Geometric phase via stress induced birefringence

Martynas Beresna, Gilberto Brambilla
Optoelectronics Research Centre
University of Southampton
Southampton, United Kingdom
m.beresna@soton.ac.uk

Xuewen Wang, Saulius Juodkazis
Centre for Micro-Photonics
Swinburne University of Technology
Melbourne, Australia

Raymond C. Rumpf
EM Lab
Department of Electrical & Computer Engineering
University of Texas at El Paso, USA

Abstract—**Optical components exploiting Pancharatnam-Berry phase are implemented by harnessing laser induced stress birefringence. Beam converters for obtaining beams with orbital angular momentum are demonstrated in glass and crystalline materials using this technique.**

Keywords: femtosecond laser, orbital angular momentum, Pancharatnam-Berry phase

I. Introduction

In the last few years an increasing number of optical components exploiting Pancharatnam-Berry phase have been demonstrated [1]. Instead of relying on phase delay introduced by the material, these components exploit birefringence or dichroism. Typically, large birefringence is introduced by nanostructuring the material surface or bulk of the material thus introducing so called form birefringence. This not only allows to achieve high retardance values in thin sheets of material but also permits to control the slow axis local orientation. This last feature enables rapid developing of various optical components such as lenses, gratings or optical vortex converters [2, 3].

Another well known path to introduce birefringence is stress [4], which occurs while stretching or compressing the material. The level of birefringence depends on the amount of stress and on the photoelastic coefficient [5]. The stress frequently occurs during laser processing. Normally, it is considered as detrimental effect. However, harnessing it could be extremely useful for developing novel optical components. Stress can be induced in the bulk of a wide range of materials providing more flexibility to the design of optical components as compared to surface modification.

There are several sources of stress which occur after femtosecond laser irradiation. For crystals this is mainly material rarefication in the irradiated zone related to micro-explosion [6]. The stress produced in this way exhibits spherical symmetry for a single shot conditions. If stress is induced by a laser inscribed line, the stress is perpendicular to the written structure. This type of stress is also widely exploited for implementing waveguiding structures in crystalline materials. The expanding material in the irradiated zone induces strain in the vicinity of the track and as a result refractive index increases. Waveguiding structures can be induced between two or more adjacent laser tracks [7].

Another source of stress is nanostructure formation, which can be easily obtained with sub-picosecond pulses in silica glass. The nanograting formation leads to material expansion and stress. The stress lacks spherical symmetry and is stronger in the direction of the nanograting [8].

In this paper we describe a technique which exploits stress induced by laser irradiation as a source of birefringence. We demonstrate that by controlling stress distribution we can implement complex phase patterns. As an example, we fabricated an optical converter for generating higher charge optical vortex embedded in silica glass.

II. Experimental Setup

Stress was introduced by using a femtosecond laser system Pharos, Light Conversion Ltd emitting 230 fs pulses at 200 kHz repetition rate. The second harmonic beam (515 nm) was focused with a 0.5 NA objective lens into the bulk of the sample. To avoid unsymmetrical stress distributions resulting from nanogratings induced by laser irradiation, a quarter-waveplate was inserted into the beam to circularly polarize the beam. For comparison, we chose to irradiate three different materials: 1 mm thick soda lime glass, 1 mm thick fused silica, and 0.35 mm thick sapphire. Different pulse energies after objective were tested varying from 90 nJ to 900 nJ, with varying writing speed from 5 mm/s to 20 mm/s in order to achieve the best fabrication conditions for practical applications. After irradiation the fabricated elements were tested at 532 nm using two crossed circular polarizers.

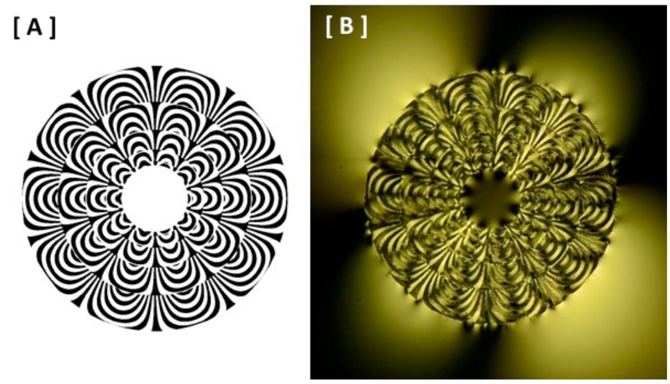

Figure 1. Optical element for generating optical vortex charge 10. [A] Computer generated geometry. [B] Actual element fabricated in the silica glass substrate (imaged in crossed polarized light).

