# Characterization of the Nonlinear Optical Properties of Glass Using the Z-scan Technique for Advancing Laser-Glass Processing in Photovoltaics

Gregoris K. Boulogiannis[1,2,*], Lasse Bienkowski[1,3], Anna Münzer[1], Fabian Meyer[1], Andreas Brand[1], Jan Nekarda[1] and Katrin Dulitz[3]

[1] Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany
[2] Physikalisches Institut, Universität Freiburg, Hermann-Herder-Straße 3, 79104 Freiburg, Germany.
[3] Institut für Ionenphysik und Angewandte Physik, Universität Innsbruck, 6020 Innsbruck, Austria
*Corresponding author email: grigorios.boulogiannis@ise.fraunhofer.de

Laser processing of soda-lime glass, typically used as a cover in photovoltaic (PV) modules, to enhance mainly its optical and anti-soiling properties, is of significant importance for the PV industry. However, laser processing of a transparent, brittle and heat-sensitive material, such as glass, is challenging. Throughput and cost are still key issues and further improvements must be done to establish laser-glass processing as the standard processing method for PV module glass. Owing to the possibility of exploiting nonlinear light-matter interactions, the use of ultrashort pulsed lasers (USP) for laser-glass processing has already been proposed [1], offering excellent quality, when compared to any other conventional or laser processing technology. Nevertheless, the throughput of USP laser processing is still low in comparison to other laser technologies, such as nanosecond lasers.

In this work, surface modification threshold experiments reveal ≈ 20 % increase in the ablation efficiency (see Figure (a)) of soda-lime glass when heated from 20 °C to 200 °C. This stimulates currently conducted research to understand the temperature dependent absorption mechanism behind this effect, which can prove instrumental in increasing the throughput of USP laser processing. Motivated by this result, we use the Z-scan technique [2] to determine the nonlinear optical properties of soda-lime glass. A fully automated Z-scan setup is designed and built to be capable of measuring over a wavelength range from 310 nm to 2600 nm with adjustable substrate temperatures from 20 °C to 1500 °C. As an optical source, we use an Yb-doped regenerative amplifier, with an average power of 6 W, pulse duration of 180 fs and a central wavelength of 1030 nm. We calculate a four-photon absorption coefficient of $\alpha_4 = (2.8 \pm 1.1) \times 10^{-35}\ \mathrm{cm^5W^{-3}}$ (see Figure (b)) and a nonlinear refractive index of $n_2 = (2.2 \pm 0.5) \times 10^{-16}\ \mathrm{cm^2W^{-1}}$ (see Figure (c)) for soda-lime glass at room temperature and at 1030 nm. To the best of our knowledge, this is the first time that the four-photon absorption coefficient of soda-lime glass has been reported in the scientific literature.

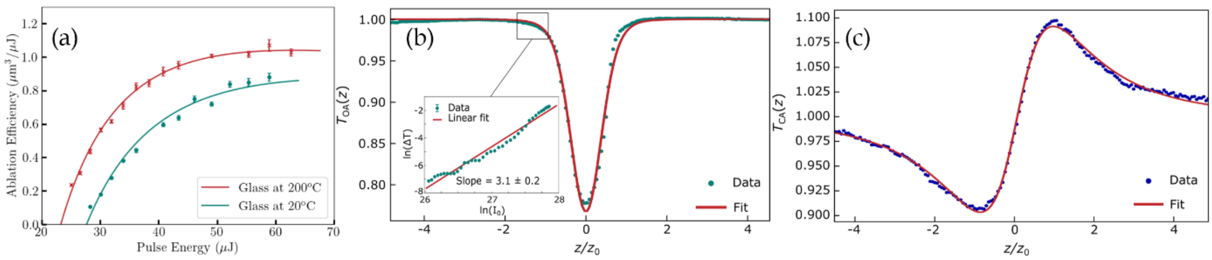


Figure: Nonlinear optical response of soda-lime glass at 1030 nm. (a) Soda-lime glass ablation efficiency as a function of the pulse energy at 20 °C and 200 °C. (b) Open aperture Z-scan experimental data and the corresponding four-photon absorption fitting curve. (c) Closed aperture Z-scan experimental data and the corresponding 3rd-order nonlinear refraction fitting curve.

**References**: [1] Skoulas, E., Mimidis, A., Papadopoulos, A., Lemonis, A. and Stratakis, E., Multifunctional laser-induced nanostructuring of glass., 2022, PhotonicsViews, 19: 46-49. [2] M. Sheik-Bahae, A. A. Said, and E. W. Van Stryland, High-sensitivity, single-beam $n_2$ measurements., Opt. Lett. 14, 955-957 (1989)