the method described in Section 2. The parameters of the design and the performance measures of the WMDPE are shown in Tables 1 and 2 (ID #3), respectively.

So far we have not taken into account the fabrication error of the WMDPE. However, continuous phase level is difficult to fabricate, so the phase modulation values should be quantized. In our method, to suppress performance degradation by quantization, the number of the phase levels is assumed to be five. Figure 7 shows a diagram to explain the phase quantization. Phase belongs to any one of the domains (i)–(v). The phase quantization is achieved by approximating the phase value by any one of 0, $\pi/2$, π, $3\pi/2$, and 2π. Note that 0 and 2π are treated as different to reduce the quantization errors for different design wavelengths. Although the phase modulations of 0 and 2π are equivalent for a wavelength, these values cannot be identical for a different wavelength. For example, 2π phase modulation for wavelength 633 nm corresponds to $2\pi \times 633/442(\cong 3\pi)$ for wavelength 442 nm. If we take phase 0 instead of 2π, π of phase error occurs for wavelength 633 nm. To avoid such a situation, the phase modulations of 0 and 2π are treated as different values in our method.

Figure 8 shows the distribution of the quantized phase modulation of the designed WMDPE #3 and the calculated output patterns for three wavelengths. The performance measures are listed in the right-most column of Table 2. The uniformity error and the light efficiency are degraded by the quantization, whereas the contrast shows little changes. The quantization process can be included in the iteration of the phase-optimization procedure, which enables us to improve the performance of the WMDPE.

