The study of 80 MHz Self starting passively mode-locked Erbium-Doped Fiber Laser via nonlinear polarization rotation with SESAM

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ABSTRACT

Erbium-Doped Fiber Laser, EDFL, passively mode-locked via only Nonlinear Polarization Rotation, NPR, and via NPR with Semiconductor Saturable Absorber Mirror, SESAM, is studied. Self start single pulse train with pulse width of 114 fs and repetition rate (PRR) of 80 MHz has been obtained when 55 cm EDFL, passively mode-locked via NPR only. Inserting SESAM in EDFL cavity leads to shorten the pulse width up to 88 fs, increases the amplitude stability up to 96% and lower the phase noise jittering to around 26 fsec. Stable second harmonic self starting passively mode-locked EDFL with pulse width of 284 fs has also been observed only when SESAM was used in the cavity. Multi-pulsed system passively mode-locked via NPR for EDFL length of 80 cm with time difference between the successive multi-pulses ranged from few picoseconds to nanoseconds, has been observed. The time difference can be controlled by the polarizer controller and the half wave plate. Further controlling of the cavity polarization leads to developing the multiple mode-locking pulses train to second harmonic mode-locking pulse train with PRR of 160 MHz and pulse width of 156 fs. Three harmonic superposed trains of mode-locked pulse have been achieved only when SESAM added to the cavity.

Key words: Erbium-Doped Fiber Laser, Passive mode-locking, Nonlinear polarization rotation, Semiconductor saturable absorber mirror.

دراسة ليزر ليفي مطعم بالإربيوم بتكرارية 80 ميغاهرتز ذاتي البدء ومغلق النمط بشكل عابر (المنفعل) بالدوران اللاخطي للاستقطاب مع مرآة SESAM

فادي قمر

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الملخص

درس الليزر الليفي المطعم بالإربيوم EDFL المغلق النمط بشكل منفعل باستعمال الدوران اللاخطي للاستقطاب NPR لوحده وباستعمال الدوران اللاخطي للاستقطاب NPR مع مرآة نصف ناقلة من النوع الماص القابل للإشباع SESAM. تم الحصول على قطار من نبضة مفردة ذاتية البدء عرضها 114 fs وبمعدل تكرار (PRR) قدره 80 MHz عند استعمال طريقة غلق الأنماط المنفعلة بواسطة NPR مع EDFL طوله 55cm فقط. وتبين أن إدخال الـــ SESAM في مجاوبة الليزر يؤدي إلى تقصير عرض النبضة الليزرية إلى 88 fs، وزيادة استقرار السعة إلى 96 %، وانخفاض الضجيج الطوري إلى نحو 26 fs. كما حصل على مدروج توافقي من الدرجة الثانية من EDFL مغلق النمط المنفعل والمستقر، ذاتي البدء بنبضات عرضها 248 fs مع استخدام SESAM في التجويف (مجاوبة) فقط. لُوحظ نظام متعدد النبضات مغلق النمط المنفعل بواسطة NPR عند زيادة طول EDFL إلى 80 cm. ويراوح الفاصل الزمني بين النبضات من مجال النانو ثانية إلى مجال البيكو ثانية وذلك اعتماداً على وضع الصفيحة نصف الموجية وضابط الاستقطاب. وأدت زيادة ضبط الاستقطابية في المجاوبة السابقة إلى تحول القطار متعدد النبضات إلى قطار نبضات المدروج التوافقي من الدرجة الثانية وبمعدل تكرار قدره 160 MHz، ونبضات عرضها 114 fs. كما أمكن الحصول على ثلاثة قطارات نبضية توافقية متراكبة عند إضافة SESAM إلى المجاوبة فقط.

الكلمات المفتاحية: ليزر مطعم بالأربيوم، مغلق النمط بشكل منفعل (عـــابر)، دوران الاستقطاب اللاخطي، المرآة نصف الناقلة الماصة القابلة للإشباع.

