Stability Analysis of Mode Locked Figure-eight Fiber Laser

M. K. Islam and P. L. Chu
City University of Hong Kong, Hongkong

Abstract

Mode locked fiber laser, as a source of short pulse generation finds applications in telecommunications and optical signal processing where low noise and stable pulse train is the main requirement. It is therefore important to analyze its shot to shot pulse amplitude stability and timing jitter. By introducing a gradual twist in fiber and using a length of normal dispersion EDF to stretch and amplify the pulse, high energy and stable pulse train generated from a figure eight laser has been analyzed. Fluctuations in pulse repetition time and in pulse energy as well as jitter in pulse width occur simultaneously. All these types of noise have been characterized quantitatively by examining the higher harmonics of the RF spectrum. By optimizing the total dispersion and cavity length of the laser, it was found by measurement that a peak to peak stability of 99.2% and a timing jitter of 5.59 psec for 2.31 MHz pulse train was obtained. This is quite remarkable. However, it is observed that the variation of cavity parameters results in increased timing jitter and peak pulse instability.

Introduction

Generation of ultra short pulses is of great importance for applications in optical signal processing, communications, high-speed electronics, and time resolved study of many physical, chemical and biological processes. However, it is desirable to be able to generate these pulses at an arbitrary repetition rate with high stability.

There are various techniques of generating short optical pulses but gain switching and mode locking are the two commonly used methods. In mode locking, an intra cavity gain, loss, or phase element is used to lock the longitudinal modes into some physical relationship in order to produce short optical pulses. Mode locked fiber lasers employing rare earth doped element, as a gain medium are important systems for the generation of short, high power optical pulses. However, in this system the fiber loss plays an important role in determining the energy density of the pulses. Small fiber loss allows its interaction length to range any where from a few centimeters to several kilometers. This property makes possible various lasers to be constructed such as laser with very low threshold, or laser using low gain materials, or high gain amplifiers with low pump power. Erbium doped fibers have received more attention for their application as fiber amplifier (EDFA), which is a key element in the structure of a mode locked fiber laser. This amplifier, operating around 1.55 μm, has many desirable characteristics such as high gain, low pump power requirement, high saturation power, large bandwidth, low noise, low polarization dependent gain and low temperature sensitive gain. All these features provide an ideal gain medium for the generation of wavelength tunable ultra short optical pulses.

However, fiber lasers do have certain limitations. They are subject to environmental changes; timing jitter and shot to shot instability. Irrespective of the laser geometry, with subpicosecond operation the lasers do not exhibit a strictly periodic output. Also the appearance of down shifted and up shifted spectral components (side bands) limits the pulse width and deteriorates the pulse quality. Furthermore, It is difficult to achieve high-energy short pulses from these lasers.

The instability has been attributed to the sensitivity of the birefringence of the fiber in the cavity to the environment such as change in temperature, accidentally applied pressure and unintentional bending, etc [1]. Various techniques have been proposed to generate a stable, high-energy pulse train from a mode locked fiber laser, but quantitative stability analysis of these lasers is lacking.

The purpose of this paper is to show that a highly stable mode-locked figure eight fiber laser can be constructed by taking advantage of applying gradual twist to the fiber in the cavity, and using normal dispersion erbium doped fiber to stretch and amplify the pulse and as well as using all the couplers made from dispersion shifted fibers with anomalous dispersion. Stability in terms of the timing jitter and shot to shot pulse stability of this laser is quantitatively analyzed and optimized using its RF spectrum for different cavity parameters.

Experimental Setup

The schematic diagram of the figure eight fiber laser is shown in figure 1.