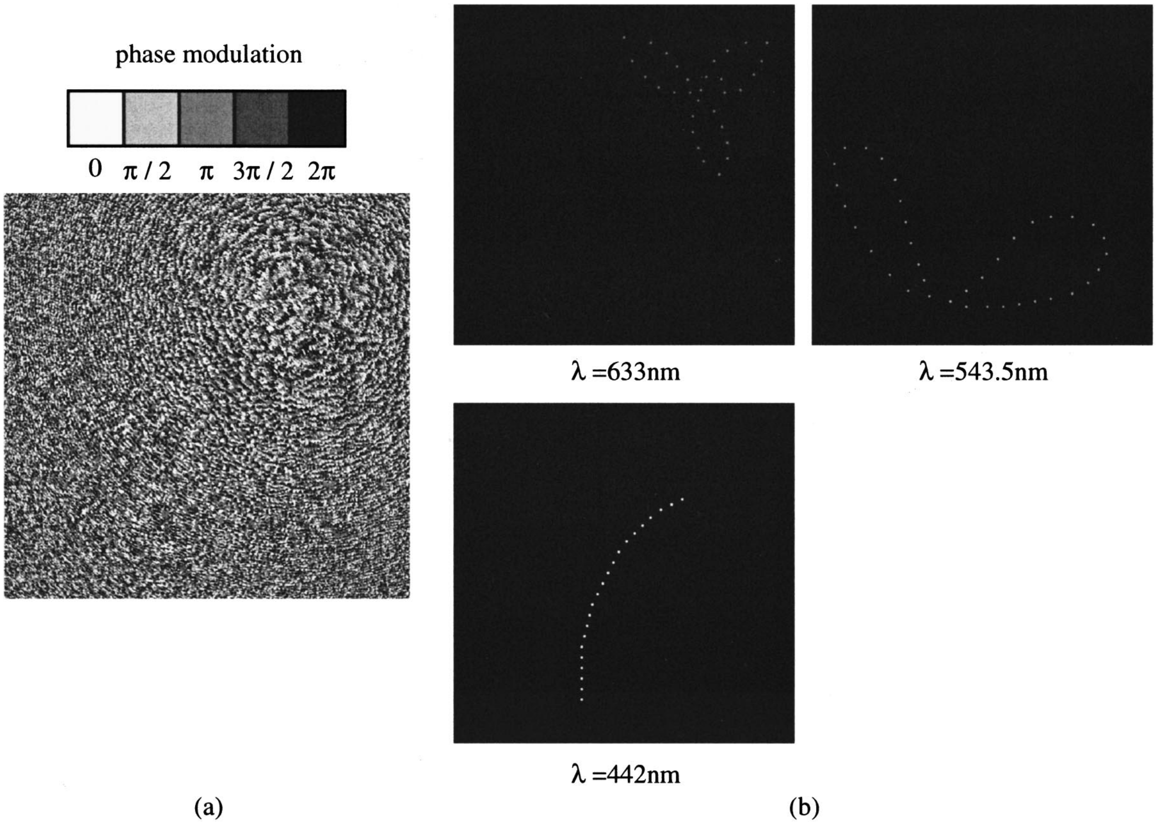

Fig. 8. Design results of the WMDPE for three wavelengths; (a) distribution of quantized phase modulation and (b) calculated output patterns for three wavelengths.

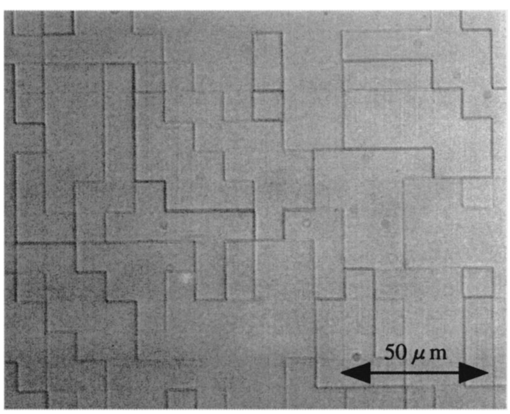

Fig. 9. Optical microscopic picture of the fabricated WMDPE.

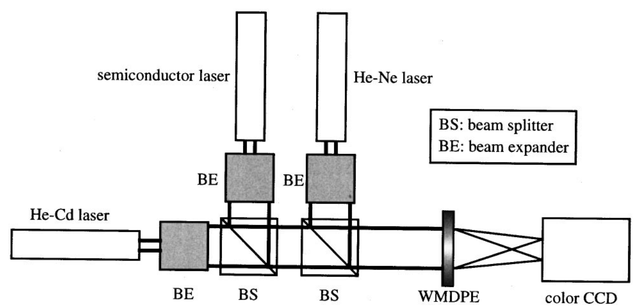

Fig. 10. Optical setup for observing output pattern of the fabricated WMDPE.

The WMDPE designed with five phase levels is fabricated by electron beam lithography. Electronic beam photoresist (OEBR-1000, Tokyo Ohka Kogyo Co., Ltd.) is spin coated on a glass substrate, and the pattern for phase modulation is drawn by an electron beam lithography system (JBX-5000SI, JEOL, Ltd.). The phase modulation is achieved by adjusting the dose amounts of the electron beam and controlling residual thickness of the photoresist on the substrate after development. The ideal differences in the thickness of the photoresist (the refractive index is 1.49) are 0, 323, 646, 969, and 1292 nm for five phase levels. An optical-microscopic picture of the fabricated WMDPE is shown in Fig. 9. Although a few errors caused by imperfect adjustment of the dose amounts exist in the relief height and the surface profile, an acceptable structure of the WMDPE is obtained.

Figure 10 shows the optical setup to verify the functions of the fabricated WMDPE. Three laser beams are incident on the WMDPE, and the output pattern is observed. The light sources are a red semiconductor laser (633 nm), a green He–Ne laser (543.5 nm), and a blue He–Cd laser (441.6 nm). These laser beams are aligned by the beam splitters and lead to the WMDPE. The pattern generated on the output plane is observed by a color CCD (AVC550, Toshiba). The distance between the WMDPE and the CCD is 20 cm, which is the design value of the WMDPE #3. The observed output pattern is shown in Fig. 11. This picture shows that the elemental patterns for different wavelengths are generated at the proper positions and that the whole target pattern is reconstructed correctly. In the experiment, the uniformity

