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Mode instability in high power all-fiber amplifier with large-mode-area gain fiber

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ABSTRACT

We studied the mode instability (MI) of the signal light in high power all-fiber amplifier with large-mode-area (LMA) gain fiber experimentally. The MI phenomenon of the output beam was observed and analyzed in the all-fiber amplifier, and the MI power threshold was compared by coiling gain fiber with different radii in multi-kilowatt level (more than 3 kW). In the experiments, MI power threshold was improved and optimized with coil radius reduction of the LMA gain fiber in the all-fiber amplifier.

1. Introduction

High power fiber lasers and amplifiers with the LMA fiber have a great development in the latest decade [1,2]. With the power increasing of the fiber laser system, the nonlinear effects such as stimulated Raman scattering (SRS) effect, thermal effect etc. will limit the developing of the fiber laser and amplifier [3]. Recent studies point that MI effect of the fiber amplifier is one of the mainly limiting factors of the power scaling up [4–6]. The MI effect of the active fiber shows that the output beam of the fiber amplifier has fast fluctuation of the power when a certain power threshold is reached. The energy of the signal light transfers between the fundamental mode and high-order modes (HOMs) on a millisecond time scale, and the beam quality of the light emitted by the fiber amplifier is suddenly degraded once the power reached the MI power threshold.

The MI effect is explained by the self-induced long-period refractive index grating creased in the fiber due to the thermo-optical effect [7–10] and the Kramers-Kronig enhanced effect [11,12], and the beam energy can be transferred between the transverse modes by mode coupling through the grating.

In this paper, we have demonstrated a highly efficient all-fiber amplifier seeded by a continuous wave (CW) all-fiber laser. The MI effect of the fiber amplifier was observed and analyzed with the seed power injection. When the MI effect occurred in the experiment, the signal power did almost not increase with the pump power increasing. A certain pump power threshold of the MI effect of the all-fiber amplifier was affirmed in the experiment. The beam quality of the signal light was measured with different pump powers, and it was degraded obviously when the MI phenomenon was appeared. The MI power threshold was studied by comparing different coil radii as 8.5 cm, 7 cm and 6 cm of the gain fiber in the experiments, and it could increase by using relative small bend radius in multi-kilowatt level. More than 3.7 kW output power of the all-fiber amplifier was obtained by coiling the gain fiber with 6 cm bend radius before the appearance of MI phenomenon, and the corresponding slope efficiency was about 83% in the experiment.

2. Experimental setup

The all-fiber amplifier schematic configuration is shown in Fig. 1. The seed laser output fiber is fused with the signal fiber of the (6+1)x1 fiber coupler, and the seed power is injected to the gain fiber of the fiber amplifier. The gain fiber is a LMA double-cladding Yb-doped fiber (YDF) with 30 μm/0.06 NA core and 400 μm/0.46 NA inner-cladding, and the nominal small-signal pump absorption is 2.2 dB/m at 976 nm. The gain fiber length is about 12 m in the all-fiber amplifier system. The pump lights with 976 nm wavelength of the six pump lasers are coupled into the gain fiber by the (6+1)x1 fiber coupler of the fiber amplifier, and the pump power of single pump laser is 700 W. The signal fiber and the output fiber of the (6+1)x1 fiber coupler are the 20/400 μm and 30/400 μm double-cladding fibers respectively. The pump power coupling efficiency of the (6+1)x1 fiber coupler is about 98%, and the insertion loss of the signal power is less than 0.2 dB. The unabsorbed pump light propagated in the cladding of the passive fiber is stripped out of the fiber by the cladding mode stripper (CMS). The signal power is measured from the beam delivery system with collimating lens of the all-fiber amplifier.

The seed laser is a single-mode CW all-fiber laser with 1080 nm

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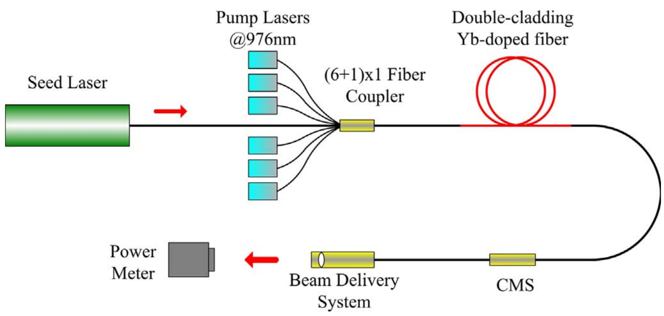

Fig. 1. Schematic configuration of the all-fiber amplifier.

wavelength, and the maximum output power is about 1.5 kW with near diffraction-limited beam quality (M^2 =1.1). The pigtail fiber of the seed laser is 20/400 μm double-cladding passive fiber. It is fused with the signal fiber of the (6+1)x1 fiber coupler of the fiber amplifier. There is no fiber isolator inserted between the seed laser and the fiber amplifier, and they can work stably and normally during the experiments [13]. In the all-fiber amplifier system, the fiber splicing between the fiber components is aligned precisely. In order to obtain the signal light with good beam quality from the all-fiber amplifier, the gain fiber was coiled as a mode-filter to suppress HOMs [14]. The pump lasers and the all-fiber amplifier system were cooled by a water chiller during the experiments.

