$LiNbO_3$ Whispering-Gallery Mode Micro-resonator

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***Abstract*—Lithium niobate micro-resonators have been fabricated by surface tension reshaping of pre-defined surface microstructures produced at temperatures close to the melting point. Surface-tension-reshaping produced micro-resonator structures with ultra-smooth side surfaces while maintaining the useful crystalline properties. Preliminary optical characterisation on non-optimized structures yielded a Q factor of 5600 at a free spectral range of 4.55nm.**

***Keywords*—lithium niobate, resonator.**

I. INTRODUCTION

Optical whispering-gallery mode (WGM) resonators trap the propagating light in the resonator by total internal reflection (TIR) due to the refractive index difference between the guiding and surrounding media. The condition for resonance is achieved via phase matching of the wavefront on every round trip. WGM resonators enable storage of light at specific (resonant) frequencies which can be coupled into and out of the resonator by optical fibres or planar waveguide structures. This optical storage and the subsequent increase of the intensity in the resonator can thereby lower the thresholds for lasing in active materials [1]. The first observations of optical WGMs was in solid-state WGM lasers based on $Sm:CaF_2$ crystalline resonators [2], whose size was in the millimeter range. Further development in the design and fabrication of high-quality optical resonators requires the development of novel optical materials and technologies. Lithium niobate (LN) is an attractive material for the fabrication of high-Q resonators due to its wide optical transparency window, high electro-optic coefficient and optical nonlinearity. Advances in polishing techniques have allowed the fabrication of large (~5mm diameter and 100μm thick) LN disk resonators that can operate as highly efficient electro-optical modulators [3] and harmonic generators [4]. Q factors as high as 10^8 have been achieved [3] in such structures. If optical polishing is adopted, the original crystal structure and composition can be preserved, and the nonlinear response is enhanced due to the high optical intensity which can be obtained due to the confinement within the small volume of the high-Q cavity. Regarding the fabrication of μm-scale photonic structures in LN, the microstrucuring techniques of wet-etching [5], ion slicing [6], and Ar^+ sputtering [7] provide high lateral optical-confinement. Micro-ring resonators (radius < 100μm) with 1.5 − 2.0nm FSR have been fabricated using the aforementioned methods. Recently, LN WGM resonator structures fabricated via surface tension reshaping of micro-structured crystalline substrates have also been demonstrated [8]. This fabrication method can produce ultra-smooth surfaces while maintaining the useful crystalline properties of the original material. The method is based on the observation that annealing of a crystal at temperatures close to, but lower than the melting point induces preferential melting of a surface layer [9] (surface melting). Upon cooling the melted surface layer re-crystallises, seeded by the bulk that remains solid during the process, and is reshaped by the surface tension to form ultra-smooth single crystal superstructures. In this paper, we will present the capability of this fabrication method to produce different micron-scale WGM structures in LN by using different pre-defined initial micro-structures reshaped under different thermal treatment conditions. Some preliminary optical characterization of non-optimized WGM structures will also be presented.

II. FABRICATION

The LN crystal substrates used for the fabrication of the WGM resonators were 0.5mm thick, undoped congruent LN crystals sourced from Crystal Technology, Inc. (US). The fabrication process involves three steps of: 1) domain engineering to define domain structures of limited depth, 2) HF etching which differentiates between polar surfaces to produce the initial surface microstructures that have an undercut, and 3) thermal treatment to temperatures close to the melting point to achieve preferential surface melting which allows the surface tension to reshape the initial structure. The three fabrication steps are schematically illustrated in Fig. 1.

A. Domain Engineering and HF Etching

Domain engineering was achieved either by poling-inhibition [10] or light-assisted poling [11], both methods being able to produce inverted domains of limited (few μm scale) depth. The domain engineering methods were applied to

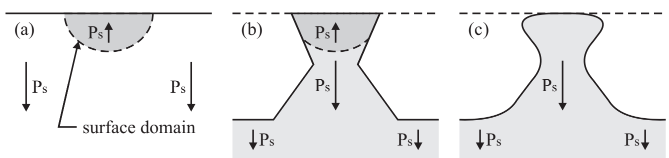

Figure 1. Schematic of the process to fabricate LN resonators via surface melting. (a): domain engineering to produce a surface domain. (b): preferential HF etching to fabricate the initial surface microstructures. (c): thermal treatment.

