# Broadband DBR Recorded Holographically into Cu-Doped Ti-Indiffused Channel Waveguide on Z-Cut LiNbO$_3$

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A broadband DBR has been recorded by use of a holographic technique into Z-cut Ti-indiffused channel LiNbO$_3$ waveguides, which were doped by proton-assisted copper exchange. In a first approach we obtain a reflectivity of 17 % and bandwidth (FWHM) of 1.2 nm for IR light with center wavelength 1534.3 nm.

**Keywords:** lithium niobate, Ti-indiffused waveguide, photorefractive grating, DBR filter

## Introduction

Waveguide gratings in LiNbO$_3$ operating around 1550 nm have attracted much interest in integrated optics. Holographically written photorefractive gratings are shown already [1-3] to be one of the most effective and technologically simplest ways for realization of a narrow-band distributed Bragg reflector (DBR) filter integrated with a channel waveguide. On the other hand, broadband operation is much desired in a variety of applications, for example in high-speed guided-wave electro-optic modulators in LiNbO$_3$. A broadband filter requires a grating of high reflectivity and a short interaction length ($\leq$ 0.5 mm). Therefore, extremely strong index modulation ($\geq 5*10^{-4}$) within the photorefractive grating is necessary, which poses a difficult problem, since it requires a high doping level with transient ion impurities (Fe or Cu). Another problem is related to the fact, that all the recent photorefractive grating technologies [1-3] have been developed only for channel waveguides of Y(or X)-cut, Z-propagating geometry. Of course, such geometry cannot be employed in the electro-optic modulators based on LiNbO$_3$.

In this communication, we discuss a DBR recorded directly in Z-cut channel Ti:LiNbO$_3$ waveguides, those photorefractive sensitivity has been increased by a recently developed technique of proton-assisted copper exchange [4] that can achieve a doping level much higher than that available with the commonly used indiffusion and bulk doping techniques. Unique mechanism of photorefractive recording [5], having no equivalent in bulk materials, was used for fabrication of a holographic grating in Z-cut LiNbO$_3$ waveguides.

## Experimental methods and samples fabrication.

An array of channel waveguides was fabricated by indiffusion of an array of Ti strips with width ranging from 2 to 10 μm in Z-cut LiNbO$_3$. The 100-nm-thick strips were indiffused for 18 h at temperature of 1000 $^o$C. To increase the photorefractive sensitivity of these waveguides, two technological procedures were implemented. Firstly, LiNbO$_3$ samples were immersed in a melt of benzoic acid mixed with 0.75 mol% of CuCO$_3$ and 0.65% of Li$_2$CO$_3$. Processing was performed at 240$^o$C for 80 to 110 min and produced a Cu-doped surface layer. Li$_2$CO$_3$ was used to suppress strong proton exchange and avoid surface damage. Secondly, the samples were annealed in dry air at 370$^o$C for 28 to 40 hours. Such annealing significantly decreased the proton concentration and hence, restored the electro-optic effect in the near-surface layer, where Ti-indiffused channel waveguides were located. At the same time, Cu spread into the substrate more efficiently due to the proton-assisted enhancement of Cu diffusion (1/e depth is expected to be about 5 μm). Moreover, oxidation of a significant proportion of Cu ions from (1+) to (2+) valence state took place [4]. As result, a significant photo-induced space-charge field was expected to build-up upon spatially inhomogeneous illumination of the copper-doped region [3].

Photorefractive gratings were written using a He-Cd laser ($\lambda$ = 441.6 nm) in a holographic setup with writing times ranging from 0.5 to 2.5 hours at light intensities within the 0.1 – 0.3 mW/cm$^2$ range. Note, that the upper limit of light intensity used is caused by maximally available output power of our He-Cd laser. A spatial filter was used to produce a clean wavefront of He-Cd laser light. The beam was not collimated. A mirror placed immediately next to the sample at $90^0$ splits a portion of the beam in two. These two writing beams of an equal intensity illuminate the whole sample with the waveguide layer on its top face. The light polarization is chosen to be in the plane of incidence. These beams intersect at an angle $2\Theta = 79.366^0$ in air. Assuming a planar wavefront, the grating period $\Lambda$ is related to the angle $\Theta$ by $\Lambda = \lambda/ (2 \sin \Theta)$. Our setup permits very precise adjustments to the grating period because the optics are placed on a single motorized rotation stage with an angle accuracy of 1/1000 of a degree and, therefore, the gratings are reproducible with average periods accurate to better than 0.1 nm.

The use of an uncollimated beam resulted in a more uniform exposure over an illuminated area of the sample, but could have yielded a chirped grating. To minimize the chirp and nonuniformity of light intensity across the small area of the sample, the beam diameter at the distance where the sample was positioned was chosen to be large enough (30 cm). As result, the grating chirp was reduced to 0.18 nm/cm; that is, a period shift of 0.18 nm along 1cm of the grating.

