Low repetition rate passively mode-locked thulium-doped fiber laser for LIDAR system

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Abstract. An all-fiber passively mode-locked thulium-doped fiber (TDF) ring laser with a repetition rate of 736 kHz was demonstrated. This is the lowest repetition rate among those of mode-locked TDF lasers to the best of our knowledge. Numerical calculations to find the best solution for successful mode-locking in a highly lossy oscillator were made based on Haus’s master equation with variables such as oscillator loss, small signal gain and modulation depth. Based on the calculation, the laser was configured, where nonlinear polarization rotation (NPR) and two stages of TDF amplifier were properly applied. The overall length of oscillator is about 290 m. The output optical spectrum has a FWHM of 28 nm at 2 μm.

1. Introduction

The optical fiber lasers are of great interest in various fields including research and industries due to robustness, compactness and high beam quality. The mode-locked optical fiber lasers have been applied to micro-machining, high resolution raging, frequency comb and bio-medical applications [1-5]. Especially, the optical fiber lasers operating around 2 μm has promising features, where various materials exhibit high absorption around wavelength of 2 μm [6]. For example, OH ion exhibit high peak absorption at 1.95 μm and absorption band is as narrow as a few tens nanometers, that is suitable feature for application of differential absorption LIDAR (DIAL) to measure the atmospheric concentration. Plus, LIDAR system for autonomous vehicles requires low scattering by dust in the air and low absorption by water like as fog. At wavelength of 2.2 μm, absorption by water goes lowest in mid-infrared region. So, developing pulsed laser operating at this wavelength range is promising for LIDAR systems for autonomous vehicles. For this application, repetition rate of pulses is preferred to be under MHz owing to easiness of signal processing and maximum raging distance. It also prefers pulse duration under ps for higher spatial resolution of LIDAR system. The passively mode-locked fiber lasers would be a good choice as a light source for LIDAR system in terms of pulse duration, even though their typical repetition rate is about a few tens of mega-hertz. To generate the femto-second pulses with repetition rate under MHz, in previous studies, acousto-optic (AO) modulator has been employed for

\textsuperscript{3} This research was supported in part by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science, ICT, and Future Planning (2015M1A3A3A03027287) and in part by the Korea Research Institute of Standards and Science project ‘ Establishment of National Physical Measurement Standards and Improvements of Calibration/Measurement Capability,’ grants 18011043 and 18011033.
pulse picking to lower repetition rate of pulses generated from mode-locked fiber lasers having a few tens of MHz repetition rate. However, it requires the electronic apparatuses to drive active modulators, that makes system complex and expensive. So, the low repetition rate passively mode-locked fiber lasers with long fiber oscillator has been studied to meet these conditions. [8,9]

It’s not simple to build the low repetition rate TDF laser with long silica fiber oscillator due to high loss at 2 μm. Because high loss oscillator needs high small signal gain for compensation of the loss, and the high gain results in high gain dispersion that drives the mode-locked laser operation unstable [10].

In this paper, we conduct numerical simulations of passively mode-locked laser applying Haus’s master equation based on the fast saturable absorber model to find out the best condition for stable mode-locking with key parameters that should be optimized in the lossy laser oscillator. Based on the results of simulation, we built the passively mode-locked TDF ring laser with repetition rate of 736 kHz employing 290 m silica fiber oscillator and NPR method. Two stage TDF amplifiers, that is emplaced at the opposite side of each other in the ring laser oscillator, is applied to compensate the loss of oscillator effectively. This is the lowest repetition rate mode-locked TDF laser, to the best of our knowledge. The 3dB bandwidth of optical spectrum is 28 nm, that is atypically broad compare to typical passively mode-locked fiber lasers. We expect that it arises from large total nonlinearity per roundtrip by the help of the long length of the oscillator.

2. Principle and simulation of Haus’s master equation
In mode-locking operation, two main effects do important role for stable mode-locking with high loss oscillator [9]. The one is gain dispersion and the another is saturable absorption. The gain dispersion is the dispersion caused by limited spectral bandwidth of gain, when pulses pass through the gain medium. The beam at the wavelength at the center of gain spectrum experience higher gain than beam at the wavelength away from the center. So, optical spectrum of pulse would become narrower by the gain, then, pulse duration would be longer. And, this dispersion would be enhanced as gain goes higher. When the laser start lasing, the laser beam is shaped into pulses by SAs. The strength of saturable absorption is represented by modulation depth (MD) that is transmission difference between maximum and minimum of absorption by SAs. Since, these two effects act counterworks each other, pulse shaping by SA should be stronger than gain dispersion for stable mode-locking operation. In lossy and long length oscillator, high gain dispersion is unavoidable due to high gain to compensate the loss of oscillator, that will consequently drive the mode-locking operation unstable. For stable mode-locking operation, the MD of SAs should be large enough, and overcome the gain dispersion in lossy and long length oscillator.

