KFM 4: Focus: Whispering-Gallery-Mode Resonators

Whispering Gallery Mode (WGM) resonators confine and enhance electro - magnetic fields almost entirely within a transparent dielectric. Strong light - matter interactions such as optical nonlinearities are the consequence. Therefore, these resonators are a link between the two continuously merging worlds of photonics and solid state physics. Research and applications using this type of resonators rely heavily on the availability of high quality linear and nonli near materials. Furthermore, advanced material processing for the fabrication of high quality resonators, in particular for on - chip integration is required. On the other hand, the strong light - matter interaction allows to study linear and nonlinear dielec tric material properties with high sensitivity over a huge wavelength regime from visible over infrared down to terahertz and microwave frequencies. WGM resonators can also serve as a widely tunable source of classical as well as quantum light which can be used for different types of high precision spectroscopy. The aim of this session is to cover the topics of this field and bring together the communities of photonics and solid state physics.

Chair: Florian Sedlmeir (Max Planck Institute for the Science of Light)

Time: Monday 9:30–13:30 Location: H47

Invited Talk KFM 4.1 Mon 9:30 H47

Mixing microwave and light: up-conversion and frequency combs — •Harald G. L. Schwefel — Dodd-Walls Centre for Photonic and Quantum Technology, New Zealand — Department of Physics, University of Otago, Dunedin, New Zealand

Dielectric whispering gallery mode resonators are a great tool to entrap electro-magnetic radiation throughout the dielectric's transparency range [1]. In small resonators this leads to high enough field amplification that nonlinear effects can readily be harnessed. I will discuss hybrid systems which are resonant for both microwave and optical fields and which are based on anisotropic crystalline dielectrics that allow for second order nonlinear effects, such as sum- and difference frequency generation.

In an efficient resonant system and for strong microwave and optical fields, sum- and difference frequency generation can cascade, leading to optical frequency combs [2]. Such combs are useful for telecommunication application such as wavelength division multiplexing and for sensing. For the limit of very weak microwaves and only sum frequency generation, coherent conversion of microwave signals allows the quantum state of individual microwave photons to be transferred into the optical domain [3]. This offers a way to coherently connect superconducting qubits to quantum networks, and allow the rapid scaling of quantum computers.

[1] D. V. Strekalov, *et al.*, J. Opt. **18**, 123002 (2016).
[2] A. Rueda, *et al.*, arXiv:1808.10608 [physics] (2018).
[3] A. Rueda, *et al.*, Optica, **3**, 597–604 (2016).

KFM 4.2 Mon 10:00 H47

Frequency comb up- and down-conversion in synchronously driven $\chi(2)$ optical microresonators — •Jan Szabados[1], Simon Johannes Herr[1], Victor Brasch[2], Ewelina Obrzud[2,3], Yuechen Jia[1], Steve Lecomte[2], Karsten Buse[1,4], Ingo Breunig[1,4], and Tobias Herr[2] — [1]Laboratory for Optical Systems, Department of Microsystems Engineering - IMTEK, University of Freiburg, Georges-Köhler-Allee 102, D-79110 Freiburg, Germany — [2]Swiss Center for Electronics and Microtechnology (CSEM), Time and Frequency, Rue de l'Observatoire 58, CH-2000 Neuchâtel, Switzerland — [3]Geneva Observatory, University of Geneva, Chemin des Maillettes 51, CH-1290 Versoix, Switzerland — [4]Fraunhofer Institute for Physical Measurement Techniques IPM, Heidenhofstraße 8, D-79110 Freiburg, Germany

We demonstrate the broadband conversion of a high-repetition rate frequency comb from the near-infrared (NIR) to the mid-infrared (MIR), visible (VIS) and ultraviolet (UV) wavelength domains. The employed lithium niobate WGRs are synchronously pumped by a frequency comb with a repetition rate in excess of 10 GHz and pico- to femtosecond pulse duration. Cascaded second-order nonlinear processes transfer significant parts of the fundamental frequency comb to harmonic and sub-harmonic optical frequencies. This way, the second and the third harmonics in the visible and the fourth harmonic in the ultra-violet spectral region are generated. Also, subharmonic generation of the fundamental comb lines into the mid-infrared spectral range via degenerate parametric oscillation is demonstrated. Non-degenerate processes enable wavelength-tunable signal- and idler-comb generation.