Transmission and reflection spectra of the fabricated gratings were measured using a tunable laser source HP 8168 (range from 1500 to 1570 nm) and an optical spectrum analyzer HP 70951A. Laser radiation is coupled into a channel by a PM single-mode fiber and radiation reflected by waveguide grating is outcopled from the channel with the aid of same fiber. By this way interaction of the $TM_0$ guided mode with waveguide gratings was studied. Fiber directional coupler is used to extract reflected radiation and send it to the optical spectral analyzer. IR radiation transmitted through a waveguide is collected by microscope objective and imaged on photodetector.

## Experimental results and discussion.

Recently, the feasibility of efficient photorefractive gratings in Z-cut $LiNbO_3$ waveguides has been demonstrated using holographic recording in planar waveguides with extraordinarily polarized guided beams [4,5]. For this crystal orientation, photovoltaic currents perpendicular to the sample surface and the grating vector induce space-charge fields. We have carried out experimental verification of this mechanism, which has no equivalent in bulk materials [5], and used it, for the first time, for direct recording of a DBR in channel waveguides. It is important to note, that realization of this mechanism requires limitation of a grating fringe length in depth direction in order to reach a sufficient magnitude of space-charge field, e.g. in case of $LiNbO_3$ fringe depth should be ≤ 10 μm. To obtain necessary limitation of grating fringe depth in substrate with channel waveguides, we propose to use shallow surface doping of $LiNbO_3$ substrate with photorefractive impurities. Proton-assisted copper exchange gives unique possibility to make the heavy surface doping for gradually variable depth up to ten micrometers. Note, that an interference pattern fringe is not limited by waveguide depth, but it extends over whole thickness of a substrate. However, as a space-charge voltage is following to depth distribution of photovoltaic currents, which should copy roughly copper concentration profile, a marked photorefractive grating is formed within copper-doped surface layer only.

Measured reflection and transmission spectra indicate that the diffraction efficiency and reflectance of the fabricated gratings increase with longer copper exchange and subsequent annealing. Such dependence is in full accordance with the results of our previous study [4] on the effect of $Cu^{+/2+}$ and $H^+$ concentration profiles on the photorefractive sensitivity of $LiNbO_3$ waveguides doped by proton-assisted Cu exchange. It should then be expected that a further improvement of the grating efficiency can be achieved by increasing the Cu salt content in the melt used for Cu exchange and by extending the time of Cu exchange. Note, that the highest grating efficiency was achieved at the highest light intensity used for holographic recording. Thus, a significant enhancement of the grating efficiency may be expected if a more powerful laser is used for recording.

The data for waveguide gratings recorded in a strongest Cu-doped (doping time is 110 min) and longer annealed (for 40 hrs) sample are most promising. For example, the peak reflectivity of 17 ± 1 % (measured in TM polarization) has been observed for a 0.73-mm-long grating in a 8.5 μm wide single mode waveguide, it has maximum value at the wavelength $\lambda_m$ = 1534.3 nm. There is good correspondence of this reflection peak wavelength to the Bragg wavelength in transmission spectrum. Decrease of grating length allows increase the FWHM filter bandwidth up to 2.7 nm, but grating reflectance drop for a very small value of 2 - 3 %. Of course, such value is out of any practical interest, but further optimization of doping and holographic recording technologies could improve significantly this parameter.

