Whispering gallery mode lithium niobate micro-resonators for photonics applications

Lute Maleki, Anatoliy A. Savchenkov, Vladimir S. Ilchenko, and Andrey B. Matsko

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099

ABSTRACT

We review various photonics applications of whispering gallery mode (WGM) dielectric cavities and focus on possibilities of generation of trains of short optical pulses using WGM lithium niobate cavities. We introduce schemes of optical frequency comb generators, actively mode-locked lasers, and coupled opto-electronic oscillators where WGM cavities are utilized for the light amplification and modulation.

Keywords: Whispering Gallery Modes, Electro-Optical Modulator, Mode-Locked Laser, Coupled Opto-Electronic Oscillator

1. INTRODUCTION

Photonics technology has the potential to significantly improve spacecraft communications system by increasing performance, reducing size and power requirements, and thus the associated costs. In the past decade limited use of capabilities associated with the higher performance of optical techniques has been demonstrated in space. For example, in a Space Shuttle experiment for synthetic radar mapping, the use of photonics techniques provided the needed flexibility to deploy a 60 m boom.

Space communications systems require efficient means to receive and transmit data at ever increasing rates. This requirement has led to the development of systems that operate at microwave frequencies in excess of 10 GHz, to improve antenna beam pointing and efficiency requirements, as well as provide larger communications bandwidth. Such architectures are being planned for earth orbiting, as well as deep space probes. In particular, architectures for satellite to satellite communications are being considered that have requirements similar to that of deep space probes being linked to planetary landers, rovers, and orbiters.

Photonics links are fundamentally efficient because of high efficiency lasers, waveguides, and detectors. But the advantage of photonics systems extends beyond link efficiency and includes signal processing functions. In particular, several approaches based on photonics techniques are under development for both analog and digital processing of communications signals. These include functions ranging from direct downconversion of analog signals to photonic A/D conversion. These approaches allow for the extension of the of photonics system to the entire communications systems including the transmission/receive links and data processing.

A major challenge in implementing such systems in spacecraft communications is the development of extremely efficient components that can serve as the building blocks. Our research at JPL has been directed to address this challenge. In particular, we have developed novel sources such as Opto-Electronic Oscillators (OEO) and Coupled Opto-Electronic Oscillators (COEO) for high spectral purity and low jitter sources at frequencies greater than 10 GHz.[1–5] We have also developed ultra-high Q optical domain RF filters,[6–8] and ultra-high efficiency modulators and photonic microwave receivers[9–11] to enable signal processing functions. Our studies, along with similar studies of other groups, that involve filters,[12] OEO and COEO,[13–17] and modulators[18–21] demonstrate great potential of photonic devices for planetary explorations applications, where orbiters, landers, and rovers require low power, low mass, and high efficiency communications.

In this paper we focus on photonic applications of optical resonators supporting optical whispering gallery modes (WGM) which recently have attracted considerable attention. Combinations of very high Q-factor (typically $10^6 - 10^9$ depending on the material) and small physical dimensions makes these resonators attractive

Send correspondence to A.B.Matsko: Andrey.Matsko@jpl.nasa.gov

new components for photonics applications. Effective methods of coupling light into and out of WG modes in microspheres have been developed, including the "pigtailing" technique for WGM cavities[22, 23] and technique of coupling of the cavities and semiconductor lasers,[24] which significantly simplify the design of practical devices based on these resonators.

Novel applications of the WGM photonics based devices, demonstrated recently at JPL and in other laboratories, provide a compelling argument for implementing more capabilities based on this technology in space communications system. In this regard propagation of short optical pulses through nonlinear WGM cavities and their application for mode-locking becomes an important issue.

First of all, electro-optical modulator is one of the most important parts of an actively mode-locked laser. It has been demonstrated that WGM cavities made of a nonlinear optic material are the basis of efficient electro-optic modulators.[9–11, 18–21] Motivation for the optical cavity-based modulator stems from the requirement of relatively large powers required to drive conventional modulators. Both broadband integrated Mach-Zender modulators and free space RF cavity-assisted narrow-band modulators require about one Watt of RF power to achieve a significant modulation index. By utilizing high-Q resonance instead of zero-order interferometry or polarization rotation as the principle for electro-optic modulation, one can potentially reduce the controlling power by many orders of magnitude, at the expense of a limited bandwidth that is nevertheless adequate for a number of applications. Optical losses in lithium niobate are small enough to allow for relatively high Q of whispering-gallery modes. Hence, even small voltages applied across the area of optical field confinement is enough to provide displacement of WGM resonance by an amount comparable to its bandwidth. This is a basis for efficient modulation.

