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# New methods of fabricating gratings for deformation measurements: A review

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## ABSTRACT

Gratings have been widely accepted as practical and effective deformation carriers/sensors and are commonly used in many deformation measurement methods. Since the deformation measurement sensitivity is directly proportional to the grating frequency, and the measurement accuracy is strongly affected by the grating quality. Thus, it is crucial to prepare an appropriate grating on the specimen surface that is to be measured. Over the past few decades, an increasing number of grating fabrication methods have been developed, including holographic photolithography, electron beam lithography, focused ion beam etching, nanoimprinting, soft lithography, and others. Although substantial literature regarding grating fabrication can be found, a comprehensive review is still necessary to promote the application of these methods. This review introduces the technical details and characteristics of recently developed grating fabrication methods and provides suggestions of which grating fabrication methods to use in correspondence with different deformation measurement methods. Emphasis is placed on the introduction of grating fabrication processes and the quality and applicability of the resulting gratings.

## 1. Introduction

Full-field measurement of the deformations of materials and structures subjected to various loads is an important task in experimental mechanics. Aside from the widely used pointwise strain gauge technique, various full-field non-contact optical methods [1], including both interferometric techniques (such as moiré interferometry [2,3], holographic interferometry [4,5], speckle interferometry [6,7], and coherent gradient sensing [8,9]) and non-interferometric techniques (such as the geometric moiré method [10,11], the grid method [12,13], GPA[1] [14,15], and DIC [16,17]) have been developed and applied for this purpose. Among the abovementioned methods, moiré interferometry, the geometric moiré method, the grid method, and GPA, which are referred to as grating-based methods, employ gratings as deformation carriers/sensors; these gratings are referred to as specimen gratings or deformation gratings. Benefitting from the use of specimen gratings, the grating-based methods exhibit advantages of high sensitivity, low noise, stability against rigid-body displacements, and flexibly in terms of their abilities to determine the in-plane and off-plane deformation fields of specimens over a broad range of scales.

A grating is a periodic structure consisting of lines or dots with contrasting thicknesses or that produce light of contrasting intensities. In order to satisfy the increasing accuracy requirements in scientific research and engineering, various grating-based methods must be developed to ensure applicability and accuracy. However, grating preparation on a specimen surface is challenging, and several technical parameters must be considered to ensure a successful test. For example, a grating that is to be used in a moiré interferometry test should have a highly uniform frequency, large working area (with dimensions on the order of millimetres or larger), and high diffraction efficiency. A grating that is employed in SEM moiré(a variation of the geometric moiré method) should possess high contrast, be thin, and have an appropriate electrical conductivity. The gratings used in the grid method and GPA should exhibit fine micromorphology under the selected imaging system, since error could be induced when extracting deformation information from an indistinct grating image. Since different grating characteristics are required in different deformation measurement methods, many studies have been conducted in order to establish appropriate techniques to meet the requirements of each method.

To date, many techniques for producing high-frequency specimen

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[1] GPA: geometric phase analysis; DIC: digital image correlation; SEM: scanning electron microscope; NIL: nanoimprint lithography; SL: soft lithography; FIB: focused ion beam; EBL: electron beam lithography; FLA: femtosecond laser ablation; HP: holographic photolithography; TG: transfer grating; ZTG: zero-thickness grating; DMLG: deposited metal layer(s) grating; MEMS: micro-electromechanical systems; TBC: thermal barrier coating; T-NIL: thermal NIL; UV-NIL: ultraviolet NIL; SAMIM: solvent-assisted microcontact molding; 3S: solute-solvent separation; PDMS: polydimethylsiloxane; MPS: medium polymer substrate

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gratings have been developed. These techniques can be categorized as masked or maskless. In a masked technique, a mask is prepared and is used to shield or mould the adjacent material; as a result, the grating structure on the mask is duplicated on the material by using physical or chemical means, or both. General photolithography [18], mask deposition [19], NIL [20–22], and SL [23–25] are masked techniques. In a maskless technique, a controllable beam (e.g. a laser beam, electron beam, or FIB) is used to write a pattern on a special material. The beam is generally controlled by computer programs and writes according to the pre-set track point by point; thus, maskless techniques are flexible and convenient. EBL [26–28], FIB lithography [29,30], and FLA [31] are maskless methods. HP (or laser interferometry photolithography) [32–34] is another maskless technique and is highly efficient; in this method, the photoresist is exposed to an intensity field formed by laser beams, and the produced grating has a very large area, with dimensions on the order of centimetres.

Although substantial literature related to grating fabrication is available, a comprehensive review that introduces the technical details and advantages of all the currently used grating fabrication techniques is still lacking, though it would facilitate appropriate fabrication technique selection and grating application. This paper provides such a review by introducing the technical details and characteristics of recently developed grating fabrication methods and suggesting which grating fabrication methods are appropriate for use in combination with different deformation measurement methods. Emphasis is placed on introducing the grating fabrication processes and the quality and applicability of the resulting gratings.

