



HAL
open science

High-quality factor microsphere as sensors

Poffo L., El Metouy Et-tijani, Christelle Velly-Pareige, Laetitia Abel-Tiberini

► **To cite this version:**

Poffo L., El Metouy Et-tijani, Christelle Velly-Pareige, Laetitia Abel-Tiberini. High-quality factor microsphere as sensors. 2024 24th International Conference on Transparent Optical Networks (ICTON), Jul 2024, Bari, Italy. pp.1-4, 10.1109/icton62926.2024.10647631 . hal-04688497

HAL Id: hal-04688497

<https://hal.science/hal-04688497v1>

Submitted on 30 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

High-quality factor microsphere as sensors

Luiz Poffo, El Metouy Et-Tijani, Christelle Velly, Laetitia Abel-Tiberini*

Université de Rennes, CNRS, Institut FOTON - UMR 6082, F-22305 Lannion, France

* Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, F-13013 Marseille, France

e-mail: luiz.poffo@univ-rennes.fr

ABSTRACT

Whispering gallery mode (WGM) microspheres have gained prominence as sensors in various applications due to their ability to significantly enhance light-matter interaction. In fact, the sensitivity of these sensors is directly correlated with their quality factor (Q), and melted glass microspheres typically exhibit a Q-factor of approximately 10^5 when used as sensors (functionalized and/or in the measurement environment). Usually, the predominant sensing mechanism involves monitoring mode shifts, where the resonant wavelength of the WGM is employed to measure the desired signal. However, at higher Q-factors, characterized by narrower bandwidths, sophisticated equipment is required for accurate measurements.

In this study, we utilize an active microsphere as a sensor with an exceptional Q-factor exceeding 10^8 in the measurement environment, thanks to its gain. We opt for an alternative sensing mechanism that leverages the microsphere's gain to measure the signal of interest. Lastly, we compare this innovative sensing approach with other techniques commonly employed in optical sensors based on WGM micro resonators.

Keywords: whispering gallery mode, micro-resonators, optical sensors.

1. INTRODUCTION

Optical sensors for biological and medical applications are an active area of research due to their ability to acquire information with low concentrations of a specific analyte [1]. Various detection methods are used in optical sensors, such as absorption in waveguides [2], phase shifting using interferometers [3], or light resonance in cavities [4]. The most common optical sensor is based on fibers, where the interaction between light and matter is ensured by the length of the fiber [5]. Resonator structures offer the most compact and sensitive optical sensors due to their high quality factor Q, which allows resonant light to travel multiple times within the cavity [6].

Whispering gallery mode (WGM) microspheres possess a very high quality factor (Q) of around 10^8 or more, compared to the Q of 10^4 for polymers used in our earlier sensors [1]. This high quality enables the realization of ultra-sensitive sensors capable of detecting a single virus, as proposed by Frank Vollmer [7] and illustrated in Figure 1. It uses a glass microsphere as a resonator because the sphere naturally has a high quality factor.

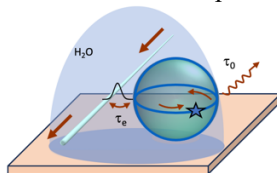


Figure 1. Schematic of the WGM microsphere nanoparticle sensor.

In this sensor configuration, the microsphere is immersed in an aqueous solution, which reduces the quality factor Q from 10^6 to 10^5 or even 10^4 . Additionally, considering functionalizing the surface of the microsphere may further decrease the quality factor and consequently the sensor's sensitivity.

2. USING ACTIVE MICROSPHERES

To maintain the quality factor (Q) of the microsphere in aqueous solution or when functionalized, we propose using an active microsphere. This would allow us to introduce optical gain (through optical pumping) to compensate for the additional losses of the microsphere. It would also be feasible to achieve gain compensation so that the transmission, or transfer function, of the micro-resonator in resonance is represented by $T(\omega) = 1$ with a phase shift characteristic of the resonator. We refer to this as a Transparent Resonator, and the finesse (F) is higher in this configuration, providing maximum sensitivity.

