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Efficient second-harmonic generation from polarized thulium-doped fiber laser with periodically poled $MgO:LiNbO_3$

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ABSTRACT

We present an efficient method for polarized 963 nm emission based on second-harmonic generation from a high-power, polarized thulium-doped fiber laser using periodically poled MgO:LiNbO3 as the nonlinear material. The maximum 963-nm output power of 710 mW has been achieved with a pulse duration of 34 ns at the repetition rate of 100 kHz and a Gaussian spatial beam profile. The frequency doubling efficiency is up to 56%, and the total optic-to-optic conversion efficiency is more than 12.9%. In addition, third- and fourth-harmonic generations have been observed.

1. Introduction

High-power, compact, and efficient laser sources in the near-infrared wavelength region (900–970 nm) are of practical interest in fields such as sensing of water vapor in the atmosphere [1], high-resolution spectroscopy [2], frequency doubling to blue wavelength for applications in data storage and gratings record [3,4]. However, this wavelength region can hardly be directly obtained by conventional laser sources. Operation below ~970 nm cannot be achieved by ytterbium lasers [5]; generation in 910 nm region in the neodymium laser is a three-level transition, and its conversion efficiency can be strongly reduced caused by the parasitic lasing in 1060 nm region [6,7].

Frequency doubling of a thulium-doped fiber laser (TDFL) is an attractive alternative for 900–970 nm generation. TDFLs with their potential broad emission bandwidth (1860–2050 nm) [8] offer distinct superiorities compared to solid-state lasers, including compact size, reduced thermal effects and good beam quality. High-power, pulsed TDFLs have been demonstrated by several groups [9–12]; such systems with high peak power can meet the requirement for second-harmonic generation (SHG). Moreover, efficient frequency doubling can be provided by quasi-phase-matched (QPM) materials, such as periodically poled $MgO:LiNbO_3$ (MgO:PPLN), attributed to their large nonlinear coefficients combined with reduced walk-off effects [13]. An efficient approach for 9XX nm generation can be achieved by combining these two mature techniques. By frequency doubling of a TDFL, Frith et al. have obtained about 60% conversion efficiency of the pulsed 1908 nm source, with about 800 mW average power at 954 nm [14]. However, the master oscillator (MO) in their TDFL system did not produce linearly polarized output, and hence the large launch loss through a polarization-sensitive isolator led to small launched power into the power amplifier (PA). Furthermore, small MO seed power and strong reabsorption in the thulium fiber would result in low polarization extinction ratio (PER) of the PA output power; only a beam in appropriate polarization orientation was useful in SHG, and therefore the total optic-to-optic conversion efficiency in this system was restricted.

In order to improve the total optic-to-optic conversion efficiency of SHG from TDFL, a high-power linearly polarized seed source is necessary; our approach is to scale the output power of an all-fiber, polarized, thulium-doped MOPA system which is reported in our previous work [12]. In this paper, an efficient SHG from polarized TDFL system based on MgO:PPLN is presented; a theoretical model is also employed. With the optimal operating temperature of the MgO:PPLN, we have achieved 963 nm output power of 710 mW, with up to 56% frequency doubling efficiency and total optic-to-optic conversion efficiency more than 12.9%. These results are consistent with the theoretical model we performed. In addition, third- and fourth-harmonic generations have been observed.

2. Experiment

The experiment configuration consists of three subsystems: a TDFL seed source, a stage of amplification at fundamental wavelength and a

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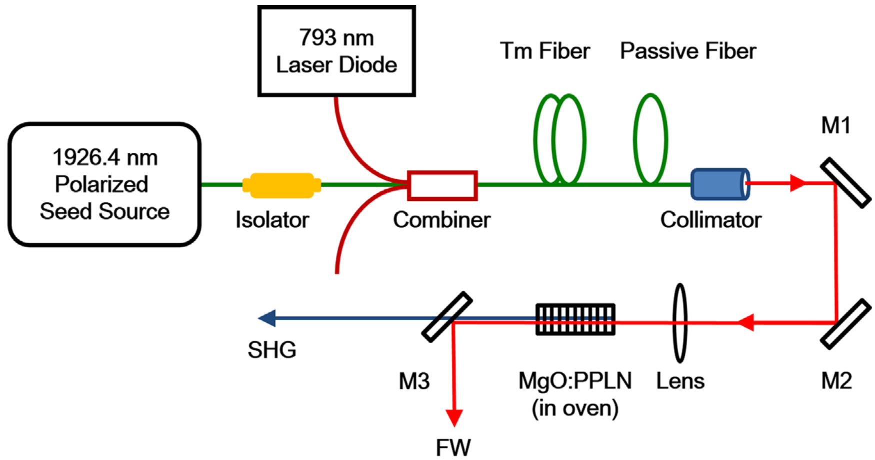

Fig. 1. The scheme of the amplification stage of the thulium-doped fiber seed source and second-harmonic generation experiment based on MgO:PPLN.

