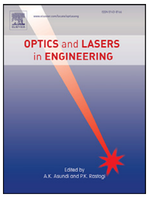
Optics and Lasers in Engineering 110 (2018) 288–295

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Simulation of laser induced absorption phenomena in transparent materials

D. Savastru, R. Savastru, S. Miclos*, I.I. Lancranjan

National Institute of R&D for Optoelectronics – INOE 2000, 409 Atomistilor Str., Magurele, Ilfov RO-077125, Romania

ARTICLE INFO

Keywords:
Transparent materials
Laser breakdown
High intensity
Damage
Processing

ABSTRACT

The laser-induced damage in transparent optical materials represents an important active field of research as part of laser/material interactions studies. Most of research activities within this field are aiming to laser micro-processing of transparent optical materials, glasses and ceramics. An example of such laser micro-processing techniques is drilling micro channels through a glass plate and drilling transverse holes through single mode optical fibre cladding and core. The latter example of research activity has an important purpose consisting of designing and manufacturing micro-nanoscale optical fibre sensors with improved capabilities. Regarding these applicative research activities, there are two important correlated issues here to be underlined. The first one consists in the fact that high intensity laser field induced electron density variation into a transparent material is the main mechanism of breakdown and damage, that is, basis of micro-processing. The second one refers to the necessity of developing simulation procedures based on accurate theoretical models of these physical processes in order to use an accurate computer control of micro-processing technology. The main purpose of this work is to present the results of simulations in electron density variation induced by high intensity laser pulses in various transparent materials.

1. Introduction

There is a strong need of photonic and optoelectronic devices with improved characteristics and capabilities for a large number of researches and medical, industrial, communications and military applications. These photonic and optoelectronic devices are mostly manufactured of transparent optical materials, such as semiconductors, glasses and/or ceramics. Laser micro-processing became an important technique in manufacturing such photonic and optoelectronic devices, in many cases essential [1–7]. Applicative research concerning the transparent materials laser micro-processing imperatively imposes the necessity of accurate laser/material interactions modelling and simulation, namely to predict the damage threshold and to improve the design of photonic and optoelectronic components manufacturing technology [1–7]. Modelling and simulating of laser/material interactions means mainly to define the electron density distribution at the surface and in the bulk of the material [1–13]. Many simulation models of this kind are based on the work developed by L. V. Keldysh in 1964 [8]. The importance of Keldysh's work results from the analysis of damage mechanisms at short and ultra-short laser pulses timescales which became available long time after his works [6–13]. Namely, this timescale covers laser pulse widths longer than a few tens of picoseconds to nanosecond pulses. In the case of ultra-short pulses, once a sufficient energy is absorbed by the material, irreversible damage will result [6–13]. When the pulse width of the laser is on the timescale mentioned above, the absorbed laser energy is transferred by the material's excited electrons to its lattice. This results in a thermal diffusion of energy out of the focal volume finally leading to damage by means of melting and/or fracturing [9–11]. The rates of energy deposition and thermal diffusion together determine the damage threshold of the material which is now known to scale with the square root of the pulse duration [11–13].

Manufacturing of photonic devices by laser micro-processing is accomplished by using two main techniques, alone or combined: one consisting into shape deformation of constituent bulk material, while keeping unmodified its internal structure at micro scale, at atomic scale [14–18] and the other based on modifying internal structure by laser-induced breakdown at the surface and in the bulk of transparent optical materials [17–19]. It is worth observing that both these two main laser micro-processing techniques rely at different extents on generation of free electrons at the surface and in the bulk of transparent materials. Laser-induced breakdown in such materials could mean that their internal structure is modified by outside expulsion of atoms and/or ions from their fixed position by ablation or desorption. Laser-induced breakdown implies irreversible damage of transparent optical materials and its analysis is important for setting the final operational limits of such materials [20–27]. A physical phenomenon produced when high intensity laser pulses generating unbounded electrons when absorbed into transparent optical materials is the colour centres formation, essential for inscribing gratings in the core of single mode optical fibre core, Fi-

---

* Corresponding author.
E-mail address: miclos@inoe.ro (S. Miclos).

https://doi.org/10.1016/j.optlaseng.2018.04.025
Received 1 September 2017; Received in revised form 14 March 2018; Accepted 29 April 2018
0143-8166/© 2018 Elsevier Ltd. All rights reserved.

bre Bragg Grating (FBG) or Long Period Grating (LPG) [28,29]. It appears imperative to develop simulation models for laser induced absorption in transparent materials having description of electrons generation and their density time variation as basic bricks to properly design photonic devices and experiments when using them [30–35]. The simulation results obtained by running these models have a clear impact on design and fabrication of in-fibre Mach-Zehnder interferometric optic sensors using laser ablation micro-processing of transparent materials techniques applied, in this case, on single mode (SM) optical fibres in order to induce gratings with optimized characteristics [36–40]. The interest in such in-fibre Mach-Zehnder interferometric optic sensors comes from the importance of their applications in design and fabrication of smart composite materials and of pathogen bacteria detection devices [36–40]. The main purpose of this paper is to present the results obtained by using the first stage of a self-made simulation model of this kind. The developed simulation model consists of two main stages: the first one evaluating the electron generation in transparent material under intense ultra-short laser pulses irradiation at different wavelengths and the second one for defining thermal effects and irreversible damage thresholds. The developed simulation model can be used for various transparent optical materials such as different optical ceramics, crystals, chalcogenide, germanate, tellurite and silicate glasses [20–33]. At this point of investigations, the main interest is focused on the control over the induced electron density as a function of incident laser intensity geometry and of time shape. In Section 3 two kinds of simulation results can be noticed and presented as examples: one kind is regarding fused silica, a transparent dielectric material widely used in optoelectronic and the second kind is concerning GaAs, a transparent semiconductor material also commonly used in photonics. The obtained results are in a fairly good agreement with the experimental and simulation data presented in literature concerning transparent materials thermal processing and irreversible laser-induced breakdown damages [30–35,41–49]. The developed simulation model aims to improve design and fabrication of in-fibre grating with custom optimized pitch shape, profile and/or modifying the SM optical fibre geometry by digging transverse channels through its core or dwells of controlled depth into its core.

