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Characteristics of single longitudinal mode oscillation of the 2 μm Tm,Ho:YLF microchip laser

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Abstract

The lasing condition and frequency stability of the single longitudinal mode oscillation of a diode laser pumped 2 μm Tm,Ho:YLF microchip laser at room temperature are reported. It is shown that the microchip laser with an output mirror of 99.0% reflectivity had better single longitudinal mode performance than that with an output mirror of 99.5% reflectivity. The frequency tuning rate when varying the crystal temperature was estimated to be 1.9 GHz/°C. Frequency stability of the microchip laser is examined by the self-beating heterodyne detection method for several delay times between 0.48 and 4.8 μs. It is indicated that the spectral fluctuation is in proportion to the delay time and the increasing rate is 2.3 kHz/μs. © 2001 Published by Elsevier Science B.V.

Keywords: Microchip laser; Tm, Ho:YLF laser; Eye-safe laser; Coherent lidar; Doppler lidar

A 2 μm laser is expected to apply to a lidar, a range finder, and an optical source for communication because of eye safety and good transparency in the atmosphere. Especially, it is important for coherent lidar applications to investigate the operating stability of the single frequency mode oscillation of the 2 μm laser. There are several laser crystals, such as Tm,Ho:YAG, Tm:YAG and Tm,Ho:YLF lasing in the 2 μm region. Two orthogonally polarized mode oscillations in Tm,Ho:YAG microchip laser were observed by Killinger et al. [1]. On the other hand, a cw Tm,Ho:YLF laser can oscillate in the linear polarized mode due to the optical anisotropy of YLF crystal [2–4]. In addition, a microchip laser is very useful for obtaining the single mode oscillation because of the short cavity length (~1 mm). Therefore, a lot of papers on lasing characteristics of microchip lasers have been published until now [5–8]. But only a few papers of Tm,Ho:YLF microchip lasers have been published concerning frequency stability of the single mode oscillation

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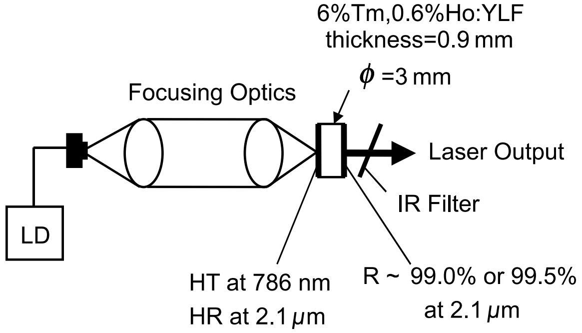

Fig. 1. The experimental scheme of the Tm,Ho:YLF microchip laser. HT: high transmission, HR: high reflectivity.

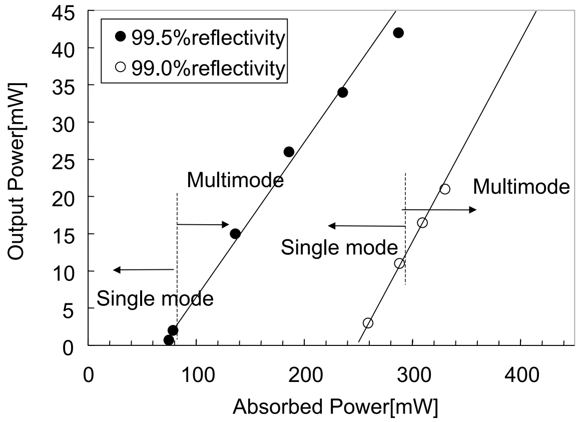

Fig. 2. The output power of two microchip lasers with different reflectivities of the output mirrors as a function of the absorbed pump power. The crystal temperature was kept constant at 20 °C.

