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Effect of heating on the optical properties of Yb^{3+}-doped fibres and fibre lasers

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***Abstract*. The effect of heating on the optical properties of Yb^{3+}-doped fibres is studied. It is shown that the lasing efficiency of fibre lasers depends on the fibre temperature, the type and extent of the effect being substantially dependent on the laser wavelength. It is proposed to use fibre heating to increase the efficiency of lasers emitting in the 1.15 – 1.2-μm region.**

Keywords: *active optical fibres, Yb^{3+}-doped fibre laser.*

1. Introduction

High-power Yb^{3+}-doped fibre lasers pumped into the cladding were recently actively developed and studied [1, 2]. Such lasers find applications for pumping SRS converters in fibreoptic communication systems [2, 3], for processing materials, in medicine, laser rangefinders, etc. A natural requirement imposed on them is the stable output power. The output power can vary, in particular, due to a change in the temperature of the active element caused by variations in the ambient temperature or by the fibre heating owing to excess optical absorption losses. The latter factor is especially important for high-power fibre lasers because in this case even weak optical losses can produce a noticeable heating of the fibre.

Because the emission spectrum of a Yb^{3+}-doped fibre laser and the stability of its output parameters depend on the absorption and luminescence spectra of ytterbium ions doped into the fibre [4, 5], it is interesting to study the effect of temperature on the optical properties of diode-pumped double-clad Yb^{3+}-doped fibre lasers.

2. Energy level diagram of ytterbium ions in fused silica

The energy level diagram of ytterbium ions is very simple. Apart from the $^2F_{7/2}$ ground level, there exists the only $^2F_{5/2}$ excited level, so that transitions between these levels can be used for lasing only due to a strong Stark splitting. The energy level diagram of Yb^{3+} ions is shown in Fig. 1a [4]. The absorption spectra of Yb^{3+}-doped fibres are determined by electronic transitions between the Stark levels and have a complex structure. The narrow 976-nm absorption line corresponds to the transition from the sublevel a to the sublevel e. The 915-nm absorption line corresponds to the transitions from the sublevel a to sublevels f and g. The absorption band at 1034 nm corresponds to transitions from the sublevel b. The corresponding absorption spectrum is shown in Fig. 1b.

The luminescence spectrum consists of a narrow line at 976 nm, which corresponds to the transition from the sublevel e to the sublevel a, and a band at 1034 nm extending approximately up to 1200 nm, which corresponds to transitions from the sublevel e to sublevels b, c, and d.

The peak absorption and luminescence cross sections known from the literature virtually coincide and are

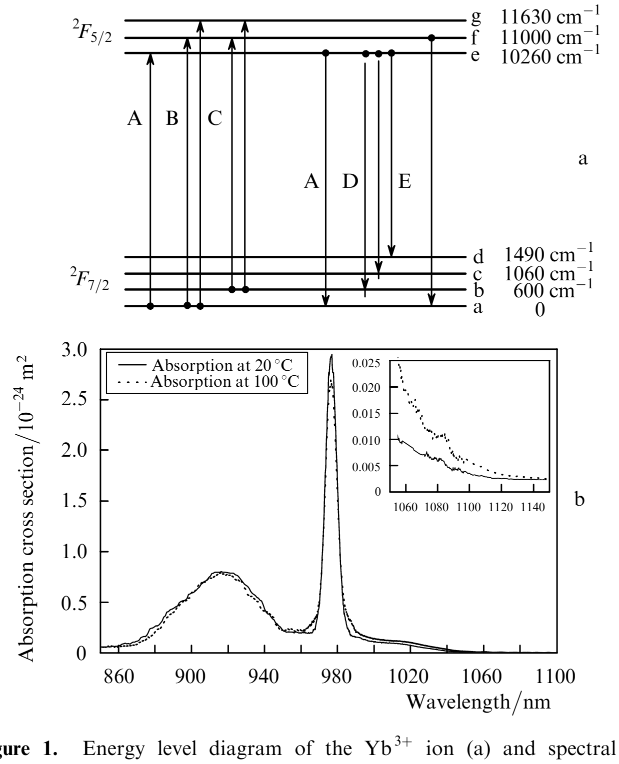

Figure 1. Energy level diagram of the Yb^{3+} ion (a) and spectral dependences of the absorption cross section in the fused silica network at two temperatures (b). The inset shows absorption cross sections in the long-wavelength egion at $T = 20$ and 100 °C.

