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Supercontinuum generation with all-fiber QML and CWML

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Abstract- In this paper our experimental on comparison of supercontinuum (SC) generation based Q-switched Mode-locked (QML) and continuous wave mode-locked (CWML) are demonstrated using a passively mode locked EDFL, which is amplified by an EDFA as a pump source. The QML EDF laser generates a pulse train operating at 1560.5 nm is amplified up to 18 dBm of average power by the EDFA to produce SC ranging from about 1350 nm to 1900 nm. On the other hand, SC generated by CWML operating at 1565, the SC ranging from about less than 1200 nm to 1950 nm, shows a better performance compared to QML.

Keywords: Mode-lock, Q-switched Mode-lock, supercontinuum generation

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1 Introduction

A supercontinuum (SC) generation describes an extreme spectral broadening induced by the coupling of a high peak power pulsed laser in an adequately long nonlinear optical fiber. It has obtained a great interest in recent years due to its potential applications in spectroscopy, frequency metrology, device characterization and medical science [1–2]. Many works have been performed to understand the phenomenon as well as to implement the intended practical devices. An SC can be generated using femtosecond to nanosecond pulses, or even a continuous wave pump where spectral broadening is initiated in the so-called ‘‘long pulse’’ regime [4-6]. On the other hand, mode-locking operation can be classified into two categories, which are continuous wave mode-locked (CWML) and Q-switched mode-locked (QML). For CWML, the ultra-short pulses can be generated for each round trip time in the laser cavity, which typically produces megahertz pulse repetition rate. Meanwhile, QML possesses Q-switching modulation pulse repetition rate in kilohertz range. In this paper, we investigate SC generation in QML and CWML. These pulses are formed under nonlinear polarization rotation (NPR) effect in the Erbium-doped fiber laser (EDFL) cavity. The SC generation is investigated in 100 m long highly nonlinear fiber (HNLF) with a zero dispersion wavelength of around 1550 nm and nonlinear coefficient of 11.5 $W^{-1}km^{-1}$.

2 Experimental arrangement

The experimental setup for SC generation from a QML and CWML is shown in Fig. 1. The mode-locked laser resonator consists of a 3.5 m long EDF as the linear gain medium, wavelength division multiplexer (WDM), polarization-dependent isolator (PDI), polarization controller (PC) and 200 m single-mode fiber (SMF). The EDF has a cutoff wavelength of 945 nm, core diameter of 4 µm and numerical aperture of 0.23. Since the core diameter of the fiber is small, the fiber nonlinearity is expected to be reasonably high in this EDF compared to the standard EDF with core diameter of around 8 µm. The absorption of the EDF is 11.9 and 17.5 dB/m at 979 and 1531 nm, respectively. The dispersion parameter of the SMF is 17 ps/nm km. A 1480 nm laser diode is used to pump the EDF via the WDM. A PDI and PC are incorporated in the laser cavity to ensure unidirectional propagation of the oscillating laser and to enable nonlinear polarization rotation (NPR) process in the ring cavity, respectively. The SC generation performance is also investigated with the conventional QML, which was obtained by adjusting a PC. The output of the laser is tapped out from the cavity via 5/95 fiber coupler while allowing 95% of the light to oscillate in the cavity. The 5% output from the ring resonator is then amplified by an Erbium-doped fiber amplifier (EDFA) before it is launched into 100 m long HNLF which acts as nonlinear gain medium for SC generation

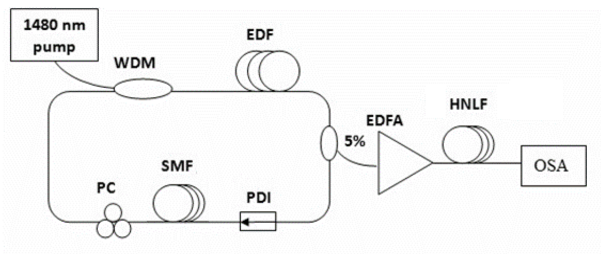

Figure 1: Schematic showing experiment setup for QML and CWML laser prior to using them an input to the HNLF to generate supercontinuum effect.

