Optical Engineering

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SPIE

Optical Engineering 53(7), 071821 (July 2014)

Barium fluoride and lithium fluoride whispering-gallery-mode resonators for photonics applications

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Abstract. Crystalline whispering-gallery-mode disk resonators are finding an increasing number of applications in photonics. Their exceptional energy storage capacity is of great interest in the area of ultrastable oscillators for aerospace and communication engineerings as well as for sensing applications. Here, we investigate the physical properties of some unconventional crystalline materials. We show that these resonators can display quality factors higher than ten million at 1550 nm and we discuss their potential for various applications. [DOI: 10.1117/1.OE.53.7.071821]

Keywords: whispering-gallery-mode resonators; crystalline photonics; high-quality factor.

Paper 131668SS received Nov. 6, 2013; revised manuscript received Jan. 17, 2014; accepted for publication Feb. 11, 2014; published online Mar. 26, 2014.

1 Introduction

Whispering-gallery-mode (WGM) resonators are optical cavities that are able to trap photons through total internal reflection. They are usually considered as high-Q resonators when the photon lifetime is higher than a nanosecond. The WGM resonators can have a very wide variety of sizes and shapes.[1–4]

However, many applications arose recently for millimeter-size disk resonators pumped around 1550 nm. These disk resonators can be manufactured using amorphous materials like fused silica or fused quartz. In this case, the quality factor typically ranges from 10^7 to 10^9 at 1550 nm. It has been shown recently that manufacturing these amorphous resonators can be done in an automated fashion using a CO_2 laser with a fabrication time of the order of 1 min.[5]

Another option is to use crystalline materials, and here, the most common bulk materials are quartz, magnesium fluoride (MgF_2), and calcium fluoride (CaF_2). The quality factors here are generally from 1 to 2 orders of magnitude higher than for amorphous crystals. It is worth recalling in this context that the record quality factor at 1550 nm is set at 3×10^{11} using a CaF_2 disk resonator.[6]

These resonators have generated a broadband interest in recent years. From a fundamental point of view, they enable to investigate various phenomena related to light-matter interactions as well as the dynamics of photons confined in nonlinear media from both the classical and quantum perspectives. From the applied viewpoint, WGM resonators are considered as a core photonic component in the emerging discipline of microwave photonics. They are considered as promising central elements for optical filtering, add-drop systems, miniature solid-state lasers, efficient light modulators, and so on. In particular, WGM resonators were proposed as a promising paradigm shift for ultrapure microwave and lightwave generation. The fact that this topic intersects so many areas of fundamental science and technology indicates its strong potential impact on a wide range of disciplines. In particular, aerospace and communication engineering technologies are currently in need of versatile microwave and lightwave signals with exceptional coherence.[4,7,8]

Innovation in the area of fabrication technologies enables improvement of the quality factor figure for a wider diversity of crystals, thereby opening the door for even more demanding application in metrology- or quantum-based applications.[9] The small volume of confinement, high-photon density, and long photon lifetime (proportional to Q) induce a very strong light-matter interaction, which may excite the various WGMs through various nonlinear effects as well, namely Kerr,[10–14] Raman,[15,16] or Brillouin[17] effects.

In this article, we present an exploratory study which focuses on unconventional crystals. Our objective is to investigate the suitability of barium fluoride (BaF_2) and lithium fluoride (LiF) for the storage of light in millimeter-size disk resonators. Our aim in this article is to provide an insight into this new field as well as of the various perspectives on the challenges that will have to be met.

The plan of this article is the following. In the next section, we will describe the grinding and polishing protocols used to manufacture the resonators with these two fluoride crystals. Then, Sec. 3 will focus on the BaF_2 and LiF resonators, respectively. The last section will summarize the article.

