Optimization of optical refrigeration in Yb$^{3+}$:YAG samples

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1. Introduction

The vibration modes of all physical systems are a source of thermal energy. The idea to remove the thermal energy from a system optically using anti-Stokes fluorescence was first proposed in 1929 by Peter Pringsheim [1]. Today the area of physics investigating a process by which a physical system cools as a result of interaction with laser light is known as laser cooling or optical refrigeration. The experimental works devoted to laser cooling of solids started in 1995 [2]. In this first proof-of-principle demonstration, a high purity ytterbium-doped fluorozirconate ZrF$_4$–BaF$_2$–LaF$_3$–AlF$_3$–NaF–PbF$_2$ (ZBLANP) glass sample was cooled down by only 0.3 K below room temperature. In 2014 optical refrigeration with record temperature of 114 mK was achieved with a 10% Yb:YLF sample with a room temperature cooling power of 750 mW [3]. Laser cooling of solids with anti-Stokes fluorescence can be realized not only in rare-earth (RE) doped low phonon glasses and crystals, where the ground and the first excited manifolds of RE ions are involved in the cooling cycle, but also in direct band-gap semiconductors, where the valence and conduction bands are involved. Laser cooling of semiconductors is a very difficult task and only CdS nanobelts have been cooled in 2013 with a temperature drop of 40 K starting from room temperature [4]. So far, laser cooling of bulk semiconductors has not been realized. Laser cooling of solids is interesting not only from the fundamental point of view as a process of light and material interaction. The growing interest in optical refrigeration of solids is driven by its application in portable space-based sensor systems.

Since its first experimental observation, laser cooling has been realized with Yb$^{3+}$, Er$^{3+}$, and Tm$^{3+}$ ions doped in a wide variety of low phonon glasses and crystals (see for e.g. the literature reviews [5–7]). Comparing the results from these experiments the most suitable RE ion for laser cooling application is ytterbium (Yb$^{3+}$). Ytterbium has only one excited manifold which is free from excited state absorption, a source of undesirable non-radiative decay resulting in heat generation. However, not only "correctly" chosen RE ions and the host material are needed for the successful realization of the laser cooling process; it is necessary to optimize the shape and size of the sample as well as the ion concentration and pump intensity for achieving very low temperatures.

The aim of this paper is a comprehensive theoretical analysis of optical refrigeration in Yb$^{3+}$:YAG samples with different ion concentrations, shapes and sizes ranging from cm- to the nm-scale. The temperature dependence of parameters of the system is taken into account. The impact of cooperative effects such as re-absorption, energy migration in the dipole–dipole approximation and cooperative luminescence on the cooling process are considered and analyzed for the first time to our knowledge. The preferred ion concentrations for the different sample sizes are determined. The shapes of the samples for different sample size ranges are also suggested.
phonon decay and as a consequence, undesirable heat generation in the system. Yttrium aluminum garnet (YAG) is one of the most widely used optical materials. It has high thermal stability, good chemical resistance, and low phonon energy of $\sim 630$ cm$^{-1}$.

2.1. Optical refrigeration in Yb$^{3+}$:YAG samples

Let us consider the laser cooling cycle in a RE-doped host. In order to realize cooling with anti-Stokes fluorescence, electrons have to be excited from the top of the ground manifold to the bottom of the excited manifold. This implies the pump wavelength has to be in the long wavelength tail of the absorption spectrum, where the absorption cross section is very small. After thermalization accompanied by phonon absorption, anti-Stokes fluorescence photons remove energy from the system (Fig. 1). The small absorption cross section is a source of poor pump power absorption.

In the simplest, idealized scheme, the laser cooling process can be characterized by the cooling efficiency as a difference between the energies of the anti-Stokes emitted and pump photons normalized by the energy of the pump photons [8]:

$$\eta_{\text{cool}} = \frac{\hbar \nu_f - \hbar \nu_p}{\hbar \nu_p} = \frac{\lambda_p}{\lambda_f} - 1,$$

where $\nu_p$ and $\nu_f$ are the frequency and the wavelength of the photons of the pump, $p$, and the mean fluorescence, $f$, respectively. $\hbar$ is Planck's constant. In this ideal and unrealistic picture, free from non-radiative decay, spontaneously emitted photons escape the sample without reabsorption by Yb$^{3+}$ ions. Indeed, total internal reflection (TIR) at the sample boundaries, and energy migration between neighboring ions, which takes place at very high Yb$^{3+}$ ion concentration, is ignored. In a real and realistic system, the cooling efficiency is determined by a relation between the cooling process and the migration of the excited electrons.