Ultrashort light pulses were chosen for material irradiation because this would allow to reduce collateral damage which would lead to cracks in the material. Crack formation would release stress and reduce added phase retardance and introduce spurious phase distribution in the vicinity of the modification.

III. Results and Discussion

Among the three tested materials, soda lime glass exhibited much weaker birefringence, possibly the result of heat accumulation which partially anneals modified material releasing the stress. Sapphire exhibited sufficiently large birefringence. A single layer produced weak birefringence over thicknesses of the order of 20-40 nm. Thus multiple layers were inscribed in the bulk of the material to achieve higher Gaussian beam to vortex beam conversion efficiency. Each layer was separated by 10 µm to avoid large axial stress overlaps that can result in cracks.

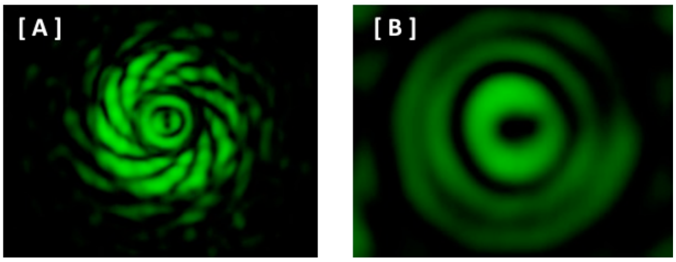

Figure 2. Beam generated with stress induced phase variation after 0.5 m [A] and 2 m [B] free space propagation.

However, after stacking multiple layers cracks started developing compromising performance of the fabricated element. As a result, silica glass was chosen for final tests since it was able to sustain larger amount of stress allowing to reach high phase retardance.

As it was described in the introduction, the stress produced by material expansion is normally perpendicular to the inscribed line. Thus by controlling direction of the line one can control orientation of the stress. The simplest case is inscribing series of concentric rings which will produce radially variant stress. As a result, the birefringence will be radially variant as well. Such configuration is known to produce charge 2 optical vortex from circularly polarized light.

For characterizating series of charge 2 optical vortex converters were written in silica glass with different numbers of layers (10-70). With structures containing 60-70 layers we managed to reach 88% conversion efficiency. However, we observed high scattering reaching 70% of incident light. Scattering can be reduced by optimising the writing conditions.

In conclusion, we produced a complex geometry which introduced periodic tangential variation of stress (Fig. 1) and allowed generating charge 10 optical vortexes. Beam profiles taken at 0.5 m and 2 m confirmed the presence of orbital angular momentum (Fig. 2), thus demonstrating that complex phase elements can be fabricated by exploiting solely stress induced birefringence.

References

[1] N. Yu and F. Capasso, “Flat optics with designer metasurfaces,” Nat. Mat., vol. 13, pp. 139–150, 2014.

[2] Z. Bomzon, G. Biener, V. Kleiner, and E. Hasman, “Space-variant Pancharatnam–Berry phase optical elements with computer-generated subwavelength gratings,” Opt. Lett., vol. 27, pp. 1141-1143, 2002.

[3] R. Drevinskas, M. Beresna, J. Zhang, A. G. Kazanskii, and P. G. Kazansky, “Ultrafast laser-induced metasurfaces for geometric phase manipulation,” Adv. Opt. Mat., vol. 4, 1600575, 2016.

[4] B. McMillen, C. Athanasiou, and Y. Bellouard, “Femtosecond laser direct-write waveplates based on stress-induced birefringence,” Opt. Express, vol. 24, pp. 27239-27252, 2016.

[5] M. Gecevicius, M. Beresna, J. Zhang, W. Yang, H. Takebe, and P. G. Kazansky, “Extraordinary anisotropy of ultrafast laser writing in glass,” Opt. Express, vol. 21, pp. 3959-3968, 2013.

[6] S. Juodkazis, K. Nishimura, S. Tanaka, H. Misawa, E. G. Gamaly, B. Luther-Davies, L. Hallo, P. Nicolai, and V. T. Tikhonchuk, “Laser-induced microexplosion confined in the bulk of a sapphire crystal: evidence of multimegabar pressures,” Phys. Rev. Lett., vol. 96, 166101, 2006.

[7] A. G. Okhrimchuk, A. V. Shestakov, I. Khrushchev, and J. Mitchell, “Depressed cladding, buried waveguide laser formed in a YAG:Nd3+ crystal by femtosecond laser writing,” Opt. Lett., vol. 30, pp. 2248–2250, 2005.

[8] B. McMillen and Y. Bellouard, “On the anisotropy of stress-distribution induced in glasses and crystals by non-ablative femtosecond laser exposure,” Opt. Express, vol. 23, pp. 86-100, 2015.

This work was funded by Royal Academy of Engineering, UK.