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Power scaling of Tm-doped fibre lasers using an all-fibre composite Michelson-type cavity

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Abstract. **We report a 4-W all-fibre Tm-doped fibre laser using a composite cavity with a centre wavelength of 1952.02 nm. The composite cavity consists of two interferometric laser arms that are efficiently combined. Each interferometric laser arm contains a double-clad Tm-doped silica fibre operating in cw mode and pumped by pigtailed laser diodes with a centre wavelength of 793 nm. A high combining efficiency of 93.9% and a narrow linewidth of 0.1 nm are obtained. The output power of the laser can be scaled straight forwardly by improving the pump power and optimising the component parameters at 2 μm.**

Keywords: *thulium-doped fibre, all-fibre lasers, coherent combining of lasers, Michelson-type configuration.*

1. Introduction

Tm-doped fibre lasers (TFLs) are the most important recent achievements in high-power fibre laser technology because of their wide application in machines, lidars, material processing systems and systems of nonlinear frequency conversion to mid-IR wavelength region [1 – 4]. However, from the power scaling analysis performed by Dawson et al. [5] it follows that there exists a maximum extractable power limited by the presence of thermal effects, optical damage, finite pump brightness and nonlinear effects (see also [6]).

Efficient coherent combining of lasers provides an effective solution which can both increase the laser output and maintain the beam quality. An efficient method of coherent beam combining relies on the use of a composite Michelson-type cavity configuration. Several approaches to this configuration have been proposed and reliable coherently combined Yb-doped and Er-doped fibre laser arrays have been demonstrated [7 – 9]. To date, studies in the field of high-power fibre lasers and technique of their coherent combing have been primarily focused on Yb-doped fibres operating around 1 μm because of low quantum defects inherent in them and abundance of high-brightness pump sources. The same solution has been realised in Er-doped fibre lasers emitting around 1.5 μm [10, 11].

The aim of this paper is to investigate the possibility of designing a high-power TFL system by using composite cavity technology, which can be attributed to two reasons. Firstly, 2-μm high-power fibre laser systems benefit from operating at eye-safer wavelengths, which permits transmitting in free space the power that is several orders of magnitude higher than that at 1 μm. In addition, McComb et al. [12] noted the excellent transmission property of TFL radiation in turbulent atmosphere. Secondly, due to a longer wavelength, TFLs should have a higher SBS threshold than Yb-doped fibre lasers [4, 13], which allows a more efficient power scaling of a single fibre laser. Because of the increasing demand for high-brightness TFLs in many applications, composite cavity regime is a key technology that deserves a separate investigation.

Previously, we reported the use of active and passive coherent beam combing of TFLs in which the output power was at a milliwatt level [14]. In this paper, we demonstrate efficient all-fibre combining of two high-power Tm-doped fibre lasers by using a composite cavity. As a result, a 4-W coherent output power with a coherent combining efficiency of 93.9% is obtained.

2. Experimental results

The experimental setup of the TFL with a composite Michelson-type cavity is shown in Fig. 1. Each arm of the TFL cavity is end-pumped by pigtailed laser diodes (LDs) with a centre wavelength of 793 nm. Each main oscillator consists of a section of Tm-doped double-clad fibre, a 105-μm pigtailed 793-nm laser diode, a highly reflecting (HR) FBG (reflectivity of 99.5% with a centre wavelength of 1950 nm). The Tm-doped fibre has a core 10 μm in diameter (NA = 0.15), surrounded by a hexagonal inner cladding whose diameter is 130 μm (NA = 0.46). The absorption coefficient of this fibre at 793 nm is 3 dB m^{-1}. In one of the arms use is made of a passive fibre several metres in length to prevent the interferometric instabilities. In addition, each laser cavity makes use of a sufficiently long passive fibre to provide pump damp-

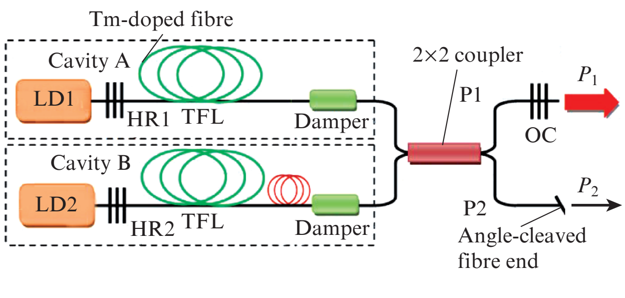

Figure 1. Experimental setup of a composite-cavity Tm-doped fibre laser.

