Optical Resonators With Whispering-Gallery Modes—Part II: Applications

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***Abstract*—We review photonic applications of dielectric whispering-gallery mode (WGM) resonators—tracing the growth of the technology from experiments with levitating droplets of aerosols to ultrahigh-Q solid state crystalline and integrated on-chip microresonators.**

***Index Terms*—Four-wave mixing (FWM), high-order optical filters, lasers, laser resonators, monolithic optical total internal reflection resonators, morphology dependent resonances, nonlinear optics, optical filters, optical resonators, parametric optics, Q-factor, solid state lasers, spectroscopy, tunable filters, wave mixing, whispering-gallery mode (WGM) resonators.**

I. Introduction

In THIS paper, we address applications of open dielectric resonators and leave the detailed descriptions of their properties to textbooks [1], [2] and reviews [3]–[8]. The basic properties of resonators that are important to their practical applications are also summarized in the previous paper of this issue [9].

An talking about "photonic applications," we use a broad meaning of photonics, which includes linear, nonlinear, and quantum optics, optical engineering, and other related branches of science and technology. Special attention is given to microwave photonics, where dielectric resonators are used to process microwave signals by optical means.

We discuss the resonators that are made of transparent optical dielectrics and have monolithic ring resonator design (we do not consider macroscopic fiber ring resonators based on directional couplers). The optical modes in such resonators; e.g., morphology-dependent resonances or whispering gallery modes (WGMs), can be understood as closed circular beams supported by total internal reflections from boundaries of the resonators.

Modern open dielectric optical resonators have cylindrical, spherical, spheroidal/toroidal, ring, and other shapes and topologies with various confining principles. For the sake of unification, we use throughout this review the terms whispering gallery resonators (WGRs) and whispering gallery modes to describe those resonators and their modes.

It is useful to note that, strictly speaking, the term WGM cannot be applied to quasi-one-dimensional objects such as microrings. In such cases, the curvature of the resonator does not play a significant role in the formation of the spatial mode structures, and these objects could simply be described as loops made out of an optical waveguide.

Original WGMs do not have a lot in common with such a waveguide propagation. Originally studied as sound waves propagating very close to the cylindrical wall of the gallery in St. Paul's cathedral, London [10], the WGMs (Lord Rayleighs's term) were found to be partially confined due to the suppression of the wave diffraction by the sound reflection from the curved dome walls. The effective volumes and field distributions of those modes depend on the radius of the "resonator" [11].

To avoid this discrepancy, in our review, we redefine an optical WGR as a monolithic ring resonator based on total internal reflection of light.

II. Devices With Passive WGM Resonators

Unique spectral properties of WGMs, including narrow linewidth, tunability, and high stability under environmental conditions, make WGRs attractive for numerous practical applications. In this section, we review applications of passive WGRs for filtering, frequency stabilization, and sensing.

Photonic filters based on optical WGRs are currently among the most developed devices that involve WGMs. For optical telecommunication purposes, the main task of the filters is to select channels in wavelength division multiplexing (WDM) schemes. In this domain, where channel spacing is usually no less than 10 GHz, planar ring resonators with WGM and similar devices with $Q < 1 \times 10^5$ are adequate.

Ultra-high-Q WGRs with MHz range resonance bandwidths offer a unique opportunity for creation of photonic microwave filters in which optical domain selection is used for separating the RF channels imprinted as sidebands on a stable optical carrier. Important applications of WGRs occur in metrology for optical and microwave frequency stabilization, where a long photon storage time helps to suppress phase and frequency deviation of oscillators.

High-Q and long recirculation of light in compact WGRs offer interesting new capabilities in spectroscopy and sensing, where the change in Q or resonance frequency of WGMs can serve as a measure of absorption in the surrounding medium, or in a small (down to single molecule) quantity of deposited substance on a resonator surface. The resonator can also be used for measurement of change in ambient parameters, such as temperature, pressure, motion, etc.

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A. Optical and Photonic Single Resonator Filters

The simplest resonator-based filter includes a WGR and an optical coupler; e.g., a prism coupler. Transmission of a monochromatic electromagnetic wave of frequency ω by an optical WGR in a single prism configuration may be characterized by the coefficient

$$T = \frac{\gamma_c - \gamma - i(\omega - \omega_0)}{\gamma_c + \gamma + i(\omega - \omega_0)} \tag{1}$$

where T describes the amplitude transmission, γ, γ_c, and ω_0 are the absorption and coupling linewidth, and resonance frequency of a mode of the resonator, respectively [we assume that $|\omega - \omega_0|$ is much less than the cavity free spectral range (FSR)]. The power transmission $|T|^2$ through the resonator is Lorentzian. Condition $\gamma = \gamma_c$ corresponds to critical coupling of the resonator [12], [13].

The filter described by (1) is a stop-band filter because it is characterized by the absorption resonance. A WGR with two input and output couplers is characterized by a transmission resonance. This is an example of a passband filter. The transmission and reflection coefficients through the resonator are

$$T = \frac{\gamma_c}{\gamma_c + i(\omega - \omega_0)}, \quad R = \frac{i(\omega - \omega_0)}{\gamma_c + i(\omega - \omega_0)} \tag{2}$$

where T and R describe the amplitude transmission (light goes into one coupler and exits the other coupler) and reflection (light goes and exits the same coupler), respectively, and $\gamma_c \gg \gamma$ is assumed for simplicity.

Single ring-shaped WGR-based filters were studied in [14]–[19], see also [8], [20] for a review. An all-optical passive four-port system including a fused silica microsphere and two tapered fibers was used as a channel adding–dropping device [21]. The filter response of single-ring resonators with integrated semiconductor optical amplifiers based on GaInAsP–InP is presented in [22]. A channel dropping filter based on a dielectric microsphere integrated to a silicon photodiode was studied in [23].

Two dielectric waveguides that are evanescently coupled to a few micron sized square or rectangular region of increased refractive index can serve as a very compact integrated optical microresonator, similar to a ring WGR. Applications of the device for filtering are discussed in [24].

Unfortunately, the Lorentzian lineshape of the filter function associated with a single microresonator represents a limitation for its application in many systems that require large sidemode rejection, in addition to a narrow bandpass and a large tuning range.

B. High-Order Filters

Cascaded resonators, such as coupled optical fiber resonators, are widely used as optical and photonic filters [25], [26]. WGRs offer new possibilities for multipole filtering because of their small size, low losses, and integrability into optical networks.

Multipole filters based on cascaded integrated microring resonators fabricated with silica have been demonstrated in compact and robust packages. The filters have 10–100 GHz bandwidths and corresponding optical Qs on the order of 10^5–10^4 [15], [27]–[31], and are, in fact, commercially available. These filters provide passbands with flat tops and sharp skirts, suitable for high performance applications, especially in optical WDM. A second-order optical filter with a MHz bandwidth was realized with two coupled high-Q (10^8) microsphere resonators, one of which was tunable. The tunable WGR was made of germanate glass [32].

A tunable three-resonator filter made of $LiNbO_3$ WGRs was demonstrated in [33]. The filter has the following distinctive features/advantages over other WGM filters: 1) agile tunability accompanied by a high-order filter function; 2) narrow linewidth ($\leq$20 MHz); and 3) low fiber-to-fiber loss. A combination of the three features makes this filter a unique device for a wide range of applications in optics. Since the microwave signals in photonic systems are sidebands of an optical carrier, these filters, in principle, can be used at any microwave frequency, providing the same characteristics throughout the band, from 1 to 100 GHz and higher.

Multiresonator filters have significantly more sparse spectra compared with a standalone WGM resonator. This feature is due to the so called Vernier effect [34], and is similar to the feature observed in coupled fiber-ring resonators [25], [26] which are noted for a rare spectrum. An efficient finesse of such multiresonator systems, introduced as a ratio of frequency difference between the transmission bands of the filter divided over the frequency width of a band, is very large; e.g., the FSR of the filter reported in [33] exceeds one terahertz. Polymer double microring filters with thermooptic as well as electrooptic tuning were demonstrated and reported in [35].