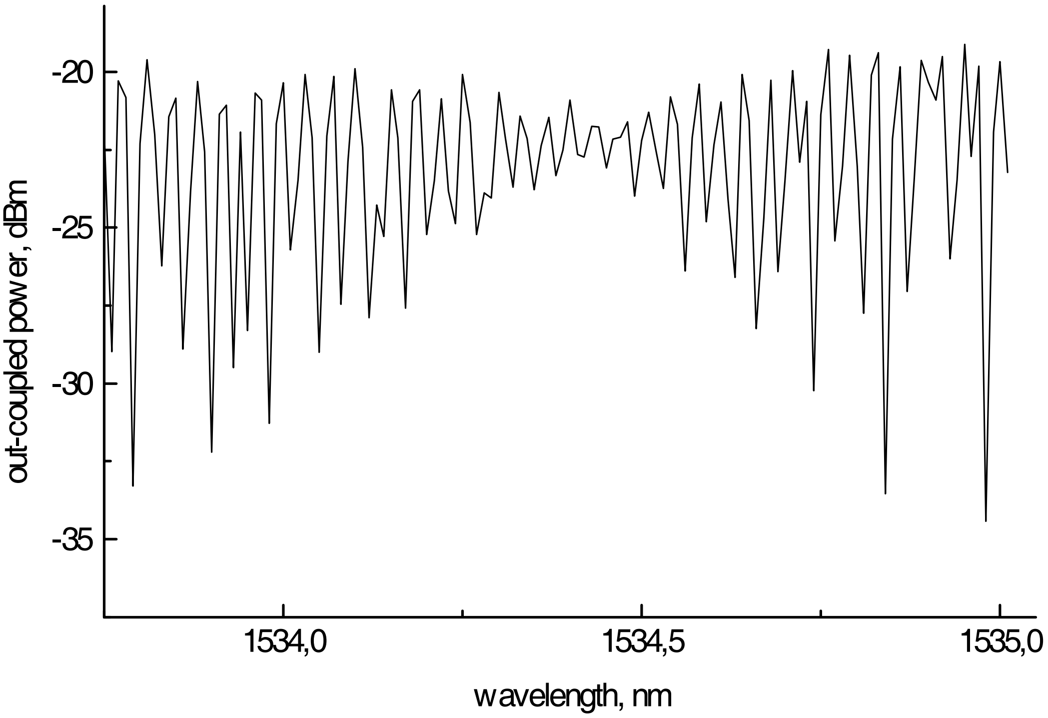

Fig. 1. Spectral dependence of backward out-coupled power for asymmetric Fabry-Perot interferometer formed by a waveguide grating and polished air-waveguide interface. The grating Bragg wavelength is 1534.3 nm. Grating was recorded by He-Cd laser radiation with intensity of 0.2 mW/cm$^2$ for 1 hour in the sample copper-exchanged for 100 min and annealed for 40 hrs. Before grating recording, there is no any spectral band with significant attenuation of Fabry-Perot fringes contrast and some increase of average power $P_{av}$ (where $P_{av} = (P_{max} + P_{min})/2$ ). Wavelength step of tunable laser sources was 0.01 nm.

Main lot of our Integrated Optical Chips (IOC) were fabricated by polishing their ends at a sufficient slant angle ($10^o$) to avoid Fresnel backward reflection from air-waveguide interfaces and, hence, to escape a parasitic Fabry-Perot interferometer (FPI). However, some test samples have perpendicular air-waveguide interfaces at the both optical-grade polished lateral edges. It was used, as application of such test samples for holographic recording allows evaluation of a grating efficiency, as an asymmetric FPI was created through photorefractive grating formation. The term "asymmetric" is used to refer to the case of two reflectors (air-waveguide interface and DBR) with vastly different reflection spectra.

In fact, grating formation induced the specific wavelength-selective change of both contrast and period of Fabry-Perot fringes in reflection spectra of a channel waveguide (Fig.1). The maximum change was observed at wavelength range of 1534.38 to 1534.42 nm, coinciding closely with Bragg wavelength of 1534.3 ± 0.04 nm for holographically recorded DBR. FWHM of differential reflectivity related to asymmetric FPI was wider than a FWHM of the peak in reflection spectrum of similar waveguide DBR recorded in a sample with slanted interfaces at lateral edges. For example, a 1.41-mm grating, having 0.62-nm-FWHM peak in the reflection spectrum, provides ~0.8-nm-FWHM band in response of asymmetric FPI. For shorter gratings the difference between these two FWHMs is smaller and it is not detectable for gratings with $L \leq 0.73$ mm. It is important to note, that evaluation of grating reflectivity, according to the common theory of asymmetric FPI, gives a value around 9.5 ± 0.5 % in the case shown here (Fig.1), while direct measurement of reflection spectrum of same waveguide grating in IOC with slanted ends gives the significantly smaller value of 5 ± 1 %. It was also found that grating reflectance increased monotonically with grating length for up to 3 mm and remained nearly the same after that. This anomaly may be related to the imperfections of the holographic recording processes, such as long-term instability [3], parasitic recording of noise gratings caused by light-induced scattering [6,7], etc.

## Conclusion

Our first attempt at making a broadband DBR yielded a filter with a reflectivity of 17% and bandwidth (FWHM) of 1.2 nm centered at 1534.3 nm. Some gratings exhibited bandwidths as broad as 2.7 nm, however with lower reflectivity. Further improvement of DBR performance is expected, according to the previous studies [4,7] of holographic recording in the Cu-doped $LiNbO_3$ waveguides, to be possible by optimizing Cu content in molten benzoic acid, annealing time, and writing light intensity.

[1] J. Hukriede, I. Nee, D. Kip, E. Kratzig, *Opt. Lett.* **23**, 1405-1407, 1998.
[2] Ch. Becker, A. Greiner, Th. Oesselke, W. Sohler, H. Suche, *Opt. Lett.* **23**, 1194-1196, 1998.
[3] J. Hukriede, D. Kip, E. Kratzig, *J. Opt. A: Pure Appl. Opt.* **2**, 481-487, 2000.
[4] S.M. Kostritskii, Yu.N. Korkishko, V.A. Fedorov, A.N. Alkaev, *Proc. SPIE* **4358**, 88-97, 2001.
[5] D. Kip, F. Rickermann E. Krätzig, *Opt. Lett.* **20**, 1139-1141, 1995.
[6] J. Frejlich, P.M. Garcia, A.A. Freschi, *Proc. SPIE* **2778**, 941 –944, 1996.
[7] S.M. Kostritskii, P. Moretti, *In "IR Holography for Optical Communications: Techniques, Materials and Devices"*, P. Boffi, D. Piccinin and M.C. Ubaldi (Eds.), *Topics in Applied Physics*, vol. **86,** pp. 59-74 (Springer-Verlag, Berlin, 2002).