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Selective appearance of several laser-induced periodic surface structure patterns on a metal surface using structural colors produced by femtosecond laser pulses

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ABSTRACT

Ripples with a subwavelength period were induced on the surface of a stainless steel (301 L) foil by femtosecond laser pulses. By optimizing the irradiation fluence of the laser pulses and the scanning speed of the laser beam, ripples with large amplitude (∼150 nm) and uniform period could be obtained, rendering vivid structural colors when illuminating the surface with white light. It indicates that these ripples act as a surface grating that diffracts light efficiently. The strong dependence of the ripple orientation on the polarization of laser light offers us the opportunity of decorating different regions of the surface with different types of ripples. As a result, different patterns can be selectively displayed with structural color when white light is irradiated on the surface from different directions. More interestingly, we demonstrated the possibility of decorating the same region with two or more types of ripples with different orientations. In this way, different patterns with spatial overlapping can be selectively displayed with structural color. This technique may find applications in the fields of anti-counterfeiting, color display, decoration, encryption and optical data storage.

1. Introduction

In past several decades, laser induced periodic surface structures (LIPSSs) on the surfaces of various materials (including metals, semiconductors and dielectrics) with periods approximately equal to the laser wavelength have been investigated extensively by using pulsed lasers such as nanosecond and picosecond lasers [1–5]. In recent years, this study has been extended to femtosecond (fs) lasers and it has been known that LIPSSs (e.g., ripples) can be created on the surface of a material when the laser fluence near the ablation threshold of the material [6–14]. In most cases, the periods of LIPSSs are found to be slightly smaller than laser wavelength [8–14]. In addition, the ripples usually appear to be perpendicular to the polarization of laser light. The interference between the incident laser light and the surface scattered wave was proposed many years ago to explain the formation of LIPSSs [3]. Recently, it is suggested that the surface plasmon plaritons (SPPs) excited by fs laser irradiation play a crucial role in the formation of LIPSSs [11,14,15].

Very recently, LIPSSs with periods significantly smaller than laser wavelength have attracted considerable interest because of their potential applications [16–21]. While the LIPSSs with periods approximately equal to the laser wavelength are called low spatial frequency LIPSSs (LSFLs), the LIPSSs with periods much smaller than laser wavelength are referred to as high spatial frequency LIPSSs (HSFLs). Apparently, HSFLs induced by fs laser pulses cannot be interpreted by using the physical models described above [3,4]. So far, several mechanisms have been proposed to explain the formation of HSFLs induced by fs laser pulses, such as self-organization [22], second harmonic generation (SHG) [16], excitation of surface plasmon polaritons [23], and Coulomb explosion [24] etc. However, the actual physical mechanism responsible for the generation of HSFLs is still in debate. Very recently, we proposed a physical mechanism to explain the HSFLs formed on metal surface [25].

Due to their potential applications, periodic surface structures have attracted great interest in color display, anti-counterfeiting, decoration, sensing, and optical data storage etc [26–28]. For color display, LSFLs are usually employed because the periods of LSFLs fabricated by fs lasers with a central wavelength at 800 nm can effectively diffract white light and exhibit vivid structural color. For example, the use of LSFLs for color marking or color display has been successfully demonstrated [29–31]. In comparison, HSFLs may exhibit advantages in optical data storage because of their small periods. The subwavelength period and polarization dependent orientation of ripples makes them attractive for material and

