Femtosecond laser preforming of millimeter-scale whispering gallery mode resonant disks from crystalline substrate

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Abstract: Millimeter-sized whispering gallery mode resonators produced from bulk crystalline substrates show great potential as optoelectronics components but are still delicate to produce. We report here on an improved manufacturing technique based on femtosecond laser ablation, which allowed us to obtain state-of-the-art performance (quality factor around 10^9) in calcium fluoride with only half the processing time required before. Our results are supported by optical profilometric and cavity ringdown measurements, and could be extended to a variety of other substrates.

1. Introduction

Whispering gallery mode resonators (WGMR) have received extensive interest in the past decades, as they provide a wide family of compact, rugged and versatile photonics components. They can be implemented in a wide range of substrates, either amorphous, crystalline or integrated, at scales ranging from micrometric to centimetric. This wide variety in size and shape, as well as their excellent behavior in both linear and non-linear regimes, has made them suitable for many applications, including narrow-linewidth opto-electronic oscillators, integrated Sagnac gyrometers, quantum optics and optical Kerr combs generation [1-6].

Among the available substrates, fluoride crystals such as magnesium, calcium, barium and lithium fluorides (MgF_2, CaF_2, BaF_2 and LiF) have attracted particular attention. Indeed, they offer a good combination of mechanical and optical properties: medium to high MOHS hardness, fairly good thermal stability, high transparency at telecom wavelengths, and insensitivity to water vapor absorption. Thus very low intrinsic loss can be achieved after polishing, enabling high quality factors ($Q_i = \Delta f/f_0$ above 10^8). Also, their low refractive index, inferior to that of standard silica fibers, facilitates coupling since fiber tapers can be employed. Moreover, these substrates can support second- and third-order optical nonlinearities, allowing such effects as frequency generation and Kerr, Raman or Brillouin effects [7].

Fabrication of microdisks or microrods using laser processing techniques have been reported before in amorphous substrates [8]; however crystalline disks in the millimeter range have so far been produced mostly via mechanical grinding and polishing, which presents severe limitations. Indeed, since some force has to be applied to the substrate, the only possible shape is that of a single, isolated edge. The range of achievable bevel angles is also restricted, particularly with softer materials (MOHS hardness 4 for CaF_2). As a result, to prevent chipping or breaking, the bevel angle needs to be kept well above 20°. Consequently, the transverse curve radius of the polished edge remains high (tens of microns) which is detrimental when single transverse mode operation is desired. Also, deviations from the ideal shape (eccentricity, ellipticity) are likely to occur as a reason of the unavoidable resulting mechanical stress. These defects, as well as disk breaking, typically occur in the early stages of the process, when the general shape of the WGMR is produced from a blank and a significant amount of material needs to be removed.

As a result, laser processing is a candidate of choice to improve the processing of crystalline substrates, as it is contactless and thus removes the drawbacks induced by mechanical stress. Femtosecond laser machining in particular has shown great potential, as it provides drastically reduced side effects such as heating and shock wave induced damage when compared to either thermal (CO_2) or nanosecond (YAG) processing. Moreover, submicron precision over a wide range of materials has been demonstrated. However, though water-assisted femtosecond cutting of crystalline substrates has been reported [9], it has only been applied to micro-toroïds yet, and relies on CO_2 laser annealing to provide both for surface shaping (rounding) and polishing, which is difficult to implement for larger disks. In this communication, we report on the femtosecond laser cutting and shaping of CaF_2 WGMRs 12 mm in diameter. After mechanical polishing, an intrinsic Q-factor of $9.1\ 10^8$ has been obtained, with significantly reduced processing times.

2. Fabrication process

A general schematic of the machining setup is represented in Fig. 1. The source we used is a commercially available Amplitude Tangerine amplified femtosecond laser. For the purpose of our setup, the beam was fixed and the sample was moved along five degrees of freedom (3D translation, plus pitch and yaw) using Aerotech PRO-LM stages with an accuracy of ±1 µm. The pulses were focused on the target using a f' = 50 mm lens. The source delivered 280 fs pulses at 1030 µm wavelength in single shot bursts, with a pulse energy of 100 µJ at a 5 kHz repetition rate.

