Quasi-Dammann grating with proportional intensity array spots

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A quasi-Dammann grating is proposed to generate array spots with proportional-intensity orders in the far field. To describe the performance of the grating, the uniformities of the array spots are redefined. A two-dimensional even-sampling encode scheme is adopted to design the quasi-Dammann grating. Numerical solutions of the binary-phase quasi-Dammann grating with proportional-intensity orders are given. The experimental results with a third-order quasi-Dammann grating, which has an intensity proportion of 3:2:1 from zero order to second order, are presented. © 2008 Optical Society of America

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Modulation of the periodic structure of a binary diffraction grating to shape the intensity distributions of diffracted orders has attracted considerable interest in recent years [1–4]. Conventional Dammann gratings are binary-phase Fourier holograms capable of generating one-dimensional and two-dimensional array spots with high efficiency and high uniformity [5]. However, for certain practical applications, two-dimensional uneven intensity array spots with special proportions are preferred in the far field, which cannot be produced with conventional Dammann gratings. Extensions of the Dammann method are necessary for those applications that require uneven arrays, especially the generation of arrays with proportional-intensity orders.

Conventional Dammann gratings are pure, binary-phase gratings whose phase transition points are optimized to produce equal-intensity spots. In theory, encoding technology for conventional Dammann gratings is still applicable for quasi-Dammann gratings (QDGs) with proportional-intensity orders. Besides the separable encoding technology for Dammann gratings, Vasara *et al.* introduced inseparable two-dimensional gratings [6]. In this Letter, a two-dimensional even-sampling encoding scheme is adopted for simplification. As is known, the merit function is the key point in the design of binary phase gratings. The merit function used in the design of Dammann gratings to obtain even intensity is not applicable for QDGs to obtain proportional intensity arrays. Therefore a new merit function is defined. In this Letter, the concept of a QDG with proportional intensity orders is proposed. The design of an optimal QDG is described, and the experimental results are presented to verify the validity of this kind of QDG.

The experimental optical system is shown in Fig. 1. A collimated laser beam illuminates the QDG in front of the lens. In the focal plane, an array pattern with proportional intensity orders is formed, which is captured by a laser beam analyzer and displayed on a computer monitor. The key component of this optical system is the QDG. The design of this kind of QDG is described as follows.

It is assumed that this kind of QDG satisfies the scalar diffraction theory. The He–Ne laser beam is approximately expressed as a flattop laser beam. For high diffraction efficiency, pure modulation of the grating is preferred; i.e., there should be no amplitude modulation. The phase modulation can be binary, multilevel, or continuous. For simplification of fabrication, we used binary phase modulation. The two-dimensional even-sampling encoding schemes (Fig. 2) yield the intensity distribution measured at the output plane:

$$I_{0,0} = I(0,0) = \left(\frac{A}{\lambda f}\right)^2 |[\exp(j\phi_2) - \exp(j\phi_1)]L + \exp(j\phi_1)|^2,$$

$$I_{+m,+n} = I_{-m,-n} = \left(\frac{A}{\lambda f}\right)^2 |\exp(j\phi_2) - \exp(j\phi_1)|^2 \sin c^2\left(\frac{m}{d}\right)\sin c^2\left(\frac{n}{d}\right)\left|\sum_{l=1}^{L} \times\exp\left\{-j2\pi\left[\frac{m}{d}\left(x_l+\frac{1}{2}\right)+\frac{n}{d}\left(y_l+\frac{1}{2}\right)\right]\right\}\right|^2,$$

$$I_{-m,+n} = I_{+m,-n} = \left(\frac{A}{\lambda f}\right)^2 |\exp(j\phi_2) - \exp(j\phi_1)|^2 \sin c^2\left(\frac{m}{d}\right)\sin c^2\left(\frac{n}{d}\right)\left|\sum_{l=1}^{L} \times\exp\left\{-j2\pi\left[\frac{m}{d}\left(x_l+\frac{1}{2}\right)-\frac{n}{d}\left(y_l+\frac{1}{2}\right)\right]\right\}\right|^2, \quad (1)$$

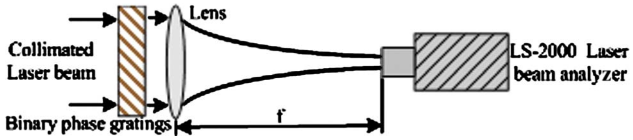

Fig. 1. (Color online) Experimental system for optical demonstration of a QDG. The He–Ne laser beam is expanded and collimated as a uniform laser beam to illuminate the grating, and the proportional-intensity array pattern is captured by a laser beam analyzer in the focal plane of the lens.

where λ is the wavelength of the laser and f is the focal length of the lens. The phase distribution of one period in the uniform sampling rectangle aperture grating is made of grid aperture cells (Fig. 2). The phase delays of the cells are ϕ_1 (white cells) and ϕ_2 (black cells), respectively. L represents the number of cells, and the coordinate of the lth cell's nearest apex to the origin is (x_l, y_l).

