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Laser-induced switching of GST films using a spatial light modulator

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Abstract. One of the promising materials enabling tuning of optical response in photonic devices is the class of chalcogenide optical phase-change materials (oPCMs), such as GeSbTe (GST). These materials exhibit nonvolatile amorphous and crystalline phase states under normal conditions, while offering quick (ns-) phase switching and prominent optical contrast, which can be induced via laser irradiation. Direct laser modification of PCM films is usually realized through a point-by-point approach, by sequentially scanning a focused laser beam over the film surface. Although this technique is straightforward and easy to implement, it significantly limits potential fabrication speeds. In this work, we study a method of laser-induced switching of the phase state of GST films using a spatial light modulator. We demonstrate that this approach enables fast patterning of large areas of the material.

Keywords: phase-change materials, GeSbTe, laser imprinting, spatial light modulator

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Лазерно-индуцированное переключение фазового состояния пленок GST с помощью пространственного модулятора света

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Аннотация. Перспективными материалами, позволяющих реализовать перестраиваемый оптический отклик в фотонных устройствах, является класс халькогенидных оптических материалов с фазовой памятью (МФП), таких как GeSbTe (GST). Эти материалы стабильны при нормальных условиях, при этом обладают высокой скоростью переключения (нс-) и заметным оптическим контрастом, который может быть индуцирован лазерным излучением. В данной работе мы исследуем метод лазерно-индуцированного переключения фазового состояния пленок GST с помощью пространственного модулятора света. Этот подход позволяет быстро модифицировать большие участки материала, без механического сканирования образца или объектива.

Ключевые слова: материалы с фазовой памятью, GeSbTe, лазерная обработка, пространственный модулятор света

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Introduction

Optical phase-change materials (PCMs) enable variety of applications for tunable photonics, due to a unique combination of such properties as nonvolatality, ns-switching speeds and large refractive index contrast (e.g., $\Delta n = 2.24$ at 1550 nm) [1]. Additional feature of these materials is the possibility to induce the phase transition by thermal, electrical and laser stimuli, enabling mixed-operation photonic designs. Direct laser writing applied for PCMs appears to be a promising nanofabrication technique, as recently demonstrated for the direct imprinting and rewriting of photonic integrated circuits (PICs) [2] and the fabrication of metasurfaces [3]. This technique can be further advanced by replacing the point-by-point imprinting approach, in which the laser beam is sequentially scanned over the sample surface, with imprinting by modulated laser irradiation using a spatial light modulator (SLM). SLMs has been successfully applied for precision modulation in holographic displays, optical tweezers and lithography [4]. Possibility of using an SLM for the crystallization of thick 1 μm films of $Ge_2Sb_2Se_4Te$ (GSST, Se-substituted phase-change alloy) was demonstrated earlier [5]. In this work we focus on applications for integrated devices, studying the laser-induced modification of a thin (20 nm) film of $Ge_2Sb_2Te_5$ (GST-225, or just GST) deposited on top of a silicon nitride guiding layer. We show that using an SLM enables large-scale – up to tens of microns – crystallization of the PCM, through two approaches: direct imprinting of the full pattern and steering of multiple laser spots.

Materials and Methods

Amorphous $Ge_2Sb_2Te_5$ films with a thickness of 20 nm were deposited using a DC magnetron sputtering system on a thermally oxidized silicon wafers (2.6 μm thick SiO_2 layer) with a 450 nm thick stoichiometric low pressure chemical vapor deposited (LPCVD) silicon nitride (Si_3N_4) layer. The pressure of Ar ions during the GST deposition process was 4 mTorr, the sputtering power was 25 W. To prevent oxidation of GST, the films were covered with a 20 nm thick SiO_2 capping layer. The composition and distribution of elements for the GST films were controlled by the time-of-flight secondary ion mass spectrometry (IonTOF TOF SIMS 5) together with the Auger spectroscopy (PerkinElmer PHI-660).

Figure 1, *a* shows a schematic of the optical setup. We utilized emission of a Yb:KGW femtosecond laser system PHAROS, which operates at 1030 nm with a pulse duration of 290 fs, and a continuous wave (CW) laser that works at 1064 nm. The intensity of the laser emission was controlled by an attenuator, which consisted of a half-waveplate and a Glan polarizer. A beam expander was used to increase the beam size to match the vertical size of the SLM matrix, maximizing its illuminated area. Light modulation was realized with a reflective phase-only SLM Holoeye Pluto-2.

