In memory of Mikhail Gorodetsky

As a pioneer in the research on ultra-high-quality dielectric microresonators and their applications in nonlinear optics, frequency metrology and laser science, Mikhail Gorodetsky is badly missed.

Igor Bilenko, Vladimir Ilchenko, Farid Khalili and Tobias J. Kippenberg

On 13 January 2019, Mikhail (Michael) Gorodetsky passed away unexpectedly during hospitalization, at the age of 52. His early pioneering work with Vladimir Braginsky and Vladimir Ilchenko on optical microresonators[1] triggered a research field that today has become one of the cornerstones of modern photonics. His untimely passing is a major loss to the research community.

Michael Gorodetsky. Credit: International Center for Quantum Optics & Quantum Technologies Limited Liability Company

Gorodetsky's research career started in the Physics Department of Moscow State University (MSU) in 1986. He joined, as an undergraduate student, the group of Braginsky, which was one of the few groups in the world at the time that focused on theoretical aspects and measurement techniques aimed at detection of gravitational waves. Gorodetsky worked on the studies of small fundamental microwave absorption in dielectrics using whispering gallery mode (WGM) resonators and participated in emerging experiments on implementation of WGM resonators in optics. The work was done together with Ilchenko, who by that time had completed his postdoctoral study devoted to cryogenic microwave dielectric cavities with WGMs.

By 1989, Gorodetsky had completed his diploma work, which is equivalent to a master's degree in science, on millimetre-wave absorption in semiconductors. He co-authored a seminal paper[1] that demonstrated, for the first time, megahertz-wide optical WGM resonances at the He–Ne laser wavelength of 632.8 nm in solid fused silica microspheres. The motivations of this research were various: to exploit the unique combination of the high quality (Q) factor and small modal volume of the WGM microresonators, to reduce the threshold of nonlinear effects, such as self-phase-modulation, to achieve quantum non-demolition regimes at small power levels, and to obtain bistability and switching regimes at small photon numbers. The direction of their WGM research was complementary to the early studies of high-Q Mie resonances in aerosols where the presence of very high-Q modes was confirmed by the observation of elastic resonances in levitated droplets[2], and indirectly confirmed via low-threshold Raman scattering[3]. The goal of Braginsky's group had been towards implementing a micro-optical device in which cavity-mediated light–matter interaction would support non-classical states and quantum measurement.

The idea of an ultra-high-Q WGM optical microresonator was briefly mentioned in *Systems with Small Dissipation*, a 1981 book by Braginsky, V. P. Mitrofanov and V. I. Panov (see English translation published by the University of Chicago Press, 1985, with an introduction by Kip S. Thorne). Braginsky and colleagues pointed out the extremely low optical attenuation of silica and suggested splicing a tiny ring out of communication fibre that would become an optical resonator with a fundamental limit of Q at the level of $\sim 10^{11}$. Since splicing of a tiny ring was virtually impossible, clues to a more practical approach were sought and found.

Instead of carving an ellipsoidal shape out of bulk silica, Ilchenko suggested melting the tip of a fibre with a 40 W carbon dioxide laser at a wavelength of 10 μm, and this was how the first solid silica microsphere resonator was produced. In a couple of years, $Q > 10^8$ was confirmed with the addition of a proper evanescent coupling method and an adequate tunable laser[1]. Gorodetsky's early assignments included the building of a hydrogen–oxygen microtorch, and thus the flame technique was added to allow more flexible processing of low-melting glasses, which were considered at the time as promising alternatives to silica in terms of a better combination of Q and the cubic nonlinearity coefficient χ^3. Eventually, in the mid-2000s, the carving and polishing technique was implemented for the demonstration of crystalline WGM resonators with $Q > 10^{10}$.

Gorodetsky's work during his PhD candidate years (1990–1993) focused on the improvement of fabrication methods, increase of the Q-factor in optical WGM resonators of different glasses, optimization of coupling methods, and demonstration of device integration capabilities for narrow-band optical filters and compact narrow-linewidth lasers based on resonance intracavity backscattering. His early theoretical work included analyses of evanescent couplers, modal structure, intracavity Rayleigh scattering in WGM resonators[4], and frequency tuning and ponderomotive (that is, radiation pressure) effects in coupled optical microsphere resonators, which are an early precursor to recent optomechanical studies in WGM resonators.

In the 1990s, research on ultra-high-Q WGM microresonators picked up in many institutions, namely École Normale Supérieure, Paris, the California Institute of Technology and NASA's Jet Propulsion Laboratory, and later in many research labs and technology start-ups around the world. This was catalysed by the ideas and tacit knowledge developed by Gorodetsky and his teammates at MSU at the time of his early career. In 2001, Gorodetsky completed his doctor of science (habilitation) degree while already on a professorial tenure track at his alma mater, the Physics Department of MSU.

At the end of the 1990s, Gorodetsky became an active participant of gravitational-wave research as a member of the Laser Interferometer Gravitational-Wave Observatory (LIGO) scientific collaboration. Together with Braginsky and Farid Khalili, he developed an intracavity readout class of gravitational-wave detector topologies[5], which has the potential to radically reduce the required optical power circulating in the detector, providing at the same time the sensitivity exceeding the standard quantum limit. Together with Braginsky and Sergey Vyatchanin, he predicted and explored in detail a number of a non-trivial kind of thermal noise sources in the gravitational-wave detectors' test mirrors and their multilayer dielectric coatings. Gorodetsky and his colleagues showed that thermal fluctuations led to at the time an unknown type of noise (often referred to as VBG, after its inventors Vyatchanin, Braginsky and Gorodetsky). This noise arises from temperature-induced fluctuations that lead to optical-path-length changes via temperature-dependent refractive index of expansion coefficients.