It was noted that one of several advantages of using coupled microrings for filtering is the possibility of a high tuning enhancement factor M given by

$$M = \frac{1}{1 - a_2/a_1} \tag{3}$$

where a_1 and a_2 are the radii of the two rings. The tuning range of the double microring filter is M times the tuning range of a single ring [36]. Since M can be very large in double-WGR structures, the faster but much smaller electro-optic effect can be used for tuning. It is important to note that the the derivation of the parameter is valid for the resonators with such a radius ratio, and that M stays less than the finesse of the resonators.

Each ring resonator has a set of transmission spectra and the wavelength period determined by its FSR f_{FSR}. The two rings have slightly different radii (or effective indices). Therefore, the two sets of transmission peak combs have small different peak spacing. Wavelength tuning is achieved by aligning the peaks in the two sets of combs with the adjustment of index in one or both ring resonators. The filter transmission discreetly jumps from transmission at wavelength f_0 to $f_0 + f_{\text{FSR}}$, with M times less voltage applied to one of the rings compared with voltage necessary to continuously shift the spectrum of the ring by f_{FSR}.

A tuning enhancement factor of $M = 40$ in a double-ring filter was achieved at wavelengths near 1.55 μm [35]. The tuning rate for the thermooptic device is 120 GHz/mW, and for the electrooptic device is 120 GHz/12 V. A tunable laser with a side-mode suppression ratio greater than 30 dB was demonstrated using this filter and erbium-doped fiber amplifier gain. Thermal tuning over 35 nm was achieved [35].

One of apparent applications of the optical filters is in optical delay lines. Optical delay devices based on chains of coupled WGRs have been studied in [37], [38]. It was shown that the Q-factor of the coupling-split modes for a system of N identical coupled resonators is greater than that of a single resonator in the chain by a factor of N, and even more in the case of optimum coupling [39]. Stopping light all optically with a chain of interacting tunable optical resonators was discussed in [40].

Another concept of coupled resonator optical waveguides was developed in [41], [42]. In particular, such waveguides can be realized in chains of coupled WGRs [44]. A numerical simulation of light propagation in microcylinder coupled resonator waveguides was reported in [43]. The simulations show that light propagates slower in the WGM chains formed by coupling of the modes having bigger azimuthal numbers. The light propagation by WGMs of the same azimuthal number have the same speed regardless of the size and the material of the resonators.

Generally, WGR tunable filters allow shifting the spectrum of the resonators; however, they do not provide linewidth tuning capabilities. Cascaded resonators were proposed to be used for real-time shaping of their modal structures [45], [46]. A key feature of the approach is that it points to a simple tuning of the frequency and the width of the filter transmission window, resulting in the tuning of the group delay of optical signals—a highly desirable feature for signal processing applications.

The transmission spectral window of the filter could be curiously narrow. Theoretically, in the case of resonators without absorption, the width of the window can be arbitrarily narrow [45]; however, in reality, the minimum width of the resonance is determined by the material absorption. The physical principle of the filter operation that results in the narrow spectral window has been recognized in [15], [25], [26]. The existence of the window has also been demonstrated experimentally [47].

C. Tunable Filters

Tunability is a highly desirable property of any application of resonators. Though WGRs are solid state devices and their tunability is not readily conceivable, tunability can, in fact, achieved by several methods. Mechanical trimming of WGMs with applied strain [48]–[50] and temperature tuning [51], [52] have been previously used. Though the mechanical as well as temperature tuning ranges are relatively large; e.g., on the order of a few to several tens of nanometers for thermal tuning, these methods are not very convenient for many applications because of small tuning speeds and low tuning accuracy. The tuning accuracy is especially important for high-Q resonators with narrow filter bandwidth. An all-optical tunable filter design based on "discontinuity-assisted ring resonators" that does not have the previously mentioned disadvantages has also been proposed theoretically [53], but, to our knowledge, no experimental implementation of the configuration has been reported.

A technique for WGM resonance tuning was demonstrated using microring resonators with a photosensitive coating. In that study, glass microrings were dipped in a polymer coating material and were exposed to UV light. This method produced resonators with relatively small Q (about 800) because of the polymer-induced absorption; yet it still allowed large tunability of the optical resonance of the microring, enough for wavelength selective applications [47].

A method for the trimming of polymer optical microresonators was proposed in [54]. The method is based on photobleaching CLD-1 chromophores. A maximum wavelength shift of 8.73 nm was observed at 1.55 μm. The resonators had a 3dB bandwidth of 0.12 nm, an FSR of 1.11 nm, an intrinsic Q value of $\sim 2 \times 10^4$, and a finesse of ~ 10.

Another approach for trimming the frequency of microresonators exploits the photosensitivity of the germanate silica glass. When exposed to UV light, this material undergoes a small permanent change in structure that alters its index of refraction. In the case of a WGR, the spatially uniform change in the index of refraction results in a uniform translation of the resonant frequencies. Such a tunable resonator, as well as a second-order optical filter based on two coupled resonators, one of which was tunable, was experimentally realized for optical high-Q (10^8) WGMs [32], [55], [56].

Recently, fabrication of optical WGM resonators with lithium niobate [57] has led to the demonstration of a high-Q microwave filter with a linewidth of about 10 MHz and fast electrooptic tuning with a tuning range in excess of 10 GHz [58]. The best tunability for a $LiNbO_3$ single resonator filter was ± 20 GHz by applying dc voltage of ± 50 V to an electrode placed over the resonator.

The frequency shift of the TE and TM modes in a WGR may be found from the theory of the electrooptic effect [59]. For the $LiNbO_3$ WGR filter discussed in [58], we find

$$\Delta\omega_{\rm TE} = \omega_0 \frac{n_e^2}{2} r_{33} E_Z, \quad \Delta\omega_{TM} = \omega_0 \frac{n_o^2}{2} r_{13} E_Z \qquad (4)$$

where $\omega_0 = 2\pi \times 2 \times 10^{14}$ Hz is the carrier frequency of the laser; $r_{33} = 31$ pm/V and $r_{13} = 10$ pm/V are the electrooptic constants; $n_e = 2.28$ and $n_o = 2.2$ are the refractive indices of $LiNbO_3$; and E_Z is the amplitude of the electric field applied along the cavity axis. TM modes were used in the experiment reported in [58] because they have larger quality factors than the TE modes. If the quality factor is not very important, it is better to use the TE modes, because their electrooptic shifts are three times as large as those of TM modes for the same values of the applied voltage.

Theoretically, $\Delta\omega_{\rm TE}$ and $\Delta\omega_{\rm TM}$ do not depend on the resonator properties, and are related to the fundamental limitations of optical resonator-based high speed electrooptic modulators [60]. For example, the domain reversal in a congruent $LiNbO_3$ crystal occurs at $E_Z \simeq 20$ kV/mm, which corresponds to a relative WGR frequency shift of $\Delta\omega_{\rm TE}/\omega_0 \simeq 1.6 \times 10^{-3}$ and $\Delta\omega_{\rm TM} \simeq 5 \times 10^{-4}$, which is well above the observed shifts.

Lithium niobate filters are convenient; however, their linewidth is restricted by a few MHz because of the residual absorption of the material. Crystalline WGRs could possess many orders of magnitude narrower lines. For instance, optical filters with bandwidths of about 10 kHz using CaF_2 WGM resonators was demonstrated in [61]. The CaF_2 resonators have stable ultrahigh Q-factors compared with fused silica resonators, where Q degrades with time. Limited tuning of the CaF_2 filters can be realized with temperature. The insertion loss of the filter was at the 5 dB level.

