Optical Waveguides Written Deep Inside Silicon by Femtosecond Laser

Ihor Pavlov[1], Onur Tokel[1], Svitlana Pavlova[2], Viktor Kadan[2], Ghaith Makey[1], Ahmet Turnali[1], Tahir Colakoglu[4], Ozgun Yavuz[3], Fatih Omer Ilday[1,3]

[1]Bilkent University, Physics Department, Cankaya, Ankara, 06800, Turkey

[2]Institute of Physics, National Academy of Sciences of Ukraine, Kiev, 03028, Ukraine

[3]Bilkent University, Electrical and Electronics Department, Cankaya, Ankara, 06800 Turkey

[4]Middle East Technical University, Physics Department, Cankaya, Ankara, 06800, Turkey

Photonic devices that can guide, transfer or modulate light are highly desired in electronics and integrated silicon photonics. Through the nonlinear processes taking place during ultrafast laser-material interaction, laser light can impart permanent refractive index change in the bulk of materials, and thus enables the fabrication of different optical elements inside the material. However, due to strong multi-photon absorption of Si resulting delocalization of the light by free carriers induced plasma defocusing, the subsurface Si modification with femtosecond laser was not realized so far [1, 2]. Here, we demonstrate optical waveguides written deep inside silicon with a 1.5-μm high repetition rate femtosecond laser. Due to pulse-to-pulse heat accumulation for high repetition rate laser, additional thermal lensing prevents delocalization of the light around focal point, allowing the modification. The laser with 2-μJ pulse energy, 350-fs pulse width, operating at 250 kHz focused in Si produces permanent modifications. The position of the focal point inside of the sample is accurately controlled with pump-probe imaging during processing. Optical waveguides of ~20-μm diameter, and up to 5.5-mm elongation are fabricated by translating the beam focal position along the optical axis. The waveguides are characterized with a 1.5-μm continuous-wave laser, through optical shadow-graphy (Fig. 1 a-b, e) and direct light coupling (Fig.1 c-d, f). The measured refractive index change obtained by quantitative shadow-graphy is $\sim 6\times10^{-4}$. The numerical aperture of the waveguide measured from decoupled light is 0.05.

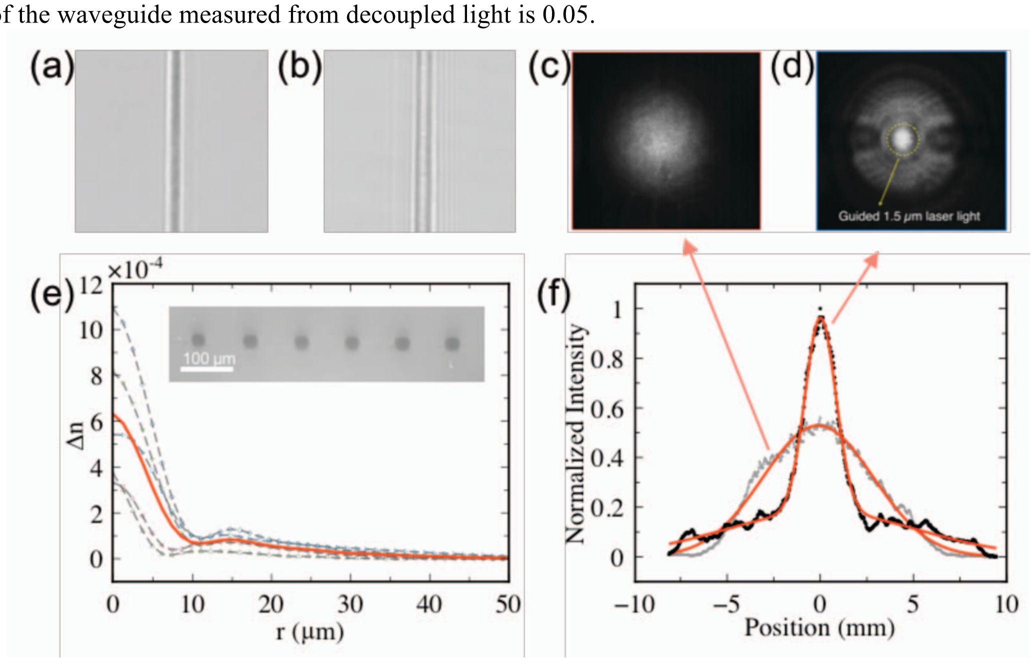

Fig. 1 (a-b) Shadow images of waveguide obtained when the object is 200 μm translated from the focal plane, towards the camera (a), and 200 μm from the focal plane away from the camera (b). (c-d) Far-field images of 1.5 μm cw laser light passing through unmodified area (c), and waveguide output (d). (e) The retrieved refractive index profiles for 5 different waveguides (grey dashed lines), and average of them (red solid line) obtained by inverse Abel transform from (a-b). Inset: cross-section view of multiple waveguides obtained with infrared microscopy. (f) Intensity profiles and numerical fits to far-field images. The red curve is a Gaussian fit to the data.

As a conclusion, we demonstrated the first optical waveguide at telecommunication wavelength directly written deep inside Si with femtosecond laser. We believe, this new laser-writing method will have a significant impact in 3D integrated optics, Si-photonics, and optical chip-to-chip communications.

References

[1] E. Zavedeev, V. Kononenko and V. Konov, "Delocalization of femtosecond laser radiation in crystalline Si in the mid-IR range," Laser Phys. **26**, 016101 (2015).

[2] D. Grojo, A. Mouskeftaras, P. Delaporte, and S. Lei, "Limitations to laser machining of silicon using femtosecond micro-Bessel beams in the infrared," J. Appl. Phys. **117**, 153105 (2015).

978-1-5090-6736-7/17/$31.00 ©2017 IEEE