Mode-locking and Q-switching in multi-wavelength fiber ring laser using low frequency phase modulation

Chang Su Jun* and Byoung Yoon Kim

Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), 373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701, South Korea
*tridra@kaist.ac.kr

Abstract: We describe experimental investigation of pulsed output from a multi-wavelength fiber ring laser incorporating low frequency phase modulation with large modulation amplitude. The Erbium-doped fiber (EDF) ring laser generated more than 8 wavelength channels with the help of a phase modulator operating at 26.2 kHz and a periodic intra-cavity filter. For most cases, the laser output is pulsed in the form of mode-locking at 5.62 MHz and/or Q-switching at harmonic and sub-harmonic of the phase modulation frequency. Chaotic pulse output is also observed. The behavior of the output pulses are described as functions of pump power and phase modulation amplitude. The relative intensity noise (RIN) value of a single wavelength channel is measured to be under –100 dB/Hz (–140 dB/Hz beyond 1.5 GHz).

OCIS codes: (140.3510) Lasers, fiber; (140.3540) Lasers, Q-switched; (140.4050) Mode-locked lasers; (140.1540) chaos.

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1. Introduction

Cost-effective multi-wavelength (MW) light sources have attracted much attention for their applications in wavelength-division-multiplexing (WDM) communications and sensor systems. Among several different approaches studied, frequency-shifted feedback fiber lasers demonstrated possibilities to generate MW spectrum with readily available practical optical components [1–4]. In this approach, the consecutive frequency-shift of cavity modes provided by an intra-cavity acousto-optic modulator (AOM) interferes with the buildup of otherwise the predominant lasing mode. This process suppresses the effect of homogeneously broadened gain spectrum, and with the help of a periodic filter in the laser cavity, MW operation could be achieved. However, the use of a bulk optic AOM in the fiber laser cavity introduces optical loss and limited long term stability that are not desirable for practical applications.

Another more recent approach replaces the AOM with an all-fiber phase modulator (PZT cylinder) operating at relatively low frequency (tens of kHz range) [5,6]. The modulation of the cavity length suppresses the efficient buildup of the predominant cavity mode and thus allows MW operation. The advantage of this approach is that the all-fiber phase modulator simplifies the laser structure with negligible insertion loss. Q-switched MW pulses were produced and numerical simulations supported the experimental observations in Ref [6]. For further advancement of this approach, more detailed characterization of the laser properties including pulsing behaviors and, noise figures of single wavelength channel is desirable.

In this paper, we report the observation of mode-locking, Q-switching and chaotic behaviors in a MW erbium-doped fiber (EDF) ring laser with low frequency phase modulation (PM). The dependence of the pulsing behavior on pump power and PM amplitude is presented. To the best of our knowledge, the mode-locking and the chaotic pulse generation from a phase modulated MW fiber laser have not been reported so far. We also report the measurement of relative intensity noise (RIN) of the total output as well as that of a single wavelength channel. RIN was measured to be below −100 dB/Hz for a single wavelength channel and possible applications are discussed.

2. Experimental setup

Figure 1(a) shows the schematic of the phase-modulated fiber ring laser. Two isolators ensured unidirectional propagation of the laser light in the 5.3 m-long EDF. The small signal absorption coefficient of the EDF was 5 dB/m at 1550 nm and the core diameter was 5.6 μm. The rest of the fiber circuit was built with conventional single mode fiber (SMF-28) having 8.2 μm core diameter. The pump source was a 980-nm laser diode and the maximum pump power after the WDM coupler was greater than 80 mW. The all-fiber phase modulator was a bulk PZT cylinder wound by 100 turns of optical fiber as shown in the inset of Fig. 1(b), and the hoop mode resonance frequency was 26.2 kHz. The peak-to-peak amplitude of the optical path length modulation in the fiber was measured using a Mach-Zehnder interferometer setup and, as shown in Fig. 1(b), it was 69.9 ~431.8 μm for 1 ~10 V_{p-p} PZT driving voltage used for our experiment. This corresponds to approximately $\Phi_{p-p} = 90 \times \pi \sim 555 \times \pi$ (radian) peak-to-peak PM amplitude which is far greater than those used in the previously reported experiments [5,6]. The nonlinear relation between the applied voltage and the PM amplitude is due to the thermal loss and the slight resonance frequency shift of about 0.1 kHz of the PZT cylinder as the PZT driving voltage varies. The Fabry-Perot (F-P) comb filter is an air-gap fiber spacer with the free spectral range of about 0.78nm (~100 GHz) and full width at half maximum (FWHM) of 0.02 nm. A polarization controller (PC) and an output coupler complete the setup. The total cavity length was about 36 m. Additional band-pass filter (BPF) with the flat transmission band of 1542 ~1558 nm and pass-band isolation of about 20 dB was used in a separate experiment for noise reduction and RIN measurement.

