Multiwavelength Er-doped Fiber Laser Using All Fiber Lyot Filter

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Abstract: we experimentally demonstrated a multiwavelength Er-doped fiber (EDF) ring laser system by employing an all-fiber Lyot filter (AFLF) and highly nonlinear fiber (HNLF). The AFLF was employed as a polarizing filter to generate nonlinear polarization rotation (NPR) effect and the highly dense and narrow bandwidth comb-like channels. 1 km long HNLF was used to enhance the nonlinearity of laser cavity and suppress the mode competition for multiwavelength operation. In the experiment, total 97 channels laser output within 3dB bandwidth simultaneously was excited under 224mW pump power. Power fluctuation of lasing channels was less than 0.182dB and wavelength shift was less than 0.04nm in 100 minutes, after treating AFLF in a thermostatic icebath. Meanwhile, output laser was highly polarized with degree of polarization (DOP) up to 99.9%.

1. Introduction

Multiwavelength fiber laser has attached more interests in the field of fiber sensing, optical instrumentation and optical communication systems. Moreover, highly polarized fiber laser output is crucial in various occasions like magnetic field sensing, coherent beam combination and wavelength division multiplexing (WDM) systems. Based on different type of amplification gain, researchers have realized multiwavelength fiber laser working at different range, including: semiconductor optical amplifier (SOA) [1-3], Raman amplifier [4-6], random distributed feedback amplifier [7], Er-doped fiber amplifier[8] and Thulium doped fiber amplifier based laser system[9,10]. Among of them, the EDFA has the flatter gain spectra and higher saturation power. More important is that most of communication and sensing systems were working in the EDFA gain spectral wavelength range. However, the EDFA is type of homogeneous gain, which is difficult to achieve multiwavelength laser generation, due to very strong mode competition. There are several technique employed to suppressed the mode competition including cooling the EDF with liquid nitrogen [11], nonlinear optical loop mirror (NOLM) [12-13], nonlinear polarization rotation (NPR) [8], and hybrid gain media [14-16]. Except of the suppression mechanism of mode competition, the laser system also needs a channel selection mechanism to achieve multiwavelength operation. It has been reported a highly nonlinear fiber and a Fabry-Perot Filter (FPF) based EDF multi-wavelength laser system [17-18], in which the laser system has a relatively simple setup and flatter output spectrum but also random polarization output. Output laser usually have a random polarization output because two orthogonal polarization modes would compete with each other randomly due to the affection of various environmental conditions and resulting an unstable polarization output [19]. By employing a segment of polarization maintaining (PM) fiber and a polarizer into the laser cavity, ratio of the two orthogonal polarized modes would be stabilized so that the output laser could be stable and highly polarized. In this paper, we experimentally demonstrated a highly polarized multiwavelength fiber laser using AFLF and HNLF.

2. Experimental setup

Lyot filter, invented by Bernard Lyot in 1933, was formed by sandwiching a birefringence medium between two polarizers [20]. Consequently, an AFLF could be formed by sandwiching a segment of PM fiber between two in-fiber polarizers. In our previous work, we have reported an in-fiber linear polarizer structured by UV-inscribing a 45° tilted fiber grating (TFG) into PM fiber [21]. We have successfully fabricated AFLFs by sandwiching two 45° TFGs and one segment of PM fiber, and examined their characteristics [22]. It turned out that due to its finer comb-like transmission spectrum, AFLF could be perfectly utilized as the wavelength selector for multiwavelength lasing operation. Except its wavelength selecting function, the AFLF also functionalized as a polarization selector, resulting highly polarized laser output at the same time. The free spectrum range (FSR) and bandwidth of the AFLF we employed in this experiment can be expressed as [22]:

$$FSR \cong \frac{\lambda^2}{L\Delta n}, \quad \text{Bandwidth} \cong \frac{\lambda^2}{2L\Delta n} \tag{1}$$

Where, L (~46m) was the length of PM fiber cavity of the filter, Δn (3.27×10^{-4}) is the birefringence of PM fiber and λ (1550nm) is the working wavelength. Fig. 1 showed the transmission spectrum of the Lyot filter used in this paper (the inset is the basic structure of AFLF), which was obtained by an amplified spontaneous emission (ASE) source and an optical spectrum analyzer (OSA, YOKOGAWA, AQ6370D, resolution: 0.02nm). This Lyot filter has FSR of ~0.162nm, bandwidth of ~0.081nm and extinction ratio of ~14dB.

