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LATVIJAS UNIVERISTĀTES NACIONĀLĀ ZINĀTNES PLATFORMA

The 4th International Conference

# Quantum Optics and Photonics 2021

organised by the
ERA Chair Project and NSP FOTONIKA-LV of the University of Latvia

Riga, 22–23 April 2021

# BOOK OF ABSTRACTS

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# Thematic Sessions

# From Ultra-stable Laser Resonators for Atomic Spectroscopy and Fiber-based Femtosecond Optical Frequency Combs to Whispering-gallery-mode Micro Resonator Sensors and Microsphere Optical Frequency Combs for Telecommunication Data Transfer

**Jānis Alnis, Aigars Atvars, Roberts Berķis, Dina Bērziņa, Uldis Bērziņš, Inga Brice, Artūrs Ciniņš, Kristians Draguns, Kārlis Grundšteins, Viesturs Ignatāns, Lāse Mīlgrāve, Pauls Kristaps Reinis, Arvīds Sedulis, Alma Ūbele**

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Improving the precision of optical spectroscopy of atomic hydrogen over several decades at the Max Planck Institute of Quantum optics [1] has led to the development of an optical frequency comb method that allows one to count the frequency of light and has activated a field of optical atomic clocks. The stability of the laser spectral line has reached the thermal noise limit of sub-Hz linewidth [2]. The thermal noise limit was also reached in the optical whispering gallery mode (WGM) micro resonators [3]. Ultra-stable laser radiation can be transferred using an interferometrically stabilised optical fiber link across the continent between the metrology labs [4].

The Fotonika-LV Project [5] in Latvia has allowed the establishment of a Quantum optics lab in 2013, acquiring a fiber-based optical frequency comb (Menlo Systems 250 MHz) and building a stable laser resonator [6]. In order to learn how to use the comb, we re-measured the rubidium saturated absorption line frequencies [7]. We have built a two-mirror ring-down resonator for acetone measurements in breath [8]. Afterwards we switched from classical two-mirror resonators to so-called whispering gallery mode (WGM) micro resonators that circulate the light by total internal reflection and can be used in biosensors [9]. a resonance condition occurs when in a roundtrip fits an integer number of light waves. We make $SiO_2$ microsphere WGM resonators by melting a tip of high purity telecom fiber and reach optical Q factors in the $10^{6}$–$10^{8}$ range. The most straightforward application is a WGM temperature sensor [10] as both the index of refraction and physical dimensions change with temperature. The next application is to coat the micro resonator surface with a thin coating, for example, ZnO using atomic layer deposition method [11], and a glucose oxidase enzyme for glucose sensing [12]. Sensitivity can be further enhanced by adding gold nanoparticles to the coating to excite surface plasmon resonances [13]. Drifts of microsphere resonances can be referenced to atomic rubidium lines [14]. WGM resonances can also be excited in a liquid droplet, and we demonstrated glycerol droplet WGM with very high sensitivity to relative humidity [15].

Another application is to induce nonlinear optical phenomena such as four-wave mixing, Kerr and Raman effects by pumping microspheres with several hundreds of milliwatts of CW laser power. Thanks to the high optical Q factor, the circulating power in an approximately 10 $mm^2$ mode area can reach $GW/cm^2$. At such high intensities new optical frequencies are generated. The resonator allows generating frequencies that satisfy constructive interference after a roundtrip. This leads to the generation of a Kerr frequency comb in the micro resonator manifesting as equally spaced lines in the optical spectrum [16]. We have demonstrated the use of the Kerr frequency comb in a silica microsphere for telecommunications by using comb lines as a carrier for telecom data [17]. Comb use for telecommunications requires only a single comb generator laser instead of separate lasers for each colour.

## Acknowledgements

The research was supported by the ERDF project No. 1.1.1.1/18/A/155 "The Development of optical frequency comb generator based on a WGMR and its applications in telecommunications" and the Latvian Council of Science project No. lzp-2018/1-0510 "Optical whispering gallery mode micro resonator sensors".