1. Introduction

Diode-pumped passively mode-locked EDFL's are compact, highly efficient, reliable and flexible sources of femtosecond pulses. The system becomes attractive for applications traditionally utilized large solid-state lasers. Various active or passive technologies have been utilized in continuous-wave mode-locking (CWML) EDFL fiber lasers [1-6]. All active mode-locked pulsed lasers contain bulk elements, which make their design relatively complicated; thus, much attention has been paid to the development of passive fiber lasers. Various passive mode-locking techniques, such as nonlinear loop mirror method [1, 2], nonlinear polarization rotation (NPR) technique [3], semiconductor saturable absorber method [4, 5] including the use of SESAMs for different cavity setups and for a broad spectrum ranging from 800 to 1600 nm [6], have been utilized to mode-lock fiber lasers. Independent of the applied mode-locking techniques it was found that the soliton operation of all fiber lasers exhibited a common feature under strong pumping where, strength multiple soliton pulses are always generated in the laser cavity[7]. All solitons have exactly the same pulse properties in the steady state i.e. the same pulse energy and width, when they are completely separated. This case is known as the "soliton energy quantization effect" [8]. But the multiple soliton generation and the soliton energy quantization effect limit the generation of optical pulses with larger pulse energy, and narrowing the pulse width in fiber lasers [9]. Multiple soliton generation could result in genrating passive harmonic mode-locking (HML) in soliton fiber lasers [10]. It has been demonstrated that the harmonic mode-locking fiber laser performance could be further improved by using a SESAM in combination with a nonlinear amplifying loop mirror because SESAM not only acts as a fast saturable absorber but also as a passive phase modulator. Such a laser is capable of generating 500 fs pulses at repetition rates exceeding 2 GHz. A method for manipulating the output of a ring-cavity EDFL, by which the laser can be operated in CW and various short-pulse states using SESAM and polarization control in fiber laser has been demonstrated in [11]. Different operation states such as continuous-wave, stable Q-switching, Q-switched mode-locking, continuous-wave mode-locking, pulse splitting, and harmonic mode-locking can be obtained without changing the pump power [11].

In this paper, special setup was assembled to discover, for the first time, the effect of using SESAM with NPR method. An EDFL with free space capable of moving between SESAM high reflection mirror without affecting the free space length was built. Comparison is made between passive mode-locking using only NPR, and using SESAM with NPR for short and long length of doped fiber. Short pulse of 88 fs was reported.

2. Experimental work

The used cavity is shown in fig.1. The total length of the cavity is about 3.75 m; this contains 62 cm free space (air) part and the rest was fiber. Single mode Er-doped fiber (80-8/125 from Thorlabs) was pumped via wave division multiplexing WDM by 410mW of 980 nm diode laser with centre wavelength of 974.34 nm measured at 25C˚. Extra pieces of single mode fiber (SMF28) at 1550 nm were used to complete the fiber part of the cavity. The polarization of the cavity was controlled using a polarizer controller PC. A half wave plate and a cube polarizer were used to rotate the polarization at free fiber part of the cavity as well as to obtain the output laser at 1550 nm.

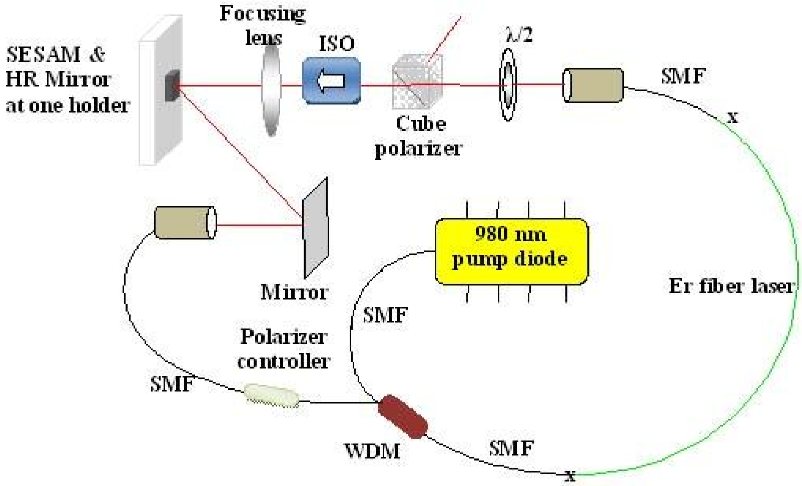
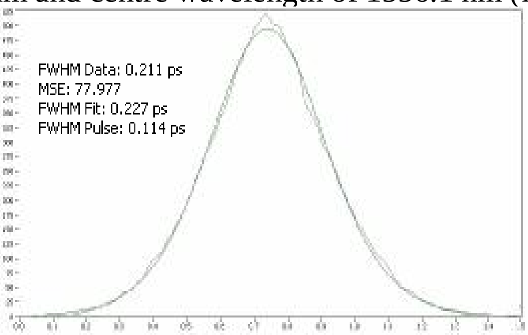