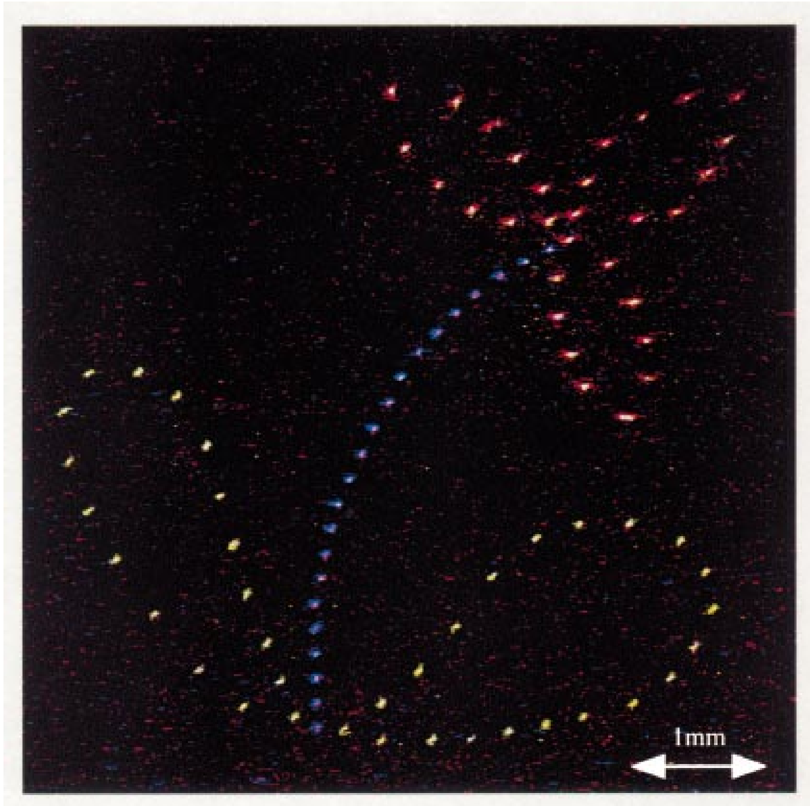

Fig. 11. Obtained output pattern in the experiment.

error is 15.1%, and the contrast is 0.442 as the averages of the three wavelengths. Although some differences are found between the simulation and the experiment, improvement of fabrication accuracy for thickness control of the photoresist and the surface profile is effective enough to solve the problem. As a notable result, we have confirmed that function of the WMDPE can be implemented correctly with a few phase levels.

5. EVALUATION OF THE PERFORMANCE OF THE WAVELENGTH-MULTIPLEXING DIFFRACTIVE PHASE ELEMENTS

Performance of the WMDPE is affected by various design conditions: those of system configuration, such as the number of the output spots and the multiplexed wavelengths; those of fabrication, such as the maximum phase modulation; and those of the device usage, such as the output distance. Thus performance variation of the WMDPE in various conditions is evaluated by computer simulations. The parameters used are summarized in Table 3. The evaluations are based on the uniformity error, the light efficiency, and the contrast defined in Section 2. In Figs. 12–16, the symbols denote the values for individual wavelengths, and the solid curves show the averaged values for all design wavelengths.

A. Spot Number

First we investigate dependence of performance on the number of the output spots. Five WMDPE's, which generate 16, 25, 36, 49, and 64 spots for each of four wavelengths (the total spot numbers are 64, 100, 144, 196, and 256, respectively) are designed and evaluated. The target patterns are spot arrays arranged in a rectangle. Dependence of the performance measures on the spot number is shown in Fig. 12. These results show that the light efficiency does not depend on the spot number and keeps almost constant and that the contrast decreases with increasing spot number. The reason is considered to be as follows: The absolute peak intensity of each spot goes down with increasing spot number because the incident light is divided into each spot. The ghost patterns show a tendency to broaden and the maximum ghost intensity decreases, but this does not affect more than the spot case. Therefore the intensity of the spot relative to the ghost patterns decreases. The uniformity error generally increases with increasing spot number. The reason is that the power to equalize the spot intensities decreases because the contribution of each spot to the summation in Eq. (7) decreases. This effect depends on the total spot number in all wavelengths, not just on the spot number for a specific wavelength. A decrease in the absolute spot intensity is also effective for degradation of the uniformity error as the case of the contrast. The curve of the uniformity error sometimes fluctuates (when spot number is 49), and such behavior is obtained in the following subsections. But the variance is within several percent and is not a real problem except when that the uniformity is crucial.

