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Fabrication of Bragg Gratings on $LiNbO_3$ optical waveguides

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ABSTRACT

We report on three approaches to achieve 1086 nm period Bragg Gratings structures (BGs), corresponding to the third Bragg order at 1550 nm, on X-cut lithium niobate ($LiNbO_3$) substrates. The first method relies on Reactive Ionic Etching (RIE) with fluorine gases, associated with e-beam lithography and electroplating deposition. BGS with etched angles close to 60°, an aspect ratio AR = 1.4 and a reflectivity of 13% have been fabricated. The second process is based on Focused Ion Beam (FIB) milling. BGs are etched in standard optical waveguides. The process has led to etched angles close to 85° with AR = 6.3 and to a reflectivity of 50%. Finally, we propose an original method based on the use of lateral FIB etching on the edge of deep-etched ridge optical waveguides predefined by "optical grade dicing". Etched angles close to verticality with AR > 9 have been obtained and optical characterizations are under work.

1. Introduction

Structuring $LiNbO_3$ for photonic applications has been attracting much attention over the last decade [1–4] owing to the potentialities offered by this material in terms of electro-optical, acousto-optical or nonlinear interactions. The fabrication of $LiNbO_3$ BGs is of particular interest for the development of various optical functions (such as narrow-spectrum filters, mirrors or couplers) [5,6]. BGs structures consist in periodic or aperiodic variations of the effective refractive index in $LiNbO_3$ optical waveguides. Thus, a maximal reflectivity is achieved around a central wavelength. The nano-structuration of $LiNbO_3$ material represents a challenging task due to the well known resistance of the material to standard machining methods [1–4]. BGs in $LiNbO_3$ have already been developed using different methods such as: photorefractive technique [7], electron-beam lithography and Reactive Ion Etching [8], laser ablation [9] or proton-exchanged technique and Inductively Coupled Plasma etching (ICP) [10,11]. But none of these publications reports the possibility to obtain 1086 nm period BGs with high aspect ratio on $LiNbO_3$ substrates.

In this paper, we have studied different ways to optimize the optical interaction between the optical waveguide and the BGs structures by improving the aspect ratio, the etched angles and the smoothness of the etched structures. We notably propose an original method based on the possibility to etch laterally BGs structures by FIB milling on very thin optical ridge waveguides predefined by "optical grade dicing".

2. Fabrication of Bragg Gratings with RIE etching technique

The first method relies on Reactive Ionic Etching (RIE) with fluorine gases, associated with e-beam lithography and electroplating deposition. The BGs have been implemented on 7 µm-wide standard Ti-indiffused waveguides which have been fabricated with an 85 nm-thick ribbon of titanium diffused at 1020 °C for 10 h. These parameters are chosen in order to obtain the optical mode core close to the surface while keeping the single mode propagation at 1550 nm. The global process fabrication is schematically presented in Fig. 1. A 450 nm-thick ma-N 2405 negative resist is firstly spin-coated on a Cr/Ni conductive seed layer and patterned by electron-beam lithography (EBL) using an accelerate beam voltage of 30 kV. This conductive layer is essential on dielectric substrates to prevent charge accumulation. A 350 nm-thick Ni layer is then defined by the electroplating method onto the substrate. After the usual resist removal, the pattern is finally transferred to the substrate using sulphur hexafluoride (SF_6) based plasma-chemical etching processes. Because of its good resistance to fluorine-based plasma etching, electroplated Ni has been chosen to make high-aspect ratio metallic masks featuring sub-micron patterns. Fluorine gases are indeed generally used for $LiNbO_3$ plasma etching due to the good volatility of fluorinated niobium species at temperature around 200 °C. However, the major problem is the formation and re-deposition of lithium fluoride (LiF) that results in a decrease in the etching rate and in sloped sidewall profiles. Finally, the remaining metallic mask layers are etched away using wet etching solutions. Fig. 2 shows a SEM view of a 30 µm-wide, 0.75 µm-deep and 1 mm-long BG defined in a single mode waveguide. In order to evaluate the etch depth and the sidewall slope angle, a FIB cross-section is performed (Fig. 3) and reveals

