# Mode switching in InN microresonators

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**Abstract.** InN optical resonators, which can support whispering-gallery modes of low orders up to room temperature, were made by MBE on patterned substrates. The observed effect of mode switching with a temperature rise was ascribed to the change of optical parameters induced by the shift of an absorption edge and modification of its shape. The results of modelling taking into account variation of refraction index reproduce typical distribution of the intensity of electromagnetic field within the resonators.

## 1. Introduction to optical resonators with different optical modes

Resonant stationary waves, that are so called whispering gallery modes (WGM) following Rayleigh [1], appear in closed optical systems using effect of total internal reflection. The necessity of amplification of very low signals of quantum oscillators by means of optical resonators of different types stimulates increasing interest in them. The most explored systems are planar Bragg structures with dielectric or semiconductor mirrors. However, difficulties of their creation are significant. At the same time, modern technologies allow to make optical resonators with WGMs in the shape of microdisks, microcolumns, *etc.* [2]. We can point two basic methods of creation of such types of these resonators: 1) epitaxial growth, that allows to make an active region inside the resonator at the same growth cycle [3], and 2) lithography with dry or wet etching [4]. During the development of methods and technology of forming WGM microresonators, theoretical research of mode variety in such structures was done [5-8].

We have recently shown the way of creation of the optical microresonators that were formed during InN growth by molecular beam epitaxy (MBE) on patterned substrates [9]. Such microresonators could be promising in order to create nanolasers and sources of single photons, since they can amplify very weak emission intensity of two-level system by means of the Purcell effect. Generally, people use high order WGMs because of their higher quality factor in resonators. This reason sets some restrictions on the size of crystals, which should be quite large. In this paper, we investigate the application of the low-order WGMs, excited in the microcrystals of InN with a cup-like shape. In particular, we analyze the effect of temperature switching of dominant type of the modes. We demonstrate that this effect is related to a shifted absorption edge and respective temperature-induced changing refractive index in microcrystals.

## 2. Creation and optical properties of samples

Structures were fabricated by plasma-assisted MBE on cone-shaped patterned c-$Al_2O_3$ substrates, where the half-spherical cones have a diameter 3 and height 1.5 microns. Microcrystals have very specific shape of inverted truncated hexagonal pyramids, which results from different lateral and vertical growth velocities. They are formed on about 15% of all cones (Fig. 1). As shown by micro-Raman studies, structural quality of microcrystals was higher than in the area around them. Their plane tops have smooth surface [8]. In addition, the results of energy-dispersive X-ray microanalysis (EDX) showed decreasing In/N ratio in the crystals that excludes the Purcell effect associated with plasmonic resonance of metallic In particles.

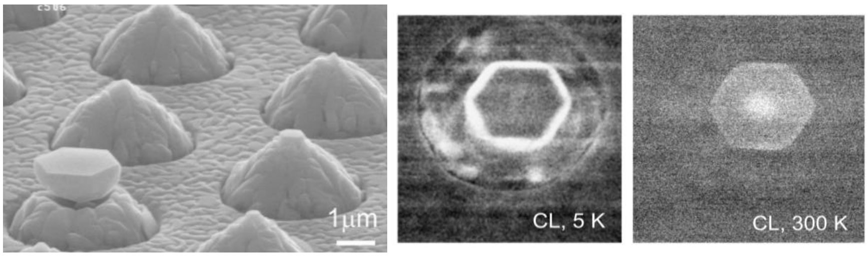



**Figure 1.** (from left to right). Image of InN structure with microcrystals taken by scanning electron microscopy (SEM), cathodoluminescence (CL) images taken at 5K and 300K.

In order to clarify the mode content and its temperature change we used micro-photoluminescence (μ-PL) spectroscopy. The wavelength of a laser used for excitation was 532 nm. The laser beam was focused in a spot with a diameter about 1 μm; thus a spectrum μ-PL can be measured from a single crystal. Spectrum of transmission and reflection were taken using a tungsten lamp; they characterize integral properties of area about 1-2 mm$^2$, which includes both the crystals and an InN planar layer. Figure 2 shows the results of these studies.

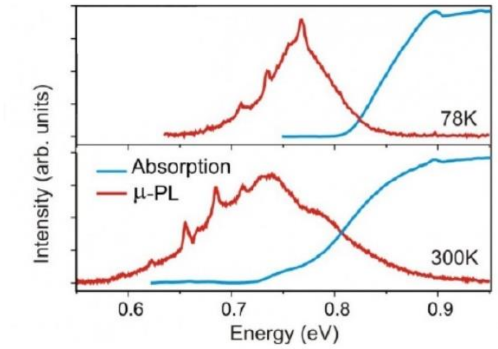



**Figure 2.** Spectra of μ-PL (red lines), measured in the same crystal with the diameter of ~2.2 μm, and absorption spectra of InN lstructure (blue lines) at different temperatures.

Illustrations of distribution of electromagnetic energy in microresonators, obtained by micro-cathodoluminescence (μ-CL), are shown in Fig. 1. These pictures show that the azimuthal type of mode is dominant at low temperature with highest intensity on the edges of the crystal. However, the type of modes changes while temperature rises (at ~80-100K) and mostly become radial at 300 K, which corresponds to highest electromagnetic energy intensity in the center of the crystal. It is worth saying that changing optical properties of semiconductor is the reason of different mode content. In the simplest cylindrical approximation, it is well known that the frequency of a resonator mode of *m*-order appears to be $\omega \propto mc/Dn$, where $D$ - diameter, $n$ - refractive index, $c$ - speed of light. Therefore, while $D$ is constant, only $n$ can change the type of modes.

