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# Mode Locked Fiber Lasers

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## 1. Introduction

Nowadays, to satisfy the increase of internet demands and requirement, two multiplexing techniques are used: WDM (Wavelength Division Multiplex) and TDM (Time Division Multiplex). WDM still more used than TDM. However, for practical system applications, such as optical CDMA (Code Division Multiplex Access) and OTDM (Optical Time Division Multiplex) systems, high speed optical communications require light sources with a repetition rate control. In this area, pulsed fiber lasers have become very attractive.

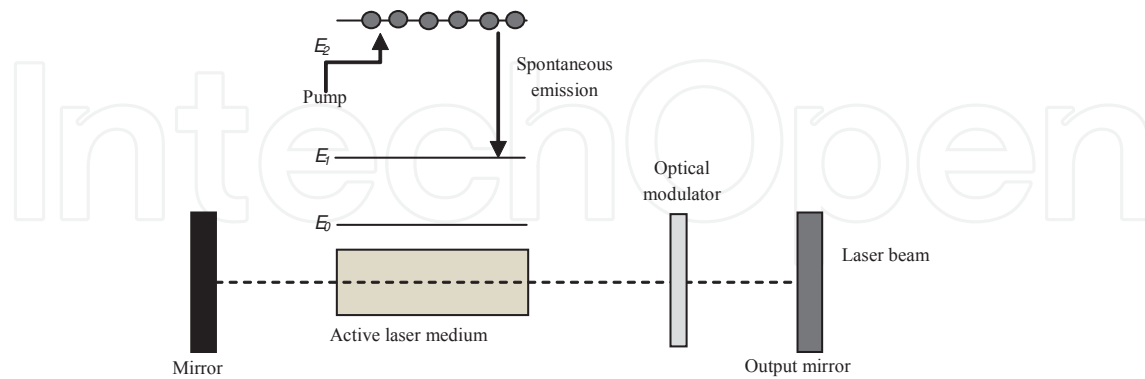
Fiber lasers have a number of qualities which make them very attractive for ultra short pulses generation via Q-switching, active or passive mode locking mechanisms. The gain bandwidth of rare-earth-doped fibers is large, typically tens of nanometers, which allows the generation of femtosecond pulses. The high gain efficiency of active fibers makes possible such lasers to operate with fairly low pump powers and tolerate intra cavity optical elements with relatively high optical losses. Fiber laser setups are very compact and can be done with a low cost. Furthermore, mode locked fiber lasers can rely on telecom components.

## 2. Q-switching mechanism

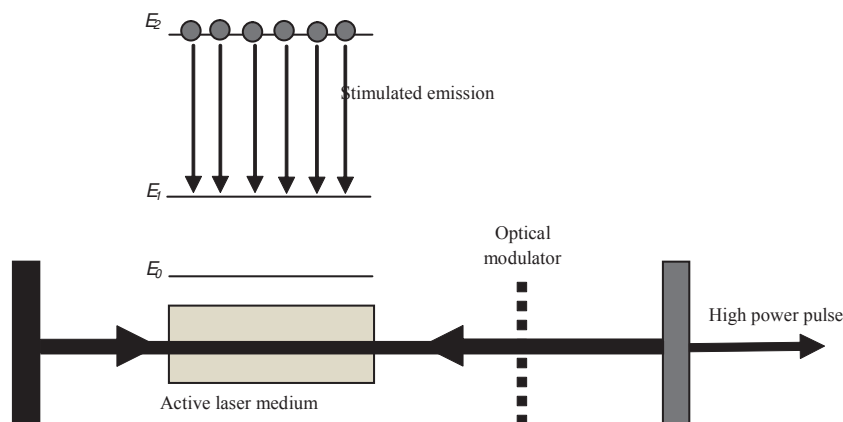
Storing ions in a higher energy level can be achieved by limiting ions flow to the bottom level. So, it's necessary to prevent stimulated emission prevalence.

By means of light modulators able to generate high optical powers when transiting between the off and on states, we prevent light propagate within the laser cavity. For a radiative transition, the only possible drain to the bottom level is caused by spontaneous emission (see Fig. 1). The  $E_2$  level population very significant, the cavity losses are suddenly reduced and

the oscillation becomes possible. The stimulated emission becomes prevalent and the laser starts emitting abruptly. All ions stored up go down emitting stimulated photons (see Fig. 2).



