All-fiber Tm-Ho Codoped Laser Operating at 1700 nm

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We demonstrate continuous-wave operation of an all-fiber thulium-holmium codoped laser operating at a wavelength of 1706.3 nm. To realize laser operation in the short-wavelength region of the emission-band edge of thulium in silica fiber, we employ fiber Bragg gratings having resonant reflection at a wavelength around 1700 nm as a wavelength-selective mirror in an all-fiber cavity scheme. We first examine the performance of the laser by adjusting the central wavelength of the in-band pump source. Although a pump source possessing a longer wavelength is observed to provide reduced laser threshold power and increased slope efficiency, because of the characteristics of spectral response in the gain fiber, we find that the optimal pump wavelength is 1565 nm to obtain maximum laser output power for a given system. We further explore the properties of the laser by varying the fiber gain length from 1 m to 1.4 m, for the purpose of power scaling. It is revealed that the laser shows optimal performance in terms of output power and slope efficiency at a gain length of 1.3 m, where we obtain a maximum output power of 249 mW for an applied pump power of 2.1 W. A maximum slope efficiency is also estimated to be 23% under these conditions.

Keywords : Fiber laser, Tm-Ho codoped laser, Medical laser, Fiber Bragg gratings
OCIS codes : (140.3510) Lasers, fiber; (060.2320) Fiber optics amplifiers and oscillators; (060.3735) Fiber Bragg gratings

I. INTRODUCTION

For decades since the development of optical-fiber amplifiers [1], fiber lasers have been studied extensively, with several advantages such as ease of alignment, high wall-plug efficiency, excellent spatial beam profile, small footprint, and better power-handling capability compared to counterparts among bulk solid-state lasers. Optical fibers doped with rare-earth elements such as erbium (Er), ytterbium (Yb), thulium (Tm), or holmium (Ho) were mostly used as the gain medium in fiber lasers. Thulium-based gain in silica typically covers a spectral band from 1800 to 2100 nm, called the "eye-safe" wavelength region, and fiber lasers based on this become attractive light sources for applications including laser surgery of biological tissue, light detection and ranging, remote environmental sensing, and free-space optical communication [2-5].

The fluorescence of thulium in silica glass, originating from the $^3F_4$$^3H_6$ transition, can potentially extend the range of operation to shorter wavelengths around 1700 nm, where rich spectroscopic features can be found due to the C-H, O-H, and C-O bond resonances. In particular, hydrocarbons contained in some materials show strong absorption at wavelengths around 1700 nm because of the C-H bond resonance, whereas water has a local minimum in absorption in this wavelength range. This feature allows selective treatment of hydrocarbon-containing sites such as fat in the human body, while the surrounding tissue containing high water content remains unaffected. Therefore, a laser source around 1700 nm could be potentially used in medical treatment applications, such as effective removal of lipid-rich tissue without significant damage to other tissues of high water content [6, 7].

There have been several efforts to realize fiber lasers operating at wavelengths around 1700 nm. As a recent approach, the authors in [8] suggested using bismuth (Bi)

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-doped germanosilicate optical fibers as an active gain medium to cover wavelengths around 1700 nm. Although there have been intensive studies to understand and develop both continuous-wave (CW) and pulsed laser operation at 1700 nm in Bi-doped fibers [9-12], several issues such as relatively low quantum efficiency, thermal effects, and photobleaching effects in the gain medium remain unsolved. Another approach to the realization of a 1700-nm fiber laser is to use the short-wavelength band edge of the emission spectrum in thulium-doped fiber (TDF) or thulium-holmium-doped fiber (THDF) gain media, originating from the $^3F_4$$^3H_6$ transition. Continuous-wave (CW) operation in a TDF laser was reported by optimizing the gain length with a core-pump scheme [13]. In this work, the laser delivered wavelength-tunable output by adjusting the period of a fiber Bragg grating (FBG) included in the laser cavity. More recently, a mode-locked THDF laser covering the wavelength band of 1700~1800 nm was reported, employing an acousto-optic tunable filter in the cavity [14]. In this work, a hybrid mode-locking scheme by frequency shifting and nonlinear polarization rotation was exploited to deliver subpicosecond optical pulses at laser output. In addition, an optical amplifier with a complex configuration based on thulium-doped-fiber gain medium in this wavelength region was also studied [15]. However, it is still difficult to access the band edge around 1700 nm in thulium gain medium due to notable three-level behavior and signal reabsorption during laser operation.