In our previous work, we demonstrated a prototype of such an electro-optic modulator in the X-band (at 9 GHz), and also presented some preliminary data on the prototype working in the Ka-band (at 33 GHz). For high-speed modulation at radio frequencies exceeding the optical resonance bandwidth the frequency of applied electrical field has to coincide with the separation between adjacent whispering-gallery modes. This process requires phase matching conditions to be fulfilled. We achieve phase matching by optimal design of the microwave cavity.

Therefore, a mode-locked laser based on a WGM modulator may possess advanced properties due to the advanced properties of the modulator.

On the other hand, usage of short cavities is important for establishing stable generation of optical pulses with high repetition rates. The dense mode spectrum and nonlinearity of long fiber ring cavities results in various kinds of instabilities. For instance, an optical soliton becomes unstable as the soliton-laser cavity approaches the length of several soliton periods.[25, 26] Long cavity based harmonically mode-locked oscillators suffer from the supermode noise.[27] Short cavities allow for solution of those problems. 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[28]; 420 GHz subharmonic synchronous mode locking was realized in a laser cavity of total length approximately 174 μm.[29] 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.[30, 31]

Pulse propagation in WGM resonator was intensively studied. It is convenient to distinguish between two regimes of optical pulse propagation in a microresonator: i) the pulse duration exceeds inverse free spectral range (FSR) of the cavity, and ii) the pulse duration is shorter than the inverse cavity FSR. Studies presented in[32–35] are primary focused on the first regime. Namely, transient behavior of light intensity inside a dielectric sphere excited by a light pulse was discussed in.[32, 33] Long enough optical pulses were used for pumping of ring conducting polymer microlasers.[34] Linear and nonlinear optical properties of a waveguide consisted of side-coupled spaced sequence of WGM resonators was theoretically studied.[35]

The second case, propagation of short pulses in WGM cavities, was also studied.[36–39] Namely, general theoretical analysis of the propagation was presented in.[36] Time resolved measurements of picosecond optical pulse propagation in dielectric spheres[37] and subpicosecond terahertz pulse propagation in a dielectric cylinder[38] were recently reported. Microcavity internal fields created by picosecond pulses was discussed theoretically.[39]

The minimum pulse width as well as timing that characterizes an optical pulse train generated by a system that involves a high-Q cavity is determined by the cavity dispersion. In this paper we show that, depending on the dielectric host material and geometrical size, WGM cavity may possess either positive, or negative, or zero group velocity dispersion (GVD). Cavities possessing positive group velocity dispersion may be used for GVD compensation in optical fiber lines. Negative GVD cavities sustain nonlinear Schrodinger soliton propagation and may be used for pulse shaping and soliton shortening in conventional mode-locked lasers (see, e.g.[42–44]). Zero GVD cavities may be used as high-finesse etalons to stabilize actively mode-locked lasers (as in[31]).

We propose to use WGM electro-optical modulator for generation of short optical pulses by a direct conversion of a continuous laser beam into a stable pulse train. It is known that electro-optical modulator placed in an optical cavity may generate an optical frequency comb.[45–48] The output of such a device is similar to that of a mode locked laser. However, unlike to 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 overall cavity dispersion decrease. The modulation index may be very large in a WGM modulator, that may significantly improve performance of the system.

We propose a scheme of an actively mode locked laser where a WGM cavity fabricated from a nonlinear dielectric material with quadratic nonlinearity is used for the light modulation. The pulses generated by the laser may reach sub-picosecond duration and have several hundred GHz repetition rate.

We also propose an architecture of an advanced monolithic integrated mode-locked source based on WGM dielectric cavity. This source would generate low jitter picosecond optical pulse trains with repetition rate up to 100 GHz, consume low microwave power, and have low oscillation threshold. The active element would have several millimeter in size and it would not need any active control of the optical cavity length. The idea of this laser is based on two recently realized WGM devices: electro-optical modulator and Er-doped microsphere glass laser.[23, 49–52]

Finally, we show that WGM electro-optical modulator may improve performance of a coupled opto-electronic oscillator. The main advantage of the WGM OEO is that it also play a role of a photonic filter that stabilizes the system.