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# Poster Sessions

# Whispering Gallery Mode Silica Microsphere Resonator Applications for Biosensing and Communications

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Inside whispering gallery mode (WGM) resonators, the light beam can be confined in a circular symmetry structure and sustained with small reflection losses. By choosing an appropriate material with a very low absorption, and fabricating a very smooth surface, WGM resonators can reach ultra-high quality (Q) factors. High Q factors allow light to circulate inside longer and have very narrow resonances. This makes them suited as laser cavities, resonant filters, sensitive sensors, generation of nonlinear effects at relatively low powers. The simplest 3D WGM resonator is a sphere. These microsphere resonators are easy to fabricate. The principle is based on melting the tip of an optical waveguide fiber and allowing the surface tension of liquid glass do all the work to reform the material into a sphere. The sphere has low surface roughness, helping the resonator achieve ultra high Q-factors in the range of $10^6$–$10^9$.

## WGM microsphere resonators for biosensing

WGMR sensor operation principles are based on a shift of WGM resonance due to external influence (temperature, pressure, humidity etc.). WGM resonances in the WGMRs are a function of their geometry and refractive index. To enhance optical properties or detect molecules or biomolecules the surface of a WGMR has to be functionalised with a nanomaterial layer. Sensing molecule adhesion to the surface is a good step towards biosensor development but not enough to call it a biosensor. One of the requirements for WGMR biosensors, which is often forgotten, is selectivity – the ability to distinguish the desired biomolecules from other molecules. Many enzymes, for example, glucose oxidase (GOx) which oxidizes glucose, or genes/antigens have selective properties and have to be tailored for each biomolecule.

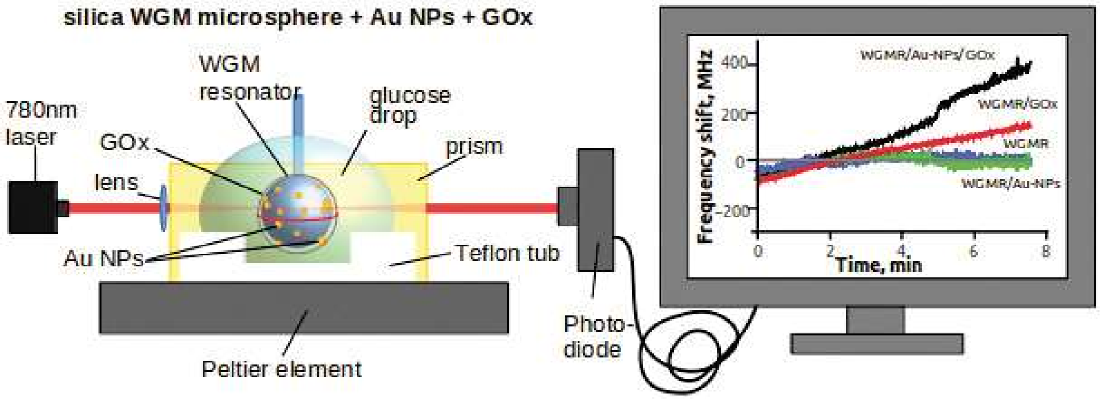

***Fig. 1.*** *Responses of a glucose sensor based on differently modified silica microsphere WGM resonators: bare resonators – WGMR (blue curve), resonators coated with gold nanoparticles – WGMR/Au-NPs- (green curve), resonators coated with glucose oxidase layer – WGMR/GOx (red curve) and both layers to enhance sensitivity and provide selectivity – WGMR/Au-NPs/GOx (black curve)*

The fabricated silica microsphere WGM resonator's surface was coated with multiple different functionalising layers. Gold nanoparticles (Au NPs) were used to enhance the sensitivity together with GOx to ensure selectivity (Fig. 1). The research demonstrated that WGM resonators can be coated with materials, which increase the sensitivity towards the selected analyte – glucose – and to enhance the sensitivity of the WGR microsphere based sensor.

Several ZnO structures were tested to increase the surface area for protein binding which were selective for analyte/antibody reactions. Three types of ZnO coating on the WGM resonator's surface (WGMR/ZnO) structures were tried. ZnO nanorods had too rough a surface for potential application in the WGM resonator's sensors. ZnO nanolayer coated using atomic layer deposition and 10–15 nm layer thickness showed the best results and highest Q factors [2]. The ZnO nanocrystal structure obtained by drop coating zinc acetate solution on WGM microspheres was the easiest and fastest method, but only 50% of the samples were usable for further modifications. Bovine leukaemia virus (BLV) cattle virus and Bovine serum albumin (BSA) was added to the WGMR/ZnO structure to test BLV-positive test samples (Fig. 2.).

