Magnesium Fluoride Whispering Gallery Mode Disk-Resonators for Microwave Photonics Applications

Hervé Tavernier, Patrice Salzenstein, Kirill Volyanskiy, Yanne Kouomou Chembo, and Laurent Larger

***Abstract*—We have manufactured a high-Q whispering gallery mode resonator with magnesium fluoride for microwave photonics applications in the gigahertz frequency range. This crystal is scarcely used for resonator fabrication despite its numerous advantages, that are mainly high mechanical hardness, low sensitivity to water vapor pollution, and low sensitivity to photo- and thermo-refractive fluctuations at optimal temperatures. Using a customized machining procedure, we have successfully fabricated and characterized a 5-mm resonator with a surface rugosity of the order of 1 nm (from 3 to 12 atoms). Cavity ring-down measurements enabled us to determine that the resonator has a quality factor $Q = 3.4 \times 10^8$ at 1550 nm.**

***Index Terms*—Magnesium fluoride, optical cavity, whispering gallery mode (WGM) resonator.**

WHISPERING gallery mode (WGM) optical resonators have been the focus of an increasing amount of scientific research in recent years. This interest has been driven by the essential advantages of monolithic WGM technology: low-cost, conceptual simplicity, and low energetic losses (see [1] and references therein). WGM resonators are also particularly interesting because they are central components for a wide variety of applications in optics and in microwave photonics. In the linear regime, for example, WGM resonators can be used as extremely narrow optical filters [2], [3], useful in optical communications or in optoelectronic oscillators [4]. In the nonlinear regime, they can enable optical frequency comb generation [5], [6], erbium-ions-induced lasing [7], Raman lasing [8], or Brillouin lasing [9]. From a broader perspective, WGM resonators are expected to play a key role in time-frequency metrology, integrated photonic circuits, sensing, and aerospace engineering.

So far, in microwave photonics applications, passive millimeter-size WGM resonators have mainly been manufactured with fused silica, quartz, or calcium fluoride (CaF_2). On the one hand, fused silica is an amorphous medium that is nowadays a standard transparent material at 1550 nm, owing the optical fiber communications applications. The related manufacturing processes enabled the fabrication of WGM resonators with $Q = 8 \times 10^9$ at 633 nm (very near the ultimate theoretical limit, see [10]), where Q is the ratio between the central frequency and the bandwidth of the resonance. It can, therefore, be deduced by inference that Q-factors superior to 10^9 can in principle be obtained at 1550 nm. On the other hand, crystalline media generally enable to achieve superior performances. For example, quartz WGM resonators with a Q-factor of 5×10^9 at 1550 nm have already been reported [11]. However, CaF_2 seems to be the most interesting alternative as it yields the highest Q-factor reported so far at 1550 nm, a record value of 1.1×10^{10} [12].

In this letter, we consider an unusual bulk medium for the resonator, magnesium fluoride (MgF_2). This tetragonal crystal has many specific advantages that may be of particular interest for various applications. For example, MgF_2 is not sensitive to water vapor pollution [13], [14]. Its lifetime in free atmosphere is, therefore, significantly longer that the one of fused silica, which generally needs a purged nitrogen local atmosphere, or a special surface treatment. Another advantage of MgF_2 is its mechanical hardness, which is in the range of 6 Mohs. This relatively high value makes this material resistant to mechanical shocks and to hazardous surface scratches, at the opposite of CaF_2 which is mechanically softer. Therefore, MgF_2 resonators are relatively easy to manipulate and their Q-factors are satisfyingly stable over time. Table I presents a comparison of some interesting properties of fused silica, quartz, CaF_2 and MgF_2 materials. The advantageous properties of MgF_2 appear straightforwardly: it is the unique material having at the same time a good resistance to mechanical shocks and a high resistance to water pollution.

Magnesium fluoride WGM resonators also have other positive characteristics. In [15], the authors have performed a detailed analysis of the influence of photo- and thermo-refractive fluctuations on the noise performance of WGM resonators, and they have found that in MgF_2, there are optimal temperatures for which these fluctuations are strongly inhibited. This is one of the properties that strongly motivate our interest for this material in view of microwave photonics applications, where noise is a critical parameter. To the best of our knowledge, the typical Q-factor of MgF_2 resonators is not available in the literature, even though they have already been fabricated in the past [16]. One of our main objectives is, therefore, to provide this quantitative evaluation in order to facilitate comparison with state-of-the-art CaF_2 and fused silica WGM resonators.

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H. Tavernier, K. Volyanskiy, Y. K. Chembo, and L. Larger are with the Optics Department, FEMTO-ST Institute (UMR CNRS 6174), 25030 Besançcon Cedex, France.