3. Experimental results and discussions

3.1. MI phenomenon in all-fiber amplifier

In the amplification experiment, the signal light from the seed laser was injected into the fiber amplifier. The seed light was propagated through the all-fiber amplifier, and part of light was lost due to the absorption of the active fiber and propagation loss. The remaining seed power measured from beam delivery system was about 1070 W. With the increasing pump power of the fiber amplifier, the signal power increased linearly under 2.8 kW pump power. The maximum output power was about 3.3 kW, and the slope efficiency of the fiber amplifier was about 83%. Continue increasing the pump power, the output power of the fiber amplifier did not increase as shown in Fig. 2. That meant the MI phenomenon occurred when the pump power reached the MI power threshold of the fiber amplifier, and it was about 2.8 kW in the experiment.

The temporal instabilities of the signal beam with different pump powers were analyzed by an InGaAs photo-detector (PD) at the end of the beam delivery system of the fiber amplifier as shown in Fig. 3(a). The abrupt temporal instabilities of the signal light were detected when the pump power reached the MI power threshold. The fast mode transferring was presented obviously from the normalized time-serial signals collected by the PD at the pump power of 3.3 kW. The corresponding Fourier spectral distributions are shown in Fig. 3(b), and the transferring frequency of the MI is mainly distributed in several kHz.

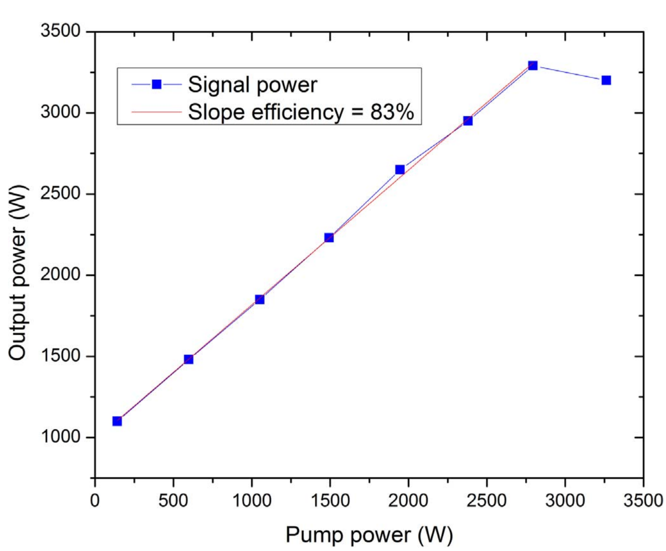

Fig. 2. Output power versus injected pump power of the all-fiber amplifier.

The signal light of the fiber amplifier was analyzed by an optical spectrum analyzer (OSA) at the same time as shown in Fig. 4. The spectra of the signal beam with different pump powers were compared. The MI phenomenon was appeared when the pump power exceeded 2.8 kW, but there was no obvious difference between the spectra of the output light with different powers. The Raman light with wavelength of 1135 nm was not detected even when the MI occurred in such high power level, and no evidence showed that the MI effect was directly related to the SRS effect of the all-fiber amplifier according to the results of the experiments.

At the end of the beam delivery system, the signal beam quality (M^2) of the all-fiber amplifier was measured with different pump powers as shown in Fig. 5. The beam quality of the seed light was degraded when propagating through the LMA fiber and the fiber components, because the splicing between different fibers could create HOMs and the LMA YDF could support the propagating of the HOMs. When the pump lasers of the fiber amplifier worked in low power level, the signal beam quality was relative better because less HOMs created in the active fiber, and the factor M^2 of the all-fiber amplifier was steady about 1.7 without MI effect appearing. When the threshold power of the MI effect was reached, the signal beam quality was degraded obviously, and the M^2 was measured about 1.82 with pump power of 3.3 kW. The beam profiles of the signal light were compared with different pump powers as shown in Fig. 5.

The energy of the signal light transferred between the fundamental mode and HOMs rapidly when the MI effect occurred from the results of the experiments. Most of the HOMs did not meet the propagative condition of the fiber, and then overflowed the fiber core. Only a small amount of HOMs could propagate together with the fundamental mode in the LMA fiber of the fiber amplifier. Therefore, the signal power was almost not scaling up with the increasing pump power when the MI power threshold was reached, and the signal beam quality was degraded obviously because of the increasing power of HOMs in the signal beam.

3.2. All-fiber amplifier with different coil radii of gain fiber

HOMs of the signal light are easily created and propagated in LMA fiber such as 30/400 μm fiber used in the experiment. In order to suppress the high-order modes, the gain fiber is coiled and the bend loss of the fiber can be simulated by using the bend loss formula [15].

$$2\alpha = \frac{\sqrt{\pi}\kappa^2 \exp(-\frac{2\gamma^3}{3\beta^2}R)}{e_\upsilon \gamma^{3/2} V^2 \sqrt{R} K_{\upsilon-1}(\gamma a) K_{\upsilon+1}(\gamma a)} \quad (1)$$

where 2α is the power loss of the light, R is the bend radius, and a is the fiber core radius. K terms are the modified Bessel functions, and υ is azimuthal mode number. e_υ =2 when υ =0, and e_υ =1 when $\upsilon \neq 0$. κ and γ are the field decay rates in the fiber core and cladding expressed respectively as

$$\kappa = \sqrt{(n_{co}k)^2 - \beta^2} \quad (2)$$

$$\gamma = \sqrt{\beta^2 - (n_{cl}k)^2} \quad (3)$$

where β is the propagation constant, and k=$2\pi/\lambda$.

According to the YDF parameters, the bend losses in units of dB/length of the LP modes are obtained from the formula (1) as shown in