To characterize the absolute tunability of an optical resonator-based photonic filter, it is useful to introduce the ratio of the resonator FSR and linear tunability range given by the host material. Tuning the filters does not change the FSR in the first approximation, but only shifts the comb of the optical modes, making it overlap with itself for each frequency shift proportional to the FSR. Hence, the filter can be tuned at any prescribed single frequency if the linear tunability exceeds the FSR. The lack of selectivity in a single-resonator filter can be compensated with the application of coupled-resonator filters. If each resonator in the filter can be tuned by its FSR, the whole filter can be tuned at any frequency, whereas the spectrum of the multiresonator filter can be very rare due to the Vernier effect.

Some photonic applications call for narrowband filters simultaneously passing both the carrier and sidebands. For example, this is important for the generation of spectrally pure microwave signals in optoelectronic oscillators [62], where beating of the optical sidebands and the carrier on a fast photodiode generates microwaves. Tunability of the microwave frequency of the oscillator requires that the frequency difference between the filter passbands change controllably. This property is lacking in existing tunable filters, where the entire filter spectrum shifts as a whole as the tuning voltage is applied. A critical component of a novel miniature filter with electro-optically reconfigurable spectrum was recently reported. The filter is based on a WGR fabricated from a commercially available lithium niobate wafer having a specially engineered domain structure [63].

D. WGM Filters in Optoelectronic Oscillators and Lasers for Stabilization

1) WGM Filters for OEO: Generation of spectrally pure signals at 1 to 100 GHz is required in communications, radar, and navigation. The advent of high throughput optical communication links points to the prospects for networks operating at data rates as high as 160 Gb/s and consisting of multiples of channels separated by a few GHz. Schemes for realizing this type of capability rely on sources capable of providing high frequency, low phase noise signals, without which error-free high data rate systems would not be possible. Similarly, high performance radar systems require low phase noise oscillators to allow detection of feeble signals from a dense background clutter.

The optoelectronic oscillator (OEO) is a device that produces spectrally pure signals at many tens of gigaltertg based on photonic techniques, and thus overcomes some of the inherent limitations of the conventional electronic devices [62], [64]–[69]. The OEO is a generic architecture consisting of a laser as the source of light energy. The laser radiation propagates through a modulator and an optical energy storage element, such as an optical fiber, before it is converted to the electrical energy with a fast photodiode. The RF electrical signal at the output of the photodiode is amplified and filtered, and then fed back into the modulator, closing the loop. If the total gain exceeds linear loses of the loop, the system oscillates at the frequency determined by the filter.

The use of optical storage elements allows for the realization of extremely high Qs and thus spectrally pure signals in optical oscillators, since the noise performance of an oscillator is determined by the energy storage time, or quality factor Q. In particular, a long fiber delay leads to realization of microsecond storage times, corresponding to Qs of about a million at a 10 GHz oscillation frequency. This is a high value compared to conventional dielectric microwave cavities used in oscillators [70], [71]. The fiber delay line also provides for wideband frequency operation unhindered by the usual degradation of the oscillator Q with increasing frequency. Thus, spectrally pure signals at frequencies as high as 43 GHz, limited only by the modulator and detector bandwidth, have been demonstrated.

In a generic OEO [62], the long fiber delay line supports many microwave modes imposed on an optical wave. A narrow band electrical filter should be inserted into the electronic segment of the OEO feedback loop to achieve a stable single mode operation. The center frequency of this filter determines the operational frequency of the OEO. While this approach yields the desired spectrally pure high frequency signals, the physical size of the OEO is rather bulky because of the kilometers of fiber delay needed. Moreover, the long fiber delay is very sensitive to the surrounding environment so the OEO does not produce an output with high long term frequency accuracy and stability. The OEO is typically phase locked to a stable reference for long term stability.

The properties of the OEO with a high-Q WGR in place of the electronic filter, as well as the fiber delay, was studied in [72]. It was shown that the method allows one to choose virtually an arbitrary frequency of oscillation by tuning the resonator.

2) WGM Filters for the Laser Stabilization: In addition to the stabilization of the OEO, WGRs can be used for laser stabilization. Optical feedback from a high-Q microsphere resonator was used to narrow the spectrum of a miniature high-coherent diode laser, and a nearly half-pitch gradient-index lens served as a coupling element [73]. As was estimated from the variation in frequency-tuning range (chirp-reduction factor), the fast line width of the laser was reduced by more than three orders of magnitude.

A modification of external optical feedback that includes a WGR was used to narrow the line of a diode laser [74]. A WGM of a high-Q microsphere was excited by means of frustrated total internal reflection, while the feedback for optical locking of the laser was provided by intracavity Rayleigh backscattering. A beat note of the two laser diodes optically locked to a pair of orthogonally polarized modes of the same microresonator had the indicated a spectral width of 20 kHz, and the stability of 2×10^{-6} over averaging times of 10 s. A theoretical model for the laser stabilization with a WGR was presented in [75].

Finally, instead of locking a laser to a WGM, the opposite was realized in [76]. A WGM of a fused-silica microsphere was locked to a frequency-scanning laser. The resonance frequency was modulated by axial compression of the microsphere, and phase-sensitive detection of the fiber-coupled optical throughput was used for locking. Such a system is particularly useful in WGR-based chemical sensors, which the following section is devoted to.

E. Spectroscopy and Analysis of Chemical and Biological Agents

Starting from liquid WGRs used for resonator-enhanced spectroscopy (see [77] for review), solid state WGRs were utilize to enhance the interaction between light and atoms/molecules. One of the first experiments on the subject was realized in the frame of cavity-QED [78]. The radiative coupling of free atoms to the external evanescent field of a WGM was detected. The coupling manifested itself as a narrow absorption line observed in the resonator transmission spectrum. It was proven that the evanescent field of the high-Q (5×10^7) and small mode volume (10^{-8} cm^3) fused silica microsphere enables velocity-selective interactions between a single photon in the WGM and a single atom in the surrounding atomic vapor. An ultrasensitive spectrometer based on a stretched silica microsphere was proposed in [50], [79].

The next stage in the sensor development was related to WGR-based biosensors [80]–[82]. Optical biosensors are typically transducers that detect the presence of molecules at a surface. They have several desirable features, particularly for the detection of biological molecules, that include: 1) high sensitivity (less than nanomoles); 2) non-destructivity to the sample; 3) high selectivity; and 4) applicability to various substances. The transduction processes in optical biosensors generally take place on a surface and can be tailored to sense almost any kind of molecule, chemical and prebiotic, as well as biological.

WGR sensors belong to the evanescent wave sensors, which are among the most sensitive class of biosensors [83], [84]. An evanescent wave produced by the total reflection of light within the waveguide interacts with analytes on the waveguide surface in the evanescent field sensors. The evanescent wave protrudes above the waveguide surface by $\sim$100 nm (the actual distance depends on the relative index of refraction of the waveguide and the sample medium), and samples only the analyte on the surface. Surface treatments such as antibodies or oligonucleotide strands can provide specificity for the analyte; the sensor then detects only those bound to the surface. Transduction mechanisms for bound analyte include fluorescence, mass change in the evanescent region [85], and change in the index of refraction [86]. Typical sensitivity of evanescent wave biosensors based on fiber optic sensors or planar waveguide sensors is in the range of nano-moles to pico-moles.

The basic detection scheme that utilizes WGRs is that binding of molecules to the microresonator surface induces an optical change proportional to the quantity of bound molecules. The paradigm for this process is a change in the cavity Q as the surface bound molecules affect the photon storage time, either through increased scattering or absorption. In effect, the analyte spoils the Q, and the resulting change can be measured.

