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Full Length Article

Laser induced ripples' gratings with angular periodicity for fabrication of diffraction holograms

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ABSTRACT

Laser induced ripples (also known as Laser Induced Periodic Surface Structures, LIPSS) have gained a considerable attention by both researchers and industry due to their surface functionalization applications. These ripples act as diffraction gratings for the visible light therefore it is widely used in some optical applications and color marking. In this research, a method is proposed for producing holograms by varying the ripples' orientation along the beam path during the laser scanning and thus producing a pattern of ripples orientations. It was demonstrated that, by employing this method, it was possible to produce linear and radial pattern of gratings by changing the ripples' orientations following a given periodic function. As a result, smooth transitions of diffracted monochromatic light along the beam path were achieved, especially in diffracting colors from different locations when changing the azimuthal and incident angles of the incident white light. In addition, the reflection of polarized white light by such periodic gratings was investigated and it was shown that it was fully dependent on the ripples' orientations in respect to the light linear polarization vector.

1. Introduction

Since laser induced ripples (also known as Laser Induced Periodic Surface Structures, LIPSS) were observed for the first time by Birnbaum [1] five decades ago, they attracted the interest of many researchers and industries due to their surface functionalization capabilities. LIPSS are considered the smallest structures that can be generated by using light [2] on most of the materials, e.g. metals, semiconductors, glasses and polymers [3,4], and also in any environment, in particular in air, gases, liquids or vacuum [5,6]. LIPSS have found applications in many fields including, but not limited to, brazing [7], modifying surfaces' wetting properties [8], improving surfaces' tribological performance [9–11], color marking [12–16], inhibiting bacteria attachments and facilitating cell growth [17].

In general, LIPSS have three main characteristics: depth, periodicity and orientation. The capabilities to control them become very important in the effort to produce surfaces with given functional responses. Therefore, their formation mechanism has been investigated by many researchers in order to understand how the laser processing settings affect these three LIPSS characteristics and thus to meet the specific requirements of different applications. However, there is still no comprehensive understanding of this phenomenon [3,4,18] and the role of surface plasmon polaritions is still questionable [19]. From many reported empirical studies, it is evident that the LIPSS depth is nonlinearly dependent on laser fluence [20]. Regarding periodicity, LIPSS can have either low spatial frequency (LSFL) or high spatial frequency (HSFL). HSFL can be achieved using relatively low fluence [19,21]. The periods of both LIPSS types are dependent on the laser wavelength (λ) [15]. For a normal beam incident angle, the LSFL period is approximately in the same order as λ, while for HSFL it is much smaller and depends on the material refractive index, typically $\lambda/2$ [22] or even smaller by one order [23,24]. In case of LSFL, an increase in the laser incident angle leads to an increase of LIPSS period [25] (although some researchers have reported that the beam incident angle does not affect it [20]).

LIPSS orientation is dependent on the electric field vector of the laser polarization [20,26]. Generally, their orientation is orthogonal to the linear polarization vector; however, LIPSS parallel to the polarization vector have been reported, too [18,22]. Thus, the laser polarization state is very important and has a major impact on laser-matter interaction, especially on the absorbed laser energy that directly affects the damage threshold [27] and laser-matter interaction results, e.g., the width of the scanning lines [2,28] and also the LIPSS orientation [2,29]. Consequently, polarization state affects most of the laser-based processes such as, drilling

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[29–31], cutting [29,32], welding [29] and texturing, e.g., the generation of complex surface structures [33]. Hence, the ability to control the polarization state during laser processing is important both for ablation and surface texturing applications [26].

The polarization state can be controlled employing different methods, such as using wave plates [30,31,34] or by employing diffractive optical elements, e.g. spatial light modulators (SLM) and liquid crystal polarizers [26,35–38]. The effects of changing the polarization state were studied in the context of different laser processing applications, in particular, to control the orientation of nano gratings by superimposing two pulses [21]; to generate holograms inside glasses [39]; to produce polarization dependent diffraction gratings [40]; to imprint images on metallic surfaces [41]; to selectively control the appearance of two [42] or multiple symbols [13]; to generate HSFL and LSFL in one field [43]; to superimpose and overwrite LIPSS [19]; and also to generate LIPSS with different orientations within one spot using SLM [44]. Also, the influence of continuously altering the laser polarization state on drilling, sheet metal cutting and texturing operations was reported [26,30,31,33,35,45,46]. Recently, Hermens et al. [38] reported a synchronized use of a liquid crystal polarizer, laser scanner and 5-axis stage to generate LIPSS with different orientations on free form surfaces.

