Electro-optic based adiabatic frequency conversion in a non-centrosymmetric microresonator

Yannick Minet[a,b], Ingo Breunig[a,c], and Karsten Buse[a,c]

[a]Laboratory for Optical Systems, Department of Microsystems Engineering – IMTEK, University of Freiburg, Georges-Köhler-Allee 102, 79110 Freiburg, Germany
[b]Gisela and Erwin Sick Chair of Micro-Optics, Department of Microsystems Engineering - IMTEK, University of Freiburg, Georges-Köhler-Allee 102, 79110 Freiburg, Germany
[c]Fraunhofer Institute for Physical Measurement Techniques IPM, Heidenhofstraße 8, 79110 Freiburg, Germany

ABSTRACT

A rather unknown method to perform optical frequency tuning is the adiabatic frequency conversion. But this method has some appealing advantages compared to conventional frequency conversion schemes, i. e. non-linear-optical based ones: The internal conversion efficiency can reach unity even on a single-photon level. No threshold and no phase-matching conditions need to be fulfilled. Previous realizations of adiabatic frequency conversion suffer from short photon lifetimes, limited tuning range and challenging experimental setups. Here, we employ the Pockels effect for adiabatic frequency conversion (AFC) in a non-centrosymmetric ultrahigh-Q microresonator made out of lithium niobate. With a 70-µm-thick resonator we observe frequency shifts of more than 5 GHz by applying a moderate voltage of 20 V. In contrast to former schemes our setup is considerably simplified and provides a linear electric-to-optical link that enables us to generate also arbitrary waveforms of frequency shifts. Furthermore, our presented conversion scheme is well-suited for on-chip fabrication. Volume fabrication and application of larger electric fields for reasonable voltages become possible. By doing this, it is feasible to achieve tuning on the order of hundreds of GHz.

Keywords: Electro-optics, Adiabatic frequency conversion, Whispering gallery resonators, Microresonators, Pockels effect, Lithium niobate, Frequency conversion

1. INTRODUCTION

Changing the frequency of laser light is needed in many disciplines. For example for sensing and spectroscopy, here especially light detection and ranging (LIDAR) as well as gas analysis benefit from tunable laser light, increasing the demand for frequency agile devices. Wavelength regions that can not be covered by laser diodes so far are accessed by laser frequency synthesizers. These are based on three different techniques: The most common one is the nonlinear-optical frequency conversion which relies on the nonlinear response of the material polarization caused by intense laser light. This is used for frequency doubling or in optical parametric oscillation.[1,2] However, high intensities are required to achieve high conversion efficiencies, as well as phase matching needs to be fulfilled. Moreover, a pump threshold must be overcome for the most versatile conversion mechanism, optical parametric oscillation. A second important frequency conversion technique is single-sideband (SSB) modulation. By modulating light in an electro-optic modulator with radio-frequencies (RF), shifts of the optical frequencies by several tens of GHz can be provided. The optical output signal consists of the original pump light and the added sidebands. To remove the pump light filters are needed. Also the conversion efficiency is pretty limited. Lately, frequency chirps of 200 GHz by employing dual-parallel Mach-Zehnder modulators have been demonstrated.[3] A third technique to change the frequency of light is the adiabatic frequency conversion (AFC). Here, the frequency of light changed by the changing the optical length of an optical resonator or more general an optical system. Light has to follow the eigenfrequency changes, as long as they occur faster than the photon lifetime. With

Further author information: (Send correspondence to I.B.)
I.B.: E-mail: optsys@ipm.fraunhofer.de, Telephone: +49 761 203 97944.

in: Kudryashov, A.V.; Paxton, A.H.; Ilchenko, V.S.; Armani, A.M.; Society of Photo-Optical Instrumentation Engineers –SPIE: Laser Resonators, Microresonators, and Beam Control XXII. Proc. SPIE 11266, Paper 1126606 (2020); doi: 10.1117/12.2544706