Before evaluating the performance, it is necessary to define the following parameters for characterization of the QDG with proportional-intensity orders: (1) Order M of the QDG. The point with $m=0$, $n=0$ was defined as the zero order of the QDG, and all the points with $|m|=1$ and $|n|\leqslant 1$ or $|n|=1$ and $|m|\leqslant 1$ are defined as first order; i.e., the first order of the QDG includes all the points whose $|m|=1$ and $|n|\leqslant 1$ or $|n|=1$ and $|m|\leqslant 1$. In like manner, the Mth order includes all the points whose $|m|=M$ and $|n|\leqslant M$ or $|n|=M$ and $|m|\leqslant M$. According to this definition a three-order QDG can be expressed as in Fig. 3. (2) The uniformity of the QDG including in-order uniformity $U_{o,M}$ and the proportional uniformity of orders U_p. The former is defined as $U_{o,M}=\Sigma(I_{mn}-\bar{I})/I_s$ to evaluate the uniformity of a single order, where I_{mn} is the intensity of the points of the Mth order, $\bar{I}$ is the average intensity of these points, and I_s is the sum of the intensity of these points. The latter is defined as $U_p=\bar{I}_0/I_0:\bar{I}_1/I_1:\ldots:\bar{I}_M/I_M$ to evaluate the deviation of the designed and ideal intensity proportions, where $\bar{I}_0,\bar{I}_1,\ldots\bar{I}_M$ and $I_0,I_1,\ldots I_M$ are the designed and ideal average intensities of the points of order $0,1,\ldots M$, respectively. (3) The diffraction efficiency is defined directly from the description of a conventional Dammann grating.

The merit function is important for the design of the QDG. The merit function in Eq. (2) for a conventional Dammann grating is not larger applicable to the QDG:

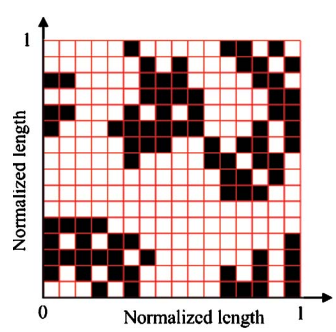

Fig. 2. (Color online) Illustration of the phase distribution of one period of the grating with white cells for zero-phase delay and black cells for π-phase delay.

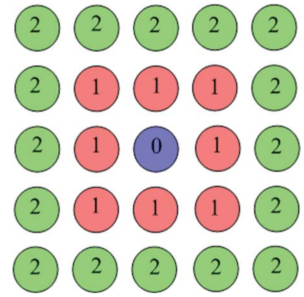

Fig. 3. (Color online) Orders of the QDGs. The spots with the same color belong to the same order.

$$E^2=\alpha\left[\sum_{m=-M}^{M}\sum_{n=-N}^{N}(I_{m,n}-\eta_E\hat{I}_{m,n})^2\right]+(1-\alpha)(1-\eta_E)^2, \quad (2)$$

where $\alpha\subseteq[0,1]$ is the weight coefficient, $\hat{I}_m$ is the ideal intensity of the orders, $I_{m,n}$ is the intensity of point (m,n), and η_E is the diffraction efficiency of the gratings. The first item in Eq. (2) is used to judge the variance between the designed and the ideal intensities; the second item is used to evaluate the diffraction efficiency. For the QDG with proportional intensity orders, weight coefficients should be considered according to the proportion of the orders to evaluate the uniformity. Therefore the merit function of the QDG is defined as follows:

$$E^2=\alpha\{[\beta_1(I_{(0)}-\eta_E\hat{I}_{(0)})]^2+[\beta_2(I_{(1)}-\eta_E\hat{I}_{(1)})]^2+\ldots+[\beta_M(I_{(M)}-\eta_E\hat{I}_{(M)})]^2\}+(1-\alpha)(1-\eta_E)^2, \quad (3)$$

where $\beta_1,\beta_2,\ldots,\beta_M$ are the weight coefficients of the orders and $I_{(0)},I_{(1)},\ldots I_{(M-1)}$ are the intensities of orders $0,1,\ldots,M$. To obtain the proportional intensity orders, the intensity deviation of each order should also have the given proportion, which means that the weight coefficients should have the inverse given proportion. In addition, because of the symmetrical characteristic of the QDG, the weight coefficient of zero order should be doubled. If the design target is a three-order QDG with an intensity proportion of $I_{(0)}:I_{(1)}:I_{(2)}=k_1:k_2:k_3$, the weight coefficients should be $\beta_1:\beta_2:\beta_3=1/k_1:1/2k_2:1/2k_3$.