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2.5×10^{-24} m^2 [4]. The inset in Fig. 1b shows the spectral dependence of the absorption cross section in the 1.06 – 1.2-μm region. The measurements were performed with fibres of different lengths and different concentrations of Yb^{3+} ions. Note that, although the absorption cross section in this spectral region is small, for double-clad fibres it is nevertheless substantial. This is explained by the fact that absorption of pump radiation in such fibres is determined not only by the absorption cross section and concentration of active ions but also the relation between the areas of the doped fibre core and its inner cladding. As a result, the absorption of pump radiation is reduced by two orders of magnitude compared to pumping into the fibre core, so that the inversion degree is, as a rule, less than 50 %. At the same time, the reabsorption of laser radiation occurs in full measure because the radiation propagates only through the fibre core.

Changes in the absorption and luminescence spectra caused by heating are determined by a change in the population of the ith sublevel according to the Boltzmann distribution

$$\frac{N_i}{N} = \frac{\exp(-E_i/kT)}{\sum_i \exp(-E_i/kT)},$$

where N is a total number of particles. Figure 2 shows the Boltzmann distributions over the ground-state sublevels for Yb^{3+} ions calculated as functions of temperature. Therefore, the heating will cause first of all a change in the absorption spectrum because the population of the ground sublevel a decreases with increasing temperature, whereas the population of the sublevel b increases, resulting in a change in not only total absorption but also in the absorption at different wavelengths. The luminescence spectrum in the wavelength region above 1 μm should not change upon heating because all the radiative transitions occur from the same level e.

3. Effect of heating on the absorption and luminescence spectra

We studied the effect of heating on the absorption spectra of several Yb^{3+}-doped alumosilicate fibres with different Yb^{3+} concentrations, different core diameters, and different cladding shapes. This allowed us to perform measurements in a broad spectral range. The data obtained for different samples were 'sewed' at the boundaries of spectral regions studied.

The absorption spectra of the Yb^{3+}-doped alumosilicate fibre measured at temperatures 20 and 100 °C are shown in Fig. 1. One can see that the change in absorption with increasing temperature corresponds to the change in the populations of the levels. Thus, absorption at 976 nm decreases with increasing temperature because the population of the ground-state sublevel a decreases. Absorption at 915 nm also decreases, in accordance with the decrease in the population of the ground-state sublevel a and the increase in the populations of the excited-state sublevels f and g. At the same time, absorption in the 1034-nm band increases because the population of the ground-state sublevel b considerably increases with temperature. Absorption in the long-wavelength tail of this band also increases.

Figure 2 shows the Boltzmann distributions over the ground-state sublevels of the Yb^{3+} ion calculated as functions of temperature. The changes in absorption are in good agreement with these dependences.

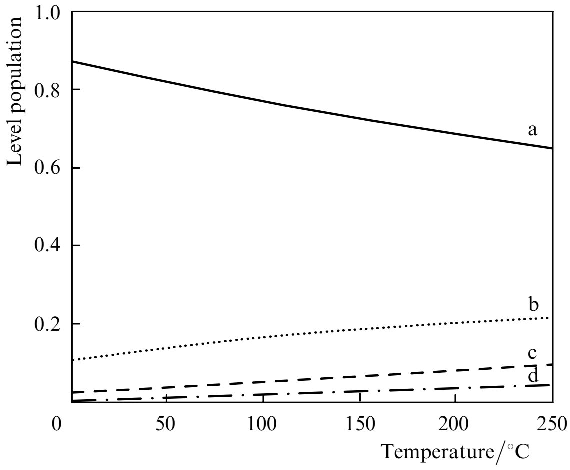

Figure 2. Temperature dependences of the populations of ground-state sublevels of the Yb^{3+} ion.

