

## Writing of 3D optical integrated circuits with ultrashort laser pulses in the presence of strong spherical aberration

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**Abstract.** A novel technique was proposed for 3D femtosecond writing of waveguides and optical integrated circuits in the presence of strong spherical aberration, caused by inscription at significantly different depth under the surface of optical glasses and crystals. Strong negative effect of spherical aberration and related asymmetry of created structures was reduced due to transition to the cumulative thermal regime of femtosecond interaction with the material. The differences in the influence of spherical aberration effect in a broad depth range (larger than 200  $\mu\text{m}$ ) was compensated by dynamic adjustment of laser pulse energy during the process of waveguides recording. The presented approach has been experimentally implemented in fused silica. Obtained results can be used in production of a broad class of femtosecond written three-dimensional integrated optical systems, inscribed at non-optimal (for focusing lens) optical depth or in significantly extended range of depths.

### 1. Introduction

Femtosecond writing technology provides single-step maskless inscription of waveguides in optical glasses and crystals [1-3]. Due to point-by-point formation process the technique allows easy adjustment of the waveguide's geometry and parameters of the optical integrated circuits based on it. Moreover, thanks to nonlinear nature of the phenomenon, the effect of permanent alteration of the refractive index occurs only in the focal region, providing an opportunity to inscribe three-dimensional structures on optically transparent glasses and crystals [4]. Unfortunately, operational depth range (under the surface of crystal) of 3D optical integrated circuits is essentially narrowed by spherical aberrations of a focusing lens [5] to the width of  $\pm 20$  Rayleigh length from the depth of optimal aberration correction ( $\pm 50 \mu\text{m}$  for  $\text{NA} = 0.45$  or  $\pm 17 \mu\text{m}$  for  $\text{NA} = 0.8$ ) [6, 7]. For a number of applications such as large mode area waveguides, multimode waveguides, and optical chips that are easy to couple with standard telecom fibers (described in details below), it is necessary to use direct femtosecond writing technique in a depth range extended to, at least,  $\pm 70$  Rayleigh length ( $\pm 180 \mu\text{m}$  for  $\text{NA} = 0.45$  or  $\pm 62.5 \mu\text{m}$  for  $\text{NA} = 0.8$ ). In the investigation we proposed a solution of the challenge and described modified femtosecond inscription technique with an extended operational depth range.

Up to date one of the most widespread techniques of femtosecond written waveguides has consisted in formation of waveguide's cladding with decreased refractive index [4]. Typical geometry

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of an induced waveguide is shown in figure 1(a, b). Two neighboring tracks with high aspect ratio are inscribed at optimal depth under the surface of a crystal (depth of optimal spherical aberrations compensation for the lens and  $\pm 20$  Rayleigh length range, as described above). In such a case, refractive index in the central region between tracks increases due to mechanical stress produced by the written cladding. Such tracks could be written with weak focusing of fs-laser emission (NA = 0.2-0.4), low pulse repetition rate ( $< 0.5$  MHz), and relatively high pulse energy ( $> 0.1$   $\mu$ J), which induces strong self-focusing and formation of tracks with high aspect ratio ( $> 3$ ) in the cross section. The waveguides produced by the described technique exhibit high propagation losses (0.9-3 dB/cm) and only maintain a single linear polarization state (horizontal) due to low containment of light in vertical direction, which sufficiently restrains practical applications.

Typical solution of the problem lies in a full circle writing of cladding, as shown in figure 1(c). The solution increases numerical aperture of the waveguide and reduces optical losses, but unfortunately it fails to resolve such problems as maintenance of all polarization states (propagation conditions for the orthogonal polarization sufficiently differ due to inhomogeneous structure at the top and bottom of the induced tracks, as shown in figure 1(c)) and writing of waveguides at a non-optimal depth under the surface of crystals (due to negative influence of spherical aberration that causes alteration of the track's geometry and leads to the optical breakdown).

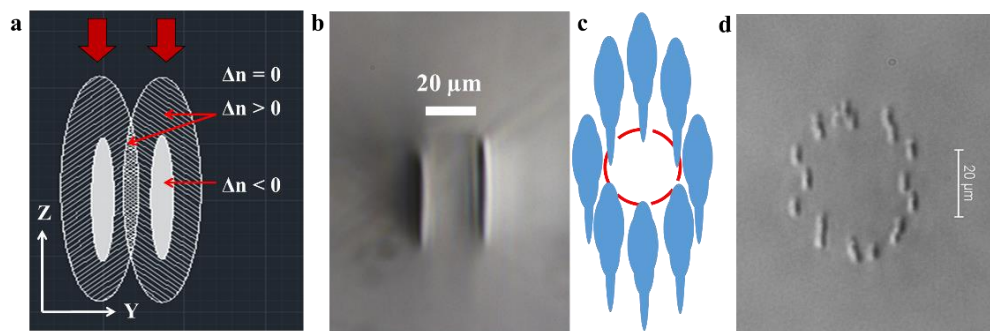


**Figure 1.** (a) Schematic and (b) microphotography of typical anisotropic 2-tracks stressed-induced cladding of waveguide, written with fs-laser; (c) schematic of inhomogeneous full-circle stress-induced cladding of waveguide; (d) microphotography of highly symmetric depressed cladding waveguide, written in thermal cumulative regime.