P. Salzenstein is with the Time-Frequency Department, FEMTO-ST Institute (UMR CNRS 6174), 25030 Besançcon Cedex, France.

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TABLE I
COMPARATIVE PROPERTIES OF VARIOUS MATERIALS USED FOR MANUFACTURING WGM RESONATORS

Material	**Fus. Si**	**Quartz**	**CaF_2**	**MgF_2**
Crystal class	Noncrystalline	Hexagonal	Cubic	Tetragonal
Transparency window (μm)	0.18–2.5	0.19–2.9	0.2–9	0.12–8.5
Refract. index at 1550 nm	$n = 1.44$	$n_o = 1.54$ $n_e = 1.53$	$n = 1.42$	$n_o = 1.37$ $n_e = 1.38$
Hardness (Mohs)	6–7	7	4	6
Resistance to mech. shocks	Good	Good	Bad	Good
Resistance to H_2O pollution	Low	Low	High	High

A special equipment was developed for manufacturing the MgF_2 disk-resonator. We used a precision adapter and a dedicated polishing machine affording a 200-nm eccentricity. The whole system is hold on an air-bearing support in order to prevent the mechanical influence of vibrations. The polishing process is started from an initial MgF_2 bulk-disk with a diameter of 6 mm and a thickness around 500 μm. A hole is drilled in the center to allow an easy positioning, and special care should be taken in order to avoid eccentricity problems during the polishing procedure. The rim of the disk has to be reduced to less than 50 μm in order to optimize the selectivity of the fundamental WGMs. This thin rim is obtained with two 20° angle bevels, performed at the edge of the resonator. It is necessary to perform carefully this step with appropriated grindstone and disk speed in order to avoid any splinter that can enlarge dramatically the edge and allow the excitation of higher order WGMs.

After preshaping, manual polishing is then realized carefully with low speed. We need a very good optical quality with very low and regular roughness all around the surface of the disk periphery. Powders with decreasing grain size are used, as for example colloidal silica, cerium oxide, and alumina oxide. Their dilution has to be controlled very precisely. The characterization of the resonator external surface is performed by measuring Newton interference fringes. Using a white light phase shifting interferometer, the rugosity of the rim surface has been evaluated. The result of this measurement is presented in Fig. 1, which displays the surface rugosity of our resonator along two nonparalel axes (perpendicular in our case), over 60 μm. This double measurement aims to verify that the surface profile is statistically flat, independently of the direction (that is, locally free from scratches). The rugosity is in the range of 1–5 nm, corresponding to 3–12 atoms. Unfortunately, the available instrument permits only the measurement of a small area, while a smooth defect-free surface is required in the whole equatorial region of the resonator.

There are several method to couple the disk-resonator to an optical fiber, such as the prism coupling, the angle-shaped fiber coupling, and the tapered fiber coupling. We have chosen to use the latter because it is generally easier to implement in a laboratory. In this case, the taper is glued on a holder. The holder alloy and geometry match the thermal expansion of the resonator. The taper waist is inferior to 3 μm. The tapered fiber is set on a three-axis nano-positioning system with a 10- to 20-nm resolution.

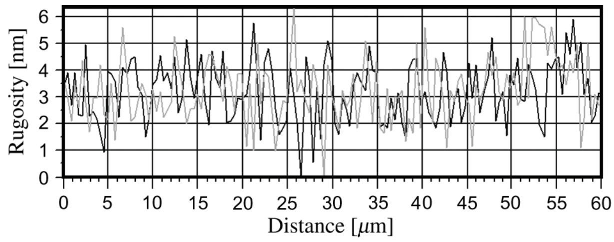

Fig. 1. Experimental characterization of the surface rugosity of our MgF_2 resonator using a white light phase shifting interferometer. The rugosity is of the order of few nanometers, and it is measured over 60 μm along two perpendicular axis (black and gray lines).

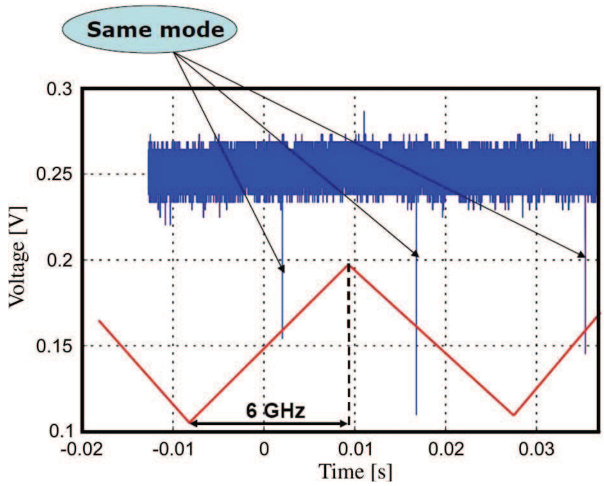

Fig. 2. Detection of a WGM resonance peak near 1550 nm. The same WGM is neatly detected as the laser wavelength is swept back and forth.