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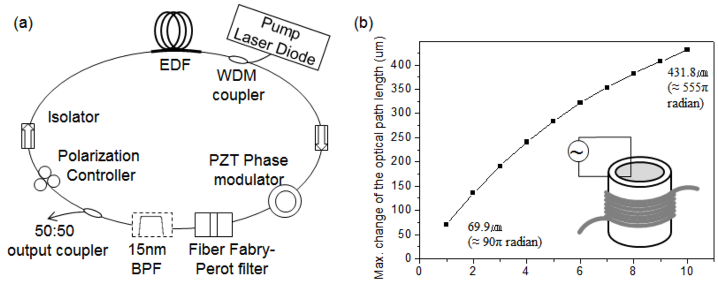

Fig. 1. (a) Phase-modulated fiber ring laser with a periodic filter. (b) All-fiber PZT phase modulator and the modulation amplitude relations at 26.2 kHz resonance frequency.

3. Results and discussions

When the PM was turned off, the laser output was a continuous-wave (CW) (inset of Fig. 2(a)) with the threshold pump power (P_{th}) of 7 mW and wavelength hopping between a few wavelengths was observed (Fig. 2(a)). We confirmed that the laser output did not show any significant self-pulsing [7] up to the pump power level of r (= P/P_{th}) ~10. As the PZT driving voltage was increased from 0 to 10 $V_{p\text{-}p}$, the number of lasing wavelengths increased. It should be noted that the PM amplitude corresponding to the PZT driving voltage between 1 ~10 $V_{p\text{-}p}$ used in our experiment was far greater than 2π radian that would correspond to about 0.02 $V_{p\text{-}p}$. With our experimental parameters, MW operation was obtained over the entire range of pump power above threshold. This is different from earlier results [5,6] where specific PM amplitude and/or proper combination of a few laser parameters was required for MW operation. While the increase of the pump power mainly raised the intensity of each wavelength channel, PC adjustment improved the power uniformity among channels and enhanced the spectral span. Figure 2(b) is an exemplary MW spectrum when r ~10 and PZT driving voltage was 10 $V_{p\text{-}p}$. The background noise level for the central 8 wavelength channels was between 30 ~46 dB below the signal (OSA spectral resolution of 0.05nm). The signal intensity fluctuation was about 1 dB level, which could be reduced significantly to about 0.1 dB level by inserting an additional BPF with 16nm bandwidth. As can be seen in the inset of Fig. 2(b), the time domain output was pulsed, and similar pulsing behavior could be observed for most of the PZT driving voltages above 1 $V_{p\text{-}p}$ and the pump power level r > 2.

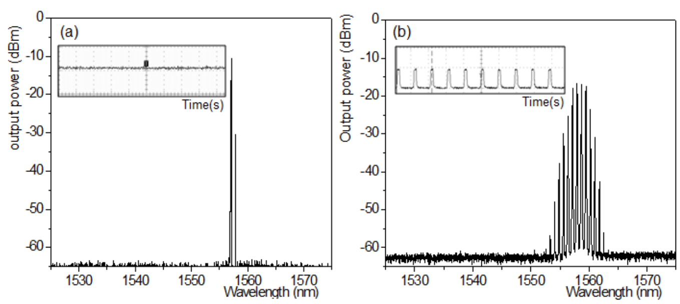

Fig. 2. Optical spectrum and time domain output for (a) when the PM was turned off showing CW and wavelength hopping and (b) when the PZT driving voltage was 10 $V_{p\text{-}p}$ and P/P_{th} ~10 showing MW and pulsed output.