Fig.1. Mode-locked EDFL by nonlinear polarization rotation and SESAM layout.

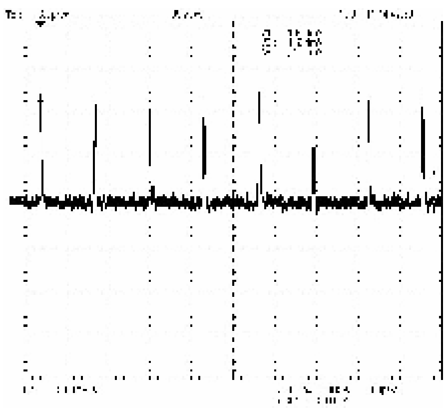
To ensure the unidirectional lasing for the cavity an Isolator (ISO) was used. The laser beam that passes through the isolator is focused by the lens into a high reflection mirror (95% reflection at 1550 nm) or 5% absorber SESAM with anti-reflection coating at 1550 nm. The beam reflected back and passes again through the same focusing lens to another 45˚ mirror. It is necessary to carefully adjust the mirror (or the SESAM) to be exactly at the focal point of the focusing lens; this ensures a smallest beam spot size on SESAM, in one hand, and on the other hand it ensures the collimation of the beam after the second pass of the focusing lens side to obtain the best launching of the beam into the second end of the fiber. Two focusing lenses were tested one with focal length of 5 cm to obtain smaller beam spot on the SESAM and another with focal lens of 10 cm. However the output power is improved by about 14 % with longer focal length lens. The 45˚ mirror directs the beam to be launched to the second end of the fiber through collimating lens. Two different lengths of the Er-doped fiber (55 cm and 80 cm) were used. To keep the cavity length to totally constant which ensures the PRR of about 80 MHz, an extra SMF was added when short fiber was utilized. Two beam splitters at 1550 nm were used outside the cavity to divide the beam to three parts. One part goes directly to a fast diode (Et 3500) from E.O.Tech. The fast diode is connected to Tektronics 1GHz oscilloscope to measure PRR and the stability of the pulse. The second part, is launched to the fiber which is connected to AQ6315E optical spectrum analyzer, allows measuring directly the spectrum of laser output. The same part can also be connected to other two dvices one measures phase noise of mode-locked signal (Agilent E505 signal source analyzer) and the other shows the harmonic trains of mode-locked signal (Agilent spectrum analyzer, Swept, SA). The final part of the divided beam is directed through steering mirrors to auto-correlator to measure pulse width in femto-second scale. To ensure that all measurements when NPR alone used and when NPR used with SESAM were taken at the same conditions the high reflection (HR) mirror and the SESAM were mounted at the same holder. X-Y Micrometer transition stage was used to move from one mirror to another and adjusting the repetition rate. Reference beam (red diode pointer laser) was also used to help adjusting the alignment of the SESAM to be exactly the same as it was for high reflection mirror. This ensures that any difference in results will be due only to the use of the SESAM in the cavity instead of HR mirror not because of the change in alignments when HR replaced by SESAM.

