UV laser-assisted fabrication of ridge waveguides in lithium niobate crystals

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Abstract—**We present a UV laser-assisted method for the fabrication of ridge waveguides in lithium niobate. The UV laser irradiation step provides the refractive index change required for the vertical light confinement in the waveguide and also defines the ferroelectric domain pattern which produces the ridge structures after chemical etching.**

I. INTRODUCTION

Lithium niobate (LN) is an optical ferroelectric crystal with a distinctive combination of inherent physical properties. This has resulted in its use for a diverse range of applications such as mobile and optical telecommunications, optical wavelength conversion, and for integrated optical devices such as high speed electro-optic modulators.

As the need for further improvement of the efficiency and compactness of integrated optical devices is increasing it is necessary to use superstructures such as ridge waveguides (instead of conventional diffused waveguides) that provides better lateral confinement of the optical mode due to the higher index contrast. Additionally, the stronger optical confinement and smaller modal dimensions enhance the efficiency of any nonlinear processes implemented using these waveguide.

Several different methods have been trialled to produce ridge waveguides in LN. In general almost all of these methods utilize an etching step that defines the ridge geometry and a separate waveguide fabrication step, such as ion-diffusion or proton-exchange which requires lithographic alignment with the ridge structure. Delineation of the ridge is achieved either via wet etching in an acid mixture containing HF acid or through dry etching processes such as ion beam milling [1] or plasma etching [2]. Since acid-based wet etching for structuring of LN is commonly based on the differential etching behaviour of the two complementary crystalline *z*-faces, domain inversion [3] has also been reported as an obvious and easy choice for defining ridges in LN. Interestingly, ridge waveguides have also been fabricated by mechanical dicing of planar MgO:LN bonded on to LN [4].

The mandatory step required to induce the vertical refractive index contrast either precedes or succeeds the wet or dry etching process. The compatibility of the two steps is essential and hence the recipe with the right sequential steps has to be adhered to for producing ridge waveguides in LN.

In this contribution we report on a method for producing ridge waveguides in *z*-cut LN whereby the definition of the ridge pattern and the vertical confinement are defined by a *single* step of direct continuous wave (c.w.) UV laser waveguide writing [5, 6]. This initial UV exposure of the +z face of LN crystals is known to inhibit domain inversion locally during subsequent electric field poling (EFP) [7]. As a result a ferroelectric domain structure which corresponds to the UV irradiated tracks is formed after EFP. In conjunction with wet etching this effect then provides an easy alternative method for fabricating useful domain and surface relief structures [7]. UV-induced refractive index change and poling-inhibition, pave the way to self-aligned ridge waveguides in LN.

II. EXPERIMENTS AND RESULTS

The first step in the sequence for the fabrication of the ridge waveguide structures involves the inscription of a refractive index change in LN using the UV direct writing procedure. This initial direct writing step not only helps to establish the vertical refractive index contrast for the ridge waveguides, but will also precisely outline the actual shape of the formed superstructures. A beam from a c.w. Ar-ion laser, which was focused to a spot radius of ~3 µm, was used for the writing on the +*z* face of a congruent un-doped LN crystal. Precise control over the positioning and exposure of the illuminating laser beam was achieved by a computer-controlled, three-axis stage system coupled with a mechanical shutter. The laser wavelength used in our experiments was 275 nm. Sets of parallel lines were drawn on the +*z* faces of the crystals along the crystallographic *y* direction by moving the stages at speeds ranging from 0.1 to 1 mm/s. The incident intensity was varied between 1 – 2 GW/m^2.

The samples with the sets of UV exposed parallel lines were then poled using the EFP set-up described in [7].The sample was first cycled through several forward and reverse poling cycles before the final forward poling step. In this final poling step, the voltage was ramped at 0.1 kV/s to a value of ~ 10 kV which corresponds to an electric field of ~20 kV/mm across the 0.5 mm thick sample. This lower value of the

