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## High type A refractive index change by multi-scan cumulative inscriptions in photosensitive glasses

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## **Foreword**

On behalf of the OPAL' 2022 Organizing Committee, I introduce with pleasure these proceedings devoted to contributions from the 5<sup>th</sup> International Conference on Optics, Photonics and Lasers (OPAL' 2022). The conference is organized by the International Frequency Sensor Association (IFSA) in technical cooperation with our media partners: Institute of Physics (IOP), UK, MDPI Photonics (ISSN 2304-6732) and MDPI Chemosensors (ISSN 2227-9040) journals, Switzerland.

In keeping with tradition begun in 2018 in Barcelona, Spain the Series of Conference attracts researchers and practitioners in the related fields, from around the world including 2 keynote speakers from Germany and India.

The conference proceedings contains all papers of regular and keynote presentations. We hope that these proceedings will give readers an excellent overview of important and diversity topics discussed at the conference.

We thank all authors for submitting their latest work, thus contributing to the excellent technical contents of the Conference. Especially, we would like to thank the individuals and organizations that worked together diligently to make this Conference a success, and to the members of the International Program Committee for the thorough and careful review of the papers. It is important to point out that the great majority of the efforts in organizing the technical program of the Conference came from volunteers.

*Prof., Dr. Sergey Y. Yurish  
OPAL' 2022 Chairman*

(024)

## High Type A Refractive Index Change by Multi-scan Cumulative Inscriptions in Photosensitive Glasses

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**Summary:** In femtosecond laser inscription, the multi-scan technique has already proved to increase the refractive index change associated to the embedded structures for both low and high repetition rate regimes. However, for the latter case, the thermal effects induced by the subsequent absorption of the laser pulses tend to tightly narrow the DLW window for smooth type I material modifications, making it difficult to control the refractive index change. On the other hand, femtosecond laser inscription of silver-sustained (type A) refractive structures in silver-containing glasses with high repetition rate was recently shown to occur in an athermal regime. The present work shows that this remarkable athermal regime, in combination with the multi-scan technique, enables for achieving high type A refractive index changes, up to  $1.3 \times 10^{-2}$ , in a commercial silver-containing glass.

**Keywords:** Direct laser writing, Multi-scan laser inscription, High refractive index change, Ultrafast laser-matter interaction, Athermal regime, Type A refractive index modifications, Laser induced silver clusters, Photosensitive media.

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### 1. Introduction

Since the first demonstration of femtosecond laser inscription in fused silica [1], many techniques have been exploited to achieve three-dimensional material structuring for the fabrication of waveguides and of more complex optical devices. In this regard, Direct Laser Writing is a well-known technique that allows for the fine control of the localized energy deposition and associated material modification. Femtosecond laser focusing in glasses leads to different types of material modifications: Type I, the only one associated with smooth refractive index contrast compatible with low-loss waveguiding applications, while Type II and Type III correspond to nanogratings and voids creation, respectively. In 2017, our group demonstrated the existence of a new type of refractive index change in silver-containing glasses, labeled Type A, which is not related to matrix modifications. Indeed, such a new type appears at a different laser irradiation regime, and it is sustained by the photo-induced creation of molecular silver clusters, such new chemical species providing new chemical bonds associated to intense UV absorption bands and broadband VIS fluorescence emission [2, 3]. Femtosecond laser inscription generally takes place in two regimes: at low repetition rate (from 1 kHz to 250 kHz) and high pulse energy, or at high repetition rate (above 1 MHz) and low pulse energy. The difference between these two regimes lies on the thermal management during the pulse-to-pulse energy deposition during the laser pulses train irradiation. Indeed, in the case of low repetition rate, the large time scale between successive pulses allows for heat diffusion out of the interaction voxel, preventing thermal accumulation. Laser induced modifications are, thus, smooth but the associated refractive index

change is rather weak, up to  $3 \times 10^{-3}$  in fused silica. In the high repetition rate regimes, instead, the resulting absorption of focused laser pulses increases the temperature of the glass above the glass transition temperature in the interaction voxel, inducing the glass matrix to locally melt and quickly quench. Due to heat diffusion, the induced material modifications show a profile with radial symmetry associated to dimensions larger than that of the interaction voxel. The associated refractive index change is higher than that obtained in the low repetition rate regime, however, it might be positive, negative or show both behaviors, depending on the writing parameters and the glass composition.

