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Lithium niobate micro-disk resonators of quality factors above 10^7

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We report on the fabrication of crystalline lithium niobate microresonators with quality factors above 10^7 , as measured around 770 nm wavelength. Our technique relies on femtosecond laser micromachining for patterning a mask coated on the lithium niobate on insulate (LNOI) into a microdisk, followed by a chemo-mechanical polishing process for transferring the disk-shaped pattern to the LNOI. Nonlinear processes including second-harmonic generation and Raman scattering have been demonstrated in the fabricated microdisk. © 2018 Optical Society of America

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The realization of micro-disk resonators (MDRs) of high quality (Q)-factors using lithium niobate on insulator (LNOI) as the substrate has spurred great interest in developing on-chip nanophotonic structures, which hold the promise for efficient nonlinear wavelength conversion, fast electrooptic light modulation, and high-density photonic integration [1–3]. The key to achieving high Q -factors in the fabricated lithium niobate (LN) MDRs is the incorporation of focused ion beam (FIB) milling or ion dry etching in the patterning of the LNOI, which gives rise to smooth sidewalls for minimizing the scattering loss [4–19]. Typical Q -factors on the level of 10^6 can now be routinely obtained for freestanding LN MDRs [7–11]. Moreover, it is recently reported that a Q -factor of 3×10^6 measured around 976 nm wavelength can be achieved for the LN MDRs fabricated by a reactive ion etching followed by a chemo-mechanical (CM) polishing process, and the intrinsic Q -factor could have possibly reached 10^7 around the optical

communication wavelength of 1.5 μm [10]. The CM polishing greatly improves the surface smoothness, leading to a significant increase of the Q -factor.

Here, we show that by combining the femtosecond laser direct writing and the CM polishing, we are able to realize LN MDRs of Q -factors exceeding 10^7 near the wavelength of 773 nm. This is almost one order of magnitude higher than the state-of-the-art Q -factors around the visible and near-infrared wavelengths reported so far [7–10]. More importantly, we now provide an alternative to the FIB milling process, by which the fabrication throughput can be dramatically boosted, and fabrication of large-scale photonic chips beyond the range of motion of the FIB is readily achievable. Although we do not investigate the combination of other mass-fabrication technologies based on the ion dry etching or ultraviolet lithography with the CM polishing, similar Q -factors are expected for the LN MDRs obtained with such approaches. The high- Q LN MDRs fabricated with the fast and flexible laser writing technology will provide a fascinating platform for LNOI photonics application.

In our experiment, the LN MDRs were produced on a commercially available x -cut LN thin film wafer fabricated by ion slicing (NANOLN, Jinan Jingzheng Electronics Co., Ltd.) [1]. The LN thin film with a thickness of 900 nm is bonded to a 2 μm thick SiO_2 layer grown on a LN substrate. The fabrication process includes four steps, as schematically illustrated in Fig. 1. First, a thin layer of chromium (Cr) with a thickness of 900 nm was deposited on the surface of the LNOI by thermal evaporation coating. Subsequently, the Cr film on the LNOI sample was patterned into a circular disk using space-selective femtosecond laser direct writing. Specifically, to minimize the heat effect as well as the redeposition of the ablation debris on the disk surface, the femtosecond laser ablation was conducted by immersing the LNOI sample coated with Cr in water.