**Figure 1.** Q-switching first step.



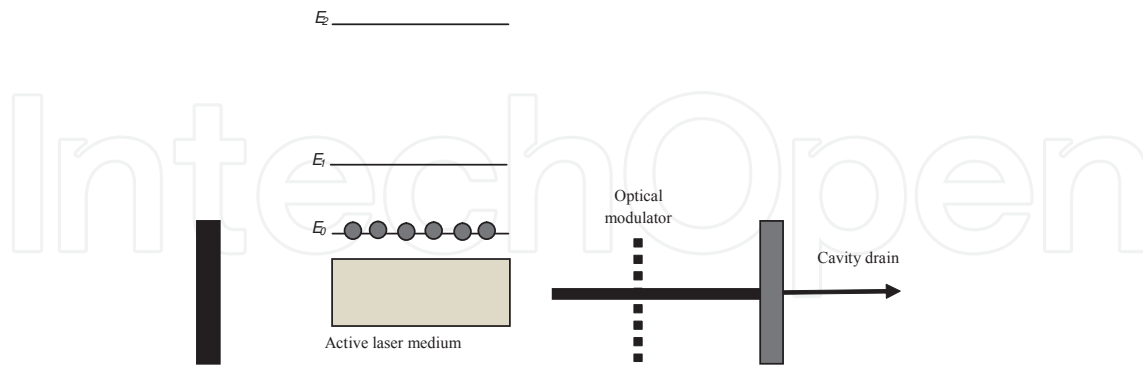
**Figure 2.** Q-switching second step.

At a given time, there is no way for stimulated emission to happen and the cavity is emptied by resulting losses of the output mirror (see Fig. 3).

The abrupt variation of the number of photons into the cavity results in emitting a high peak power optical pulse. Generally, several journeys between the two mirrors are necessary to completely depopulate the up-level and empty the cavity. So, the pulse width would be higher than the time of a coming and going through the cavity. With lengths lower than one meter, it is possible to generate nanosecond pulses. The repetition rate varies between few hundreds of  $Hz$  and few hundreds of  $KHz$ .

The  $Q$  quality factor of a laser cavity describes its capacity to store the energy light in standing waves. The factor  $Q$  is the ratio between the stored and the lost energies after each round trip

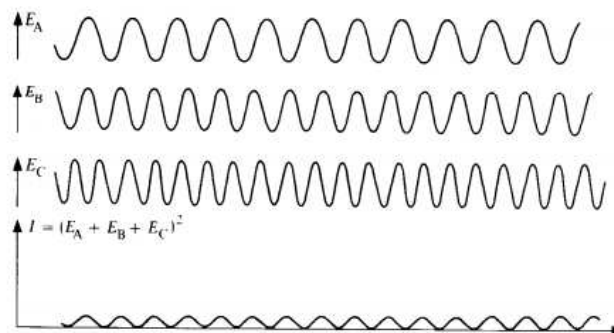
through the cavity. In fact a Q-switch device is an optical modulatorable to control the energy losses of the cavity with generally a repetition rate varying between 1 and 100 KHz [1].



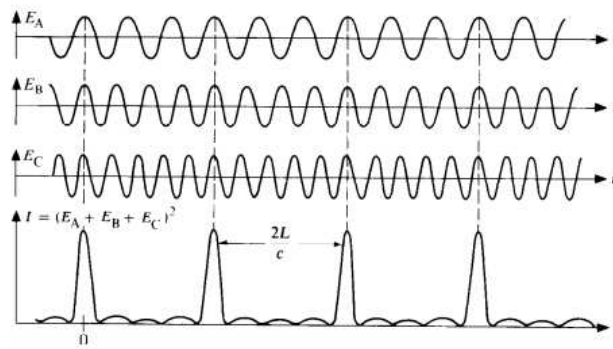
**Figure 3.** Q-switching third step.

### 3. Mode locking mechanism

In a laser cavity, frequencies circulating into the resonator and having more gain than losses are called longitudinal modes. They can be considered as an assembly of independent oscillators. These modes gain increases after each round trip through the cavity. These modes are separated by  $\Delta F = 1/TF = v/2L$  for a linear cavity case of Fabry Perrot cavity or  $v/L$  for a loop cavity case of fiber laser.  $L$  is the cavity length and  $v$  is the light speed. When these modes oscillate independently of each other, the laser emits continuously. Fig. 4 illustrates a laser cavity output signal resulting on the propagation of three independent longitudinal modes. However, when a fixed phase shift exists between the various modes, the cavity emits a pulses train and becomes phase locked. Fig. 5 shows a mode locked laser cavity output signal resulting on the propagation of three phase dependent longitudinal modes. In fact, the mode locking technique consists in creating a certain phase relationship between the different modes oscillating into the cavity.



