# Dammann gratings as integratable micro-optical elements created by laser micronanofabrication via two-photon photopolymerization

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Dammann gratings, as beam splitters and coherent signal generators, were produced in a short fabricating cycle by femtosecond laser fabrication via two-photon photopolymerization. These holograms that each generated $2\times2$, $3\times3$, $4\times4$, $5\times5$, and $6\times6$ spot sources in the fan-out demonstrated diffraction efficiency of 36%, 25%, 29%, 52%, and 49%, respectively, comparable with the theoretical values. This work shows the promising prospect of femtosecond laser fabrication in compatibly manufacturing various micro-optical devices including Dammann gratings and their integrated systems. © 2008 Optical Society of America

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Nowadays the development of scientific apparatus has been on a trend toward integration of optical, electrical, and mechanical functions, which are required to be more and more miniaturized, integratable, and multichanneled. However, traditional optical elements generally made of glass, which are comparatively large in extent and weight, cannot satisfy the requirements adequately. Micronanofabrication by femtosecond lasers has been increasingly considered to be a promising solution to create appropriate optical and mechanical microelements since it was first introduced as characterized by its reasonably high precision and three-dimensional processing capability [1,2]. Meanwhile, a highly integrated system is supposed to have multiple channels to promise high processing efficiency. The Dammann grating [3,4], born in the 1970s, is considered as the perfect character that shifts a single input into an array of identical outputs. Over the past three decades much research and effort has been put into the design [5,6] and fabrication of this device. So far, a comparatively ripe and prevalent technology for fabrication of these kinds of grating structures is photolithography. However, the whole procedure of fabrication is complicated in that it requires a long cycle of fabrication and a high expenditure, due to, for example, the making of an elaborate mask. Because of this a new technology, writing fabrication, was called out. It allows a laser or electron beam to figure the expected structure directly, and has been applied to the microfabrication of some optical elements in silica glass [7–10]. However, the precise control of refractive index change and of the thickness of the phase transition area in glass is still problematic owing to the simultaneous involvement of many nonlinear effects, including self-focusing.

In this Letter, we will show the solution to the problem by using femtosecond laser-induced two-photon photopolymerization of a photoresist, a technology that has been successfully employed in figuring mechanical and optical microstructures [11–14]. With the known refractive index of photoresist after polymerization, we are capable of depicting the thickness of phase bulks at a high accuracy to create precise grating structures.

Shown in Fig. 1(a) is an overlooked scanning electron microscopic (SEM) image of a Dammann grating; Figs. 1(b)–1(f) are locally magnified ones of five different types of grating structures prepared by two-photon photopolymerization of the commercial a photoresist SU-8. The data that was adopted in simulating the Dammann gratings shown in Fig. 1 came from Morrison *et al.* [15] and Zhou and Liu [16]. Femtosecond laser pulses of a wavelength of 800 nm with a pulse width of 120 fs, mode locked at 82 MHz (from

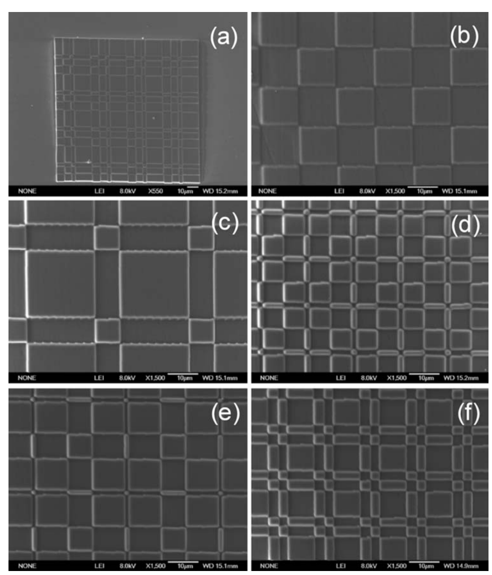


Fig. 1. Dammann gratings fabricated by two-photon photopolymerization. (a) Top-view SEM image and locally magnified views of the Dammann gratings that generate (b) $2\times2$, (c) $3\times3$, (d) $4\times4$, (e) $5\times5$, and (f) $6\times6$ spot sources, respectively.

 

Tsunami, Spectra-Physics), were tightly focused by a high numerical aperture (NA=1.40) oil immersion objective lens. The focal spot was scanned laterally by manipulating a two-galvano-mirror set and along the optical axis by a piezo stage, both with motion as accurate as 1 nm. The photoresist embedding the laser written structures was to be rinsed by the developer for 10 min so that the unpolymerized photoresist would be removed, leaving a solid skeleton.