Note that not only absorption at fixed wavelengths changes with temperature but also the ratio of the absorption coefficients at different wavelengths, which is important in the development of a laser. Because the 915-nm and 976-nm bands correspond to absorption from the same sublevel, the ration of their absorption cross sections does not change strongly. The ratio of the absorption coefficients for transitions from the sublevel a (the 915-nm and 976-nm bands) and the sublevel b (the 1034-nm band) changes with temperature. This strongly affects the amplified spontaneous emission spectrum and, hence, the lasing properties, because emission reabsorption increases with temperature, resulting in the change in the luminescence spectrum of the fibre.

We studied the temperature dependence of the luminescence spectrum of Yb^{3+}-doped fibres using lasers emitting at 915 and 976 nm and bulk samples of thickness 1 – 5 mm, which were cut of the Yb^{3+}-doped fibre performs. The use of bulk samples allows us to avoid amplified spontaneous emission and also to minimise the distortion of the luminescence spectrum due to reabsorption. The typical luminescence spectrum of a bulk sample is shown in Fig. 3. The decrease in the luminescence intensity with increasing temperature is explained by the decrease in absorption at the pump wavelength. A weak shift of the luminescence

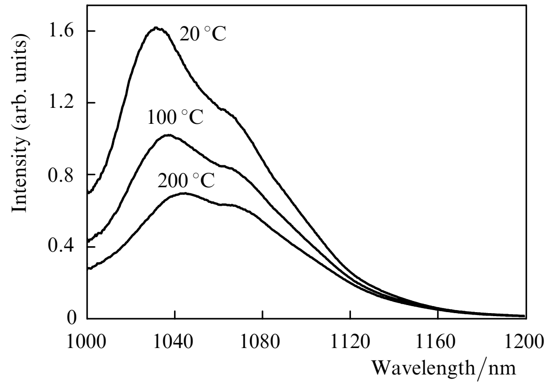

Figure 3. Luminescence spectra of Yb^{3+}-doped preforms at different temperatures.

maximum can be explained by the fact that the effect of reabsorption has not been completely excluded.

4. Effect of heating on the lasing efficiency of fibre lasers

Two mechanisms of the effect of heating on the efficiency of fibre lasers are possible. The first one is related to a change in absorption in the pump band. In this case, a decrease in the output power of the laser can be expected due to incomplete absorption of the pump radiation. However, fibre lasers are pumped, as a rule, by a set of laser diodes emitting at slightly different wavelengths. One can see from Fig. 2 that heating leads to the broadening of the absorption band. Therefore, one can expect that the radiation of diode lasers emitting at wavelengths shifted with respect to the absorption band centre will be absorbed more efficiently. This can compensate for a decrease in the absorption of radiation emitted by other laser diodes at the optimal wavelength. Moreover, if the pump spectrum is shifted as a whole from the absorption band maximum, the lasing efficiency can increase upon fibre heating. Therefore, this mechanism is determined by specific parameters of a pump source.

Another mechanism is related to the increase of absorption in the 1034-nm band and, correspondingly, in its long-wavelength tail. It should be expected that for fibre lasers emitting near the centre of this band, the increase in absorption will result in the decrease in the output power.

Figure 4 shows the lasing spectra of lasers with different sets of Bragg gratings selected to demonstrate various variants of lasing.