AFC, conversion efficiencies up to 100 % down to the single photon level are possible.[4,5] Here, no threshold has to be overcome and no phase-matching has be considered. The AFC has been implemented in structures that provide a sufficiently long interaction time between photons and the confining structure, such as it is the case in fiber grating cavities ,[6] photonic crystals ,[7–9] and in waveguides.[5,10–12] Another important device that can provide sufficient photon lifetimes is a microresonator. In such resonators photon lifetimes up to milliseconds are obtained.[13] Here, the eigenfrequency can be changed e.g., by a refractive index change Δn of the material of the microresonator. Consequently, the frequency of the light confined in it will change according to[14]

$$\Delta\nu \approx -\nu\frac{\Delta n}{n}. \tag{1}$$

One solution to change the refractive index of the material of the resonator fast enough is by generating free electrons by pulsed laser excitation.[15] Doing so, frequency shifts of 300 GHz have been accomplished. But the free electrons, unfortunately decrease the photon lifetime due their induced absorption. Another method is to use the AC Kerr effect to change the refractive index.[16] This method does not influence the quality factor of the material, but the achieved frequency shifts of 150 MHz are relatively small compared with the one achieved with the method of generating free electrons in Preble et al.[15] Recently we demonstrated AFC by employing the Pockels effect in an ultrahigh-Q microresonator,[17] with an experimentally less challenging setup, getting rid of the need of an additional laser. By doing this, relatively large frequency shifts are possible without affecting the photon lifetime. In contrast to previous implementations, it is now also possible to generate positive as well as negative frequency shifts. Furthermore, using the linear electro-optic effect provides a excellent control of the optical domain by electrical signals.

2. THEORY

In this contribution, we use microresonators, in particular whispering-gallery resonators (WGR). The WGRs are spheroidal structures made out of a dielectric material guiding light via total internal reflection.[18] The eigenfrequency ν_{WGR} of such an optical resonator is defined as

$$\nu_{\mathrm{WGR}} = m\frac{c}{2\pi R n_{\mathrm{eff}}}, \tag{2}$$

where R is the major radius of the microresonator (Fig. 1a)), c is the vacuum speed of light and n_{eff} is the effective refractive index containing all dispersions effects. By Eq. (2) it is clear that the eigenfrequency can be changed by varying R or n. In this work, we utilize the Pockels effect to change the refractive index. For lithium niobate

$$\Delta n = -\frac{1}{2}n_{\mathrm{eff}}^3 r E, \tag{3}$$

hold,[19] where r is the Pockels coefficient and E the externally applied electric field. The frequency shift $\Delta\nu$ of the eigenfrequency ν_{WGR} is calculated by inserting Eq. (3) in Eq. (1):

$$\Delta\nu = \frac{1}{2}\nu_{\mathrm{WGR}} n_{\mathrm{eff}}^2 r E_z, \tag{4}$$

where E_z is the electric field in z-direction. In the case of z-cut congruent lithium niobate (CLN), an electric field in z-direction and light polarized parallel to the z-axis (extraordinarily-polarized) the Pockels coefficient reads $r_{33} \approx 24.6\,\mathrm{pm/V}$ and for light perpendicular to the z-direction (ordinarily-polarized) $r_{13} \approx 8.1\,\mathrm{pm/V}$ at a wavelength of $\lambda \approx 1000\,\mathrm{nm}$.[20] To provide an estimate for the magnitude of the frequency shift that can be expected, we calculate the shift for an electric field of $E_z = 10$ V/mm and extraordinarily-polarized light in a WGR which is resonant at a wavelength of $\lambda_{\mathrm{L}} = 1040\,\mathrm{nm}$. This results in a shift of $\Delta\nu_{\mathrm{e}} \approx 165\,\mathrm{MHz}$. The contribution by the piezo-electric effect, which also changes the eigenfrequency of the resonator by influencing R, is more than one order of magnitude smaller and does not depend on the light polarization.[17] Additionally the effect is most likely too slow to affect the tuning during the lifetime τ. Hence, it will be neglected in the following. Another important parameter that characterizes a resonator is the quality factor Q. The higher Q,