Working with high-quality factors, however, requires high-performance equipment capable of measuring very fine changes in resonance frequency. The conventional method involves exciting the resonator using a tunable laser with very high spectral resolution, whose frequency is linearly scanned at slow rate ν [8]. Unfortunately, this method does not allow for the measurement of the phase shift properties of the resonator.

In this paper we propose to use the hybrid spectral/temporal method [9] for detection. This involves measuring the photon lifetime in the device while seeking cavity resonance by fast sweeping the input laser frequency at fast rate, ν . When the laser frequency is tuned to the resonance frequency ν_0 , the field resonates in the cavity and is re-emitted to the output port with a decay time τ . As the laser frequency evolves, the field extracted from the cavity

interferes with the input signal of frequency $\nu_0 + \Delta\nu$. The resulting beat appears on the detected signal as oscillations, as shown in Figure 2.

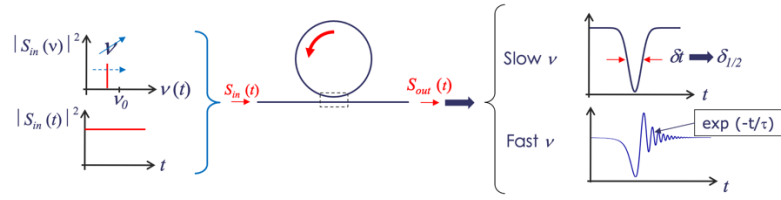


Figure 2. Cavity Ring-Down principle.

From these oscillations, we can obtain all the linear properties of the micro-resonator, such as coupling losses, propagation losses, and the coupling regime. The idea behind the sensor is that when a particle comes into contact with the surface of the microsphere, it will alter the cavity characteristics. By compensating for this variation to restore the transparency mode thanks to the gain within the cavity, we can measure the concentration of particles present on the surface of the microsphere relative to the change in gain required to restore the coupling regime.

3. EXPERIMENTAL SETUP

3.1 Active Microsphere Optical Property

The proposed WGM optical sensor utilizes an erbium-doped glass microsphere. The erbium ion exhibits a significant emission band around 1550 nm, making it a relevant choice for our study. Several pumping wavelengths are available for erbium, including 980 nm (between the fundamental level $^4I_{15/2}$ and the level $^4I_{11/2}$) and 1480 nm (also between the level $^4I_{15/2}$ and the level $^4I_{13/2}$) [10]. We opted for the 1480 nm wavelength because of its optimal overlap with the pump (1480 nm) and probe (1550 nm) fields in the microsphere used in our experimental setup.

3.1.1 Plasma torch: Microsphere Shaping

To produce the glass microspheres, we utilize a plasma torch, enabling us to work with various types of glass including erbium-doped glass. The glass pieces are manually crushed using a mortar, and the resulting powders can be sieved to calibrate the size of the spheres to be produced. These powders are then guided into the torch nozzle. As they pass through the flame and spheroidize, they cool in the air, preserving their spherical shape and achieving the necessary quenching to maintain the amorphous structure. The formed microspheres are collected at the base of the torch and placed in glass Petri dishes. The oxygen and argon flow rates, as well as the microwave power, are adjusted according to the type of glass being used.

3.1.2 Microsphere support

Storing free spheres in glass Petri dishes has the disadvantage that the spheres lack individual support, making them difficult to manipulate. Each sphere must be individually caught and handled. To serve as a support for the spheres, we use a stretched fiber with an end diameter smaller than the sphere diameter. After selecting the desired sphere, we use a vacuum micro-syringe to pick up the sphere and place it near the support. To prevent capillary effects, we apply a minimal amount of polymerizable glue to adhere the sphere to the support.