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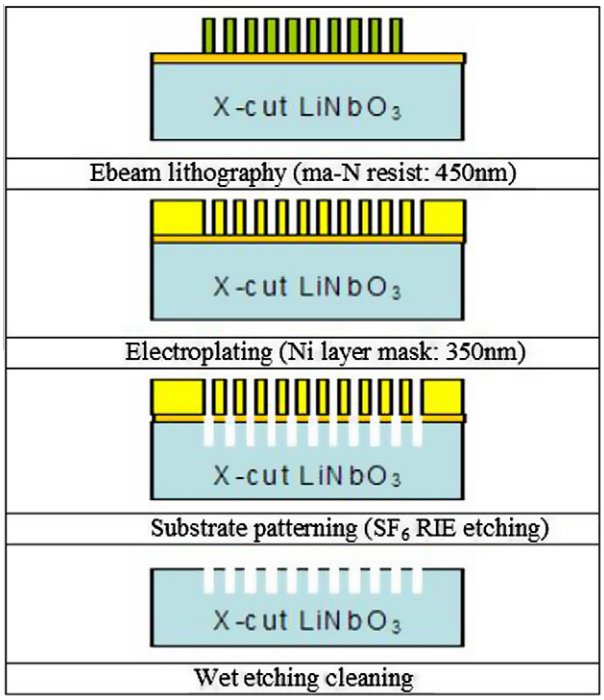

Fig. 1. Global flow-chart with the different process steps for BGs fabrication.

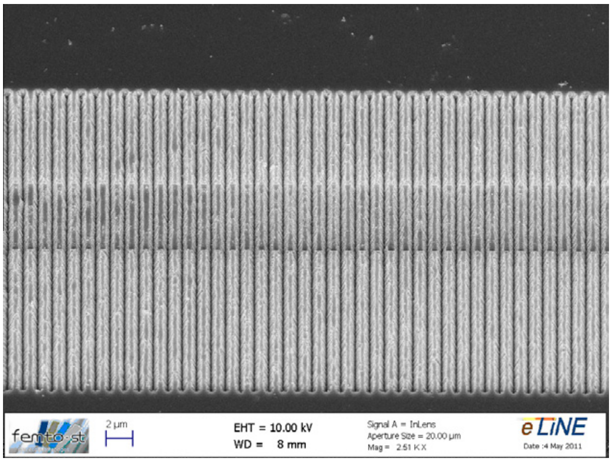

Fig. 2. SEM picture after $LiNbO_3$ RIE etching.

a significant roughness of sidewalls due to LiF redeposition and etched angles close to 60° with a AR = 1.4.

3. Fabrication of Bragg Gratings with direct Focused Ion Beam method

In order to increase the etched depth and the sidewalls smoothness, the FIB method has been used to achieve BGs structures. FIB systems operate in a similar way to a scanning electron microscope (SEM) by using a focused beam of ions that can be operated at high beam currents for site specific milling. Moreover, in comparison with standard methods, FIB milling has the advantage to direct etch the sample without any additional technological steps. The BGs nanostructures are patterned on Ti-diffused waveguide by focused ion beam (FIB) milling (Orsay Physics Canion 31/LEO 4400 FIB), with Ga^+ liquid metal ion source (LMIS), 30 keV ion acceleration energy, 300pA probe current and multiple successive exposures.

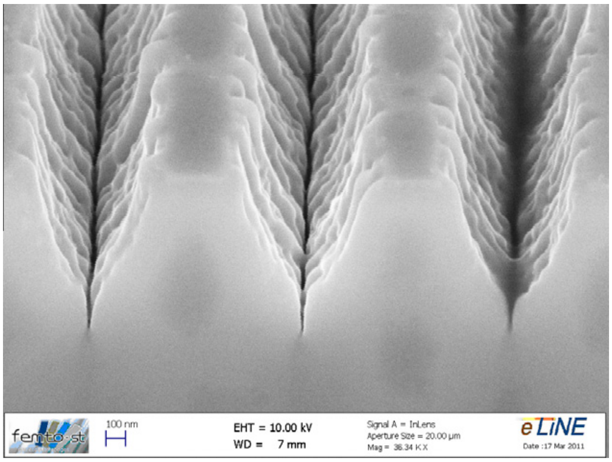

Fig. 3. FIB cross-section on RIE etched structures.