Any protein will adhere to glass surface of a generic WGR, and hence fire-polished spheres are entirely nonspecific. Two conditions must be met for chemical modification of the microsphere surface: first, the glass must be coated with a compound that will minimize nonspecific binding. Second, an antibody or other protein with sensitivity to a particular ligand must be linked to the sphere in such a way that both the protein's functionality and the sphere's Q are preserved. A thin film of a material with thickness smaller than the WGM's evanescent field will not significantly alter the Q of the micro-resonator; thus, a thickness of $\sim$10–100 nm can be applied to the microsphere while retaining its high-Q.

A possibility of enhancement of the detection sensitivity of evanescent-wave optical biosensors was discussed in [87]–[92]. It was shown that the resonant coupling of power into the WGR allows for efficient use of the long photon lifetimes of the high-Q WGMs to increase the interaction of the light and the particles under the study. This enhancement results in stronger fluorescence and in changes of the resonator parameters.

A spectroscopic technique for high-sensitivity, label-free DNA quantification was developed in [93]. It was demonstrated that a WGM excited in a micron-sized silica sphere can be used to detect and measure nucleic acids. The surface of the silica sphere is to be chemically modified with oligonucleotides.

A first-order perturbation theory was developed for WGMs in a dielectric microsphere [94], [95]. The theory were applied to three sensor applications of the microsphere to probe the medium in which the sphere is immersed: a refractive-index detector, an adsorption sensor, and a refractive-index profile sensor.

Biosensors based on the shift of WGMs in microspheres accompanying protein adsorption were described by use of a perturbation theory in [94]. For random spatial adsorption, theory predicts that the shift should be inversely proportional to microsphere radius a, and proportional to protein surface density and excess polarizability.

Hybrid zinc oxide/silica microdisk lasers were utilized to sense volatile organic compounds, such as toluene and nitrobenzene [96]. Nonspecific adsorption of these organic molecules onto the WGR surface causes an increase in the disk refractive index, ultimately resulting in a red shift of the observed lasing wavelengths.

Improvement of photonic WGM sensors using the fano-resonant line shape was proposed in [97]. Polystyrene microring resonators were fabricated by the nanoimprinting technique, and the optical spectra were measured in glucose solutions of different concentrations. The shift in resonant wavelength and variation of the normalized transmitted intensity were linearly related to the concentration of the glucose solution.

Application of WGRs in high field high frequency electron magnetic resonance measurements was discussed in [98].

F. Mechanical Sensors

High-Q WGMs result in increase in sensitivity of various mechanical experiments. For instance, WGMs could be used for the measurement of strain in optical fibers [48]. A two-resonator sensor of small displacements that utilizes high-Q and mechanical tunability of normal modes in coupled optical WGRs was proposed in [99].

An accelerometer utilizing high-Q WGRs was presented in [100]. Induced console displacements were monitored through changes in the resonance characteristics of a spherical optical cavity coupled to the flexure. Instantaneous measurement sensitivity of better than 1 mg at 250 Hz bandwidth, and a noise floor of 100 μg, were achieved.

The idea of usage of passive and active optical ring interferometers for detection of rotation was developed and implemented a couple of decades ago [101]–[103]. A miniature integrated WGM optical sensor for gyroscope systems was recently proposed [104]. It was predicted that the sensor may possess high enough sensitivity even on a millimeter size scale. A passive WGM gyroscope was discussed in [105]. The basic difference of the gyroscope compared with the existing ring resonator gyroscopes is in the usage of crystalline WGR instead of the usual ring resonator. The WGR-based gyroscope is expected to have much less backscattering and polarization rotation noises compared with conventional fiber-based gyroscopes.

G. Fundamental Physics With Passive WGMs

WGRs offer interesting possibilities from both classical as well as quantum points of view. High Q-factors as well as small mode volumes of WGMs result in a multitude of interesting and important phenomena. In this section, we discuss those phenomena related to "passive" WGMs, which do not lead to generation of light, leaving fundamental properties of WGM lasers and other active devices to a subsequent section.

1) Chaos: One of the fundamental problems is related to WGMs in an asymmetric WGR. It was shown that departure from an axial symmetry results in the occurrence of chaotic behavior of light in the resonator. This has been predicted to give rise to a universal, frequency-independent broadening of the WGRs, and to highly anisotropic emission [106]–[110]. A solution of the problem which confirms these predictions, but also reveals frequency-dependent effects characteristic of quantum chaos, was presented in [111]. It was shown that for small WGR deformations, the lifetime is controlled by evanescent leakage, the optical analog of quantum tunneling [112]. The problem of the directional emission from egg-shaped asymmetric resonant cavities was discussed in theoretical terms in [115].

The lifetime of light confined in a WGR can be significantly shortened by a process known as "chaos-assisted tunneling" [113]. Surprisingly, even for large deformations, some resonances were found to have longer lifetimes than predicted by the ray chaos model due to the phenomenon of "dynamical localization" [114].

Modes of partially-stable WGRs were discussed in [116] using a theory, where in exponentially suppressed tunneling interaction between regular and chaotic modes was considered as a perturbation. It was shown that chaos-assisted tunneling can lead to splitting of regular WGMs in asymmetric optical resonances. A theory of influence of the chaos-assisted tunneling on lifetimes and emission patterns of the optical modes in generic microresonators was developed in [117] using approach presented in [118].

The first experiment on chaos-assisted tunneling in a two-dimensional annular billiard was reported in [119]. Highly directional emission from WGMs was demonstrated in deformed nonaxisymmetric fused-silica "microspheres" [120].

2) "Photonic Atoms": Another fundamental area of application of WGRs is based on the ability of the resonators to mimic atomic properties. It was shown that WGMs can be thought of as classical analogy of atomic orbitals [121]. It was pointed out that WGM mode numbers correspond to angular, radial, and the azimuthal quantum numbers, respectively, the same as in the atomic physics. Such an approach resulted in introducing the term "photonic atoms" with respect to WGM resonators [122], [123]. "Photonic molecules," based on coupled WGRs, was studied in [124], [125].

3) Cavity QED: There is great activity in both theoretical and experimental investigations of cavity quantum electrodynamics [126]–[130] effects in WGRs. For instance, spontaneous emission processes may be either enhanced or inhibited in a cavity due to a modification of the density of electromagnetic states compared with the density in a free space [131], [132]. This effect was studied theoretically [133]–[135] as well as experimentally [136], [137] in WGRs.

Methods for control of atomic quantum state in atoms coupled to single-mode and multimode cavities and microspheres were discussed in [138]. Those methods include excitation, decay control, location-dependent control of interference of decay channels, and decoherence control by "conditionally interfering parallel evolutions."

Properties of atomic interaction with the field of a high-Q cavity was studied in [139] using "pseudomode" theory. It was shown that the theory can be derived by applying the Fano diagonalization method to a system in which the atomic transitions are coupled to a discrete set of cavity "quasimodes." The cavity modes decay into a continuum set of external "quasimodes." It was shown that each "pseudomode" can be identified with a discrete "quasimode," which contains structure to the actual reservoir.

Ponderomotive interaction of an atom and a WGM was discussed in [143], [140], [141], see also [142], [144], for review. In particular, it was shown that the external fields of optical WGMs may be used to confine atoms in stable orbits around a dielectric microsphere [143]. The bound state structure and dynamics for the atom trap were investigated in [140]. The dynamics of the center-of-mass of an ultracold excited atomic oscillator in the vicinity of a dielectric microsphere was studied in [141].

The ponderomotive interaction of an atom and photons confined in a WGM, can be used for quantum nondemolition measurements. It was shown [145]–[147] that the dipole force experienced by an atom in an off-resonant spatially inhomogeneous light field is quantized by the discrete nature of the photon. Similar schemes to perform quantum nondemolition detection of optical photons by observing the deflection of a beam of atoms flying close to an open dielectric resonator were proposed in the studies.