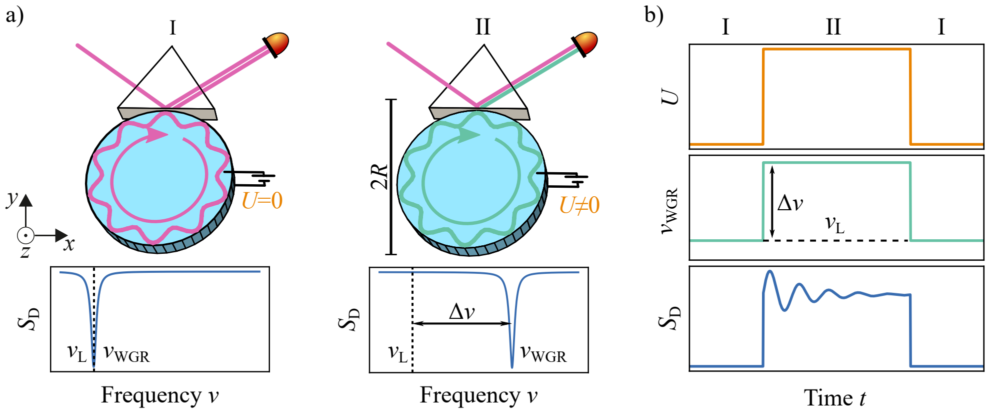

Figure 1. a) (I) When no electric field is applied the laser light of frequency ν_{L} is coupled into a resonator mode ν_{WGR}. In (II) an electric field is applied between the resonator's $+z$- and $-z$-side before the lights gets lost: The Pockels effect changes the refractive index $\Delta\nu$, causing a change of the eigenfrequency ν_{WGR}. The light trapped in the resonator is follows this change and hence is converted. This light leaves the resonator via the prism together with the uncoupled light that is reflected at the prisms base. b) When a voltage U is applied as shown, the light in the resonator changes its frequency following ν_{WGR}, while the laser frequency ν_{L} stays constant. The light leaving the resonator and the input laser light that is now reflected at the prism base since it does not fit anymore into the cavity mode are superimposed on a photodiode. The recorded signal S_{D} is an exponentially decaying oscillation. The rise/drop of the base level S_{D}, when the voltage is switched on/off has its origin in the fact that when a voltage is applied no pump light is coupled into the resonator anymore is thus reflected. Because of this, the light power reaching the photodiode increases.

the longer the light is traveling in the resonator before it will vanish due to loss channels such as absorption or scattering. Consequently, the photon lifetime τ in the resonator is directly proportional to the quality factor Q:[18]

$$\tau = \frac{Q}{2\pi\nu_{\mathrm{WGR}}}. \tag{5}$$

The photon lifetime τ is be measured by observing the decay of the out-coupled light I_{WGR}. In Fig. 1 the scenario for a resonator undergoing an eigenfrequency change $\Delta\nu_{\mathrm{WGR}}$ during the decay time τ is illustrated. As the electric field is applied, the resonator changes its eigenfrequency and is not resonant with the static input laser light frequency ν_{L} anymore. Hence, no light is coupled into the cavity. Thus, two beams with two different frequencies, ν_{L} and ν_{WGR}, reach the photodiode now: The frequency-changed light from the resonator and the laser light reflected at the prism base. Here, a beat note is observed. The signal S_{D} can be described as

$$\begin{aligned} S_{\mathrm{D}}(t) = {} & I_{\mathrm{L}} + I_{\mathrm{WGR}} \exp\left(-\frac{t}{\tau}\right) \\ & + 2\sqrt{I_{\mathrm{L}} I_{\mathrm{WGR}}} \cos(2\pi\Delta\nu t + \phi_0) \exp\left(-\frac{t}{2\tau}\right), \end{aligned} \tag{6}$$

where I_{L} is the intensity of the laser light and I_{WGR} the intensity of the light coupled out of the resonator. The beat frequency is $\Delta\nu = |\nu_{\mathrm{L}} - \nu_{\mathrm{WGR}}|$, with the an exponentially decaying amplitude.