Figure 4a shows the lasing spectrum of the laser with Bragg gratings operating at 1064 nm. The laser operates stably at this wavelength at room temperature. As the fibre temperature is increased, absorption in this spectral range also increases, resulting in the decrease in the output power at this wavelength. As the fibre temperature is further increased, the laser begins to oscillate at the wavelength of the maximum of amplified spontaneous emission, and because the resonator is formed in this case due to Fresnel reflection from the fibre ends, the laser operates in a pulsed regime.

Figure 4b shows the lasing spectrum of the laser with the resonator formed by Bragg gratings operating at 1150 nm. Lasing at this wavelength was observed in the entire temperature range studied. Some increase in the output power at the initial stage of heating is explained by a decrease in the intensity of amplified spontaneous emission in the spectral range between 1000 and 1100 nm due to an increase in absorption in this spectral region.

Figure 4c shows the emission spectrum of the laser with a set of Bragg gratings operating at 1180 nm. In this case, the luminescence power at room temperature is substantially lower than that at the luminescence maximum so that no lasing appears at 1180 nm, and as the pump power is increased, lasing appears in the region of the luminescence maximum. The reabsorption of luminescence increases with temperature. As a result, the intensity of the short-wavelength part of the luminescence band decreases so that the conditions for lasing in the long-wavelength region are satisfied.

Figure 5 shows the temperature dependences of the output power of lasers. The lowering of the output power

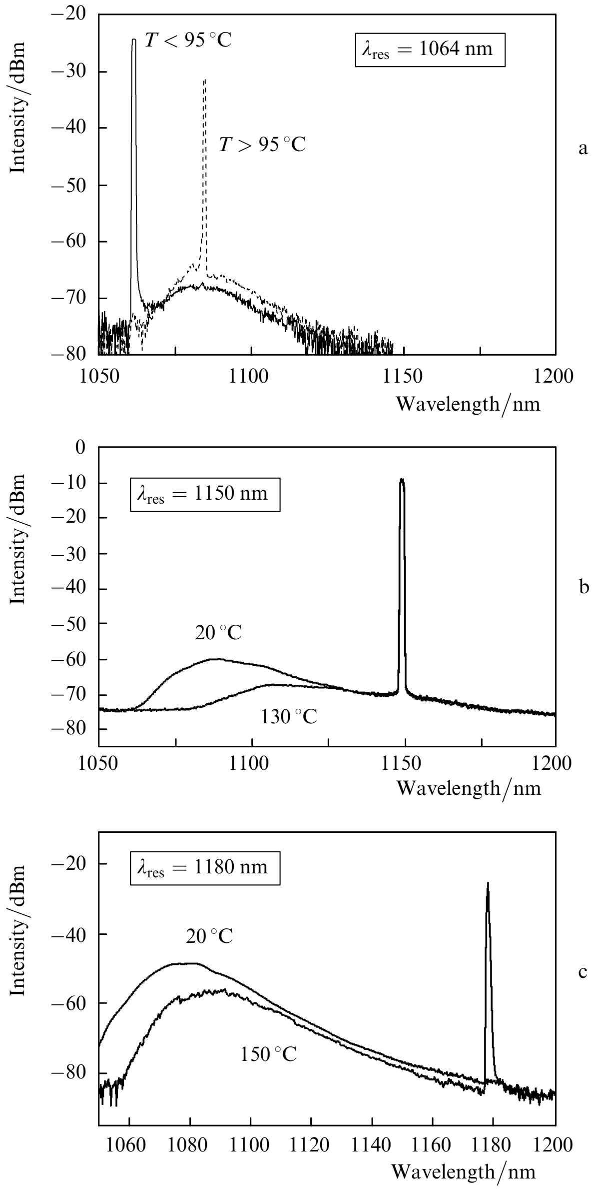

Figure 4. Emission spectra of lasers with resonators producing different output wavelengths λ_{res}.

at 1064 nm with increasing temperature is explained by the reduction in the population inversion due to the decrease in