2. DISPERSION AND ABSORPTION OF A WGM CAVITY

To study a pulse propagation in a WGM cavity one needs to find the cavity mode dispersion. We do it following.[36] Let us compare a ring cavity made of a dispersive dielectric fiber and a solid WGM cavity fabricated from a dispersionless transparent dielectric material. The cavities are expected to have the same radius R. We estimate parameters of the fiber to make the cavities be identical, in the sense that mode frequency differences $\omega_{\nu+1}-\omega_\nu$ and $\omega_{\nu+1}+\omega_{\nu-1}-2\omega_\nu$ should be the same for both cavities, $\nu \gg 1$ is the mode number (here and in what follows we are talking about the main sequence of WGM modes).

Frequency of the WGMs in a spherical dielectric cavity may be estimated as[40]

$$\frac{n_0}{c}\omega_\nu \simeq \frac{\nu}{R}\left[1+\frac{1.86}{\nu^{2/3}}\right]. \tag{1}$$

It is easy to find

$$\frac{n_0}{c}(\omega_{\nu+1}-\omega_\nu) \simeq \frac{1}{R}\left[1+\frac{0.62}{\nu^{2/3}}\right], \tag{2}$$

$$\frac{n_0}{c}(\omega_{\nu+1}+\omega_{\nu-1}-2\omega_\nu) \simeq -\frac{1}{R}\frac{0.41}{\nu^{5/3}}. \tag{3}$$

For a fiber-made cavity the resonant mode frequencies may be found from

$$\frac{n_{\omega_\nu}}{c}\omega_\nu = \frac{\nu}{R}. \tag{4}$$

To estimate similar values for this cavity we use a conventional decomposition

$$\frac{\omega}{c}n(\omega) \simeq \frac{\omega_0}{c}n_0 + \beta'(\omega-\omega_0) + \frac{1}{2}\beta''(\omega-\omega_0)^2, \tag{5}$$

where

$$\beta' = \frac{1}{v_g} = \frac{1}{c}\left(n + \omega\frac{dn}{d\omega}\right), \tag{6}$$

$$\beta'' = \frac{1}{c}\left(2\frac{dn}{d\omega} + \omega\frac{d^2n}{d\omega^2}\right), \tag{7}$$

v_g is a group velocity in the fiber. Then

$$\omega_{\nu+1} - \omega_\nu \simeq \frac{1}{R\beta'}, \tag{8}$$

$$\omega_{\nu+1} - 2\omega_\nu + \omega_{\nu-1} = -\frac{\beta''}{R^2\beta'^3}. \tag{9}$$

Therefore, the parameters of a fiber that results in the same mode structure in a ring cavity as a solid WGM cavity are

$$\beta' = \frac{n_0}{c}\left[1 + \frac{0.62}{\nu^{2/3}}\right]^{-1}, \tag{10}$$

$$\beta'' = \frac{n_0}{c\omega_\nu}\frac{0.41}{\nu^{2/3}}, \tag{11}$$

where we use $n(\omega_\nu) = n_0$.

It is useful to estimate now the second order dispersion coefficient and compare it with that of a fiber. In fiber-optic literature dispersion parameter D is commonly used. We have for WGM

$$D = -\frac{2\pi c}{\lambda^2}\beta'' = -\frac{n_0}{\lambda c}\frac{0.41}{\nu^{2/3}}.$$

For usual parameters such as $\nu = 5000$, $\lambda = 1.55$ μm, and $n_0 = 1.47$ we have $D = -6$ ps/(km nm). This value is comparable with the dispersion of usual optical fiber.

The *geometrical* dispersion of the cavity is *normal*. It means that longer wavelength pulses travel faster. It might be explained by the fact that longer wavelength modes are localized deeper in the microsphere and, therefore, their path is shorter.

It worth noting that the *material* dispersion together with the *geometrical* dispersion of the cavity may result in positive as well as negative group velocity dispersion. Really, the effective group velocity dispersion coefficient for a WGM cavity modes is

$$\beta''_{eff} = \beta'' + 0.41\left(\frac{n_0\lambda^5}{32\pi^5c^6R^2}\right)^{1/3}. \tag{12}$$

where β'' is the host material dispersion. It is easy to see that for large enough cavity the input of the geometrical part of the cavity dispersion may be smaller than the material dispersion. For example, for silica microcavity ($\beta'' \simeq -25$ ps^2/km) the zero dispersion point in the vicinity of the carrier wavelength $\lambda = 1.55$ μm is achieved for $R \approx 350$ μm (approximately 100 GHz FSR). If the radius of the cavity exceeds this value, the dispersion of the cavity is negative. For instance, for cavity FSR equal to 10 GHz, the cavity radius $R \approx 3.23$ mm, so that $\beta''_{eff} \simeq -20$ ps^2/km. Stable propagation of nonlinear Schrodinger solitons is possible in the cavity with negative dispersion.

