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Experimental investigation of the 2.1-μm single-mode Tm-Ho : KYF laser

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ABSTRACT We report on the development and comprehensive characterization of a room-temperature single-mode 2-μm Tm-Ho : KYF laser. A maximum CW output power of ∼ 70 mW at the central wavelength of 2.078 μm has been obtained. Using a 5-mm long intracavity birefringent filter the single-mode emission wavelength can be tuned over a range of ∼ 40 nm. Both frequency and relative intensity noise have been investigated showing a 1-ms emission linewidth of ∼ 600 kHz and an intensity noise spectrum that is quantum-noise limited for Fourier frequencies higher than 1 MHz.

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1 Introduction

Widely-tunable solid-state lasers operating around the 2-μm wavelength play an important role in remote sensing, high-resolution spectroscopy, frequency metrology, biomedical applications, and frequency synthesis of mid-infrared wavelengths. Different solid-state lasers have been investigated to date for efficient generation of 2-μm coherent radiation, including Tm-doped and Tm-Ho co-doped oxide crystals [1–3], Tm-doped and Tm-Ho co-doped fluoride crystals [4, 5], Tm-doped fiber lasers [6], and transition metal lasers [7]. Because the Tm and Tm-Ho co-doped systems can be efficiently pumped by semiconductor lasers, they are natural candidates for the realization of compact, efficient, and long operating lifetime solid-state oscillators needed for the implementation of airborne optical systems. As compared to Tm-doped lasers, lasing action in Tm-Ho codoped deserves a major interest owing to the lasing emission in holmium, which occurs at wavelengths longer than in thulium (i.e., around 2.1 μm), and with a wider tunability range. Fluoride crystalline matrices, as compared with the oxide matrices, are attractive materials for laser applications, thanks to their low phonon energy, which makes them suitable hosts for IR laser transitions. In addition, the negative variation of the index of refraction with temperature leads to a reduced thermal lensing under strong pumping conditions.

In this paper, we report on the development of a 2-μm room-temperature single-frequency laser oscillator with 40-nm wavelength tunability range, based on a diode-pumped KYF_4 (KYF) fluoride crystal co-doped with ions of Tm and Ho. This novel material is characterized by a slight internal disorder, producing a broad emission band [8] that can be exploited for the realization of widely-tunable continuous wave oscillators, as well as for the generation of femtosecond pulses in the 2-μm spectral region. The laser oscillator design and its full characterization in the CW regime, in terms of output power, wavelength tunability, relative intensity noise (RIN) and frequency noise are presented in the following sections. To the authors' knowledge, this is the first demonstration of single-frequency laser action in this fluoride material. Due to the wide wavelength tunability and the very-low intensity noise, this oscillator may find direct applications in the fields of coherent Doppler lidar systems, high-resolution spectroscopy, and frequency metrology.

2 Laser configuration

A schematic drawing of the Tm-Ho : KYF laser cavity is shown in Fig. 1. The laser resonator consists of two plane mirrors and one curved mirror with a total resonator length of ∼ 180 mm. The active material, a Brewster cut $6.5 \times 7.0 \times 1.9\ mm^3$ sample of KYF_4 crystal is co-doped with Tm^{3+} at $5.38 \times 10^{20}\ ions/cm^3$ and Ho^{3+} at $5.2 \times 10^{19}\ ions/cm^3$ [8], corresponding to a nominal doping level of 5.2% and 0.5%, respectively. The Tm-Ho : KYF crystal is placed in the short-

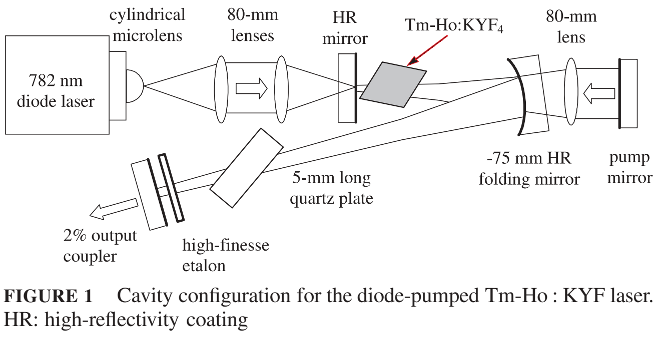

FIGURE 1 Cavity configuration for the diode-pumped Tm-Ho : KYF laser. HR: high-reflectivity coating

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est arm of the resonator (42 mm long), close to the high-reflectivity (HR, reflectivity > 99.9% at 2.1 μm) plane input mirror. The HR curved mirror has a radius of curvature of 75 mm and is used to fold the laser resonator with an angle of 22°, which compensates for the astigmatism introduced by the active medium itself. The second arm of the resonator is terminated by the output coupler, a plane mirror with 2% transmission at the laser wavelength. In this arm are located the optical components needed for the laser wavelength tuning (birefringent filter) and the single longitudinal mode selection (high-finesse etalon).

