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High quality-factor optical resonators

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Abstract

Various resonators are investigated for microwave photonic applications. Micro-sphere, disk and fiber ring resonators were designed, realized and characterized. Obtained quality factors are as high as $Q = 10^{10}$.

Keywords: optical resonator, quality factor, silica, ZBLALiP, MgF_2, fiber ring, optoelectronic oscillator

1. Introduction

For many applications in opto-electronics, metrology or fundamental physics, optical resonators with high quality factor (Q-factor) are particularly interesting [1–3]. They can be used in optical filtering, all optical switching and low threshold non-linear optics. Recent results have been obtained with mono-crystals such as MgF_2, quartz or CaF_2 whispering gallery mode (WGM) resonators [4–8]. Rare-earth doped micro-spheres are tiny lasers that can generate narrow line-width emission [9, 10]. Another interesting type of resonator is fiber ring resonators, which can feature high quality factors and are easy to use [11]. In order to characterize these resonators, there is the need to realize a good coupling. These resonators are characterized using different methods such as slow and fast frequency sweeping [12, 13]. In this paper we discuss the characterizations techniques of passive optical resonators or active, Erbium-doped ZBLALiP [14, 15] and silica micro-spheres coated by film with molar composition $70SiO_2$-$30HFO_2$ activated with 0.3% mol Er^{3+} [16, 17] WGM resonators in terms of Q-factor determination.

2. Micro-spheres

2.1. Silica micro-spheres coated by film

Silica micro-spheres coated by Er^{3+}- activated silica-hafnia films are designed and realized at IFN-CNR [16, 17]. The microspheres were produced by melting the tip of a standard optical telecommunications fiber. The diameter of the microsphere was found to be $140 \pm 10\,\mu m$ using a standard optical microscope. The microspheres were coated with a film with the molar composition $70SiO_2$-$30HfO_2$ activated with 0.3% mol Er^{3+}. The films were coated using a dip-coating technique. The measurement of the whispering gallery modes was done using a microsphere-taper coupling and a 1480 nm (S-band) fibre diode laser was used for the pumping. A typical WGM spectrum is shown in figure 1. Sharp modes in the region 1540–1565 nm are observed, and attributed to the WGMs. The spectrum presented in figure 1 is only one spectrum measured for a particular coupling point between the microsphere and the taper. The number of modes excited and their intensities depend on the coupling point and on the

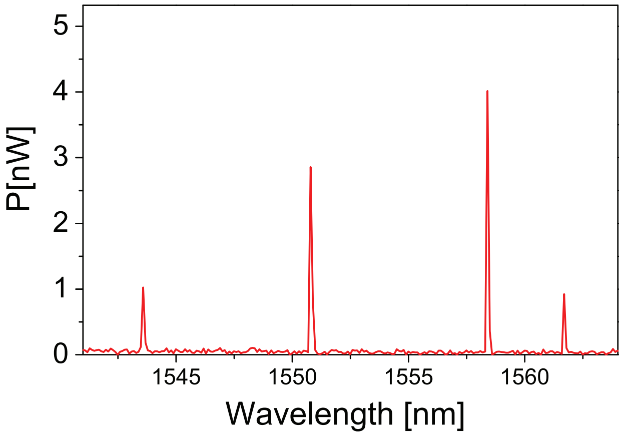

Figure 1. Laser whispering gallery modes of a silica sphere coated by 1 μm film 70SiO$_2$-30HfO$_2$ activated with 0.3% mol Er^{3+} ions.

coupling strength which is determined primarily by the distance from the microsphere to the taper. The spectrum shown in figure 1 shows four modes (but most of the spectra we made show only one or two modes in total). By moving the taper closer to and further from the sphere it is possible to excite different modes. In total we observed five modes centered at about 1543.6, 1550.8, 1554.4, 1558.3 and 1561.8 nm. This mode chart forms an equidistant sequence with a FSR (free spectral range) of about 3.7 ± 0.2 nm. Since the coupling of the pump power into different modes depends on the coupling point, by moving the taper in respect to the micro sphere we can achieve excitation of only some modes. Furthermore, the intensities of the modes should depend exponentially on the pump power and therefore we should have great variation of the mode intensity in respect of the coupling point. This was confirmed: For a given mode we observed a wide range of intensity when changing the coupling point, from 1 nW up to 30 nW.