The cooling process can be described with the well known rate equation [10]:

$$\frac{dn_2}{dt} = \frac{b_p}{\hbar \nu_p} \eta_{\text{cool}} \nu_p - \left( \frac{b_p}{\hbar \nu_p} (\alpha_p + \alpha_s) \right) + \frac{1}{\mathcal{t}_x} n_2 - X n_2^2,$$

where $n_2$ is the population of the excited $^2F_{5/2}$ level normalized by the Yb$^{3+}$ ion concentration, $N_{\text{yb}}$, in the sample. $\nu_p$ is the pump frequency, $I_p$ is the pump intensity. $\sigma_p(\nu_p)$ and $\sigma_s(\nu_p)$ are the absorption and emission cross sections at the pump frequency. $\tau_x$ is the lifetime of the excited level, $^2F_{5/2}$. In samples with high concentration of ytterbium ions cooperative effects, such as cooperative emission and the migration of the excited electrons become important. In Eq. (5) $X$ is the rate of cooperative emission. The term $X n_2^2$ indicates the loss in the population of the excited level by cooperative radiation from Yb$^{3+}$ ion pairs. In a system with high ion concentration the migration of the excited electrons from ion to ion influences the lifetime of the excited level and can be described by the well known relation

$$\tau_x = \left[ 1 + \frac{9}{16} \frac{n_{\text{nuc}}}{N_0} \right]^{-1},$$

where $N_0$ is the critical concentration of Yb$^{3+}$ ions for which excitation transfer and spontaneous relaxation have equal probability. For Yb$^{3+}$:YAG $N_0 = 2.3 \times 10^{21}$ cm$^{-3}$ [11]. $\tau_x$ is the lifetime of the ions in an infinite medium with index $n$ that is in the bulk Yb$^{3+}$:YAG sample. If the Yb$^{3+}$:YAG sample has small dimensions, much smaller than the wavelength of light, the lifetime $\tau_{\text{xsmall}}$ of the excited level of the Yb$^{3+}$ ion doped in a nanocrystal with refractive index $n_{\text{nuc}}$ surrounded by a medium with index $n_{\text{med}}$ is equal to [12]

$$\tau_{\text{xsmall}} \approx \frac{1}{f(E\Delta)} \left[ \frac{1}{3} \left( \frac{n_{\text{eff}}}{n_{\text{med}}} + 2 \right) \right]^{1/2} n_{\text{eff}},$$

where $f(E\Delta)$ is the oscillator strength for the electric dipole (ED) transition, $\lambda_0$ is the wavelength in vacuum.
\[ n_{\text{eff}}(x) = x n_{\text{nc}} + (1 - x) n_{\text{med}}, \]  
\[ \text{(7a)} \]

where \( x \) is the “filling factor”, which describes the volume fraction occupied by the nanocrystals in the surrounding medium averaged over the wavelength of light. The lifetime of the excited RE ions in nanocrystals may be longer than in similar bulk materials.

The cooling power density in the system of RE-doped host can be estimated as a difference between the absorbed pump power density and the power density removed from the system with anti-Stokes spontaneous, stimulated, and cooperative emission

\[ P_{\text{cool}} = -\hbar \left[ \alpha \left( \lambda_p \right) N_{\text{nc}} - \alpha \left( \lambda_f \right) N_f \right] + \hbar \frac{c}{\lambda} N_f + \frac{\hbar c}{\lambda} N_{\text{nc}} \right] \]

\[ \text{+ } \frac{\hbar c}{\lambda_f} N_{\text{nc}} + \frac{\hbar c}{\lambda_f} \chi N_f^2 \frac{\lambda_f^2}{N_{\text{nc}}}. \]  
\[ \text{(8)} \]

Since most laser cooling experiments have been performed in a vacuum chamber, the same conditions are applied here. Hence, there is only a radiative heat load in the system and the equilibrium temperature of the sample can be calculated following the well known Stefan–Boltzmann law

\[ \nu P_{\text{cool}} = \varepsilon \sigma (T_e^4 - T_s^4). \]  
\[ \text{(9)} \]

where \( T_e \) is room temperature, \( T_s \) is the equilibrium temperature of the sample. \( \varepsilon \) is the hemispherical emissivity of the sample, and \( \sigma \) is the Stefan–Boltzmann constant. \( V \) and \( S \) are the volume and the total surface area of the sample, respectively. The cooling power density, \( P_{\text{cool}} \) is a function of the temperature. Using the transcendent Eq. (9), the equilibrium temperature of the \( \text{Yb}^{3+} : \text{YAG} \) sample can be estimated.

