CHAPTER VII

CONCLUSIONS

7.1 INTRODUCTION

A thorough investigation on erbium-doped fiber amplifiers (EDFAs) with optical feedbacks has been presented in this thesis. The research work included the effects of introducing different feedback schemes, namely counter-, co- and regenerative-feedback. This chapter concludes the work done based on different feedback schemes. An overall summary of the work is given and the possible future paths of the research are also suggested.

7.2 COUNTER-FEEDBACK

Although the oscillating laser was supposed to be eliminated at the amplifier output in the counter-feedback scheme, the oscillating laser still existed at the amplifier output due to the back reflection in the cavity. The existence of the oscillating laser induced the gain clamping effect, resulting in markedly increase in the dynamic range where the linear amplification could be sustained up to a fairly high input signal level before getting saturated. However, it suffered from ~10 dB of gain compression. As a result, signal gain and noise figure were significantly deteriorated compared with the system without feedback. The lower signal gain was due to the clamping of the inversion at a lower level after the onset of laser oscillation whereas degradation in the noise figure could be attributed to the laser-induced saturation at the EDF input end [1]. The dip effect in the noise figure as a function of the input signal power was found to be enhanced by the laser-induced saturation. The maximum achievable small-signal gain was just 24.3 dB. The desired amplifier performance, including the signal gain, noise figure, gain flatness and dynamic range could be achieved by choosing an appropriate lasing wavelength.

7.3 CO-FEEDBACK

Co-feedback scheme exhibited much lower noise figure in the high pump regime due to the effectiveness of the backward ASE suppression by the oscillating laser in the clock-wise direction compared with the counter-feedback scheme and the system without feedback [2]. However, the signal gain was found to be degraded by ~1 dB as compared to the counter-feedback system. Laser-induced saturation in counter-feedback scheme and laser-induced backward ASE suppression at the EDF input end in the co-feedback scheme caused both schemes exhibited an opposite behavior in terms of noise figure. Study of attenuation level in the co-feedback system showed that the performance of the gain-clamped EDFA in terms of signal gain, noise figure and dynamic range are cavity-loss dependent. The laser SNR was found to be dependent on both injection level and wavelength separation between the oscillating laser and the injected signal [3]. Similar to the counter-feedback scheme, the desired amplifier performance, including the signal gain, noise figure, gain flatness and dynamic range could also be achieved by choosing an appropriate lasing wavelength [4].

7.4 REGENERATIVE-FEEDBACK

Erbium-doped fiber amplifier with regenerative-feedback has been presented. Operating below the threshold of self-oscillation, resonant-amplification was found to be preserved only for small input signal [5]. Resonant gain as high as 35.1 dB was achieved with the pump power as low as 29.4 mW, just below the oscillation threshold. A flat gain spectral could only be obtained with the saturating input signal. Due to the strong amplification at resonance, the saturation input power was much lower than the case without feedback. Operating above the oscillation threshold, gain-clamping effect was established. Existence of the oscillating laser effectively suppressed the generation of the backward ASE, thus, increasing the noise performance markedly. Intrinsic noise figure as low as 3.2 dB was achieved with the maximum pump power of 134.5 mW, revealing a near-complete inversion at the EDF input end. However, the application of regenerative amplifier in optical communication system was severely deteriorated due to the interference effect [6]. The potential application as a high-power frequency-stabilized laser source was proposed based on the study of injection-locking. An interesting feature was that the gain and noise figure could be improved by injecting another signal with the wavelength ~1530 nm and with a moderate level of power (~-20 dBm). We proved that such a phenomenon was attributed to the backward ASE suppression instead of attributing the second injection as a secondary pump source [7]. Comparison between unidirectional- and bidirectional-feedback regenerative amplifier showed that saturation induced by the oscillating laser in the anti-clockwise direction played an important role in the degradation of the system performance.

7.5 SUMMARY OF THE WORK

Effects of optical feedback in the EDFA have been reported. In conclusion, the following effects were observed, depending on the feedback scheme:

1). **Gain-Clamping Effect**

Under moderate level of pumping power, gain-clamping effect was established, regardless of feedback directions. This effect was getting stronger by simply increasing the pump power. The power conversion efficiency decreased after the onset of laser oscillation. Lasing action fixed the total population inversion, therefore, the gain for all the wavelengths were only dependent on their absorption and emission cross sections and the overlap factor at the fiber cross section. Any variation in other conditions such as pump power and input signal power is compensated for by the adjustment of the lasing signal power. However, the gain-clamping effect diminished when the injected signal was strong enough that caused gain quenching of the oscillating laser. Under this heavily injection condition, the effects of the optical feedback became insignificant and the amplifier system behaved like the conventional EDFA system without the feedback.

2). **Increase in Dynamic Range**

Increase in the dynamic range with respect to the input signal power was contributed by the existence of the gain-clamping effect induced by the oscillating laser in the cavity. The existence of the oscillating laser enabled the input signal to experience a constant gain in the amplifier system before gain quenching induced by the laser taking place. Thus, dynamic range of the EDFA system with the optical feedback was found to be larger.

3). **Laser-Induced Saturation**

This effect was observed in the EDFA system with optical counter-feedback. Without the feedback, the co-pumping EDFA scheme exhibited a higher noise figure at the higher pump power with the unsaturated signal. Besides the backward-ASE-induced saturation at the EDF input end, strong oscillating in the cavity with the counter-feedback contributed to the deterioration of the noise performance in which it induced saturation or depopulation at the EDF input portion. In consequence, the EDFA with counter-feedback manifested a higher increase in the noise figure with respect to the pump power, compared to the case without the optical feedback.

4). **Suppression of Backward ASE**

Instead of inducing saturation at the EDF input end, the oscillating laser in the co- and regenerative-feedback schemes restored the inversion back to a higher level through suppression of the backward ASE. Thus, the noise performance was improved significantly. Laser-induced saturation in the counter-feedback scheme and suppression of backward ASE in the co-feedback scheme caused the noise of both configurations manifested a behavior opposite to each other as a function of pump power and signal wavelength. The suppression of the backward ASE was found to be enhanced by injecting second signal with a moderate level of power. Gain enhancement and noise improvement were achieved under this condition.

5). **Injection-Locking**

Under moderate injection level, the gain of the oscillating laser was quenched, leaving the injected signal oscillating in the cavity. Such a phenomenon, namely *injection-locking*, took place in the regenerative-feedback scheme without the wavelength selective element. The oscillating mode and the stability of the mode was found to be controlled by the injected signal, exhibiting a potential of this scheme as a high-power frequency-stabilized laser source.

7.6 SUGGESTIONS FOR FUTURE WORK

EDFA with the optical feedback is in fact a laser cavity. Investigation on the EDFA with optical feedback was done only on the steady-state (wavelength domain) characteristics. The dynamical (frequency or time domain) behaviors, on the other hand, remain as a wide area to be explored. A lot of theoretical work [8-13] has been done, predicting various dynamical behaviors of laser and amplifier systems such as bistability, bifurcation and period-doubling route to chaos.

In particular, the configuration of regenerative-feedback had been reported to be as a nonlinear optical resonator [14] which exhibited the bistable behavior. Without the pump, the erbium-doped fiber acts as a nonlinear absorptive medium [15-16]. Further study can be done since the nonlinear resonator has the potential as a bistable device. Several work had been done by L G. Luo et. at. [16-18]

Research work can be carried out to explore other potential applications based on the similar fiber ring resonator. It had been proposed that the similar configuration could be used as an active filter to enhance the finesse of the laser source [19-20]. The potential for such a high finesse is for high-resolution optical spectrum analysis [20].

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