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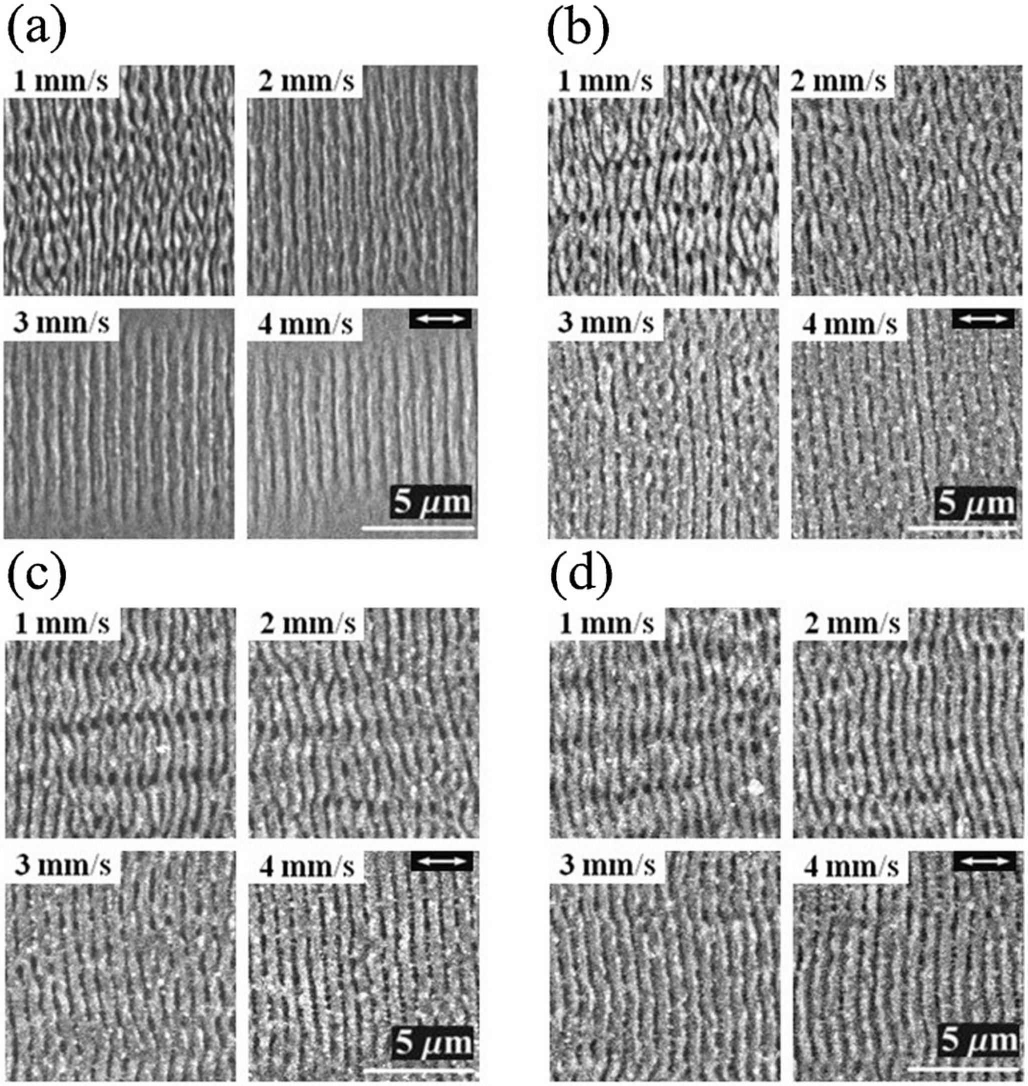

Fig. 1. SEM images of the ripples formed on the surface of the stainless steel by fs laser pulses with different fluences. (a) 0.16 J/cm^2, (b) 0.40 J/cm^2, (c) 0.64 J/cm^2, and (d) 0.80 J/cm^2. In each case, four scanning speeds, which are 1 mm/s, 2 mm/s, 3 mm/s, and 4 mm/s, have been employed to produce ripples. The arrows in the images indicate the polarization of fs laser light which is parallel to the scanning direction.

device applications. From the viewpoint of practical application, it is essential to produce deep and uniform ripples that can be extended to a large area. Therefore, the scanning of focused laser beam is necessary. In this case, the quality of the formed ripples depends strongly on the irradiation fluence of the laser pulses and the scanning speed of the laser beam. How to obtain high-quality ripples that behave as an efficient surface grating through optimizing these two critical parameters has become a major issue to be solved in the fabrication. In addition, it is desirable that the polarization dependence of the orientation of ripples can be utilized to selectively decorate surface with structural colors that are sensitive to incident light coming from a certain direction. More importantly, it is interesting to know whether the same area of a surface can be encoded with laser-induced ripples oriented in different directions.

In this article, we demonstrated the formation of deep and uniform ripples on the surface of a stainless steel foil by scanning fs laser with an optimized energy density and scanning speed. Vivid structural colors that span the entire visible spectrum were observed when illuminating the surface with white light and viewing at different angles. In addition, we showed that the selective decoration of the metal surface with ripples oriented in different directions could be used to display different patterns that are sensitive to illumination direction. Finally, we confirmed experimentally that the polarization dependence of ripples could be utilized to encode the same area with at least two types of ripples oriented in different directions. This polarization multiplexing may find applications in the fields of anti-counterfeiting, color display, decoration, encryption and optical data storage.

2. Experimental

In experiments, we used a Ti: sapphire fs amplifier (Legend, Coherent) that delivers 800 nm, 90 fs, and horizontally polarized pulses at a repetition rate of 1 kHz. The metal we studied was 301 L stainless steel that is widely used in industry. It was mechanically polished and washed in an ultrasonic cleaner with acetone. The surface roughness of the stainless steel sample was less than 10 nm. It was fixed on a three-dimensional motorized translation stage (7SC3-4, 7-Star) with a position accuracy of 625 nm. The diameter of the unfocused laser beam with a Gaussian profile is $\sim$ 8 mm. The M^2 factor of the laser beam is $\sim$1.16. It was focused