2.2. Phonon modes in \( \text{Yb}^{3+} : \text{YAG} \) nanocrystals

At nano-size level almost all effects become quantized. The phonon density of states (DOS) in nanoparticles is different from the phonon DOS of the bulk material [13]. The phonon DOS of nanocrystals is quantized into discrete levels and low energy acoustic phonons are cut-off. This quantization can affect the thermalization process in the RE-doped nanocrystal. We consider RE-doped nanocrystals as spheres with the radius \( R \). Following Refs. [14–16] we consider a stress-free boundary condition at the surface of the sphere and a finiteness condition on both elastic displacement and stress at the center. The spheroidal modes (vibration with dilation) and torsional modes (vibration without dilation) in this system can be described using the following equations:

\[ 2 \left[ \eta^2 (l + 1) (l + 2) \left( \frac{j_{l+1}(\eta)}{j_l(\eta)} - \frac{j_l(\xi)}{j_{l+1}(\xi)} \right) + \frac{j_{l+1}(\eta)}{j_l(\eta)} \right] \]

\[ + \eta^2 (l + 1) (l + 2) \left( \frac{j_{l+1}(\eta)}{j_{l+1}(\xi)} + \frac{j_l(\xi)}{j_{l+1}(\xi)} \right) \]

\[ + \left( \frac{l(l + 1) (l + 2)}{j_l(\xi)} \right) \left( \frac{j_{l+1}(\eta)}{j_{l+1}(\eta)} - \frac{j_l(\eta)}{j_{l+1}(\eta)} \right) + (l - 1)(2l - 1) \eta^2 = 0, \]  
\[ \text{for } l \geq 0, \text{ and} \]

\[ j_{l+1}(\eta) - \frac{l + 1}{\eta} j_l(\eta) = 0, \]  
\[ \text{(11)} \]

For \( l \geq 1 \), respectively, where \( \eta = \Delta R/\xi, \) and \( \xi = \Delta R/\eta. \) Here \( \Delta R \) is the phonon frequency, \( \eta \) and \( \xi \) are the sound velocities of the longitudinal and transverse modes, respectively. \( j_l \) is the \( l \)th order spherical Bessel function.

3. Results and discussion

The energy levels of the \( \text{Yb}^{3+} \) ions in bulk \( \text{Yb}^{3+} : \text{YAG} \) samples are presented in Fig. 1. These values almost do not change with size of the samples even at the nano-size scale. The experimental investigation of the energy levels of \( \text{Yb}^{3+} \)-doped YAG nanocrystals has been reported in Ref. [17]. The energy levels of 10% doped YAG nanocrystals is almost similar to the energy levels of bulk \( \text{Yb}^{3+} : \text{YAG} \) samples presented in Refs. [17,18]. Stark sub-levels of the \( 2F_{7/2} \) level of \( \text{Yb}^{3+} : \text{YAG} \) nanocrystal are 0 (0), 563 (581), 606 (619), 786 (786) cm\(^{-1}\). Stark sub-levels of the \( 2F_{5/2} \) level of \( \text{Yb}^{3+} : \text{YAG} \) bulk sample are 10,298 (10,327), 10,638 (10,634), 10,905 (10,927) cm\(^{-1}\). The numbers in the brackets are the energies of Stark sub-levels of the \( 2F_{7/2} / 2F_{5/2} \) levels of the \( \text{Yb}^{3+} : \text{YAG} \) bulk sample. The average size of particles investigated in Ref. [17] ranges from 20 nm to 50 nm. The concentrations of \( \text{Yb}^{3+} \) ions in the nanocrystals investigated in this paper are 0.2%, 1%, 2%, 5%, 10%, and 50%. These nanocrystals are prepared by the Pechini method. As seen in Ref. [17] the hydroxyl group (OH\(^{-}\)) does not influence the quenching of luminescence in \( \text{Yb}^{3+} : \text{YAG} \) nanocrystals annealed at 900°C. It is important to note that cooperative effects take place in \( \text{Yb}^{3+} : \text{YAG} \) nanocrystals at significantly lower \( \text{Yb}^{3+} \) concentrations than in similar concentrations of bulk samples [19]. This shift in the concentration threshold can be explained by a gradient of \( \text{Yb}^{3+} \) concentration from the center to the surface of the nanocrystal. This gradient provides higher concentration of the ion pairs at the distorted lattices near the surface of the nanocrystal.