A method for producing holograms on metallic surfaces by dynamically varying the laser electric field vector is reported in this paper. In particular, a method is proposed to continuously vary the orientation of the neighboring LIPSS along the beam path by dynamically changing the orientation of a linear polarization vector during the scanning process. In this way, the LIPSS orientations within single spots or even within smaller areas (depending on the ratio between the polarization vector angular velocity and the scanning speed) were continuously varied to achieve smooth diffraction transitions along the beam path in the processed field. Then, to validate the method, linear and radial pattern of gratings were generated by following given periodic functions and scanning strategy.

2. Method

Before proceeding with the description of the proposed method, the LIPSS formation and its behavior when interacting with a white light is discussed. In particular, when ultrashort pulsed laser with fluence close to the ablation threshold interact with metal substrates, periodic ripples are generated on the surface. The period, *d*, of these ripples is mainly dependent on the laser wavelength but also on laser incident angle and dielectric constants of both the medium and the substrate as shown in Eq. (1) [25,46].

$$d = \frac{\lambda}{Re\left(\sqrt{\frac{\varepsilon_d * \varepsilon_m}{\varepsilon_d + \varepsilon_m}}\right)} \text{ for normal incident angle} \tag{1}$$

where: λ - laser wavelength, and ϵ_d and ϵ_m are the dielectric constants of the dielectric medium and the metal substrate, respectively.

Such ripples act as diffraction gratings when their periodicity is higher than the wavelength of the incident light. The diffraction order, angle and sensitivity are all dependent on the ripple periodicity and the light incident angle, as depicted in Fig. 1. The functional dependence between them is as follows [47]:

$$m\lambda = \mathrm{d}(\sin\theta_m - \sin\theta_{in}\cos\varnothing) \tag{2}$$

where: m is the diffraction order, θ_m - diffraction angle of the m_{th} order, θ_{in} - light incident angle, and ϕ - the azimuthal angle between the grating vector and the light incident vector in the grating plane.

Ripples diffract white light when the azimuthal angle of the incident light meets specific conditions. In particular, the light is diffracted when the incident light is normal to the ripples (parallel to the LIPSS vector) in the grating plane. The intensity of the diffracted light depends on the azimuthal angle and it reaches its maximum when $\phi = 90°$ and drops down sinusoidally to its minimum at $\phi = 0°$. Thus, hologram patterns can be generated by a control rotation of polarization vector and thus make the ripple orientation dependent on their position along the beam path.

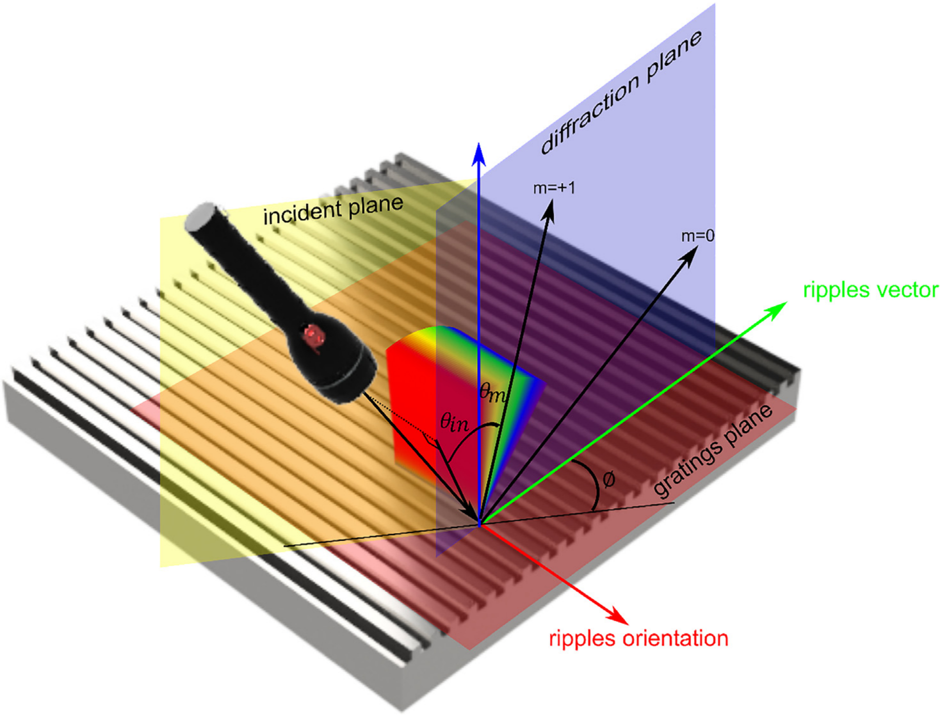

Fig. 1. Interaction of white light with diffraction gratings.