2 Experimental Setup

2.1 *Grinding and Polishing Process*

In order to obtain the high-quality factor disk resonators, we start with an optical window crystalline resonators available from optical component retailers. These disks are first shaped and polished in order to convert them into high-quality WGM resonators. The resonators are glued on a metallic stub that can be held by the air-bearing spindle motor. Then, a V-shaped metallic guide is coated with a polishing support tissue and an abrasive liquid constituted with micrometer-size abrasive powders (aluminum oxide and

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*Address all correspondence to: Yanne K. Chembo, E-mail: yanne.chembo@femto-st.fr diamond or silicon carbide) mixed with water. The guide is used to grind the spinning disk, thereby giving its biconvex shape to the resonator. This “grinding and polishing” is repeated with abrasive particles of decreasing size.

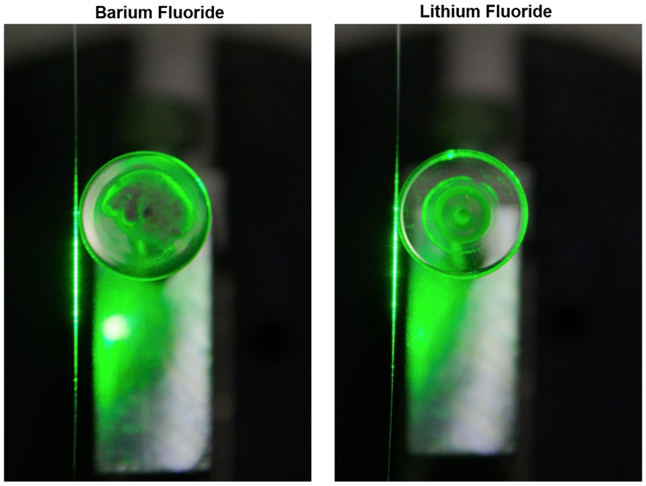
An optical microscope is used to visually control the state of the surface, until the so-called “optical polish” has been reached (the rim of the resonator reflects visible light). At this stage, the quality factor of the resonator is typically around 10^7 at the wavelength of 1550 nm. These values of the quality factor allow the laser light to be efficiently coupled by using a tapered fiber (green light for illustration purpose).

2.2 *Tapered Fiber*

In order to couple the light in the resonator, we draw customized tapered fibers with a waist as low as 3 μm. A standard single-mode silica fiber is first stripped off its polymer coating on a length of few centimeters. Each size of the uncoated section of the fiber is then fixed to two computer-controlled motors. In between, a blowtorch is used to heat the fiber, which is simultaneously pulled by the motors in a motion characterized by a constant acceleration. When executed smoothly, this procedure yields tapered fibers with a minimum waist of the order of few micrometers. This fiber taper can be used to couple the laser light inside the resonator via its evanescent field.

2.3 *Light Coupling*

The resonator is fixed on a three-axis piezo-controlled translation stage. The fiber is approached to the disk at a distance of the order of few hundreds of nanometers. We use a microscope to control the relative position between the fiber taper and the resonator. A mirror is also used to control the vertical positioning and tilt angle of the disk and to optimize the coupling. When the coupling is efficient, the disk is illuminated, as it can be seen in Fig. 1.



(a) (b)

Fig. 1 Top view of the BaF_2 (a) and LiF (b) resonators. Here, they have been coupled for illustration purposes to green laser light using a tapered fiber. The quality factors of these resonators are higher than 10^7 at 1550 nm.