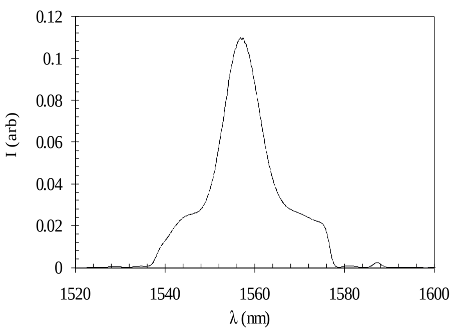
3. Result and discussions

The result in fig.2 (a, b, c) shows that it is possible to obtain single clean mode-locked train pulses via NPR for 55 cm length of EDFL by adjusting $\lambda/2$. The CW output power of the system was 62 mW and became 58 mW when the laser mode-locked. The pulse width measured by auto-correlator was 114 fs (fig.2 (a)). Oscilloscope trace shows that the PRR of the pulse was about 80 MHz and the stability of the pulses train was 91 % with energy of 0.72 nJ per pulse (fig.2 (b)). The phase noise measurements shows that the 1k-10MHz RMS jitter was 89 fsec and frequency analyzer measurement yield spectrum width of 11.6 nm and centre wavelength of 1556.1 nm (fig.2 (c)).



(a)





(c) **(b)**

Fig.2: (a) Pulse width, (b) spectrum analyzer and (c) train of pulses for mode-locked EDFL with NPR for doped fiber length of 55 cm.

However, when the HR mirror is replaced by SESAM the average power and power per pulse was the same but the pulse width is reduced to 88 fs (fig.3 (a)) with the spectrum width of 8.9 nm and centre wavelength of 1555.9 nm (fig.3 (b)). The stability of pulse train improved to be 96% (fig.3 (c)) and the RMS jitter decreased down to 26 fsec.

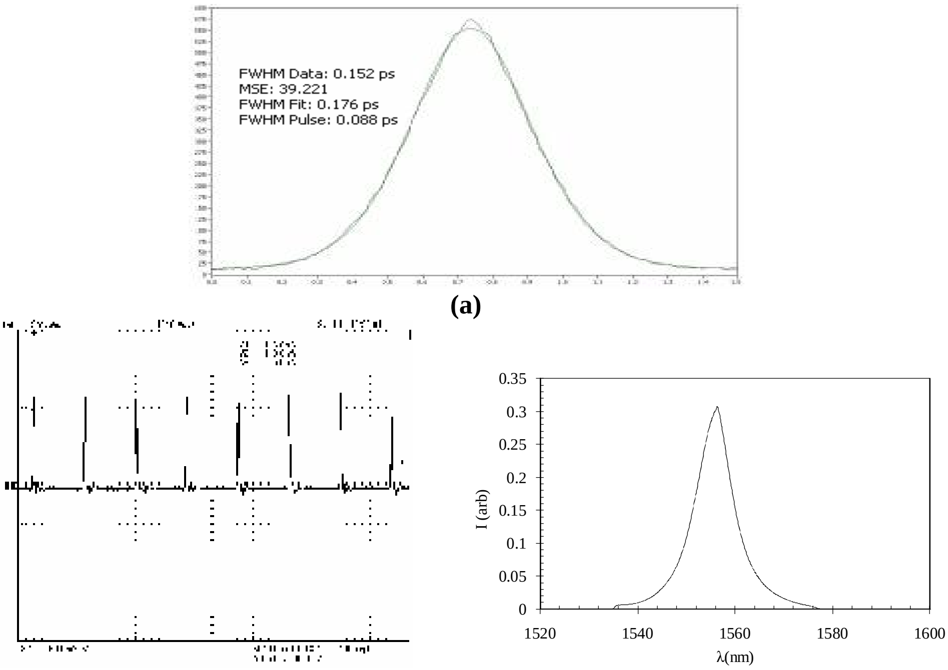


Fig.3: (a) Pulse width, (b) spectrum and (c) train of pulses for mode-locked EDFL with NPR and SESAM for doped fiber length of 55 cm.