The ponderomotive interaction of an electron, instead of an atom, and photons in a WGM, was proposed for a quantum nondemolition measurement of photon number (the photon number is defined as the energy stored in the mode divided by $\hbar\omega_0$, where ω_0 is the frequency of the mode). The technique is based on the effect of quadratic scattering of electrons traveling along the resonator with a velocity close to the phase velocity of the wave in the resonator [148]. The measurement idea relies on the fact that an electron traveling along a bare dielectric waveguide (or surface of a WGR), at a velocity near the phase velocity, acquires a transverse momentum proportional to the photon energy of the light in the waveguide. It was noted that this momentum can be measured [149]. The scattering effect was analyzed with consideration for the waveguide (and WGM) dispersion, radiation friction, and the spurious Cherenkov radiation.

A radiative coupling of a nanoparticle/atom with a WGM was studied in [78], [150]; see also [130], [152] for a review. The possibility of strong coupling between a photon confined in a WGM and an atom was analyzed in [153]–[155]. The resonant interaction of an atom with dipolar $J = 0 \leftrightarrow J = 1$ angular-momentum transition with the quantized field in dielectric spheres and spheroids was studied in [153]. The possibility of the application of a microdisk WGR for the detection of a single trapped atom was studied in [156].

A measurements of cavity-QED effects for the radiative coupling of atoms in a dilute vapor to the external evanescent field of a WGM was reported in [78]. Experiments on the coupling of a single nanoemitter and WGMs were discussed in [150], [151].

A composite system consisting of a GaAs quantum well structure placed in the evanescent field of a fused silica microsphere, and evanescent coupling between excitons in the quantum well and WGMs of the composite system, was demonstrated in [157].

A composite system consisting of CdSeZnS nanocrystals and a fused-silica microsphere was demonstrated in [158]. The Q-factors of the system were of the order of 10^8, providing a model for investigating cavity QED and microlasers at the level of single quantum dots.

Optical properties of confined photon states in an extremely small spherical WGRs with sizes of $2\lambda < R < 10\lambda$ (dubbed "photonic dots") resonantly excited by photons emitted from semiconductor nanocrystals (the quantum dots) were studied in [159], [160] with particular focus on QED properties of WGRs containing CdSe quantum dots and quantum rods. Both glass and polymer WGRs were characterized by spatially and temporally resolved microphotoluminescence.

III. WGRs With Active Modes

Small volumes and high Q-factors of WGMs result in enhancement of nonlinear optical processes. Due to this enhancement, WGR based nonlinearoptic devices possess unique characteristics. For example, usage of WGMs allows the realization of lasers and wave-mixing devices with microWatt thresholds. Narrow linewidth of WGMs result in narrow spectral characteristics of the lasers. In this section, we review results of recent studies in the field.

A. Continuous-Wave (CW) WGM Lasers

Miniature lasers are among the most obvious applications of WGRs. The high quality factor of the resonators leads to the reduced threshold of the lasing. The first WGM lasers were realized in solid materials [161]–[163]. However, probably because of the lack of input-output techniques for WGMs, the work was discontinued at that point. The next development of the WGM-based lasers was in liquid aerosols and individual liquid droplets [164]–[169]. Finally, during the last decade, the lasers based on sole solid state WGRs were rediscovered, demonstrated experimentally, and intensively studied. In this section, we review recent results with WGR CW lasers, leaving WGR Raman lasers for Section III-B.

1) Lasing in Capillaries: The WGR laser can be realized in a cylindrical resonator. The simplest resonator of this kind is a capillary. The gain medium could reside inside the capillary, where WGMs are localized. For instance, laser emission from WGMs in a highly refractive dye-doped solvent flowing in a normally illuminated silica capillary fiber was demonstrated in [170]. The cylindrical WGM laser differs from the spherical droplet laser [164] in that it has an internal refractive index discontinuity. The light penetrates into the active medium if the refractive index of the medium is higher than the one of the capillary materials; e.g., no laser peaks are observed when the refractive index of the solvent is less than that of silica [170]. An example of microring lasing using CdSe nanocrystal quantum dots incorporated into microcapillary tubes was demonstrated in [171].

The lasing in a capillary based on the evanescent field coupling with the gain medium is also possible. The layered microcavity was realized in [172], [173] by flowing dye-doped ethanol through a thinwall fused silica capillary tube whose refractive index was larger than that of the liquid. The lasing spectrum showed a strong mode selection, and nearly even single constructive interference peaks, due to the interferential coupling of WGMs at the inner boundary. Various mode orders, which are not allowed in the ray optics picture, were made to oscillate due to the evanescent propagation of WGMs at the outer boundary. The estimated cavity quality factors were higher than 10^6. The lasing characteristics of resonance modes in a thin dye-doped dielectric ring cavity made on the inner wall of a cylindrical capillary were also studied in [174].

A WGM laser with pulsed optical pumping fabricated by surrounding a small section of a glass capillary with a solution of Rhodamine 6G, and by coupling the pump light into the capillary wall, was demonstrated in [175]. The lasing threshold pump energy was 100 nJ/pulse at a pump pulse duration of 6 ns.

2) Lasing in Doped WGRs: Another way to create a WGR laser is the use of solids doped with active elements; e.g., rare earth ions as a WGR host material.

A WGM laser based on neodymium-doped silica microspheres with a 200 nW threshold was realized [176] with microspheres of radius $a \sim 25$–50 μm, formed by heat-fusing the tip of a length of doped silica fiber. Neodymium ions provide a favorable four-level laser system that can be pumped on the $^4I_{9/2} -^4 F_{5/2}$ transition at ~810 nm with a diode laser. The laser transition $^4F_{3/2} -^4 I_{11/2}$ in the 1.06–1.09 μm range connects a long lived upper level to a lower level that is depleted by strong phonon relaxation so that population inversion is easily achieved. Similar experiments with a neodymium-doped silica microsphere laser operating at 2 K and absorbing 200 nW pump power were reported in [177]. CW laser oscillation on both the $^4F_{3/2} \rightarrow^4 I_{11/2}$ and $^4F_{3/2} \rightarrow^4 I_{13/2}$ transitions of Nd^{3+} ions in fluoride glass WGRs was also achieved [178]. Fabrication of Nd-doped tellurite glass WGRs and observations of laser oscillation corresponding to the optical transition $^4F_{3/2} \rightarrow ^4I_{11/2}$ at 1.06 μm was reported in [179].

A WGM laser utilizing a microsphere made of highly doped erbium:ytterbium phosphate glass was used to generate light at 1.5 μm [180]. Laser threshold pump power of 60 μW and fiber-coupled output power as high as 3 μW with single-mode operation were obtained. A bisphere laser system consisting of two microspheres attached to a single fiber taper was also demonstrated.

An Er^{3+}-doped tellurite glass L-band WGR laser was demonstrated and discussed in [181]. The microspheres were made by a "spin method." Fiber tapers were utilized to couple 975 nm pump into the sphere and couple generated light (1.56–1.61 μm) out of the sphere. The erbium ion concentration of the tellurite glass was 1.7×10^{20} ions/cm^3.

A green room temperature up-conversion laser was demonstrated in a 120 μm diameter microsphere of Er^{3+} doped ZBLAN [182], [183]. Lasing occurred around 540 nm with a 801 nm diode laser pump. The lasing threshold was 30 μW of absorbed pump power.

Experimental results on the realization and spectral characterization of Er:ZBLAN microspherical lasers at 1.56 μm were presented in [184], [185]. The lasing was obtained with the external 1.48 μm pumping. Multimode operation and a laser threshold as low as 600 μW were observed.

Green lasing having 4 mW threshold was demonstrated in an erbium-ion-doped fluoro-zirconate glass WGR [186]. Periodic narrow peaks of the emission spectra corresponding to the WGRs were observed.