Usage of glass ($\beta'' \simeq -42$ ps^2/km), for example, allows one to shift zero dispersion point to $R \approx 157$ μm. These properties of WGM along with the efficient broadband techniques of coupling of the dielectric cavities and optical fibers[22–24] makes WGMs attractive for shaping optical pulses.

To find dispersion of $LiNbO_3$ we use Sellmeier's equation[53]

$$n_0^2(\lambda) = a_1 + \frac{a_2}{\lambda^2 - a_3^2} + a_4\lambda^2, \tag{13}$$

where λ is the free-space wavelength (nm), and a_i are fit parameters. For a stoichiometric crystal of $LiNbO_3$ and extraordinary polarization of light $a_1 = 4.5567$, $a_2 = 9.7 \times 10^4$, $a_3 = 201.$, and $a_4 = -2.24 \times 10^{-8}$. For ordinary polarization of light $a_1 = 4.931$, $a_2 = 1.173 \times 10^5$, $a_3 = 212.$, and $a_4 = -2.78 \times 10^{-8}$. Eq. (13) with the listed above values of the fitting coefficients is valid at temperature $t_0 = 24.5^o C$. This gives rather large dispersion value $\beta'' \simeq -500$ ps^2/km for $LiNbO_3$ at $\lambda = 1.55$ μm. For such a large material dispersion the geometrical dispersion of a millimeter-size WGM cavity introduces almost negligible contribution to the total dispersion. For longer wavelength $\lambda \approx 1.7$ μm, however, the dispersion crosses zero axis.

The dispersion of WGMs may also be modified by usage of graded-index materials for cavity fabrication,[41] so zero-dispersion point may be efficiently shifted:

$$\beta''_{eff} = \beta'' + 0.41 \left(\frac{n_0 \lambda^5}{32 \pi^5 c^6 R^2} \right)^{1/3} \left(1 - \frac{R}{2} \frac{\epsilon'}{n_0^2} \right)^{2/3}, \tag{14}$$

where we assumed that the susceptibility of the cavity material is radially inhomogeneous and has radial distribution $\epsilon = n_0^2 + \epsilon'(R - r)$, for $R > r > R - R/\nu^{2/3}$, and $\epsilon' < 2n_0^2/R$.

The absorption per round trip in the cavity may be found from expression

$$l = \frac{2\pi\nu}{Q}, \tag{15}$$

where Q is the quality factor of the mode. Taking $Q = 10^5$ we get $l = 0.006$.

3. OPTICAL COMB GENERATION WITH A WGM ELECTRO-OPTICAL MODULATOR

Optical frequency comb generators are usually based on an intracavity electro-optical modulator. Such devices can produce picosecond or even sub-picosecond optical pulses.[48] The devices can be small in size. The operation frequency is determined by the pump laser so short optical pulses can be produced in a broad range of wavelengths using the same comb generator and changing pump lasers. The repetition rate of the pulses may be very high and, unlike to an active mode-locked laser, it is equal twice the EOM modulation frequency.

EOM based on a WGM cavity[11] may produce a comb of optical harmonics in the same fashion as conventional EOMs do. Because of a high finesse of WGMs and small geometrical dispersion introduced by the cavity structure compared with the material dispersion (see previous section) the number of harmonics may be as large as in a Fabry-Perot resonator with a conventional EOM inside.

The optical lithium niobate cavity is placed between two plates of microwave resonator Fig. (1). The resonant frequency of the microwave field can be adjusted to fit the frequency difference between optical modes by change of the microwave resonator shape. Due to $\chi^{(2)}$ nonlinearity of $LiNbO_3$ the modes of the microwave resonator and optical cavity are effectively coupled. This coupling increase significantly for resonant tuning of the fields due to high quality factors of the modes of optical cavity and microwave resonator as well as small mode volumes.