3.1. Optical refrigeration in the \( \text{Yb}^{3+} : \text{YAG} \) samples with different sizes

Let us analyse the \( \text{Yb}^{3+} : \text{YAG} \) samples starting from the external quantum efficiency, \( \eta_{\text{ext}}. \) Since it is the most important parameter characterizing the laser cooling process. Indeed, one needs to know \( \eta_{\text{ext}} \) to obtain the relation for cooling efficiency (1b), which permits an estimation of the efficiency of conversion of absorbed pump power to the cooling power in the system. As an example we consider cube samples with different ion concentrations, and simulate \( \eta_{\text{ext}} \) with relation (3). The relation for the cooling efficiency (1b) also includes the absorption efficiency, \( \eta_{\text{abs}}, \) described with relation (2) where the resonant absorption, \( \alpha_n, \) and background absorption, \( \alpha_b, \) coefficients are functions of the ion concentration. Unfortunately the dependence of the background absorption on the ion concentration for \( \text{Yb}^{3+} : \text{YAG}, \) which depends on the technology of crystal growth, is not available in the literature at the moment. We consider \( \alpha_b \approx 2.2 \times 10^{-4} \text{ cm}^{-1} \) for all ion concentrations. We also estimate the threshold relation between the volume and the total surface area of the sample for a predetermined final temperature of the sample, \( T_c, \) and ion concentration \( N_f. \) As we already mentioned, reabsorption and TIR, which results in an increase in the reabsorption, influences the external quantum efficiency and as a result, the cooling process. The process of fluorescence reabsorption and trapping in solids has been investigated in details in Ref. [9], where a bulk RE-doped cube sample as an example has been considered and relation (4) has been obtained. Following Ref. [9] we have estimated the number of anti-Stokes photons, which leave the \( \text{Yb}^{3+} : \text{YAG} \) sample after emission and do not undergo reabsorption as, \( F_{\text{abs}} = 1 - \cos(\theta) = 1 - \left[ 1 - (1/n_i^2) \right]^{1/2} \approx 0.162 \) that is 16.2%. Here \( n_i = 1.833 \) is the refractive index of the \( \text{Yb}^{3+} : \text{YAG} \) sample. \( \theta = \sin^{-1}(1/n_i) \approx 33^\circ \) is the critical angle for total internal reflection in our system. In the case of the \( \text{Yb}^{3+} : \text{YAG} \) sample with refractive index of 1.49, 25.9% of photons leave the sample without reabsorption, i.e. the decrease in TIR is very important for improving cooling. The reabsorption in the samples increases with the increase in the ion concentration and the size of the samples. The increase in the reabsorption causes a decrease in the external quantum efficiency. The dependence of the external quantum efficiency of the sample, \( \eta_{\text{ext}} \) on its size is illustrated in Fig. 2 for a \( \text{Yb}^{3+} : \text{YAG} \) cube samples with edge \( L, \) and three concentrations of \( \text{Yb}^{3+} \) ions. As one can see in Fig. 3 the increase in the size of the sample causes a decrease in external quantum efficiency.


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analyze the role of cooperative emission in the cooling process, a cube sample with $L=1$ cm and $30\%$ Yb$^{3+}$ concentration is considered with a pump intensity $I_p = 10^{-4}$ W/µm$^2$. The power density of the stimulated emission in this sample is comparable to the power density of the spontaneous emission and estimated to be several $10^{-8}$ W/µm$^3$. The power density of cooperative emission in the sample is negligible compared to the power density removed from the system with spontaneous or stimulated emission and estimated to be $10^{-13}$ W/µm$^2$. In our simulations we used the relation for the emission cross section presented in paper [19]:

$$\alpha_e(T) = [0.44 + 9.5 \exp(-T/165)] \times 10^{-20} \text{ cm}^2. \quad (13)$$

The absorption cross section has been calculated using Eq. (13) and the well known McCumber relation. The change in the mean fluorescence wavelength with temperature has been calculated with the relation

$$\lambda_F (\text{nm}) = 1027.5 \text{ nm} - 0.105 (\text{nm/K}) T(\text{K}), \quad (14)$$

which was obtained using experimental data published in Ref. [21]. From these simulations one can conclude that contrary to the process of migration of the excited electron, which causes significant reduction in the external quantum efficiency, the process of cooperative emission is not important for laser cooling even at high (30%) concentration, and can be neglected.