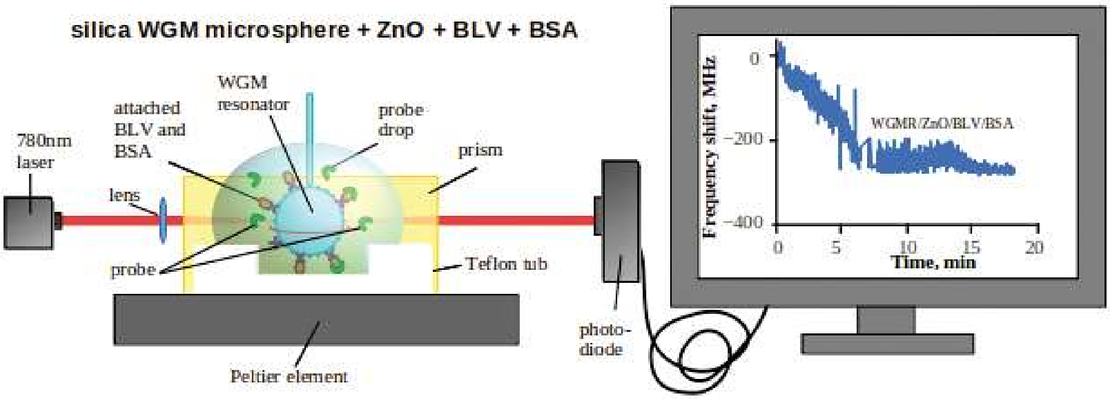

***Fig. 2.*** *Responses of the cattle virus sensor based on antigen/antibody reaction modified silica microsphere WGM resonator*

## WGM microsphere resonators for communications

An Optical frequency comb (OFC) can be generated using third-order Kerr-nonlinearity induced four wave mixing (FWM), generating the equidistant optical side-bands in the WGM micro resonators. The generated equidistant frequencies may allow the substitution of an expensive laser array solution for a wavelength-division multiplexing (WDM) data transmission system.

Silica microsphere WGM resonators with 170 μm diameter were used to generate OFCs with ~400 GHz repetition rate. Two more intense generated optical carriers (+1) and (–1) were filtered and used to demonstrate data transmission [3]. Stability is an important parameter for telecom data transmission and long-term stability was explored. The temperature influence on the system was deemed crucial as it could affect multiple points, like the coupling position, impacting WGM resonator OFC resonances and polarisation of the input, which were determined to be integral for OFC generation [4].

## Acknowledgments

This research was funded by ERDF project No. 1.1.1.1/16/A/259 “Development of novel WGM micro resonators for optical frequency standards and biosensors, and their characterization with a femtosecond optical frequency comb” and ERDF project No. 1.1.1.1/18/A/155 “Development of an optical frequency comb generator based on a whispering gallery mode micro resonator and its applications in telecommunications”.

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# The Dispersion Engineering of Whispering Gallery Mode Resonators

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Whispering gallery mode resonators (WGMRs) are axisymmetric optically transparent structures with a size of a few hundred micrometres. The light can be confined inside the resonator by total internal reflection. The mode density of the WGMRs is very high, so we can observe strong light-matter interactions. One of the interesting applications is the generation of optical frequency combs using for-wave mixing [1].

Every wavelength of light inside a medium, experience a different refractive index n due to material dispersion. But also, the geometry of the resonator contributes to the total dispersion [2]. We can use geometric dispersion to engineer the geometry of the resonator such that the dispersion is desirable. Kerr combs can be generated in anomalous dispersion, so it is important where the zero-dispersion wavelength (ZDW) lays. For optimal comb generation, it is good that the dispersion line is not steep. For telecommunication's applications, the pump wavelength is 1550 nm.