A peculiarity of the device is that the microwave field is excited in a microwave resonator and the amplitude of the field changes along the rim of the cavity, not only in time, as in usual short modulators. This geometry allows us to achieve an efficient modulation and interaction among cavity modes.[11]

Let us assume that the length of a pulse that propagates in a WGM modulator is much smaller than the modulator length. Than the round trip transmission through the modulator is given by

$$e^{i\delta(t)} = \exp \left[\frac{i}{2} \omega_0 n_0^2 r_{eff} \int_0^{\pi/\omega_M} E_M(\tau, t) d\tau \right], \tag{16}$$

where t characterizes the time of entrance of the pulse into the modulator, $E_M(\tau, t)$ is the microwave electric field that the pulse sees, r_{eff} is the electro-optic constant of the material. The electro-optic constant is not necessary

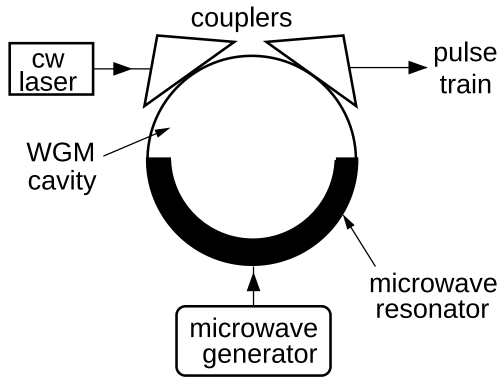

Figure 1. A schematic of a whispering-gallery mode optical frequency comb generator.

coincides with r_{33} because we may use either TE or TM modes, and the electric field in the resonator may be not exactly aligned with z direction due to boundary effects for the microwave cavity.

The electric field that short pulse sees at time τ in the modulator may be approximated as

$$E_M(\tau,t) = E_{M0}\sin\left(\frac{\pi}{2} - \omega_M\tau\right)\cos\left[\omega_M(\tau+t)\right], \qquad (17)$$

where the " cos " term appears due to temporal modulation of the field, and " sin " results from the pulse motion in the microwave resonator. Eq. (17) shows, for example, that the maximum modulation is on the boundaries of the resonator and there is no modulation in the middle of the resonator. The amplitude of the electric field may be presented as

$$E_{M0} = \sqrt{\frac{8\pi W_M Q_M}{\epsilon_M \omega_M V_M}}, \qquad (18)$$

where W_M is the microwave power feeding into the resonator, Q_M is the quality factor of the microwave resonator, ϵ_M is the susceptibility of $LiNbO_3$ at the microwave frequency, and V_M is the volume of the microwave resonator.

Substituting (17) into (16) we derive

$$e^{i\delta(t)} = e^{2i\delta_e \cos\, \omega_M t}, \qquad (19)$$

where

$$\delta_e = \frac{\pi}{8}\nu n_0^2 r_{eff} E_{M0}. \qquad (20)$$

We should note here, that we come to the expression similar to the expression used for a description of short cavity modulators implemented in a mode-locked laser cavities. Therefore, even in the case of long modulator the conventional mode locking theory[54, 55] is valid. In our case t is the relative time of entrance of the pulse into the modulator. In accordance with usual FM mode locking theory, a pulse should enter the modulator at the point of maximum field amplitude $\cos\, \omega_M t = \pm 1$.

Let us find the numerical value for δ_e for the parameters used in the experiment.[11] Taking $r_{eff} = 10^{-11}$ m/V $= 3\times 10^{-7}$ CGS, $V_M = 10^{-4}$ cm^3, $W_M = 1$ mW $= 10^4$ erg, $\nu = 5000$, $n_0 = 2.14$, $\epsilon_M = 29$, $\omega_M = 2\pi \times 10$ GHz, and $Q_M = 100$, we get $\delta_e = 10^{-3}$.

The value of power of a k^{th} sideband generated by the EOM (W_k) operating in an unsaturated regime may be estimated from[45]

$$W_k \simeq W_0 \exp\left(-\frac{\pi|k|}{\delta_e F}\right), \qquad (21)$$

where k is a number of harmonic, δ_e is a single pass modulation coefficient (see Eq. (19)), F is the finesse of the cavity, and W_0 is the optical pump power.

The number of the sidebands is restricted by the cavity dispersion. In approximation $F \to \infty$ the maximum frequency span of the generated harmonics is[47]

$$2\pi\delta f_1 \simeq \left(\frac{\delta_e}{\beta''\pi R}\right)^{1/2}, \tag{22}$$

where we assumed that the length of the EOM is approximately πR.