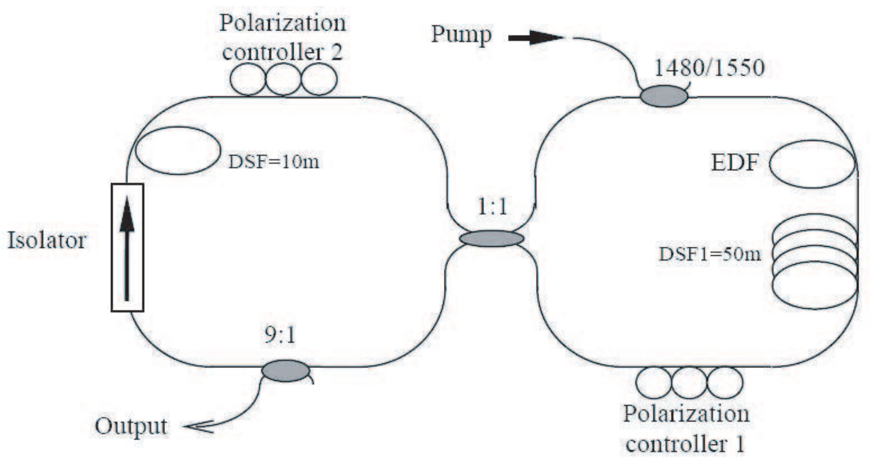

Figure 1: Schematic of figure of eight laser

The Erbium-doped fiber (EDF) has normal dispersion of +0.65 $\mathrm{ps}^2/\mathrm{km}$ at λ=1560nm, Erbium concentration of 730ppm, mode field diameter of 4.9μm and an optimized length of 10 m. The optimization is achieved by replacing different lengths of the same EDF in the amplifier and 10m length gives the maximum gain for pump power of 40mW. The NALM contains a 50m segment of dispersion-shifted fiber with dispersion of -2.1 $\mathrm{ps}^2/\mathrm{km}$. A gradual twist of 1^0/cm is introduced to the fibers in the loop by winding them onto a drum of 15 cm in diameter. This technique has also been used to stabilize a cw fiber ring laser [2]. All the couplers used in the set up are made from the dispersion-shifted fiber with anomalous dispersion. The cavity contains two polarization controllers, a polarization independent fiber isolator and a 10% coupler to tap the pulse train.

The pedestal free optical spectrum with FWHM of 25 nm measured with a resolution of 0.1 nm revealing the negligible cw background is shown in figure 2. The corresponding autocorrelation trace recorded by Inrad 5-14-LDA with a measured pulse width of 125 fsec assuming sech^2 shape is shown in figure 3.

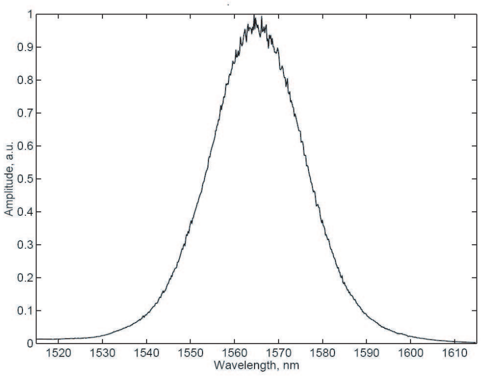

Figure 2: Optical spectrum of the mode-locked pulse train

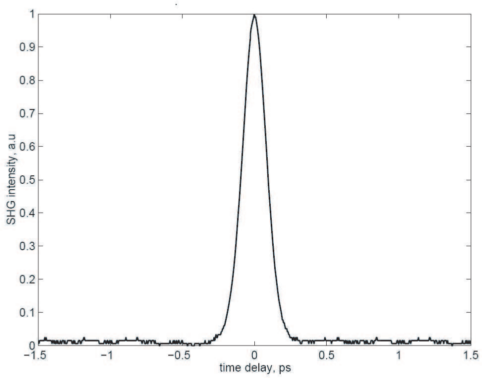

Figure 3: Autocorrelation of the mode locked pulse

The time-bandwidth product of 0.38 is very close the theoretical transform limit of a soliton. The pulse peak power of 4kW and energy of 0.5 nJ corresponds to the measured average output power of 1.2 mW. Stable pulse train when the laser was in operation for few hours is shown in figure 4.