The thickness of phase transition areas is associated with several parameters, as $\Delta n d = \varphi / k$ shows. Herein $\Delta n$ is the difference of the refractive index of polymerized photoresist and that of air; $d$ is the thickness of phase transition areas; $\varphi$ is the value that phase shifts by; and $k$ is associated with the wavelength $\lambda$ of incident light, as $k = 2\pi/\lambda$. The refractive index of polymerized SU-8 is known to be 1.5930 for wavelength 632.8 nm while that of air is 1.0003. For Dammann gratings, $\varphi$ should be $\pi$ to ensure the maximum diffractive efficiency. All the Dammann gratings we fabricated were supposed to split a He–Ne laser beam with the wavelength of 632.8 nm. So the thickness was calculated to be 533 nm. To make sure the thickness was exactly equal to the theoretical value, we designed a base that the grating layer lay on and that was the standard plane of altitude zero. In this way, the radii of points that made up the top surface of a grating were counteracted by those on the base surface, thus the deviation from the theoretical value of thickness could be attributed only to the unavoidable surface smoothness fluctuation evaluated as ~10 nm. Owing to the high refractive index of polymerized photoresist, a grating structure can be much thinner than one made in glass. The incident light has to travel much farther to reach $\pi$ for phase shift in a material whose shift of the refractive index is rather small, which means a large thickness, whereby it always takes a long time to fabricate a Dammann grating in glass. Lee and Nikumb [10] reported they spent 2.2 h to create a single-layer Dammann grating, while Li *et al.* [9] spent much more. In contrast, by optimizing the parameters, such as exposure time, density of points, etc., we spent no more than 32 min to accomplish a Dammann grating with its base, and the influence of instability of laser power could be ignored.

To observe the diffractive pattern of a Dammann grating, we adopted a He:Ne laser beam with the wavelength of 632.8 nm as the incident light. Figures 2(a)–2(e) show the diffractive patterns of the Dammann gratings that each generate an array of $2\times2$, $3\times3$, $4\times4$, $5\times5$, and $6\times6$ spots with theoretical diffractive efficiencies of 81.06%, 66.42%, 70.63%, 77.38%, and 84.52%, respectively [16]. The diffractive efficiency of an odd-number-spot generator and of an even-number-spot generator is calculated by $\eta_{\mathrm{odd}} = (I_0 + 2\Sigma_{i=1}^{N} I_i)/I_{\mathrm{inc}}$ and $\eta_{\mathrm{even}} = (2\Sigma_{i=1}^{N} I_{2i-1})/I_{\mathrm{inc}}$. Herein $\eta$ is the diffractive efficiency, $I_0$ is the intensity of the zero order, $I_i$ is that of a higher order required in the fan-out, and $I_{\mathrm{inc}}$ is that of the incident light. Note that the zero order is not involved for an even-number spot array generator. The diffractive efficiency of the gratings shown in Figs. 1(b)–1(f) was calculated to be 36%, 25%, 29%, 52%, and 49% in order. Several kinds of fabrication errors, such as dilation, sidewall errors, etc., are probably the factors that decrease the diffractive efficiency. Besides, they have significant influence on the uniformity of the spot intensities, which is another criterion used to judge a Dammann grating. For an intuitional view, the uniformity is expressed as Fig. 2(f) shows. Each peak indicates the intensity of its corresponding spot along the dashed lines $X$ and $Y$ shown in Fig. 2(c). Besides those mentioned above, which affect the uniformity [17], there are some other factors that cause more or less disuniformity as well. In fabrication, phase transition points did not locate exactly as expected in positions worked out by computer simulation, which generally achieved an accuracy of more than five decimal digits. So there was always inevitable deviation, which resulted in disuniformity to some extent. Phase errors also played a part, but a much less important one, in causing an increase of the zero order intensity.

