Mode-Selective Fiber Laser Using a Photonic Lantern

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Abstract *We experimentally demonstrate a transverse mode-selective fiber laser using a photonic lantern. The output modes of laser are switchable among the 6 LP modes supported by the gain fiber. Their slope efficiency, optical spectra, and mode profiles are measured.*

Introduction

Large mode-area optical fiber can support high-order of linear polarization (LP) modes. There are many motivations for producing high-order transverse modes of laser radiation. For example, it has been shown that high-order LP modes have higher threshold for detrimental nonlinear loss processes, such as stimulated Brillouin scattering (SBS), in comparison with the fundamental mode[1]. It has also been shown that high-order modes can reduce the sensitivity to mode profile distortion[2] and improve energy extraction in pulse laser systems. In fiber sensor systems, high-order LP modes in few mode fiber (FMF) allow for increasing the measurement sensitivity of fiber bending[3]. Recent research also indicate that specific laser beam profiles have benefits in material processing such as higher processing speeds[4] as well as improved cutting quality[5].

Therefore, methods for generating specific high-order modes have attracted increased interest within laser community for a number of years. Several techniques have been implemented successfully. For example, using a few-mode fiber Bragg grating (FBG) and a tunable filter, it is possible to select from the two lowest LP modes[6,7]. However, this method cannot yield higher-order modes due to the limited resolution of both the FBG and the filter. A digital laser employing software defined spatial light modulator (SLM) has also been demonstrated to generate desired modes[8], but the laser efficiency is low owing to the property of gain media. Another approach is dynamic intra-cavity beam control with an electronically addressable deformable mirror[9]. This approach can only generate a small number of mode profiles because of the phase profiles that can be accommodated by the deformable mirror is limited.

In this paper, we demonstrate a transverse mode-switchable fiber laser based on a 6-to-1 mode-selective photonic lantern (PL). The output mode of the laser can be easily switched among the six lowest-order LP modes by simply changing the input port of the PL. The slope efficiencies, optical spectra, optical signal-to-noise ratio (OSNR) and mode profiles were characterized.

Principle and experimental setup

Fig. 1(a) shows the experimental setup. Mode-selective photonic lanterns are passive all-fiber devices capable of efficiently multiplexing single-mode inputs and converting each input into a specific LP mode. It has a great potential for spatial-division multiplexing (SDM) communication systems[10]. In the PL, all input SMFs are adiabatically tapered down inside a low-refractive index capillary to create an FMF output at the taper waist. The mode selectivity feature can be obtained if the core sizes of input fibers are different. Each input fundamental mode can evolve into a particular mode in the output FMF with a matching propagation constants[11]. Fig. 1(b) shows the input cross section of a 6-to-1 mode-selective PL. It contains 6 fibers with core diameters of 23, 18, 18, 15, 15, and 6μm, mapping to the LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02} modes, respectively. After tapering, the output FMF's cladding diameter is 110μm while its core diameter is 20μm. The resulting PL does have mode-dependent losses which is measured to be the smallest for the LP_{01} mode and the highest for the LP_{02} mode.

As shown in Fig. 1(a), light from the pump diode with a central wavelength of 976nm went through a polarization controller (PC) and then a wavelength-division multiplexer (WDM). The other input port of the WDM was connected to an FBG with a center wavelength of 1536.8nm and a bandwidth of 0.8nm. The output of WDM could

