Transactions on Computer Science and Intelligent Systems Research
ISSN: 2960-1800, eISSN: 2960-2238 | Volume 7
TPCEE 2024

Whispering-Gallery Mode Lasers: A New Frontier in Micro resonators

Guowen Xu *

School of science, Shandong Jianzhu University, Jinan, China

* Corresponding author: yucai@ldy.edu.rs

Abstract. Whispering Gallery mode (WGM) optical microcavities represent a significant focus in current laser research. Initially, this paper elucidates the concept of WGM and its acoustic significance, before delving into its development in the optical field and its crucial role in optical devices. Subsequently, the author explores the theoretical foundations of WGM, elucidating the photon confinement effect due to total internal reflection. These optical microcavities are noted for their high symmetry and surface smoothness, which confer an exceptionally high Q-factor. The enhanced light-matter interactions in these microcavities lead to substantial improvements in nonlinear optical effects, laser gain, and photonic crystal effects within the amplified optical fields. The author discusses micro resonators, the fabrication methods of microcavities, and the unique nonlinear optical effects arising from high Q-factors and small mode volumes, including Stimulated Brillouin Scattering, Stimulated Raman Scattering, the Kerr effect, and four-wave mixing. These effects hold broad application prospects in fields such as precision spectroscopy, optical communication, and frequency comb generation. The advantages of WGM optical microcavities in laser fabrication and the study of nonlinear optical effects are summarized, with an outlook on their potential applications in future optical fields, such as high-sensitivity sensors and low-threshold lasers.

Keywords: Whispering Gallery mode; Optical Resonators; Coupling Mechanisms; Nonlinear optical effects.

1. Introduction

WGM was first discovered in the dome of St. Paul's Cathedral, London, in the early 20th century by British scientist Lord Raleigh. He observed that people whispering on one side of the dome could be clearly heard by those on the other side, a phenomenon known as the "echoing wall effect". This phenomenon was extended to the field of optics, where photons are constantly reflected in a microcavity with a ring-like structure, which is now known as the WGM optical microcavity. In optics, WGM research began in the 1970s, and with the rapid development of fiber optics and laser technologies, scientists began using microcavity structures to confine and manipulate photons. In the 1980s, researchers successfully produced optical microsphere cavities with high quality factor, leading to a rapid expansion of the application of WGM microcavities in optical research [1,2].

Microsphere resonant cavities take advantage of the high symmetry and surface smoothness of microspheres to achieve extremely high Q factors, allowing light to be recirculated thousands of times inside the microsphere with minimal loss. Since then, microring, microdisk and other types of microcavity structures have emerged, providing more opportunities for WGM research and applications. Since the beginning of the 21st century, with the development of nanotechnology and micromachining, the size of WGM microcavities has been continuously reduced and their performance has been continuously enhanced, which has led to a wide range of applications in the fields of biosensing, microcavity photonics and nonlinear optics [3].

2. Theoretical Framework

2.1. The Fundamentals of WGM

WGM is an optical phenomenon. It occurs when light is fully reflected in a microcavity with a ring or spherical structure. This confines the light to propagate only within the cavity walls. The first one is confinement, WGM mode is a high angular momentum electromagnetic mode. Photons undergo total internal reflection inside the WGM microcavity. Angular momentum is the momentum particles or waves possess in their rotational motion. Angular momentum is divided into two types: spin angular momentum and orbital angular momentum. We focus on the orbital angular here. The photon propagates inside the cavity with a high number of reflections; thus, it is close to circular motion, forming a high-density wrap-around mode [4]. In spherical or annulus WGM microcavities comprising high refractive index materials, photons undergo total reflection when the angle of incidence is in excess of the critical angle for photon propagation. Total internal reflection within the microcavity confines the photons to the cavity, enabling their propagation along the cavity boundary in a circulatory pattern. The resulting reduction in light loss is significant [2, 3, 5, 6]. From a geometric standpoint, the guidance of such bound modes can be attributed to the phenomenon of repeated reflections. This process, which does not take into account absorption, scattering, and material dispersion, persists indefinitely. Next is the quality factor. The Q-Factor is an important parameter that describes how an optical resonator performs. A high Q-factor means that the resonator is able to store energy for a long period of time and therefore has a low energy loss. For optical micro resonators, such as spherical micro resonators, a high Q-factor means that light can circulate inside the micro resonator for a long time. This reduces the loss of light and therefore means that the interaction of light with matter can be enhanced. High Q-factor makes these micro resonators important for laser cavity, sensor, and nonlinear optical applications by enabling high sensitivity and low-threshold lasing [1]. The Q-factor is affected by a number of factors, including the absorption loss of the material, the scattering loss of the surface, and the radiation loss. In the design and manufacture of optical resonators, the Q-factor can be significantly improved by selecting low-loss materials and optimizing the resonator structure and surface quality. For example, using high-quality silica glass or crystal materials can reduce the material absorption loss, while fine machining can reduce the surface scattering loss, thus improving the Q-factor [2-4].