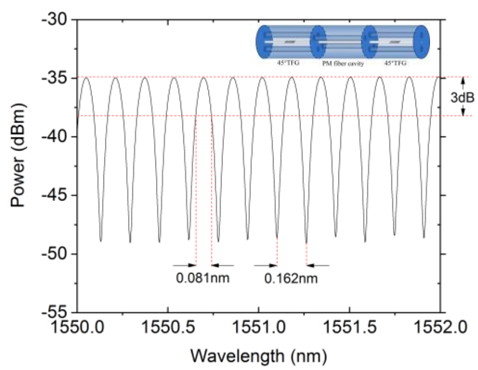

Fig. 1: Transmission spectrum of the AFLF.

The configuration of fiber laser was shown in Fig. 2, a polarization independent isolator ensures the unidirectional operation of the ring cavity. The gain of the fiber laser was provided by a segment of 1.5m EDF (I25) pumped by a 980nm laser diode (LD). 1km highly nonlinear fiber (dispersion of -0.396ps/nm/km at 1545nm and nonlinear coefficient of 11/W/km) was used to reduce the competition among longitudinal modes and balanve the power at different channels by using the comb filtering characteristics of Lyot filter, to generate multi-wavelength laser output simultaneously. A polarization controller (PC) was employed to control the polarization state in the laser cavity and to achieve flatter output spectrum. The total laser cavity length is around 1059.5m which includes 1000m high nonlinear fiber, 1.5m I25 EDF, 46m PM1550 polarization maintaining fiber and 12m SM 28 single mode fiber. The net GVD is around -0.39ps^2. The output light was extracted from the ring cavity by a 90/10 optical coupler (OC).

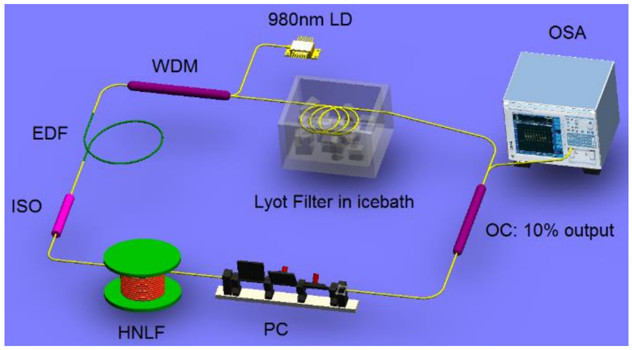

Fig. 2: Schematic of the ring laser cavity associated with an AFLF and HNLF.

3. Results and discussions

In the experiment, we employed the NPR technique to suppress mode competition caused by the homogeneous line broadening property of the EDFA. Lots of works have proved that the mode competition would be suppressed by involving the high nonlinear effect in the laser cavity, such NPR and NOLM. The NPR can be used as fast saturable absorber in the ultrafast laser generation. And the polarizing element is the key to achieve NPR effect in the laser system. By employing an AFLF in the laser system, which is a polarizing functional multi-channel element, we have achieved several different numbers multi-wavelength laser outputs. By adjusting the pc and different pump power, we could also achieve different number multi-wavelength output. However, Considering with channel quality and effective channels number in 3dB bandwidth, we have only achieved 50, 69, 80 and 97 channels laser output(see in Fig. 3). And the 97 wavelengths laser output was generated at the 224mW pump power, which has 0.044nm linewidth for each channel, ~19dB side-mode suppression ratio and 10.97mW output power, as shown in Fig. 3 (d).