Let us consider the influence of the size and shape of the sample on the cooling process. From Eqs. (9) and (1b) one can estimate the temperature of the sample as follows:

$$T_s^2 - T_{eq}^2 = \eta_{Samp} \frac{1}{\exp\eta_{ext} \phi} \frac{\lambda_F}{\lambda_{f}} - 1 \left(\alpha_s + \alpha_c \right) I_p, \quad (15)$$

Here we have introduced the parameter

$$\eta_{Samp} = \frac{V}{S}, \quad (16)$$

which we call the geometrical efficiency factor (GEF) of the sample for the cooling process. Of course, a sphere is the best choice for cooling due to its high volume to surface ratio. Indeed, for a sphere sample $\eta_{Samp} = R/3$, where $R$ is the radius of the sphere. For the cube, $\eta_{Samp} = L/6$. As one can see in Eq. (15) if one wants to reach some predetermined temperature, $T_s$, in samples with equal ion concentrations but different sizes, the pump intensity, $I_p$, has to be chosen carefully. Fig. 4 illustrates the dependence of the pump intensity on the edge length, $L$, of the cube sample if the equilibrium temperature of the sample $T_{eq} = 100$ K. As we can see in Fig. 4 the pump intensity has to be increased if one wants to reach, for example, $T_s = 100$ K in a sample with the same shape but with reduced size. This dependence is especially important for samples with low ion concentration. It should be noted that not all predetermined temperatures can be reached using a sample with an arbitrary size. The threshold GEF of the sample for any predetermined final equilibrium sample temperature, $T_s$, can be easily estimated. Let us assume that the pump intensity is equal to the saturation pump intensity. In this case the absorbed power density in the sample is $P_{abs} = N_R \phi \lambda_F \alpha_s$. As one can see in Eq. (1b) the cooling power density generated in the sample in this case $P_{cool} = \eta_{cool} P_{abs}$. Substituting this cooling power density in Eq. (9) and taking into account the relation for sample GEF (16) one can easily estimate the threshold GEF of the sample, $\eta_{Samp}^\text{min}$, for any predetermined temperature of the sample $T_s$, with the relation

$$\eta_{Samp}^\text{min} = \frac{V}{S}.$$
As one can see in Fig. 6, to reach a temperature $T_f$ of the sample, the radius of the fiber causes an increase in the temperature, $T_s$, which can be reached with this fiber. For example, if Yb$^{3+}$ concentration in the fiber is ~15% and one wants to cool it down to $T_s = 100$ K the threshold radius of the fiber has to be $R_f \approx 375 \, \mu$m. This means, as an example, the Yb$^{3+}$:YAG single crystal fiber with a radius of 500 \, \mu m and length 40 mm can be cooled down to cryogenic temperatures. The fiber geometry of the sample can enhance the pump intensity especially with the increase in the length of the fiber; however, spontaneously emitted fluorescence especially at the wavelength with high absorption can deteriorate cooling considerably. However, a narrow band tilted Bragg grating at the wavelength with high absorption may be used to remove fluorescence and improve the cooling process.

### 3.2. Phonon modes in Yb$^{3+}$:YAG nanocrystals

As a sample becomes nano-sized, quantization becomes important. In this part of the paper how quantization of phonon modes influences the cooling process in Yb$^{3+}$ doped YAG sphere nanocrystals is investigated. Using Eqs. (10) and (11) we have estimated the phonon cut-off frequency as a function of the radius of the nanocrystal. In our simulations we assume that the sound velocities of longitudinal and transverse modes are identical with, $v_{l} = v_{t} = 3500 \, \text{m/s}$. This dependence is illustrated in Fig. 6. In Fig. 6 the phonon cut-off frequency increases with decreasing nanocrystal size and can even hinder the thermalization process in very small ($R < 6 \, \text{nm}$) Yb$^{3+}$:YAG sphere nanocrystals. Indeed, to bridge sub-levels ($612 \, \text{cm}^{-1}$) and ($565 \, \text{cm}^{-1}$) in the $^2F_{7/2}$ manifold the phonons with energies equal to or less than 47 cm$^{-1}$ have to be present in the sample. As the radius of the Yb$^{3+}$:YAG nanocrystal increases the phonon cut-off frequency decreases. Fortunately, phonon quantization does not prevent thermalization in nanocrystals with radii of several hundred nanometers, which are suitable for the laser cooling process.