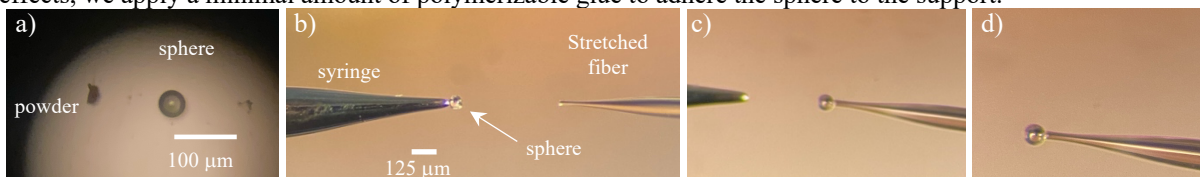


Figure 4. Different stages in mounting a sphere on its support before handling: a) select the sphere b) pick up the sphere using a micropipette and align it opposite a thinned fiber with glue, c) after the glue has polymerized, remove the micropipette, d) the sphere is now glued to its support.

3.2 Fiber Taper coupling

To efficiently excite WGMs in microspheres, we exploit the evanescent field through a tapered fiber, or taper. A taper involves the local stretching of a fiber to form a narrow thread, or waist, encompassing both the core and cladding. As the diameter decreases to a few microns, the core ceases to exist, and the light becomes guided by the cladding-air interface. A taper is considered adiabatic when the taper angle remains sufficiently small throughout its length, resulting in minimal power coupling from the fundamental mode to higher-order and unguided modes. This minimizes power loss as the light propagates along the taper [11].

The optimal diameter of the taper is achieved when there is a close phase matching between the propagation constant in the taper, β_{taper} , and that in the sphere, β_{sphere} . If the waist is small, the fundamental mode will have an evanescent tail extending significantly into the free space surrounding the taper. By knowing the propagation constants in the sphere and the fiber, it becomes possible to identify the maximal diameter of the taper that ensures optimal phase matching for a given sphere diameter. In our case at 1550 nm and 1480 nm, and a sphere diameter

of 80 μm the best mode is obtained with a taper diameter thinner than 3 μm . Due to the limited interaction length imposed by the curvature of the microsphere surface, the overall coupling is not expected to be sensitive to small variations in the taper diameter or sphere size.

3.2.1 Manufacture of the fiber taper

Figure 5a shows a schematic diagram of the experimental set-up used to produce the tapered fiber. The method consists in heating part of the fiber with a flame gun, while stretching it with motors. To monitor transmission during the stretching process, a 1550 nm laser signal is transmitted through the fiber, and the transmission data is captured by a photodiode connected to an oscilloscope, Figure 5b. During the stretching/melting process, small oscillations are observed in the transmission at the fiber output, resulting from interference from different modes supported by the fiber. As the fiber diameter decreases, it approaches its adiabatic state, where the taper filters out all modes higher than the fundamental mode. This filtering leads to the disappearance of the beats. Monitoring these oscillations helps us determine when to stop stretching and obtain an adiabatic state.

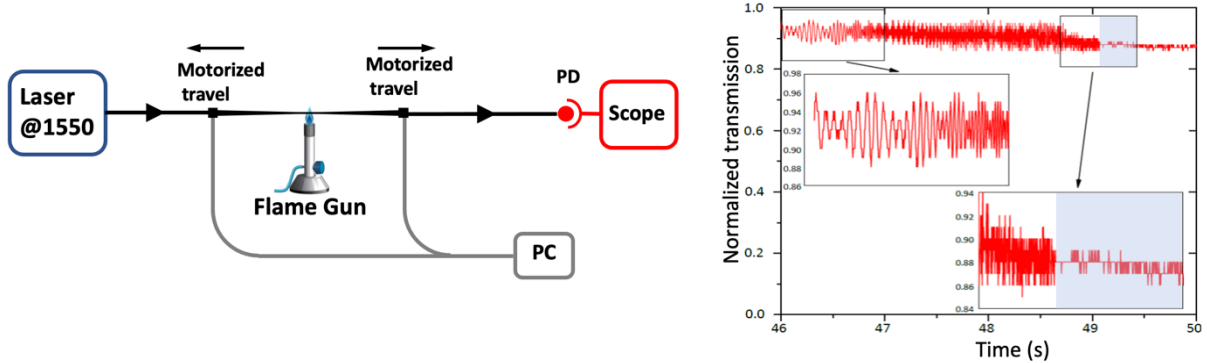


Figure 5. a) Experimental set-up for manufacturing tapered fibers. b) Transmission at the output of the tapered fiber as a function of elongation time for $\lambda = 1550$ nm.