An erbium-doped microlaser on silicon, operating at wavelength of 1.5 μm and characterized with pump threshold as low as 4.5 μW, was demonstrated in [187]. The 40-μm diameter toroidal laser WGR was made using a combination of erbium ion implantation, photolithography, wet and dry etching, and laser annealing, using a thermally grown SiO_2 film on a Si substrate as a starting material. Single mode lasing was observed.

Another erbium-doped high-Q silica toroidal WGR microlaser (25–80 μm in diameter) was demonstrated in [188]. The WGR was coupled with a tapered optical fiber. Erbium ion concentrations were in the range 0.009–0.09 at.%. Threshold pump power was as low as 4.5 μW.

A Tm^{3+}-doped tellurite glass WGR laser was discussed in [189]. The laser, pumped at 800 nm with a tapered optical fiber, oscillates in both the S band and the 1.9-μm band. The peak at 1.5 μm (S-band) corresponds to emission of the $^3H_4 \rightarrow ^3F_4$ transition, while the peak at 1.9 μm corresponds to the $^3F_4 \rightarrow ^3H_6$ transition.

Numerical analysis of a microdisk laser, taking into account full gain saturation effect and the vector character of the field, was presented in [190]. The authors suggested that Nd:YAG microdisk lasers are the excellent candidates for a light source for optical fiber communications operating at 1.064 and 1.3 μm. A theoretical study of the influence of deformation of a WGR on lasing properties was reported in [191].

3) Lasing in Coated WGRs: Instead of using doped materials, a passive WGR can be coated with gain medium. For example, erbium-doped solgel films were applied to the surface of silica microspheres to create low-threshold WGR lasers [192]. Lasing action in an ultra-high-Q spherical WGR coated with gain medium was reported in [193].

Lasing in a square cavity with round corners coated with poly methyl methacrylate and with Rhodamine 6G molecules, was studied in [194]. A thin gain layer was coated only on the outer boundary of cavity. The thickness of the gain layer varied from one micrometer to several micrometers.

Ultraviolet microdisk lasers on silicon substrate with a layer of zinc oxide gain medium grown on top of the silica microdisks were demonstrated in [195]. Lasing occurs in the WGRs at room temperature. The hybrid ZnO–SiO_2 WGR was optically pumped by the third harmonics (355 nm) of a mode-locked Nd:YAG laser with $\sim$10 Hz repetition rate and 20 ps pulse width. A microscope objective lens is used for focusing pump light on the resonator as well as for collecting the ultraviolet emission at $\sim$390 nm.

A WGM-enhanced inelastic emission from a monolayer of A488 fluorophores on the surface of a 9.8 μm WGR (polystyrene bead trapped in an optical trap) was observed and reported [196]. It was pointed out that it was likely that the WGM-enhanced emission is due to A488 lasing, with a lasing threshold between 0.29 and 0.87 W $\cdot$ cm^{-2}.

4) WGM Lasers With Semiconductor Gain Media: WGM-based lasers can be created with semiconductor quantum dots coupled to the WGMs. One of the most important problems here is fabrication of a single quantum dot microlaser. Such a microlaser made by capturing the light emitted from a single InAs–GaAs quantum dot in the WGM of a glass microsphere was proposed theoretically in [197]. A master equation model of a single quantum dot microsphere laser was described in [198]. The operation of a single quantum-dot-microsphere laser and a semiconductor microsphere bistable element was theoretically studied in [199].

A quantum dot-microcavity system consisting of CdTe nanocrystals attached to a melamine formaldehyde latex microsphere was realized experimentally [200]. The high optical transparency, and thermal and mechanical stability of melamine formaldehyde, make it interesting as a potential candidate in optical applications. The refractive index of melamine formaldehyde in the visible region ($n = 1.68$) is greater than that of silica ($n = 1.47$) or other glass materials ($n \approx 1.5$). Photoluminescence spectra of the microspheres covered by a thin shell of CdTe nanocrystals were studied in order to examine the emission intensity as a function of excitation power.

Ultralow-threshold (the pump was less than 2 μW) CW lasing was achieved at room temperature in a fused-silica microsphere that was coated with HgTe quantum dots (colloidal nanoparticles) [201].

WGRs can significantly improve operation of semiconductor quantum well lasers. A microlaser design based on the high-reflectivity WGMs around the edge of a thin semiconductor microdisk was described, and initial experimental results were presented in [202]. It was shown that optically pumped InGaAs quantum wells provide sufficient gain when cooled with liquid nitrogen to obtain single-mode lasing at 1.3 and 1.5 μm wavelengths with threshold pump powers below 100 μW.

A realization of an InGaAs–InGaAsP room temperature quantum well disk laser 1.6 μm in diameter and 0.18 μm in thickness, operating at 1.542 μm and using 0.85 μm optical pumping, was reported in [204]. Methods for directional coupling of light output from and to WGR microdisk lasers were described in [203].

An optically pumped, pulsed GaN microdisk laser operating at room temperature was created [205]. WGMs of the disk had linewidth as narrow as 0.1 nm. WGRs with diameters covering the range 25750 μm were tested. Optical pumping was performed perpendicular to the disk plane by the third harmonic (355 nm) or the fourth harmonic (266 nm) of a Q-switched Nd:YAG laser. The output light emission from these structures was collected by a reflecting objective located 80° from the surface normal, Quantum-cascade WGM disk lasers emitting at 9.5- and 11.5-μm wavelengths were reported in [206]. Taking advantage of the high-quality resonator ($Q \sim 200$), the threshold current density of disk lasers emitting at 9.5 μm was reduced to below the value of the corresponding ridge waveguide geometry.

A "microgear" laser composed of a microdisk and a rotationally symmetric Bragg grating was described in [207]. A GaInAsP-InP device with micron size was fabricated, and the room temperature CW operation was obtained by 17-μW pumping.

An optically pumped microdisc GaN-based laser was demonstrated in [208]. The optically pumped WGRs had distinct modes at excitation powers ranging from about 8 to 16 W $\cdot$ cm^{-2}. Quality factors for the microdisks were of the order of 4600. The observed lasing threshold was 12.1 W $\cdot$ cm^{-2}.

B. Resonator Modified Scattering

There are at least three scattering processes playing significant roles in WGRs. They are Brillouin, Rayleigh, and Raman scattering.

1) Brillouin Scattering: Stimulated Brillouin Scattering (SBS) was demonstrated in liquid droplets [209]–[218], though no SBS in high-Q solid WGRs was registered because of selection rules [215].

2) Rayleigh Scattering: Rayleigh scattering leads to the limitation of the Q-factor of WGMs as well as to the inter-mode coupling. The scattering is largely suppressed in high-Q WGRs because of restrictions imposed on scattering angles by cavity confinement, so very high-Q WGMs are feasible [219]. The scattering, on the other hand, couples initially degenerate counterpropagating modes in the WGRs and creates the intracavity feedback mechanism instrumental for the laser frequency locking application [74]. Rayleigh scattering mediated intracavity backscattering reaches 100%, as was shown theoretically [219] and demonstrated experimentally [220]. In the frequency domain, intracavity backscattering is observed as the splitting of initially degenerate WGM resonances and the occurrence of characteristic mode doublets [221], [222]. Influence of Rayleigh scattering on Q-factors of high refractive index contrast WGRs fabricated from silicon-on-insulator wafers was studied using an external silica fiber taper waveguide [223], [224].

3) Raman Scattering: Substantial optical power enhancement within a high-finesse optical cavity has recently yielded CW Raman lasers with low threshold and large tunability (see, e.g., [225], [226]). Such properties make cavity-enhanced CW Raman lasers attractive for high resolution spectroscopy, remote sensing, atomic physics, and telecommunications. Reducing the cavity size may further improve the performance of the lasers. Open dielectric spherical microcavities are promising for those purposes.