It is possible to propose another estimation for the maximum frequency span if modulation coefficient δ_e is small enough and the finesse of the cavity is finite[41]:

$$2\pi\delta f_2 \simeq \frac{c}{n_0 R}\left|\frac{\omega_0}{2Q(\omega_{\nu+1} - 2\omega_\nu + \omega_{\nu-1})}\right| \simeq \frac{n_0}{2F\beta''c}, \tag{23}$$

Both estimations show possibility of generation of wide spectra corresponding to a trains of picosecond pulses in the system.

4. ACTIVELY MODE-LOCKED WGM LASERS

WGM electro-optical modulators can improve performance of actively mode locked lasers because the EOMs produce significant modulation with low power microwave pump at very high microwave frequencies. The modulator not only modulates light, it plays a role of an etalon if it is placed in a long cavity of a mode-locked laser (see Fig.(2)). However, because of high optical quality factors of WGMs, the WGM cavity itself may be used as a laser cavity. The active medium may be connected to the cavity either internally, via doping lithium niobate, or externally.[24] In this section we focus on this case because usage of a WGM cavity as a laser cavity will allow one to produce compact fundamentally mode-locked lasers (see Fig. 3).

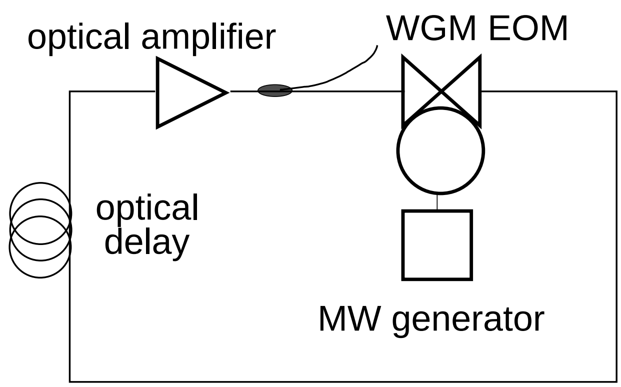

Figure 2. A schematic of a conventional actively mode-locked laser with a whispering gallery mode electro-optical modulator.

There is a significant difference between construction of phase modulator in our case compared with the modulators described in[54, 55] and other studies where time dependent description of mode locking was used. In those works the length of the modulator was much shorter than the length of the pulse round trip in a cavity. Therefore, it was possible to assume that the interaction time of the pulse and the modulator is short enough and use this fact for a decomposition of the expression for the modulator response by a small parameter $\omega_M t$, where ω_M is the modulation frequency, and t is the interaction time.

In our case a pulse travels a half of its round trip time in the modulator, i.e. $\omega_M t \simeq \pi$. The same condition is valid in the experiments with Er:Ti:$LiNbO_3$ mode locked lasers[58] where length of the modulator is comparable with the path length of a pulse. In the theoretical description of such a mode locking[59] floquet theory was used. This theory is powerful for numerical simulations, however it does not give a clear analytical expression for the pulse parameters. We have shown in the previous section how to modify the problem of a long modulator mode locked laser to solve it analytically.

The active medium is responsible for the lasing itself (amplification of the signal); for the absorption of the pump and, therefore, for the reduction of the effective quality factor for the whispering gallery mode the pump interacts with; and, finally, for the filtering of the signal pulses. Erbium and semiconductor optical amplifiers may be used as an active medium. Erbium amplifiers may be characterized by homogeneous linewidth $\delta\lambda \approx 10$ nm or, in frequency units, $\Gamma \approx 2\pi \times 1.2 \times 10^{12}$ rad/s.[60] Gain linewidth of semiconductor amplifiers may be approximately $\delta\lambda \approx 40$ nm or, in frequency units, $\Gamma \approx 2\pi \times 5 \times 10^{12}$ rad/s.[61]

We assume that the pulses are much longer than the inversed homogeneous gain linewidth. In this case the amplitude gain may be presented in form[54, 55]

$$g(\omega) \simeq e^{g} \exp\left[2i\frac{g}{\Gamma}(\omega-\omega_0) - \frac{g}{\Gamma^2}(\omega-\omega_0)^2\right], \tag{24}$$

where g is the saturated amplitude gain through the active medium at the line center for one round trip in the cavity. We estimate duration of the pulses generated in the system using an expression from[54]

$$\delta t = \frac{\sqrt{2\sqrt{2}\,\ln 2}}{\pi}\left(\frac{g}{\delta_e}\frac{(2\pi)^4}{\Gamma^2\omega_M^2}\right)^{1/4}. \tag{25}$$