The pulsing behavior includes mode-locking (ML) and Q-switching, and for certain parameter ranges, we also observed chaotic behaviors. We investigated the output characteristics in detail as functions of PM amplitude and pump power. Figure 3(a) is the CW output when the PM was turned off. With the PZT driving voltage at 1 ~3 $V_{p\text{-}p}$, pulses begin to appear at pump power r ~3 with the repetition rate of 5.62 MHz (period of about 178 ns) that matched the cavity length (Fig. 3(b)). When the pump power and PZT driving voltage were

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increased to r ~5 and $V_{p\text{-}p}$ ~3 volts, respectively, much more stable mode-locked pulse train could be observed as shown in Fig. 3(c). The pulse-width of the total output that includes all the wavelength channels was about 2 ns that varied when the cavity loss and PM amplitude were changed. The pulse duration is longer than the transform-limited value expected from 0.02 nm spectral width of each wavelength channel that would be about 126 ns assuming sech^2 pulse shape. We believe that the 2-ns pulse-width we observed is from the wavelength chirping within the pulses from each wavelength channel as well as between the pulses from the multiple wavelength channels.

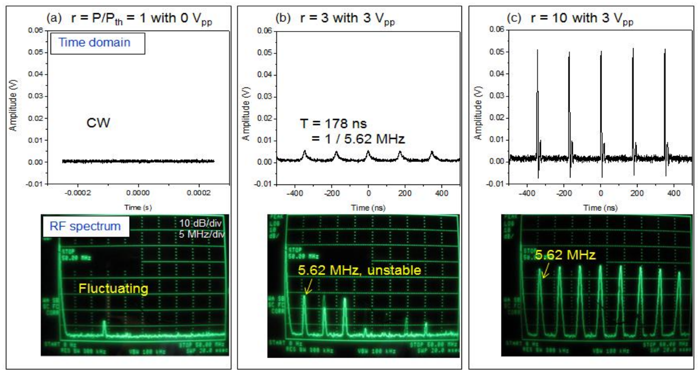

Fig. 3. Output behaviors in time domain (top row) and RF spectral domain (bottom row) at low PZT driving voltages of 0 ~3 $V_{p\text{-}p}$ as the pump power level increased (a) CW operation when r = 1 with PM turned off (b) Initiation of ML when r = 3 with 3 $V_{p\text{-}p}$ (c) Stable mode-locked pulse train when r = 10 with 3 $V_{p\text{-}p}$.

When we look closely the mode-locked output shown in Fig. 3(c), we found small modulation of the pulse amplitude at the phase modulation frequency of 26.2 kHz as shown in Fig. 4(a). When the PZT driving voltage was then increased to 6 $V_{p\text{-}p}$, the laser output changed to Q-switched mode-locking as shown in Fig. 4(b). Note that the Q-switching frequency was at 17.5 kHz which was 2/3 of the PM frequency. This indicates that the laser is now operating in a chaotic regime. The width of the Q-switched pulse was about 3.3 μs, and the duty cycle was 8.6% [8]. In fact, we could also observe non-periodic or random noise pulse output as shown in Fig. 4(c) when r ~8 with the PZT driving voltage of 5 $V_{p\text{-}p}$. For different settings of the pump power level and PM amplitude, several different pulsing behaviors could be observed as summarized in Fig. 5. Although Q-switching in the phase modulated MW laser was previously reported [6], the chaotic pulsations including the Q-switching at sub-harmonic frequencies of the PM frequency has not been reported to the best of our knowledge.

