Neutron and gamma radiation effects in proton exchanged optical waveguides

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Abstract: The effect of neutron and gamma ray irradiations on the optical properties of proton exchanged Z-cut lithium niobate optical planar waveguides were investigated. The damage thresholds were found by optical characterization for waveguides exchanged either in pure or diluted proton source.

OCIS Codes: (130.3730) Lithium niobate; (230.7390) Waveguides, planar; (350.5610) Radiation

References and links

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1. Introduction

For a number of years, lithium niobate ($LiNbO_3$)–based technology was largely used for fabricating integrated optical devices on an industrial scale for telecommunications and sensing applications, including electrooptic and acoustooptic modulators, filters and multiplexers for dense WDM systems, guided-wave sensors and so on. Increasing interest was also devoted to the applications of photonic technologies to space, including velocity sensors for gyroscope systems, spatial light modulators, acousto-optic Bragg cells [1] and semiconductor lasers [2], or high energy particle environments, where the experimental investigations were mainly applied to optical fibre components [3] or nonlinear crystals [4]. However, little effort was spent on the influence of irradiation particles on the optical characteristics of planar waveguides, which support a number of guided-wave optical devices. For these reasons, in this paper we investigate the sensitivity of lithium niobate planar waveguides to ionizing particles and establish their damage threshold.

2. Experiments

Planar optical waveguides were fabricated by proton exchange on Z-cut lithium niobate samples. The beaker with pure or diluted (with lithium benzoate) benzoic acid was immersed in an oil bath at different temperatures (200-235 °C, ± 0.1°C). A slow cooling procedure (25 °C/min) of the samples was followed after the proton exchange, in order to avoid any crystal thermal shock.

Optical characterization was carried out by He-Ne laser at λ = 632.8 nm by rutile prism coupling. Index profile reconstruction for the multi-mode waveguides was obtained by the

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inverse WKB (IWKB) method by using a generalized Gaussian function for interpolation purposes, as:

$$\Delta n = \Delta n_s \exp\left[-\left(x/d \right)^{\alpha} \right] \quad (1)$$

where Δn_s (surface index change), d (waveguide thickness) and α (Gaussian function exponent) are parameters to be simultaneously extracted. The accuracy of this procedure was verified. In fact, the reconstructed profile was used to numerically evaluate the waveguide effective indices by the transfer matrix method and compare them with the experimental ones, their difference being always less than 0.3%. All the waveguides fabricated in pure benzoic acid showed four modes, while those obtained by diluted sources were single-mode, as it can be seen in Table I. Measurements of in-plane scattering levels (defined as the variation of scattered power at 1°/centre spot power ratio measured into free space along the m-line of fundamental mode versus the distance between the input and output coupling prisms) were performed on all the samples by an experimental set-up including lock-in amplifier, photodiode, data acquisition card and PC (standard deviation < 0.025 dB).

Table I. Optical waveguide fabrication conditions.

SAMPLE	Dilution (lithium benzoate)	Exchange temperature [°C]	Exchange time [min]	Mode number
B3	0 %	220	240	4
B5	0 %	220	240	4
B6	0 %	220	240	4
BD4	1 %	235	120	1
BD6	2 %	235	120	1
BD7	1 %	235	120	1
BD7bis	1 %	235	120	1
BD7tris	1 %	235	120	1

As a first step, 1 MeV neutron radiations were applied by the Prospero Reactor at CERN to the samples B3, B5, B6 and BD4 (I irradiation), changing the experimental parameters (see Table II). The total dose of $2 \cdot 10^{11}$ n/cm^2 corresponds to 10 years of radiation at Large Hadron Collider (LHC), $2 \cdot 10^{12}$ n/cm^2 to 100 years [5]. After that, the samples were again optically characterized. The comparison of optical measurements before and after the neutron irradiation is given in Table III, showing a slight effective index change, the in-plane scattering remaining of the same order of magnitude with a moderate improvement (from 0.49 to 0.26 dB/cm) only for the B5 sample. In this last case, the stronger neutron radiation induces a moderate local annealing, which probably contributes to the homogeneous distribution of substitutional protons inside the waveguide. On the contrary, the increase of in-plane scattering loss in the other cases should be related to the harmful migration of interstitial protons, which act as scattering centres [6].