3. METHODS

For this contribution, we use WGRs that are made out of z-cut 5-%-MgO-doped congruent lithium niobate (CLN), coated on the $+z$- and the $-z$-side with a 150 nm-thick chromium layer. They are manufactured with a femtosecond laser and afterwards hand-polished with a diamond slurry. More details can be found elsewhere.[17] The fabricated resonator possesses a thickness of $d_z = 70\,\mu\mathrm{m}$ with a major radius of $R = 1$ mm and a minor radius of $\rho = 600\,\mu\mathrm{m}$. This results in free spectral ranges (FSRs) of $\Delta\nu_{\mathrm{FSR}} = 21.7$ GHz (extraordinar-polarization) and $\Delta\nu_{\mathrm{FSR}} = 20.8$ GHz (ordinar-polarization) at $\lambda_{\mathrm{L}} = 1040$ nm. The resonator has an intrinsic quality factor of $Q = 7 \times 10^7$, which is lower than the theoretical limit,[21] maybe caused by the chromium electrode, which would

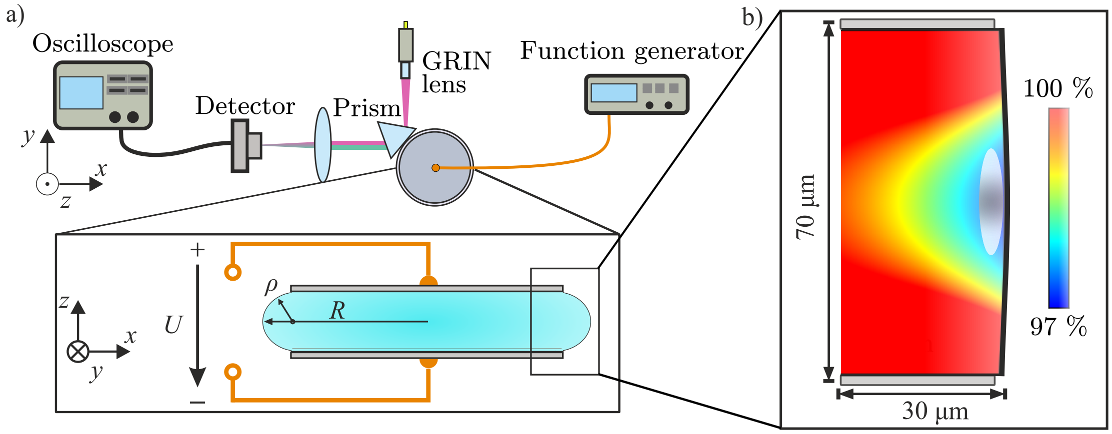

Figure 2. a) Schematic drawing of our setup. The close-up shows a side view of the resonator which posses on the $+z$- and the $-z$-side a chromium electrode. b) The simulated electric field strength along the $z-$direction. As a guide to the eye, position and size of the fundamental mode is indicated by the grey ellipse.

reduce Q due to absorption.[22] Our setup is shown in Fig. 2. The laser light with a wavelength of $\lambda_\mathrm{L} = 1040\,\mathrm{nm}$ is focused with a GRIN lens into a prism in order to generate an evanescent light field on the prism base. By changing the distance between the prism base and the rim of the resonator we control the coupling strength. In the experiments present here, we couple a few $100\,\mu\mathrm{W}$ of our $1\,\mathrm{mW}$ pump light into the WGR. The light leaving the resonator and the uncoupled light reflected at the prism base are focused on a fast photodiode that is connected to a 12.5-GHz oscilloscope. The electrodes of the resonator are connected to a function generator with $20\,\mathrm{V}$ maximum output. The rise and fall time of the function generator are less than $10\,\mathrm{ns}$ for a rectangular output signal.

Since light in the fundamental mode of the WGR is traveling at its rim, which is outside of the electrodes, the effective electric field is reduced compared to the electric field between them. In Fig. 2b) the distribution of the electric field along the $z-$axis by using COMSOL Multiphysics simulation is shown for our real geometries. Based on this simulation we determine a 3% reduction of the strength of the electric field E_z at the position of the fundamental mode.