The Tm-Ho : KYF crystal was grown in a computer-controlled resistive Czochralski furnace in a 5N-purity argon atmosphere at a temperature of 805 °C (see [9] for more details). The spectra are considerably broadened, due to some amount of disorder in the host matrix [9, 10]. The crystal was oriented by X-ray backscattering Laue technique and Brewster cut with the *c*-axis tilted by 33° relative to the polished faces. In this way the TM-polarized laser field (polarization selected by the Brewster incidence) is parallel to the *c*-axis inside the crystal and the largest emission cross-section of holmium ion can be exploited [8].

The Tm-Ho : KYF crystal is longitudinally pumped by a GaAlAs laser diode with an emission wavelength of 782 nm. In principle, for each absorbed pumping photon two Tm^{3+} ions are raised in the $^3F_4$ excited state by means of a cross-relaxation process between the Tm^{3+} levels $^3H_4 \rightarrow {}^3F_4$ and $^3H_6 \rightarrow {}^3F_4$. The population inversion in the Ho system is obtained by means of a resonant energy transfer process between the Tm ($^3F_4 \rightarrow {}^3H_6$) and Ho ($^5I_8 \rightarrow {}^5I_7$) ions. The pump beam is focused into the KYF crystal through the HR plane mirror (overall transmission 92% at 782 nm) using a pair of uncoated spherical lenses with focal lengths of 80 mm. To provide higher pump absorption a doubled pass scheme is adopted, where the unabsorbed pump beam coming from the folding mirror is back reflected into the cavity using a spherical lens (80 mm of focal length) and a plane mirror [11]. In this way a more uniform inversion profile along the active medium is obtained, which strongly reduces the unwanted re-absorption losses in this quasi-four-level laser oscillator. To minimize the Fresnel reflection at the Brewster faces of the active medium also the pump beam is TM polarized. In the double-pass pumping configuration the absorbed pump power is ∼ 63% of the incident one. During the laser experiments the Tm-Ho : KYF crystal is held in a copper heat sink directly mounted on a Peltier cooler, which is used to remove the pump-generated heat and to keep the crystal at a temperature near 20 °C. In order to exploit the broad emission spectrum of the $^5I_7 \rightarrow {}^5I_8$ holmium transitions a 5-mm thick quartz plate, with the optical axis parallel the plate faces, is placed at Brewster angle into the laser resonator close to the output coupler, as shown in Fig. 1. The quartz plate is mounted on a precision rotator to allow for a fine control of the angle between the optical axis and the laser field; in this way it is possible to finely control the emission laser wavelength. The birefringent filter has a free-spectral range of ∼ 100 nm around 2 μm. Single-longitudinal-mode selection is obtained using the birefringent filter and a high-finesse intracavity fused-silica etalon. The etalon, 150-μm thick and coated for a reflectivity of 80% at the laser wavelength, is placed within the cavity close to the output coupler where the beam divergence is minimum.

3 Characterization of the single-mode Tm-Ho : KYF laser

Figure 2 shows the laser output power as a function of the absorbed pump power. A maximum single-frequency output power of 70 mW at 2.08 μm is achieved for ∼ 1 W of absorbed pump power; the optical to optical slope efficiency is ∼ 10%. In the same figure the multimode characteristic (without etalon in the laser cavity) is also reported. When compared to multimode operation [11], the single-frequency performance is clearly degraded (increasing of the threshold power and reduction of the slope efficiency) due to additional losses of the coated etalon, which are estimated to be around 1.5%. These losses are also responsible for an additional thermal load in the active material, resulting in a slight saturation of the output power characteristic. Without the intracavity etalon the laser operates on several longitudinal modes with a typical emission bandwidth of ∼ 1.8 nm. As an example, Fig. 3 shows the output spectrum of the multi-