Harmonic mode-locking at 160 MHz (fig.4 (a)) was only possible using NPL with SESAM. The Harmonic signal obtained by controlling the polarization of the cavity using PC and λ/2 plate. The average power and energy per pulse were respectively 58 mW and 0.36 nJ with pulse width of 284 fs (fig.4 (b)) and spectrum width of 11.3 nm and centre wavelength of 1558.8 nm (fig.4 (c)).

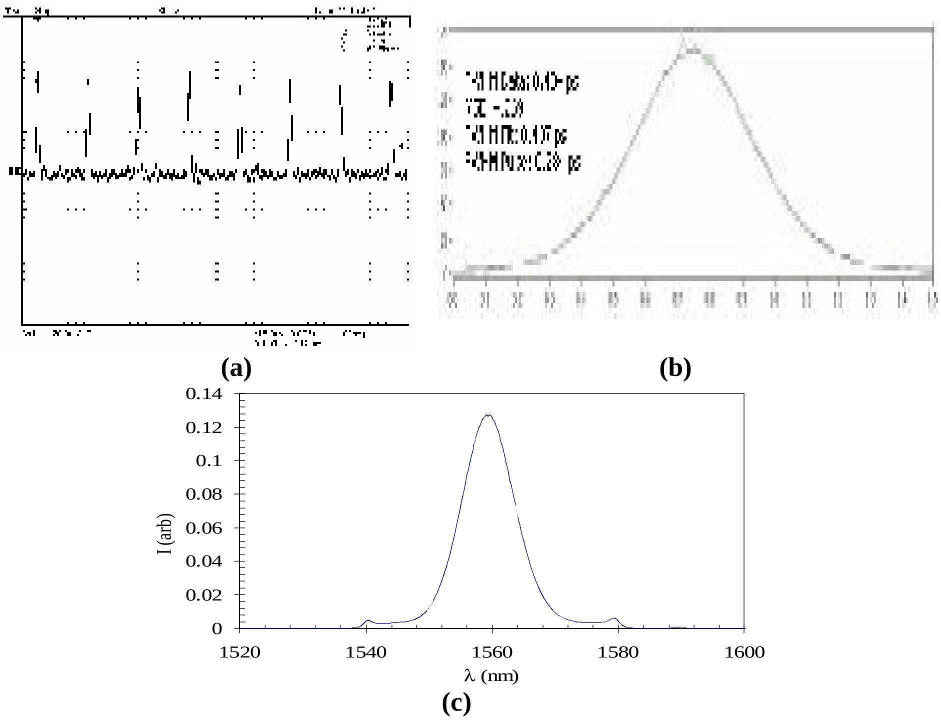
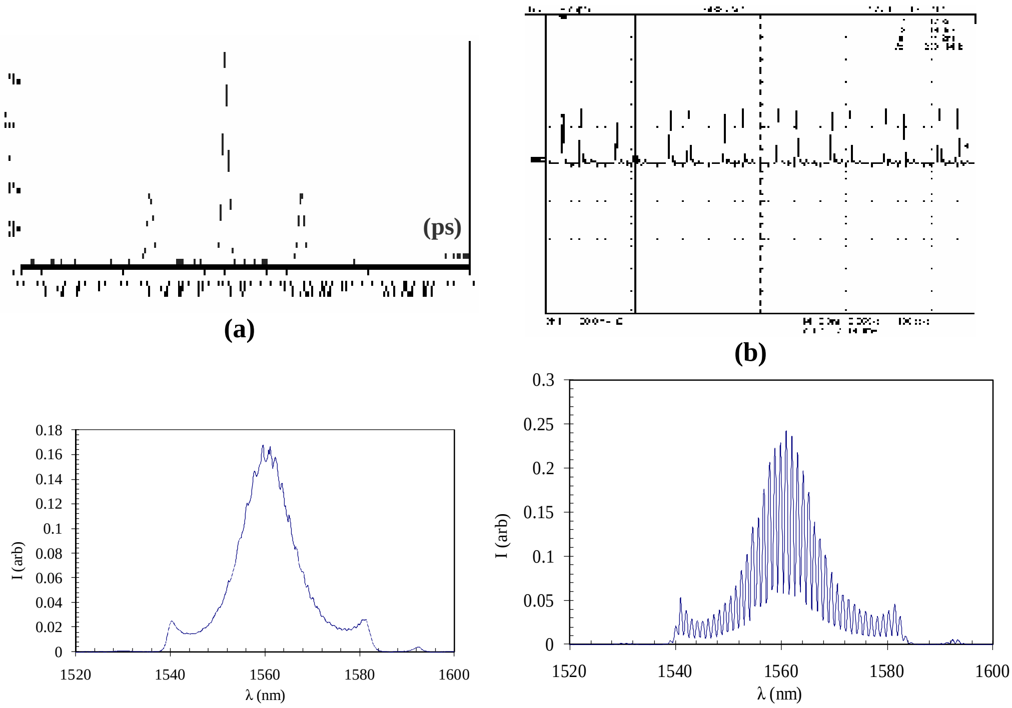