4. RESULTS AND DISCUSSION

In Fig. 3 the signal detected on the photodiode is shown when we apply a rectangular electrical signal similar to the scheme described in Fig.1. The frequency of the beat note is $\Delta\nu = 78\,\mathrm{MHz}$ for extraordinarily-polarized light at $\lambda_\mathrm{L} = 1040\,\mathrm{nm}$ and $1.5\,\mathrm{V}$ applied to the resonator electrodes. We determine $\tau = 34\,\mathrm{ns}$ decay time corresponding to 6×10^7 Q-factor. The discrepancy between this value and the intrinsic Q-factor status from the coupling and is as expected.[18,23] Next we repeat the measurement of the beat signal for different voltages and polarizations. The results are plotted in Fig. 3 b). The data fits excellent to theoretically expected linear behavior of the Pockels-effect-based tuning. We determined the frequency-shift-per-Volt applied to the electrodes of the resonator by a linear fit and obtain $(266 \pm 1)\,\mathrm{MHz/V}$ (extraordinary polarization) and $(86 \pm 1)\,\mathrm{MHz/V}$ (ordinary polarization) at $\lambda_\mathrm{L} = 1040\,\mathrm{nm}$. The approximately 3-times larger tuning for extraordinarily polarized light than ordinarily polarized light is also in good agreement with the expectations.[24]

5. OUTLOOK AND CONCLUSION

So far our frequency shift achieved is limited by the maximum available voltage only. But it is known that lithium niobate can withstand electric fields as high as $65\,\mathrm{kV/mm}$.[25] This leads to a change of the refractive index of $\Delta n = 4.8 \times 10^{-3}$ (ordinarily-polarized). Such a refractive index change would correspond to a frequency shift of a few THz! Another perspective is to realize the presented scheme as an on-chip device. The massive reduction in the thickness of the resonator results in a drastic increase of the electric field with the same voltage applied.[26,27] Since by this means it is feasible possible to create linear frequency shifts covering hundreds of GHz,

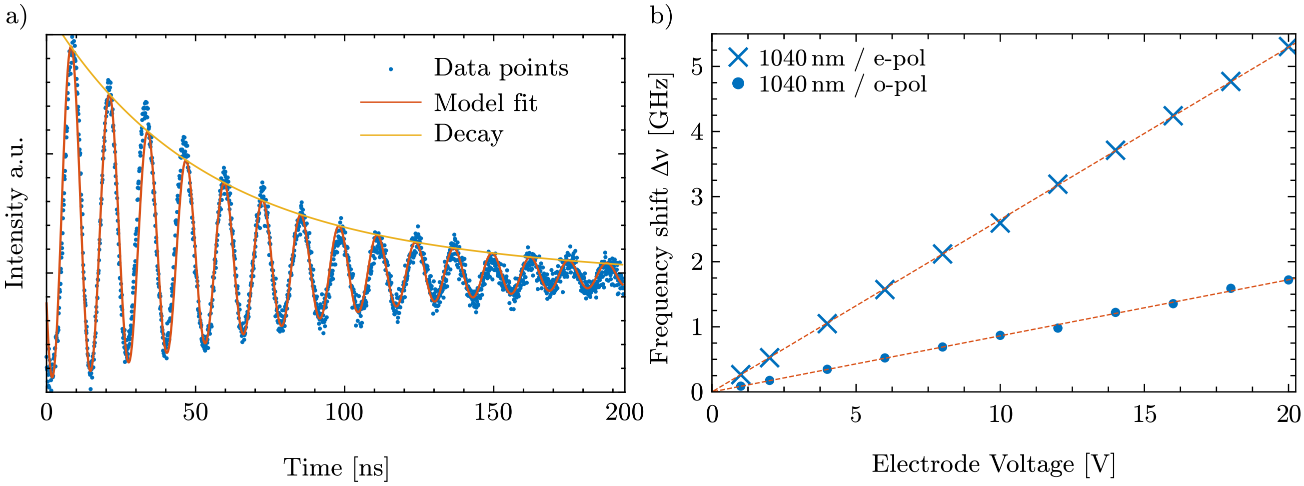

Figure 3. a) Beat note signal from the WGR with an applied voltage of U = 1.5 V on the electrodes. We observe a frequency shift of $\Delta\nu = 78\,\mathrm{MHz}$. The decay time of $\tau = 34\,\mathrm{ns}$ corresponds to a quality factor of $Q = 6 \times 10^7$ for extraordinarily-polarized light with a wavelength of $\lambda_\mathrm{L} = 1040\,\mathrm{nm}$. The model fit and the decay line serve as assistance to see where the parameters are extracted from. The model comes from Eq. (6). b) The determined frequency shift for different strengths of the external applied electric field and light polarization.