3 Results and discussion

CWML and QML are formed under NPR effect in the laser cavity at threshold pump power of 45 mW by proper adjusting of the intra-cavity PC. A typical output in the QML range is sustained until the maximum pump power of 145 mW. Fig. 2 shows the output spectrum, operating at center wavelength about 1560.5 nm, measured before EDFA at pump power of 145 mW. Spectral broadening due to self-phase modulation (SPM) effect in the cavity can be clearly observed. Figure 3(a) shows a pulse train at 145 mW pump power with a Q-switching repetition rate of 49 kHz and pulse width of 3.53 μs, while figure 3(b) shows a single Q-switched pulse with mode-locking repetition rate of 9.4 MHz and constant pulse width of 1 ps. The pulse energy is calculated to be around 81 nJ, whilst the maximum average output power is measured as 4 mW at maximum pump power of 145 mW throughout the tuning range. The autocorrelation traces for 1 ps pulse, pulse train and sech2 profile are shown in Fig. 4, the FWHM pulse is measured as 1 ps. Figure 5 shows RF spectrum of the QML pulse at pump power of 145 mW, with a constant pulse repetition rate of 9.4 MHz. The stability of QML pulse is further studied by RF spectrum analyzer, and the SNR is measured to be around 34 dB at fundamental frequency of 9.4 MHz.

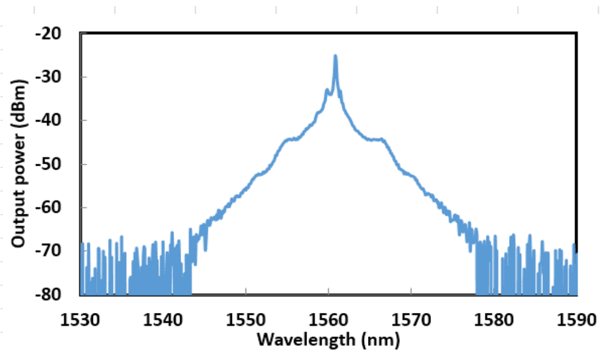

Figure 2: Output spectrum at pump power of 145 mW.

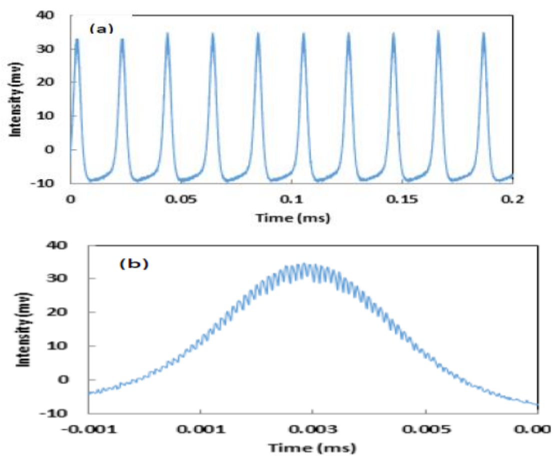

Figure 3: Typical output of the Q-switched mode-locking operation mode. (a) Pulse train at pump power of 145 mW, 49 KHz (b) A single pulse

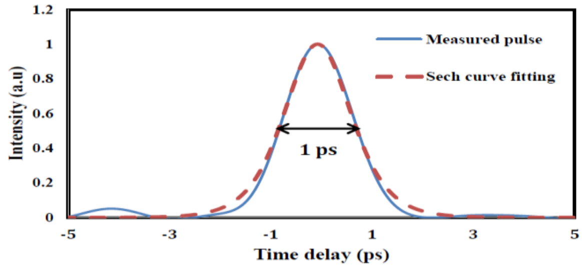

Figure 4: Autocorrelation trace of the QML output pulse

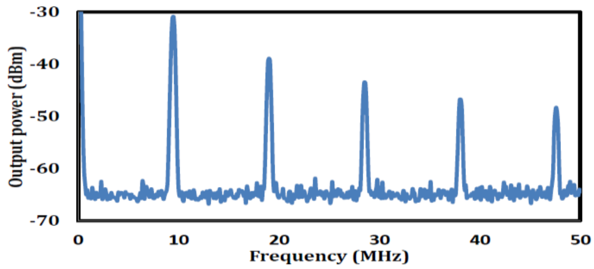

Figure 5: RF spectrum of the QML pulse at pump power of 145 mW.

The QML pulse can be switched to the CWML pulse by adjusting the PC in laser cavity of Figure 1. The CWML pulse train is generated in the modified ring cavity due to nonlinear polarization rotation (NPR) effect. Fig. 6a shows the output spectrum of the CWML pulse laser at 145 mW pump power, operating at center wavelength around 1565 nm. The spectral bandwidth of the laser is broadened due to changes in dispersion characteristics of the cavity. Fig. 6b shows the typical pulse train of the laser, which a repetition rate of 942kHz and pulse width of 367 ns. The spectrum of the CWML pulse laser operates at center wavelength around 1565 nm, and the pulse energy is calculated to be around 2.7 nJ, at maximum pump power of 145 mW.