3.3 Complete setup

The input probe signal is coupled to the WGM resonator via the tapered fiber. The coupling conditions (τ_c) can be adjusted by varying the distance between the sphere and the taper. A counter-propagative pump field from the laser diode (1480 nm) is coupled to the resonator through a half-tapered fiber. Before initiating the frequency sweeping of the probe signal, we identify and select a resonance of the microcavity by analyzing its transmission signal using an Optical Spectrum Analyzer (OSA). The probe signal reflected from the coupler C to the OSA is employed to tune the probe laser frequency to the chosen microsphere resonance. A narrowband tunable laser operating around 1550 nm serves as the linearly frequency-scanned probe signal. An optical attenuator is used to maintain the small signal regime and avoid gain saturation. The signal extracted from the microsphere is initially optically amplified by an erbium-doped fiber amplifier (EDFA) and subsequently filtered using a narrowband tunable filter. An amplified fast photodiode collects the output optical signal.

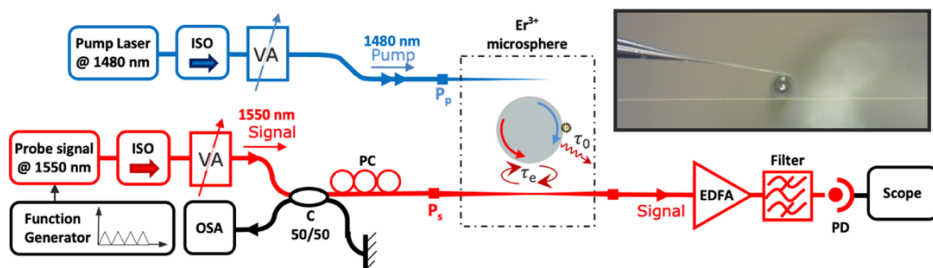


Figure 6. Experimental set-up. ISO: optical isolator, AV: variable attenuator, OSA: optical spectrum analyzer, C: 50/50 coupler, CP: polarization controller, EDFA: Erbium-doped fiber amplifier, F: optical filter, PD: amplified photodiode.

4. PRELIMINARY RESULTS

First, we set up and aligned our configuration using a passive microsphere. After identifying the resonance of the microcavity by analysing its transmission with an OSA, we performed a frequency sweep around this resonance. Figure 7a shows the transmission profile $T(t)$, obtained by slowly sweeping the signal frequency around 1550 nm, in a pure silica microsphere with a diameter of 150 μm . This diagram also illustrates the probe laser's frequency control signal (in blue). This control signal enabled us to check and adjust a resonance to be characterized at the center of the ramp. By transforming the time axis into frequency, we obtain the transmission $T(\nu)$, as shown in figure 7b. We measured a quality factor ($Q = \nu/\Delta\nu_0$) of around 8.10^7 .

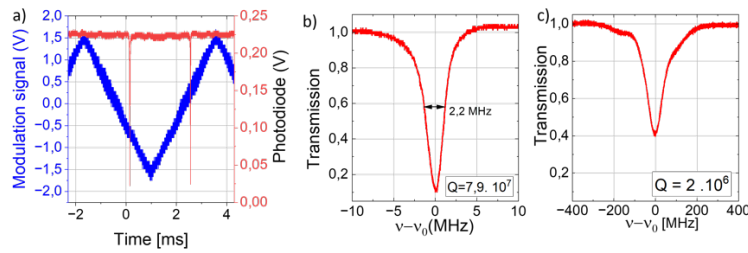


Figure 7. a) Scanning the probe laser frequency around a resonance at 1550 nm. The electrical signal applied to the laser is shown in blue, while the optical signal received by the photodiode is illustrated in red. Transmission as a function of the normalized frequency detuning for b) passive and c) active microsphere.