Stability Analysis

The pulse stability is an important issue and it must be considered before it can find practical applications. Different types of noise present in the system can seriously degrade the pulse quality. The information on the fluctuations of the pulse energy, pulse repetition time, and pulse duration can be recognized from the examination of a high harmonic of its RF spectrum [3]. All these types of noise can be characterized individually in a quantitative way, even if they occur simultaneously. Each harmonic consists of the sum of a constant amplitude noise spectrum, which is due to the pulse energy fluctuations, and a component from pulse width fluctuations,

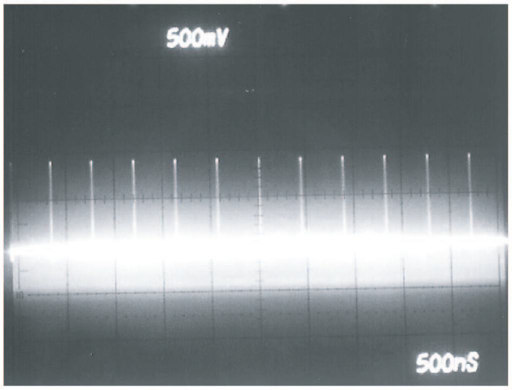

Figure 4: Stable mode-locked pulse train

and timing jitter which increases as the square of the harmonic number [4].

We apply this technique to our laser by displaying the microwave spectra of the fundamental and 30th harmonic over a span of 80 kHz with bandwidth resolution of 300Hz, in a HP 8591A spectrum analyzer as shown in figure 5 and figure 6.

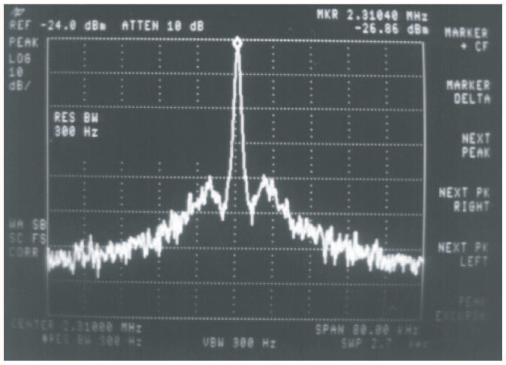

Figure 5: RF spectrum of fundamental harmonic

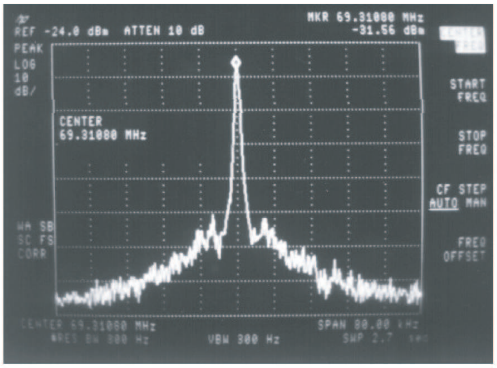

Figure 6: RF spectrum of 30th harmonic

The fluctuations in pulse energy can be calculated from the fundamental component of the RF spectrum as [3],

$$\frac{\Delta E}{E} = \sqrt{\left(\frac{P_c}{P_a}\right)_f \frac{\Delta f_a}{\Delta f_{res}}}, \tag{1}$$

where P_c and P_a are the maxima of the noise band and the signal respectively, subscript f stands for fundamental frequency. Δf_a and Δf_{res} is the full width half maximum of the noise floor and spectral resolution of the spectrum analyzer respectively. The energy fluctuation calculated for our laser is only 0.8%. The very high amplitude stability is quite remarkable.