To resolve the problem and to write highly symmetrical waveguides with both polarization states maintenance even at non-optimal writing depth (in the presence of strong spherical aberration) we have proposed an advanced technique of femtosecond writing. It consists in writing at relatively high NA (0.6), but in a thermal cumulative regime [8], which offers up to twofold increase of the induced refractive index contrast, aspect ratio decrease down to 1.5 (see figure 1(d)), and greater than threefold reduction of the optical losses, down to 0.3-0.5 dB/cm, for both polarizations. Thanks to significant reduction of the aspect ratio and compensation of the spherical aberration influence on the track's geometry due to symmetric thermal effects, the proposed technique provides an opportunity to write waveguides in extended depths range (more than  $\pm 70$  Rayleigh length, as will be experimentally shown below).

## 2. Experimental setup

For realization of thermal regime, we used experimental setup described in detail in [8]. Femtosecond laser pulses (340 fs, 1040 nm) from the oscillator (HighQ femtoTRAIN, 0.1-10 MHz) were focused with aspheric lens (NA=0.6) into fused silica sample, which was mounted on a 3D-translational stage and moved with velocity 10-800  $\mu$ m/s to form extended tracks through the total length of the sample (3 cm).

### 2.1. Effect of increased numerical aperture

Tight focusing with  $NA = 0.6$  instead of widespread  $0.3-0.4$  provides low size of focusing area ( $0.9-1.2 \mu\text{m}$  instead of  $2-4 \mu\text{m}$ ). Thus, to maintain induced refractive index effect a relatively low peak power is required ( $0.1-0.3 \text{ MW}$  from low  $M^2$  oscillator instead of  $> 1 \text{ MW}$  MOPA-laser), that causes reduced influence of self-focusing and consequently the absence of filamentation, providing formation of nearly-circle cross section tracks with aspect ratio  $< 2.5$  instead of  $> 3-5$  in the case of low NA writing technique.

On the other hand, in the case of tight focusing, even a small alteration of writing depth from the optimal one could sufficiently increase the spherical aberrations effect, that in turn will increase treated volume, required peak power and, as a result, aspect ratio of the induced tracks due to self-focusing. To prevent formation of highly asymmetric tracks, we additionally propose to compensate the effect of spherical aberrations and suppress self-focusing by writing in thermal cumulative regime described below.

### 2.2. Effect of thermal cumulative regime

Thermal cumulative regime could be realized at high pulse repetition rates (more than  $1 \text{ MHz}$ ), when characteristic time of thermal diffusion from the focal spot exceeds the period between subsequent laser pulses (thermal cumulative parameter  $\alpha$  from [8]). In that case, temperature in the focal spot rapidly rises higher than the melting point, and at high temperature the photochemical processes proceed easily even at lower operational energies of the laser pulse. As shown in figure 2(a), this allows to decrease operational pulse energy by more than 2 times, and to decrease self-focusing simultaneously. Moreover, transition to thermal cumulative regime offers to decrease the track's cross section aspect ratio by more than 1.5 times down to 1.5 value due to the isotropic thermal melting effect, as shown in figure 2(b).

