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Laser surface patterning using a Michelson interferometer and femtosecond laser radiation

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ABSTRACT

We report on a simple method to obtain surface gratings using a Michelson interferometer and femtosecond laser radiation. In the optical setup used, two parallel laser beams are generated using a beam splitter and then focused using the same focusing lens. An interference pattern is created in the focal plane of the focusing lens, which can be used to pattern the surface of materials. The main advantage of this method is that the optical paths difference of the interfering beams is independent of the distance between the beams. As a result, the fringes period can be varied without a need for major realignment of the optical system and the time coincidence between the interfering beams can be easily monitored. The potential of the method was demonstrated by patterning surface gratings with different periods on titanium surfaces in air.

1. Introduction

Surface patterning and texturing are becoming increasingly important for a wide range of applications [1,2]. However, in order to bring these processes to industrial use easy-to-handle and cost effective microfabrication methods are required. Femtosecond lasers are powerful tools for this purpose, owing to their considerable advantages over long-pulse duration lasers [3,4]. Due to their extremely short pulse duration, a very high peak power is achieved leading to intense non-linear effects. As a result, almost any type of material can be processed, including transparent dielectrics, polymers and metals, without undesirable collateral thermal effects [5–8].

In recent years, periodic surface structures were successfully fabricated by two-beam interferometric techniques using femtosecond pulsed laser radiation [9–15]. The principle of operation of these techniques is simple: when two pulses overlap in time and space, an interference pattern is generated that can be used to create surface gratings. Several optical schemes have been proposed up to now and gratings were successfully engraved in a number of different materials. Kawamura and co-workers [10–12] proposed an optical scheme where a femtosecond laser pulse is split into two by a beam splitter, then recombined by a set of mirrors and two focusing lenses to produce the interference pattern. The main drawback of this technique is the difficulty in precisely adjusting the two focusing lenses to focus the two pulses simultaneously at the same spot. Moreover, in order to change the angle between the two intersecting beams and vary the fringe spacing, the entire optical system must be realigned. As an alternative to this method, Venkatakrishnan and co-workers [14,15] proposed an optical configuration based on the generation of two parallel beams which are focused by the same lens. Since the two beams are focused by the same lens, they will be focused exactly at the same spot in the focal plane of the lens. This setup simplifies the alignment required to focus the two beams at the same spot but a compensating plate must be introduced to equalize the optical path of the two beams.

Here, we present a simple method to produce surface gratings using an optical scheme based on a Michelson interferometer. The main advantages of this method with respect to those reported previously [9–15] are the simplicity of the interferometer design and of the procedure used to monitor time coincidence. Similarly to Venkatakrishnan [14,15], a beam splitter is used to generate two parallel beams that are focused on the same area by the same focusing lens. However, in our design the difference of optical paths of the two beams is independent of the distance between them. As a result, no compensating plate is needed. Moreover, time coincidence can be easily monitored with an infrared viewing card, thus avoiding the need for complex time monitoring techniques such as the sum-frequency generation method using non-linear crystals [9] or the third harmonic generation in air [16].

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To demonstrate the potential of the optical scheme presented, surface gratings were patterned on polished grade 2 titanium surfaces. This material was chosen because it is used in dental implants and other medical devices, and it is known that surface texturing enhances the osseointegration ability of titanium and the strength of the bone/implant interface [17,18].

2. Optical set-up

The laser source is a commercial Yb:KYW chirped-pulse-regenerative amplification laser system (Amplitude Systèmes, s-Pulse HP) providing linearly polarized laser pulses with a duration of 560 fs at a central wavelength of $\lambda = 1030$ nm and a maximum repetition rate of 100 kHz. The spectral linewidth is $\Delta\lambda = 4$ nm yielding for the coherence length $L_c = \lambda^2/\Delta\lambda = 265$ μm and for the temporal coherence $\tau_C = L_C/c = 884$ fs.

The patterns were produced using two configurations of an optical set-up based on the Michelson interferometer, as shown in Fig. 1. Configuration 1 (Fig. 1(a)) was used to achieve time coincidence between the interfering beams, while configuration 2 (Fig. 1(b)) was used to create the patterns on the sample surface. In both configurations the laser beam is split into two beams by a non-polarizing beam splitter. Beam 1 is reflected by mirror M1 and, after crossing the beam splitter, directed to the focusing lens (FL). Similarly, beam 2 is reflected by mirror M2 and, after being reflected by the beam splitter, directed to the focusing lens. Finally, the two beams are focused by the focusing lens to a common focal point on the sample's surface. The main difference between the two configurations is the angle between mirrors M1 and M2 and beams 1 and 2. In configuration 1, the mirrors are perpendicular to the beams, while in configuration 2 both mirrors are tilted by an angle θ.