**Figure 4.** Output signal from laser operating without mode locking mechanism.



**Figure 5.** Mode locked laser output signal.

If we consider  $M=2S+1$  optical modes with  $S$  an integer and  $A_q$  the complex envelope of mode  $q$ , the complex wave of the  $q$  mode and the total signal propagating into the cavity are respectively:

$$\begin{aligned}
 U_q &= A_q \exp\left(j2\pi f_q \left(t - \frac{z}{c}\right)\right) ; f_q = f_0 + q\Delta_f ; U(z,t) = \sum_{q=-S}^{q=S} A_q \exp\left(j2\pi f_q \left(t - \frac{z}{c}\right)\right) ; q = 0; \pm 1; \pm 2; \pm 3; \dots \\
 \text{If } A(t) &= \sum_{q=-S}^{q=S} A_q \exp\left(j\frac{2\pi q t}{T_f}\right) ; U(z,t) = A\left(t - \frac{z}{c}\right) \exp\left(j2\pi f_0 \left(t - \frac{z}{c}\right)\right) \\
 \text{If } A_q &= A_0 ; A(t) = A_0 \sum_{q=-S}^{q=S} \exp\left(j\frac{2\pi q t}{T_f}\right) = MA_0 \frac{\text{sinc}\left(Mt/T_f\right)}{\text{sinc}\left(t/T_f\right)}
 \end{aligned} \tag{1}$$

The resulting light intensity is:

$$I(t,z) = M^2 |A_0|^2 \frac{\text{sinc}^2\left(M\left(t - \frac{z}{c}\right)/T_f\right)}{\text{sinc}^2\left(\left(t - \frac{z}{c}\right)/T_f\right)} \tag{2}$$

Fig. 6 shows the resulting output pulses sequence of a mode locked laser cavity allowing the oscillation of  $M$  longitudinal modes. The mode locking mechanism allows having pulses train with peak power  $M$ -times more significant than the average power.

#### 4. Pulsed fiber laser

In case of fiber laser, the 100% reflective mirror is replaced by the optical fiber loop, the output mirror by an output coupler and the active laser medium by an optical amplifier such as Erbium Doped Fiber Amplifier. Many sophisticated resonator setups have been used particularly for mode-locked fiber lasers, generating picosecond or femtosecond pulses. A fiber la-

ser can contain an electro-optic modulator, an acousto-optic modulator or a saturable absorber to actively or passively mode lock the different longitudinal modes oscillating in the cavity.

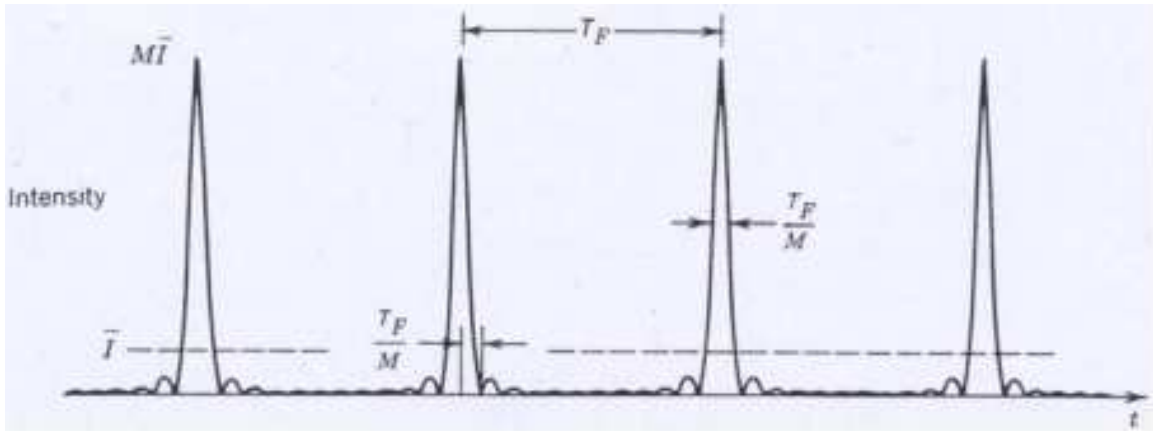


Figure 6. Mode locked laser output  $I(t,z)$  [2].