[9–11]. The frequency stability of the 2 μm microchip laser was measured for only a 1.5 μs delay time by Izawa et al. [11]. To our knowledge, time dependence of lasing frequency stability in the microchip laser has not reported. Frequency fluctuation is very important to application of the microchip laser as the seeder of the coherent lidar. In this paper, the single longitudinal mode lasing condition of the Tm,Ho:YLF microchip laser is reported, and we clear the relation between the frequency stability and the delay time by changing the length of an optical fiber.

The Tm,Ho:YLF microchip laser system was fabricated to measure the oscillation characteristics. Fig. 1 shows its experimental scheme of the Tm,Ho:YLF microchip laser. A fiber-coupled 1 W laser diode (LD) with an oscillation wavelength of 786 nm is used as a pump source. The output power of the 1 W LD is focused onto the end surface of the Tm,Ho:YLF microchip laser. The Tm,Ho:YLF laser crystal is doped with 6% Tm and 0.6% Ho ions. The YLF crystal is oriented with its *a*-axis parallel to the polarization vector of the pump laser to utilize the higher π spectrum absorption. The microchip laser crystal has a thickness of 0.9 mm and a diameter of 3 mm, whose both surfaces are flat and parallel. We prepared two microchip crystals with two different output mirrors having 99.0% and 99.5% reflectivities at 2.1 μm, respectively. One surface of the crystal is coated with high transmission at 786 nm and high reflectivity at 2.1 μm, whose surface is used as a total reflector, and the pump power was focused onto this surface. The minimum spot size of the pumping beam was measured to have a diameter of 150 μm and was kept constant during the experiments. The output surfaces are coated with 99.0% and 99.5% reflectivities at 2.1 μm, respectively. The output power was measured by using a cw powermeter beyond a silicon plate for protection from the pumping beam. The single longitudinal mode was monitored with a scanning Fabry–Perot interferometer, while the oscillation wavelength was measured with a monochrometer for every experiment.

Fig. 2 shows the output power as a function of the absorbed pump power at the crystal temperature of 20 °C. The lasing threshold values in Fig. 2 are clearly different for the cases of the output mirrors with 99.0% and 99.5% reflectivities, respectively. The former case (99.0% reflectivity) is measured to be 250 mW, while the latter case (99.5% reflectivity) is 80 mW. It means that low cavity loss leads to low threshold value. The slope efficiencies relative to the absorbed pump power are 25% for the former case and 20% for the latter case, respectively. The maximum output power for the former case in the single longitudinal mode oscillation is 11 mW, while for the latter case that is 2 mW. The oscillation wavelength for the former case was 2.0623 μm in the single mode region below an output power of 11 mW. In the region above 11 mW, two mode oscillations with 2.0623 and 2.0639 μm were observed. From the spacing between these different oscillation wavelengths, we calculated the cavity length of 0.9 mm, which agrees with the other direct measurement result using a microscope. The oscillation wavelength for the latter case (99.5%) was 2.0617 μm over the very narrow single mode region. Above this region multimode oscillation was observed. At the absorbed pump power of 140 mW, three oscillation wavelengths of 2.0617, 2.0633, and 2.0651 μm were observed. With increasing absorbed pump power, four mode oscillations occurred. At the absorbed pump power of 300 mW, the oscillation wavelengths were 2.0625, 2.0641, 2.0655, and 2.0671 μm. With increasing absorbed pump power, the lasing wavelengths shifted towards longer values. This phenomenon is resulted from a thermal effect based on the increase of the absorbed pump power [12]. Similar phenomena were also observed in previous experiments [13]. This phenomenon can be explained by the changes of the absorption and emission profiles with temperature. The expansion of the cavity length took place by the thermal effect due to the increase of the absorbed pump power. At the same time, the increase of the population in the upper laser level occurred due to the increase of the absorbed pump power, which decreased the threshold of the lasing. As a result, the center of the each oscillation wavelength shifted toward the longer wavelength and the multimode oscillation occurred. Since the active length of the microchip laser is very short, the difference in the cavity loss produces the different lasing performance.