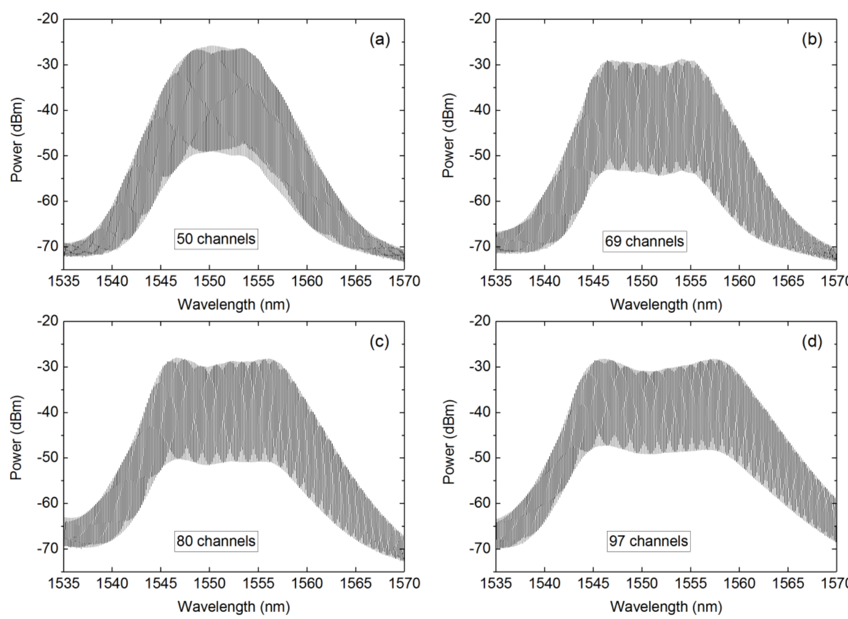

Fig. 3: output spectrums with different output channels: (a) 50 wavelength channels; (b) 69 wavelength channels; (c) 80 wavelength channels; (d) 97 wavelength channels.

Furthermore, we also investigated laser output characteristic by increasing the pump power. The pump power was firstly set at the threshold lowest around 58.42mW, and a fine multiwavelength laser output could be obtained by adjusting the PC. Then, as increasing the pump power, we have noticed gain-bandwidth was broadened and new lasing channels can be observed (see in Fig. 4 (a)), meanwhile, the line width of single channel became broader and the signal-noise ratio (SNR) was getting worse as shown in Fig. 4 (b). For a better illustration of this, we have also plotted the SNR, linewidth versus pump power, which have been shown in Fig. 4(c) and (d). Both lasing level and noise level were increasing as increasing the pump power at the same time, but noise level increased faster than the one of the lasing level, which induced the worse SNR. Besides, the linewidth of output laser became broad as well. As we known, fiber laser could readily oscillate at multiple longitudinal modes with frequency space of $c/2L'$, where L' is the optical length of the ring cavity and *c* is the speed of light in vacuum. In our laser system, the frequency space of longitudinal modes is much smaller than the FSR of AFLF, which means that there are multiple longitudinal modes readily to excite in a single channel. According to the principle of laser, longitudinal modes with lower transmission loss would be excited, and the modes with higher transmission loss caused by the Lyot filter would be suppressed, and contribute to the noise of the laser. In our experiment, the amplitude equalization effect induced by NPR has suppressed the mode competition, and as increasing of the pump power, the four-wave mixing caused by high nonlinear effect would become stronger, in which modes with higher power which contributed to lasing level would share their power to the other suppressed modes [17]. This has explained that the power of noise level increased faster than lasing level. Channels became dumpier with their SNR decreasing and linewidth increasing. As the pump power increased from 58.42mW to 179.8mW, the line width was increased from 0.038nm to 0.062nm, and the SNR was decreased from 23.339dB to 12.675dB.