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applied electric field (less than coercive field) ensures that domain inversion occurs slowly, which is desirable since the kinetics of the domain wall motion is seen to greatly influence the shape, quality and more essentially the continuity of the resultant ridge structures. As described in [7], the UV written lines inhibit subsequent domain inversion and retain their $+z$ domain orientation whereas the rest of the un-illuminated crystal undergoes domain inversion to a $-z$ orientation. Because of the differential etch characteristics of the complementary z faces, whereby the +z face does not etch, when the poled samples with the sets of UV written parallel lines, are etched in pure HF acid at room temperature, sets of parallel ridges are formed. Fig. 1 shows an optical microscope image of two sets of parallel ridges formed using this fabrication route. All of the ridges have been produced by scanning the c.w. UV laser beam at a speed of 0.1 mm/s, however, the set of four lines on the left of the image have been written with a slightly higher incident intensity of ~ 1.4 GW/m^2 whereas the ones on the right have been written using ~ 1.2 GW/m^2. A slight variation in the widths of these two set of ridges is a result of the difference in the incident power which influences the width of the poling-inhibited region. Fig. 2 shows a plot of the etched poling-inhibited width, which corresponds to the width of the ridge structure, as a function of the UV laser intensity. As shown in the plot a range of laser intensities exists where the width increases almost linearly with the laser intensity. The cross-section of a polished end face of one such a ridge is shown in the scanning electron microscopy (SEM) image presented in Fig. 3. The trapezoidal cross-section of the ridge is possibly a consequence of the inherent etching behaviour of different crystalline planes that are revealed during the etch process. The width of the ridge near the top is ~ 7 µm, and its height is ~ 3.1 µm. As the ridges have been formed by drawing lines parallel to the crystallographic *y* direction they consequently have a symmetric cross-sectional profile. The noticeable roughness along the sidewall of the ridge is a consequence of the wet etching process which was performed in pure HF. However, use of modified etchant mixture have been reported to produce smoothly-etched surfaces [8]. Further optimization of the etching conditions will be investigated in order to eliminate the deleterious sidewall roughness. The current choice of etching conditions was driven mainly by speed rather than quality. The UV laser intensity, during the UV writing step, has a significant impact on the quality of the ridge structures. Specifically, UV intensities higher than ~ 1.6 GW/m^2 lead to damage of the top-surface, whereas intensities lower than ~ 1.1 GW/m^2 result in poorly defined ridge side-walls. After edge polishing of the samples laser light (633 nm HeNe laser) was end-fire coupled into the ridge waveguides using a microscope objective lens in order to investigate the optical characteristics of the structures. Fig. 4 shows the near-field intensity profile collected using a second objective lens to image the output of the ridge on to a CCD camera. This mode profile corresponds to a ridge structure formed using a UV laser scanning speed of 0.1 mm/s and an incident intensity of ~ 1.2 GW/m^2. We did not observe any deterioration of the vertical confinement in the UV written waveguides after the EFP and wet etching processing steps. Contrary to that we did observe a significant refractive index change increase (more than 50 %) in the UV written optical waveguides following the poling-inhibition step (before etching to fabricate the ridges).

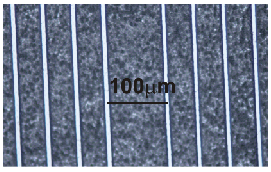

Figure 1. Optical microscope image of two sets of ridges.

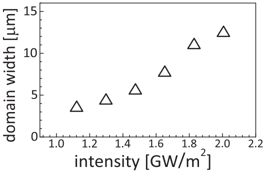

Figure 2. Plot showing variation of poling-imhibited domain width versus intensity.

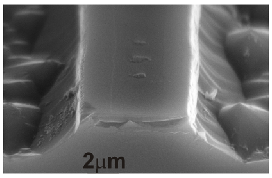

Figure 3. SEM of the polished end face of the ridge

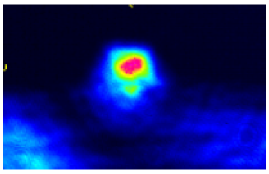

Figure 4. Near-field intensity profile obtained at 633nm

III. CONCLUSIONS

In conclusion we have presented preliminary results on a UV laser-assisted method for the fabrication of ridge waveguides in LN crystals. The method utilizes UV laser direct writing to i) provide the vertical confinement of the light in the waveguide and ii) assist the domain engineering process (poling-inhibition) which, after chemical etching, defines the ridge structures.

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