Sapphire and Ti:sapphire Buried Waveguide Structures

Markus Pollnau
Advanced Photonics Laboratory, Institute of Imaging and Applied Optics,
Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland.
E-mail: markus.pollnau@epfl.ch

Due to its excellent thermal, mechanical, and optical properties, sapphire is one of the most suitable material for integrated optical devices. Although this hard crystalline material is particularly difficult to process, fabrication of Ti^{3+}-doped sapphire surface channel waveguides by surface structuring [1,2] of planar waveguides or ion in-diffusion [3] has been demonstrated. Generally, device performance can be considerably improved by burying the guiding structure into the bulk of the sample. Advantages of buried waveguides derive not only from surface scattering losses being avoided, but also from a reduction in mode asymmetry compared to surface waveguides, thus providing higher efficiency for mode coupling to optical fibers.

We reported the fabrication of complex waveguiding structures such as buried and stacked planar as well as buried single and parallel channel waveguides in sapphire by high-energy proton implantation [4]. Compared to the significant damage created in sapphire by He^{+} implantation, which resulted in poor waveguiding quality, protons create less damage in the guiding region, thus assuring better waveguiding quality. Moreover, deeper damage profiles are obtained with protons, for the same incident energy, thus providing larger design flexibility. Pure c-cut, optically polished sapphire substrates of dimensions 8 mm x 8 mm x 1 mm were irradiated by use of a Van de Graaf accelerator with incident ion energies of 0.4-1.5 MeV and doses of 10^{15}-10^{16} ions/cm^{2}. Good control of the implantation parameters enables writing of precisely localized optical barriers with well-defined decrease of refractive index, resulting in excellent confinement of the propagating light in each structure, with significantly reduced vertical mode asymmetry in the case of buried waveguides. Different mode shapes can be obtained by adjusting the implantation parameters, which demonstrates the versatility of the fabrication method. Fundamental-mode, buried channel waveguides with propagation losses <2 dB/cm are obtained without post-implantation annealing. Horizontal and vertical parallelization is demonstrated for the design of one- or two-dimensional waveguide arrays in hard crystalline materials. Transfer of the method to the fabrication of Ti^{3+}:sapphire active waveguides and fluorescence guiding after excitation by an Ar-ion laser has been demonstrated. This work was performed in a collaboration with the University of Lyon, France [4].

We also employed femtosecond laser writing in order to induce refractive-index changes and waveguides in Ti^{3+}-doped sapphire [5]. The femtosecond writing system was a Ti^{3+}:sapphire laser at a repetition rate of 1 kHz, with a center pulse wavelength of 790 nm and a pulse energy between 0.5 and 6 µJ. Doping the sapphire crystal with an appropriate ion significantly reduces the threshold for creating structural changes, thus enabling the writing of waveguide structures. Possible sensitization mechanisms are firstly, exploitation of two-photon absorption into the Ti^{3+} absorption band as an intermediate level and secondly, initial changes in the crystalline structure of sapphire by replacing the Al^{3+} ion with the larger Ti^{3+} ion. Passive and active buried channel waveguiding is demonstrated by end-coupling a HeNe laser at 633 nm and exciting the Ti^{3+} fluorescence centered at 760 nm by a laser, respectively. Comparison of measured fluorescence spectra in the waveguiding and bulk regions of the sample exhibit the same shape and input-output curves after excitation by an Ar-ion laser provide an efficiency of several 10^{-5}, which is as high as in investigations of surface channel waveguides produced by other methods [1,2]. Negative refractive-index changes in the laser-damaged region are measured by digital holography. The guiding area of typically 20-µm diameter is located around the laser-damaged region, indicating that the guiding effect is stress-induced. Waveguide losses of typically 2.5-4 dB/cm have been detected without optimization of the irradiation parameters. Proper active doping should enable femtosecond processing and waveguide writing in various crystalline materials. This work was performed in a collaboration with the Politecnico di Milano, Italy [5].

[1] A. Crunteanu, M. Pollnau, G. Jänchen, C. Hibert, P. Hoffmann, R.P. Salathé, R.W. Eason, C. Grivas, and D.P. Shepherd, Appl. Phys. B **75**, 15 (2002).

[2] C. Grivas, D.P. Shepherd, T.C. May-Smith, R.W. Eason, M. Pollnau, A. Crunteanu, and M. Jelinek, IEEE J. Quantum Electron. **39**, 501 (2003).

[3] V. Apostolopoulos, L.M.B. Hickey, D.A. Sager, and J.S. Wilkinson, Opt. Lett. **26**, 1586 (2001).

[4] L. Laversenne, P. Hoffmann, M. Pollnau, and P. Moretti, Conference on Lasers and Electro-Optics, San Francisco, California, Technical Digest (Optical Society of America, Washington, DC 2004), paper CTuU5.

[5] V. Apostolopoulos, L. Laversenne, T. Colomb, C. Depeursinge, R.P. Salathé, M. Pollnau, R. Osellame, G. Cerullo, and P. Laporta, Conference on Lasers and Electro-Optics, San Francisco, California, Technical Digest (Optical Society of America, Washington, DC 2004), paper CMY4.