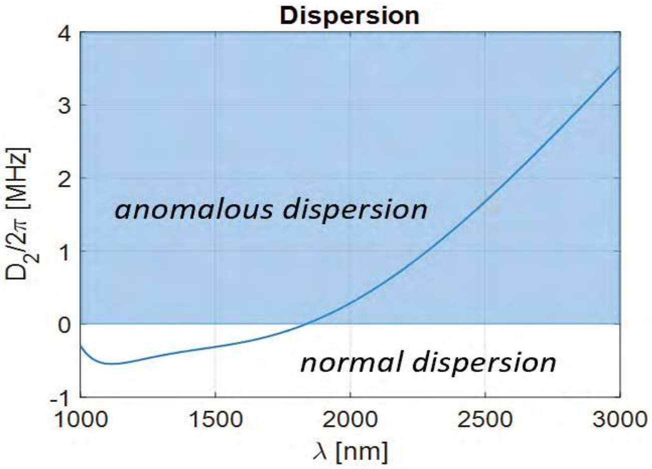

***Fig. 1.*** *Dispersion for R = 332 μm belt type WGMR*

Various WGMR geometries are being explored to achieve optimal dispersion for comb generation.

## Acknowledgment

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# Microsphere-based OFC-WGMR Multi-wavelength Source and Its Applications in Telecommunications

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The "Development of optical frequency comb generator based on a whispering gallery mode micro resonator and its applications in telecommunications" project aims to obtain new knowledge on whispering gallery mode resonator-based optical frequency combs (WCOMBs) and to develop, construct and test a comb generator prototype for telecommunication's applications. The planned result of the project is a portable WCOMB prototype for a commercial fiber optical communication system.

Optical frequency combs (OFCs) using different kinds of whispering-gallery-mode (WGMRs) micro resonators have a high potential to replace tens of tuneable continuous-wave (CW) lasers with a single laser source in telecom (WDM) optical communication systems. For the first time, the use of silica microspheres ($SiO_2$) for OFC represents a cheap alternative over the other microcombs. By using arc discharge of a commercially available fusion splicer, it is possible to quickly fabricate microspheres with repeatable parameters such as diameter, and it is easy to control the free spectral range (FSR) which is proportional to the sphere diameter. Our designed microspheres have a high Q-factor ($10^7$–$10^8$), where the carrier wavelengths of WGMR-OFC are relatively stable over time and FSR matches the ITU-T spectral grid [1].

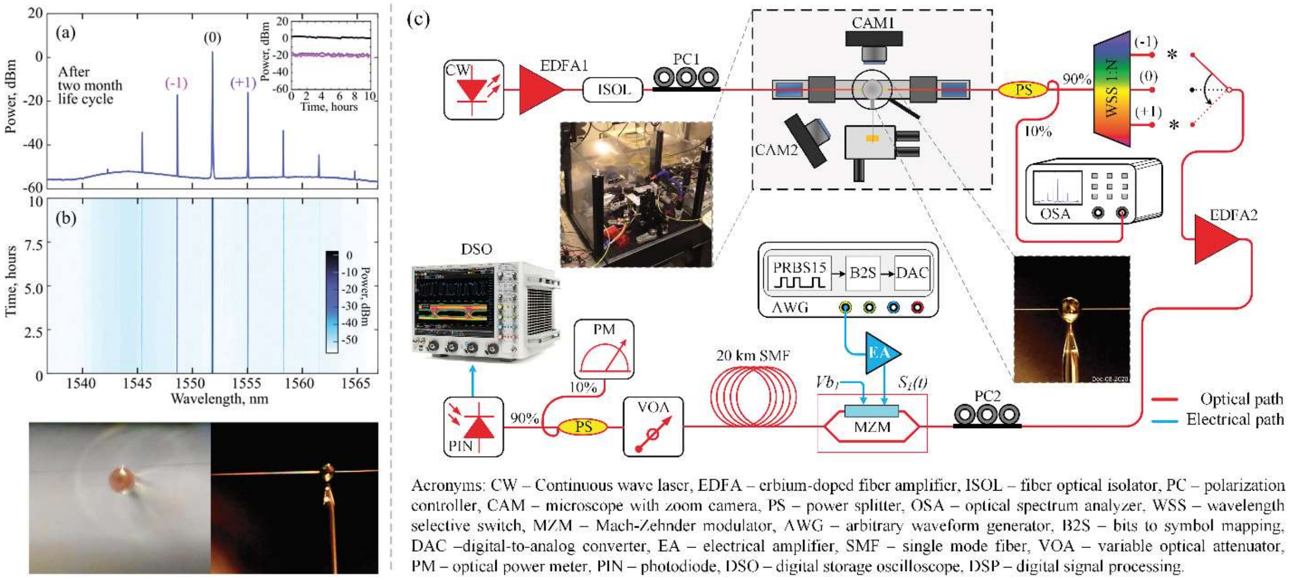
One way to enter the light into the resonator is by prism coupling [2]. This scheme is an alternative to the tapered fiber coupling scheme and has some advantages and disadvantages. Advantage – that the setup can be made with standard optical components and the setup does not have the fragileness that is present in a tapered fiber coupling setup. Disadvantage – coupling efficiency is only about 5–40%. Considering the aspect, that the tapered fiber method of microsphere excitation allows to fine-tune the coupling conditions, which is not possible for chip-based resonators, we have chosen them for OFC generation in optical communication systems.