KFM 4.3 Mon 10:20 H47

Electro-optic tuning of whispering gallery resonators made of KTN crystals — •Ingo Breunig[1,2], Jan Szabados[1], and Karsten Buse[1,2] — [1]Laboratory for Optical Systems, Department of Microsystems Engineering - IMTEK, University of Freiburg, Georges-Köhler-Allee 102, 79110 Freiburg, Germany — [2]4Fraunhofer Institute for Physical Measurement Techniques IPM, Heidenhofstraße 8, 79110 Freiburg, Germany

The electro-optic response of most centrosymmetric materials is neglected. Due to their symmetry, the Pockels coefficients are zero. The DC-Kerr coefficients are typically of the order of 10^{-22} m^2/V^2, i.e. very small. Consequently, refractive-index changes in centrosymmetric materials are induced by changing the temperature or by applying mechanical stress. However, potassium tantalate niobate crystals (KTN) operated at temperatures close to the paraelectric-ferroelectric phase transition provide DC-Kerr coefficients in the 10^{-15} m^2/V^2 range. Thus, although the material is centrosymmetric, it exhibits a strong electro-optic response. We have fabricated a millimeter-sized whispering gallery resonator made of KTN with a quality factor beyond 10^7 at 1 μm wavelength. By applying an electric field between its top and bottom surfaces, the eigenfrequencies of the cavity are shifted due to the DC-Kerr effect. For moderate field strengths of 250 V/mm, we achieve more than 100 GHz tuning. This exceeds the value reached with lithium niobate crystals by more than one order of magnitude. The results obtained here are of relevance for the realization of electro-optically tunable adiabatic frequency converters or Kerr frequency combs.

KFM 4.4 Mon 10:40 H47

Adiabatic frequency conversion in high-Q lithium niobate whispering gallery resonators — •Yannick Minet[1], Luís Reis[1], Ingo Breunig[1], and Karsten Buse[1,2] — [1]Laboratory for Optical Systems, Department of Microsystems Engineering, IMTEK, University of Freiburg, Georges- Köhler-Allee 102, D-79110 Freiburg, Germany — [2]Fraunhofer Institute for Physical Measurement Techniques IPM, Heidenhofstraße 8, D-79110 Freiburg, Germany

Optical frequency conversion in Whispering gallery resonators (WGRs) is mostly based on the nonlinear response of material polarization caused by intense laser light. For example in WGRs made of noncentrosymmetric materials tunable OPOs have been realized and in WGRs made of centrosymmetric materials frequency combs. Another way for frequency conversion is adiabatic tuning. Here, the optical length of the circumference of the resonator is changed during its ringdown time. This induces a frequency shift of the circulating light. Conventionally, this is achieved by changing the refractive index by generating free electrons or via the ac-Kerr effect. Both schemes require an additional pump laser. We present an alternative approach based on the linear electro-optic effect. Compared with the other schemes, the experimental setup is considerably simpler. Furthermore, it is applicable for all wavelengths in the transparency range of the resonator material used. Using this method, we can generate almost arbitrary waveforms and frequency shifts of several tens of GHz. We will also discuss a possible use of this technique for sensing and LIDAR applications.

KFM 4.5 Mon 11:00 H47

Dielectric tuning of millimeter-wave whispering-gallery modes for electro-optic phase matching — •Gabriel Santamaria Botello[1], Kerlos Atia Abdalmalak[1], Daniel Segovia Vargas[1], Luis Enrique Garcia Muñoz[1], and Zoya Popovic[2] — [1]Universidad Carlos III de Madrid — [2]University of Colorado Boulder

It has been shown that highly efficient electro-optic modulators can be designed in millimeter-sized high-Q whispering-gallery (WG) disk resonators made of nonlinear crystals, where a resonant optical field mixes with the modulating microwave field to produce a resonant sideband. This is potentially useful for high-sensitivity millimeter-wave detection, optical comb generation and up-conversion of quantum states. The interaction takes place only when the optical and microwave modes are phase matched, implying that the angular velocity is matched in the case of fundamental WG modes. Due to the high optical Q, the phase-matching condition is sensitive to fabrication tolerances of the resonator requiring an accuracy within less than 10um in all dimensions. In past demonstrations, a time-consuming iterative polishing process was performed to adjust the radius in small steps. In this work, we show that the phase-matching point can be found by perturbing the microwave mode with low-loss dielectric layer loadings on one or both sides. Thus, millimeter-sized lithium niobate resonators can be fabricated with tolerances up to 20um in height and 100um in radius. The conversion efficiency is not appreciably affected with this approach since no significant degradation of the microwave Q and field distribution is observed.

Break 20 min

Invited Talk KFM 4.6 Mon 11:40 H47

Nonlinear whispering gallery resonators for quantum optical technologies — •Christoph Marquardt — Max-Planck-Institut für die Physik des Lichts, Staudtstr. 2, 91058 Erlangen

In quantum information optical quantum states are an essential building block. Encoding quantum states in the optical field is important for travelling quantum states that can transfer quantum information, as well as in quantum sensing, imaging and photonic quantum computation. Nonlinear optical processes can be used to generate and process special quantum states. Nonlinear whispering gallery resonators provide an efficient platform towards these goals. I will review the current state of the field and discuss possible applications in quantum optical technology.