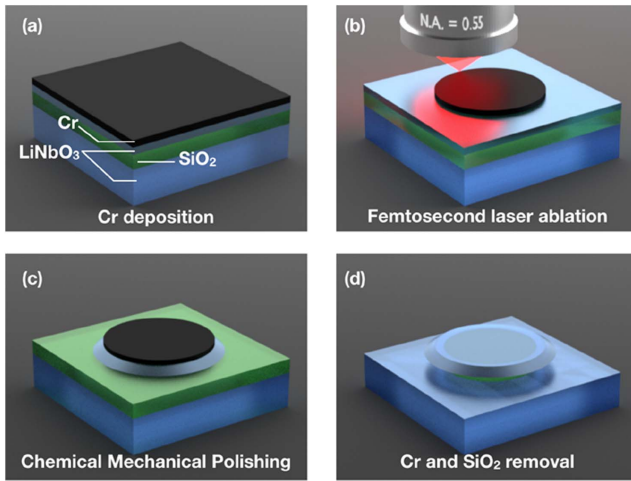


Fig. 1. Illustration of fabrication flow. (a) Coating a Cr thin film on top of the LNOI. (b) Patterning the Cr thin film into a microdisk. (c) Transferring the disk-shaped pattern to LNOI by chemo-mechanical polishing. (d) Removing the Cr thin film and the SiO₂ buffer layer with two consecutive chemical wet etching processes.

The key in this step is to carefully choose a pulse energy of the femtosecond laser so as to enable a complete removal of the Cr film with laser ablation while keeping the underneath LNOI intact thanks to the high precision and low heat generation in the interaction of femtosecond laser pulses with materials [20]. The detail of femtosecond laser micromachining is described as follows. We used a Ti:sapphire femtosecond laser (Libra, Coherent, Inc.) of a center wavelength of ~ 800 nm, a pulse width of ~ 40 fs, and a repetition rate of 1 kHz in patterning of the Cr film into a microdisk. A variable neutral density filter was used for adjusting the average power. An objective lens with a numerical aperture (NA = 0.55, Nikon LU Plan) was used to produce the tightly focused spot with a diameter of ~ 1 μ m. The laser beam was then focused at the surface of Cr film coated on the top of the LNOI sample, which was immersed in water. The sample was mounted on a computer-controlled XYZ translation stage with 50 nm resolution. A charged coupled device (CCD) connecting with the computer was installed above the objective lens to monitor the fabrication process in real time. The laser power was chosen to be 0.2 mW to remove the Cr thin film, while the LNOI underneath the Cr film remains almost intact at such a low laser power. The Cr disk formed on the LNOI serves as a hard mask for the subsequent CM polishing. Next, the LNOI coupon was covered by a resin, making it easy to be handled in the subsequent CM polishing process. The CM polishing process was conducted using a wafer polishing machine (NUIPOL802, Kejing, Inc.). In the CM polishing process, we used a piece of velvet polishing cloth, and the polishing slurry (MasterMet, 60 nm amorphous colloidal silica suspension) was provided by Buehler, Ltd. The soft velvet cloth allows not only the Cr film but also the exposed LN film to be in contact with the polishing slurry. Since the Cr film is of a higher hardness than that of the LN film, the exposed LN film was removed in the CM polishing process. By carefully controlling the duration of the CM polishing process, the side wall angle with respect to the vertical direction can be controlled from a few degrees for a

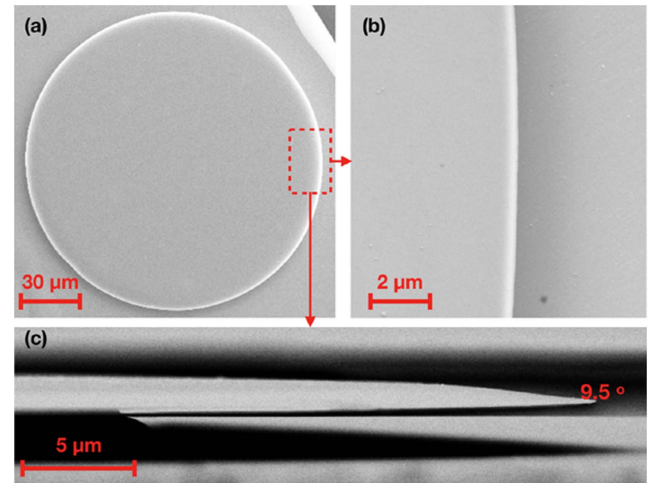


Fig. 2. (a) Top view SEM image of a fabricated LN MDR. (b) Close up view SEM image of the area indicated by the red box in (a). (c) Side view SEM image of the fabricated LN MDR with a wedge angle of 9.5°.