2.2. Optical Resonators and Microresonators

An optical resonator is a structure formed by an arrangement of two or more mirrors that improves the interaction of light with matter by confining the propagation of light within a specific region of space. Mirrors or total internal reflection within the resonator are typically used to achieve this confinement.

Optical resonance is the fundamental phenomenon in optical resonators. Optical resonance occurs when a light wave is repeatedly reflected and coherently superimposed on itself in a particular structure. That is, resonance occurs when the path length of the lightwave in the resonator is an integer multiple of the wavelength of the Lightwave, $L = m\lambda$, where L is the path length of the lightwave in the resonator, λ is the wavelength of the lightwave, and m is an integer number called the mode number. This condition ensures that each reflected light wave is superimposed on itself in a phase-matched manner to achieve the amplification effect. When a light wave meets the resonant condition in a resonator, it forms a standing wave mode. Steady wave modes are a special form of light waves in which the distribution of the electric and magnetic fields of the light have a fixed pattern in space which is non-shifting in time. This pattern is formed because light waves reflected back and forth are uniformly superimposed in phase at each point, resulting in a concentration of energy at certain locations and virtually zero at other locations [2].

A key parameter in the performance of an optical resonator is its Q. A higher Q indicates less energy loss within the resonator, longer energy storage, and higher efficiency; the Q is affected by material absorption, surface scattering, and radiation loss, and can be significantly improved by optimizing the design. For example, spherical micro resonators and microdisk resonators use total internal reflection of light waves at the boundaries of the microcavity, so that the light beam is continuously reflected inside the microcavity, thus reducing the reflection loss of light and material absorption loss, and achieving high quality [4, 7].

Many different types of resonators can be used to achieve optical resonance. There are Fabry-Perot resonators, which consist of two parallel mirrors, where light waves are reflected back and forth between the two mirrors to create resonance. There are also ring resonators, in which light waves propagate in a closed ring path, such as in fiber-optic rings or in micro resonators. There are also spherical micro resonators which use the total internal reflection of a spherical medium to form a closed path where the light wave travels in a circular path along the edge of the sphere.

3. Design and Fabrication of WGM Lasers

3.1. Material Selection

The selection of an appropriate material is of paramount importance in the design and fabrication of WGM micro resonators. The selection of an appropriate material will not only influence the quality factor of the laser diode but will also determine the potential applications for the laser. Silicate is a frequently utilized material. The high transparency of silicates makes them an optimal material for the fabrication of microcavities with a high Q-factor, which minimizes light loss and enhances the efficiency of the laser. Silicate materials possess a high melting point and demonstrate excellent thermal stability. This property enables them to maintain structural and performance stability under temperature changes or high-temperature environments, rendering them suitable for high-temperature operation. Pure silicate materials possess favorable mechanical strength and hardness, thereby enabling the fabrication of structurally stable microcavities. This mechanical stability is of critical importance for the maintenance of the geometric and dimensional accuracy of the microcavity, particularly in applications where high Q factors must be sustained over extended periods of time. Furthermore, the refractive index of silicates is identical to that of commonly utilized optical fibers, thereby facilitating the seamless integration of silicate microcavities with fiber optic systems and simplifying the design and construction of optical systems. Another frequently utilized material is polymeric material. Polymers are a common material used in microcavity fabrication. Two of the most utilized polymers are PMMA (polymethylmethacrylate) and PDMS (polydimethylsiloxane). Polymer materials are often cost-effective, particularly in comparison to traditional optical materials such as silicates and semiconductors. This makes them a popular choice for research and commercial applications with limited budgets. Additionally, polymers have excellent compatibility with existing electronic and optoelectronic components, which is crucial for the development of integrated optoelectronic systems [8, 9].