D. Strekalov et al., Journal of Optics 18(12) 123002 (2016)

KFM 4.7 Mon 12:10 H47

Non-classical light from a nonlinear crystalline whispering gallery mode resonator — •Alexander Otterpohl[1,2], Florian Sedlmeir[1,2], Thomas Dirmeier[1,2], Ulrich Vogl[1,2], Gerhard Schunk[1,2], Golnoush Shafiee[1,2], Dmitry Strekalov[1,2], Harald G. L. Schwefel[3], Tobias Gehring[4], Ulrik L. Andersen[4], Gerd Leuchs[1,2], and Christoph Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany — [2]Institute of Optics, Information and Photonics, University Erlangen-Nürnberg, Staudtstr. 7 B2, 91058 Erlangen, Germany — [3]The Dodd-Walls Centre for Photonic and Quantum Technologies, Department of Physics, University of Otago, 730 Cumberland Street, 9016 Dunedin, New Zealand — [4]Department of Physics, Technical University of Denmark, Fysikvej, 2800 Kgs. Lyngby, Denmark

Macroscopic crystalline whispering gallery mode resonators (WGMR) made out of $LiNbO_3$ have turned out to be an efficient and compact source of non-classical light generated via optical parametric down-conversion [1,2]. We report on the generation of squeezed vacuum, which is a special subclass of non-classical light, and the associated experimental challenges such as temperature stabilization. Furthermore, we discuss possible future applications like CV quantum computing and optomechanics [3].

[1] J. U. Fürst *et al.*, Phys. Rev. Lett. **106**, 113901 (2011).
[2] M. Förtsch *et al.*, Nat. Commun. **4**, 1818 (2013).
[3] V. Peano *et al.*, Phys. Rev. Lett. **115**, 243603(2015).

KFM 4.8 Mon 12:30 H47

Single photon generation in a whispering gallery mode resonator — •Golnoush Shafiee[1,2], Florian Sedlmeir[1,2], Gerhard Schunk[1,2], Alexander Otterpohl[1,2], Ulrich Vogl[1,2], Dmitry Strekalov[1,2], Harald G. L. Schwefel[3,4], Gerd Leuchs[1,2], and Christoph Marquardt[1,2] — [1]MPL, Erlangen, Germany — [2]FAU, Erlangen, Germany — [3]University of Otago, Dunedin, New Zealand — [4]Dodd-Walls Centre for Photonic and Quantum Technologies, New Zealand

A whispering gallery resonator (WGR) is a versatile source of tunable, narrow-band and efficient single photons which can be used for quantum information processing [1,2,3]. Our WGR is made of nonlinear lithium niobate and its working principle is based on spontaneous parametric down-conversion where a pump photon decays into two cavity modes of different wavelengths named signal and idler. Here, we investigate parametric down-conversion in counter-propagating modes of one WGR. The interference of two photons from different propagation directions opens up the possibility of generating polarization-entangled states using only one resonator. A source of polarization-entangled states can greatly enhance the success rates of the proposed quantum repeaters. [1] M. Förtsch et al., Nat. Commun. 4, 1818 (2013). [2] J. U. Fürst et al., Phys. Rev. Lett. 106, 113901(2011). [3] G. Schunk et al., Optica 2, 773-778 (2015).

KFM 4.9 Mon 12:50 H47

The optical Möbius strip cavity: Tailoring geometric phases and far fields — •Jakob Kreismann and Martina Hentschel — Technische Universität Ilmenau, Ilmenau, Germany

The Möbius strip, a long sheet of paper whose ends are glued together after a 180° twist, has remarkable geometric and topological properties. Here, we consider di- electric Möbius strips of finite width and investigate the interplay between geometric properties and resonant light propagation. We show how the polarization dynamics of the electromagnetic wave depends on the topological properties, and demonstrate how the geometric phase can be manipulated between 0 and π through the system geom- etry. The loss of the Moöbius character in thick cavities and for small twist segment lengths allows one to manipulate the polarization dynamics and the far-field emission, and opens the venue for applications.

KFM 4.10 Mon 13:10 H47

Super-directional light emission from arrays of deformed microcavities — •Jakob Kreismann[1], Martina Hentschel[1], Arne Behrens[2], and Stefan Sinzinger[2] — [1]Institute for Physics, Theoretical Physics II/Computational Physics Group, Technische Universität Ilmenau, Germany — [2]Department of Mechanical Engineering, Optical Engineering Group, Technische Universität Ilmenau, Germany

Microcavity lasers made of deformed dielectric disk resonators such as the Limaçon-shaped cavity have attracted a lot of interest due to directional light emission from high quality factor modes. Here we investigate them in various array configurations of Limaçon-shaped microcavities and show that the directional emission is enhanced drastically. At the same time, emission into side peaks is reduced. Furthermore, we study the coupling mechanisms between Limaçon-resonators arranged in different array configurations. We show that far-field properties depend strongly on the coupling between the resonators in the array that is mostly determined by the inter-cavity distance as well as geometric imperfections.