long polishing duration to nearly 80° for a short duration of the polishing process. Finally, the fabricated structure was first immersed in a Cr etching solution (Chromium etchant, Alfa Aesar GmbH) for 10 min, and then underwent a chemical wet etching in a buffered hydrofluoric acid (HF) solution (BUFFER HF IMPROVED, Transene Co., Inc.) to partially remove the SiO₂ layer beneath the LN microdisk. The LN microdisk supported by the SiO₂ pedestal was produced to form the freestanding LN MDRs. Figure 2 shows the scanning electron micrograph (SEM) images of a fabricated LN MDR with a diameter of 140 μ m.

To characterize the optical mode structure of the LN MDR, a tunable laser was used to couple light into and out of the fabricated MDR through a tapered fiber with a waist of 0.9 μ m. The linewidth of the tunable laser (TLB 6712, New Focus, Inc.) is 200 kHz. The optical modes could be excited by controlling the relative position between the tapered fiber and the MDR. The transmission power of the tapered fiber coupled with the MDR was recorded by a transient optic receiver (1801-FC, New Focus, Inc.). Figure 3(a) shows the transmission spectrum for the wavelength range from 772.8 nm to 773.9 nm. The free spectral range (FSR) of the MDR is measured to be 0.45 nm as determined by comparison with a finite-element simulation that was carried out using COMSOL software. The calculated FSR is 0.47 nm, which is very close to the measured FSR. One of the whispering-gallery modes at the

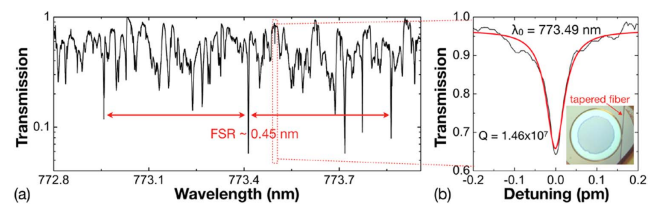


Fig. 3. (a) Transmission spectrum of the LN DMRs. (b) The Lorentz fitting (red curve) reveals a Q-factor of 1.46×10^7 . Inset: optical micrograph of the MDR coupling with the fiber taper.

resonant wavelength of 773.49 nm was chosen for the measurement of the Q -factor by fitting with a Lorentz function, which reaches 1.46×10^7 , as indicated by the Lorentz fitting curve in Fig. 3(b).

The nonlinear optical properties of the high- Q MDR were examined with another tunable laser, which was boosted by an erbium-ytterbium-doped fiber amplifier to serve as the pump source (EYDFA, Golight, Inc.). The tunable laser (New Focus Inc., Model 688-LN) has a linewidth of 10 MHz and a wavelength tuning range between 1510 nm and 1620 nm. The pump laser power was adjusted by a variable optical attenuator. The polarization of the pump laser was controlled to have the quasi-TM (transverse magnetic) polarization using an inline fiber polarization controller. The emission signal from the MDR was recorded by a spectrometer (SR 303i, Andor, Inc.). Two pieces of short-pass filters (FESH1000, Thorlabs, Inc.) were used to block the pump laser during the spectral measurements of the nonlinear optical signals.