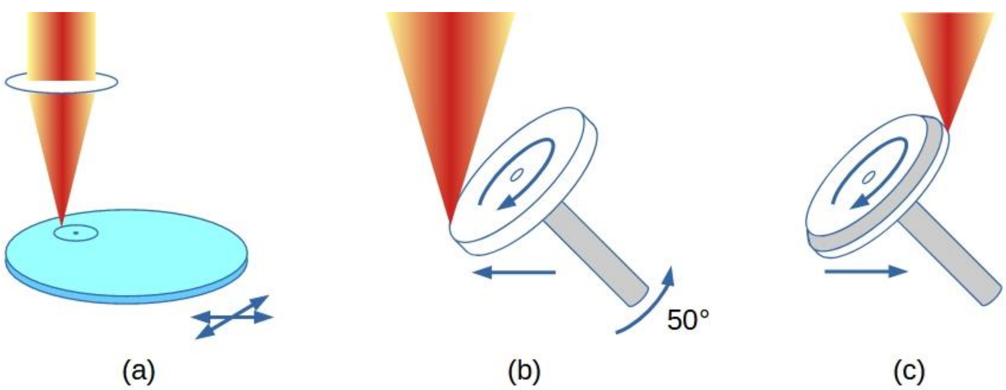

Fig. 1 - Schematic of the machining procedure. (a) Cutting of blank disk from 2” wafer; (b) machining of first bevel angle; (c) machining of second angle. The arrows illustrate the degrees of freedom actively employed during each step. Please note that the beam focusing angle is exaggerated for clarity.

First, the 12 mm-diameter disks were cut from 2”, 1 mm thick commercial CaF_2 wafers (Korth Kristalle GmbH) using the same setup (see Fig. 1.a). A 1.1 mm through-hole was also drilled at this stage to allow the gluing of a handling stub. The disk preforming was then realized in two sequential steps as illustrated in Fig. 1.b,c. First, the disk was tilted at the desired angle of 50°. The disk was then rotated while the beam progressively ablated the substrate in a lathe-like manner. Machining was stopped when half the disk thickness had been almost reached, minus a safety margin of a few microns. Then, the disk was translated as shown in Fig. 1.c so that machining of the second edge could be performed in a similar fashion. During each step, regular microscope observation was performed to control progress and ensure machining quality, using the in-situ imaging system.

The overall geometry (disk diameter, eccentricity and bevel angle) was measured using optical microscopy. The mechanical characterization results are summarized in Fig. 2, with a photographic image of the disk after preforming but before polishing (2.a) as well as a geometric profile of the disk bevel obtained via microscopic scanning (Nikon proprietary software, 2.b). This reconstructed profile showed that the bevel angle was well defined and symmetric, with a diedric half-angle of 39.9°. The disk circularity was also found satisfactory, with a radius of 604 µm and an ellipticity inferior to 1 µm. It should be noted that diffraction effects produce slightly tilted edges with an angle of 3.1° with respect to disk normal. This defect was however inconsequential as it was compensated during the following steps. As expected from preliminary work the machined surfaces exhibited significant diffusion under microscopic observation, consistent with > 100 nm surface roughness. This was in accord with measurements performed via white-light vertical scanning interferometric profilometry during our preliminary tests on CaF_2 wafers.

Once both disk edges were obtained, subsequent mechanical polishing was performed following the procedure reported in Ref. [10]. An abrasive compound (aluminum oxide or diamond powder suspension for lower grains) was deposited on polishing tissue, which was held in place by a metallic guide. The guide was translated at low speed (1 cm/minute typical) while the disk was rotated at high velocity (2500 to 5000 RPM) by an air-spindle motor. Progress was checked on site at regular intervals with a binocular microscope, especially before moving to the next abrasive grade. An important aspect is that most of the excess material having been removed via laser ablation, this procedure could begin with a significantly lower grain size (1 µm instead of 29 µm), thus reducing the number of polishing steps and hence the processing time before reaching optics-grade surface roughness. As a summary, representative durations are given in Table 1.

