Conference materials
UDC 538.958
DOI: https://doi.org/10.18721/JPM183.107

Visualization of electric field of e-beam-formed charge patterns in glass

A.N. Terpitskiy [1] ✉, I.V. Reshetov [1, 2], S.A. Scherbak [1, 2], A.A. Lipovskii [2, 1]

[1] Alferov University, St. Petersburg, Russia;

[2] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

✉ terpiczkij@mail.ru

Abstract. We have formed a given pattern of the second order optical nonlinearity in the subsurface region of a glass by electron irradiation. The nonlinearity was induced by the electric field of the electrons captured by the glass. Formed structure consisted of periodic “strips” and, being irradiated normally to the glass surface with an IR laser, generated the second harmonic (SH) radiation pattern similar to one of a phase diffraction grating. The pattern presented the results of an interference of the SH waves generated by nonlinear strips. Mapping of the SH radiation pattern in orthogonal polarizations of the fundamental laser beam allowed concluding about the distribution of the electric field of electrons captured in the glass.

Keywords: second harmonic generation, glass, e-beam lithography, grating structure

Funding: State assignment FSRM-2023-0009.

Citation: Terpitskiy A.N., Reshetov I.V., Scherbak S.A., Lipovskii A.A., Visualization of electric field of e-beam-formed charge patterns in glass, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.1) (2025) 44–47. DOI: https://doi.org/10.18721/JPM.183.107

Материалы конференции
УДК 538.958
DOI: https://doi.org/10.18721/JPM.183.107

Визуализация электрических полей зарядовых структур, сформированных электронным лучом в стекле

А.Н. Терпицкий [1] ✉, И.В. Решетов [1, 2], С.А. Щербак [1, 2], А.А. Липовский [2, 1]

[1] Академический университет им. Ж.И. Алфёрова РАН, Санкт-Петербург, Россия;

[2] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия

✉ terpiczkij@mail.ru

Аннотация. Продемонстрирована возможность формирования заданной нелинейной периодической структуры в приповерхностной области стекла электронным облучением. Нелинейность индуцировалась электрическим полем электронов, захваченных стеклом. Сформированная структура при облучении поверхности стекла по нормали ИК лазером генерировала вторую оптическую гармонику с диаграммой направленности, аналогичной диаграммам от фазовых дифракционных решеток. Картирование излучения второй гармоники при ортогональных поляризациях фундаментальной волны позволило сделать вывод о распределении электрического поля захваченных в стекле электронов.

Ключевые слова: генерация второй оптической гармоники, стекло, электронная литография, периодическая структура

Финансирование: Государственное задание FSRM-2023-0009.

Ссылка при цитировании: Терпицкий А.Н., Решетов И.В., Щербак С.А., Липовский А.А. Визуализация электрических полей зарядовых структур, сформированных электронным лучом в стекле // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.1. С. 44–47. DOI: https://doi.org/10.18721/JPM.183.107

Introduction

Currently, nonlinear optical effects are used in various devices, such as optical modulators, optical frequency converters, etc. One of the main fields of research in nonlinear optics relates to the second harmonic generation (SHG). In general, such an effect can only be achieved in materials without the inversion center. However, a lot of optical elements is based on glasses. This is because of their low price, optical transparency in a wide range of wavelengths and a high variability of other characteristics. In glasses, the presence of the inversion center forbids SHG, with the exception of the glass surface. However, SHG in glasses can be provided by the EFISH (electric field induced second harmonic) effect [1] that is nonlinear conversion involving 3rd order electric susceptibility $\chi^{(3)}$ and DC electric field E^{DC} created by a charge "frozen" in the glass. Among such approaches to create a frozen electric charge as thermal poling [2, 3], optical poling [4], etc., the e-beam irradiation stands out primarily due to its high resolution and the opportunity of direct writing of complicated patterns [5].

The visualization of the distribution of electric field is an important problem in the design of various micro- and optoelectronic components. If optically transparent materials are used, SHG can be a convenient tool for this, e.g. mapping of the SHG signal. In this paper we demonstrate the visualization of the electric field distribution in nonlinear periodic structures created by electron irradiation in a glass.