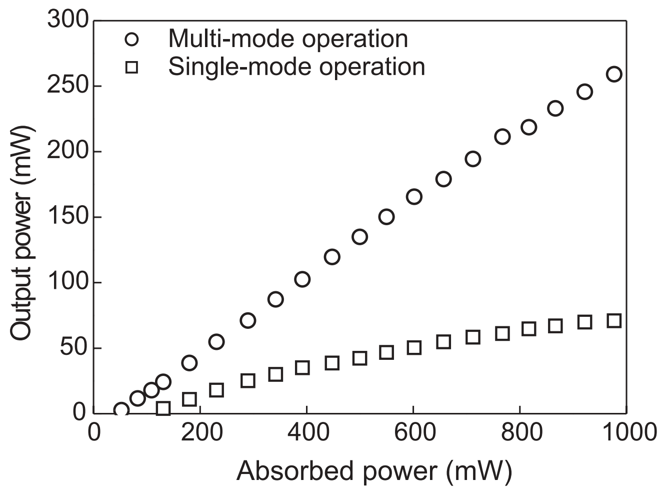

FIGURE 2 Tm-Ho : KYF output power versus incident pump power for 2% output coupling in multimode (*open circles*) and single-mode (*filled circles*) operations

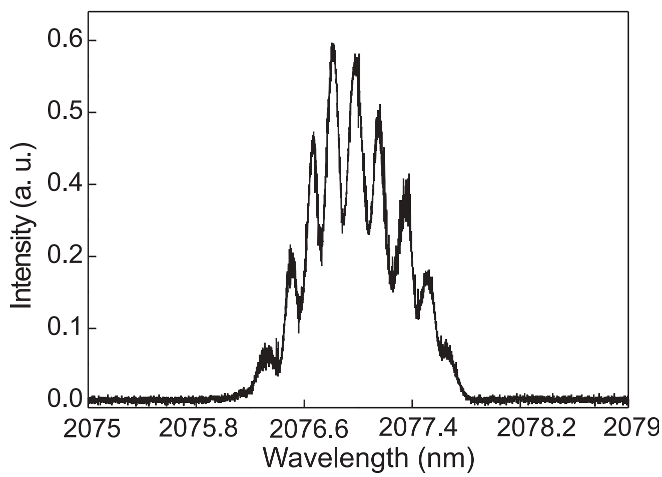

FIGURE 3 Multi longitudinal mode output spectrum of Tm-Ho : KYF laser

mode laser recorded with a 0.1-nm resolution monochromator. Nine different longitudinal modes separated by 0.2 nm, corresponding to 14 GHz, are resolved. When the high-finesse etalon is placed within the resonator, only one of these longitudinal modes is selected. The single-frequency operation is monitored by means of a scanning Fabry–Pérot interferometer with 50 GHz of free spectral range and a frequency resolution of 0.37 GHz, which can easily resolve the laser longitudinal mode separation of 0.8 GHz. A typical spectrum of the Tm-Ho : KYF laser operating in a single longitudinal mode is shown in Fig. 4 for an output power of 50 mW, corresponding to an absorbed pump power of ~ 0.6 W.

The single-mode 2-μm radiation is characterized by an excellent linear polarization with measured extinction ratio of ~ 30 dB, due to the use of two intracavity elements placed at the Brewster angle (the active medium itself and the birefringent filter), and can be tuned from 2.06 μm to 2.1 μm combining the rotation of the birefringent filter with the tilting of the etalon.

Important properties of optical sources for high-sensitivity measurements are low RIN and high spectral purity. Intensity noise in solid-state lasers is induced by external sources of acoustical, mechanical and thermal noise as well as by pump power and pump wavelength fluctuations. In particular, the RIN spectrum is strongly enhanced at around the relaxation oscillation frequency, which is usually located in the range between a few tens of kilohertz and a few megahertz. A peculiar feature of the Tm-Ho laser is that the noise sources acting on Tm (like pump power fluctuations) are filtered out by both the cross-relaxation process between Tm^{3+} ions (one $^3H_4$ excited Tm ion gives rise to two ions in the $^3F_4$ level) and the energy transfer process between Tm^{3+} and Ho^{3+} ions. It follows that pump noise effects are strongly reduced [12]. To characterize the RIN of the developed Tm-Ho : KYF laser the 2 μm radiation is focused onto a 5-MHz bandwidth, low-noise photodetector. The power spectral density of the output photocurrent, which is directly proportional to the spectrum of the laser power, is then measured with an electrical spectrum analyzer. The RIN spectrum is shown in Fig. 5, where the quantum-noise floor corresponding to the value of