Assuming that $g \simeq l = 0.006$, $\delta_e = 0.001$, $\Gamma \approx 2\pi \times 1.2 \times 10^{12}$ rad/s, and $\omega_M = 2\pi \times 10$ GHz we obtain $\delta t \approx 6$ ps. This value may be further reduced if higher modulation frequency is used, that is possible with WGM modulators.[11] For example, for 100 GHz modulation/repetition rate we will have 2 ps pulses. For the mode-locked laser with semiconductor amplifier the pulse duration may be 0.9 ps. Increasing of the microwave power sent to the WGM EOM further reduces the pulse duration.

It was shown recently that doped electro-optic materials allow for monolithic integration of an active mode-locker.[62] Erbium doped $LiNbO_3$ is attractive for such applications because of its excellent electro-optic properties on one hand, and Er solubility in $LiNbO_3$ crystals without fluorescence quenching on the other.[63]

Active mode-locking at up to 10 GHz pulse repetition rate have been already demonstrated in Ti:Er:$LiNbO_3$ broad-band Fabry-Perot waveguide cavities.[56–58, 64] The integrated cavity should be long enough to achieve significant frequency modulation necessary for the mode locking for these lasers. Stable pulse generation at high repetition rate with long active cavity needs supermode selection with additional passive cavity. Electro-optical modulator (EOM) integrated into the cavity requires about 0.5 Watt of applied microwave power to achieve full modulation.

We propose an architecture of an advanced monolithic integrated mode-locked source based on whispering-gallery mode (WGM) nonlinear dielectric cavity. The idea of this laser is based on two recently realized WGM devices: EOM and Er-doped microsphere glass laser.

A continuous wave (cw) pump laser radiation at $\lambda_p = 1.48$ μm is sent into z-cut Er:$LiNbO_3$ spheroid optical cavity via coupling diamond prism. Oblate spheroid cavity shape is essential to clean up the cavity spectrum. Modes of the cavity with frequencies $\lambda_s \simeq 1.54$ μm experience amplification due to interaction of the pump and the erbium ions. The system emits coherent cw radiation at λ_s when the pump power exceeds some threshold value. The device becomes a classical example of an actively mode-locked laser when both cw microwave radiation and optical pump are applied. Interaction of the fields results in generation of pulses in the cavity. Because the optical amplification procedure is not phase sensitive, pulses running in both directions around the cavity rim should be observed.

It is worth noting here, that instead of doping $LiNbO_3$ crystal with erbium, it is possible to use erbium doped solgel films applied to the surface of lithium niobate disc cavity to create low threshold laser, as it was done with fused silica microspheres.[52] Placing microwave cavity onto such a cw laser will create a mode-locked laser.

Each element of the proposed setup may be described in the way similar to the seminal consideration by Kuizenga and Siegman.[54] Therefore, in spite the system looks different from usual mode-locked laser structure, it will work in the mode locked regime. The threshold of the generation should be fairly low compared with

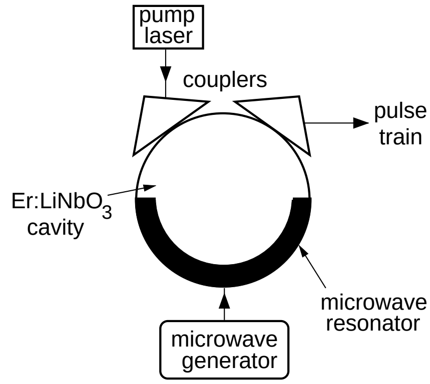

Figure 3. A schematic of an actively mode-locked laser based on an Er:$LiNbO_3$ whispering gallery mode electro-optical modulator.

conventional FM mode locked lasers because of the high quality factor of the whispering gallery modes one may achieve. The consumption of the microwave power is low as well because in our system the performance of electro-optic modulator is resonantly enhanced. Finally, the size of the integrated device is rather small.