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ing. The two arms of the active interferometer are two independent fibre lasers connected to a 2 × 2 single mode coupler (50 : 50), which coherently combines the fields. The output ports of arm A and arm B are fusion spliced to the two input ports of the coupler. One output port of the coupler is connected to the FBG optical circulator (OC) (reflectivity of 10% with a centre wavelength of 1950 nm) to provide coherent combining (P1 port), whereas the output fibre of the other port (P2) is angle-cleaved to provide sufficient loss discrimination between the two output ports. The system is conduction-cooled by a heat-removing metal plate.

Measurements of the output power of the composite cavity have shown that when LD1 and LD2 operate independently, the maximal output powers of arm A and arm B from port P1 are 1.13 and 1.21 W, respectively. Incoherent sum of the powers is defined as the sum of P1 port output powers of two TFLs, which operate independently. The experimental data and their polynomial curve fitting are shown in Fig. 2.

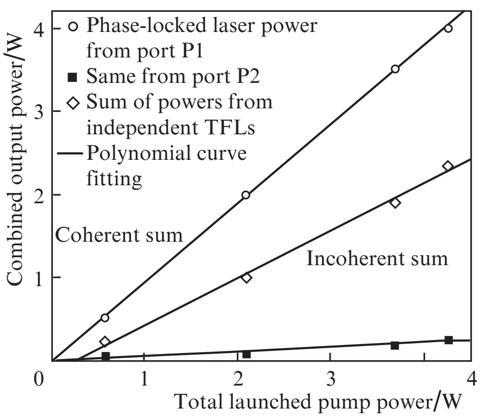

Figure 2. Dependence of the laser output power on total launched pump power.

When the TFL cavities connected by the coupler, which introduces the combining scheme, operate together [15], a higher power is always emitted from port P1, which has a lower loss. When both pump lasers are turned on, the maximal output power P_1 in the case of coherent combining is 4 W. Figure 2 also shows the output power P_2 from the angle cleaved port P2. It follows from the fitting curves of the coherent and incoherent sums that coherent combining allows the threshold of the TFL cavities to be reduced.

To evaluate the combining efficiency [11], we introduce the figure of merit, which is defined as $\eta = P_1/(P_1 + P_2) \times 100\%$. Then, the combing efficiency at the maximal pump current is 93.9%.

The emission spectrum from port P1, measured by an optical spectrum analyser, is shown in Fig. 3 for the case of coherent combining. One can see from the figure that the combining efficiency and optical spectrum are stable. The centre wavelength λ_c is 1952.02 nm at a linewidth of 0.1 nm. It important to note that the heat loss should be reduced by improving thermal conductivity of the coupler.

Thus, we have successfully built an efficient all-fibre Tm-doped fibre laser ensuring coherent combining. Stable coherent combining has been achieved with a 93.9% efficiency. We should note that the output power obtained is still low compared with 1-μm counterparts; however, further

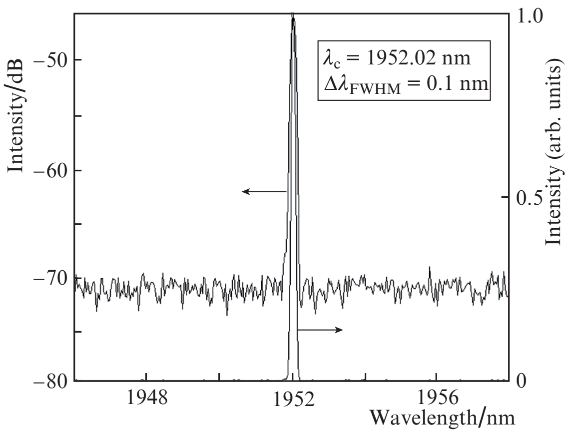

Figure 3. Emission spectrum from the grating port P1.

power scaling of a coherently combined Tm-doped fibre laser array is possible by using an optimised pump source, large-mode-area fibres, large-mode-area fibre couplers and multiple numbers of TFLs.

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