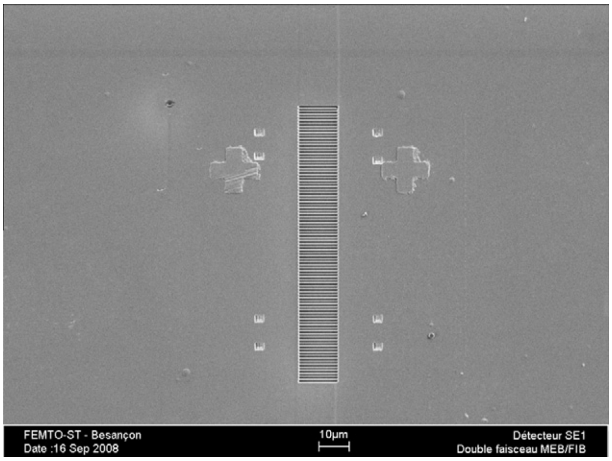

Fig. 4. FIB view of a 100 periods Bragg grating.

Fig. 4 shows a top view of a 8 µm-wide, 3.4 µm-deep and 100 µm-long BG, elaborated by FIB milling on a X-cut, Y-propagating $LiNbO_3$ waveguide. We can see a homogeneous structure with well reproduced periodicities. In order to evaluate the etch depth and the sidewall slope angle, a FIB cross-section is performed (Fig. 5) and reveals etched angles close to 85° and a AR $\approx$ 6. The etching profile exhibits a conical shape, due to the re-deposition of $LiNbO_3$ on sidewalls during the FIB milling process. To increase the structure verticality, reactive gases can be added to the milling process, for example by employing XeF_2 gas-assisted gallium ion-beam etching [12].

4. Optical characterizations

Optical characterizations have been performed on BGs elaborated by these two methods. The normalized transmission responses through the BGs are shown in Fig. 6 (dashed black line for RIE and red line for FIB). From this figure, we can deduce a reflectivity of 13% and 50% at 1550 nm, respectively for RIE method and FIB milling method. To assess the spectral response of the fabricated BGs, we have developed an experimental setup to check the reflectivity. The measurement is performed by using a tunable laser source (Photonetics Tunics BT): the laser light is injected into the 7 µm-wide waveguide via a fibered optical circulator. The output is collected with a SMF28 fiber connected to an optical

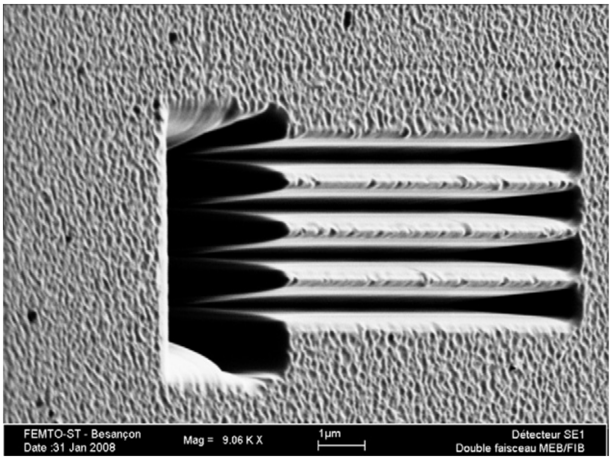

Fig. 5. FIB cross-section on FIB etched structures.

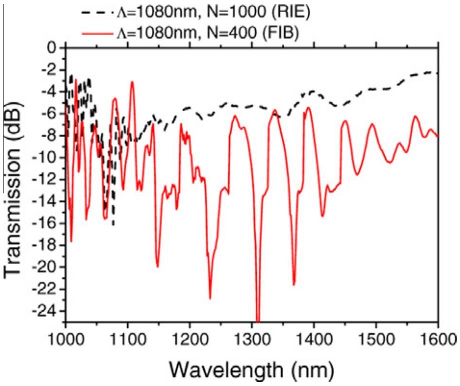

Fig. 6. Normalized transmission response through two kinds of BGs (RIE and direct FIB milling).

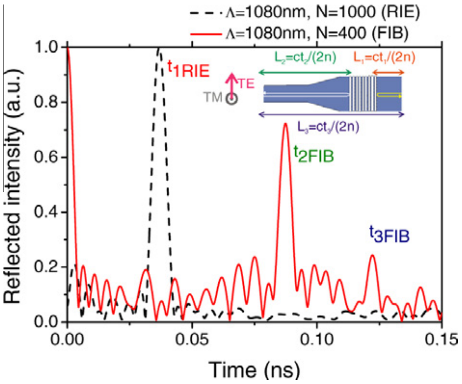

Fig. 7. Impulse response correlation of the reflected light on the BGs. Inset: schematic view of the device, and overview of the FP effects within the waveguide.