2.2. Erbium-doped ZBLALiP micro spheres

Erbium-doped ZBLALiP micro spheres are obtained by fusion in a microwave plasma torch at FOTON [9]. Diameters of the micro spheres are between 50 μm and 150 μm. The spheres are coupled to a taper. The method used to measure high Q-factors consists of a careful analysis of the cavity ring down signal obtained by exciting the resonator with a fast frequency-modulated laser [12]. Figure 2 presents the ringing signal corresponding to quasi-critical coupling where intrinsic Q_0 and external Q_e factors are almost equal. When pumping the resonator at 1480 nm, this regime of loss compensation is obtained for ZBLALiP 0.1 mol% Er^{3+}-doped microspheres. The analysis gives intrinsic ($Q_0 = 1.055 \times 10^{10}$) and external ($Q_e = 1.063 \times 10^{10}$) Q-factors. The global ($Q^{-1} = Q_0^{-1} + Q_e^{-1}$) Q-factor is then determined to be 5.294×10^9. Further work will be dedicated to use of a lower doping rate and higher diameter resonators in order to make possible higher Q-factors.

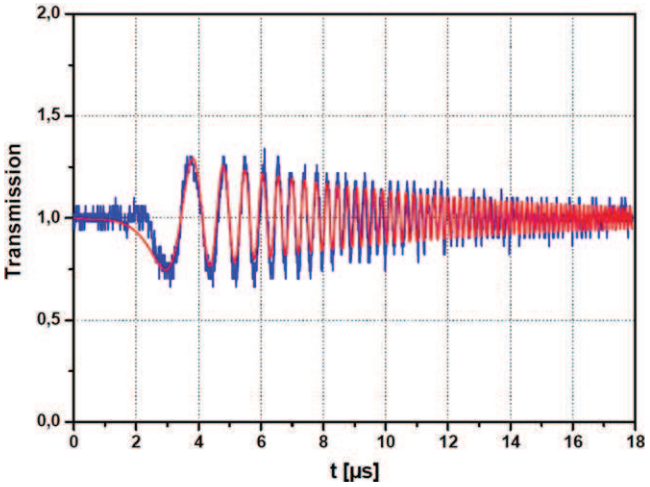

Figure 2. Ringing signal at quasi-critical regime of losses compensation. The intrinsic quality factor is $Q_0 = 1.055 \times 10^{10}$ and the external quality factor $Q_e = 1.063 \times 10^{10}$.

3. Disk-resonators

It was demonstrated that an oscillator referenced on a disk resonator with taper coupling delivers a Free Spectral Range (FSR) microwave signal [1]. The use of a high Q-factor WGM resonator with magnesium fluoride (MgF$_2$) or calcium fluoride (CaF$_2$) is adequate for microwave photonics applications. At FEMTO-ST, we have fabricated and characterized 5.5 mm diameter toroid MgF$_2$ and CaF$_2$ resonators with a surface roughness in the range of few nanometers. We use dedicated processes and instrumentation to prepare the optical resonator. The required shape of the resonator is realized by polishing and performing several treatments. Thereafter, the resonator can be characterized in terms of Q-factor. Resonance peaks are detected and characterized by cavity ring down as reported in references [12, 18]. Cavity ring-down measurements demonstrate a quality factor of 1.7×10^9 for a MgF$_2$ disk. This measurement is presented in figure 3, with a picture of the resonator as an insert. This is a significant improvement on similar resonators Q-factors [6, 18]. To build an optoelectronic oscillator, an optical channel can be used as a frequency-selective component in the OEO loop. We can therefore underline that the use of the disk-resonator leads to a significant reduction of the OEO size.