We used a 4*f* system with 20 cm focal length lenses to image the phase pattern, formed by the SLM onto the back focal plane of an objective. The modulated laser beam was focused on the sample with a Zeiss A-Plan 60× objective when using the CW laser and with a 20× Mitutoyo Plan Apo NIR objective with the fs-laser.

Phase masks for the SLM were calculated using the Fidoc algorithm [6]. To avoid modification of the patterns by the zero diffraction order, we summed the calculated masks with a blazed grating, shifting the patterns by approximately 3/4 of their characteristic size. The effective refractive indexes of the waveguide modes were calculated using COMSOL Multiphysics software.

Results and Discussion

We demonstrate that the switching of phase state of the GST film can be realized through two approaches. In the first approach, a desired pattern can be imprinted by forming a corresponding intensity distribution with an SLM using a single pre-calculated phase mask. In this case, the pattern can be imprinted all at once, using a fs-laser to provide fluence values sufficient for crystallization, which is approximately 5 mJ/cm^2 at 1030 nm. Figure 1, *b* shows a phase mask on the SLM matrix, corresponding to a 5×5 array of dots with a spacing of 10 μm. The phase mask irradiated with a fs-laser produces the pattern in the focal plane of the objective, leading to the crystallization of the material at the intensity maxima. An optical image of the pattern imprinted in the as-deposited amorphous GST film is shown in Figure 1, *c*. Here, the crystallized areas appear brighter due to the higher reflectivity of the crystalline phase ($R_{a\text{-}GST}/R_{c\text{-}GST} = 0.77$ at 570 nm).

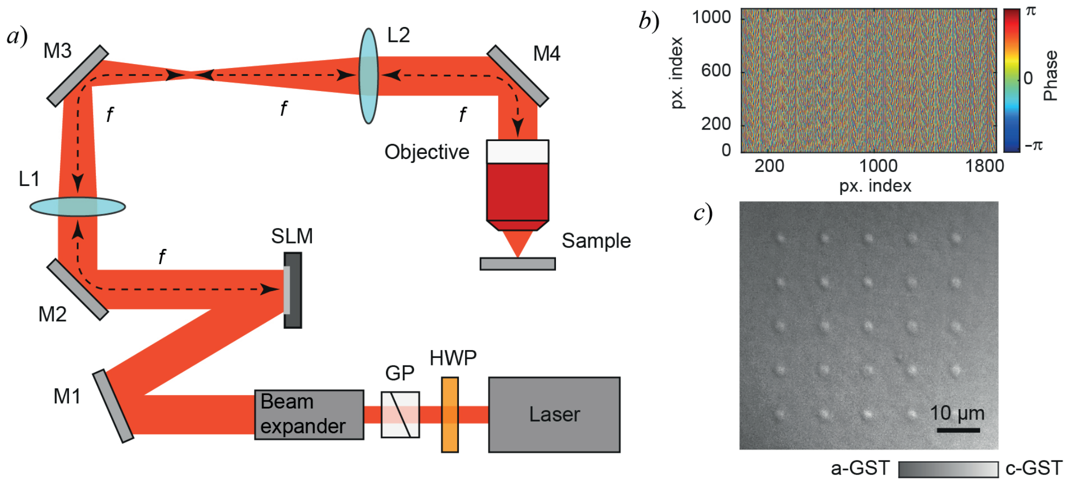

Fig. 1. Large-scale GST laser patterning. (*a*) schematic of the optical setup; here HWP – half-wave plate, GP – Glan polarizer, Mi – mirror, SLM – spatial light modulator, Li – lens with the focal length of f. (*b*) phase mask on SLM, corresponding to the array of dots, (*c*) optical image of the imprinted pattern

The second approach relies on splitting the pump laser beam with the SLM to steer multiple laser beams over the surface of the film in parallel. Here, the phase mask $\varphi_{tot}(m, n)$ presents a superposition of blazed diffraction gratings, calculated as follows [7]:

$$\varphi_{tot}(m,n) = \arg\left[\sum_{k}^{N} \exp(i\varphi_k(m,n))\right], \tag{1}$$

where $\varphi_k(m, n)$ is the blazed phase grating, corresponding to the *k*-th beam and *m*, *n* are the indexes of pixels of the phase mask in horizontal and vertical directions, respectively. The phase grating providing a given displacement x_k, y_k of the beam is

$$\varphi_k(m,n) = \frac{2\pi\Delta}{\lambda f_{obj}}(x_k m + y_k n)$$

where λ is the laser wavelength, f_{obj} is the focal length of the objective, and Δ is the pixel pitch (8 μm for our SLM matrix). The total phase mask $\varphi_{tot}(m, n)$ corresponds to the intensity distribution of N laser spots, placed at given coordinates x_k, y_k. Due to the smaller instantaneous modification area, this approach can be implemented to increase the speed of the imprinting process, if there is a limitation on laser power.