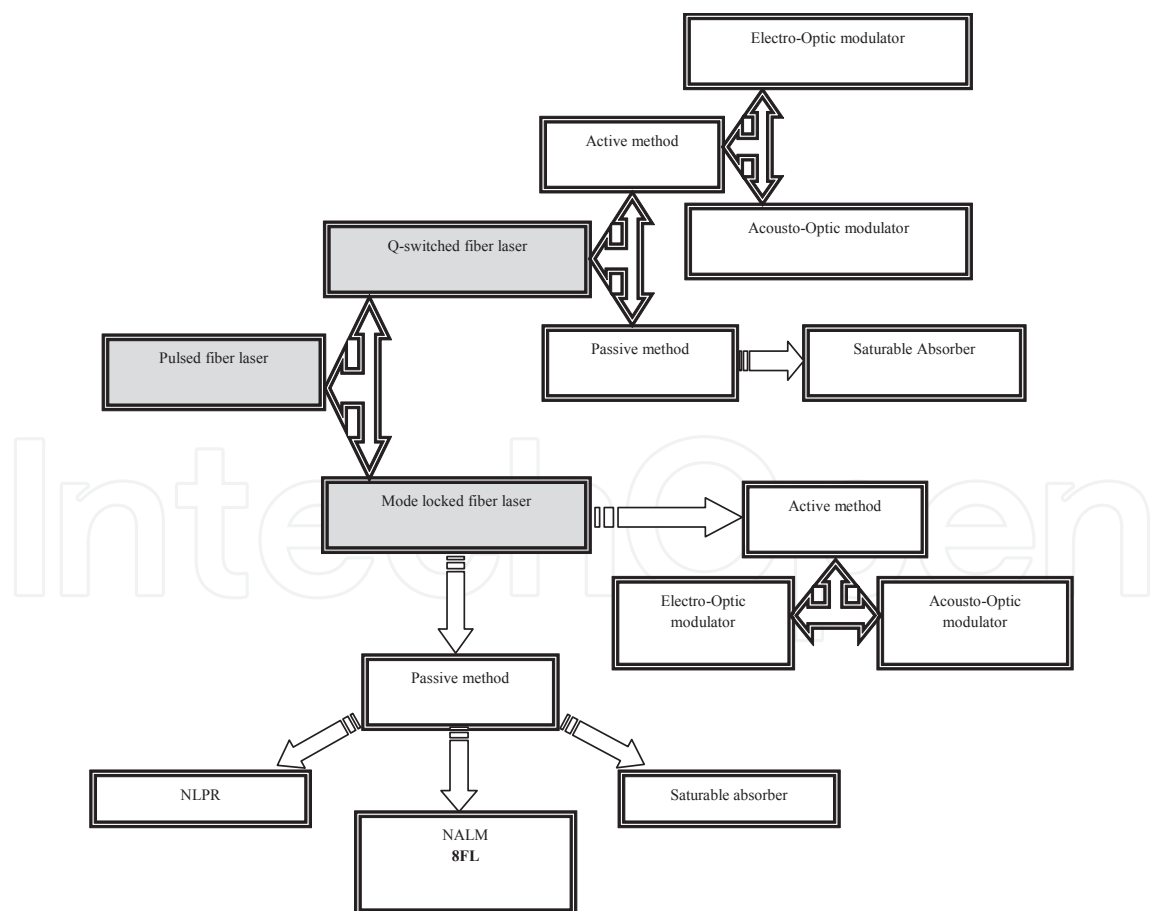
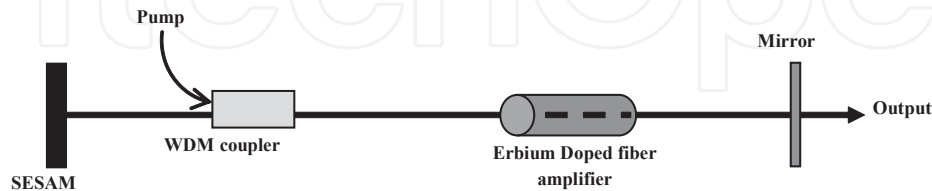