## 2. Grating fabrication techniques

Since micromachining is the fundamental and most important step in the grating preparation process, each grating fabrication method is named after the employed micromachining technique. After performing the abovementioned steps, several typical micromachining procedures (post-processing techniques) are generally needed to produce different types of gratings; these steps include etching, film coating, and film transferring. In this section, the basic steps in grating fabrication via HP, EBL, FIB etching and depositing, NIL, SL, and FLA are introduced in detail, and the typical micromachining processes that are subsequently employed are briefly described.

### 2.1. Holographic photolithography

A schematic diagram of grating fabrication by HP is presented in Fig. 1. When two coherent collimated laser beams ($L_1$ and $L_2$) overlap in air, a series of periodic fringes (intensity peaks and valleys) is formed due to the interference of the beams. For laser beams of wavelength λ and incident angle $\varphi$, and fringe frequency $f$ can be calculated using

$$f = \frac{2\sin\varphi}{\lambda}. \tag{1}$$

If a photoresist-coated substrate is exposed in the interference region and is subsequently developed and fixed, a grating structure can be fabricated on the photoresist. Because the laser irradiation can change the stability of the photoresist, selective dissolution of the photoresist in the developer occurs. A parallel grating can be fabricated by using a single exposure, and a crossing grating can be obtained by using an additional exposure after rotating the substrate by 90°.

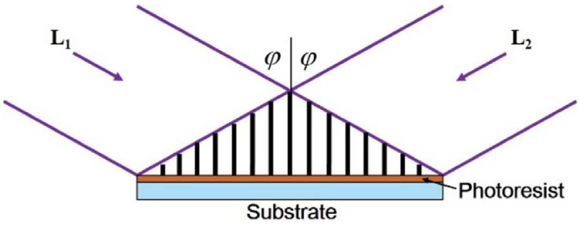

**Fig. 1.** Schematic diagram of grating fabrication by HP.

Generally, the substrate surface is perpendicular to the internal bisector of the two laser beams, and the obtained grating has the same frequency as that of the interfere fringes. Obviously, the grating frequency is proportional to the incident angle and inversely proportional to the laser wavelength (see Eq. (1)). Thus, there are two ways to increase the grating frequency: by shortening the laser wavelength and by enlarging the incident angle. However, it is inconvenient to align an optical system when the laser wavelength is extremely short or is outside of the visible light range, and the optical components of short-wavelength lasers are expensive. On the other hand, it is straightforward and common to increase the grating frequency by enlarging the incident angle. Since the incident angle cannot exceed 90°, the maximum grating frequency is theoretically limited to several thousand lines per millimetre. Regardless of this limitation, HP is widely used for grating preparation, particularly the preparation of gratings for moiré interferometry, due to its advantageous characteristics, such as its ability to produce large gratings with appropriate frequencies, negligible distortion, and uniform diffraction. However, the fringes formed by HP gratings in SEM moiré methods exhibit weak contrast, owing to the smooth sinusoidal topography of the grating lines.

Many techniques have been derived to improve the quality and to extend the applicability of gratings fabricated by HP. For example, Post et al. replaced the static light source with a moving point light source to eliminate the coherent noise [32]. Chen et al. developed a three-directional grating (using exposures at 0°, 45°, and 90°) to improve the residual measurement precision [34]. Shi et al. developed the refractive medium exposure method and grating frequency multiplication technique to improve the grating frequency to 6000 lines/mm using a laser wavelength of 457.9 nm [35]. In general, two types of methods can be employed to fabricate gratings on specimen surfaces: replication methods (TG [2]) and direct exposure methods (ZTG or etch grating [2,36] and DMLG [37–39]), as shown in Fig. 2. TGs are widely used in tests that are performed at temperatures below 120 °C due to its advantages of simplicity, versatility in terms of specimen size and material, and low cost. In contrast, the direct exposure methods were developed to produce gratings that are usable in extreme environments, particularly at high temperatures. However, fabricating a grating directly on a specimen surface is complicated and expensive. First, the specimen material should be mirror-polished, which seems impossible for porous materials; in addition, the resist should be removed from the window, implying that no residual resist may remain in the grooves, which places quite strict demands on the exposure and developing processes. Thus, direct exposure methods are not utilized unless required for a particular application [33].

### 2.2. Electron beam lithography

EBL is a standard technique that is widely used in micromachining. In this method, a focused beam of electrons is scanned to draw custom shapes on a surface that is covered with an electron-sensitive resist film. The electron beam can change the solubility of the resist and enable subsequent, selective removal of either the exposed or non-exposed regions of the resist during the developing process. EBL, which is schematically illustrated in Fig. 3, is similar to HP except in terms of the beam source and the resist. Owing to the use of an ultra-short-wavelength electron beam, EBL has a very fine resolution (20 nm); thus, it can be employed to fabricate gratings with ultra-high frequencies (more than 10,000 lines/mm). The steps of grating preparation by EBL are listed in Fig. 4.

EBL is a serial manufacturing method, and the resist is exposed point by point, which leads to a very low efficiency. It takes on the order of several hours and several thousands of dollars to prepare a grating with an area of 1 $cm^2$. Therefore, EBL is suitable for the