In the present work, we demonstrate a compact thulium-holmium codoped all-fiber laser operating at a wavelength of 1706.3 nm. We first study the spectral properties of amplified spontaneous emission (ASE) in THDF gain while adjusting the gain fiber length. We then build an all-fiber laser, including FBGs that exhibit high reflectance around 1700 nm. The FBG enables efficient lasing at a wavelength around 1700 nm, while suppressing ASE and parasitic lasing at the band center located around 1800 nm. After integrating two FBGs into the laser cavity, we investigate the laser's operating properties as functions of pump power, pump wavelength, and gain length, to optimize laser operation. Finally, we observe stable CW laser operation of the THDF laser at a wavelength of 1706.3 nm, where a maximum power of about 250 mW is achieved for an applied pump power of 2.1 W.

II. EXPERIMENTAL SETUP

The ASE spectrum of the fiber gain medium is measured to study its fluorescence in the short-wavelength region of the $^3F_4$$^3H_6$ transition of thulium in silica. The gain fiber used in the measurement is commercial TDHF (CoreActive TH530), where the ion concentrations of Tm_2O_3 and Ho_2O_3 are 0.9 wt% and 0.15 wt% respectively. An amplified laser diode at a wavelength of 1565 nm is used as a core-pumping source to generate the ASE signal.

Figure 1 shows the measured ASE spectra for two different lengths of gain fiber. The central wavelength of the ASE spectrum for a gain length of 1 m is measured to be 1839 nm. When the gain length is reduced to 0.5 m, the central peak of the ASE spectrum shifts to a shorter wavelength of 1829 nm because of the spectral characteristics of absorption and the emission cross section of thulium [13]. The relative power-level difference at 1700 nm from the peak position in the ASE spectrum is measured to be about -15.1 dB and -24.9 dB respectively for gain-medium lengths of 0.5 m and 1.0 m. This indicates that it would be preferable to use a shorter gain length for lasing at short wavelengths in the THDF laser. However, it should be also considered that a longer gain-length fiber is more advantageous in terms of pump-power absorption for a given system. Thus it is important to carefully design a laser cavity, considering the parameters such as gain length and reflectivity of the mirror, for optimal laser operation.

Figure 2(a) shows the schematic of the laser cavity used in the experiment. A tunable laser diode (Photonetics TUNICS-PRI) and an Er-doped fiber amplifier covering C-band wavelengths are used as a source that pumps the THDF through a wavelength-division multiplexing (WDM) coupler, as described in the figure. Two FBGs having a resonance around 1700 nm are placed on either side of the gain medium, as wavelength-selective, highly reflective mirrors. The laser output port is connected with an angled fiber connector, to suppress parasitic reflection that deteriorates laser operation. The reflection spectra of the two FBGs (FBG1 and FBG2) used in the experiment are shown in Fig. 2(b), where their reflectances are measured as 93.8% and 91.6% respectively. The FBG is fabricated by side-exposure of an ultraviolet laser to photosensitive fibers attached to a phase mask. The 20-mm length of FBG1 and FBG2 show resonance at a wavelength of 1706.25 and 1706.28 nm, with 3-dB spectral bandwidth of 0.298 and 0.295 nm, respectively. The inset of Fig. 2(b) shows a microscopic image of the fiber core illuminated by red light, in which the observed periodic interference fringe indicates that a grating is well written at the core of
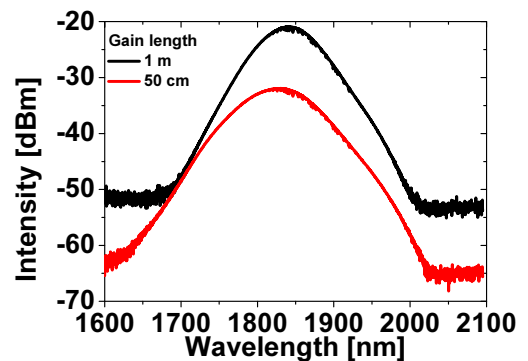