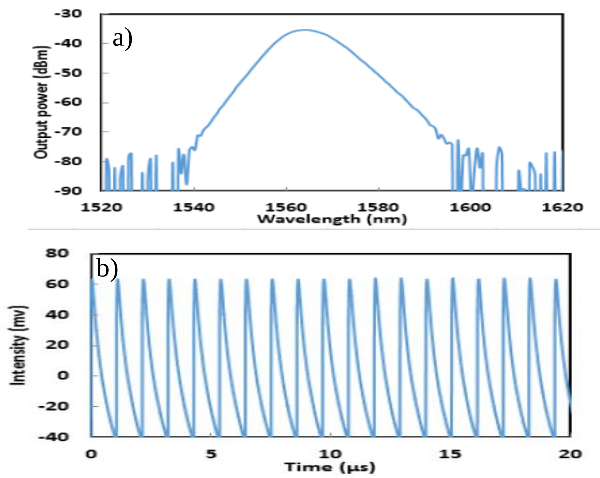

Figure 6: (a) Output spectrum of the CWML pulse, which is obtained before being launched into EDFA. (b) Typical pulse train of the CWML pulse.

Figure 7 shows,the Rf spectrum of CWML pulse at maximum pump power of 145 mW. The SNR is measured to be around 55 dB at fundamental frequency of 942 kHz. The output pulse train is is then amplified by an EDFA before it is launched into a HNLF for SC generation.
Figure 8 shows a SC generation in 100 m long HNLF, which is pumped by the amplified 1560.5 nm wavelength QML (repetition rate 49 KHz) and CWML (repetition rate 942 KHz) at pulse peak power levels.

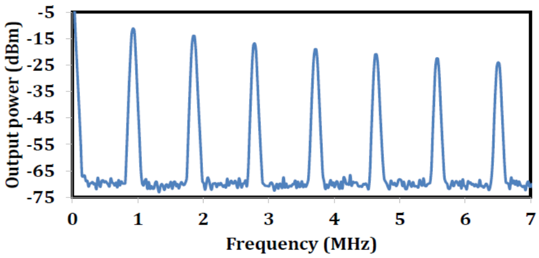

Figure 7: RF spectrum of the CWML pulse at pump power of 145 mW

Figure 8 compares the attenuated SC spectra from a 100 m long HNLF between QML and CWML pulse. As shown in the figure, the CWML pulse generates a broader SC spectrum compared to the QML pulse. The spectral broadening below 1200 nm region is not examined due to spectral sensitivity of the OSA. The output power intensity is also higher with the CWML mode lock pulse even though the pulse energy was higher in the QML pulse before amplification. This proves that the SC generation is more efficient with CWML pulse compared to the conventional QML pulse. This is most probably due to the CWML pulse are less affected by the fiber loss and background noise than the QML pulse [6].

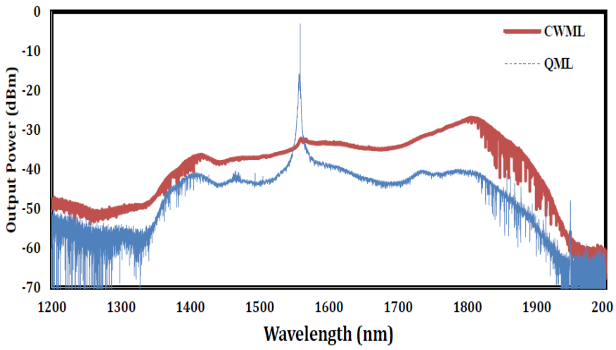

Figure 8: Comparison of SC generation between QML and bright pulse.

4 Conclusion

A SC generation based QML and CWML are demonstrated using a passively mode locked EDFL, which is amplified by an EDFA as pump source. The QML EDF laser generates a pulse train operating at 1560.5 nm which is amplified up to 18 dBm of average power by the EDFA to produce SC ranging from about 1350 nm to 1900 nm. On the other hand, SC generated by CWML operating at 1565 nm, with the SC ranging from about less than 1200 nm to 1950 nm, shows a better performance as compared to QML.

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