Design and Experimental Study of Tunable Fiber Ring Laser of C+L Band

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Abstract. A tunable fiber ring laser based on L band EDFA (erbium-doped fiber amplifier) was proposed. It has high signal-to-noise ratio and wide tuning range. The influence factor of the tuning range and the time delay of relaxation oscillation were studied. And the FFP-TF(Fabry-Perot tunable filter) was used as a wavelength selector to produce tunable laser. Experiments show that by using appropriate time-delay and auto-adjusting the intra-cavity loss, the signal-to-noise ratio can be increased and the tunable range can be broadened to C+L band.

Introduction

Compare with traditional laser, the tunable fiber ring laser has many merits such as narrow laser linewidth, simple structure, steady working state¹¹, and so on, furthermore, the output laser wavelength covers a wide range, it is suitable to the domain of optic fiber communications, laser sensing and measurement²². Because of the characters such as high gain, wide frequency band, and low noise figure⁴, EDFA is used as gain medium to constitute the tunable fiber ring laser, many research and applies are done on it⁵⁶⁷. But most works are about researching the effect of one parameter on system performance; the effect of relationship among each parameter on system performance is seldom researched.

Theoretically, the tunable range of EDF can cover from C band to L band, and reach about 50nm, but limited by the input power of optical device, the tunable range of EDF can only reach about 30nm¹⁰¹¹, the narrow tunable range limited EDF laser as a light source, or as a sensing measure device¹²¹³. Furthermore, the power change rate and noise of L band tunable laser are too large; it is not suitable for sensing measurement.

In this paper, all research was based on a business EDFA with L band, by researching the effect of pump power, system loss, sampling method and laser output, a kind of EDF laser with low noise and widely tunable range has been designed.

Laser System Working Principle

In a tunable fiber ring laser system, when system gain is higher than system loss, the light with chosen wavelength will oscillate and enlarge until it becomes a stable laser. When the voltage value changed, the output laser wavelength will change, too. In system, the EDFA is mainly used to adjust intra-cavity loss to control the output power of laser, isolator is used to control the one way transmission of light to avoid space burning hole.

Obtainment of Wide Tunable Laser

In one oscillation mode in intra-cavity, the condition can be obtained as follow:
$g^0(\nu_q) > g_t$ \hspace{1cm} (1)

Where $g^0(\nu_q)$ represent gain coefficient of small signal, and $g_t$ represent gain factor.

$g^0(\nu_q) = \Delta n^0 \sigma_{21}(\nu_r, \nu_q)$ \hspace{1cm} (2)

As shown in (2), $g^0(\nu_q)$ is different in different frequency because of the effect of emitting section $\sigma_{21}(\nu_q, \nu_0)$, furthermore, $g^0(\nu_q)$ increased with the increasing of pump power because of the effect of $\Delta n^0$.

Because the EDF is a gain medium which can be widened uniformly, its gain threshold $g_t$ can be represented by intra-cavity loss $\delta$ and erbium-doped fiber length $l$:

$g_t = \frac{\delta}{l}$ \hspace{1cm} (3)

Merge (1) to (3), in frequency model $\nu_q$, only when $\Delta n^0 \sigma_{21}(\nu_r, \nu_q) > \frac{\delta}{l}$ can it worked:

$\Delta n^0 \sigma_{21}(\nu_r, \nu_q) > \frac{\delta}{l}$ \hspace{1cm} (4)

Figure 1. Simulation results.

So increase the pump power, decrease the intra-cavity loss or increase the erbium-doped fiber length can increase the tunable range of laser. But as shown in Figure 1 and (5), increasing pump power and erbium-doped fiber length, or decreasing intra-cavity loss can increase the tunable range and power of laser, but high power laser is harmful to intra-cavity and optical elements, such as tunable wave filter.

\[
P = A \eta I_s(\nu_q) \left[ \frac{g^0(\nu_q) l}{\delta} - 1 \right]
\]

In (5), $P$ represent the laser power in stable state, $A$ represent the effective section of laser, $\eta$ represent the coupling ratio, $I_s(\nu_q)$ represent the saturated light intensity.

To increase the tunable range of laser and ensure the safety of system, high pump power and tunable attenuator were used in this paper to achieve laser output. High pump power can get a large tunable range, and tunable attenuator can be used to adjust intra-cavity loss and limit laser power. The adjust principle is that, set a small value of tunable attenuator when the oscillator is at an inefficient frequency can make it easy to output laser, and set a large value of tunable attenuator when the oscillator is at an efficient frequency can limit laser power and ensure the security of system. Through this way can get smoothly output power and large tunable range. The formula is shown as follows:

When $P$ is less than $P_t$,
\[
\begin{aligned}
\delta_v &= \delta_v + \Delta \delta_v \quad (0 < \delta_v < \delta_1) \\
\delta_v &= 0 \quad (\delta_v = 0 \text{ or } \delta_v \geq \delta_1)
\end{aligned}
\]

When \( P \) is greater than \( P_t \)
\[
\begin{aligned}
\delta_v &= \delta_v + \Delta \delta_v \quad (\delta_v < \delta_1) \\
\delta_v &= \delta_v \quad (\delta_v \geq \delta_1)
\end{aligned}
\]

Where \( P \) represent the output power of laser, \( \delta_v \) represent the value of tunable attenuator, \( P_t \) represent the threshold of power, \( \delta_1 \) represent the attenuation threshold of tunable attenuator.

