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Photorefractivity in WGM resonators

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Abstract:

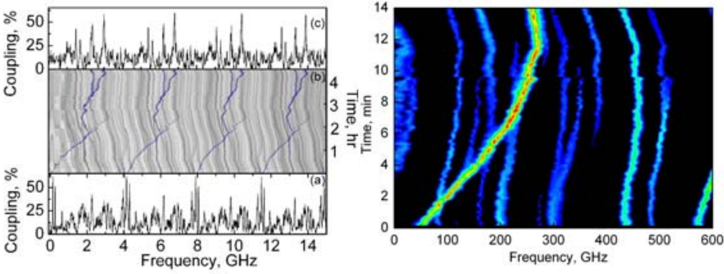
We report on observation of photorefractive effects in whispering gallery mode resonators made of as-grown and magnesium doped lithium niobate and lithium tantalate in the near as well as far infrared. The effects manifested themselves as dynamic modification of the spectra as well as quality factors of the resonators coupled to the laser radiation. We have observed a significant (exceeding 10^{-4}) change of the ordinary index of refraction of all the materials exposed with 780 nm light. Photorefractive effects have also been detected at 1550 nm. Our experiments support the conclusion that the photorefractivity does not have a distinct red boundary. We show that the maximum saturated refractive index change in the infrared is of the same order of magnitude as in the visible light.

Photorefractivity:

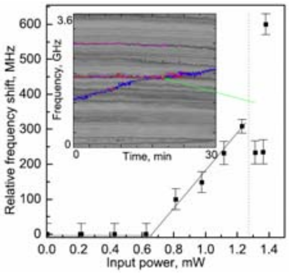
Photorefractivity is one of the basic properties of optical crystals possessing quadratic nonlinearity. The effect, observed shortlyafter the discovery of laser, results from the imperfection of real optical crystals, unlike other fundamental second-order effects, e.g. optical rectification and optical parametric frequency conversion, that could exist in an ideal crystalline lattice. The explanation of the photorefractivity requires a deep understanding of the material properties and has not been yet fixed in its present form, so that novel studies on the subject frequently appear in the literature.

Photorefractivity of lithium niobate and tantalate, being strong in the UV and visible parts of the spectrum, vanishes in the infrared and far infrared. To the best of our knowledge, photorefractivity has not been previously observed at 1550 nm and longer wavelengths. We have observed this effect at 1550 nm in a WGM resonator made of nominally pure as-grown congruent $LiNbO_3$. Our experiments shed light on the long wavelength properties of the impurities of the material and show that the photorefractivity does not have a distinct red boundary. This observation is also important for various applications because it points out to a possible "aging" of the telecom devices that use lithium niobate elements.

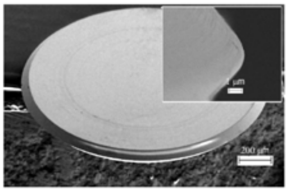
As-grown nominally pure congruent $LiNbO_3$:



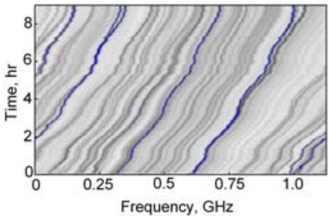
Left: Modification of a segment of the spectrum of a congruent lithium niobate WGM resonator interacting with 780 nm radiation. (a) The initial spectrum. (b) A diagram showing the modification of the spectrum with time. (c) The final spectrum of the resonator. Right: A time diagram of a fragment of the spectrum of another resonator made of the same material.



A typical dependence of the relative mode motion on the pump power. Each experimental point corresponds to the relative shift of the selected mode family acquired during a ten minute exposure interval of the resonator to 780 nm light. The change of the speed of motion on the right of the dashed line occurs due to the mode crossing, like that one shown in the inset.
The relative mode motion in congruent $LiNbO_3$ resonators could be understood as the consequence of the superlinear decrease of the refractive index in the spatial area where the selected mode is localized. Because the modes do not overlap in space entirely, it is possible to have a mode family propagating in a channel where the refractive index is different from the refractive index in the nearby areas.



An image of a lithium niobate WGM resonator obtained with a scanning electron microscope. The inset shows the resonator rim. The resonator was used in experiments with 1550 nm light.



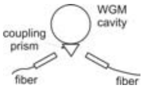
We performed similar experiments with 1550 nm light. The relative mode motion was observed as well, though it was slower than the relative mode motion at 780 nm. No decrease of the Q-factors of the modes was observed. We used a single laser in the experiment. The laser was scanned in a 1.2 GHz frequency range, and its power was 18 mW; the maximum coupling efficiency to the resonator modes was 65 %. The best quality factor of the WGMs was $Q=2\times10^8$. The average optical power coupled to the mode was 10 μW. The resonator had 1.2 mm in diameter and approximately 5 μm in thickness in the geometrical area where the modes were localized. Hence, the intensity of light in the mode was approximately 1 MW/cm^2.

