Research on Multi-wavelength Fiber Laser Based on Nonlinear Effect

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Abstract. A multi-wavelength erbium-doped fiber laser (MWEDFL) is introduced, which uses highly erbium-doped fiber (EDF) as the gain medium and uses the nonlinear effect of the single mode fiber to suppress the mode competition. In order to obtain higher side mode suppression ratio and flatness, a nonlinear fiber loop mirror is added to the structure. The results show that a stable multi-wavelength laser with 16 lasing wavelengths and a side mode suppression ratio (SMSR) higher than 30dB is obtained.

1. Introduction
Multi-wavelength fiber lasers are characterized by multi-wavelength output and tunable wavelengths, leading to many applications. Such as fiber optic communication, fiber optic sensing and microwave photonics[1-3]. Due to the mode competition of the EDF at normal temperature, it is difficult to output stable multi-wavelength lasing light at normal temperature. With the development of optical communication, higher requirements have been put forward on spectral quality. Commonly used methods for generating multi-wavelengths include Brillouin effect, four-wave mixing (FWM), cascade grating, and the like[4-6]. This paper is devoted to an extension in which the multi-wavelength fiber laser based on new highly EDF.

This paper is organized as follows. Theoretical research and the effect of high doping concentration on the output spectrum is described in Section 2. Section 3 builds the system structure with highly doped erbium-doped fiber as the gain medium. In Section 4, the experimental results of the system structure are analyzed. Finally, the experimental results of this paper are summarized in Section 5.

2. Description of Ring-cavity Laser Theory
Based on the Giles model[7], for general erbium-doped fiber lasers (EDFL), the rate equation and transmission equation for the interaction of light and matter at various points in the fiber can be written.

\[
\frac{dN_2}{dt} = \sum_{\mu, j} \sigma_{\mu j} \frac{E_j}{hv_j} N_i(r, \varphi, z) - \sum_{\mu, j} \frac{\sigma_{\mu j} E_j}{hv_j} N_2(r, \varphi, z) - \frac{N_2(r, \varphi, z)}{\tau} \quad (1)
\]

\[
\frac{d}{dz} \left( \frac{E_j}{hv_j} \right) = \left[ \sigma_{\mu j} N_2(r, \phi, z) - \sigma_{\mu j} N_i(r, \phi, z) \right] \psi_j(r, \phi, z) \frac{P_j}{hv_j} \left( \frac{\Delta \nu_j}{hv_j} \right) \quad (2)
\]

\[
N(r, \phi, z) = N_i(r, \phi, z) + N_2(r, \phi, z) \quad (N_3 = 0) \quad (3)
\]

\(N(r, \phi, z)\) is the concentration distribution of \(\text{Er}^{3+}\) in the fiber. \(\nu_j\) is the frequency of each light field,
\( \sigma_{je} \) and \( \sigma_{ja} \) are the stimulated radiation cross section and stimulated absorption cross section at frequency \( v_j \), respectively. Neglecting the variation of laser power and \( \text{Er}^{3+} \) density in the transverse direction of EDF. The time domain simulation results are shown in Fig.1 and Fig.2.

Fig.1 shows the EDFL output optical power spectrum. It can be seen that there is an output peak at 1550 nm. As shown in Fig.2, (a) shows the change of output optical power with time at 1550 nm, which corresponds to the change of the number density of \( \text{N}_2 \) particles with time in (b). After reaching the threshold, the laser starts to lasing, reaching a very high power, and consuming a large amount of \( \text{Er}^{3+} \) particles of \( \text{N}_2 \). In the Fig.2, the reaction is such that the \( \text{N}_2 \) particle number density decreases, the loss is greater than the gain, and the optical power is reduced, and the two mutually restrict each other to form an oscillating process, and finally reach a stable state.

3. Construction of System Structure

As shown in Fig.3, it is an experimental structure of a multi-wavelength erbium-doped fiber laser. The highly doped EDF (HEDF, LIEKKITM Er80-4/125) is used as the gain medium for the laser. The measured ASE spectrum is shown in Fig.4. The optimal fiber length of 500mW can be obtained at a pump power of 130cm. The intracavity loss is considered in the experiment, and the actual optimum length is about 62cm.

The 980nm pump power is used to pump the erbium-doped fiber, and the resulting laser competes with the FWM effect suppression mode in the single mode fiber. At the same time, a 3km single-mode fiber and a 3dB coupler together form a nonlinear fiber loop mirror, and the nonlinear effect based on the cross-phase modulation effect will cause a nonlinear phase shift, thereby equalizing the power between different wavelengths and improving the SMSR. A Lyot comb filter composed of a
polarization-dependent isolator (PD-ISO) and a 12m polarization-maintaining fiber (PMF) and a polarization controller (PC) serves as a tuning device for the annular cavity[8]. Finally, the annular cavity is 10% laser output through a 10/90 coupler.

![MWEDFL structure based on nonlinear effect](image)

**Fig.3 MWEDFL structure based on nonlinear effect**

![ASE spectrum of Er80 fiber with different lengths under 500mw pump power](image)

**Fig.4 ASE spectrum of Er80 fiber with different lengths under 500mw pump power**

### 4. Experimental Result

As shown in Fig.5(a), the output spectrum of the system is obtained experimentally at a pump power of 500mW. Stable multi-wavelength output is obtained in the experiment, the adjacent wavelength interval is about 0.34nm, and the number of wavelengths in the 3dB range is 13. The output is exported and processed by Origin9.1 to obtain the Fig.5(b). The output spectrum is swept once every 10 minutes, and the frequency is swept 5 times. The result is shown in Fig.5(c). The average wavelength power and the SMSR within 3dB of each spectrum of the swept spectrum are calculated, and the specific data obtained are listed in Table 1.
Table 1 Average power and SMSR of output wavelength in 3dB

| Output | 1     | 2     | 3     | 4     | 5     |
|--------|-------|-------|-------|-------|-------|
| Power/dBm | -10.52 | -10.57 | -10.59 | -10.60 | -10.55 |
| SMSR/dB | 33.14  | 33.96  | 33.28  | 32.85  | 33.24  |

It can be seen from the experimental data in Table 1 that the average power of the system is about -10dBm, the maximum difference is only 0.08dB, and the average SMSR of the output spectrum is greater than 33dB. Figure 6 shows the peak power of the three output wavelengths in the output spectrum for 10 consecutive sweeps. It can be seen that a stable laser output is obtained, the maximum output power variation is only 0.117dB.

5. Conclusion
In this paper, a method for realizing a stable MWEDFL is theoretically analyzed and experimentally obtained. Highly doped erbium-doped fibers are used as gain media and utilize nonlinear effects in single mode fibers. The experiment results show that the stable output from the MWEDFL is realized, there are 16 lasing lines in power differences less than 10dB and the side-mode suppression ratio is higher than 33dB.
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