B. Wavelength Number

We show performance dependence of the WMDPE on the number of multiplexed wavelengths. WMDPE's that

Table 3. Parameters of the WMDPE's for Performance Evaluation

Parameter	Condition To Be Tested: Spot Number	Wavelength Number	Output Distance	Maximum Phase Modulation	Wavelength Resolution
Output distance (cm)	10	20	5–30	20	10
Pixel number in WMDPE plane	256 × 256	256 × 256	256 × 256	256 × 256	256 × 256
Pixel pitch in WMDPE plane (μm)	10	10	10	10	10
Pixel number in output plane	91 × 91	45 × 45	41 × 41	41 × 41	45 × 45
Pixel pitch in output plane (μm)	20	20	20	20	20
Wavelength (nm)	500, 571 667, 800	400, 431, 467 509, 560, 622 700, 800	500, 571 667, 800	500, 571 667, 800	600, 600 − Δλ
Maximum Phase modulation	2π (for 800 nm)	4π (for 800 nm)	2π (for 800 nm)	$2\pi - 14\pi$ (for 800 nm)	4π (for 600 nm)

generate four spots of a rectangle for each wavelength are designed. The sets of the design wavelengths are generated by selecting the last several wavelengths listed in Table 3, e.g., {700 nm, 800 nm}, {622 nm, 700 nm, 800 nm}, and so on. Dependence of the performance measures on the number of multiplexed wavelengths is shown in Fig. 13. The light efficiency degrades with increasing number of wavelengths. The reason is considered to be as follows: Information for multiple wavelengths must be multiplexed and written as the phase distribution on a single plane of the WMDPE. Let us consider the propagation of light of a specific wavelength. A part of the light propagates to the spots assigned to the wavelength, but most of the light is directed around the spots for the other wavelengths. Consequently, the light propagating to the desired spots decreases with increasing number of multiplexed wavelengths, and the light efficiency decreases. On the other hand, the contrast maintains high values with little degradation as increasing the number of wavelengths. This means that at least eight-wavelengths multiplexing can be achieved in our method. These values can be improved by increasing the pixel number or the maximum phase modulation or by setting a short output distance as described in the following subsections.

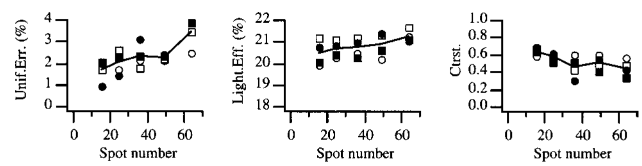

Fig. 12. Dependence of performance measures on the number of output spots.

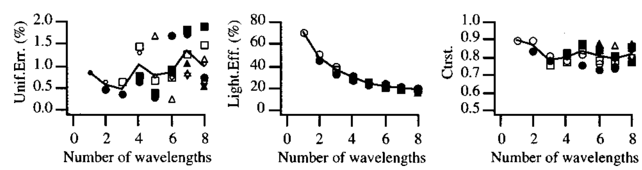

Fig. 13. Dependence of performance measures on the number of multiplexed wavelengths.

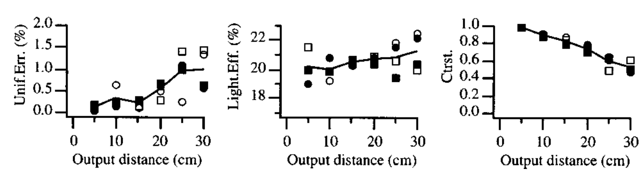

Fig. 14. Variation of performance measures versus the output distance.