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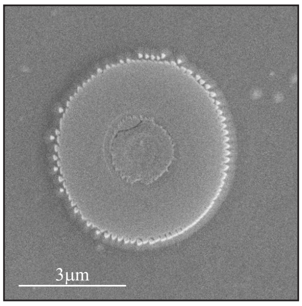

Figure 2. 5μm diameter +*z* face disk domains fabricated via poling-inhibition. Brief HF etching was used to reveal the domain structure.

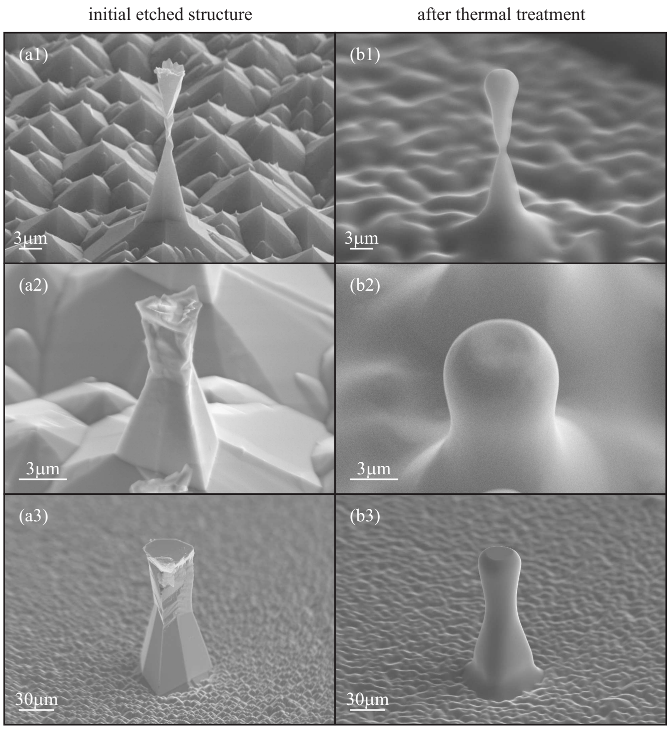

Figure 3. SEM images tilted at 60°. (a1-3): initial structures developed from HF etching of +*z* face disk domains with various dimensions. (b1-3): ultrasmooth resonator structures after thermal treatment of the corresponding initial structure in (a1-3).

define circular surface domains with 5 − 30μm diameter, like the one shown in Fig. 2. Upon differential HF etching, the circular domain pattern which resists etching develops into a pillar structure. Various pillar structures can be seen in the SEM images which are shown in Fig. 3(a1-a3) where an undercut is clearly shown just below the top section of the pillar. This is a consequence of the limited depth of the initial domain. The undercut is crucial for the formation of a structure that can provide vertical optical confinement.

B. Thermal Treatment

After fabrication of the initial etched structures in Fig. 3(a1-a3), the samples were then heated to a temperature which is close to the melting temperature of the crystal. The melting temperature for congruently melting LN crystals is 1257°C (data provided by Crystal technology, Inc. US [12]) and the Curie temperature which marks the ferroelectric to paraelectric phase transition is 1142°C. The appropriate temperature to achieve good quality resonators was found to be a function of the initial structure dimensions. Although the thermal treatment temperature is below the melting point of the bulk, preferential melting of a surface layer is possible, with the thickness of the melted surface layer being a function of the temperature reached [9].

The thermal treatment of the microstructured crystals was conducted in a furnace with an oxygen flow of 0.5L/min to suppress the Li_2O out-diffusion. The temperature ramping rate was 3°C/min for heating. The cooling rate was also set to be 3°C/min, however for the lower temperature range below 400°C this is limited by the furnace temperature controller anymore and is in general much slower than this value.