SHG stage based on MgO:PPLN (e+e→e). The schematic of our experimental setup is depicted in Fig. 1.

The seed power for the amplification stage was produced by an all-fiber 1550-nm-pumped polarized thulium-doped MOPA system [12]. The high peak power and the linear polarization of this seed source enable efficient power amplification to a sufficient level for frequency doubling.

The seed laser was launched into the PA stage through a fiberized isolator which protected the seed source from back propagating power in the amplification stage, and hence ensured the stability of the seed source. The fiberized isolator is polarization-sensitive with the insertion loss about 0.95 dB, and its fiber pigtail has a single-mode (SM) polarization-maintaining (PM) structure with a 9-μm core and 125-μm cladding (9/125). The pump laser of the amplification stage is a commercial continuous-wave laser diode operating at 793 nm, and its power was coupled into the amplification stage through a PM combiner (ITF) with a coupling efficiency of 87.5%. A 1.4-m long double-clad PM thulium-doped fiber laser with a 10/130 structure (Nufern) was utilized as the gain medium of the PA. Its length was chosen for the trade-off between reabsorption effect at seed laser wavelength and sufficient pump power absorption. A 0.5-m long SM PM passive fiber, with the same structure as the fiber pigtail of the isolator, was spliced to the thulium-doped fiber laser; this single-clad fiber acted to strip out the cladding light from double-clad thulium-doped fiber, providing a SM output of the amplification stage. Both the seed laser cavity and the amplification stage were mounted on the aluminum heat sink and cooled by forced air at room temperature.

The output from the PA was collimated with a fiberized collimator (AFR) which gave a beam radius of 1.5 mm and a vertical linear polarization. This fundamental wave (FW) beam was aligned with two silver mirror (M1, M2), and was focused into a commercial 5% doped MgO:PPLN crystal (HCP) using a lens with $f=150$ mm; the fundamental beam waist at the center of the crystal was $\omega\sim80$ μm. The measurement showed that about 87% of FW power was launched into the MgO:PPLN due to the propagating loss introduced by the alignment system. The MgO:PPLN is 48-mm long with multiple poling periods ranging from 28.5 to 31.5 μm, and is housed in an oven with a temperature stability of ±0.1 °C. The crystal faces have AR coating ($R<0.8\%$) for the SH wavelength, with high transmission ($T>99\%$) for the fundamental wavelength. Moreover, both crystal faces are angle (1°) polished for the sake of preventing parasitic process in the single-pass SHG, and its length is optimized to prevent serious dephasing effect. A dichroic mirror (M3) was used to separate the SH output beam from unconverted FW.

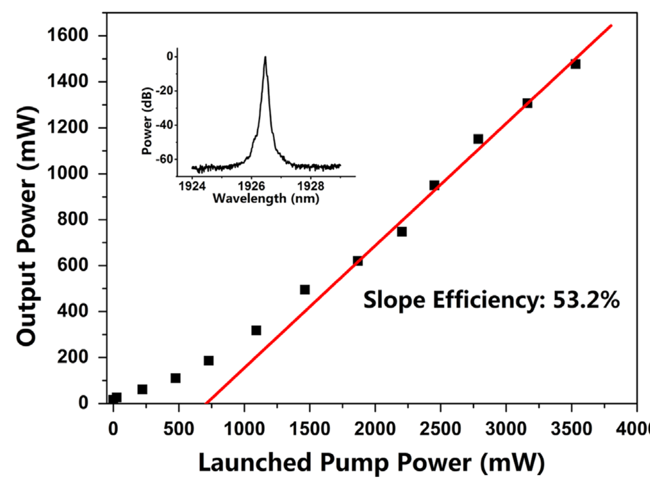

Fig. 2. The average output power versus launched pump power in the amplification stage. Inset: the spectrum of the output pulses from the amplification stage.

3. Results and theoretical model

The seed source of the system produced 45-ns pulses with average power of 700 mW at the repetition rate of 100 kHz. Linearly polarized output with average power about 595 mW was launched into the amplification stage, serving as the seed laser of the PA. There was an obvious power reduction in the seed laser when it passed through the PA without input 793-nm pump power; this was considered to be caused by the strong reabsorption effect of the thulium-doped fiber.

Fig. 2 illustrates the average power versus the launched pump power of the amplification stage. Initially, the seed power was not efficiently amplified due to the reabsorption effect; then the PA operated in the linear region when the launched pump power increased up to 1868 mW. The maximum average power produced from the PA was measured to be 1477 mW when a launched pump power was 3530 mW, with a slope efficiency of 53.2% in the linear region, which is higher than the value of 36% presented by Ref. [14]. The amplification efficiency of the PA was only 25% corresponding to a seed power of 595 mW, which was restricted by the reabsorption effect of the thulium-doped fiber and the upper limit of pump power. The power stability of the amplified output is similar to the performance of the seed laser mentioned in our previous work [12]. The spectrum of output pulses was measured by an optical spectrum analyzer (YOKOGAWA), and is