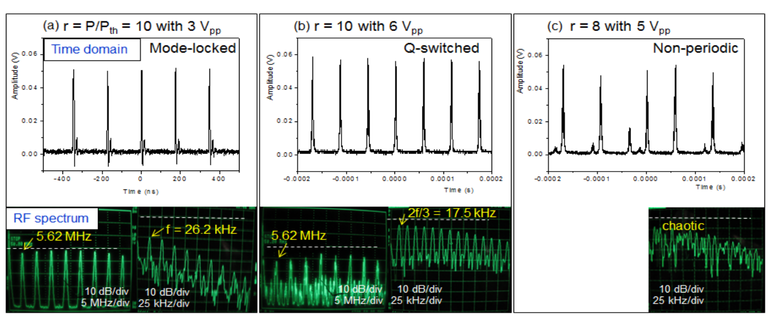

Fig. 4. Output behaviors in time domain (top row) and RF spectral domain (bottom row) at PZT driving voltages over 3 $V_{p\text{-}p}$ with different pump power levels. (a) ML pulses with strong harmonics of 5.62 MHz and weak modulation at PM frequency of 26.2 KHz, when r ~10 with 3 $V_{p\text{-}p}$ (b) Q-switched pulses with strong harmonics of 17.5 kHz when r ~10 with 6 $V_{p\text{-}p}$ (c) non-periodic pulses with chaotic RF spectrum when r ~8 with 5 $V_{p\text{-}p}$. Dashed white lines denote −30 dBm as a reference power level.

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In regime 1 of Fig. 5, ML pulses were produced as described in Fig. 3. The stability of ML pulses improved as the pump power and the PM amplitude increased, as indicated by the arrow. In regime 2, Q-switched (at PM frequency or predominantly twice the PM frequency) mode-locked pulses were generated, and the pulses became unstable for the higher PZT driving voltages. In regime 3 with high pump power level and high PM amplitude, chaotic pulsations were observed. Q-switched pulses at 1/2 and 2/3 of the PM frequency could be seen as shown in Fig. 4(b). In the non-periodic pulse regime, the noise floor of the radio-frequency (RF) spectrum is highly elevated without distinctive peak frequencies (Fig. 4(c)). Although it is not shown in Fig. 5, we should note that the Q-switching frequency could be changed by PC adjustment at certain pump powers and PM amplitude levels. It should also be noted that the pulsation map in Fig. 5 should be considered as a general reference based on the observations that the pulse behaviors can change with respect to PC settings and also the laser cavity loss. In all the pulsing regimes of Fig. 5, the optical spectrum showed MW operation.