C. Surface Tension Reshaped Structures

Several surface tension reshaped structures are illustrated in the SEM images which are shown in Fig. 3(b1-b3). These reshaped structures correspond to the initial structures which are shown in Fig. 3(a1-a3). Such structures are suitable for supporting WGMs while the smooth side surface promises low scattering loss. Its small dimensions (< 50μm) suggest that the resonant modes are spectrally widely spaced, hence have a large FSR which can be beneficial for the fabrication of optical filters and lasers.

It was observed that a correspondence exists between the initial structure, thermal-treatment conditions and the final structure. The dynamics of the surface tension reshaping process for specific thermal treatment conditions need to be further investigated for accurate prediction of the final shape. However, the present experimental results already suggest that for substantial reshaping to occur the thickness of the surface melted layer must be comparable to the dimensions of the initial microstructure. Hence, larger structures require higher temperatures for reshaping. Fig. 4 shows SEM images of a pillar structure that has been subjected to a series of successive 1-hour thermal treatments sessions at increasing temperatures,

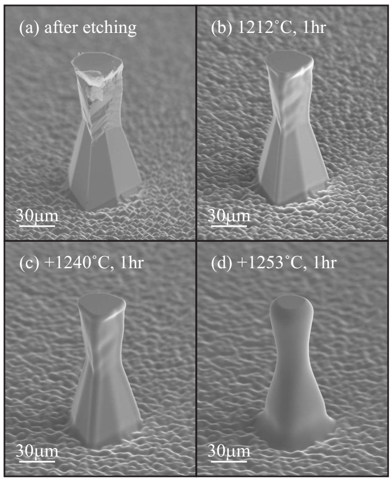

Figure 4. SEM images tilted at 60° of an initial structure that had undergone a series of 1-hour thermal treatments at progressively increasing temperatures at: 1212, 1214, 1217, 1223, 1240, and 1253°C. (a): initial structure before thermal treatment. (b), (c), and (d): the structure after the first 1-hour 1212°C, the 1-hour 1240°C, and the 1-hour 1253°C thermal treatment respectively.

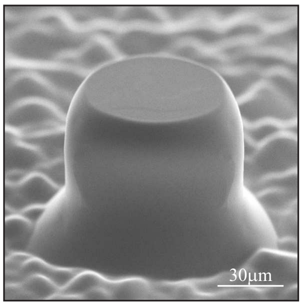

Figure 5. 60°-tilted SEM image of the resonator structure used for optical characterisation.

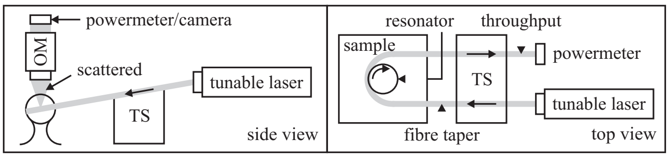

Figure 6. Schematic of the experimental configuration used to simultaneously excite and probe the optical modes in the microresonator. (TS = translation stage; OM: optical microscopy.)

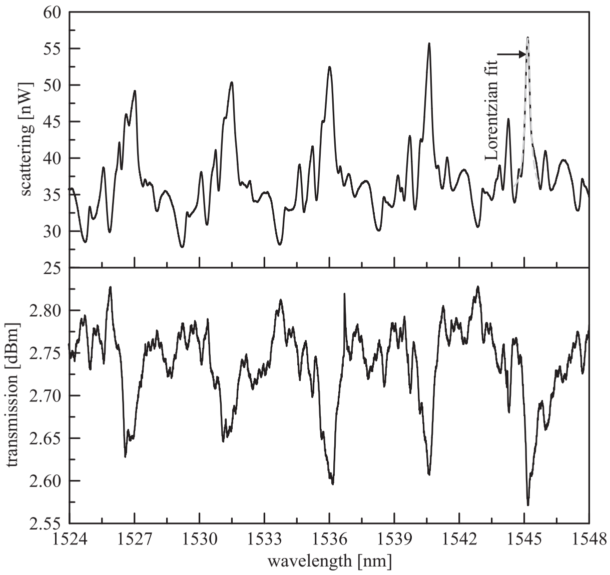

Figure 7. Scattered and transmitted signal with fitted Lorentzian profile used for the determination of Q factors of the microresonator.