**Setting of Oscillation Delay**

Through the relaxation oscillation of laser, we can know that by the continuous stimulus of pump light, the laser intensity in intra-cavity is not stable, but interact with population inversion value and tend to be stable in the form of damped periodic oscillation, so to the tunable laser, reasonable setting of oscillation delay will affect characteristic of output laser directly.

In damped oscillation phase, photon number density will change around \( N_{q0} \), and the change value is \( N'_{q0}(t) \), the formulas are shown as follow:

\[
N'_{q0}(t) = N_{q0}(0)e^{-\varphi t} \sin(\Omega_R t - \frac{\pi}{2})
\]

(6)

\[
\varphi = [w_{13} + A_{21} + \sigma_{21}(v_{q0}, v_{0})v_{q}N_{q0}]/2
\]

(7)

Where \( v_q \) represent the intra-cavity frequency in steady state, \( N_{q0} \) represent the photon number density, \( \Omega_R \) represent oscillation frequency, \( \varphi \) represent attenuation value of damped oscillation.

As shown in Figure 2, in theory, when we change the transmission wavelength of tunable filter, if the oscillation delay \( t \gg 1/\varphi \), \( N_{q0}'(t) \) will tend to zero, and the intra-cavity laser’s intensity will remain stable, and the noise of output laser will be small; but in fact, because of the drift character of tunable filter, too long a delay will cause model hopping (as shown in Figure 3, horizontal coordinates represent sampling point sequence, it corresponds to delay time, and longitudinal coordinate represent example voltage, it corresponds to laser power). Furthermore, too long a delay time is not conducive to scan real-time of tunable laser. If the delay time \( t \) is too small, the amplitude of intra-cavity photon density will change larger, and the output laser noise will change larger, too. Comprehensive consider the real-time of system and the character of output laser, we draw a conclusion that it is reasonable to set the oscillation delay time \( t \approx 1/\varphi \).

![Figure 2. The diagram of the oscillation of photon density.](image)
System Experiment

Figure 4 shows the output laser spectrum collected by the tunable fiber ring laser system (horizontal coordinates represent scanning point sequence, 0-500 corresponding to 0-1.5V; longitudinal coordinate represent sampling voltage, corresponding to power of output laser), all pump electric current are 135mA, scanning voltage range was set from 0 to 1.5V, the different in Figure 4(a) and (b) is that in Figure 4(a), attenuation value of tunable attenuator is set to 0dB, and in Figure 4(b), tunable attenuator can adjust attenuation value based on output power. In Figure 4(a), when scan voltage exceed 0.63V, because laser power exceed the limit of tunable filter’s power, system will close pump automatically, the efficient frequency range is very small, only from 0.24V to 0.63V. But in Figure 4(b), because the attenuator was adjusted automatically, laser power was limited in a range which the tunable filter can work well, and the efficient frequency range will be broadened from 0.24V to 1.23V. So, by adjusting the tunable attenuator value automatically, it can increase the output laser tunable range, and ensure system security.

As shown in Figure 5 (Horizontal coordinates represent scanning point sequence, 0-4000 corresponding to 0.5-1.0V; longitudinal coordinate represent sampling voltage, corresponding to output laser power), all pump electric current are 200mA, and scan voltage is set from 0.5V to 1.0V. Figure 5 proved that as the increasing of delay time, the noise of output laser will decrease, and power will increase. But when the laser output tend to stable, increase the delay time will not improve the output laser noise and power, so, set a appropriate delay time can give attention to both laser characteristics and system real-time.

Figure 6 shows the laser spectrum obtained before and after improving the system (Horizontal coordinates represent scanning laser wavelength; longitudinal coordinate represent sampling voltage, corresponding to output laser power), all pump electric current are 200mA, scan voltage is...
set from 0.1V to 1.5V. Before improving the system, when fixed value of tunable filter is 2dB, and oscillation delay is 0.2ms, the tunable range of output laser is about 30nm, and the noise is big; after improving the system, the new algorithm which was introduced

in chapter 2 was used, the value of tunable filter was automatic adjusted, appropriate delay time was be set, the tunable range of output laser increased to about 60nm, and the noise is significantly decreased.

**Conclusion**

In this paper, a tunable fiber ring laser based on intra-cavity loss automatic adjustment was designed. Experiments show that by using the tunable attenuator to automatically adjust intra-cavity loss and set an appropriate delay time, the tunable range of laser can expand from 30nm to 60nm; the output laser noise was significantly decreased. The laser with low noise and wide tunable range will has a wide application prospect in the field of laser sensor and measurement, and wavelength division multiplexing optical fiber communication.

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