Grade	**Without fs preforming**	**With fs preforming**
shaping	-	1h
29 µm	2h	-
10 µm	1h	-
3 µm	20-30 min	-
1 µm	10-20 min	15-30 min
0.25 µm	15-20 min	15-20 min
0.1 µm	15-20 min	15-20 min
Total	**4h-4h30**	**1h45-2h10**

Table 1 - Breakdown of polishing times per abrasive grade, with and without femtosecond laser preforming. Please note that each change in grain size requires between 15 and 30 minutes of cleaning and setting up, which has not been taken into account in the total polishing time.

3. Characterization and results

The final surface roughness was measured using a contactless optical profilometer operating under white light vertical-scanning interferometry. A 40X magnification Mirau-type objective lens and a conventional phase shifting algorithm were used. The 3D reconstructed image of the disk after optical-grade polishing is shown in Figure 2.c, over a 30x123 µm² area. The raw data was then processed to account for the disk curvature along both axes. The residual surface roughness was then extracted from the 3D image and found to be 4.4 nm RMS, which is compatible with the high quality factors sought after.

To assess the optical and resonant properties of the disk, 1550 nm-wavelength light from a Koheras Adjustik (NKT Photonics) tunable laser was coupled to the disk using a locally produced fiber taper. By scanning the input laser frequency around the resonance, cavity ringdown was observed and recorded, allowing us to extract the intrinsic and external quality factors via numerical fitting[11,12]. Fig. 3 represents our cavity ringdown results, the red curve being the measured signal and the blue curve the fitting curve corresponding to an intrinsic quality factor of $Q_i = 9.1\ 10^8$.

4. Discussion

As can be seen in Fig. 2, the geometrical and mechanical properties of the preformed disks are satisfactory. The bevel angle is well defined and accurately maintained over the whole disk circumference. Ellipticity and eccentricity are also significantly lower than what was observed in our anterior results as reported in Ref. [10]. More importantly, the processing time was drastically reduced: preforming took roughly one hour instead of three. Polishing was also obtained more easily and rapidly without reduction in surface quality. Altogether, we estimate that the total processing time (from bulk wafer to fully characterized component) is halved. Cavity ringdown measurements confirms that the intrinsic quality factor of the newly produced disks is comparable to previous art, slightly under 10^9.

We believe that optimization of the machining process could further improve performance, in particular in reducing initial surface roughness, which has a direct impact on the mechanical polishing process. Also, even though our proof-of-concept work was focused on CaF_2, we expect this process to adapt fairly well to most substrates, after suitable optimization. Further progress could take WGMRs one step closer to pre-industrial applications.