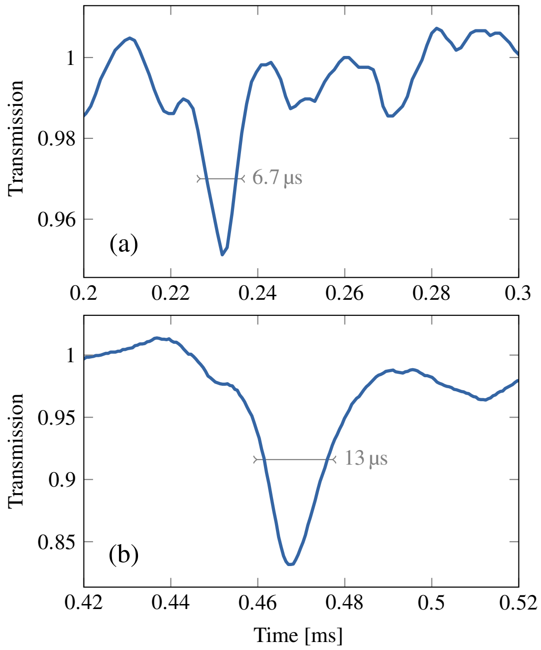


Fig. 2 Measurement of the loaded quality factors using the resonance method with a 1550-nm laser scanning at a rate $\sigma = 1.2$ GHz/ms. The loaded bandwidths are obtained by multiplying the scanning rate σ with the scanning time ΔT of the 3-dB linewidth, yielding $\Delta f_{\text{load}} = \sigma \Delta T$. The loaded quality factors are obtained through $Q_{\text{load}} = f_{\text{laser}}/\Delta f_{\text{load}}$, where $f_{\text{laser}} \simeq 193$ THz at 1550 nm. (a) Resonance of the BaF_2 resonator. The loaded quality factor is 2.4×10^7. (b) Resonance of the LiF resonator. The loaded quality factor is 1.2×10^7.

3 Results

In order to evaluate the Q-factors of the resonators, we have used the resonance scanning method, which is described in Fig. 2. This method provides the loaded quality factor Q_{load} which is defined by

$$\frac{1}{Q_{\text{load}}} = \frac{1}{Q_{\text{in}}} + \frac{1}{Q_{\text{ext}}}, \tag{1}$$

where Q_{in} and Q_{ext} are the intrinsic and extrinsic (coupling) quality factors, respectively. It appears from the above equation that $Q_{\text{load}} < Q_{\text{in}}$ and $Q_{\text{load}} < Q_{\text{ext}}$. In particular, the loaded Q-factor appears to be a lower boundary estimate of the intrinsic Q-factor.

3.1 *BaF_2 Disk*

BaF_2 is a transparent crystal whose transparency window ranges from 0.2 to 11 μm. Its refraction index is close to 1.46 in the near-infrared region. This crystal is mainly used as a scintillator for the detection of highly energetic particles.

Our BaF_2 disk is displayed in Fig. 1. It had a diameter of 12 mm before the grinding and polishing process. We have been able to perform successfully the light coupling task inside the resonator. The loaded Q-factor measured using the resonance method is equal to 2.4×10^7, as evidenced in Fig. 2.

3.2 *LiF Disk*

One of the main specificities of LiF is that its transparency window goes down deep into the ultraviolet range. It is therefore a crystal particularly suitable for applications involving ultraviolet radiations. Its refraction index is approximately equal to 1.39 for the wavelengths of interest (visible to near-infrared regions).

Our 12-mm LiF disk is shown in Fig. 1. Here also, the light coupling inside the resonator was possible, thereby indicating the presence of WGMs. As displayed in Fig. 2, the loaded Q-factor measured using the resonance method is equal to 1.2×10^7.

4 Conclusion

In this article, we have presented two unconventional bulk materials used to manufacture crystalline WGM resonators, namely BaF_2 and LiF. The loaded Q-factors are higher than 10^7 around 1550 nm, and one has to keep in mind that the corresponding intrinsic quality factors are necessarily superior to these loaded Q-factor values. We expect that the properties of these materials to be of particular relevance for some applications where their specific advantages are pertinent.

From a general perspective, both linear and nonlinear phenomena in WGM resonators are promising for a plethora of applications, particularly for aerospace engineering, and mostly for the generation of ultrastable, multicoherent radiations. This research topic also opens new horizons of research for other applications of WGM resonators, such as sensors for example, which are also of great interest for a wide variety of wavelengths.[18]

Acknowledgments

The authors acknowledge financial support from the Centre National d'Etudes Spatiales through the project SHYRO (Action R & T- R-S10/LN-0001-004/DA:10076201) and from the *Région de Franche-Comté*. They also acknowledge financial support from the European Research Council through the project NextPhase (ERC StG 278616).

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