We conduct the numerical simulations to confirm these effects on mode-locking operation, applying Haus’s master equation based on the fast SA model. Initial field profile in the cavity was set to be noisy signal like as field profile of amplified spontaneous emission. Then, we got the output power profile in time domain with 7000 roundtrips, varying the parameters including gain, oscillator loss and MD. First, we varied the gain and oscillator loss to simulate the effect of gain dispersion. The gain value and oscillator loss were correlated to keep average power constant. Figure 1(a) shows output pulse profile with respect to 5 different combinations of the gain and oscillator loss with constant output power. Figure 1(b) and (c) shows pulse duration and optical spectrum of output pulses, respectively. The pulse duration get longer and optical spectrum get narrower, as the gain value increase from 2 dB to 17 dB. Figure 1(d) shows output pulse profile with respect to MD. Figure 1(e) and (f) shows pulse duration and optical spectrum of output pulses, respectively. The pulse duration gets shorter and optical spectrum get narrower as the MD increases from 4.6% to 29%. And the laser doesn’t operate in mode-locking with the modulation depth under 4.6%. From this simulation, we confirmed the effects of gain dispersion and saturable absorption on mode-locking operation. And, we also figured out that MD should be large enough to compensate the effect of gain dispersion for stable mode-locking in high loss oscillator. The MD of natural SAs, like as graphene, carbon nanotubes, semiconductors and other 2D materials, however, typically have MD of a few tens of percent. And, it’s difficult to increase the MD without increment of non-saturable loss [11]. Therefore, natural SAs are not suitable for mode-locking with high loss oscillator. The NPR methods, on the other hand, exhibit high MD depending on the amount of
nonlinearity of the oscillator. The MD can be increased to value as large as polarization extinction ratio
of polarizer with keeping the non-saturable loss as low as insertion loss of polarizer, theoretically, if
nonlinearity is sufficient in the fiber oscillator.

![Figure 1](image)

**Figure 1.** (a) Mode-locked pulses calculated in time domain for different MDs at a fixed gain of 4.3 dB, (b) Pulse duration as a function of MD, (c) Output optical spectra for different MDs. (d) Mode-locked pulses calculated in time domain for different gains (oscillator losses) at a fixed MD of 10 %, (e) Pulse duration as a function of oscillator loss, (f) Output optical spectra for different gains.

3. Laser configuration and results

Based on simulation result, we built passively mode-locked TDF laser with 290 m long silica fiber ring
oscillator applying NPR method. Figure 2 shows the schematics of a passively mode-locked TDF laser.
We put the two TDF amplifier into the oscillator at the position where both of them are opposite side of
each other for effective compensation of the loss. The pump beam is coupled into the oscillator through
the pump beam combiners (PBCs). The output signal was coupled to output port with coupling ratio of
23%. The NPR method was realized through employing two polarization controllers (PCs) and a
polarizer. Figure 3 (a), (b) shows optical power in time domain, optical spectrum of output pulses from
the low repetition rate passively mode-locked TDF ring laser, respectively. The RF spectrum in figure
3(c) shows stable operation of mode-locking. The repetition rate is 736 kHz, that is the lowest repetition
rate among the mode-locked TDF lasers ever reported, to the best of our knowledge. The measured
average output power is 1 mW, and pulse energy calculated to be 1.4 nJ at the pump power of 3 W. The
3dB bandwidth of optical spectrum is 28 nm, that is atypically broad. We expect that broad spectrum
arise from the high nonlinearity of the long fiber oscillator.

4. Conclusions

We conduct the numerical simulation to find out proper condition for stable mode-locking in lossy and
long laser oscillator by studying the effects of gain dispersion and saturable absorption. Then, we
demonstrated the 736 kHz repetition rate passively mode-locking TDF laser based on numerical
simulation. This is the lowest repetition rate mode-locked TDF laser, to the best of our knowledge. The
3 dB band width of optical spectrum is 28 nm, which is way broader than that of typical mode-locked TDF lasers.

**Figure 2.** Schematics of a passively mode-locked TDF laser with a low repetition rate of 727 kHz. SMF: single mode fiber, OC: output coupler

![Figure 2](image)

**Figure 3.** (a) Output mode-locked pulses, (b) optical spectrum, (c) RF spectrum of output from the passively mode-locked TDF laser (Span: 15 MHz, Resolution bandwidth: 30 kHz)

![Figure 3](image)

5. References

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