Fig. 3 depicts the frequency tunability and the output power of the microchip laser with the output mirror of 99.0% reflectivity as a function of the crystal temperature. The input power was kept constant during experiments to keep the single mode oscillation. With increasing the temperature from 18 to 23 °C, the oscillation wavelength increases from 2.06227 to 2.06240 μm (this frequency difference is 9.5 GHz), therefore the frequency shift rate equals to 1.9 GHz/°C. This value is in reasonable agreement with the other experimental results of 1.5 GHz/°C [9]. These phenomena are attributed to the increasing the population in the lower laser level [13] and the thermal expansion of the crystal length. The output power is 4.4 mW

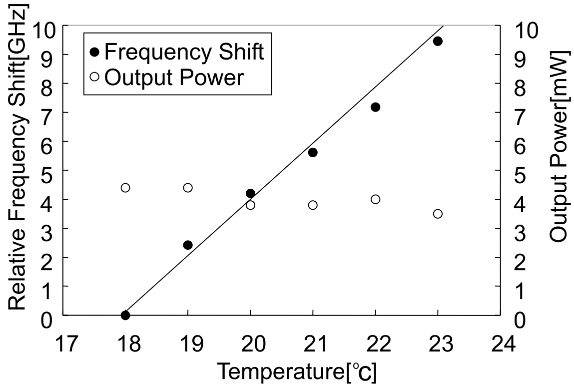

Fig. 3. The frequency shift of the oscillation and the output power in the single mode when changing the crystal temperature. The absorbed pump power of 250 mW was kept constant during experiments.

at the crystal temperature of 18 °C. When reaching the temperature of 23 °C, the output power decreases gradually to 3.5 mW, whose decrease is also due to the thermal effect. The increase of the crystal temperature increases the population of the lower laser level, though the pumping rate to the upper laser level remains constant because of the constant absorbed power. As a result, the number of the population inversion decreases with increasing the crystal temperature. Therefore, the output power decreases with increasing the crystal temperature [14].

To estimate frequency stability of the single mode oscillation of the 2 μm Tm,Ho:YLF microchip laser, we applied the self-beating heterodyne detection method. Fig. 4 shows the experimental configuration. For this measurement, the output laser beam was separated into two beams. To one of these beams, a frequency shift of 40 MHz (f_0) with an acousto–optic modulator was added, and the other was temporally delayed by passing through an optical fiber. The optical fiber used in this measurement is the single mode fiber for the purpose of optical communication. Two laser beams were mixed again on the surface of an InGaAs detector for the heterodyne detection. We estimated the frequency stability of this microchip laser by the relative fluctuation of the beat frequency spectrum (relative frequency fluctuation, f'). By changing the length of the optical fiber, we

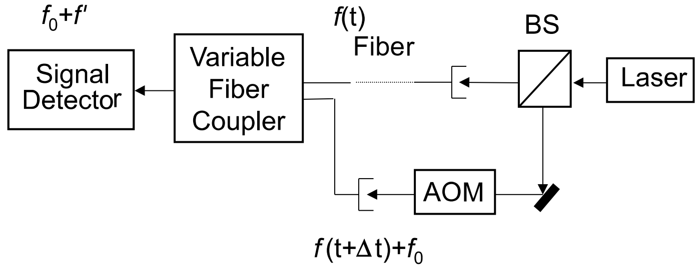

Fig. 4. The configuration of the self-beating heterodyne detection method. BS: beam splitter, AOM: acousto-optic modulator, f: laser frequency, f_0: frequency shift, Δt: delay time, f': relative frequency fluctuation.