As a second step, the same samples B3, B5 and B6 were radiated by 1 MeV gamma rays with dose rate of 8.57 rad/h and total doses as in Table II.

Table II. Radiation experimental parameters.

Sample	Reactor power [%]	Distance from source [m]	Exposition time [min]	Neutron dose [n/cm^2]	Gamma dose [rad]
B3	50	3	45	$2 \cdot 10^{11}$	34.3
B5	50	3	45	$2 \cdot 10^{11}$	50

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B6	50	6	45	$5\cdot10^{10}$	57.1
BD4	100	3	240 (*I irr.*) 240 (*II irr.*)	$2\cdot10^{12}$ (*I irr.*) $3.1\cdot10^{12}$ (*II irr.*)	-
BD6	100	3	350	$3.1\cdot10^{12}$	-
BD7	100	3	350	$3.1\cdot10^{12}$	-
BD7bis	100	3	400	$3.1\cdot10^{12}$	-
BD7tris	100	3	450	$3.1\cdot10^{12}$	-

Then, the waveguides were again characterized (see Table III) and their index profile parameters (Δn_s, d and α) summarized as in Table IV. Results shown in Table IV and Fig. 1 for the B5 sample clearly show a more gradual index profile as an effect of both the waveguide radiations. However, this low-energy (1 MeV) gamma irradiation was not strong enough to change the surface refraction index, i.e. the sample crystallographic phase, and the only remarkable radiation effect was given by the change of α values, depending on the graduality of the proton distribution between the exchanged and pure crystal regions. In fact, we can notice from Table IV that the α value was almost unchanged for the sample B6 after the first neutron radiation, while the other two samples exhibited a strong reduction (from about 30 to 13).

Table III. Optical characterization results for samples as-exchanged, after neutron radiation and after gamma following neutron radiation.

SAMPLE	Effective index			In-plane scattering		
	As-exchanged	After radiation		As-exchanged	After radiation	
		Neutron	*Gamma*		*Neutron*	*Gamma*
B3	2.330 2.309 2.277 2.232	2.327 2.300 2.267 2.228	2.327 2.299 2.269 2.227	0.80	1.00	0.88
B5	2.330 2.309 2.276 2.231	2.328 2.302 2.273 2.233	2.329 2.301 2.272 2.237	0.49	0.26	0.32
B6	2.310 2.306 2.272 2.224	2.327 2.300 2.269 2.221	2.326 2.298 2.265 2.219	0.29	0.33	0.42
BD4	2.276 (*I irr.*) 2.273 (*II irr.*)	2.273 2.271	-	0.38 0.58	0.58 0.71	-
BD6	2.271	2.274	-	0.89	1.03	-
BD7	2.272	2.271	-	0.65	0.80	-
BD7bis	2.275	2.235	-	0.95	1.28	-
BD7tris	2.276	2.323 2.292 2.255 2.206	-	0.83	0.89	-

Table IV. Index profile reconstruction parameters.

SAMPLE	Surface index change Δn_s			Waveguide thickness d (µm)			Gaussian exponent α		
	As-exchanged	*Neutron*	*Gamma*	As-exchanged	*Neutron*	*Gamma*	As-exchanged	*Neutron*	*Gamma*
B3	0.127	0.125	0.122	1.76	1.78	1.76	35.5	13.2	14.6
B5	0.127	0.124	0.126	1.75	1.81	1.88	29.1	12.5	7.3
B6	0.127	0.122	0.121	1.70	1.69	1.69	32.0	26.7	17.3

Similarly, a comparison between the last two columns of Table IV shows that the gamma radiation induced a significant effect on α for doses $\geq$ 50 rad, the B3 sample remaining practically unchanged and the sample B5 showing a stronger decrease of α (-41%) with respect to B6 (-35%), although it was radiated with lower energy (50 instead of 57.1 rad). This effect is due to the neutron-gamma combined irradiation, which tends to increase the damage induced over a waveguide, when it is already significantly damaged. In-plane scattering levels obtained after the gamma radiation showed the same order of magnitude than before it, namely 0.88 dB/cm (B3), 0.32 dB/cm (B5) and 0.42 dB/cm (B6).