2. Theory

The developed laser induced absorption in transparent materials simulation model is accomplished in several steps presented in the followings. The main idea of the developed simulation model consists in analysing the possible processes of electron generation in transparent optical materials under ultra-short intensity laser pulses [6–13]. These electron generation processes are parts of the photoionization process referring to the direct excitation of electrons by the electric field component of laser field [6–13,17–35,49–51]. Photoionization provides the “seed” electrons necessary for an avalanche breakdown to occur due to high intensity ultra-short laser pulses which are producing direct observable damages or for inducing sometimes useful point defects, i.e. colour centres in the optical material structure. In analysing these photoionization processes there are two facts to be noticed: the first one is that the interaction probability for single-photon absorption in a laser-material system is the highest and, secondly that the first harmonic photons generated by laser sources and which commonly are available for micro-processing have energy lower than the ionization potential of almost all transparent optical materials [33–35,50–55]. The experimentally observed damages produced in transparent optical materials and these two above noticed facts lead to the conclusion that if two or more lower-energy photons are simultaneously arriving there is a significant probability that by multi photon ionization (MPI) they will excite an electron within the material. MPI is a process among others which has the highest probability [33–35,50–55].

The first considered step is to define as accurate as possible the interaction zone, meaning to describe the incident laser beam. It is reasonable to consider the laser beam as having radial symmetry, a light radial frequency ω, peak intensity I_0, laser power P, beam radius w_0, E_p laser pulse energy and pulse repetition rate R. The peak laser intensity is defined, as a value on beam axis, by the following equation [56–57]:

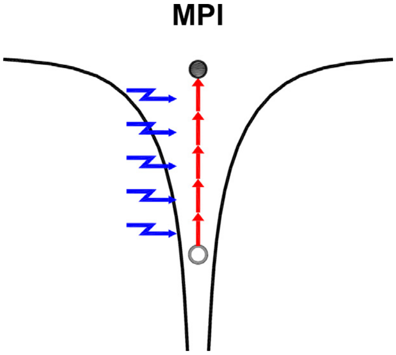


Fig. 1. Schematic presentation of Multi-Photon-Ionization.

$$I_0 = \frac{4E_p}{\tau w_0^2 \pi \sqrt{2\pi}} = \frac{4}{\tau w_0^2 \pi \sqrt{2\pi}} \frac{P}{R} \tag{1}$$

E_p is the laser pulse energy, defined as $E_p = \frac{P}{R}$. E_p is the laser pulse energy defined for radially symmetric beams [56–57]:

$$E_p = \int_{-\infty}^{\infty} \int_{0}^{2\pi} \int_{0}^{\infty} I(r,t) r dr d\theta dt \tag{2}$$

The laser pulse $I(r,t)$ is a Gaussian pulse of the following form where I_0 is the peak irradiance, τ is the FWHM time duration at which the irradiance is $1/e^2$ of the peak value I_0, and w_0 is the beam radius at which the irradiance is $1/e^2$ of the peak value I_0: [56–57]:

$$I(r,t) = I_0 \exp\left[-2\left(\frac{r}{w_0}\right)^2\right] \exp\left[-2\left(\frac{t}{\tau}\right)^2\right] \tag{3}$$

For describing photoionization processes it is useful to define the parameter F which represents the Electric Field Strength and is calculated from the following equation where I is peak laser intensity, n is refractive index, and ε_0 is the permittivity of free space [56–57]:

$$F = \sqrt{\frac{2I}{cn\varepsilon_0}} \tag{4}$$

The next step of the performed analysis is a combined complex consisting in several phenomena related to laser induced free electron generation in transparent optical materials by photoionization [8–13,33–35,50–55]. It is important to notice that the laser sources commonly used for generation of ultra-short pulses in the femtoseconds to nanoseconds range are operated at wavelengths in red and NIR spectral domains, meaning that in almost of the laser micro-processed transparent optical material cases the band gap is larger than the energy of individual incident laser photons. The laser photons incidents on a transparent optical material have more or less broad energy dispersion around a peak value [8–13]. Interaction probability for single-photon absorption in a laser-material system is the highest rate to happen; if two or more lower-energy photons simultaneously arrive, there is a significant probability that they will excite an electron within the material in several steps [8–13,33–35,50–55].

In the case of a transparent material with an ionization potential E_g, the necessary condition to be satisfied for MPI occurrence (Fig. 1), namely that simultaneous incident laser photons having slightly individual wavelengths $\lambda_1 \ldots \lambda_n$ in a range $\Delta\lambda$ centred on laser source peak emission wavelength is defined as [8–13,33–35,50–55]:

$$E_g \le hc\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2} + \ldots + \frac{1}{\lambda_n}\right) \tag{5}$$

Download English Version:

https://daneshyari.com/en/article/7131482

Download Persian Version:

https://daneshyari.com/article/7131482

Daneshyari.com