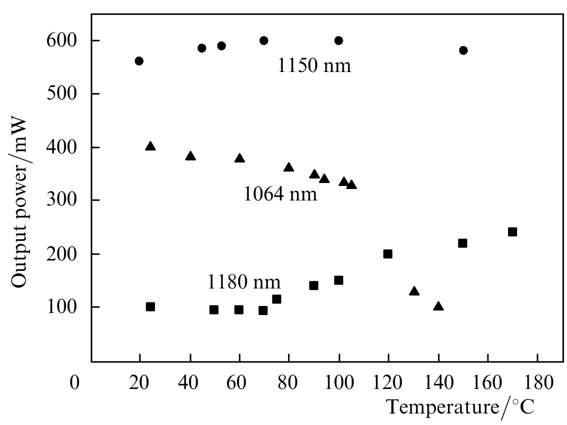

Figure 5. Temperature dependences of the output power of lasers.

absorption of pump radiation and also by the increase in reabsorption of the signal. Then, lasing at these Bragg gratings quenches at a certain temperature. The output power of the 1150-nm laser first increases somewhat at the initial heating stage, which is explained by the decrease in the intensity of amplified spontaneous emission in the 1000 – 1100-nm range due to the increase in absorption in this spectral region. The reduction of the output power at temperatures above 100 °C is explained by the fact that the growth of the absorption band tail begins affect the 1150-nm wavelength.

The effect of temperature on the luminescence spectrum is most distinct in the long-wavelength tail of the spectrum, at wavelengths longer than 1150 nm. No lasing occurs at room temperature in the laser with the 1180-nm Bragg gratings due to a strong competition with amplified spontaneous emission. As temperature was increased, the suppression of amplified spontaneous emission was observed, providing the condition for lasing at 1180 nm. Lasing appeared at 70 °C and the lasing efficiency increased with increasing temperature. The slope lasing efficiency achieved 30 % at temperature 150 °C.

5. Conclusions

We have shown that the optical properties of Yb^{3+}-doped fibres depend on temperature. This dependence should be taken into account in the development of fibre lasers operating at high or variable temperatures because the output parameters of the laser change substantially upon fibre heating or cooling. In addition, the temperature dependence can be used to increase the lasing efficiency or to obtain lasing in the long-wavelength part of the luminescence spectrum of Yb^{3+} ions, where no lasing occurs at room temperature. To demonstrate temperature effects, we have built the Yb^{3+}-doped fibre laser with Bragg gratings emitting at 1180 nm with the lasing efficiency ~ 30 % at 150 °C.

References

1. Kurkov A.S., Karpov V.I., Laptev A.Yu., Medvedkov O.I., Dianov E.M., Gur'yanov A.N., Vasil'ev S.A., Paramonov V.M., Protopopov V.N., Umnikov A.A., Vechkanov N.I., Artyushenk V.G., Fram Yu. *Kvantovaya Elektron.*, **27**, 239 (1999) [*Quantum Electron.*, **29**, 516 (1999)].
2. Kurkov A.S., Paramonov V.M., Egorova O.N., Medvedkov O.I., Dianov E.M., Yashkov M.V., Gur'yanov A.N., Zalevskii I.D., Goncharov S.E. *Kvantovaya Elektron.*, **31**, 801 (2001) [*Quantum Electron.*, **31**, 801 (2001)].
3. Dianov E.M., Kurkov A.S., Medvedkov O.I., Paramonov V.M., Egorova O.N., Kurukitkoson N., Turitsyn S.K. *Laser Phys.*, **13** (3), 1 (2003).
4. Pask H.M., Carman Robert J., Hanna David C., Tropper Anne C., Mackechnie Colin J., Barber Paul R., Dawes Judith M. *IEEE J. Sel. Topics Quantum Electron.*, **1** (1), 2 (1995).
5. Kurkov A.S., Dianov E.M., Medvedkov O.I., Ivanov G.A., Aksenov V.A., Paramonov V.M., Vasiliev S.A., Pershina E.V. *Electron. Lett.*, **36**, 1015 (2000).