5. COUPLED OPTO-ELECTRONIC OSCILLATOR WITH A WGM CAVITY

Realization of a compact actively mode-locked laser with high pulse repetition rate is generally hindered by need of a small high frequency stable microwave source to drive the electro-optical modulator inserted to the laser loop. The problem may be solved, however, if the stable microwave radiation is generated in the system as well. Such a device, in which a microwave oscillation and an optical oscillation are generated and directly coupled to each other, is dubbed Coupled Opto-Electronic Oscillators (COEO).[2, 5]

A COEO consists of two photonic loops generating light as well as microwaves. The loops are connected by means of an electro-optic modulator. The transformation of the modulated light power into microwave a signal is achieved via a photodetector. Hence, in an COEO the laser light energy is converted directly to spectrally pure microwave signals, using an electro-optic feedback loop containing a high-Q optical element, at a frequency limited only by the available optical modulation and detection elements. This frequency is the repetition frequency of the optical pulses generated in the system.

The generating light loop is a usual ring fiber laser with either erbium or semiconductor optical amplifier. If the microwave photonic loop of the COEO is open, the ring laser generates several independent optical modes. The number of modes is determined by the loop length and the linewidth of the gain of the optical amplifier. If the microwave photonic loop is closed and sufficient microwave amplification is available to insure microwave oscillations in the system in the manner of usual OEO,[1] the optical modes become phase locked.

The laser radiation propagates through a modulator and an optical energy storage element (delay line), before it is converted to the electrical energy with a photodetector. The electrical signal at the output of the modulator is amplified and filtered before it is feeded back to the modulator, thereby completing a feedback loop with gain, which generates sustained oscillation. Since the noise performance of an oscillator is determined by the energy storage time, or quality factor Q, then the use of optical storage elements allows for the realization of extremely high Q's and thus spectrally pure signals.

The EOM is one of the main sources of power consumption in the COEO because of the large power required to drive the conventional modulators. Broadband Mach-Zender modulators used in COEOs typically require one to a few Watts of microwave power to achieve a significant modulation. This means that either the photocurrent in COEO system should be amplified significantly, or the laser loop of the COEO should operate much above laser threshold to produce enough optical radiation as the source of the drive power for the OEO. If the microwave power sent to the modulator is small, the information about the microwave signal simply will not be transduced to light through the EOM.

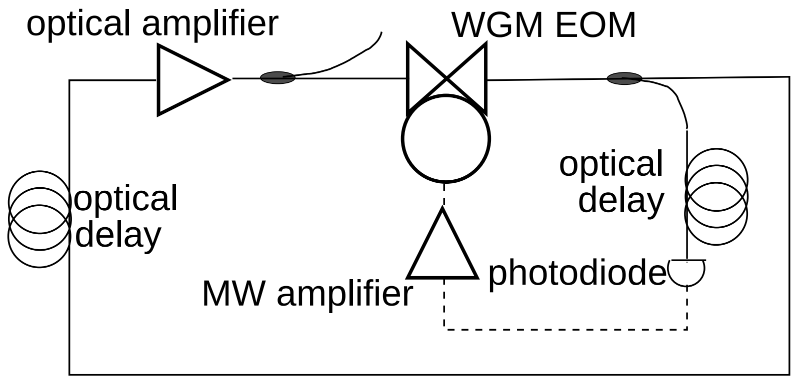

Figure 4. A schematic of coupled opto-electronic oscillator with whispering gallery mode electro-optic modulator. Solid lines show optical fiber links, while dashed lines show microwave links.

By utilizing a high-Q resonance, instead of the zero-order interferometry, as the basis for electro-optic modulation one can reduce the controlling power by many orders of magnitude and reduce the energy consumption of the COEO. For this purpose, the dielectric cavities with whispering gallery modes are useful.

Low timing jitter of generated pulses is one of the main desirable characteristics of a COEO. It was shown recently, that the timing jitter may be substantially reduced if one uses a harmonically mode locked laser with short high-finesse cavity inserted into the long laser resonator.[31] Such a laser may have better performance than a fundamentally mode-locked laser that produces an identical pulse train. Because whispering gallery mode electro-optical modulator simultaneously play a role of a filter, we expect that mode-locked lasers as well as COEOs that utilize WGM EOMs will have low timing jitter of the generated pulses.

6. CONCLUSION

In this paper we have shown that the high-Q whispering gallery mode dielectric cavity may be used as a key element in various photonic devices aimed to generate short optical pulses with high repetition rate. Whispering gallery mode $LiNbO_3$ electro-optical modulators may be used in optical frequency comb generators, in actively mode-locked lasers of various kinds, and in coupled opto-electronic oscillators. The main advantages of the devices that involve WGM electro-optical modulators is their small size, low power consumption, and high repetition rate of the optical pulses.

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