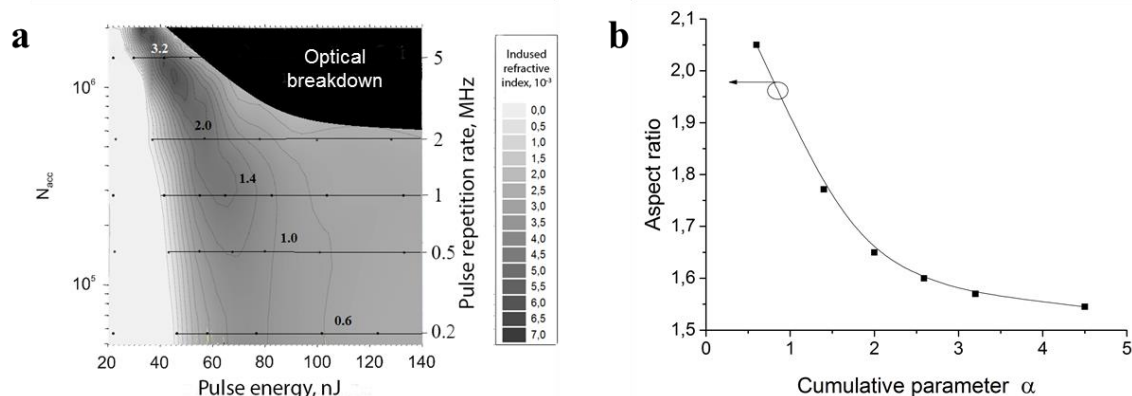


**Figure 2.** (a) Operating range diagram of the induced refractive index effect in fused silica (translation velocity  $10 \mu\text{m/s}$ , pulse repetition rate varies between  $0.1$  and  $10 \text{ MHz}$ ). Values above horizontal lines represent cumulative regime parameter  $\alpha$  [8]; (b) decreasing of the track's cross section aspect ratio with transition to the thermal cumulative regime of femtosecond writing.

## 3. Results

It was experimentally shown that developed technique of femtosecond writing allows to write optical waveguides with low propagation losses ( $< 0.3 \text{ dB/cm}$ ) for both polarisation states of propagating light even in case of writing at non-optimal depth (in presence of strong spherical aberrations). Thanks to inscription in thermal cumulative regime, we achieved the operating depth range as broad as  $\pm 70$  Rayleigh length ( $\pm 180 \mu\text{m}$  for  $NA = 0.45$  or  $\pm 62.5 \mu\text{m}$  for  $NA = 0.8$ ), which is 2 times broader than previously published data[6, 7]. As shown in figure 2(a), induced refractive index contrast was as high as  $7 \cdot 10^{-3}$ , which is 2 times larger than the value for non-thermal regime of writing. Higher refractive

index contrast provides higher numerical aperture of written waveguides resulting in the values up to 0.08. Achieved characteristics of the femtosecond waveguide writing technique open new opportunities in formation of integrated photonic elements.

#### 4. Analysis and discussion

One of the most important challenges in design and creation of optical integrated devices is the optimization of interconnections between bulk and fiber optical elements. For the connection with standard telecom fibers (diameter 125  $\mu\text{m}$ ), the optimal depth of waveguides formation equals to 62.5  $\mu\text{m}$ . In this case femtosecond written optical integrated chip and fiber could be placed at mutual alignment base (as shown in figure 3), that offers to adjust only 1 coordinate and 1 angle instead of 2 coordinates and 2 angles in the case of non-optimal depth of waveguide. Common focusing lenses and objectives do not provide correction for spherical aberrations at 62.5  $\mu\text{m}$  depth, thus in order to write waveguides at the depth, one should apply additional techniques for its correction, as described in the paper above. Proposed approach has been experimentally carried out in fused silica for writing of waveguides at depth 62.5  $\mu\text{m}$  (+70 Rayleigh length depth) with high NA (100x, NA = 0.8) micro-objective without spherical aberration compensation, as shown in figure 3(c-d).

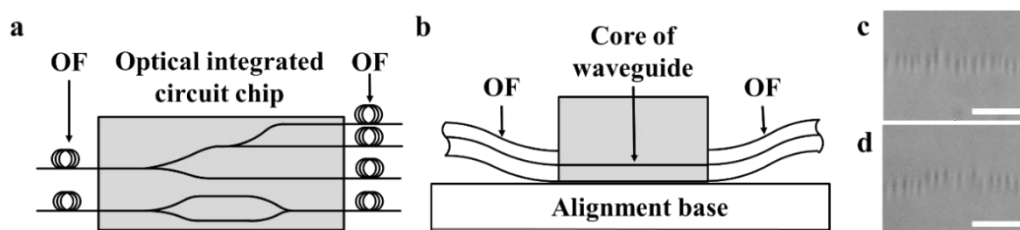


**Figure 3.** Schematic of typical optical integrated circuit chip (a) and alignment process with waveguide written at optimal (for interconnection) depth (b). Microphotographs of the induced tracks written at depth with low (c) and high (+70 Rayleigh length depth) (d) spherical aberrations.

Proposed technique allows to write three-dimensional waveguides at sufficiently different depths. To take into account the uncompensated effect of spherical aberrations, one should dynamically adjust laser pulse energy at each writing depth to maintain constant value of induced refractive index.

#### 5. Conclusion

In the paper we have proposed an improved technique for femtosecond waveguide writing that provides an opportunity to reduce self-focusing effect and to compensate negative influence of spherical aberrations. It was experimentally shown that operational depth range of the proposed technique broadens 2 times as compared with low-NA non-thermal one and reaches the value of  $\pm 70$  Rayleigh length, which opens new opportunities for design and creation of advanced photonic devices that are easily interconnectable with telecom fibers and three dimensional optical integrated circuits.

#### Acknowledgements

The work was partially supported by Foundation for Assistance to Small Innovative Enterprises in Science and Technology (4806FY1/2014 №0008340 and 8611FY/2015 №0018824).

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