The timing jitter can be easily calculated from a high harmonic [3],

$$\frac{\Delta t}{T} = \frac{1}{2\pi n}\sqrt{\left(\frac{P_b}{P_a}\right)_f \frac{\Delta f_j}{\Delta f_{res}}}, \tag{2}$$

where T is the cavity round trip time, Δt is timing jitter, n is the harmonic order of the frequency component, P_b is the power of the noise floor responsible for jitter, Δf_j is the bandwidth of the corresponding noise component. From the 100th harmonic shown in figure 7, we can easily calculate for $\Delta f_j = 20$kHz, the ratio $\Delta t/T = 1.23 \times 10^{-5}$. For a repetition rate of 2.31 MHz, the timing jitter is 5.59 ps which gives the shot to shot pulse fluctuations of only 0.0129%.

It was observed that when a mode-locked laser is unstable, its RF spectrum has some spurious sidebands around the fundamental and higher harmonics. However, when the laser was stabilized, the spurious sidebands

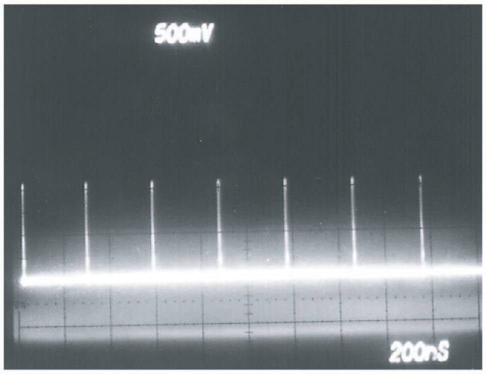

Figure 7: Mode-locked Pulse train

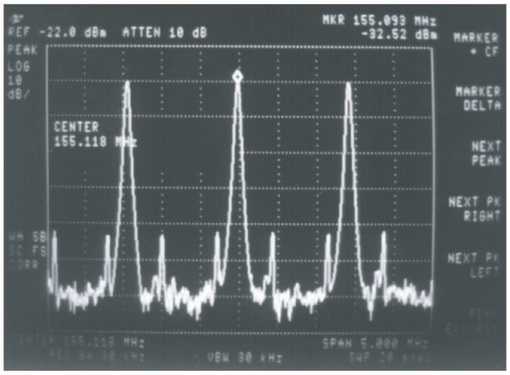

Figure 8: RF spectrum of mode-locked pulse train

completely disappeared. From the spectra shown in the above figures, it can be seen that there are no spurious side bands around the fundamental and higher harmonics of the RF spectrum. This reveals the high stability of the laser pulses.

When the laser is destabilized intentionally by replacing the erbium doped fiber and dispersion shifted fiber in the cavity, laser is still mode-locked with apparently a stable pulse train as shown in figure 7, but the RF spectrum has spurious side bands as shown in figure 8, which reveals instability.

Conclusion

The RF spectral analysis technique is quite useful in the study of the stability of lasers. This technique has been applied to the figure eight laser, which was optimized, for its stability by selecting optimal laser parameters. In spite of the well-known fact that mode-locked lasers suffer from low energy and instability problems, we have demonstrated that very stable high-energy pulses can be generated by using EDF with normal dispersion in conjunction with controllable birefringence introduced through a gradual twist to the fiber in the cavity.

Acknowledgment

This project is being supported by the Strategic Research Grant (No. 7001705) from the City University of Hong Kong.

REFERENCES

1. Dulling, I. N. III, “Subpicosecond All-fiber Erbium Laser,” *Electron. Lett.*, Vol. 27, 544-545, 1991.
2. Shi, C. X., “A Novel Twisted Er-doped Fiber Ring Laser: Proposal, Theory and Experiment,” *Optics Communications*, Vol. 125, 349-358, 1996.
3. Linde, D Von der, “Characterization of the Noise in Continuously Operating Mode Locked Lasers,” *Appl. Phys. B*, Vol. 39, 201-207, 1986.
4. Fuss, I. G., “An Interpretation of the Spectral Measurements of Optical Pulse Train Noise,” *IEEE J. Quantum Electron.*, Vol. 30, 2707-2710, 1994.