Optical-damage-free guided second-harmonic generation in 1% MgO-doped stoichiometric lithium tantalate

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Room-temperature cw second-harmonic generation from telecom wavelengths, with 30% $W^{-1}\,cm^{-2}$ efficiency and second-harmonic power levels up to 41 mW, was achieved in buried waveguides fabricated by reverse-proton exchange in 1% MgO-doped stoichiometric lithium tantalate without any evidence of optical damage. The technology proves suitable for the realization of efficient nonlinear frequency converters and all-optical devices. © 2006 Optical Society of America

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Periodically poled ferroelectric crystals have become of increasing interest in the past few years for the nonlinear conversion of optical frequencies in the quasi-phase-matching (QPM) regime. They allow one to access the highest effective nonlinearities and to generate second-harmonic beams in a broad spectral range from the ultraviolet to the near infrared. For these reasons they are commonly used in a great variety of applications both in bulk[1,2] and in guided configuration.[3–6] Among these crystals, the most widely used for duplication in the blue spectral region is periodically poled potassium titanyl phosphate (PPKTP) due to its high nonlinearity and optical damage threshold. Its drawback is mainly related to the difficulty of achieving interaction lengths longer than 3 cm, which are of main importance for realizing efficient all-optical devices for telecom applications. In such a field the best results were achieved in periodically poled lithium niobate (PPLN) because of its very high nonlinear coefficient, the availability of large substrates, and the well-consolidated techniques for fabricating highly homogeneous optical waveguides, both by annealed proton exchange,[7] possibly followed by reverse exchange, and by titanium indiffusion.[8] However, the main drawback of PPLN is its relatively low optical damage threshold, which prevents the simultaneous use of high-power density, short wavelengths, and room temperature.[3,9] When considering the critical aspects of the different materials, one of the most promising alternatives to PPLN and PPKTP is the recently developed periodically poled stoichiometric lithium tantalate (PPSLT),[10] which, despite its slightly lower nonlinearity has a high optical damage threshold and good potential for waveguide homogeneity.

In this Letter we report, for the first time to our knowledge, an efficient frequency doubling of telecom radiation in buried waveguides realized by reverse-proton exchange (RPE) in 1% MgO-doped PPSLT.[11] Normalized efficiencies as high as 30% $W^{-1}\,cm^{-2}$ and second-harmonic power levels up to 41 mW were obtained at room temperature and in the cw regime without any evidence of optical damage. These results support the RPE-PPSLT technology as a new interesting candidate for the realization of nonlinear all-optical devices.

In SLT, RPE technology has been recently proposed.[11] It involves, as in the case of lithium niobate and congruent lithium tantalate,[12] three different fabrication steps, specifically proton exchange (PE) in pure benzoic acid, annealing in air, and reverse exchange (RE) in an euthectic melt composed of $LiNO_3$, KNO_3, and $NaNO_3$. The operating temperatures are quite high, 280°C for PE and 350°C for annealing and RE, due the low diffusivity of protons in SLT. At the surface of the crystal PE generates a shallow step-index waveguide having a low index change (<0.02 at $\lambda=0.633\ \mu$m) and poor optical quality because of its quite high losses (>1 dB/cm) and a degraded nonlinear coefficient. During annealing, protons diffuse deeper into the substrate, and the refractive index, following a highly nonlinear behavior, increases up to ~ 0.03 in the first few hours while decreasing very slowly in subsequent hours.[13] The best conditions for fabricating buried waveguides were found when RE is started after annealing has produced the highest index change, so that during the burial step the refractive index profile is excavated at the surface, but it remains almost constant on the substrate side. The optical quality improves during

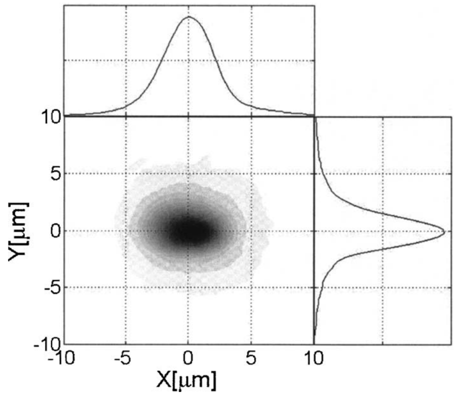

Fig. 1. Intensity profile of the fundamental mode of the waveguide at 1.55 μm.

annealing and even more during RE due to the fact that the barycenter of the index profile shifts toward the substrate, thus getting away from the degraded surface region formed by PE.

Several channel waveguides having widths between 6 and 10 μm were fabricated on a 2.5 cm long PPSLT sample provided with five poling periods from 17.7 to 18.5 μm, plus another 21 μm period designed for the bulk nonlinear characterization. The fabrication parameters of the waveguides were as follows: 1 h 45 m for PE, giving rise to a 1.7 μm thick step-index film, 3 h for the annealing, changing the refractive index profile into a step-exponential profile with a 4.9 μm $1/e$ depth, and 11 h for the RE, producing a buried index profile with a 3.7 μm transverse dimension (at $1/e$ of the maximum index value). With such parameters all the waveguides were single mode at 1.55 μm with almost circular mode profiles, as shown in Fig. 1 for a 10 μm wide channel. The upper and right-hand side of the figure report the vertical and horizontal cross sections of the mode profile, presenting a FWHM of 4.8 and 3.2 μm, respectively. With such dimensions the fiber-waveguide coupling losses due to mode spatial mismatch are approximately 22%, and an overestimated evaluation of the waveguide attenuation was obtained by simple subtraction of coupling and Fresnel losses to the insertion losses. In this way an attenuation between 0.3 and 0.5 dB/cm for the different channels was found, which is a quite satisfactory result.