## 3. Modelling of optical modes in microcrystals InN

In order to derive the temperature dependence of the refractive index, which is important for computer modelling, the measurements of the integral transmission and reflection spectra were done. Then, we calculated complex dielectric function by applying Kramers-Kronig relations to these spectra:

$$\varepsilon_1(\omega) - 1 = \frac{2}{\pi}\int_0^\infty \frac{x\varepsilon_2(x)}{x^2-\omega^2}dx\,,\ where\ \begin{cases}\varepsilon_1 = n^2 - k^2\\ \varepsilon_2 = 2nk\end{cases}$$

Figure 3 shows the result of the determination of the temperature dependent refractive index for three energies that fall within the emission band of InN.

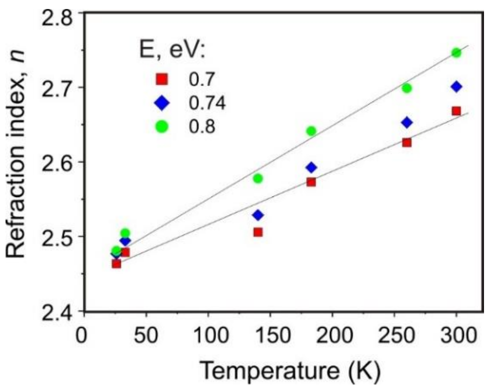



**Figure 3.** Dependence of refractive index on temperature for three different energies in InN emission band

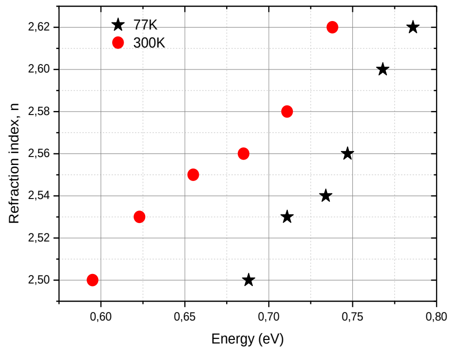



**Figure 4.** Dispersion of refractive index at low (77 K) and room (300 K) temperatures derived from modelling the resonator modes in InN microcrystals.

We have done modelling of optical modes in InN microcrystals using the spectral dependence of the refractive index. Calculation was made in Comsol Multyphysics software that allows to find the frequencies and distribution of intensity of electromagnetic waves inside the resonator by solving the Maxwell's equations. In the first approximation, we used refractive index dispersion that was found earlier. Inverted truncated hexagonal pyramids were replaced by inverted truncated cones, which size (height, and top/bottom radiuses) was obtained by scanning electron microscopy. We chose boundary conditions in order to make rapid decay of wave outside the crystal. After this iteration, more accurate analysis of frequencies was made by varying refractive index, so that experimental and calculated data were in quite agreement with each other. We considered the modes lying between 0.65-0.8 eV, which is inside the InN emitting band. Table 1 presents the optical mode energies, both calculated and detected from μ-PL experiment, along with the reconstruction of the field intensity distributions. Figure 4 shows the values of the refractive index characterizing the crystal material. They increase in the vicinity of the absorption edge, like those derived from analysis of the optical spectra. Besides, we investigated the quality factor of the WGM cavities, which is estimated to be around 200.

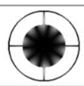
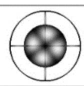
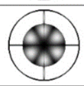
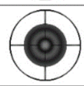
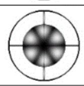
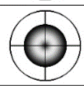
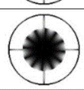
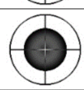
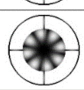
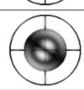
| **77 K** | | **300 K** | |
|---|---|---|---|
| Energy (eV) experim./calc | Field distribution | Energy (eV) experim./calc | Field distribution |
| 0.688/ 0.690 |  | 0.623/0.625 |  |
| 0.711/0.709 |  | 0.655/0.673 |  |
| 0.734/0.721 |  | 0.685/0.685 |  |
| 0.747/0.756 |  | 0.711/0.709 |  |
| 0.768/0.762 |  | 0.738/0.739 |  |

**Table.1.** Experimental and theoretical frequencies of optical modes in microresonators with 2.2 μm in diameter at different temperatures shown together with electromagnetic field intensity distributions.

This theoretical modelling shows that the azimuthal type of the WGMs prevails against the radial at low temperatures. This situation inversely changes at room temperature. We have observed exactly the same in the experiments. The simulations show that the main reason of that associated with the shift of absorption edge towards low-energies when temperature rising. It induces changing the refractive index resulting in the variation of the mode content and the modification of the spatial energy distribution. Besides, the increasing absorption suppresses the modes of higher orders. The modeling reveals also a large gap between the existent modes at the short-wavelength side of the emission band.

Furthermore, we need to draw attention to refractive index in figures 3 and 4. They are a little bit different. The reason of that is the fact that in Fig. 3 the data describe structure as a whole, including microcrystals and a layer between them. As we know, InN is very imperfect material, so the integral spectra have the information not only about absorption edge but the "tail" of states, which are typical for strongly compensated semiconductors [10, 11]. The data in Fig. 4 displays only the optical properties of the InN microcrystals. As we said before, their quality is much higher than those of the area around them. Thus, the second method of establishing refractive index by modelling optical modes in resonators could be more precise to describe their material.

## 4. Summary

Our data testify the possibility of amplification of weak signals in the near IR by means of low-order optical modes in InN microresonators. It is shown that changing the dielectric function of material with temperature affects the type of electromagnetic energy distribution and the frequencies of optical modes. This effect should be considered while designing nanophotonics devices, where selective amplification by WGMs determines working frequencies. Besides, we demonstrate that modelling of optical modes is one of the suitable ways to derive the material dispersion of the refractive index in microcrystals.

**Acknowledgement**

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