For measuring the resonance [17], we use the signal from a 1550-nm tunable laser diode powered at 3 mW. The 50-pm wavelength sweep corresponds to 6 GHz in the spectrum. A fast digital real time Lecroy oscilloscope (8600A-type) permits the analysis of the very sharp absorption lines at WGM resonances. It is necessary to use a high-speed resolution oscilloscope for the analysis of these peaks. The oscilloscope is inserted after the photodiode that detects an optical signal coming from the disk resonator, and the resonance peak detection is in the single-mode excitation. The small taper size selects a very thin excitation area, and the resonance measurement setup is in an open loop configuration. Although wavelength span is too small to scan a full free-spectral range (FSR) with a scan rate of 50 Hz, it is still possible to measure the Q-factor with the self-homodyne method [18]. A polarization controller is also needed, since the WGM resonances are polarization-dependent. In Fig. 2, we represent the detection of the resonance peak. As written previously, the curve clearly shows the 50-pm wavelength sweep corresponding to 6 GHz in the spectrum, so that the same mode appears regularly.

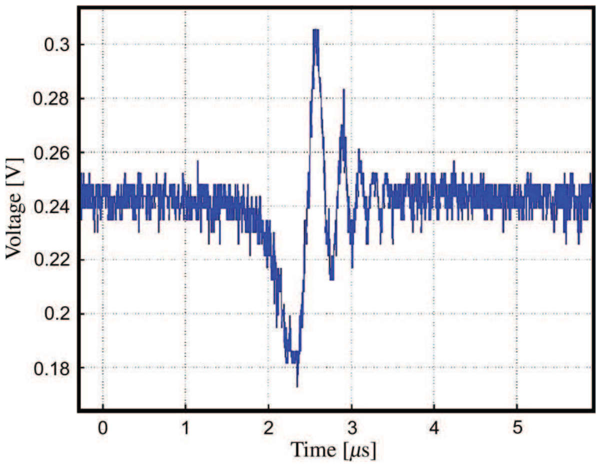

Fig. 3. Cavity ring-down measurement to deduce the Q-factor of the MgF_2 cavity. The exponential decay time is evaluated to $\tau = 0.56\ \mu$s, yielding a Q-factor $Q = \omega_0\tau/2 = 3.4 \times 10^8$ at $\lambda_0 = 1550$ nm.

The Q-factor measurement is deduced from Fig. 3 using the cavity ring-down method. Despite the fact that the resolution is not optimal with the 400-Hz scan rate, curve with voltage (in volts) versus time (in microseconds) gives enough information for the determination of Q. The Q-factor is extracted from the time delay of the interference path between two beams. The first beam comes from the laser and the second comes from the cavity. Both beams have different wavelengths, and damped oscillations can be observed during cavity unloading. That is why exponentially decaying oscillations are observed on Fig. 3. The Q-factor can be deduced as $Q = \omega_0\tau/2$, where $\omega_0 = 2\pi c/\lambda_0$ is the angular frequency of the laser light, λ_0 is the related wavelength, c is the velocity of light in vacuum, and τ is the exponential decay time of the electric field (equivalent to twice the photon lifetime). This evaluation of the Q-factor is strongly dependent on coupling conditions and the computed value is different according to the way the resonator is coupled to the optical fiber. It can indeed be decomposed in two terms according to $Q^{-1} = Q_{\text{in}}^{-1} + Q_{\text{ext}}^{-1}$, where Q_{in} is an intrinsic Q-factor, while Q_{ext} is the extrinsic contribution originating from the coupling. Therefore, in order to measure the Q-factor with the highest precision, Q must be as close as possible to the intrinsic Q_{in} which is only related to resonator's properties. This explains why the taper has to be under-coupled. However, under-coupling is not so easy to achieve practically because the tapered fiber has the tendency to stick to the resonator surface, thereby leading to over-coupling. After a careful set of measurements, the cavity ring-down method has provided the value $Q = 3.4 \times 10^8$ for our MgF_2 optical resonator at 1550 nm.

In conclusion, we have fabricated a MgF_2 WGM disk-resonator with an high Q-factor. Despite its numerous advantages, this crystal is still an unusual bulk material for WGM resonators. The Q-factor for this material can in principle be improved by at least one order of magnitude if the fabrication protocol is optimized. In the case of a successful outcome, MgF_2 WGM resonators would therefore provide an extremely high Q value that would be stable over a significant lifetime. Such resonators would also be particularly interesting in other applications where the birefringence of the MgF_2 crystal is specifically a positive feature.

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