Figure 7c shows the transmission profile measured by slowly sweeping the signal frequency around 1552 nm in an Erbium-doped microsphere with a doping level of 0.2 mol% and a diameter of 85 μm . A pumping power of 0.5 mW is used to compensate for losses. We measured a quality factor of the order of 10^6 . We tried to improve this factor by increasing pump power, but unfortunately this did not yield positive results. This is due to defects in the microspheres, a problem we are working to improve (we will improve the manufacturing processes) in order to obtain microspheres with fewer defects and a higher quality factor of at least 10^8 or more.

5. SENSING MECHANISMS USED IN WGM RESONATORS

The literature identifies three main detection mechanisms for WGM resonators. The first mechanism, proposed by Vollmer, is based on a resonance shift phenomenon and utilizes a silica microsphere immersed in water with a quality factor of 2.6×10^5 [7]. The second mechanism, known as Mode Splitting, is described in reference [12]. It involves the use of a pure silica microtoroid ($Q = 10^8$). However, this device only operate effectively in an airborne environment, limiting their utility for detecting analytes in aqueous solutions. The third mechanism, called Mode Broadening, is proposed by Shen [13], and utilizes a silica microtoroid. Under water immersion conditions, its quality factor does not exceed 10^6 .

6. CONCLUSION

In conclusion, this paper presents a promising method for detecting particles using an active micro-resonator operating in the transparency regime. This method offers considerable potential for sensitive and precise detection applications, particularly in the fields of healthcare, environmental monitoring, and industrial research. It represents a significant advancement in the field of optical nanodetection, with the prospect of reducing equipment costs and paving the way for potentially more accessible and practical applications.

REFERENCES

- [1] P. Girault *et al.* Integrated polymer micro-ring resonators for optical sensing applications. *Journal of Applied Physics*. 2015.
- [2] A. Gutierrez *et al.* Theoretical study of an evanescent optical integrated sensor for multipurpose detection of gases and liquids in the mid-infrared. *Sensors and Actuators B: Chemical*, Elsevier, 2017.
- [3] A. Kussrow *et al.* Interferometric methods for label-free molecular interaction studies. *An. Chem.*, 2012.
- [4] P. Azuelos *et al.* High sensitivity optical biosensor based on polymer materials and using the vernier effect. *Op. Exp.* 2017.
- [5] S. E. Mowbray and A. M. Amiri. A brief overview of medical fiber optic biosensors and techniques in the modification for enhanced sensing ability. *Diagnostics*, 2019.
- [6] J. Ward and O. Benson, WGM microresonators: sensing, lasing and fundamental optics with microspheres. *Laser & Photon. Rev.*, 2011.
- [7] F. Vollmer *et al.* Single virus detection from the reactive shift of a whispering-gallery mode. *Proc Natl Acad Sci USA*. 2008.
- [8] X. Jiang *et al.* Whispering gallery microsensors: a review. *Physics*; 2018.
- [9] A. Rasoloniaina *et al.* Controlling the coupling properties of active ultrahigh-Q wgm microcavities from undercoupling to selective amplification, *Scientific Reports*, 2015.
- [10] D.G. O'Shea *et al.* Upconversion channels in Er^{3+} : ZBLALiP fluoride glass microspheres, *The European Physical Journal-Applied Physics* 40.2, 2007.
- [11] Love, J. D., *et al.* Tapered single-mode fibres and devices. Part 1: Adiabaticity criteria, *IEE Proceedings J (Optoelectronics)*, 1991.
- [12] L. He *et al.* Detecting single viruses and nanoparticles using whispering gallery microlasers. *Nature Nanotech* 6, 2011.
- [13] B. Q. Shen *et al.* Detection of Single Nanoparticles Using the Dissipative Interaction in a High-Q Microcavity. *Phys. Rev. Applied* 5, 2016.