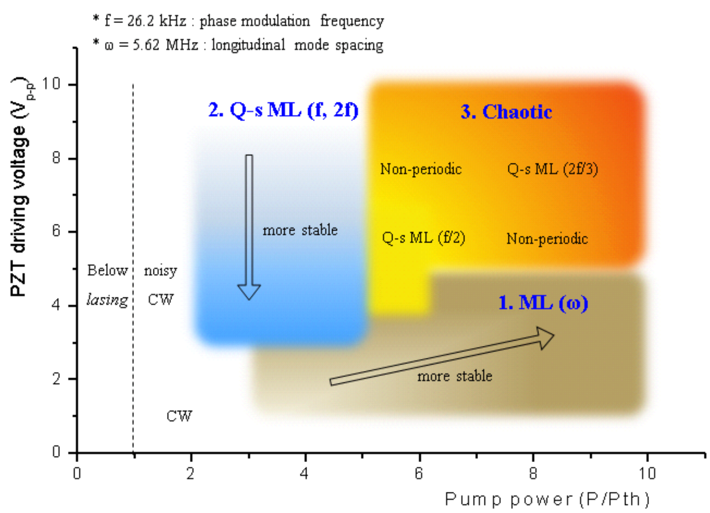

Fig. 5. Pulsation map for the pump power and the PZT driving voltage

The observed ML operation is attributed to the Kerr nonlinearity in the phase modulated fiber laser cavity [9–11]. As in the case of the frequency shifted MW lasers, continuous change of the resonance cavity mode via the cavity length modulation prevents the single-mode operation of the predominant laser mode, leading to multi-mode oscillation. In addition to this, the fiber nonlinearity couples the cavity modes, which results in ML pulse [9–11]. Larger nonlinear effect by the insertion of a bandwidth limiting, narrow intra-cavity filter and the increase in pump power will thus promote the mode-locking [11]. Moreover, self-amplitude modulation for each round-trip via the spectral filtering enhances the mode-locking, and the modulation amplitude increases for narrower filter line-width [12,13]. We confirmed this effect by replacing the F-P filter used in our experiment (FWHM of 0.02 nm) by one with FWHM of 0.16 nm that resulted in much compromised ML stability. Q-switched operation comes from the modulation of population inversion induced by the phase modulation of laser cavity having intra-cavity filter [6]. Chaotic behaviors including the Q-switching at the sub-harmonics of PM frequency can be described using the Maxwell-Bloch equations having an externally modulated parameter, when the modulation frequency is near the relaxation oscillation (RO) frequency of the laser [14,15]. In our experiment, the RO frequency was measured to be 15 ~60 kHz for the range of pump power used which covers the PM frequency of 26.2 kHz. In order to make sure that there were no other origins for the chaotic behaviors, we confirmed that there was no modulation of pump power in the cavity and that the PZT phase modulator had no sub-harmonic components. Detailed mathematical analysis of the

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chaotic pulsation is beyond the scope of this paper and will be discussed in a later publication considering the cavity birefringence and the dynamics in modulated multi-mode laser [16].

We investigated the noise characteristics of the MW laser in a separate experiment. As mentioned earlier, we inserted a flat-top 16 nm BPF as shown in a dotted box of Fig. 1(a) for the noise measurement and observed a significant reduction of intensity noise [12,13]. Figure 6 shows measured RIN values with the MW optical spectrum in the inset when the output is mode-locked with r > 10. The measured RIN values for the total output from MW operation (red line) and for filtered one wavelength channel (blue dash) as well as for amplified spontaneous emission (ASE) broadband light source (black dot) are shown for comparison. Measured RIN for a single wavelength channel was under −100 dB/Hz and, for frequencies over 1.5 GHz, RIN drops down to under −140 dB/Hz. The low frequency RIN level is from the harmonics of PM frequency and mode-locked frequencies that extends to about 1.5 GHz. The laser output spectrum was stable over several hours. Compared to the broadband ASE source, this low noise mode-locked MW laser has advantages of high power per channel and short pulse-width for high temporal resolution in time division multiplexed systems. Potential applications can include optical components testing, high speed optical fiber sensor [6,17] based on spectroscopic measurement and bio-imaging. The spacing between the wavelength channels can be tuned if a scanning F-P filter is used instead of a fixed one. For its applications in WDM communication systems, further work is needed to increase the repetition rate of the pulses beyond GHz range.

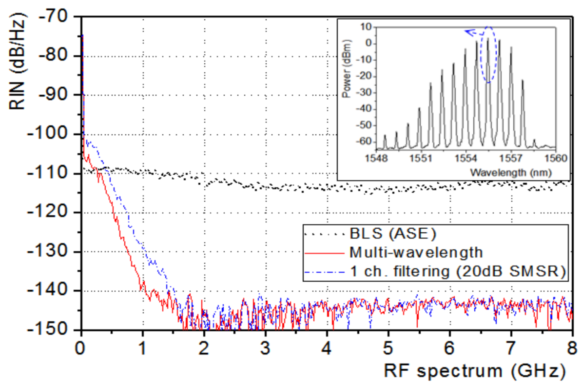

Fig. 6. Measured RIN and MW optical spectrum (inset).

4. Conclusion

In conclusion, we investigated the output characteristics including pulsing behavior and noise properties of a multi-wavelength EDF ring laser incorporating a narrow-band periodic filter and a low frequency phase modulation with large phase modulation amplitude. A pulsation map is presented as functions of pump power and phase modulation amplitude showing mode-locking with ns pulse width, Q-switching at harmonic and sub-harmonic frequencies of phase modulation frequency, and chaotic pulsing. The intensity noise of the single wavelength channel was measured to be under −100 dB/Hz (−140 dB/Hz over 1.5GHz). The mode-locked multi-wavelength laser can be useful in sensors, spectroscopy and bio-imaging applications requiring high speed and high resolution.

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