3.2. Fabrication Techniques

The fabrication of WGM micro resonators necessitates the application of precise and efficient techniques, the initial step of which is photolithography. This is one of the primary techniques utilized for the fabrication of micro resonators. Photolithography has been found to offer particular suitability for use with silicon or silicide materials. The structure of the micro resonator can be precisely defined on a semiconductor wafer by utilizing a photomask and photosensitive chemicals. This method is suitable for the fabrication of complex and fine microstructures. The second technique is etching. Techniques for etching can be broadly classified as either wet etching or dry etching. The etching technique permits the precise removal of material to form the desired shape of the micro resonator, such as a micro-ring or micro-disk. Thermal fusion represents a technique employed for the fabrication of microsphere resonators exhibiting a high Q-factor. By subjecting glass or polymer particles to temperatures approaching their melting point, the material naturally assumes a spherical shape due to surface tension. This method effectively reduces surface roughness and thus improves the Q-factor [2, 3]. The third category comprises sol-gel processes, which entail the formation of solid materials through liquid-phase deposition. These processes typically entail three main steps: the preparation of a solution, the formation of a gel, and the subsequent drying and sintering. The sintered material is then subjected to photolithography or etching. This method does not necessitate the use of high-temperature and high-pressure equipment, and it allows for the flexible control of the chemical composition, structure, and optical properties of the material [4].

3.3. Techniques for efficient coupling of light into and out of WGM resonators

The coupling of WGM micro resonators is concerned with the efficient direction of light into and out of these microstructures. The minute dimensions of the WGM microcavities, coupled with the fact that the resonant modes are constrained within the cavities, render direct injection of light into the cavities an exceedingly inefficient process. Consequently, the light can be fully coupled into the microcavity with the assistance of specific coupling devices. At present, the swift wave generated by the total reflection device is a commonly employed method for coupling. The optical signals coupled into the microcavity either originate from adjacent guided structures, such as optical fibers and channel waveguides, or are introduced via prisms and angle-polished fibers under total internal reflection [2, 4, 6].

4. Nonlinear Dynamics and Experimental Technique of WGM Laser

With an incoherent light source, it is almost impossible to obtain an electromagnetic field strong enough to observe the light-light interaction. When the laser was invented, the study of nonlinear optics started. The use of optical fibers, plasmon plasmons, hollow photonic crystal fibers, and metamaterials can reduce the optical power requirements.

4.1. Nonlinear Optical Effects in WGM Lasers

Nonlinear optics is the study of the interaction between light and matter, the electric field strength of light reaches a certain level, the response of matter to light is no longer linear. WGM lasers have unique nonlinear optical effects. The nonlinear effects include Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), Kerr Effect, and Four-Wave Mixing (FWM) [10]. The high Q-factor of the WGM micro resonator makes these nonlinear effects easier to excite and observe. SBS and SRS are two important nonlinear optical effects. SBS is a scattering phenomenon due to the interaction of light with acoustic waves in a medium, accompanied by a frequency shift, and is widely used in fiber lasers and sensors for signal amplification and noise filtering. SRS, on the other hand, is a result of the interaction of a photon with the vibrational modes of the molecules of the medium, producing Raman scattered light with frequencies lower than the Raman scattered light of the incident light, and by introducing strong pump light to form a cascade Raman gain, which plays an important role in multiwavelength fiber amplifiers and lasers. The Kerr effect refers to the change in the refractive index of the medium due to the increase in light intensity, which triggers self-phase modulation, thereby broadening the spectrum of optical pulses and generating Kerr frequency combs in WGM micro resonators, which are widely used in precision spectroscopy and clocking [6]. FWM generates new frequencies by the interaction of multiple optical waves depending on the third-order nonlinear polarizability of the medium, and has important applications in wavelength conversion, optical amplification, and coherent light source generation, especially in WGM micro resonators, where the FWM effect is significantly enhanced due to the high Q-factor and small mode volume, which is suitable for precision measurement and broadband optical communication [1].