An enhancement of stimulated Raman scattering (SRS) is one of the effects demonstrated in spherical microcavities. Low threshold SRS was observed with pulsed [213], [227]–[233] and CW [234], [235] optical pumping in micrometer-size liquid droplets. Theoretical description of the process was presented in [236]–[239].

SRS was investigated in a liquid parahydrogen droplet characterized with WGM having Q-factor exceeding 10^9 [240]. The SRS was registered not only for vibrational transition but also for rotational transition as in the gas-phase H_2 system, leading to multiorder SRS sidebands covering the whole visible spectral range.

SRS in ultrahigh-Q surface tension-induced spherical and chip-based toroid microcavities is considered both theoretically and experimentally in [241]. These fused silica WGRs exhibit small mode volume (typically 10^3 μm^3) and possess whispering-gallery type modes with long photon storage times (in the range of 100 ns), significantly reducing the threshold for stimulated nonlinear optical phenomena.

The studies of Raman gain in isolated high-Q WGRs are important to understand cavity QED properties of Raman lasing. Previously, microcavity QED enhancement of Raman gain has been inferred as the result of measurements of a dependence of the SRS threshold on the size and material of the microdroplets, and its comparison with the values of SRS threshold reported for liquid core fibers having equivalent interaction length and core composition [234], [235]. This enhancement has been linked to the cavity modification of the properties of a usual laser. A theory of the Raman gain modification that explains the experimental results was developed [242], [243]. Recent experiments with silica microspheres have not shown any significant change in SRS gain which might be attributed to quantum effects [241], [244]. This issue was addressed in [245], where it was shown that no cavity QED-associated Raman gain enhancement exists, unlike the cavity enhancement of the spontaneous emission.

C. Switches and Modulators

1) WGM Switches: WGRs can be used as efficient and compact optical switches and modulators. Nonlinear optical switches based on WGMs are primarily considered in relation with their applications to all-optical computing. A possibility of such switching and applications of WGR to create a quantum mechanical computer was first recognized in [246].

The majority of studies of optical switches that utilize WGMs are theoretical. It was shown theoretically that WGR microdisk lasers are stable and switch reliably [247], and hence are suitable as switching elements in all-optical networks.

An integrated all-optical switch based on a high-Q nonlinear cylindrical microcavity resonator was proposed [248]. The switch consists of two planar waveguides coupled to a WGR. It was argued that due to the high-Q factor and the small dimensions, fast switching at low power is feasible for the devices based on presently available nonlinear polymers as the active material.

A general electrodynamical theory of a high-Q optical microsphere resonator in an external alternating magnetic field was reported in [249]. It was shown that that such a system can change a polarization state of the WGM photons confined in the sphere due to the Faraday effect. This property was proposed for use in all-optical switches and logical devices.

Numerical evaluation of an optical response of a prism-coupled nonlinear microsphere was discussed in [250]. The numerical results have shown that the control and/or the signal lights can induce the optical switching-like variation in the light reflectance. This effect was interpreted by the variation in the dielectric constant of the sphere due to its Kerr nonlinearity.

Coupled WGRs possess different and frequently more advanced properties compared to a single WGR. Sequences of optical microresonators can be used to construct integrated structures that display slow group velocity of light, ultrahigh or low dispersion of controllable sign, enhanced self-phase modulation, and nonlinear optical switching [251].

It was pointed out that there should be a reduction in switching threshold for nonlinear optical devices incorporating fiber ring resonators [252], [253]. The circulating power in such WGRs is much larger than the incident power, and the phase of the transmitted light varies rapidly with the single-pass phase shift. It was shown that the combined action of these effects leads to a finesse-squared reduction in the switching threshold [252], allowing for photonic switching devices that operate at milliwatt power levels in ordinary optical fibers. A set of coupled differential equations that describe Kerr nonlinear optical pulse propagation and optical switching in systems coupled by a few microresonators was derived in [254]. Gap-soliton switching in a system composed of two channel waveguides coupled by microresonators was studied in [255].

A numerical demonstration of the feasibility of constructing an all-optical "AND" gate by using a microresonator structure with Kerr nonlinearity was presented in [256]. It was shown that the gate can be much smaller than similar "AND" gates based on Bragg gratings, and has lower power requirements.

There are a few experimental studies of all-optical switches that utilize WGMs. For instance, laser-induced modification of cavity Q's was achieved in a microdroplet containing a saturable absorber [257]. The elastic-scattering spectra from such droplets for higher incident intensities show that cavity Q's are increased when the absorption is bleached. The lasing spectra from a droplet containing a saturable absorber and laser dye were modified when an intense bleaching field was injected into the droplet cavity after the pump field had initiated the lasing.

All-optical nonlinear switching in compact GaAs–AlGaAs microring resonators at the 1.55-μm wavelength was demonstrated in [258]. Switching was accomplished in the pump–probe configuration in which the pump–probe signals were tuned to different resonance wavelengths of the microring. Refractive index change in the microring due to free carriers generated by two photon absorption was used to switch the probe beam in and out of resonance.

An all-optical switching technique utilizing a silica microsphere optical resonator coated by a conjugated polymer was developed in [51]. A 250-μm-diameter silica microsphere was coated by dipping into a toluene solution of the polymer. WGM resonant frequency shifts as large as 3.2 GHz were observed when 405 nm pump light with a power density on the order of 10 W/cm^2 was incident on the microsphere. The time constant of the observed frequency shifts was approximately 0.165 s, leading us to attribute the frequency shift to thermo-optic effects. Such a system is capable of switching the WGM resonant frequency having 2 MHz linewidth at speeds on the order of 100 ms.

Finally, optical memory elements were developed using WGM devices. A memory element constructed by interconnecting WGM microscopic lasers was demonstrated in [259]. The device switches within 20 ps with 5.5-fJ optical switching energy. On the other hand, it was shown theoretically and demonstrated experimentally that a random distribution of spherical microparticles may be used as a spectral hole burning memory [122], [123].

2) WGM Modulators: Microwave cellular phone systems and personal data assistant networks require devices capable of receiving, transforming, and processing signals in millimeter wavelength domain [260]. Electrooptic modulators based on electromagnetic wave interaction in nonlinear optical cavities with high-Q WGMs will play an enabling role for these and similar applications.

An approach to create coupling between light and a microwave field in a WGR was recently proposed [80], [81]. In that study, an efficient resonant interaction of several optical WGMs and a microwave mode was achieved by engineering the shape of a microwave resonator coupled to a microtoroidal optical cavity. Based on this interaction, a new kind of electrooptic modulator, as well as photonic microwave receiver, was suggested and realized [261]–[268].

D. Optoelectronic Electronic Oscillator

Besides the sources of coherent optical radiation; i.e., lasers, optical WGRs can be used in sources of coherent microwave radiation. An optoelectronic oscillator (OEO) is an example of such a source. An OEO produces microwave signals using photonic techniques [62], [64]–[69]. The modulator is one of the main sources of power consumption in the OEO because of the large power required to drive the conventional modulators. Both broadband Mach–Zehnder modulators and free space microwave cavity-assisted narrow-band modulators typically require one to a few Watts of microwave power to achieve a significant modulation. This means that either the photocurrent in the OEO system should be amplified significantly, or a powerful laser should be used as the source of the drive power for the OEO.

An OEO based on a WGM resonant modulator was recently proposed and fabricated [269]. The device is characterized by low threshold and low power consumption. The disadvantages of the device are low saturation and low output power, and a possibility of transforming the noise of the light field into the microwave signal. In general, resonant and conventional OEOs have nonoverlapping characteristics and are both useful, depending on the application.