Fig.4: (a) Train of pulses, (b) pulse width and (c) spectrum for harmonic mode-locked EDFL with NPR and SESAM for doped fiber length of 55 cm.

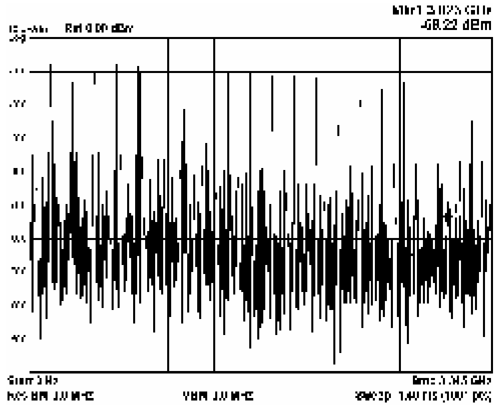
The 55 cm Er fiber laser was replaced by 80 cm. This was required to decrease the length of SMF to keep the cavity at the same length thus have the same pulse PRR i.e. 80 MHz. The CW output power of the system increased to about 107 mW. Mode-locking this laser yielded an average power of about 100 mW with single pulse energy of 1.25 nJ. Multi-pulse always was obtained when only NPR used to mode-lock the laser. The time difference between the successive multi-pulses was controlled by the polarizer controller and half wave plate and ranged from few picoseconds (fig.5 (a)) to few nanoseconds (fig.5 (b)). figs.5 (c) and (d) show the spectrum of the multi-pulse for time difference between the pulses of picoseconds and nanoseconds respectively.



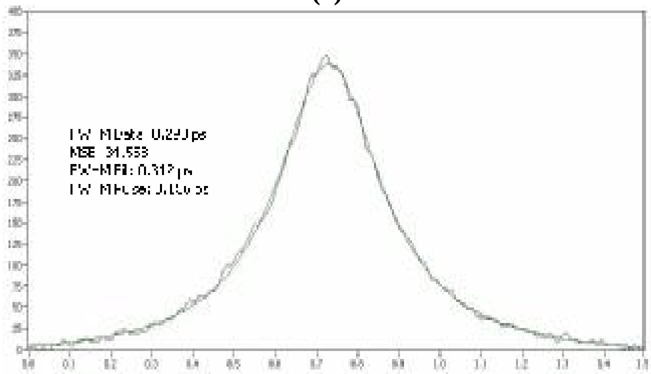
(c) (d)

Fig.5: (a) picoseconds and (b) nanosecond time difference between the pulses and their Spectrums (c) and (d) respectively of multiple pulses mode-locked EDFL by NPR.