In particular, Gorodetsky's research on thermoelastic noise[6] influenced the choice of material of the Advanced LIGO mirror — fused silica instead of sapphire, which was planned initially. He also developed strategies of optimizing the dielectric coating structure aimed at minimization of the coating's Brownian noise, which is one of the major noise sources in the contemporary gravitational-wave detectors. In 2016, he shared the Special Breakthrough Prize in Fundamental Physics with other colleagues in the LIGO scientific collaboration for his contribution to the detection of gravitational waves.

Although deprived of funding opportunities and unable to set up his own experimental laboratory at MSU, Gorodetsky was devoted to his institution and country, and never had he considered leaving MSU or Russia. Despite the difficult time for experimental research, he contributed widely recognized theoretical research to the field for many years. In contrast to many scientists that left Russia over the years, he had faith in his institution and contributed to the continued prestige of MSU by teaching specialized classes to some of the best Russian physics undergraduates. His presence at MSU later proved pivotal to the success of the Russian Quantum Center (RQC).

From 2008 to 2018, Gorodetsky engaged in an intense scientific collaboration with Tobias Kippenberg. Both met at the Max Planck Institute of Quantum Optics, Garching, where Gorodetsky was serving as a Humboldt Fellow, initially he worked with Herbert Walther on the micro-maser. Every summer of these 11 years, Gorodetsky visited the group of Kippenberg, who had moved in the meantime to EPFL. Their collaboration, combining Gorodetsky's deep theoretical insights and clever ideas for experiments, led to highly fruitful results covering the fields of optomechanics[7], frequency metrology[8], and microresonator Kerr combs[9] and solitons[10].

The most notable result was Gorodetsky's theoretical work on simulating Kerr frequency combs, which led him to theoretically predict already in 2013 the existence of solitons in microresonators (referred to as dissipative Kerr solitons) at a Bad Honnef conference[11]. The first experiments[10] took place in the summer of 2013, working with Tobias Herr in the laboratory in EPFL. Today, dissipative Kerr solitons in microresonators have been demonstrated in virtually every microresonator platform and have even been used for the calibration of astrophysical spectrographs for exoplanet searches[12,13], or in system level telecommunication transmission experiments allowing Tb s^{-1} data rates[14]. Their collaboration shed light on microresonator Kerr solitons and led to an understanding of the universal dynamics of dissipative Kerr solitons[15], the observation of soliton Cherenkov radiation[16], and injection-locked solitons[17] in microresonators.

The collaboration between Gorodetsky and Kippenberg extended over several areas of optomechanics, nonlinear photonics and frequency combs, from precision measurements of dispersion[8] and measurements of mechanical motion with an imprecision of that at the standard quantum limit[7] through to precise calibration of optomechanical vacuum coupling rates[18]. Their work also discovered the underlying noise in Kerr combs[9], the role of laser noise in optomechanical ground-state cooling experiments[19] and thermorefractive noise in microresonators[20].

Since 2014, Gorodetsky had combined his work as a full professor at MSU with the leadership of the laboratory at the RQC. At the RQC, he founded and equipped a new world-class experimental lab — Laboratory of Coherent Microoptics and Radiophotonics. In 2015, Gorodetsky assumed the position of scientific director of the RQC, and made crucial contributions to the establishment of the RQC as one of the leading research centres in the field of quantum research in Russia and in the world. He built a strong team of young researchers. They obtained world-class results in investigating nonlinear effects in optical microresonators. In particular, a new class of dissipative solitons in microresonators with normal dispersion, platicons, was found[21] and methods for their generation were proposed[22]. The effects of the Raman scattering[23] and the influence of dispersions of higher orders[24] on the properties of frequency combs and solitons were investigated. Effective ways to achieve a single-soliton generation mode in an optical microresonator, for example, by reverse frequency tuning[15] and by harmonic modulation of pumping[25], as well as the possibility of creating high-quality microresonators for the mid-infrared range of crystalline fluorides[26] and silicon[27], were demonstrated. They also developed an original theory that allowed to describe extremely interesting effects of single-frequency[28] and multi-frequency laser[29] self-injection locking to a high-quality optical microresonator.

Gorodetsky was a scientist who combined rigorous and self-demanding theoretical skills with powerful experimental intuition, as he called it — tacit knowledge, that has been instrumental to many experiments employing ultra-high-*Q* resonators. He was also a very humble scientist, a person of the highest integrity, a team player and a mentor, who was generous with his time and relentless in pursuit of perfect experiment and clear interpretation. He was a person passionate about research, and a deep thinker whose interests, publications and books transcended physics, venturing into history, history of science and scientific chronology.

Arguably, 2018 was one of the most successful years for Gorodetsky. With his newly established laboratory, he demonstrated injection locking of dissipative Kerr solitons[30], billion *Q*-factors in silicon WGM resonators[27] and spatial multiplexing of soliton microcombs[30], as well as reviewing the field of frequency combs in microresonators[11,31].

Being at the peak of his career, Gorodetsky was full of scientific plans and, regardless of the sudden, serious illness, until the last day he was sure that he would return to work soon. He left behind his wife and mother. ❐

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