FIG. 1. ASE spectrum of the THDF used in our experiment. The ASE spectra measured for different lengths (black line: 1 m, red line: 0.5 m) of THDF are compared.
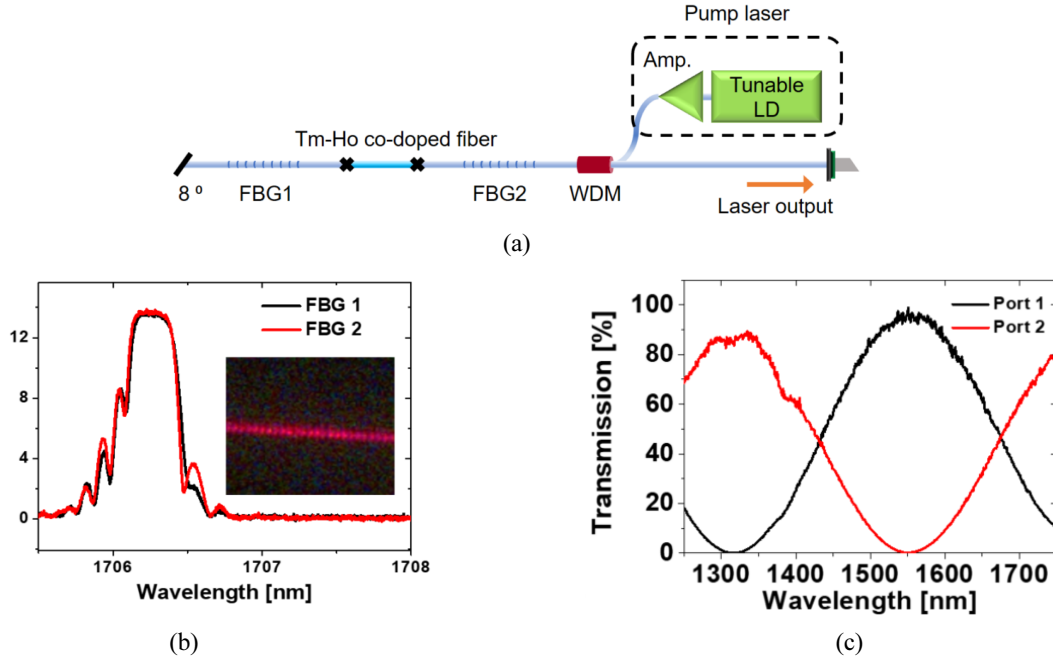
(a)

(b)

(c)

FIG. 2. (a) Schematic of the laser cavity and (b) reflection spectra of the FBGs used in the experiment. The inset figure shows a microscopic image of the fiber core in the FBG when illuminated by red light. (c) The performance of the WDM coupler used in the experiment.

the fiber. Figure 2(c) shows the performance of the WDM coupler, characterized using a broadband supercontinuum source and an optical spectrum analyzer. We use a commercial 1310~1550 nm WDM coupler as an alternative for our experiment, since a 1550~1700 nm WDM in-line coupler is not commercially available at present.

III. RESULTS AND DISCUSSION

The laser operation was studied for a 0.5-m-long THDF first. Figure 3(a) shows the spectral response of laser output as a function of pump power. An absorptive spectrum was observed at the FBG resonance for a relatively low power

of the pump source at 1565 nm. Laser operation starts from a pump-power level of 1.35 W, where we can clearly observe a converted spectrum at the wavelength of 1706.3 nm, as shown in Fig. 3(a). We measure laser output power by adjusting the pump power, Figure 3(b) showing the result. The measured power increased linearly with increasing pump power, with a maximum output power of 4.71 mW achieved at an applied pump power of 2 W. The estimated slope efficiency is 0.69%. We expect that such a low quantum efficiency mainly comes from low pump-power absorption at this short length of the gain medium.