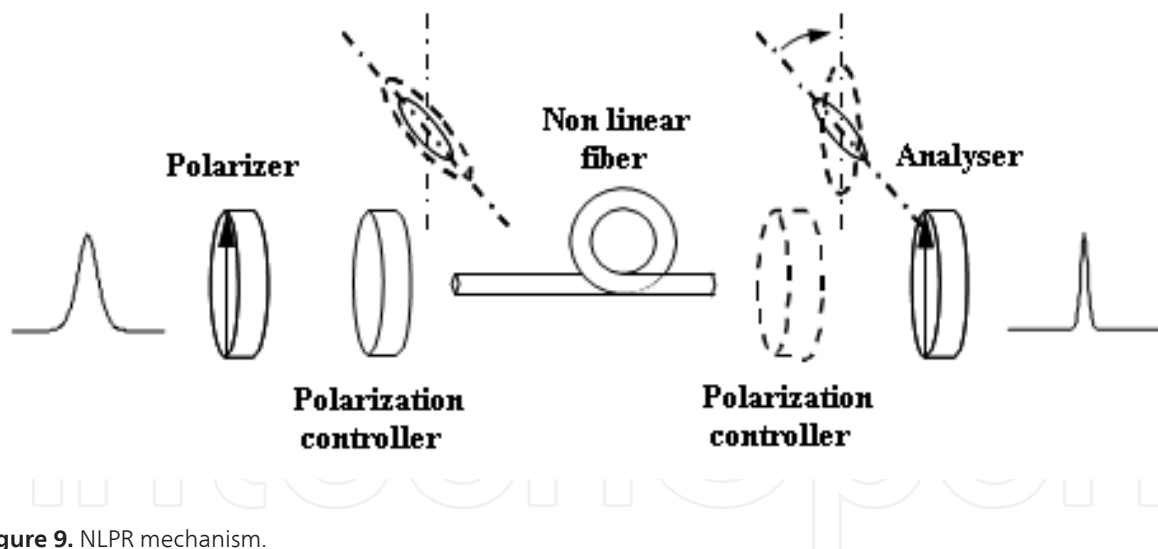
Figure 7. Different types of pulsed fiber lasers.

Passively mode locked fiber lasers have the advantage of being entirely consisted of optical components. They do not require external electrical components and the mode locking mechanism in the cavity is carried out automatically [3-4-5]. However, these lasers can't reach high pulses repetition rates. In fact, the repetition rate of generated pulses depends mainly on the cavity length [6-7]. The laser resonator may contain a saturable absorber such as SESAM (Semiconductor Saturable Absorber Mirror) to passively mode lock the cavity (see Fig. 8).



**Figure 8.** Saturable Absorber passively mode locked fiber laser.

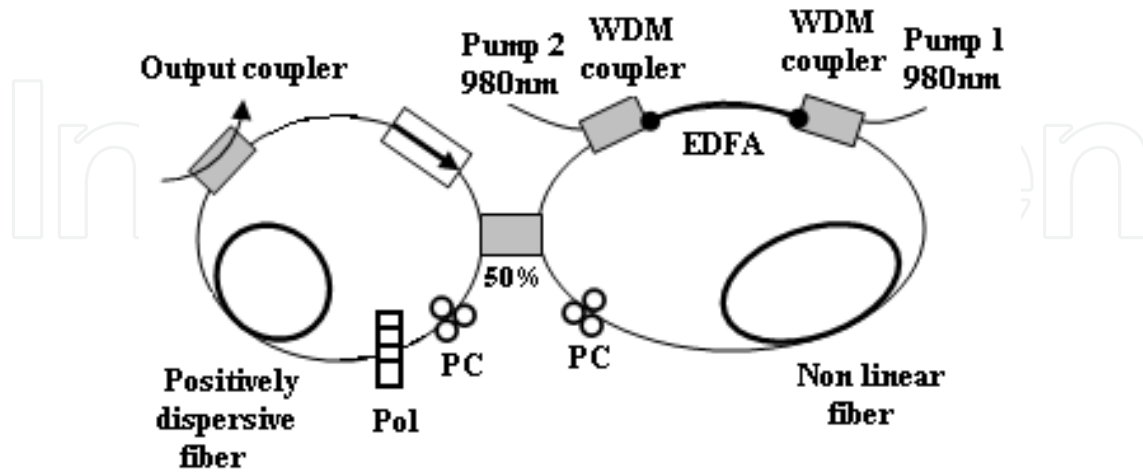
The effect of NLPR (Non Linear Polarization Rotation), as illustrated in Fig. 9, or a nonlinear fiber loop mirror, as illustrated in Fig. 10, can be used as artificial saturable absorbers [8].