a possible application of Pockels-effect-controlled adiabatic frequency conversion could be frequency-modulated continious wave LIDAR. Another avenue is to transfer our method for AFC to materials with higher electro-optic coefficients such as KTN[28] or different transparency ranges such as KDP or AgGaSe e.g. for multi-component laser spectroscopy.[29]

To conclude, we presented adiabatic frequency conversion by utilizing the Pockels effect in ultrahigh-Q whispering gallery resonators made out of lithium niobate. We achieve a maximum frequency shift of 5 GHz by applying just 20 V to the electrodes of the resonator. We prove the linear behavior of the electro-optic effect by measuring the shift for different voltages as well as the 3-times larger tuning for extraordinarily-polarized light than for ordinarily-polarized light.

ACKNOWLEDGMENTS

Funding: Yannick Minet is supported by a Gisela and Erwin Sick Fellowship.

REFERENCES

[1] Boyd, R. W., [*Nonlinear optics*], Academic Press, Burlington, MA, 3rd ed. ed. (2008).

[2] Dunn, M. H. and Ebrahimzadeh, M., "Parametric generation of tunable light from continuous-wave to femtosecond pulses," *Science* **286**(5444), 1513–1517 (1999).

[3] Lu, Z., Yang, T., Li, Z., Guo, C., Wang, Z., Jia, D., and Ge, C., "Broadband linearly chirped light source with narrow linewidth based on external modulation," *Optics Letters* **43**(17), 4144–4147 (2018).

[4] Preble, S., Cao, L., Elshaari, A., Aboketaf, A., and Adams, D., "Single photon adiabatic wavelength conversion," *Applied Physics Letters* **101**(17), 171110 (2012).

[5] Fan, L., Zou, C.-L., Poot, M., Cheng, R., Guo, X., Han, X., and Tang, H. X., "Integrated optomechanical single-photon frequency shifter," *Nature Photonics* **10**(12), 766–770 (2016).

[6] Kabakova, I. V., Yu, Z., Halliwell, D., Fonjallaz, P.-Y., Tarasenko, O., de Sterke, C. M., and Margulis, W., "Switching and dynamic wavelength conversion in a fiber grating cavity," *Journal of the Optical Society of America B* **29**(1), 155 (2012).

[7] Tanabe, T., Kuramochi, E., Taniyama, H., and Notomi, M., "Electro-optic adiabatic wavelength shifting and Q-switching demonstrated using a $p-i-n$ integrated photonic crystal nanocavity," *Opt. Lett.* **35**(23), 3895–3897 (2010).

[8] Tanabe, T., Notomi, M., Taniyama, H., and Kuramochi, E., "Dynamic release of trapped light from an ultrahigh-Q nanocavity via adiabatic frequency tuning," *Physical Review Letters* **102**(4), 043907 (2009).

[9] Kondo, K. and Baba, T., "Adiabatic wavelength redshift by dynamic carrier depletion using $p-i-n$-diode–loaded photonic crystal waveguides," *Phys. Rev. A* **97**, 033818 (Mar 2018).

[10] Kampfrath, T., Beggs, D. M., White, T. P., Melloni, A., Krauss, T. F., and Kuipers, L., "Ultrafast adiabatic manipulation of slow light in a photonic crystal," *Phys. Rev. A* **81**, 043837 (Apr 2010).

[11] Upham, J., Tanaka, Y., Asano, T., and Noda, S., "On-the-fly wavelength conversion of photons by dynamic control of photonic waveguides," *Applied Physics Express* **3**(6), 062001 (2010).