Remarkably, the inscription of Type A refractive index modifications takes place in an athermal regime, despite the use of a high repetition rate laser source. Indeed, a comparison study between Type I and Type A refractive index modification demonstrated that the laser irradiance necessary to activate the clustering of silver species is much lower than that required in the inscription of Type I material modifications [4]. Moreover, Type A refractive index change is always positive and localized at the regions where silver clusters are photo-induced, allowing for inscription of features with dimensions down to 100 nm and thus overcoming the diffraction limit. This smooth and positive refractive index change was demonstrated to support light guiding, enabling the fabrication of optical components such as waveguides, couplers, beam splitters and refractive index sensors [5].

In the present work the inscription of Type A refractive index modifications is performed in combination with the multi-scan technique. Such technique has been widely adopted in literature in order to increase the induced refractive index change in both femtosecond laser inscription regimes. In the case of low repetition rate, the work of Lapointe et al.

reported on increasing the refractive index contrast from  $1.4 \times 10^{-3}$  to  $9 \times 10^{-3}$  after 500 consecutive laser scans on the same position, in the case of short pulse duration (65 fs) [6]. In the high repetition rate regime, the thermal effects originated in the many-pulse absorption make it difficult to control the refractive

index increase while performing the multi-scan technique. Indeed, as reported in the work of Graf *et al.*, the heat accumulation leads to the formation of pearl-chained waveguides with high propagation losses [7].

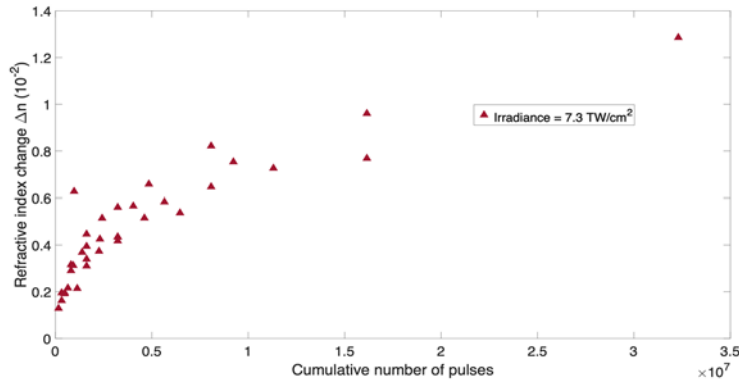


Fig. 1. Refractive index change  $\Delta n$  as a function of the cumulated number of absorbed laser pulses in a 10 MHz high repetition rate but still athermal regime.

## 2. Experimental Setup and Results

The present study benefits from the counter-intuitive athermal inscription of Type A modifications in a gallo-phosphate glass photosensitized with silver ions by means of a KGW:Yb femtosecond oscillator (up to 2.6 W, 9.8 MHz, 400 fs FWHM at 1030 nm) and the multi-scan technique. For each structure, the consecutive laser scans are repeated *in loco* a different number of times. Each structure is then imaged using the Sid4BIO device (Phasics) in order to extract the Optical Path Difference (OPD) profiles induced by the laser-induced silver clusters. Finally, by dividing the OPD by the thickness of each structure, the dependence of the refractive index change  $\Delta n$  on the different number of laser scans is extracted. Remarkably high and smooth refractive index changes up to  $1.3 \times 10^{-2}$  are achieved (see Fig. 1). The reported results demonstrate that such high refractive index change is directly dependent on the number of cumulative absorbed laser pulses, *i.e.* the number  $N_p = N_{\text{scan}} \cdot \varphi \cdot f_{\text{rep}} / v$  of pulses irradiated during the inscription of  $N_{\text{scan}}$  laser scans, at a given writing speed  $v$ , for a laser source with  $f_{\text{rep}}$  repetition rate and focused beam diameter  $\varphi$ .

## 3. Conclusion

The multi-scan cumulative femtosecond laser inscription of Type A refractive index modifications in photosensitive glasses tailored with silver ions is carried out in an athermal regime. This remarkable

condition allows to achieve high induced refractive index change whose amplitude is directly related to the cumulative number of absorbed pulses.

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