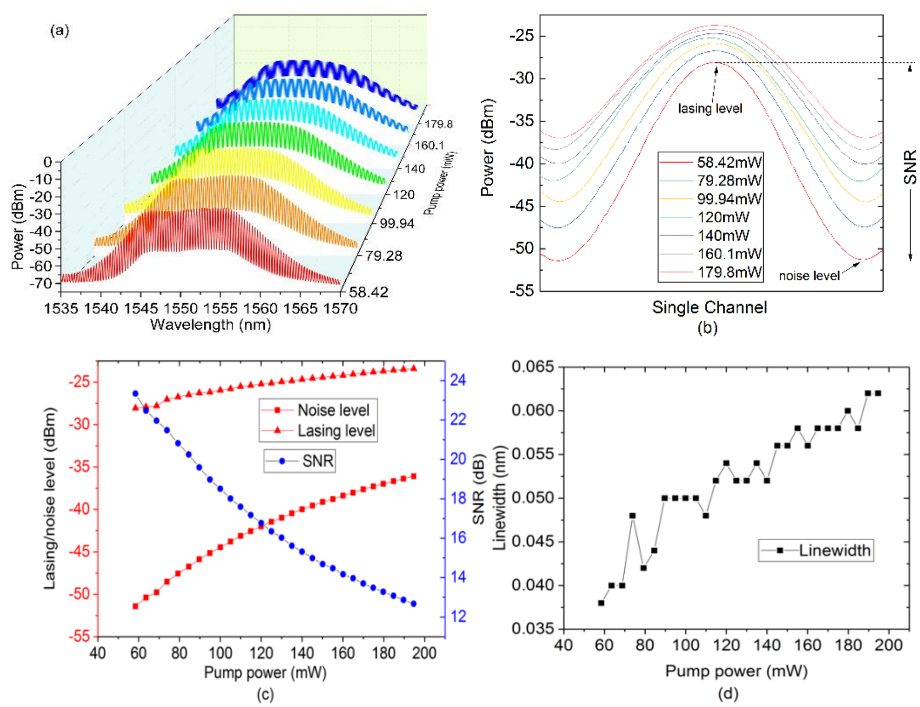

Fig. 4: Output spectrum against the increase of the pump power: (a) the whole spectrum; (b) the single channel; Power of side mode and central mode (a), linewidth and side-mode suppression ratio (b) of output laser versus pump.

For laser system, the wavelength stability of output laser is very important. Our previous work has shown that the Lyot filter is sensitive to temperature because the length and birefringence of PM fiber would be influenced by temperature [23]. The longer the cavity length is, the higher temperature sensitivity Lyot filter is. So, when the filter without any thermal management, we have captured the laser spectrum with a 2-minute interval for 40 mins, which was shown in Fig. 5 (a). Fig. 5(b) showed output laser at the central wavelength of 1550.11nm, which was shifted almost 0.2nm within 40 minutes, To eliminate the fluctuation of environment temperature and improve the wavelength stability of output laser, the AFLF need to be kept in a stable temperature environment. In the experiment, we designed a thermostatic icebath to keep a constant temperature for the AFLF (see in Fig. 2). Under the temperature controlling, the wavelength stability was improved greatly, which was shown in Fig. 5 (c) and (d). As it is shown in the figure, the output spectrum captured with 5-minute interval for 40 minutes and the wavelength at 1549.96nm was only shifting 0.019nm within 40 minutes which was very close to the wavelength repeatability of AQ6370D OSA. The slight shift towards longer wavelength is probably because the AFLF did not reach thermal equilibrium yet in the isothermal system, or the wavelength fluctuation of OSA.