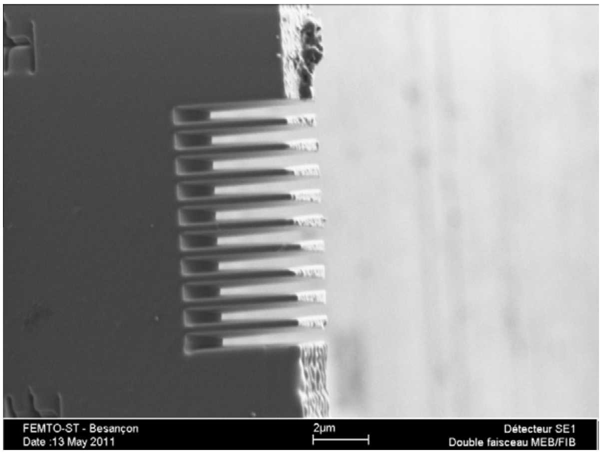

Fig. 8. FIB view of a BG laterally etched by FIB.

Power Meter. The reflected light is measured with the third port of the optical circulator, which is connected to the second channel of the optical Power Meter. By calculating the Fourier transform of the reflected signal, we obtain the impulse response autocorrelation reflected by the device: the results are represented in Fig. 7. In other words, this experiment is equivalent to a swept-source Optical Coherence Tomography: the peaks that can be isolated with this method reveal the presence of different optical cavities inside the device. In particular, the peaks t_{1RIE} and t_{2FIB} confirm that the BGs behave as a reflector. Nevertheless, the direct FIB milling method is very time-consuming (7–8 h) and effective only for the fabrication of small area structures (e.g. $\leqslant$100 μm). So we propose an original method, less time consuming, to optimize the aspect ratios of the BGs structures by using a lateral Focused Ion Beam method.

5. Fabrication of Bragg Gratings with lateral Focused Ion Beam method

This innovative method is based on the possibility to etch laterally BGs structures by FIB milling on very thin optical ridge waveguides predefined by "optical grade dicing". Concerning the fabrication of deep-etched ridges, we have previously reported an alternative method based on "optical grade dicing" [13] for the fabrication of low-loss optical waveguides. This method consists in using a circular precision SAW. More precisely, we propose to dice a sample on which a planar optical waveguide has been preliminarily implemented. The resulting straight grooves are separated by a few micrometers (3–5 μm) and form the ridge waveguides. The blade speed is controlled in order to polish the substrate during the dicing step. These optical ridges are subsequently processed by lateral FIB milling in order to achieve Bragg reflectors and to optimize the aspect ratios of the BGs structures. The fabrication process is the same as the one mentioned above, but this time, the FIB milling is made on the side of the waveguides and not on the top. If the width of the ridge is smaller than 5 μm, it is possible to etch the hole through the whole width of the ridge. Fig. 8 shows a side view of a 4 μm-wide, 5 μm-deep and 10 μm-long BG with etched angles close to verticality and a AR > 9. A large improvement of the aspect ratio can be reached with this method; in fact the re-deposition on sidewalls is partially avoided because a part of the milled materials evacuated at the opposite side of the ridge. Moreover, this new strategy of etching is less time consuming (duration divided by a factor 2.5 compared to direct FIB milling) and a better interaction between the optical waveguide and the BGs can be obtained. Optical characterizations are under work.

6. Conclusions

As a conclusion, original technological processes are suggested for the development of $LiNbO_3$ Bragg Gratings structures. A 30-μm wide, 0.75 μm-deep and 1 mm-long BG has been obtained with the RIE method but presents a AR = 1.4 and significant sidewalls roughness. In order to increase the etched depth and the sidewalls smoothness, the FIB method has been used to achieve BGs. By the top, etched angles ≈ 85° and AR ≈ 6 have been obtained but present conical shapes. With lateral FIB milling on the edge of ridge waveguides, a large improvement of the AR have been demonstrated (AR > 9) which gives promising perspectives towards the fabrication of 3D $LiNbO_3$ structures. A reflection coefficient of almost 50% is reported for the direct FIB milling method.

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