To investigate the influence of the proton source dilution, another set of samples exchanged in diluted acid was radiated according to Table II (samples BD4: II irradiation, B6, B7, B7bis and B7tris, all subjected to 20 MeV neutron dose of $3.1 \cdot 10^{12}$ n/cm^2 in the High Energy Collider at Louvain, Belgium). The optical characterization results are given in Table III.

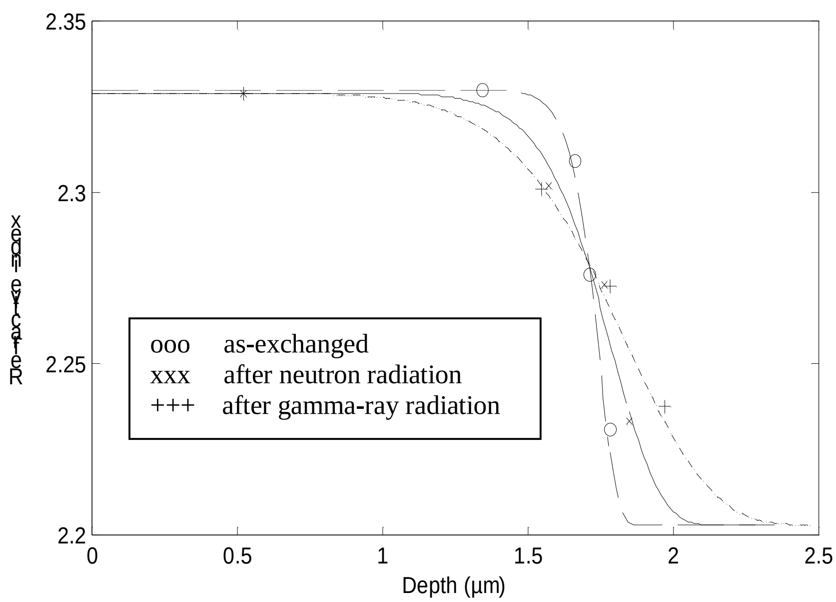

Fig. 1. Index profiles of B5 sample as-exchanged, after 1 MeV neutron ($2 \cdot 10^{11}$ n/cm^2) and after 1 MeV gamma (50 rad) following neutron radiation.

From this Table we can see that neutron radiations for times < 6 h did not significantly influence the optical characteristics of diluted waveguides. For radiation times > 6.5 h, an

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increasing influence on the guiding parameters was obtained, as in the sample BD7bis where the effective index decreased, due to less optical confinement. Sample BD7tris, radiated for more than 7.5 h, exhibited the maximum damage, since it supported four modes after the radiation, with a like-step index profile having d=1.63 μm and α = 14. This circumstance demonstrates that the radiation step significantly modified the crystallographic structure of the exchanged region, causing a strong penetration of the protons inside the waveguide and increasing the depth from 0.55 to 1.63 μm. From Table III we can see that the in-plane scattering levels after the radiation increased in any case, still remaining of the same order of magnitude. Finally, it is important to consider the significant difference found in the sample behaviour when the radiation was carried out in successive cycles or in a single one. In fact, the sample BD4 radiated for 8 h in two different cycles (I and II, 4 h each) was practically unchanged, while the sample BD7tris radiated for 7.5 h in one single cycle was strongly damaged, i.e. in the former the effect was largely reversible and in the latter fully irreversible.

3. Conclusions

In conclusion, we have demonstrated the following:

For waveguides exchanged in pure benzoic acid:

- Damage threshold using 1 MeV neutron radiation at a dose of $5\cdot 10^{10}$ n/cm^2;
- Damage threshold using 1 MeV gamma radiation at 50 rad.

In both cases a progressive increase of index profile graduality was observed.

For waveguides exchanged in diluted benzoic acid:

- Damage threshold using 20 MeV neutron radiation at $3.1\cdot 10^{12}$ n/cm^2 for times $\geq$ 6.5 h (increasing number of modes).
- Reversible effect of neutron radiation applied in successive cycles (4 h each, > 7 h in total), and fully irreversible effect obtained after a single long cycle (> 7 h).

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