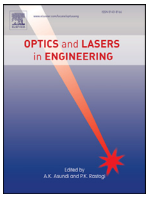
Optics and Lasers in Engineering 97 (2017) 78–85

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Quadratic grating apodized photon sieves for simultaneous multiplane microscopy

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ARTICLE INFO

Keywords:
Photon sieve
X-ray microscopy
Diffractive optics
Multiple imaging

ABSTRACT

We present a new type of imaging device, named quadratic grating apodized photon sieve (QGPS), used as the objective for simultaneous multiplane imaging in X-rays. The proposed QGPS is structured based on the combination of two concepts: photon sieves and quadratic gratings. Its design principles are also expounded in detail. Analysis of imaging properties of QGPS in terms of point-spread function shows that QGPS can image multiple layers within an object field onto a single image plane. Simulated and experimental results in visible light both demonstrate the feasibility of QGPS for simultaneous multiplane imaging, which is extremely promising to detect dynamic specimens by X-ray microscopy in the physical and life sciences.

1. Introduction

Focusing and imaging of X-ray have been a particular powerful technique for biology science, environmental science, medical science and electronic devices due to its capability of nanoscale visualization and characterization [1,2]. Especially, soft X-ray microscopy in the water window provides a unique set of high-resolution imaging capabilities that complement existing imaging techniques such as light and electron microscopy [3,4]. Recent technological demands for high-resolution imaging in the life sciences have made X-ray microscopy a rapidly developing field, facilitated by the construction of third-generation synchrotron light sources and advances in manufacturing technologies of X-ray focusing optics [5].

In recent years, many works have been made to improve spatial resolution and image quality of X-ray microscopy like high-resolution compact X-ray microscopy [6] and Zernike apodized photon sieves for high-resolution phase-contrast X-ray microscopy [7]. However, existing techniques are still limited to approximate static specimens, confining a number of applications that involve the investigation of dynamic specimens, such as the tracking of proteins or vesicles in living cells [8]. The most common approach is physically to re-focus the imaging system on each layer in sequences or micro computed tomography in X-ray [9,10]. This process is time-consuming and may yield ambiguous spatial-temporal information since image planes are not recorded simultaneously [11]. Moreover, the movement of the specimen stage during refocusing may mechanically perturb the sample [12].

To overcome these limitations, we develop a new imaging device that has the characteristic of achieving in-focus images of multiple specimen layers on a single camera synchronously. This device is named quadratic grating apodized photon sieve (QGPS) and functions as the objective to form simultaneous multiplane imaging. Traditional photon sieves (PSs) were first put forward by Kipp et al. [13], which consisted of a large number of pinholes distributed appropriately over the zones of a Fresnel zone plate. With the same specific minimum feature size, PSs allow for higher resolution and lower background compared to traditional Fresnel zone plates [14]. Besides, PSs has advantages of designing flexibility, making it easily to be modified for innovative purposes such as generating hard-X-ray vortex [15], two-dimensional hard X-ray differential-interference-contrast imaging [16] and presenting twin vortices [17]. These features have made PSs applied in X-ray imaging system as an ideal objective. However, traditional PSs cannot be applied in detection of dynamic specimens, because it can only image one object plane at the same time.

This paper aims to solve the problem of detecting dynamic specimens for X-ray microscopy using QGPS as the objective, which is a new form of photon sieve apodized with quadratic grating function. Thanks to quadratic grating, which has the ability of translating one beam into three beams with diffraction orders, but only the 1st diffraction order is focused [18]. Compromising merits of traditional PSs and quadratic grating, the developed QGPSs produce a special focusing performance that the wave-front is divided into many diffraction orders which have different focal lengths, leading to QGPS having the capacity of imaging

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http://dx.doi.org/10.1016/j.optlaseng.2017.05.002
Received 15 December 2016; Received in revised form 25 April 2017; Accepted 2 May 2017
Available online 31 May 2017

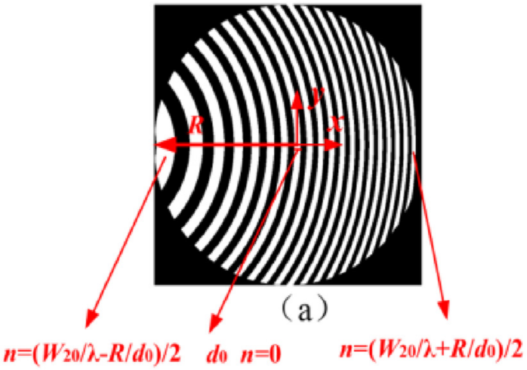

Fig. 1. Schematic diagrams of quadratic gratings with $R = 20d_0$ (a) $W_{20} = 7\lambda$ and (b) $W_{20} = 3\lambda$. The center of image is the origin of Cartesian coordinates. The white area is referred to 1 (transparent) and the black area is referred to 0 (opaque).

one object plane onto multiple image planes. With the peculiarity, multiple object planes can be imaged on a single image plane simultaneously with different diffraction orders. The most straightforward application of QGPSs is the objective in X-ray microscopy, forming simultaneous images of multiple specimen layers on a single image plane side by side. The design principles of two types of QGPSs which can respectively produce three and nine synchronous images are introduced, and we demonstrate them by preliminary results obtained from computer simulations and experiments performed in visible light.