The photorefractive change of the material properties at the basic telecom wavelength (1550 nm) is very slow. It is safe to say that this effect could be neglected in the majority of applications, e.g. WGM based filters, if a moderate intensity of light is used in the device. However, a careful study of the infrared photorefractivity should be continued to answer the question how the free spectral range of the crystalline WGM resonators changes due to the photorefractive effect, and if this change could be suppressed or reversed, e.g., by heating of the sample. The free spectral range is important in resonant WGM electro-optical modulators. The modulator becomes useless if such a shift exceeds a fraction of the FWHM of the WGMs.

Introduction:

Study of optical properties of transparent materials is one of the most promising applications of solid state whispering gallery mode (WGM) resonators. These studies have resulted in proposals and realizations of measurements of linear and nonlinear optical refraction, absorption, and scattering performed at a high precision level in amorphous resonator host materials, as well as the media surrounding the resonators. Recent experiments with crystalline WGM resonators and demonstration of ultra-high Q WGMs in a variety of crystalline materials extended the area of applications of the resonators enormously. We here further elucidate the usefulness of WGM resonators as devices suitable for material study. As an exemplary application, photorefractive properties of $LiNbO_3$ and $LiTaO_3$ in near (780 nm) as well as far (1550 nm) infrared are studied. The properties are inferred from experimentally measured quality factors and mode structures of the resonators.

Setup:



- Large quality factor
- Large tuning range: 20 GHz per 150 V
- Insertion loss: 2-7 dB
- Small size: 0.5-12 mm (smaller possible)
- Tunable filter and EOM realized

$$Q = 4\times10^{8} \ at\ \lambda = 1550\,nm$$

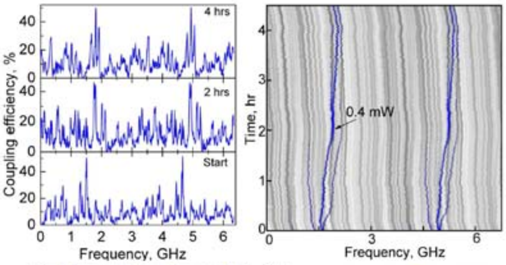
$$Q = 2\times10^{8} \ at\ \lambda = 1310\,nm$$

$$Q = 8\times10^{7} \ at\ \lambda = 1064\,nm$$

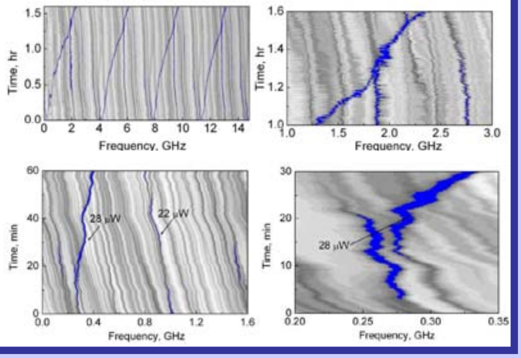
$$Q = 7\times10^{7} \ at\ \lambda = 780\,nm$$

Interaction of the modes:

An example of interaction of three WGMs.

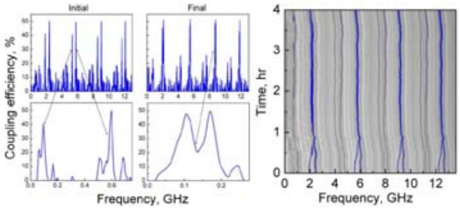


The frequency difference between interacting modes is determined by their spatial overlap. If the modes have a small overlap they do not interact, even if they have the same frequency. In this case we observe mode crossing. The overlapping modes begin to strongly interact at some point, when the frequency of the mode the is more strongly coupled to the pump laser is shifted to the other mode of interest. In this case we observe mode anticrossing.

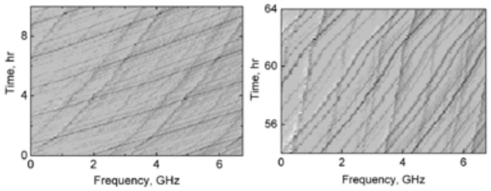


Spectrum engineering:

One can modify the refractive index of one family until the frequency shifts close to the frequency of another WGM family.



Lithium tantalate resonators:



WGM resonators made of lithium tantalate do not exhibit a relative mode motion within TE/TM WGM families. However, the frequency shift of the spectrum of the resonator as a whole is large. We observed at least 80 GHz change in the mode frequency, which corresponds to a more than 10^{-4} change in the effective extraordinary index of refraction of the material. The temperature of the resonator was actively stabilized. The absolute frequency measurement was achieved using a reference laser stabilized with a rubidium atomic cell.

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