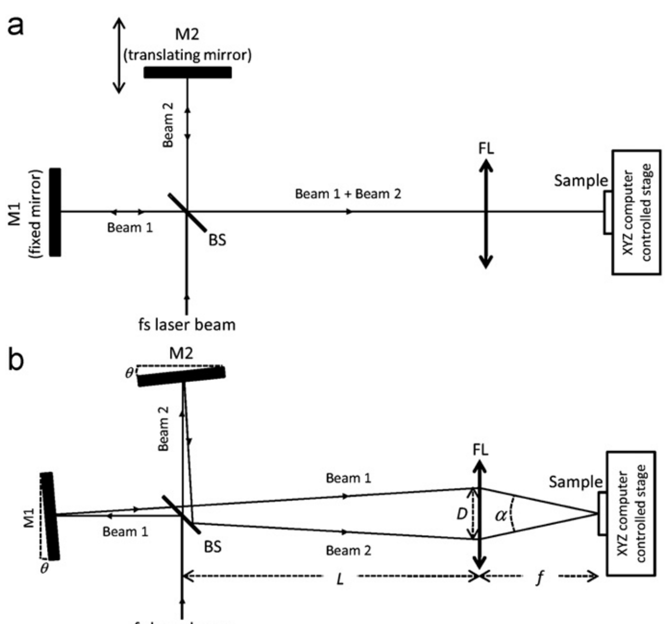

Fig. 1. Experimental set-up: (a) configuration 1; (b) configuration 2. Legend: BS=Beam splitter; M1 and M2=mirrors; FL=Focusing lens.

In order to superimpose the two beams in time, configuration 1 is used. In this configuration the optical path length of beam 2 can be controlled by a precise translation movement of mirror M2. To monitor time coincidence, an infrared viewing card is placed between the beam splitter and the focusing lens. If the difference between beam 1 and beam 2 optical paths is less than the coherence length of the laser, since the interfering beams are practically parallels an interference pattern will be visible at the naked eye on the infrared viewing card.

By moving mirror M2, the maximum and minimum positions for which the pattern is visible are determined and, afterwards, mirror M2 is fixed at the middle between these two positions in order to equal the optical paths of the two beams.

After achieving time coincidence, configuration 2 is obtained by rotating mirrors M1 and M2 of exactly the same angle θ using kinematic mirror mounts. Since the distance between the beam splitter and the focusing lens is $L = 2$ m and the distance between the two beams at the focusing lens is $D < 50$ mm, the angle θ is less than 0.012 rad. For such a small angle, the optical path difference that arises due to the rotation of the mirrors is much smaller than the coherence length of the laser and temporal coherence is preserved.

In configuration 2, the fringe spacing at the sample surface, d, can be calculated according to

$$d = \frac{\lambda}{2\sin(\alpha/2)}, \quad (1)$$

where λ denotes the radiation wavelength and α the angle between the two beams after the focusing lens. Since the angle θ is small, beam 1 and beam 2 can be considered parallel in their trajectory between the beam splitter and the focusing lens. As a result, the angle α is a function of two parameters, namely the distance between the two laser beams at the lens, D, and the focal length f of the focusing lens. From Fig. 1, it results from simple trigonometry that $\alpha = \tan^{-1}(D/2f)$. Hence the fringe spacing can be controlled by changing either D or f.

3. Examples of application

Fig. 2(a) depicts a low-magnification scanning electron microscopy (SEM) picture of a pattern produced in a 3×3 mm^2 area using a 75 mm focusing lens and a 40 mm distance between the

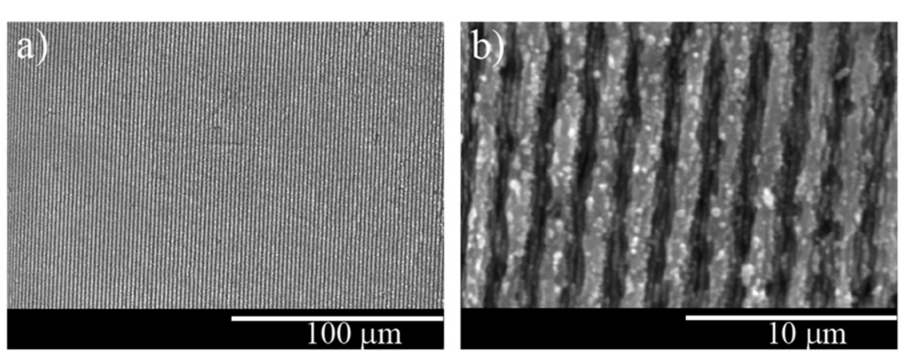

Fig. 2. SEM micrographs of a large-area grating with 1.9 μm period: (a) low-magnification image; (b) magnification of (a).