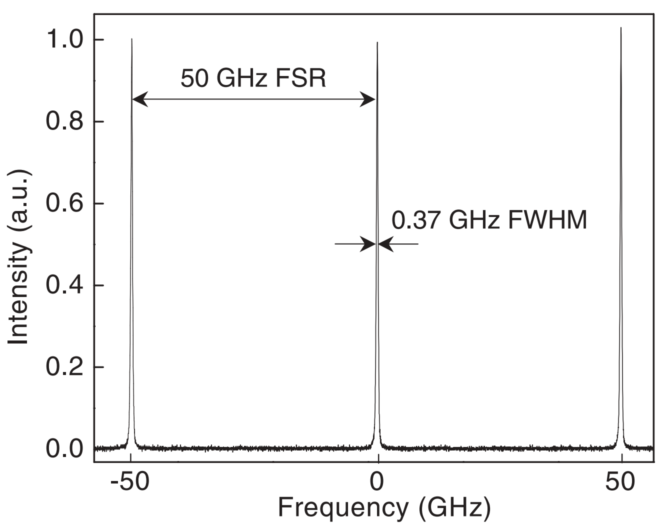

FIGURE 4 Single-frequency output spectrum of Tm-Ho : KYF laser

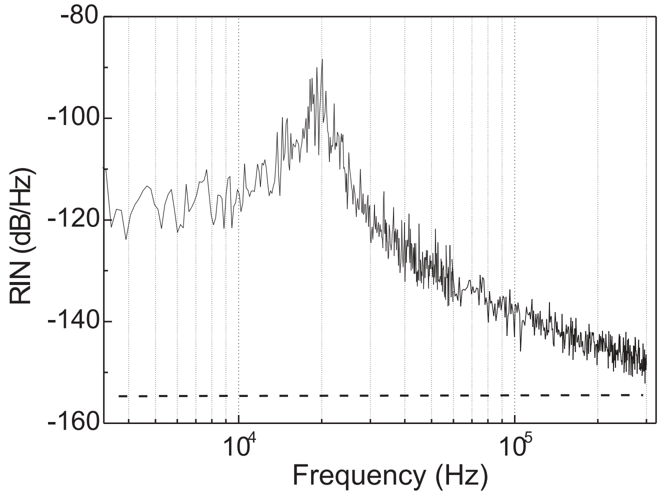

FIGURE 5 Relative intensity noise spectrum of the single-frequency Tm-Ho : KYF laser

-155 dB/Hz is also reported. The relaxation oscillation of the laser system is located at the frequency of 20 kHz and the corresponding RIN peak value is -90 dB/Hz. For Fourier frequencies lower than 10 kHz, the RIN level is of the order of -120 dB/Hz; for frequencies higher than 20 kHz the RIN, which is mainly induced by the intensity noise of pump radiation, rapidly decreases reaching the quantum-noise limit for Fourier frequencies higher than 1 MHz. The -20 dB/decade slope is due to the complex nature of Ho excitation process that involves pump photon absorption by Tm, Tm-Tm cross-relaxation and finally the Tm to Ho energy-transfer process. These results are in good agreement with those reported for the more common Tm-Ho : YAG laser system [13].

The measurement of the spectral noise density of the laser frequency fluctuations is based on a Fabry–Pérot interferometer in the fringe-side configuration [14]. The interferometer has a free spectral range of 10 GHz and a resonance linewidth of 120 MHz. The frequency discrimination is performed by using the side of the resonance fringe around the point corresponding to half the peak transmission, to convert the laser frequency deviations into variations of the transmitted power. A balanced detection scheme is adopted to cancel to first order the laser intensity noise [14]. The difference between the currents generated in the reference and transmission photodiodes is sent to a low-noise transimpedance amplifier (1-MHz bandwidth), the output voltage of which is therefore proportional to the laser frequency deviations. This output voltage constitutes the discrimination signal and is used both to evaluate the laser frequency noise and to lock the Fabry-Pérot resonance to the laser frequency through a low-bandwidth control circuit. The feedback circuit keeps the laser frequency locked to the side of the cavity resonance with a control bandwidth of approximately 20 Hz. The slope of the frequency discriminator signal is $17.4 \times 10^{-9}\,\mathrm{V\,Hz^{-1}}$. In this way the spectrum of the error signal contains the converted laser frequency noise for the Fourier components above 20 Hz. The measured spectral density of the laser frequency noise, obtained by the spectral density of the error signal, is shown in Fig. 6. In this figure the dashed line represents the experimental noise floor corresponding to $30\,\mathrm{Hz^2/Hz}$.