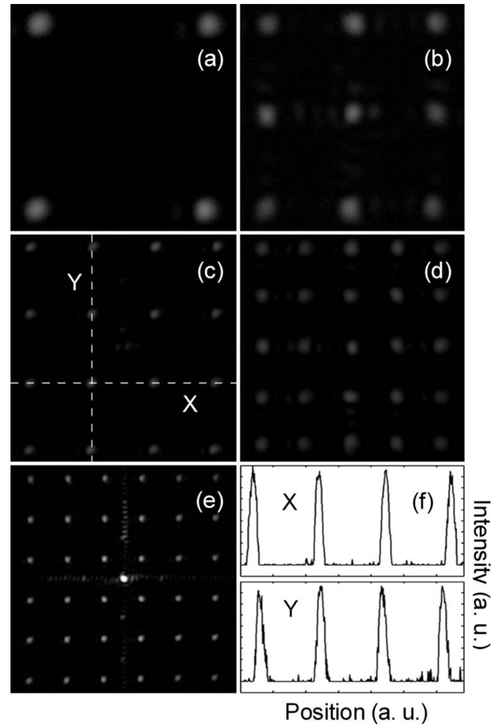


Fig. 2. Diffraction patterns of Dammann gratings that generate (a) $2\times2$, (b) $3\times3$, (c) $4\times4$, (d) $5\times5$, and (e) $6\times6$ spot sources, respectively. (f) Intensity distribution of spots along dashed lines $X$ and $Y$ [shown in (c)].

As a Fourier hologram, a Dammann grating needs a lens to generate an array of spot sources in the rear focal plane of the lens. Considering that our Dammann gratings are comparatively tiny, we produced a series of lenses with diameters of from around 100 to 500 $\mu$m and larger if necessary so as to make it easier to integrate our gratings into complicated systems. Figure 3(a) shows five samples of different sizes. We developed a simple technology so that lenses made of photoresist can be produced fast and plentifully and that involves no laser or complicated cutting and grinding machines. These minilenses ac-

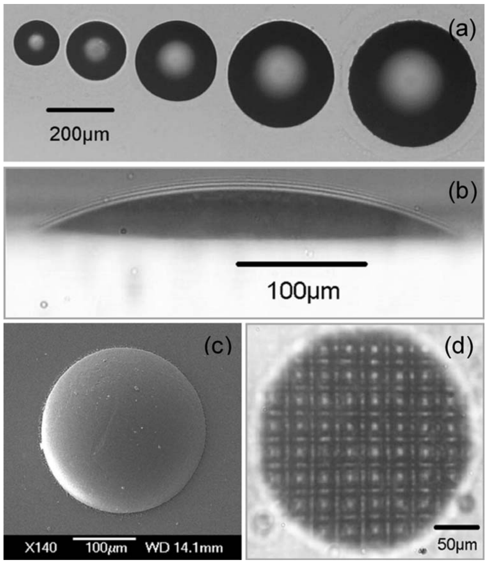


Fig. 3. Microlenses produced by a novel method. (a) Microlenses of different sizes. (b) Profile of a microlens. (c) SEM image. (d) A microlens set above a Dammann grating.

tually shifted from tiny droplets of photoresist on a substrate. Sunk in the solution of a certain kind of surface active agent, the unroundish droplet shrank into a spherical crown under its own surface tension. As the solution was expelled and evaporated, the crown sank and shifted into a spherical cap that was available as a plane convex lens, as shown in Fig. 3(b). The liquid lens was then exposed to ultraviolet to polymerize for permanent preservation. The focus of a lens is approximately twice as large as the diameter. Shown in Fig. 3(d), a lens set above a Dammann grating represents perfect properties, so that hardly any aberration appears.

Of many practical applications, an important one that Dammann gratings come to is coherent communication. As the incident light that passes through each point of a Dammann grating delivers a contribution to every spot source in the fan-out, all sources are coherent with one another. As a result, even an input signal that is not coherent results in all the outputs being coherent. This significant property is represented in Fig. 4, which shows the coherent patterns of arbitrary two and three sources in the fan-out under illumination of noncoherent white light.

In conclusion, we fabricated Dammann gratings, a kind of binary-phase Fourier hologram and of micro-optical element indispensable in integrated optical systems. The diffractive efficiency of these holograms that each generate an array of $2\times2$, $3\times3$, $4\times4$, $5\times5$, and $6\times6$ spot sources is 36%, 25%, 29%, 52%, and 49%, respectively. With an appropriate Fourier lens, a Dammann grating fabricated by the technology introduced in this Letter is applicable in an integrated system. This work shows the merits of micro-optical fabrication via femtosecond-induced two-photon photopolymerization: the reasonably high fabrication accuracy and efficiency, the high tolerance to the structural complexity of devices, and the technological and material compatibility to varied types of optically functional devices.

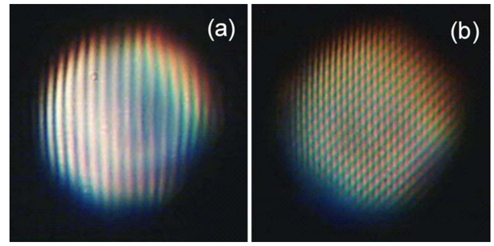


Fig. 4. (Color online) Interference patterns of (a) two and (b) three spot sources in the fan-out of a Dammann grating.

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