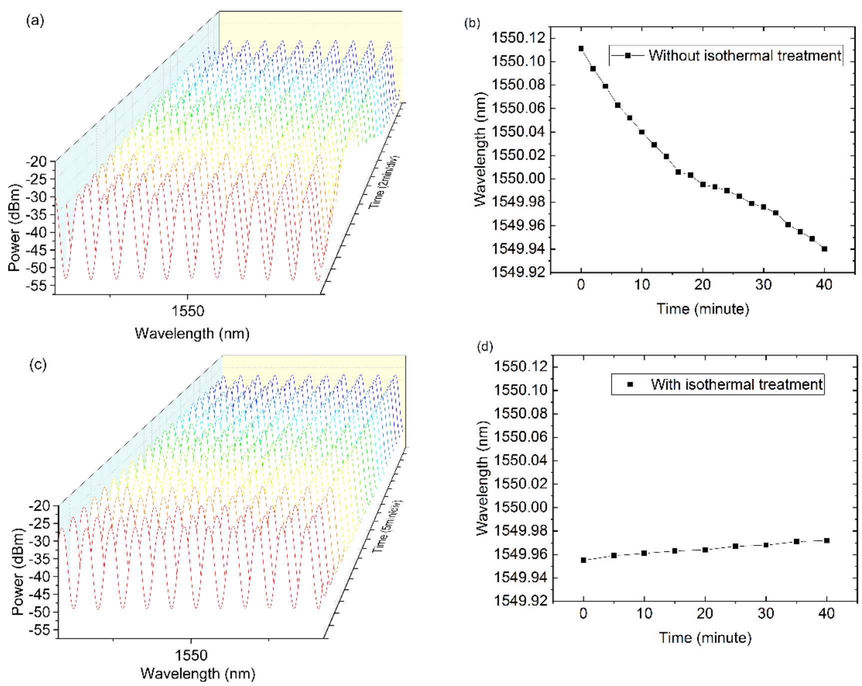

Fig. 5: Wavelength shifting without and with isothermal treatment (a), (b) and (c), (d) respectively.

The power stability of five wavelengths we chose was plotted in Fig. 6, which have shown the maximum power fluctuation of each peak was less than 0.182dB. One of important benefits was the output laser would be highly polarized by using all fiber Lyot filter as wavelength selector. In the experiment, we have measured the DOP of output laser at three different wavelengths 1547.25nm, 1550.04nm and 1552.75nm, which were 99.95%, 99.89% and 99.92%, respectively (data see in Tab. 1). In experiment, we only choose three wavelengths for DOP measurement, however, all laser channels have the same DOP value.

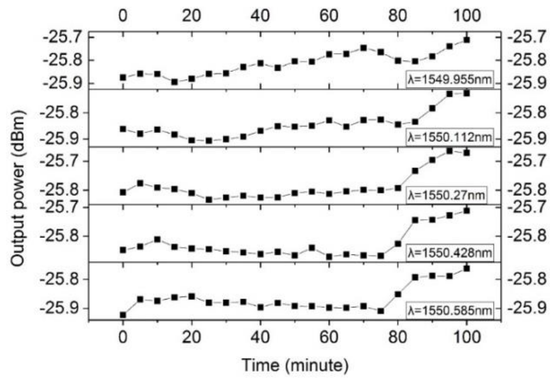

Fig. 6: Power fluctuation of five lasing channels.

Tab. 1: Measurement of DOP at 1547.25nm, 1550.04nm and 1552.75nm

Wavelength (nm)	Pmax (dBm)	Pmin (dBm)	DOP
1547.25	-31.99	-67.76	99.95%
1552.75	-28.99	-63.13	99.92%
1550.04	-29.53	-62.32	99.89%

4. Conclusions

We have experimentally demonstrated a highly polarized multiwavelength Er-doped fiber laser using AFLF and HNLF. In the experiment, maximum 97 wavelengths lasing simultaneously was obtained. DOP of the lasing channels reached up to 99.9%. By introducing icebath based temperature managing system, wavelength stability of output laser could be greatly improved. The power fluctuation and wavelength shift of a single channel are less than 0.182dB and 0.019nm, respectively. In general, it shows its great potential as a practical solution for multiwavelength fiber laser because of its simple setup and highly polarized laser output.

Acknowledgements

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