Materials and Methods

We used BF16 glass with the following composition: 27% SiO_2; 6.8% B_2O_3; 2.5% Al_2O_3; 0.6% Sb_2O_3; 0.4% As_2O_3; 10% PbO; 42% BaO; 5.7% ZnO; 5.1% CaO. Electron irradiation was carried out using a Raith EBPG5000 + ES electron beam writer. The electron energy was 100 keV, the beam size was 2 nm, and the charge density of the irradiated pattern was maintained at 8 μC/cm^2. The written structure is a set of two-dimensional gratings with the periods Λ = 4, 8, 16, and 32 μm. The gaps in the gratings coincided in width with the strips and made up half the period, i.e. $\Lambda/2$. The gratings are about 1 mm wide and 3 mm long. Optical measurements were performed using a 1064 nm pulsed picosecond laser (Nordlase IGUL-PS-205-1064-50-50-10-50). Laser beam width was 90 μm, using a short-focal-length lens allowed to reduce it to 1–2 μm. To map the SH signal, the irradiated glass was mounted on a two-dimensional translation stage. SH signal registration was carried out using a photon counter (Hamamatsu H11890-110).

Results and Discussion

The distribution of E^{DC} in this structure, which was obtained by solving the Poisson equation [6] for the given charge distribution, is characterized by specific SH radiation patterns. These patterns were observed under normal-incidence laser irradiation (see Fig. 1, *a*). Fig. 1, *b* presents the radiation patterns of the SH generated by a 16 μm grating under laser excitation with transverse polarization (relative to the grating stripes). The observed profiles are consistent with the theoretical distributions of diffraction gratings exhibiting π-phase modulation

SHG mapping was performed using a long-focal-length lens (size of the light spot (~90 μm) noticeably exceeds the periods). The obtained maps are presented in Fig. 2. The strongest SH signal is observed at the edges of the gratings – the side faces for the transverse polarizations and the end faces for the longitudinal polarization. Since in this structure SHG occurs via the

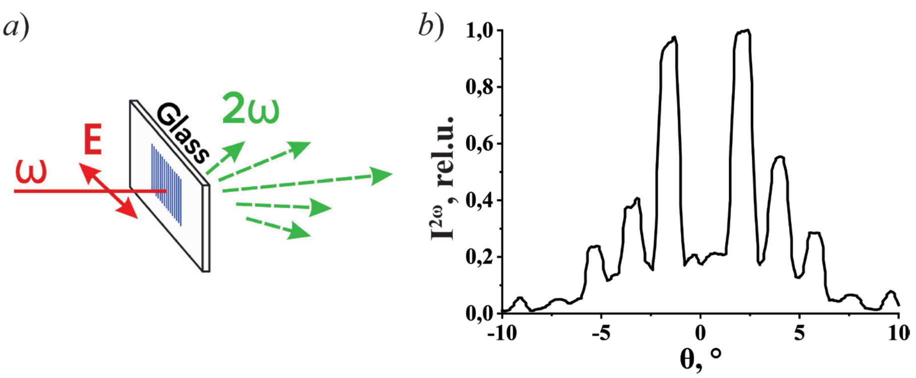

Fig. 1. Optical measurement scheme (*a*); normalized SH signal as a function of the scattering angle for periodically e-beam irradiated area with period Λ = 16 μm (*b*)

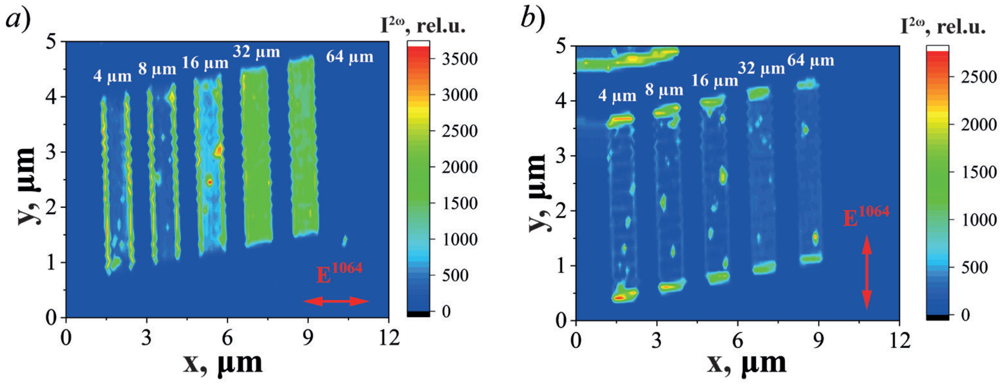

Fig. 2. SHG maps at orthogonal polarizations of the laser beam: across the strips (*a*); along the strips (*b*)

