Energy transfer processes are very important in solid-state laser systems because they can cause an enhancement of the luminescence emission, resulting in a reduction of the laser threshold. This is usually achieved by the introduction of an ion of a different type, called sensitiser or donor, into the laser host material in addition to the ion, called activator or acceptor, which is responsible for the laser emission. The donor ion absorbs strongly at the pumping source energy, and transfers this excitation energy to the acceptor.

Most of the research on LiYF₄ (YLF)-based crystals has addressed problems such as the laser threshold, output energy versus input energy curve, laser pulse characteristics, etc. [1–10]. A systematic study of the excited state dynamics of Tm ions and (Tm)³F₄→(Ho)⁵I₇ energy transfer in YLF samples with different Ho concentrations was reported in 1988 [11, 12]. Ho³⁺ lasing action assisted by energy transfer has also been observed in other host materials doped with Tm³⁺ and/or Er³⁺ ions [13–15].

We report the temperature dependence of (Tm)³F₄→(Ho)⁵I₇ energy transfer in YLF. This crystal has the following advantages over the other host materials for substituting rare-earth impurities: (i) the rare-earth ions can be substituted in the Y³⁺ sites without charge compensation, (ii) the electronic levels of the dopands have longer lifetime since YLF has a low phonon cut-off energy. This gives a better energy storage capability for the laser.

The energy levels of Tm and Ho in YLF are shown in Fig. 1. The interaction between the rare-earth ions and the crystal field of the host lattice is not strong, but does affect the energy transfer process for two reasons. First, in many cases the energy transfer process is assisted by phonons, whose frequency and population at a certain temperature depends on

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Fig. 1. Energy levels of Tm and Ho in LiYF₄
the host. Second, thermal vibrations may also affect the positions and width of sharp levels; even if such effects are small, they may be important in the case of resonant transfer.

1 Experimental and samples

The absorption spectra of the samples at room temperature were obtained by using Perkin Elmer Lambda 19 spectrophotometer. The absorption spectra at low temperatures were obtained by measuring the transmission spectra with the equipment used for the continuous luminescence measurements.

The luminescence spectra were obtained by using the following sources: a Jarrel Ash 30-W tungsten halogen lamp, a Sharp Corp. model LTO24MFO diode laser, and a Charent Inc. model 526 Ar ion laser. The luminescence was observed at 90° with respect to the direction of the excitation to reduce the noise. The signal in the infrared region was analyzed by using a Spex model 1681B Spex 0.22 meter monochromator, and detected by a Spex model 1428 PbS detector which is placed in a Spex model 1427 housing. The signal in the visible region was analyzed by a Spex model 1269 1.26-m scanning monochromator and detected by a RCA model C31034 photomultiplier (having a GaAs photocathode) cooled by a Hakee Buchler Instruments Inc. model Kl refrigerator. Both signals were amplified by a Stanford Research Systems model SR510 lock-in amplifier, processed and stored by a Spex Industries model DM1B spectrometer controller and data processor.

The excitation spectra were obtained by selecting and varying the wavelength of the incident radiation by means of a Spex model 1681B 0.22-m monochromator. The responses to pulsed excitation measurements were done by exciting the samples with a Quantel International model TDL-51 tunable dye laser pumped by a Quantel International model 660A 10 Nd:YAG laser. The length of the pulses produced by these lasers was much shorter than the decay times measured. The signal was detected by a Judson Infrared Inc. model J12TE2 InAs detector, amplified by an Analogic Data Precision Data 6000 waveform analyzer.

For the measurements below 300 K, the sample was mounted in either a Janis Research model 8DT cryostat or a CTI-Cryogenics model 12 cold-head model SC-21 compressor. The sample temperature was varied from 8 to 300 K by using either a Lake Shore Cryotronics model DRC-80C or a Spectra Physics model 5720 digital thermometer/controller.

2 Experimental results

The following experiments were carried out for three samples: YLF:Tm(0.5%), YLF:Ho(1%), and YLF:Tm(5%), Ho(0.2%). The crystals were grown by Czochralski technique [4].

2.1 Absorption and continuous luminescence measurements

The absorption spectra of the samples were obtained to find out whether any additional levels appear in the double-doped sample due to the interactions between Tm and Ho ions. The spectra obtained at room temperature show that the spectrum of the double-doped sample is simply superposition of the absorption spectra of Tm and Ho in YLF.

Figure 2 shows the luminescence spectra of the samples in the visible region at 300 K. The Ar ion laser tuned at 460 nm, which excites Tm ions into the \(^{3}G_{4}\) level and Ho ions into the \(^{3}K_{8}\) level, was used as the excitation source. The spectra of the single-doped samples in the infrared (IR) region (see Fig. 3a,b) were obtained by exciting the samples with the 30-W tungsten halogen lamp. The IR spectrum of double-doped sample was obtained by exciting only the Tm ions into their \(^{3}H_{6}\) level with the diode laser tuned at 795 nm and is given in Fig. 3c. The spectrum is simply the overlap of the spectra of the (Tm) \(^{3}F_{4}\) → \(^{3}H_{6}\) and the (Ho) \(^{5}I_{7}\) → (Ho) \(^{5}I_{8}\) transitions. This is an evidence that shows the energy transfer from Tm to Ho.

The temperature dependence of the integrated intensity of the (Tm) \(^{3}F_{4}\) → \(^{3}H_{6}\) transition was measured for two different directions of the excitation: (i) The direction of the exciting light was parallel, and the luminescence from the sample detected was perpendicular to the c axis of the sample. (ii) The direction of the excitation source was perpendicular, and the luminescence from the sample detected was parallel to...