### 3.3. Optical refrigeration in Yb$^{3+}$:YAG nano-powder

We have discussed the laser cooling process in a single sample with cm- or nm-size. In this section, laser cooling in Yb$^{3+}$-doped YAG nano-powder is considered. Nano-powder is an ensemble of nanocrystals arranged in a bulk sample with some “filling factor”, $\chi$ (also known as the porosity of the sample). Nano-crystals can have different shapes: spheres, cubes and so on. They can organize clusters. It is important to note that anti-Stokes spontaneous emission can easily escape a single nanocrystal with very low re-absorption. This is an advantage of nano-samples over the bulk case. The localization of pump radiation can enhance the pump intensity in the sample and enhance the cooling process [22]. But anti-Stokes spontaneous emission will undergo localization as well. If localization takes place, the pump or anti-Stokes photon travels along the “long” path in a sample. This is true at a wave-length with low absorption, $\alpha$. The anti-Stokes radiation at the wavelength with high absorption will be reabsorbed by ions inside the nanocrystal or in the next nanocrystals. The “long” path for anti-Stokes radiation causes a decrease in the external quantum efficiency and deteriorates the cooling process even at low Yb$^{3+}$

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**Figure 4:** The dependence of the cube edge, $L$, on the pump intensity if the equilibrium temperature of the sample $T_s = 100$ K.

**Figure 5:** The dependence of ion concentration on the minimum GEF, $\eta_{\text{Samp}}^{\text{min}}$, if $T_s = 80$ K and 100 K.

**Figure 6:** Phonon cut-off frequency as a function of the nanocrystal radius, $R$. 

\[
\eta_{\text{Samp}}^{\text{min}} = \frac{\epsilon_B (T_f^4 - T_s^4)}{\eta_{\text{cool}} v_{s} (\tau_{p} N_{f} / \eta_{f})}. 
\]
concentration. The volume of the active medium \( V \) in the sample made of nano-powder is less than the volume of the active medium of a similar bulk crystal. As a result we can conclude that the nano-powder can be laser cooled but does not offer any undisputable advantage over a similar bulk sample. The best technique to enhance the pump intensity in the system is to use a Fabry–Perot resonator to trap the pump radiation [23].

4. Conclusions

In this paper optical refrigeration in the Yb\(^{3+}\)-YAG samples with different shapes, sizes, and ion concentrations has been comprehensively investigated. The processes of reabsorption and TIR at the boundaries of the sample as well as cooperative effects such as ion migration and cooperative emission have been taken into account. The temperature dependences of the absorption cross section and mean fluorescence wavelength have been taken into account as well. From the simulations one can conclude that ion concentration influences the cooling process significantly. For samples with sizes on the cm-scale the ion concentration in the range 2–10\% can be recommended. Higher concentrations can lead to deterioration of the cooling process by reabsorption of the anti-Stokes fluorescence photons in the sample. For samples in the \( \mu \)- and nm-scale, the concentration has to be increased up to 30\%. The main advantage of the small single nano-samples is the very small reabsorption permitting the use of relatively high ion concentrations. Samples as small as several hundred nanometers can be cooled with a concentration of \( \sim 30\% \). Greater than 30\% concentration causes migration of the excited electron, which decrease external quantum efficiency significantly and deteriorates the cooling process. As seen from the simulations, the effect of phonon quantization does not influence the cooling process in samples of nano-scale. If nano-crystals are assembled into nano-powder, especially with high porosity, it may be considered more like a bulk sample. Pump radiation can be trapped in such samples, but more importantly, anti-Stokes fluorescence is trapped as well. Reabsorption increases in significance in bulk samples, so that the ion concentration has to be decreased in comparison with the ion concentration in a single nano-sample. The enhancement of pump radiation in bulk samples with a Fabry–Perot resonator, as was reported in a number of experiments, has some advantages over trapping energy within a nano-powder.

The shape of a sample for cooling is also very important. A sphere is the best choice especially for micro- and nano-samples as well as a cube. Of course, a sphere may not be acceptable for laser cooling of a detector from the design point of view. For optical cooling of detectors, a parallelepiped shape of the sample may be more suitable. The pump intensity can be enhanced by using a resonator. But the cross-section area of the resonators must not to be large since anti-Stokes radiation can be trapped. Although the parallelepiped shape can be considered as a good choice for optical refrigeration in a bulk sample, a cylindrical RE-doped fiber can undergo to optical refrigeration as well. A predetermined temperature can be reached with a fiber-shaped sample if the ion concentration, pump intensity, and the radius exceeding the threshold value, are chosen properly. Purification of the host material is very important for all samples and can be considered as a key parameter for the practical realization of optical coolers for any size range from cm- to nm-size.

References