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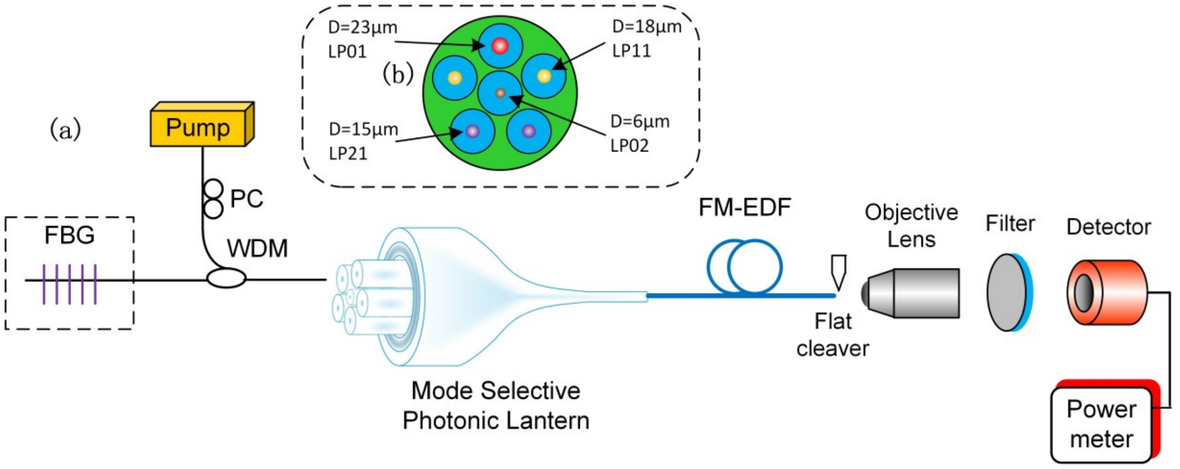

Fig. 1: (a) Experimental setup for the mode selective fiber laser, (b) Cross section of 6 to 1 mode-selective photonic lantern.

be switched to any one of the six input SMFs of the PL, in order to generate the desired laser mode. The gain media is a 5-meter long few-mode Erbium-doped fiber (FM-EDF), whose core and cladding diameter are 13 and 163µm, respectively. In order to reduce the splicing loss, we used a half-meter long intermediate FMF with core and cladding diameters of 16 and 125µm, respectively, spliced between the output of the PL and the FM-EDF. The end of the FM-EDF was cleaved to be flat, yielding a 5% Fresnel reflection coefficient. Thus, the laser cavity was formed between the FBG and the end of EDF. The laser output was focused by a 20X objective lens, and a long-pass filter at 1540nm with FWHM bandwidth of 12nm was placed right after the lens to block the residual pump light.

Results and discussions

The collected output laser power versus pump power for all 6 modes are shown in Fig. 2. The horizontal axis is the pump power at the single-mode input of the PL. It should be noticed that

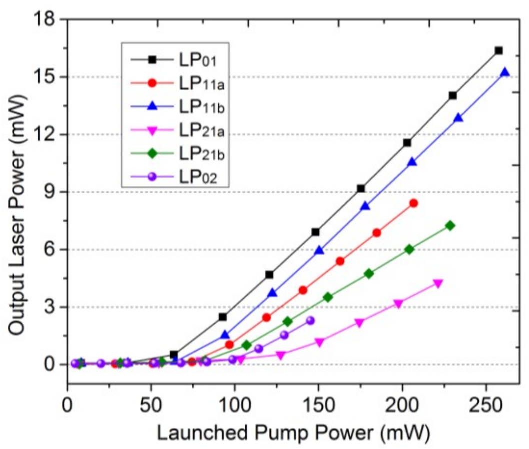

Fig. 2: Relationship between laser power and launched pump power.

because of the insertion loss of the PL for the pump are different for different modes, the pump powers that launched into the FM-EDF are not the same for all the pump modes. The LP_{01} lasing mode has the highest output power of >16mW, and slope efficiency of 8.46%. The slope efficiencies for LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b} and LP_{02} lasing modes are 6.72%, 8.21%, 4.33% 5.16% and 4.77%, respectively. The difference in slope efficiencies and threshold values are due to the mode-dependent loss of the PL at the signal wavelength as well as different overlapping integrals of the pump and signal mode profiles. In order to increase the slope efficiency, we can use a FBG with higher reflectivity, an output coupler with a high reflectivity at the end of FM-EDF, and lower-loss PL to reduce cavity loss.