4.2. Experimental Technique of WGM Lasers

In the fabrication of a WGM laser, the primary tasks are the validation of the theoretical model and the optimization of device performance. Typical tasks include Q-factor measurements and optical coupling efficiency measurements. The Q-factor is a measure of the loss of the WGM laser, which is typically determined through resonance peak analysis. The Q-factor of the resonator can be estimated by fitting the half-height and full width of the resonance peaks. Dynamic methods capture the transient response of the resonator through frequency sweeps, thereby enabling the observation of complex nonlinear optical effects such as self-phase modulation and spectral broadening. The swift-wave coupling method optimizes the coupling conditions by adjusting the distance between the fiber and the resonator, with the objective of achieving the highest coupling efficiency. When coupled with spectral analysis, the coupling efficiency can be derived by observing the depth and width of the resonance peaks [2][4].

5. Conclusion

The author systematically investigates the characteristics, fabrication methods, and nonlinear optical effects of WGM optical microcavities. These microcavities, distinguished by their high Q-factors, small mode volumes, and strong light-matter interactions, hold significant promise in the realms of modern photonics and quantum information science. Initially, the author elucidates the fundamental principles of WGM microcavities, encompassing their formation mechanism, optical resonance phenomena, and the concept of Q-factor. Subsequently, the fabrication methods of WGM microcavities are examined, including the selection of various materials and an array of fabrication techniques. Specifically, the merits, drawbacks, and applicable scenarios of silica and polymer materials are discussed. The paper also provides a detailed introduction to fabrication techniques such as photolithography, etching, thermal melting, and sol-gel processes, analyzing their principles, techniques, and applications. Furthermore, the author offers a comprehensive analysis of the nonlinear optical effects in WGM microcavities, such as SBS, SRS, the Kerr effect, and FWM, discussing their applications in precision spectroscopy, optical communication, and frequency comb generation.

The research findings indicate that WGM microcavities possess notable advantages in the fabrication of optical devices such as lasers and sensors. Their high Q-factors and small mode volumes facilitate low-threshold laser operation and high-sensitivity sensing. Additionally, the nonlinear optical effects of WGM microcavities open new possibilities for the development of innovative optical devices and applications.

Looking ahead, WGM microcavities are poised to have a broad range of applications in the optical field. With continuous advancements in fabrication techniques and in-depth material research, the performance of WGM microcavities is expected to be further enhanced, thereby spurring their applications in novel laser devices, high-sensitivity sensors, and nonlinear optical devices. Future research directions include enhancing Q-factors further, exploring new fabrication methods, and developing novel optical devices based on WGM.

References

[1] Strekalov D V, Marquardt C, Matsko A B, et al. Nonlinear and quantum optics with whispering gallery resonators[J]. Journal of Optics, 2016, 18 (12): 123002.

[2] Chiasera A, Dumeige Y, Feron P, et al. Spherical whispering-gallery-mode micro resonators [J]. Laser & Photonics Reviews, 2010, 4 (3): 457 - 482.

[3] Yang S, Wang Y, Sun H. Advances and prospects for whispering gallery mode microcavities [J]. Advanced Optical Materials, 2015, 3 (9): 1136 - 1162.

[4] Righini, G.C., Dumeige, Y., Féron, P. et al. Whispering gallery mode micro resonators: Fundamentals and applications. Riv. Nuovo Cim. 34, 435 – 488 (2011).

[5] Foreman M R, Swaim J D, Vollmer F. Whispering gallery mode sensors [J]. Advances in optics and photonics, 2015, 7 (2): 168 - 240.

[6] Gorodetskii, M.L., Demchenko, Y.A., Zaitsev, D.F. et al. High-Q Factor Optical Whispering-Gallery Mode Microresonators and Their Use in Precision Measurements. Meas Tech 57, 1386 – 1395 (2015).

[7] Boriskina S V, Benson T M, Sewell P, et al. Highly efficient design of spectrally engineered whispering-gallery-mode microlaser resonators [J]. Optical and Quantum Electronics, 2003, 35: 545 - 559.

[8] Kawaguchi H. Functional polymer microspheres [J]. Progress in polymer science, 2000, 25 (8): 1171 - 1210.

[9] Ioppolo T, Kozhevnikov M, Stepaniuk V, et al. Micro-optical force sensor concept based on whispering gallery mode resonators [J]. Applied optics, 2008, 47 (16): 3009 - 3014.

[10] Frigenti G, Farnesi D, Nunzi Conti G, et al. Nonlinear optics in microspherical resonators [J]. Micromachines, 2020, 11 (3): 303.