The nonlinear characterization of the waveguides was preceded by the measurement of the second-order susceptibility of the bulk PPSLT at 1.55 μm (so far not reported in the literature). The radiation emitted by the fiber output of a tunable Agilent 81600B laser source was collimated and then focused in the 21 μm periodically poled region with a spot size of 107 μm, giving a 98 mm confocal parameter, which is much longer than the crystal. In such conditions the tuning curve, reported in Fig. 2, reveals a 2.5 cm interaction length, i.e., equal to the sample length, and a nonlinear d_{33} coefficient of 10.6 pm/V, which is slightly higher than that reported in the literature for congruent LT and about one half that of LN.[14] Confirmation of this value was obtained by direct comparison of the SHG efficiency of the PPSLT sample with that of a PPLN sample having the same interaction length.

The nonlinear characterization of the waveguides gave the best results for the 9 and 10 μm wide channels, whose phase-matching curves are less critical in the presence of local inhomogeneities of the refractive index profile. The tuning curve of the 10 μm wide channel of the 18.1 μm periodically poled region is reported in Fig. 3. Its FWHM corresponds to an interaction length of ~1.3 cm, and its peak corresponds to a normalized efficiency of 30% $W^{-1}\,cm^{-2}$. The interaction length is quite low with respect to the sample length, mostly due to undesired thermal gradients during the fabrication process. On the other hand, the normalized conversion efficiency is lower but still consistent with the highest values reported for PPLN waveguides [i.e., 40%–50% $W^{-1}\,cm^{-2}$ with APE (Ref. 3) and 150% $W^{-1}\,cm^{-2}$ with RPE (Ref. 15)], since, because the nonlinear coefficient of PPLN is twice that of PPSLT, a 4 times factor in the conversion efficiency is expected with waveguides of comparable effective interaction area. Such an area amounts in our case to 19.4 μm^2, indicating an excellent spatial overlap between fundamental (FF) and second-harmonic (SH) fields by virtue of the buried refractive index profile.

To check the optical damage resistance of the waveguides, we measured the SH power for increasing values of the coupled pump power up to a level of

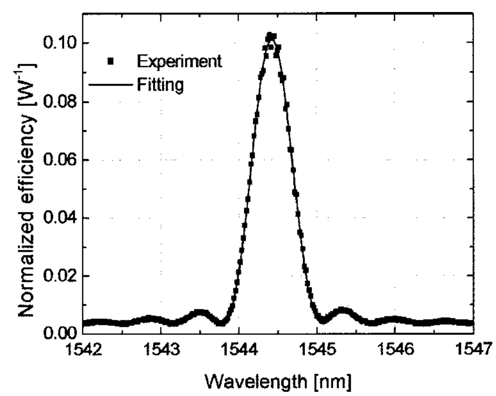

Fig. 2. Bulk second-harmonic generation efficiency versus wavelength (experimental conditions: 25 mm long sample, 21 μm poling period, 107 μm beam radius).

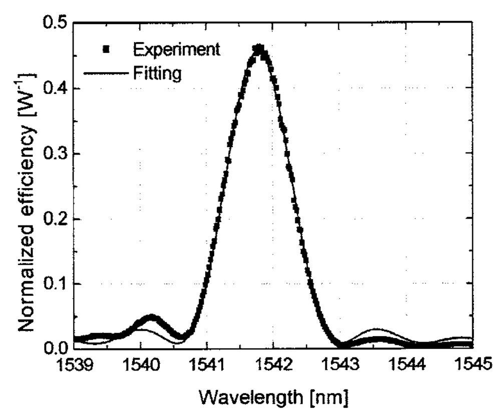

Fig. 3. Waveguide second-harmonic generation efficiency versus wavelength.

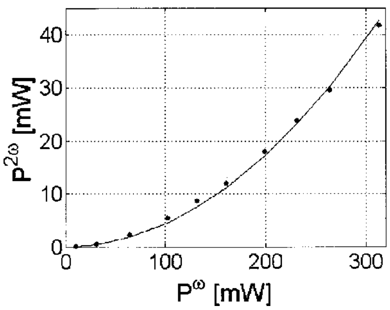

Fig. 4. Dots, second-harmonic output power versus input pump power as measured in room-temperature operating conditions. Solid curve, expected curve from low pump-depletion characterization.

313 mW, corresponding to a FF peak intensity of 1.8 MW/cm^2. The measurement was performed in the cw regime by keeping the waveguide at 25°C to verify the possibility of room-temperature high-power density operation. For each pump power the waveguide was exposed for 20 min and the SH power sampled every minute to appreciate SH power changes due to possible optical damage.[16] Extremely stable values were obtained independently of the pump power level. These values are reported in Fig. 4 (dots) together with the theoretical curve (solid curve) as expected for a 30% normalized efficiency. A very good agreement is found, indicating that no degradation of the waveguide performances occurs up to a SH power level of ~41 mW (corresponding to a peak intensity of 0.56 MW/cm^2 if taking into account the SH intensity profile). The optical damage threshold is thus particularly high if compared to waveguides in congruent PPLN.

In conclusion, a new technology based on reverse proton exchange in 1% MgO-doped PPSLT was shown to be quite promising for fabricating highly nonlinear and resistant optical waveguides, suitable for room-temperature operation in telecom-oriented devices, and in applications requiring a high-power density and/or short wavelength regime.

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