We next explore the laser output characteristics by varying pump wavelength for a given length (0.5 m) of gain medium. The central wavelength of the pump source
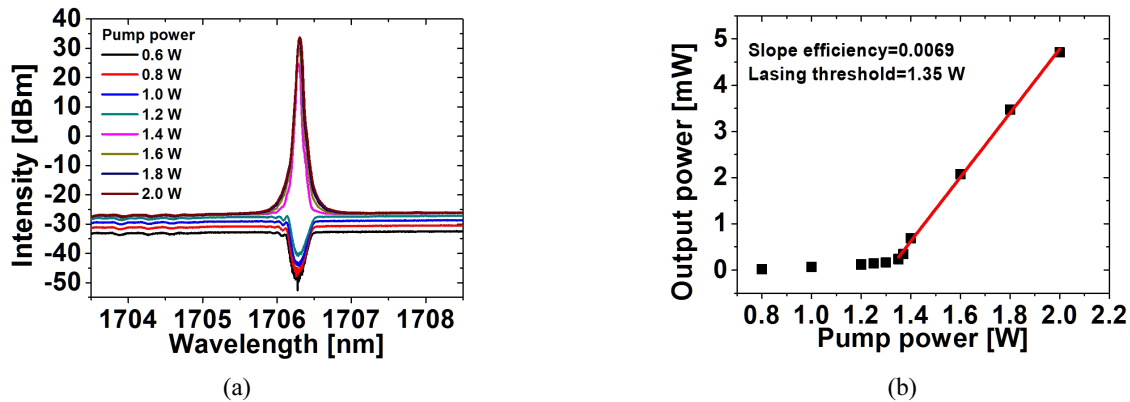

(a)

(b)

FIG. 3. Output characteristics of the THDF laser with 0.5-m gain length: (a) optical spectrum around the lasing wavelength, (b) laser output power as a function of pump power.

is controlled by adjusting the wavelength of the tunable laser diode. Figure 4(a) shows the monitored laser output power as a function of pump power, for several different wavelengths of the pump source. It is clearly observed that laser threshold power is reduced for a pump source at a longer wavelength, because of the spectral response of the absorption cross section in the THDF. However, the Er-doped fiber amplifier used for amplification of the pump laser generally shows limitation in achievable power at longer wavelengths, which leads to reduction of laser output power, as shown in Fig. 4(a). Estimated slope efficiency and laser threshold power are compared in Fig. 4(b), for several pump sources having different wavelengths. It is clear that the laser threshold power decreases from 1.80 W to 1.29 W as we shift the pump wavelength from 1550 nm to 1570 nm. The slope efficiency was also enhanced by 17% at 1570 nm, compared to that at 1550 nm. Therefore, it is generally better to employ a longer-wavelength pump source. However, considering the maximum pump power achieved using a given Er-fiber based amplifier, we can conclude that a pump source at 1565 nm is optimal for obtaining the highest laser output power at 1700 nm.

To scale up output power, we further investigate the laser performance by increasing the gain-fiber length. We measure the absorbed power in the gain medium by the cut-back method, where the estimated pump absorption per length was 0.054 dB/cm at a wavelength of 1565 nm. We conduct laser experiments by reducing the gain length from 1.4 m, where the pump power absorbed by the THDF is about 7.5 dB. When we test laser operation under different gain lengths ranging from 1.0 m to 1.4 m, the laser stably operates at around 1700 nm in all cases, because the FBGs have high reflectance. Figure 5(a) summarizes the laser performance as a function of fiber gain length. Owing to the increased pump-power absorption at long lengths of THDF, we can achieve relatively high laser output power for a given pump power. The pump-power threshold is measured similarly to be about 1.1 W in all cases. The maximum power achieved is 249 mW at a THDF length of 1.3 m, when a pump power of 2.1 W is applied at 1565 nm. Estimated slope efficiency is shown in Fig. 5(b). The slope efficiency shows an optimum value when the 1.3 m-long-length THDF is used, as shown in that figure, where the maximum slope efficiency is measured to be 23%.

It should be noted that a slope efficiency of 23% is relatively low, considering the in-band pumping scheme of
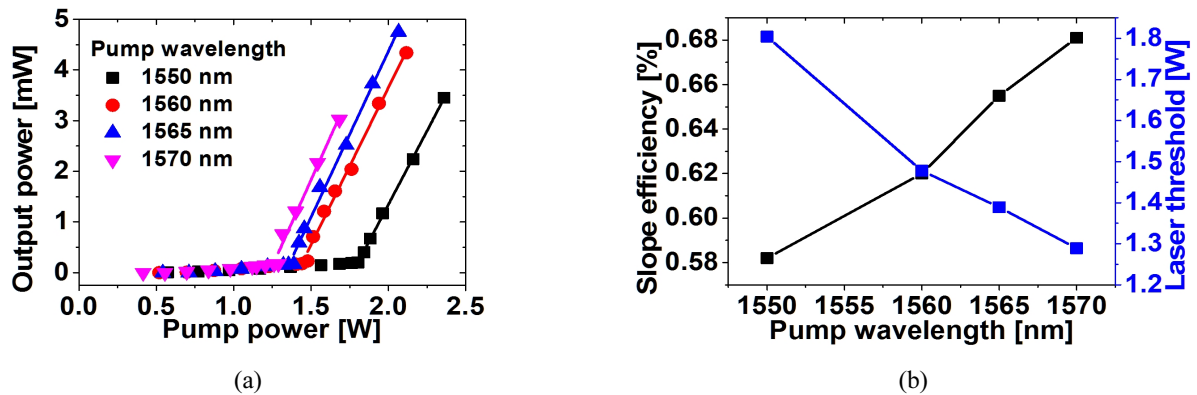