4. Fiber ring resonators

An interesting alternative to the WGM resonators is the use of ultra-high Q-factor fiber ring resonators (FRRs) to achieve notable performances in an OEO setup. These FRRs realized at LAAS are compact, easy to fabricate and to use, and they can lead to very high Q-factors above 10^{10} [19]. On the other hand, the ultra-high Q increases the circulating optical power inside the FRR and leads to the generation of different nonlinear optical phenomena at very low thresholds (Rayleigh, Brillouin, etc). These phenomena can be very useful for different applications, like high power and high spectral purity

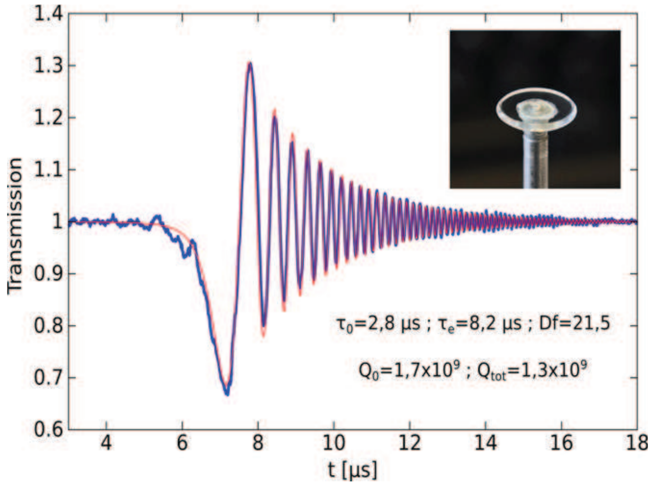

Figure 3. Cavity ring down measurements of an ultra-high quality disk resonator. Transmission is graphed versus time (in μs). Deduced intrinsic (Q_0) and total (Q_{tot}) Q-factors are reported in the figure. A picture of the characterized resonator is shown as an insert in the upper right corner.

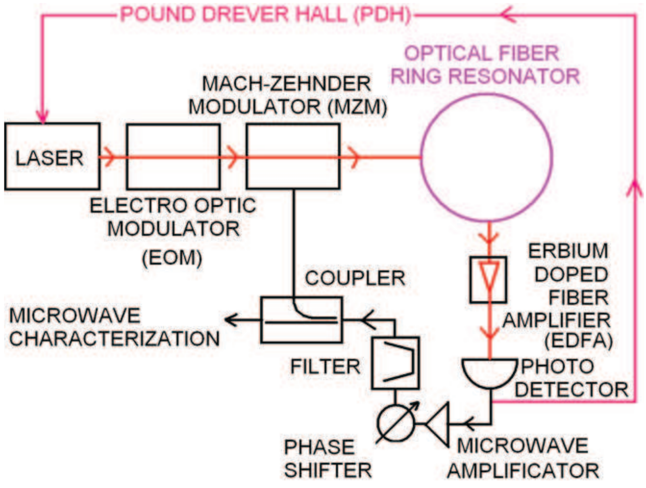

Figure 4. OEO based on a fiber ring resonator. The laser wavelength is stabilized onto an optical resonance using a Pound Drever Hall stabilization loop [21, 22].

millimeter waves generation [20]. Nevertheless, they are considered as parasitic noisy signals in an OEO setup and they can therefore degrade its phase noise [11]. For this reason, both theoretical and experimental studies were performed to be able to suppress these phenomena and reduce the phase noise in an OEO setup. These studies were performed at Toulouse and they were focused particularly on two optical scattering phenomena, i.e. Rayleigh and Brillouin scatterings. First, the use of a low injected optical power inside the FRR has allowed a good limitation of these two nonlinear scattering phenomena. As a result, a 30 dB reduction in the OEO phase noise has been demonstrated at 10 Hz offset frequency from a 10 GHz microwave carrier. Afterwards, an oscillator based on a new immunized and high-Q FRR has been demonstrated with a phase noise level of $-50\,\mathrm{dBc\,Hz^{-1}}$ at 10 Hz offset frequency from a 10 GHz carrier. The microwave opto-electronic oscillator (OEO) based on a fiber ring resonator characterized in this section is shown in figure 4.

5. Conclusion

Several types of resonators were investigated. Silica microspheres coated by Er3+- activated silica-hafnia films were investigated and characterized. Erbium-doped ZBLALiP micro spheres obtained by fusion in a microwave plasma torch provide interesting results in terms of Q-factor determination. Disk-resonators were improved and their Q-factors are high. As an alternative, the use of fiber ring resonators opens new possibilities for high-Q resonators. Concretely, micro-sphere, disk and fiber ring resonators were characterized and obtained Q-factors were as high as $Q = 10^{10}$.

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