C. Output Distance

We show performance dependence of the WMDPE on the output distance. WMDPE's that generate three spots of a triangle for each wavelength are designed. Variation of the performance measures is shown in Fig. 14 when the output distance is changed from 5 cm to 30 cm in 5-cm intervals. These results show that the contrast is degraded with increasing output distance. The reason is that the factor of the transfer function $A_{lm} \exp(j\varphi_{lm})$ in Eq. (1) becomes less sensitive to the wavelength for long output distance, so separation of the light by the wavelength becomes difficult. In contrast, the light efficiency keeps an almost constant value. The light power focused on the output spots does not change even if the peak intensity is decreased by the diffraction that is due to the long distance.

D. Maximum Phase Modulation

We study the effects of the maximum phase modulation on the performance of the WMDPE. The output pattern is the same as that for the evaluation of the output distance. Variation of the performance measures is shown in Fig. 15 with a changing of the maximum phase modulation from 2π to 14π, with a 2π interval for wavelength

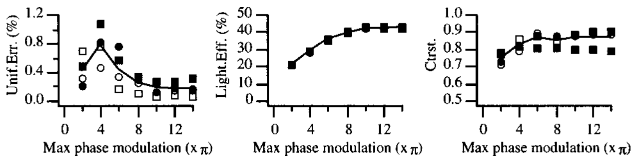

Fig. 15. Variation of performance measures versus the maximum phase modulation.

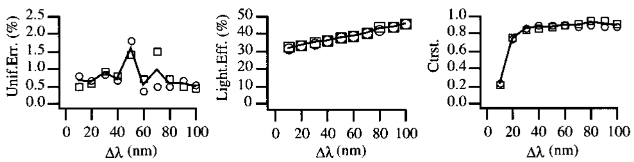

Fig. 16. Variation of performance measures versus wavelength interval Δλ.

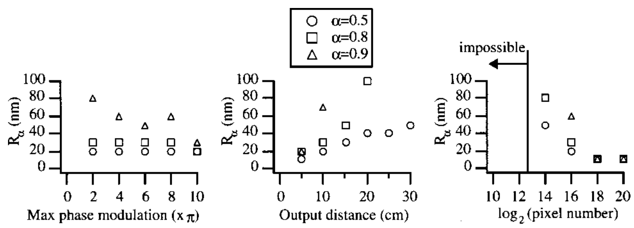

Fig. 17. Wavelength resolution of the WMDPE for two wavelengths versus the maximum phase modulation (left), the output distance (middle), and the pixel number (right).

800 nm. Both the light efficiency and the contrast become high for a large value of the maximum phase modulation. Performance of the DPE for a single wavelength does not change even if the maximum phase modulation exceeds 2π. On the other hand, wavelength separation of the WMDPE becomes easy with a maximum phase modulation larger than 2π, because flexibility in phase selection for different wavelengths is increased. Thus the performance of the WMDPE can be improved. Note that improvement of the light efficiency and the contrast saturates for the maximum phase modulation over 10π. The reason is that difference of the phase modulation between the adjacent wavelengths exceeds 2π. Consequently, one can improve performance of the WMDPE by increasing the maximum phase modulation within a limited range. Fluctuation of the uniformity error does not become a problem, because that is less than 1%.

E. Wavelength Resolution

We investigate the wavelength resolution by the WMDPE's for two wavelengths by increasing the interval Δλ between the design wavelengths. One of the design wavelengths is fixed at 600 nm, and the other is increased from 500 nm in 10-nm steps. The output pattern is "6" for 600 nm and "5" for the other wavelength. Each output pattern is composed of ten spots. The relationships between Δλ and the performance measures of the designed WMDPE are shown in Fig. 16. The light efficiency and the contrast are degraded with decreasing Δλ. In particular, the contrast is quite low for small Δλ. The same tendency appears in all designs in this subsection.