[12] Kondo, K. and Baba, T., "Dynamic wavelength conversion in copropagating slow-light pulses," *Physical Review Letters* **112**(22), 223904 (2014).

[13] Savchenkov, A. A., Matsko, A. B., Ilchenko, V. S., and Maleki, L., "Optical resonators with ten million finesse," *Optics Express* **15**(11), 6768–6773 (2007).

[14] Notomi, M. and Mitsugi, S., "Wavelength conversion via dynamic refractive index tuning of a cavity," *Phys. Rev. A* **73**, 051803 (May 2006).

[15] Preble, S. F., Xu, Q., and Lipson, M., "Changing the colour of light in a silicon resonator," *Nature Photonics* **1**(5), 293–296 (2007).

[16] Yoshiki, W., Honda, Y., Kobayashi, M., Tetsumoto, T., and Tanabe, T., "Kerr-induced controllable adiabatic frequency conversion in an ultrahigh Q silica toroid microcavity," *Optics Letters* **41**(23), 5482–5485 (2016).

[17] Minet, Y., Reis, L., Szabados, J., Werner, C. S., Zappe, H., Buse, K., and Breunig, I., "Pockels-effect-based adiabatic frequency conversion in ultrahigh-Q microresonators," *Opt. Express* **28**(3), 2939–2947 (2020).

[18] Matsko, A., Savchenkov, A., Strekalov, D., Ilchenko, V., and Maleki, L., "Review of applications of whispering-gallery mode resonators in photonics and nonlinear optics," *IPN Progress Report* **42**(162), 1–51 (2005).

[19] Saleh, B. E. A. and Teich, M. C., [*Fundamentals of Photonics*], ch. 20.1, 836, Wiley, 2 ed. (2007).

[20] Méndez, A., García-Cabañes, A., Diéguez, E., and Cabrera, J. M., "Wavelength dependence of electro-optic coefficients in congruent and quasi-stoichiometric $LiNbO_3$," *Electronics Letters* **35**(6), 498–499 (1999).

[21] Leidinger, M., Fieberg, S., Waasem, N., Kühnemann, F., Buse, K., and Breunig, I., "Comparative study on three highly sensitive absorption measurement techniques characterizing lithium niobate over its entire transparent spectral range," *Optics Express* **23**(17), 21690–21705 (2015).

[22] Javerzac-Galy, C., Plekhanov, K., Bernier, N. R., Toth, L. D., Feofanov, A. K., and Kippenberg, T. J., "On-chip microwave-to-optical quantum coherent converter based on a superconducting resonator coupled to an electro-optic microresonator," *Phys. Rev. A* **94**, 053815 (Nov 2016).

[23] Breunig, I., "Three-wave mixing in whispering gallery resonators," *Laser & Photonics Reviews* **10**(4), 569–587 (2016).

[24] Weis, R. S. and Gaylord, T. K., "Lithium niobate: Summary of physical properties and crystal structure," *Appl. Phys. A* **37**(4), 191–203 (1985).

[25] Luennemann, M., Hartwig, U., Panotopoulos, G., and Buse, K., "Electrooptic properties of lithium niobate crystals for extremely high external electric fields," *Applied Physics B* **76**(4), 403–406 (2003).

[26] Wang, C., Zhang, M., Chen, X., Bertrand, M., Shams-Ansari, A., Chandrasekhar, S., Winzer, P., and Lončar, M., "Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages," *Nature* **562**(7725), 101–104 (2018).

[27] Wolf, R., Breunig, I., Zappe, H., and Buse, K., "Cascaded second-order optical nonlinearities in on-chip micro rings," *Optics Express* **25**(24), 29927–29933 (2017).

[28] Szabados, J., Werner, C. S., Herr, S. J., Breunig, I., and Buse, K., "Electro-optic eigenfrequency tuning of potassium tantalate-niobate microresonators," *APL Photonics* **5**(1), 016106 (2020).

[29] Bass, M., ed., [*Optical properties of materials, Nonlinear Optics, Quantum Optics*], Handbook of Optics, McGraw-Hill, 3 ed. (2010).