Figure 2, *a* a shows phase masks, corresponding to the first $\varphi_1(m, n)$ and second $\varphi_2(m, n)$ laser spots (with coordinates of the ends of the arrows in Fig. 2, *b*, right pattern), and their superposition $\varphi_{tot}(m, n)$ calculated using equation (1). The gratings are dynamically updated to traverse the contour of the desired pattern by two CW-laser spots, as shown in Figure 2, *b*. Here, first, the spatial coordinates of the points of a pattern (the ITMO University logo and semicircles with a $\pi/4$ sector angle) were calculated. Next, the set of coordinates corresponding to two continuous fragments of the pattern was sequentially associated with the superposition of blazed gratings, shifting the laser spots to the corresponding coordinates. As one contour is imprinted, the formation of the next one starts immediately, allowing two beams to operate independently in parallel. Optical images of the completely imprinted patterns are shown in Figure 2, *c*.

Periodic modification of the effective refractive index of the waveguide mode by the changed phase state of the GST film ($n_{eff,\ am} = 1.67$ and $n_{eff,\ cr} = 1.73$ at 1550 nm, TM_0 mode), can be used as a tunable light coupling/decoupling structure (see Fig. 2, *c*, right pattern) [2]. By fine manipulation of the laser fluence during the formation process, it is possible to further advance this technique, forming patterns with intermediate crystallization states and achieving multilevel tuning of the optical response of the formed structure [8].

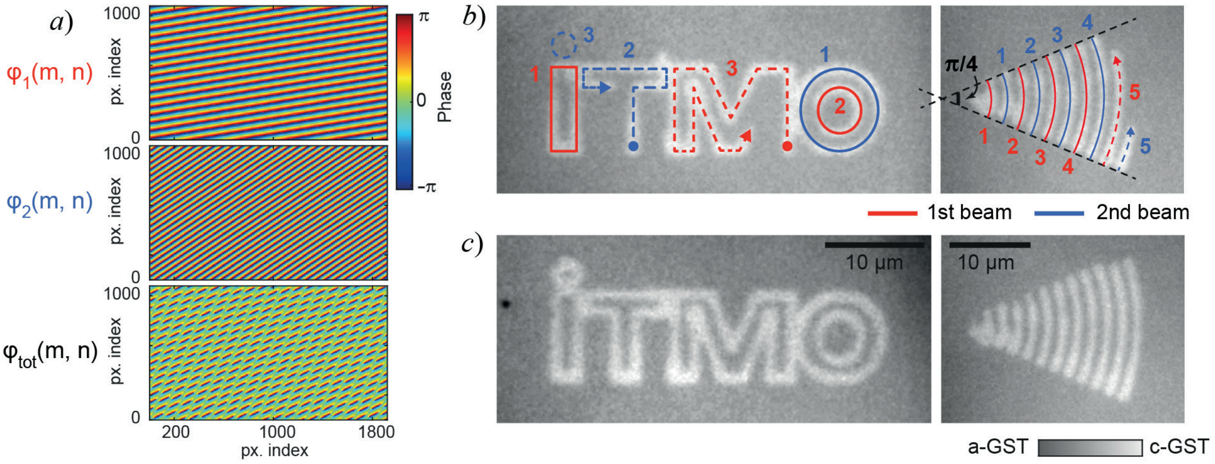

Fig. 2. Patterns imprinting by multibeam steering. (*a*) Phase gratings corresponding to the 1-st, $\varphi_1(m, n)$, and 2-nd, $\varphi_2(m, n)$, beams and the phase mask of their superposition, $\varphi_{tot}(m, n)$. The imprinting process is realized by two beams, forming the patterns in parallel (*b*), the numbers correspond to the order in which the continuous contours were imprinted; resulting patterns (*c*)

Conclusion

In this work, we have explored the large-scale phase modification of a thin GST film integrated with a silicon nitride planar waveguide, using a spatial light modulator. We have demonstrated the formation of binary phase patterns induced by CW- and fs-laser irradiation. The proposed method of phase switching opens the way for fast direct laser imprinting in PCMs for tunable PICs or holography.

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