We measured the spectra of the output lasing modes using an optical spectrum analyzer (OSA) with a 50/125µm optical input port (Ando AQ-6315e), capable of accepting high-order modes.

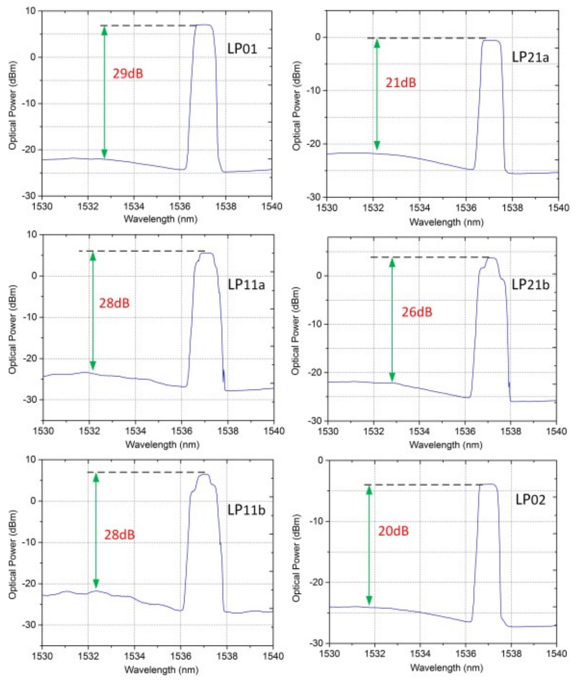

Fig. 3: Optical spectrums of six different mode lasers.

The spectra for all the six lasing modes are shown in Fig. 3 at a fixed pump power of 224mW. We can find that all six modes have a central wavelength near 1537nm and bandwidth around 1nm. That matched with the reflection spectrum of the FBG. It also indicates that the OSNR for all the six lasing modes are above 20dB, range from 20dB to 29dB.

We used a CCD camera to capture the intensity profile of each lasing mode. Because the camera is easily saturated for input powers of more than 1mW, we used two attenuators in front of the CCD camera and the intensity profiles are shown in Fig. 4.

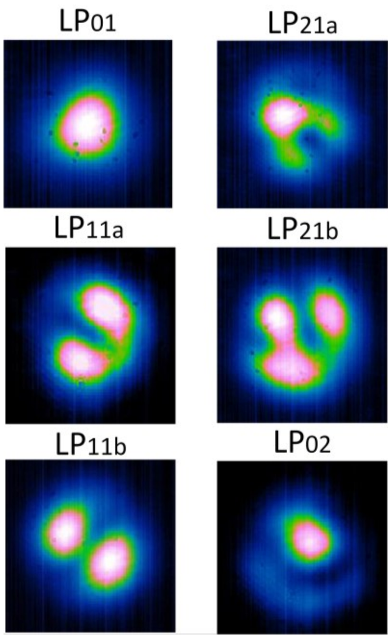

Fig. 4: Mode intensity profiles of six lasers belong to different LP modes

From Fig. 4, we can see that for the three lowest-order lasing modes (LP_{01} and LP_{11}), their profiles are almost ideal. However, the profiles for higher-order lasing modes (LP_{21} and LP_{02}) are not as good, although they can still be recognized. The main reason is likely due to mode crosstalk of the PL, leading to some of the single-mode input port exciting multiple modes in the FM-EDF. Another reason could be that there is residual mode coupling in the FM-EDF itself. Both of these imperfections can be improved in the future. In addition, the filter also affects the symmetry of the pattern.

Conclusion

We have successfully demonstrated a transverse mode-switchable fiber laser using a 6-to-1 mode-selective PL. The selection among different LP modes was realized by switching the input port of the PL. The slope efficiencies of 6 lasing modes range from 8.46% to 4.33%, and their OSNRs range from 20dB to 29dB. Their mode profiles are observed by a CCD camera, all the six modes can be clearly recognized.

Acknowledgements

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