EFISH effect [1], the signal magnitude directly depends on the electric field strength. Thus, Fig. 2 demonstrate visualization of static *E*-field in the structure. Note, since size of the light spot in these measurements (~90 μm) noticeably exceeds the periods, the *E*-field inside the gratings is unresolved.

To visualize *E*-field inside the gratings, we used a short-focal-length lens (the light spot (~2 μm) is smaller than the periods). As described by the model in Ref. [6], the charge distribution expands beyond the boundaries of the fabricated strips due to electron scattering in the glass. This leads to an increase (compared to the grating period) spacing between the E^{DC} maxima in the irradiated region. Fig. 3, *a* presents the SH signal profile for a Λ = 4 μm grating, measured with the laser polarization oriented transverse to the strips. We observe a significant increase in the SH peaks spacing within the irradiated zone (2.5 μm compared to the original 2 μm), confirming

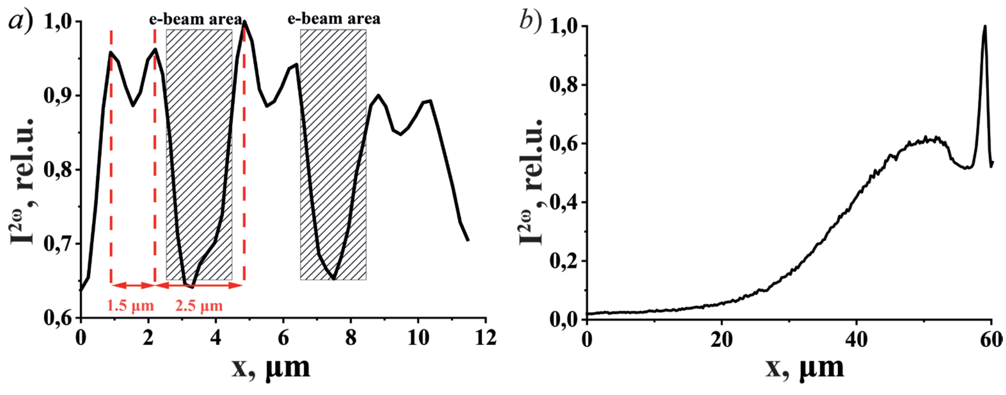

Fig. 3. SH signal profiles under laser irradiation of a Λ = 4 μm grating: within the grating area (*a*) and at the grating edge (*b*)

the corresponding increase in the E^{DC} maxima separation. Furthermore, at the outermost strip, the implanted charge is no longer confined by neighboring strip, resulting in the predicted decay of the SH signal to zero over extended distances (~40 μm for Λ = 4 μm), as shown in Fig. 3, *b*.

Conclusion

We demonstrated SHG for visualizing E^{DC} distributions in periodic structures fabricated by electron beam in glass. SHG spatial mapping revealed pronounced electric field localization at grating edges. Moreover, high-resolution SHG profiling with a short-focal-length lens allowed visualizing local electric field inside the grating. Obtained profiles of the local *E*-field are in agreement with the recent simulations [6].

Acknowledgments

The authors thank Dr V.P. Kaasik for essential assistance in the measurements.

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THE AUTHORS

TERPITSKIY Aleksey N.
terpiczkij@mail.ru
ORCID: 0000-0002-1744-5976

SCHERBAK Sergey A.
sergeygtn@yandex.ru
ORCID: 0000-0002-0507-5621

RESHETOV Ilya V.
reshetov_iv@spbstu.ru
ORCID: 0000-0002-8661-3654

LIPOVSKII Andrey A.
lipovskii@gmail.com
ORCID: 0000-0001-9472-9190

Received 08.08.2025. Approved after reviewing 27.08.2025. Accepted 27.08.2025.