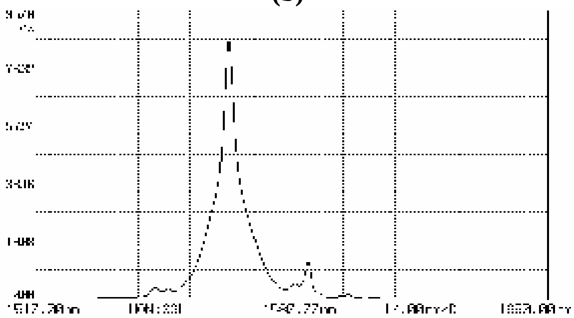
Further controlling the polarization of the cavity, the multiple mode-locking pulses could be developed to harmonic mode-locking with PRR of 160 MHz (fig.6 (a)), pulse width of 156 fs (fig.6 (b)), spectrum width of 5.3 nm and centre wavelength of 1562.5 nm (fig.6 (c)) and energy per pulse of 0.62 nJ.



(a)



(b)



(c)

Fig.6: (a) train of pulses, (b) Pulse width and (c) spectrum of harmonic mode-locked EDFL with NPR and SESAM for doped fiber length of 80 cm.

Single pulse train was not possible until the SESAM is inserted in the cavity. The pulse width was 151 fs (fig.7 (a)) with PRR of 80 MHz (fig.7 (b)) and the stability of the pulses train remained high, i.e. 97 %. The spectrum width was 12.2 nm and centre wavelength of 1560 nm (fig.7 (c)). The phase noise measurements was not possible at this case, it showed no signal and to understand the reason, another special frequency analyzer was used to look at the harmonic of the pulse train and it was founded that the train of pulse consist of 3 harmonic trains, as shown in (fig.7 (d)).

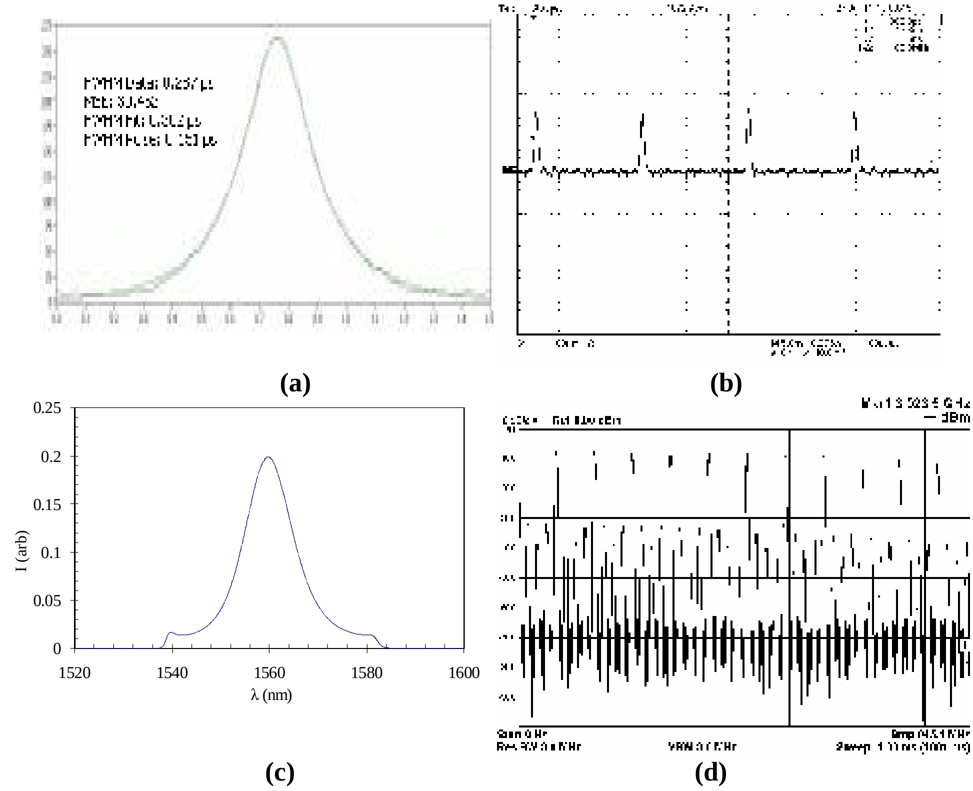


Fig.7: (a) Pulse width, (b) train of pulses, (c) spectrum and (d) harmonic train frequency of mode-locked EDFL with NPR and SESAM for doped fiber length of 80 cm.

