We report on 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 insulator (LNOI) into a microdisk, followed by a chemical-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.

3×$10^6$ measured around 976 nm wavelength can be achieved for the LN MDRs fabricated by a reactive ion etching followed by a chemical-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.

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 achieve the 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 [4-18]. Typical Q factors on the level of $10^6$ can now be routinely obtained for freestanding LN MDRs [7-10]. Moreover, it is recently reported that a Q factor of
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, since we now can completely skip the FIB milling process, 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.

![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°.](image)

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. The femtosecond laser pulses were focused at the Cr surface with an objective lens (NA= 0.55, Nikon LU Plan). 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 [19]. The Cr disk formed on the LNOI serves as a hard mask for the subsequent CM polishing. Next, the CM polishing process was performed to fabricate the LN MDRs with a wafer polishing machine (NUPOL802, Kejing, Inc.). In this case, the top surface of the LNOI defined by the femtosecond laser patterning was protected from the CM polishing because of the Cr hard mask, whereas as the open area of the LNOI without the protection from the Cr film can be accessed and in turn completed removed by the polishing slurry (MasterMet, Buehler, Ltd.). Therefore, the disk-shaped pattern was transferred to the LNOI with a smooth sidewall. Finally, the fabricated structure was first immersed in a Cr etching solution (Chromet 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 SiO$_2$ layer beneath the LN microdisk. The LN microdisk supported by the SiO$_2$ 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 μm.

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 μm. 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 to 773.9 nm. The free spectral range (FSR) of the MDR is determined to be 0.45 nm. One of the whispering-gallery modes at the resonate wavelength of 773.49 nm was chosen for the measurement of the Q factor by fitting with a Lorentzian function, which reaches $1.46 \times 10^7$ as indicated by the Lorentz fitting curve in Fig. 3(b).

The nonlinear optical properties of the high Q MDR was 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 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 online fiber polarization polarization controller. The emission signal from the MDR was record 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 $2.3 \times 10^{-5}/\text{mW}$, which is lower than the previous result obtained in an X-cut MRD with a Q factor of $10^5$ [20]. 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 pump power are plotted in Fig. 4(c) and (d), respectively. The threshold pump powers (i.e., the power of SHG) for generating the Raman peaks S1 and S2 were determined to be $0.85 \mu\text{W}$ and $1.33 \mu\text{W}$, respectively. Above the threshold powers of SHG, the powers of the Raman signals at S1 and S2 increases linearly with the pump power. From the slope of the fitting lines in Fig. 4(c) and (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 agree well with our expectation for the reasons as follows. 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.

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.

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