FIG. 4. (a) Characteristics of THDF laser output power for different pump wavelengths. (b) Comparison of estimated slope efficiency and laser threshold power obtained from (a).
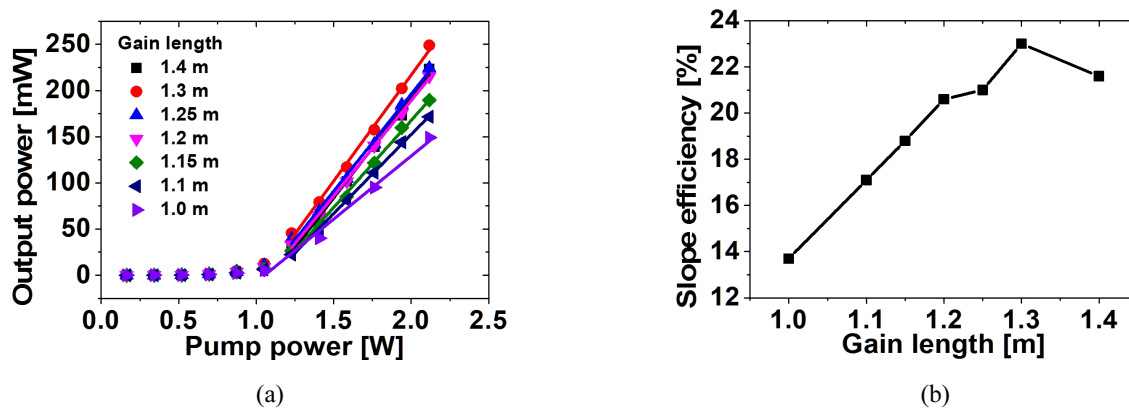

FIG. 5. (a) Laser output properties of the THDF laser as a function of fiber gain length. (b) Estimated slope efficiency for different gain lengths. The maximum slope efficiency was measured to be 23% at a gain length of 1.3 m.

our fiber laser. By numerical simulation with a commercial simulator (RP Fiber Power V6, RP photonics GmbH), we find that the slope efficiency can reach up to 38% in our laser-cavity configuration, for a given pump power. There are several reasons for the discrepancy between experiment and simulation. First, the pump light experiences about 10% loss at the WDM coupler before reaching the gain fiber. In addition, the laser output also experiences loss at the WDM coupler, since the coupler is not perfectly fit for 1560~1700-nm operation. The loss of laser signal at the WDM coupler is measured to be 37% at 1706 nm. The limited absorption of the pump at the gain medium is also one of the reasons for low efficiency. Finally, high reflectivity of the output-coupler FBG also limits the output power of the laser. Fine adjustment of the FBG's reflectivity is in progress, to experimentally find the optimal output coupling conditions for our laser.

IV. CONCLUSION

In summary, we have successfully demonstrated a CW all-fiber THDF laser operating at a wavelength of 1706.3 nm. A highly reflective FBG was employed to build the laser cavity, which enabled laser operation at the short-wavelength band edge of the THDF with high pump-power absorption. We first studied the laser's operation properties for different pump wavelengths, which revealed that a pump source at a wavelength of 1565 nm showed the best performance, in terms of laser output power for a given pump system. We also investigated the laser's properties by changing the THDF gain length from 1.4 m to 1 m, where a maximum output power of 249 mW and enhanced slope efficiency of 23% could be achieved at a THDF gain length of 1.3 m. Power scaling by optimizing the reflectance of the FBG and fine adjustment of the laser wavelength by mechanical tuning of the FBG are in progress, for medical applications. The realization of ultrafast lasers at this wavelength with a saturable absorber based on low-dimensional materials is also under investigation, with a different cavity configuration.

ACKNOWLEDGMENT

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