E. Pulse Propagation and Generation

It is convenient to distinguish between two regimes of optical pulse propagation in a WGR: 1) the pulse duration exceeds the inverse of the FSR of the cavity; and 2) the pulse duration is shorter than the inverse cavity FSR. Studies presented in [270]–[273] are primarily focused on the first regime. Specifically, the transient behavior of light intensity inside a dielectric sphere excited by a light pulse was discussed in [270], [271]. Long optical pulses were used for pumping of polymer microlasers [272]. Linear and nonlinear optical properties of waveguide coupled WGRs has also been studied theoretically [273]. The second case, propagation of short pulses in WGRs, was also examined [274]–[276], [278], and a general theoretical analysis of the propagation was presented in [274]. Time resolved measurements of picosecond optical pulses propagating in dielectric spheres [275] and subpicosecond terahertz pulse propagation in a dielectric cylinder [276], [277] were recently reported, and microcavity internal fields created by picosecond pulses was discussed theoretically [278]. The behavior of ultrashort light pulses coupled into the resonant modes of spherical microcavities was explored in [279]. A noninvasive pulse-tracking technique was exploited to observe the time-resolved motion of an ultrashort light pulse within an integrated optical microresonator [280].

The minimum pulse width, as well as the period of the optical pulse train generated by a system that involves a high-Q cavity, is determined by the resonator dispersion. Depending on the dielectric host material and the geometric size, a WGR may possess either a positive, negative, or zero group velocity dispersion (GVD) [281]. This dispersion is important when the pulse duration is shorter than the inverse cavity FSR. Resonators possessing a positive group velocity dispersion may be used for GVD compensation in optical fiber links. Negative GVD cavities with Kerr nonlinearity (e.g., fused silica cavities) sustain nonlinear Schrodinger soliton propagation, and may be used for pulse shaping and soliton shortening in conventional mode-locked lasers (see, e.g., [282]–[284]). Zero GVD cavities may be used as high-finesse etalons to stabilize actively mode-locked lasers (as in [285]). Integrated optical WGM all-pass filters can also be used for tunable dispersion compensation in the optical transmission line if the pulse duration exceeds the inverse of the FSR of the resonator [251], [286].

Small resonators, like WGRs, are important for the stable generation of optical pulses with high repetition rates. This is confirmed by the experiments with planar, not WGM, small resonators. For example, 2-ps pulses at a 16.3-GHz repetition rate were obtained for a 2.5-mm-long actively mode-locked monolithic laser [287]; 420 GHz subharmonic synchronous mode locking was realized in a laser cavity of total length of approximately 174 μm [288]. A significant supermode noise suppression was demonstrated by inserting a small high-finesse Fabry–Perot resonator to the cavity of an actively mode-locked laser [285], [289].

It was proposed to use WGRs to generate short optical pulses [281], [290]. The idea of this laser is based on two recently realized WGM devices: the electrooptic modulator, and the erbium-doped microsphere glass laser [80], [180], [183], [186], [192].

It is also known that an electrooptic modulator placed in an optical resonator can generate a frequency comb [291]–[294], and that the output of such a device is similar to that of a mode-locked laser. However, unlike the mode-locked laser, the pulse duration is not limited by the bandwidth of the laser gain because the system is passive. The pulse width decreases with the modulation index increase, and with the overall cavity dispersion decrease. The modulation index may be very large in a WGM modulator, which may significantly improve the performance of the system [281].

F. Wave Mixing and Oscillations

WGRs were used in optical parametric as well as hyperparametric wave mixing processes.

1) Hyper-Parametric Oscillator: Hyperparametric optical oscillation [295], also known in fiber optics as modulation instability [296], is based on four-wave mixing (FWM) among two pump, signal, and idler photons, and results in the growth of the signal and idler optical sidebands from vacuum fluctuations at the expense of the pumping wave. The hyperparametric oscillations are different from the parametric ones. The parametric oscillations 1) are based on $\chi^{(2)}$ nonlinearity coupling three photons, and 2) have phase matching conditions involving far separated optical frequencies that can only be satisfied in birefringent materials in the forward direction. In the contrast, the hyperparametric oscillations 1) are based on $\chi^{(3)}$ nonlinearity coupling four photons, and 2) have phase matching conditions involving nearly-degenerate optical frequencies that can be satisfied in most of the materials, both in the forward and backward directions.

Recently, the study of hyperparametric oscillations had a new stage connected with the development of WGM, as well as photonic crystal microresonator technology [297], [8]. The oscillations occurring in cavities, or cavity-like systems filled with transparent solids, were analyzed theoretically; e.g., in isotropic photonic crystals [298], and were observed experimentally in crystalline WGM resonators [299], [300]. It was suggested, in particular, that the narrow-band beat-note signal between the optical pump and the generated sidebands emerging from a high-Q WGM resonator could be used as a secondary frequency reference [300], [301].

The phase stability of the frequency reference signal increases with increase of the Q-factor of the resonator modes for the same given value of the pump power. There exists a maximum of the phase stability (minimum of the phase diffusion) of the beat-note signal that does not depend either on the pump power or Q-factor of the modes. Keeping in mind that WGMs Q-factor can exceed 10^{10} (a few tens of kilohertz resonance linewidth) [61], it was found that the Allan deviation factor of the oscillations is smaller than 10^{-12} $s^{-1/2}$ for sub-milliwatt optical pumping. The pump threshold could reach microwatt levels for reasonable experimental parameters.

2) Parametric Processes: Optical parametric oscillators (OPO) have been extensively studied since the discovery of lasers [302]–[304]. Properties of OPO are well understood by now [305], [311], [312], [295], [59]. The CW-OPO is considered an ideal device that can generate a broad range of wavelengths.

Efficient frequency doubling at $\lambda = 1.55$ μm and $\lambda = 1.319$ μm was realized [57] using the same WGR made of periodically poled $LiNbO_3$ (PPLN) [306]. The WGR was doubly resonant, both at fundamental and second harmonic frequencies. The follow up studies of the parametric processes in PPLN WGRs are important because it has been predicted that an optical parametric oscillator based on the resonator might have a power threshold below a microwatt [307]—orders of magnitude less than that of the state-of-the-art OPOs, typically at 0.5 the milliwatt level [308].

It was shown theoretically [309] that a nondegenerate multifrequency parametric oscillator has different properties compared with the usual three-wave parametric oscillator. A scheme for a resonant CW monolithic microwave-optical parametric oscillator based on high-Q WGMs excited in a nonlinear dielectric cavity was suggested. Such an oscillator may have an extremely low threshold and stable operation, and may be used in spectroscopy and metrology. The oscillator mimics devices based on resonant $\chi^{(3)}$ nonlinearity (hyperparametric process) and can be utilized for efficient four-wave mixing and optical comb generation.

G. Fundamental Physics With Active WGMs

WGRs can be used for generation of nonclassical states of light. For instance, the possibility was shown for the generation of heralded single photons and of sub-Poissonian laser light in the electrically pumped single quantum dot microsphere laser [198].

The reduced density matrix method was used to calculate the quantum-statistical properties of the radiation of a quantum dot laser operating on the WGM of a dielectric microsphere [310]. It was shown that under the conditions of strong coupling between the quantum dot and an electromagnetic field, the radiation of such a laser can be in a nonclassical (sub-Poissonian) state. The laser scheme was characterized by an extremely low lasing threshold and a small number of saturation photons; consequently, lasing is possible with close to zero population inversion of the working levels.

IV. Conclusion

In this review, we have covered recent developments in the applications of whispering gallery mode resonators in optics and photonics. We have tried to mention all the activities in the field, though we admit that some of the recent advances could have escaped our attention because the area grows very fast, and each month brings new studies related to the subject.

Though whispering gallery modes are interesting physical objects by themselves, we foresee the fastest growth in their practical applications. Filters, modulators, lasers, and other whispering gallery mode devices have multiple advantages over their "ordinary" counterparts.

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