To the best of our knowledge, we experimentally for the first time present a designed silica microsphere whispering-gallery-mode micro resonator (WGMR) OFC as a C-band light source where 400 GHz spaced carriers provide data transmission of up to 10 Gbps NRZ-OOK modulated signals over the standard ITU-T G.652 telecom fiber span of 20 km in length.

We search for stable combs on an optical spectrum analyser (OSA) by tuning external cavity CW semiconductor laser in wavelength and found that the most appropriate wavelength ($\lambda = 1552$ nm), where a CW laser with a linewidth of about 100 kHz and +6 dBm optical output power can be used as an OFC comb pump source. After OFC generation the carriers (-1) and (+1) are similar but one can be a few dBm more intense than the other if multiple solitons are circling inside the resonator. The optical carriers $\lambda = 1549$ nm depicted as (-1) and λ = 1555 nm depicted as (+1) are used further to demonstrate NRZ-OOK modulated 2.5 Gbps and 10 Gbps data transmission, please see Fig. 1 (a). The OFC performance over a 10-hour period, power stability and power distribution stability over the wavelength of the OFC carriers, please see Fig. 1 (a) and Fig. 1(b).

The experimental setup of a silica microsphere-based WGMR-OFC light source optical communication system, please see Fig. 1 (c). The light coming from the pump source is further amplified up to +23 dBm by the erbium-doped fiber amplifier (EDFA). The polarisation state of the amplified signal is adjusted using the polarisation controller (PC1) before coupling the signal into the microsphere. The isolator on the EDFA output is used to prevent back-scattered light from entering the output port of the CW laser. The silica microsphere and tapered fiber are enclosed in a separate box for dust and airflow prevention, providing even further stability to the resulting OFC. The X, Y, and Z micro-translation stage is used to position the microsphere to touch the tapered fiber at a place slightly thicker than the taper waist, which changes such coupling conditions as coupled power and the Q factor of the resonances [3].

We have chosen B2B transmission and a distance of 20 km corresponding to the NGPON2 requirements. The error-free transmission is established during the experiment in both cases of 2.5 and 10 Gbps data rates for an OFC comb pump source operating at 1552 nm wavelength. It allows using WGMR-OFC as a light source where 400 GHz spaced carriers provide 2.5 and 10 Gbps NRZ modulated data transmission over 20 km SMF fiber [1].



Acronyms: CW – Continuous wave laser, EDFA – erbium-doped fiber amplifier, ISOL – fiber optical isolator, PC – polarization controller, CAM – microscope with zoom camera, PS – power splitter, OSA – optical spectrum analyzer, WSS – wavelength selective switch, MZM – Mach-Zehnder modulator, AWG – arbitrary waveform generator, B2S – bits to symbol mapping, DAC –digital-to-analog converter, EA – electrical amplifier, SMF – single mode fiber, VOA – variable optical attenuator, PM – optical power meter, PIN – photodiode, DSO – digital storage oscilloscope, DSP – digital signal processing.

***Fig. 1.*** *Measured OFC performance over a 10-hour period:* ***(a)*** *optical spectrum with inset representing captured power stability, and* ***(b)*** *power distribution stability over the wavelength.* ***(c)*** *The experimental setup of the designed silica microsphere WGMR-OFC as a light source where 400 GHz spaced carriers provide NRZ-OOK modulated 2.5 and 10 Gbps data transmission over 20 km SMF fiber. Insets show tapered fiber and silica microsphere resonator positions of coupling conditions and WGMR-OFC reduced humidity and dust-prevention cover box*

## Acknowledgments

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