The simulated annealing algorithm [7,8] is adopted to optimize the QDG. The third-order QDG with $I_{(0)}:I_{(1)}:I_{(2)}=3:2:1$ was chosen for design and experimental verification. Figure 4 shows the designed result of this third-order QDG. The number of sampling cells of one period of the third-order QDG is 16×16 [Fig. 4(a)]. The in-order uniformities of the first and second orders are $U_{o,1}=0.2\%$ and $U_{o,2}=2.5\%$, respectively. The in-order uniformity of the zero order is insignificant because there is only one point in this order. The proportional uniformity is $U_p=1.1:1.0:0.9$, and the diffraction efficiency is 75.4%.

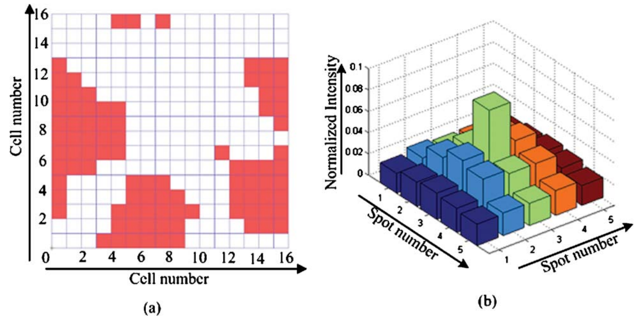

Fig. 4. (Color online) Designed result of the third-order QDG with proportional intensity 3:2:1 from zero order to second order: (a) phase distribution of one period and (b) output intensity profile.

The very large scale integration technique [9] was adopted in our experiments to fabricate this kind of QDG. The first step is to create a mask with electron-beam writing equipment. A thin layer of photoresist is spun onto a glass substrate. With ordinary microelectronic lithography technology, the mask pattern is transformed into a photoresist layer upon the glass substrate. The inductive coupled plasma technique was used to transfer the photoresist pattern onto the substrate. The refractive index of the used glass substrate at 6328 nm wavelength is 1.507, and the thickness corresponding to phase difference π is 6244 nm. The surface profile of the grating measured with Dektak 8, which is an advanced surface texture measuring system, is shown in Fig. 5, which clearly shows that the average depth of this surface-relief element is 6108 nm, a slightly deviation from the desired value.

For the experimental system shown in Fig. 1, we used a collimated 6328 nm wavelength He–Ne laser as the light source with a lens of 155 mm focal length. The third-order array pattern with an intensity proportion of 3:2:1 from the zero order to the second order captured by a laser beam analyzer in the rear focal plane of the lens is shown in Fig. 6. Figure 6(b) shows intensity distribution along the lines $n=0$ and $m=-2,-1,0,1,2$ in the pattern measured by the laser beam analyzer. The slightly lower efficiency and worse uniformity might be due to the surface roughness of the fabricated element, the phase and position errors, and the dark noise of the laser beam analyzer. Nevertheless, the experimental results verify the validity of the uneven grating.

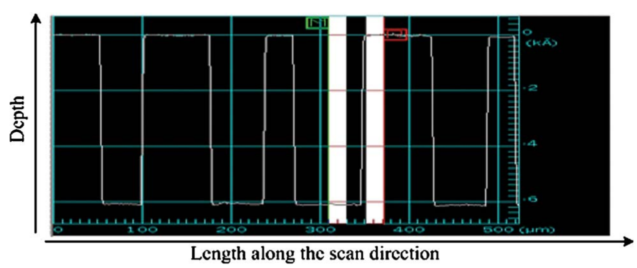

Fig. 5. (Color online) Surface profile of the fabricated third-order QDG with proportional intensity.

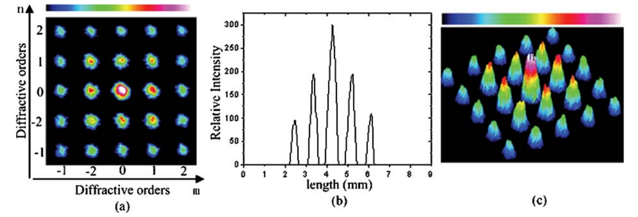

Fig. 6. (Color online) Experimental images of the fabricated third-order QDG with proportional intensity: (a) two-dimensional laser beam distribution, (b) intensity distribution along the lines $n=0$ and $m=-2,-1,0,1,2$ in the pattern measured by a laser beam analyzer, (c) three-dimensional laser beam distribution.

In summary, one QDG that can produce a high-efficiency array pattern with proportional-intensity orders in the far field has been proposed. We have presented the design and fabrication method as well as the experimental results that verify the third-order QDG with proportional-intensity 3:2:1 from zero order to second order. This kind of QDG should have many important applications in laser shaping, laser micromachining, laser fusion, and laser detection.

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