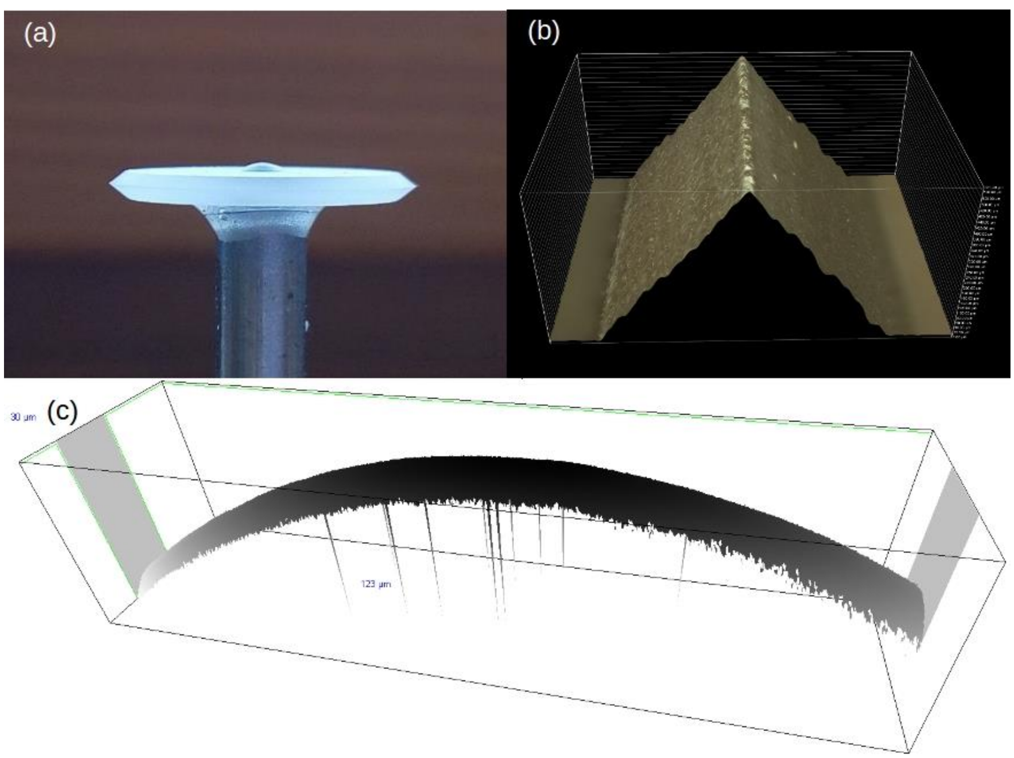

Fig. 2 - Mechanical characterization of preformed disk: (a) photographic image of disk glued to holding stub; (b) microscopic profile reconstruction before polishing; (c) optical profilometry measurement of disk surface after polishing. Measured rugosity after curvature compensation is 4.4 nm over the 20x123µm² observation window.

5. Conclusion

Femtosecond laser machining of whispering gallery mode resonators from bulk substrates is shown to be a valid alternative to mechanical grinding and polishing. Even though fine-grain polishing is still required to reach optical grade surface finish, femtosecond laser processing significantly reduces production time while maintaining state-of-the-art performance and flexibility. Further work includes optimization of the production scheme as well as portability to other crystalline substrates.

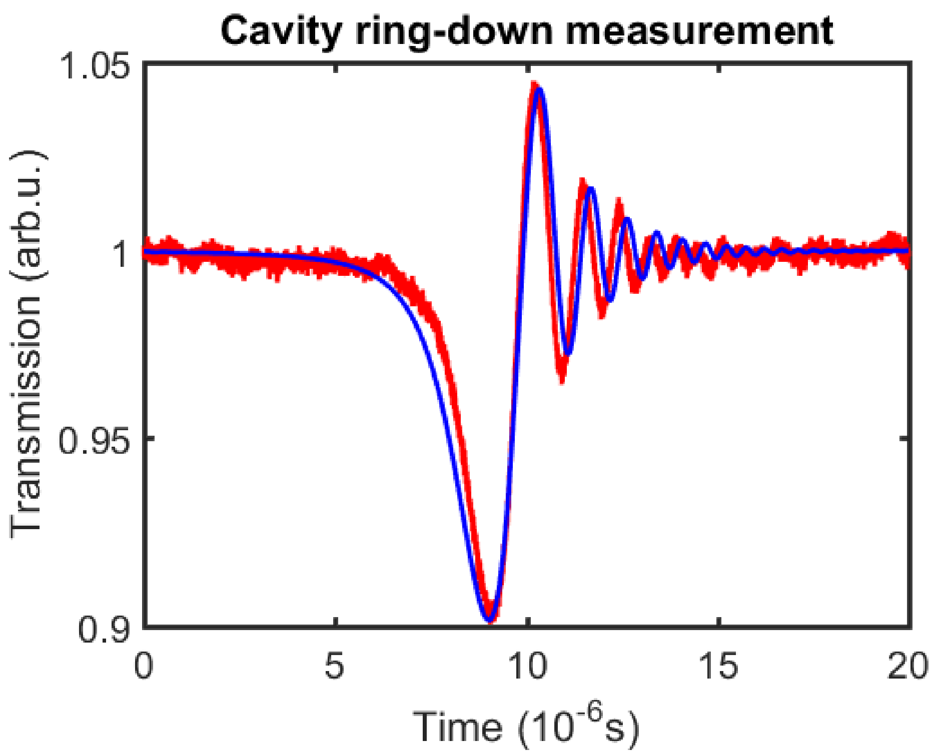

Fig. 3 - Cavity ring-down measurement of disk resonant properties. Red : measured signal, blue : numerical fitting. The intrinsic quality factor used for the fitting curve was $Q_i = 9.1\ 10^8$.

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Data Availability.

Data underlying the results presented in this paper are not publicly available at this time but may be obtained form the authors upon reasonable request.

Disclosures.

The authors declare no conflict of interest.

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