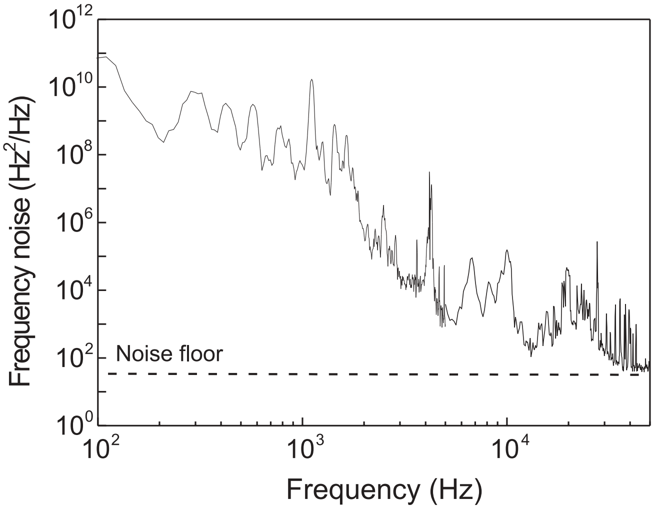

FIGURE 6 Spectral density of the Tm-Ho : KYF frequency noise

The measured power spectra density of the laser frequency noise can be fitted by a polynomial expression $S_{\Delta\nu}(f) = k_{-5} f^{-5} + k_{-2} f^{-2} (\mathrm{Hz}^2/\mathrm{Hz})$ with $k_{-5} = 3 \times 10^{21}\,\mathrm{Hz}^6$ and $k_{-2} = 10^{13}\,\mathrm{Hz}^3$. The noise peaks at ~ 1 kHz, ~ 4 kHz, ~ 10 kHz, and ~ 25 kHz, are probably ascribable to mechanical resonances of the laser setup. From the measured spectral density, according to Joss et al., [15], the laser lineshape can be calculated. To this purpose, only the dominant contribution $k_{-2} f^{-2}$ (random walk frequency noise) is considered, the k_{-5} contribution being much less significant. After defining the oscillator bandwidth, $B_{-2} = \pi(0.5 k_{-2} T_{\mathrm{obs}})^{1/2}$, where T_{obs} is the observation time, it follows that the power spectrum lineshape of the laser, in the case $B_{-2} T_{\mathrm{obs}} \gg 1$, is approximately Gaussian with a Full Width at Half Maximum linewidth given by $\Delta\nu_{-2} \cong 4(\ln 2)^{1/2} B_{-2} \cong 2 \times 10^7 (T_{\mathrm{obs}})^{1/2}$ Hz. For observation times in the order of 1 ms, this laser shows therefore a typical linewidth of ~ 600 kHz. These results compare favourably with those obtained for other free-running diode-pumped solid-state lasers, such as Nd : YAG, and in particular with the Tm-Ho : YAG [16].

4 Conclusions

A novel diode-pumped Tm-Ho : KYF laser at 2.08 μm was developed with excellent characteristics in terms of cw output power, wavelength tunability, linear polarization, and with low intensity and frequency noise. A comprehensive characterization of single-frequency 2 μm Tm-Ho : KYF laser has been performed. A maximum single mode output power of 70 mW with 10% slope efficiency has been obtained. Wide tunability of 40 mm, from 2060 nm to 2100 nm, has been demonstrated. The statistical frequency noise, as measured by a Fabry–Pérot interferometer used in the fringe-side configuration and locked to the laser, is characterized by a random walk process leading to a 1-ms linewidth of ~ 600 kHz. The RIN shows a peak value of -90 dB/Hz at the relaxation oscillation frequency of 20 kHz and decreases with increasing frequencies; for Fourier frequencies higher than 1 MHz, the limit is set to -155 dB/Hz by the shot noise.

Due to the wide tunability and the low frequency and amplitude noise characteristics, this laser may become a real competitor of the more popular Tm-Ho : YAG and Tm-Ho : YLF oscillators for many applications in high-resolution spectroscopy, frequency metrology, and remote sensing.

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