When we set the pump laser wavelength at 1561.2 nm and the pump laser power at 27 mW, cascaded nonlinear optical processes including the second-harmonic generation (SHG) and Raman scattering mediated by the SHG were observed, as shown in Fig. 4(a). The SHG signal was detected to have a quasi-TE (transverse electric) polarization at the wavelength of 780.6 nm. The vibrational modes participating the Raman scatterings were 152 cm^{-1} and 239 cm^{-1} [21], as indicated by the Raman peaks S1 and S2 in the vicinity of the SHG spectrum in Fig. 4(a). The conversion efficiency of the SHG as a function of the pump power is shown in Fig. 4(b). The normalized conversion efficiency of SHG can be determined as $2.3 \times 10^{-5} \text{ mW}^{-1}$, which is lower than the previous result obtained in an x -cut MRD with a Q -factor of 10^5 [22]. Although the same cyclic phase-matching scheme is employed in both the current and previous experiments of SHG, the relatively lower conversion efficiency is probably due to the small spatial overlapping between the pump and signal waves in the CM-polished LN MDRs with an extended disk wedge.

Further theoretical and experimental investigations are required to reach a better understanding on the details in the nonlinear optical processes.

Furthermore, the powers of the Raman signals (i.e., S1 and S2) as a function of the SHG power are plotted in Figs. 4(c) and 4(d), respectively. The threshold pump powers (i.e., the power of SHG) for generating the Raman peaks S1 and S2 were determined to be $0.85 \text{ }\mu\text{W}$ and $1.33 \text{ }\mu\text{W}$, respectively. Above the threshold powers of SHG, the powers of the Raman signals at S1 and S2 increase linearly with the pump power. From the slope of the fitting lines in Figs. 4(c) and 4(d), the conversion efficiencies as high as 0.28% and 0.22% have been determined. The conversion efficiencies are much higher than the SHG process, which agrees well with our expectation for the reasons as follow. First, the Raman process does not require phase matching, which is one of the major difficulties to overcome in achieving the high conversion efficiencies of the nonlinear processes in the whispering gallery mode microresonators. Second, the wavelengths of the two Raman peaks S1 and S2 are both close to the second-harmonic wavelength, indicating that a sufficient spatial overlap can be realized for the modes of the SHG pump wave and the two Raman signal waves. All of these are beneficial for achieving the high conversion efficiencies.

To conclude, on-chip LN MDRs of Q -factors comparable to those of the mechanically polished crystalline optical resonators (i.e., 10^7) have been achieved with the femtosecond laser micromachining combined with the CM polishing process. We stress that the femtosecond laser micromachining is employed only for patterning the protecting Cr thin film but not the LNOI. Essentially, the LN MDRs are created by transferring the patterns of the Cr layer to the LNOI in the CM polishing, leading to the ultrahigh Q -factors even at the near-infrared wavelengths around 770 nm. This fabrication strategy should be effective by replacing the femtosecond laser direct writing in the patterning of the Cr film with other mass-scale lithography-based technologies, such as ultraviolet lithography, electron beam lithography, etc.

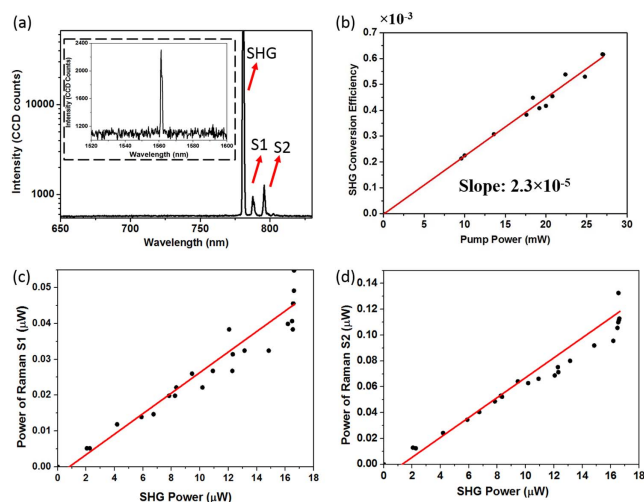


Fig. 4. (a) Nonlinear optical spectrum around the wavelength of 775 nm, Inset: the transmission spectrum around the pump wavelength. (b) The SHG conversion efficiency as a function of pump power. (c) The power of Raman S1 as a function of the SHG power. (d) The power of Raman S2 as a function of the SHG Power.

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