Spatially Modulated Channel Waveguide Elements Optically Written in Photorefractive Lithium Niobate

A D Bezpal, A S Perin, V M Shandarov
Department of Quantum Electronics, Tomsk State University of Control Systems and Radioelectronics, Tomsk 634050, Russia

Abstract. Optical inducing of the channel waveguide elements with spatial modulated parameters in lithium niobate sample with Cu-doped layer is experimentally demonstrated. The channel waveguides have been formed via the point-by-point exposure at light wavelengths of 532 nm and 450 nm. It is shown that the distance between exposing light spot centers affects to the homogeneity and width of channel waveguides.

1. Introduction
The improvement of quantum and integrated optical devices is directly related to the development of photonics, nonlinear optics and laser technologies. Therefore, the studies of such aspects as influence of laser radiation on matter, methods of formation and design of light control elements is important today [1–3]. The light fluxes can be controlled by means of channel waveguides and diffraction gratings based on photorefractive materials [4–6]. One of the most promising materials in this area is lithium niobate crystal (LiNbO₃) which demonstrates the strong photorefractive nonlinearity especially at its doping with some impurities like iron (Fe), copper (Cu), manganese (Mn) and others [7, 8]. The photonic elements may be realized due the photorefractive properties of material using optical inducing which makes it possible to set topology and control it during the formation process of such structures.

The main aim of this work is experimental studies of different channel waveguide elements with spatial modulation of their parameters, optically induced in lithium niobate sample with Cu-doped surface layer.

2. Experimental setups and conditions
Channel waveguides were formed by step-by-step exposure of laser radiation to the doped surface of lithium niobate as it is shown in Figure 1. The radiation sources were solid-state YAG:Nd³⁺ laser with λ = 532 nm and semiconductor laser with λ = 450 nm. The dimensions of the sample used are 30×3×15 mm³ along X, Y, and Z axes. The sample has been thermally doped with Cu ions from a film deposited onto the wafer surface perpendicular to the crystal Y surface by vacuum sputtering. The doped layer thickness makes up about 100 μm. The light beam is focused onto the doped crystal surface using spherical lens. In different experiments the time of formation was 1-10 seconds. The step between exposing light spot centers is varied from 20 to 60 μm. It allows us to induce channel waveguides and their systems with different spatial parameters, change waveguide width and longitudinal homogeneity of its borders.
Figure 1. Experimental setup for optical inducing of waveguide channels within lithium niobate surface layer: LN is lithium niobate sample.

Figure 2 shows the schematic image of the formed structures studies by optical probing method using the radiation of He-Ne laser ($\lambda = 633$ nm) with extraordinary light polarization. To probe the exposed areas we collimate light radiation and direct it in the Y axis direction of the sample. The diameter of collimated laser beam is $\sim 1$ mm. Then, the light image from exit facet of lithium niobate sample is transmitted to laser beam analyzer by focusing lens. So from the obtained light patterns we study optically induced structures with different spatial modulated parameters in the sample surface doped layer.

Figure 2. Experimental setup for optical probing of induced waveguide structures within lithium niobate surface layer: LN is lithium niobate sample.

3. Experimental results and discussions
Some experimental results are illustrated by light field patterns in Figure 3. Light field pattern (Figure 3 a) shows the result of induced element consisting of three longitudinally homogeneous exposed
stripes. Two light areas enclosed between these dark stripes are waveguide regions. Such dark stripe determining the border of waveguide consists of 30 exposed points with a distance between their centers 25 μm. In the case illustrated in Figure 3 b, the induced element also consists of two waveguides, but one border of the lower waveguide is longitudinally inhomogeneous (number 3 in Figure 2 b). It consists of 16 discrete exposed points with a distance between their centers 50 μm. In both cases shown in Figure 2 a and 2 b, the widths of induced waveguide regions is ~20 μm.

![Figure 3(a, b). Light images at optical probing of the induced channel waveguide elements. (a) Homogeneous in longitudinal direction; (b) With different longitudinal homogeneity (different distances between centers of exposed points).](image)

To check the waveguide properties of optically induced elements, we excite light in waveguides along their directions. Light beam of He-Ne laser (λ=633 nm) is focused onto the entrance surface of waveguide channel using spherical lens with focal length of 4 centimeters. The light images at the exit surface of the waveguide is illustrated in Figure 4a and Figure 5a. These images shows that the light is localized in the induced waveguides enclosed between dark regions. The dark areas in figure 4a and 5a correspond to the exposed stripes shown in Figure 3a and 3b.

To study the light propagation in the formed elements with different spatial homogeneities we use the intensity distribution profiles illustrated in Figure 4b and 5b. Two intensity maxima shown in Figure 4b and 5b correspond to the localized beams from Figure 4a and 5a. Figure 4b shows that the light beams, propagated in the induced waveguide element with homogeneous borders, have the same intensity level.

![Figure 4(a, b). The light patterns at the output facet of channel waveguide elements with longitudinal homogeneity (a) and its intensity profile (b).](image)
However, the intensity level of light beam, propagated in the waveguide with longitudinal inhomogeneity, is lower than the intensity level of propagating light in the longitudinally homogeneous waveguide (Figure 5b). Perhaps this is due to the fact that the longitudinally homogeneity influence to the propagation loss level of the light in such structures.

![Figure 5(a, b). The light patterns at the output facet of channel waveguide elements with different longitudinal homogeneity (a) and its intensity profile (b).](image)

In the near future we are going to study the influence of longitudinal homogeneity to light energy transition of the narrow focused laser beam from one waveguide to other when one of them is excited. Such method will make it possible to research the interconnection between induced channel waveguides with different spatial homogeneities.

4. Conclusion
In conclusion, we have demonstrated that channel waveguide elements may be optically induced in doped surface layers of lithium niobate. Waveguide configuration is not limited by simple straight elements, the waveguide channels may be longitudinally modulated with their parameters or curvature. Such optically controlled and reconfigured elements are perspective components of modern photonic devices.

Acknowledgments
This study was carried out with the financial support of Ministry of Education and Science of Russia (the project on request 3.1110.2017/PCh).

References
[1] Yamada H and Chu T, Ishida S, Arakawa Y 2006 *IEEE JSTQE* **12** 1371
[2] Rabus D G, Bian Z and Shakouri A 2007 *IEEE JSTQE*. **13** 1349
[3] Bazzan M and Sada C 2015 *Appl. Phys. Rev.* **2** 040603-1
[4] Kroesen S, Horn W, Imbrock J and Denz C 20 Opt. Express **22** 23339
[5] Vittadello L, Zaltron A, Argiolas N, Bazzan M, Rossetto N and Signorini R 2016 *J. Phys. D: Appl. Phys.* **49** 125103
[6] Perin A, Shandarov V and Ryabchenok V 2016 Physics of Wave Phenomena **24** 7
[7] Kip D 1998 *Appl. Phys. B.* **67** 131
[8] Krätzig E 1990 *Ferroelectrics* **104** 257