measured the relation between the relative frequency fluctuation and the delay time. In this measurement, we used the microchip laser with the output mirror of 99.0% reflectivity. During each experiment we kept the input power constant, and confirmed the oscillation wavelength of 2.062 μm in the single longitudinal mode. The temperature of the laser crystal was controlled at 20 °C. The relative frequency fluctuation was measured over the period of 3 min integrated time by the spectrum analyzer with the frequency resolution of 300 Hz. We estimated the frequency stability by the width (FWHM) of the relative frequency fluctuation averaged temporally. At 0.48 μs delay time (a 100 m optical fiber), the width of 1.7 kHz was observed. Fig. 5 depicts the relative frequency fluctuation integrated for 3 min with a 400 m optical fiber (1.9 μs delay time). The width is 5.2 kHz in Fig. 5. At 4.8 μs delay time (a 1000 m optical fiber), the width was measured to be 11 kHz. Fig. 6 shows the width as a function of the delay time. In Fig. 6, it is indicated that the width of the relative fluctuation, that is the spectral fluctuation, is in proportion to the delay time during 0.48–4.8 μs. The increasing rate is 2.3 kHz/μs. And every data indicate that the width of the relative frequency fluctuation is much better than the required frequency stability for wind velocity measurement by the 2 μm coherent lidar.

In conclusion, we measured the characteristics of the single longitudinal mode oscillation of the 2 μm Tm,Ho:YLF microchip laser at room temperature for the purpose of applications in the coherent lidar for wind measurement. The single longitudinal mode oscillation depends on the reflectivity of the output mirror considerably, and a

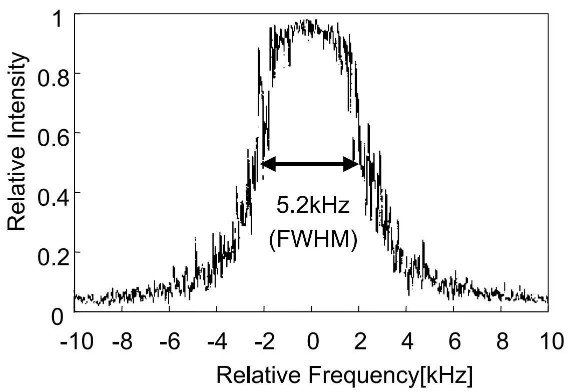

Fig. 5. The width of the relative frequency fluctuation integrated for 3 min with a 400 m optical fiber (1.9 μs delay time). During experiments the absorbed pump power and the temperature of the laser crystal were kept at 260 mW and 20 °C, respectively. The oscillation wavelength was almost constant at 2.062 μm and the output power of 4.7 mW was kept constant.

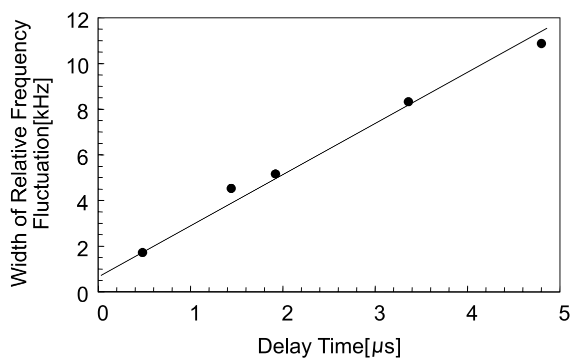

Fig. 6. The width of the relative frequency fluctuation as a function of the delay time. All experimental conditions are the same as those of Fig. 5.

maximum output power of 11 mW in the single longitudinal mode was obtained with the output mirror of 99.0% reflectivity at the oscillation wavelength of 2.062 μm. The frequency tuning rate when changing the temperature of the laser crystal was estimated to be 1.9 GHz/°C, which was quite similar to previous measurements. The width of the relative frequency fluctuation was measured to be 11 kHz with a 1000 m optical fiber (4.8 μs delay), which is estimated to be enough frequency stability required for measuring with the wind velocity accuracy of 0.1 m/s. From the self-beating detection, the proportional relation between the lasing fluctuation and the delay time was shown, and its rate was 2.3 kHz/μs. These results have important implications for use of the Tm,Ho:YLF microchip laser in the heterodyne detection coherent lidar.

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