from 1212°C to 1253°C. The succession of SEM images shows that although some smoothing of sharp feature can be observed at lower temperatures, substantial reshaping of this particular pillar requires a temperature of 1253°C which is much higher than in the case of smaller structures, e.g. 1223°C for the 3μm structure in Fig. 3(b1).

III. Optical Characterisation

Some preliminary optical characterisation results of the surface tension reshaped WGM LN microresonators will now be shown. These results have been obtained from the microresonator which is shown in the SEM image of Fig. 5. The diameter of the structure, at its widest point, was measured to be 80μm. Fig. 6 illustrates the experimental configuration which has been used to simultaneously excite and probe the optical resonances. A U-shaped silica fibre taper with a waist diameter of about 2μm was used to couple light into and out of the microresonator. Micro-positioning stages were used to position the tapered fibre in close proximity to the resonator. It was observed that when the fibre taper is positioned close to the surface of the structure it is attracted by the surface and sticks to it. The fibre taper was connected from one end to a tunable laser (Agilent 81600B) with linewidth of 100kHz. The other end of the fibre taper was connected to an InGaAs detector in order to monitor the transmitted power as a function of the input wavelength. The light scattered from the resonator was also collected by a microscope objective and its power was also monitored using a second InGaAs detector. Fig. 7 shows spectra of the transmitted and scattered radiation from the microresonator. The spectra show a regular set of resonances corresponding to a multitude of different WGM's supported by the resonator. Fitting a Lorenzian curve to one of the peaks of the scattered spectrum revealed a Q factor of ~5600 of a particular mode with an FSR of 4.55nm. The shape of the resonator (Fig. 5) resembles a truncated microbottle resonator [13]. Such open resonators are known to leak into either side of the resonator [14]. The leakage depends on the microresonator curvature. Leakage into the resonator base was experimentally observed and it is believed to contribute to the relatively low Q. Increasing the resonator curvature will improve considerably the resonator Q.

IV. Future Work

The transition from the initial microstructure to the final surface tension reshaped structure needs to be well understood, and most importantly controlled in order to be used for any practical application. It is therefore important to be able to model the heat treatment process in order to be able to predict the final reshaped structure and to optimize the processing conditions. Improvements in the optical characterisation involve improving the coupling into the high refractive index LN resonators using fibre tapers fabricated out of higher index glass. The wavelength selectivity and the strength of evanescent excitation of the resonator depend upon the degree of phase-matching and spatial overlap between the tapered-fibre field and the resonating mode fields at the different positions of the tapered fibre. Thus, the refractive index difference between silica fibre (∼1.44 − 1.46 at 1550nm) and LN (n_e ∼ 2.14 at 1550nm) can lead to an inefficient coupling process. Finally, the resonator can be doped with rare earth ions, such as Nd or Er for lasing applications. Doped resonators can be pumped collectively (without having to couple into WGM's while the resonances can be readily detected in the lasing spectrum). This is a scheme that can significantly simplify the process of optical characterisation.

V. Conclusion

Thermal treatment of micro-structured lithium niobate substrates at temperatures close to, but below the melting point, allows surface tension to reshape preferentially melted surface zones of the crystal. The fabrication process involves domain engineering, HF deep etching and thermal treatment. The reshaped surface re-crystallises upon cooling to form a single crystal again as it is seeded by the bulk which remains solid throughout the process. Various resonator structures have been fabricated. Preliminary optical characterisation was conducted in one resonator structure which gives a Q factor of 5600 and FSR of 4.55nm.

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