In contrast to conventional fiber laser ring-cavities which uses two polarization controllers or three and sometimes four wave plates in the nonlinear polarization rotating technique, only one polarization controller with one wave plate is used here in the setup of EDFL laser and the operation of CML-EDFL was stable. In principle, the nonlinear phase shift that generated polarization evolution in the EDFL connected with SMF is mainly caused by self-phase modulation (SPM) and cross-phase modulation (XPM) [12]. Additionally, the polarized electric field of the pumping source introduces a birefringence in the EDFL for intensity-dependent phase retardation as well. Consequently, the CW and short-pulse states will face different phase retardation during intra-cavity circulation. The polarization controller and wave plate work as a manually tunable phase retarder to provide pre-defined phase retardation, while the polarizer works as an analyzer. The intensity-dependent loss will be increased when the optical field passing through such an effective modulator like SESAM, providing different transmission losses for the low and high-intensity components. By properly tuning the $\lambda/2$, one kind of the operation states (CML or HML) can benefit a smaller loss for lasing .The results here agree with previous interpretation and with the other published results [11, 13 and 14]. No mode-locking can be obtained using only SESAM as the used SESAM is with low reflectivity change; only 5%, However, only resonant SESAM with a high reflectivity change allows start-up of passive mode locking in a wide range of normal or anomalous cavity dispersion [5, 6]. Adding SESAM in short fiber, where clearly the energy of pulse does not exceed energy threshold of soliton, leads to decrease in the pulse width and the line width and an increase of the stability of the pulse. This could be attributed to the overall loss modulation induced by $\lambda/2$, and polarization controller, in combination with the saturable loss by SESAM. The spectrum for fundamentally mode-locked EDFL presents non-soliton components in the form of narrow band peaks. Further adjustment of the polarization controller and $\lambda/2$ in presence of SESAM begins to splits the CML pulses and eventually lead to pulse-splitting and harmonic mode-locking of the EDFL. This is due to the interaction between solitons and the accompanying non-soliton element. Stable 2nd-order HML has been observed, with pulse PRR of 160 MHz and pulse spacing of 6.25 ns. Longer active medium increases the energy of the pulse and spilts the soliton apart causing multi-pulse system. Rotating λ/2 varies the loss inside the cavity and at some positions the second harmonic mode-locking at 160MHz is possible to take place. Using SESAM with longer active medium modulates the loss inside the cavity, thus leads to a train mode-locked at fundamental frequency with harmonic solitons. The harmonic solitons still observed even with lower pump power nearly 300 mW which is the threshold of mode-locking. This indicates that the length of the fiber in the present of the SESAM is a major factor to be optimized to avoid multi and harmonic solitons and optimize the system performance.

4. Conclusion

Novel setup of passive mode-locked fiber laser has been developed to compare the performance of the passive mode-locking ring cavity using only NPR with the same cavity when SESAM is added. It has been demonstrated that for short doped-fiber length, inserting SESAM inside the cavity improves the pulse amplitude stability form 91% to 96% and reduces pulse width from 114 fs to 88 fs and phase noise jittering from 86 fs to 26 fs. Second harmonic mode-locking also was observed only when SESAM is inserted inside the cavity yielding pulse width of 286 fs. Longer doped fiber resulted in multi soliton system when NPR only used. The multi-pulse time difference ranged between sub pico second to sub-nanosecond depending on polarizing state inside the cavity. Harmonic solitons up to 3 results in harmonic train pulses when the SESAM is added to the cavity even with low pump power near the threshold of mode-locking. The length of the active medium fiber, the SMF and the free space as well as the pump power should be optimized to obtain high stable clean passive mode-locked pulse with short pulse using SESAM with NPR.

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