To clarify the effect of the other parameters on the wavelength resolution, the parameters listed in Table 3 are changed. The wavelength resolution against the maximum phase modulation, the output distance, and the pixel number is evaluated. We define the wavelength resolution R_α as the minimum value of Δλ for which the contrast exceeds a criterion value α. For α, 0.5, 0.8, and 0.9 are assumed. The wavelength resolution for the variation of the three parameters is shown in Fig. 17. On the maximum phase modulation, the wavelength resolution is constant for $\alpha = 0.8$ and 0.5, but a large value of the maximum phase modulation is necessary to separate wavelengths by intervals of tens of nanometers interval for $\alpha = 0.9$. In contrast, the wavelength resolution decreases with increasing output distance for any α. For an output distance larger than 25 cm, it is difficult to obtain a contrast above 0.8 even if Δλ is 100 μm. An effective method for improving the wavelength resolution is to increase the pixel number. For example, a WMDPE composed of 1024×1024 pixels achieves a contrast above 0.95. On the other hand, a practical design is impossible with pixels not more than 64×64. Although the wavelength resolution of the WMDPE is determined from a set of the parameters, a rough limitation of the wavelength separation is between several and several tens of a nanometer.

6. DISCUSSION

Optical elements, including the DPE, often require high light efficiency. Although a volume hologram has the capability for wavelength multiplexing while keeping high light efficiency, fabrication of such an element is difficult and must be treated in a different way. In contrast, the WMDPE studied in this paper is implemented by a single planar element, and it is impossible to obtain high light efficiency for all wavelengths inherently. Because multiple information for different wavelengths must be recorded on a single surface of the element, the light efficiency is roughly estimated by 1/(number of wavelengths). In addition, the information from a wavelength may have a detrimental effect on the functionality of the WMDPE for other wavelengths and may cause a reduction in efficiency of the wavelengths. That is a basic difficulty in the WMDPE design, and it is important to increase the light efficiency. Thus we define an evaluating function as the weighted sum of the intensities of all spots [Eq. (7)]. With the evaluating function, we can increase the total light efficiency for all design wavelengths. In addition, the weight is increased for a spot whose intensity is relatively small [Eq. (9)]. This provides an effective increase in the light efficiency. As a consequence, the light efficiency can be increased close to the estimated limitation for all design wavelengths. As an additional advantage, it is also expected to increase the contrast. An effective strategy for reducing the information dispersion of the phase distribution is to increase the maximum phase modulation. This contributes to the obtaining of high light efficiency as presented in Section 5.

As another approach to the WMDPE design, the Yang–Gu[12–14] algorithm has been proposed. This algorithm requires double iteration loops for designing one WMDPE, which are referred to as the inner and the outer iteration loops in Ref. 14. The inner loop is used to determine a candidate for phase distribution at each outer iteration. The outer iteration is the loop for phase optimization. In our method the candidates for phase distribution can be obtained by using Eq. (7) directly, so this method is faster than the Yang–Gu algorithm. With a Pentium II processor of 450 MHz, the design of the WMDPE for nine wavelengths presented in Section 3 requires approximately 20 minutes.

7. CONCLUSION

In this paper, we have studied a WMDPE capable of generating independent spot patterns for multiple wavelengths. The iterative algorithm based on the ORA method was extended to design the WMDPE for multiple wavelengths. When the reference values of the weight factors in each iteration are updated, WMDPE's with stable performance for multiple wavelengths can be designed. The effectiveness of the method is demonstrated by the design of the WMDPE's for four and nine wavelengths. We also presented different output distances for individual wavelengths. The WMDPE for three wavelengths was designed with five phase levels and fabricated by electron-beam lithography. Optical experiments with the fabricated WMDPE verified that the three output patterns are generated simultaneously. Performance dependence of the WMDPE on various conditions was evaluated quantitatively by computer simulations. From the results the following characteristics of the WMDPE are obtained: (1) The number of the spots or the multiplexed wavelengths should be selected in conformity with the system requirements because an increase in the numbers causes performance degradation of the WMDPE, (2) the smaller the output distance, the better performance is obtained, (3) the performance of the WMDPE can be improved by increasing the maximum phase modulation to a limited extent; and wavelength between several and several tens of nanometers is a rough limitation of the wavelength resolution. These characteristics provide the approximate performance of the WMDPE and can be used as a guideline for the applications.

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