2. 1D QGPSs

2.1. Design principle of QGPSs

Prior to the introduction of the design principle of QGPSs, let us briefly review the traditional PSs theory based on Cao's explanation [14]. A photon sieve consists of isolated pinholes of diameter d_n located at a corresponding radial distance r_n. The holes can be distributed regularly or randomly in angle about the zone. The radial distance from the center of the nth bright zone to the center of the photon sieve is given by r_n:

$$r_n^2 = 2nf\lambda + n^2\lambda^2 \tag{1}$$

where n is an integer representing the sequential of the rings, and f is the focal length at a wavelength λ. Each diameter of pinhole can be expressed as

$$d_n = \frac{1.53\lambda f}{2r_n} \tag{2}$$

Besides, PSs can be modified for special purposes with parameters like sizes and distributions of pinholes. In this work, we introduce quadratic grating as an apodized window to simultaneously form multiplane imaging. The quadratic grating can be expressed as

$$w(\mathrm{x},\mathrm{y}) = \begin{cases} 1 & 2n < \frac{\mathrm{x}}{d_0} + \frac{W_{20}(\mathrm{x}^2+\mathrm{y}^2)}{\lambda R^2} < 2n+1, \mathrm{n} = integer \in \left[\frac{W_{20}}{2\lambda} - \frac{R}{2\mathrm{d}_0}\ \frac{W_{20}}{2\lambda} + \frac{R}{2\mathrm{d}_0} \right] \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where λ is the optical wavelength, x and y are Cartesian coordinates with origins of the center, d_0 defines the width of stripe at the center, and R is the radius of the aperture. The parameter W_{20} used throughout this paper, defines the degree of crook of stripes [18]. The more bigger W_{20} is, the more grating bends, as compared in Fig. 1 with two binary quadratic gratings of $W_{20} = 7\lambda$ and $W_{20} = 3\lambda$. The white area is referred to 1 (transparent) and the black area is referred to 0 (opaque).

Quadratic grating has the capability of imparting a phase delay to wave fronts scattered into the nonzero diffraction orders such that the wave-front curvature is altered [18]. The grating therefore has focusing power in the nonzero orders, and an equivalent focal length f_m for mth diffraction order can be calculated by [18]

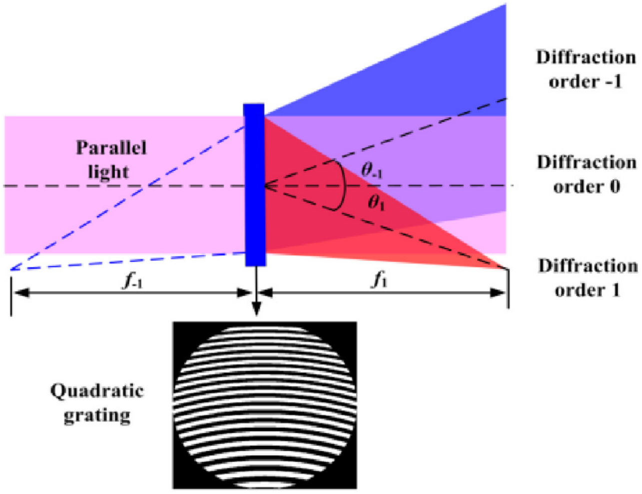

Fig. 2. Parallel light is divided into three beams with different diffraction orders by illuminating quadratic grating.

$$\mathrm{f_m} = \frac{R^2}{2mW_{20}} \tag{4}$$

and the angle of mth diffraction order is

$$\theta_\mathrm{m} = \frac{m\lambda}{2d_0} \tag{5}$$

As shown in Fig. 2, the quadratic grating is illuminated by a monochromatic parallel beam. Then the zero order diffraction propagation remains parallel along its original direction, but 1st order diffraction is focused with focal length $R^2/2W_{20}$ and angle of $\lambda/2d_0$ and -1st order diffraction becomes divergent light with focal length $-R^2/2W_{20}$ and angle of $-\lambda/d_0$.

Based on quadratic grating and traditional PS, we construct QGPSs. Quadratic grating is used as a function to select pinholes of traditional PS. Pinholes whose center are in the white area of quadratic grating are remained and other pinholes are abandoned as shown in Fig. 3. On the whole, QGPS maintains the shape of quadratic grating and pinholes still keep focusing ability from the microscopic point of view. Therefore, QGPS has its own special characteristics which are explained detailedly in the following section. Briefly a single quadratic grating acts as a set of lenses of positive, neutral, and negative power for different diffraction orders. Meanwhile, photon sieve keeps the capacity of focusing and imaging. The synthetic effect of the elaborately designed QGPS is that it can be thought as a special lens, leading to each diffraction order having