**Figure 9.** NLPR mechanism.

A nonlinear loop mirror is used in a "figure-of-eight laser". A schematic diagram of the 8FL (Eight Fiber Laser) is shown in Fig. 10. The 8FL overall design is that of a ring cavity with a Sagnac interferometer with a gain medium placed asymmetrically in the loop. By addition of pulses through the central coupler, the NALM (Non linear Amplifying Loop Mirror) transmits highest intensities of pulse and reflects the lowest ones [9-10]. The nonlinear fiber loop amplifies, shapes and stabilizes the circulating ultra short pulse [11]. With the P-APM (Polarization-Additive Pulse Mode-Locking), the polarization state of a pulse propagating through an optical fiber differs from the peak to the wings and the transmission through a

polarizer can be adjusted to eliminate the wings [12-13]. The SAs act as intensity dependent elements. The wings of the pulse exhibit more losses than the peak [14].



**Figure 10.** Figure of eight fiber laser.

The PCs (Polarization Controllers) set the input signal in an arbitrary polarization state. The azimuth and elliptical parameters define the polarization state of the output signal. Considering  $E_{inx}$  and  $E_{iny}$  as the polarization components of the input signal, the output signal is:

$$E_{out}(t) = \begin{pmatrix} \sqrt{(1-k)} \exp(j\delta_{xy}(t)) \\ \sqrt{k} \exp(j\delta_{xy}(t)) \end{pmatrix} \sqrt{|E_{inx}|^2 + |E_{iny}|^2} \quad (3)$$

Where  $k$  is the power splitting ratio parameter and  $\delta_{yx}(t)$  is the phase difference between the  $x$  and  $y$  components. The optical isolator is inserted into the loop to allow light circulate only in one direction. The major disadvantage of 8FL is that it requires a special management of the various parameters of the cavity [15]. In the steady state, the various linear and non linear effects are in balance and the pulse output power and width are unchanged or often even nearly constant after each completed round trip. Assuming a single circulating pulse, the pulse repetition rate corresponds to the resonator round-trip time.

In actively mode locked fiber lasers, as shown in Fig. 12, the pulses frequency depends on the electro-optic or the acousto-optic modulator inserted in the cavity [16-17-18]. Generally, these types of laser cavities provide typically pulses larger than those provided by a passively locked laser. This can be explained by the fact that no compression techniques are applied [19]. The most used optical modulator to actively mode lock the different modes oscillating into a fiber laser cavity is the MZM (Mach Zehnder modulator). It's an intensity modulator based on an interferometer principle. It consists of two  $3dB$  couplers which are connected by two waveguides of equal length (see Fig. 11). By means of electro-optic effects, an externally applied voltage can be used to vary the refractive indices in the waveguide branches. The



different paths can lead to constructive and destructive interference at the output, depending on the applied voltage. Then the output intensity can be modulated according to the voltage. A Mach Zehnder Modulator has often only one optical exit, the second one is hidden.

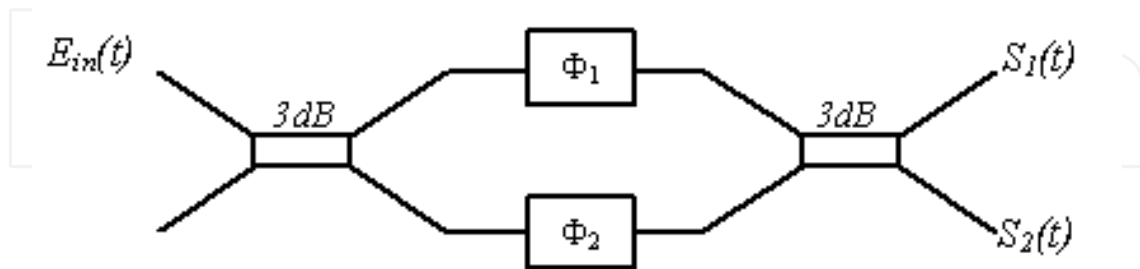


Figure 11. Mach Zehnder Modulator.

$$\begin{pmatrix} S_1(t) \\ S_2(t) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix} \begin{pmatrix} \exp(j\phi_1) & 0 \\ 0 & \exp(j\phi_2) \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix} \begin{pmatrix} E_{in}(t) \\ 0 \end{pmatrix}$$

$$S_1(t) = j \exp\left(j\left(\frac{\phi_1 + \phi_2}{2}\right)\right) \sin\left(\frac{\phi_1 - \phi_2}{2}\right) E_{in}(t)$$

$$S_2(t) = j \exp\left(j\left(\frac{\phi_1 + \phi_2}{2}\right)\right) \cos\left(\frac{\phi_1 - \phi_2}{2}\right) E_{in}(t)$$
(4)

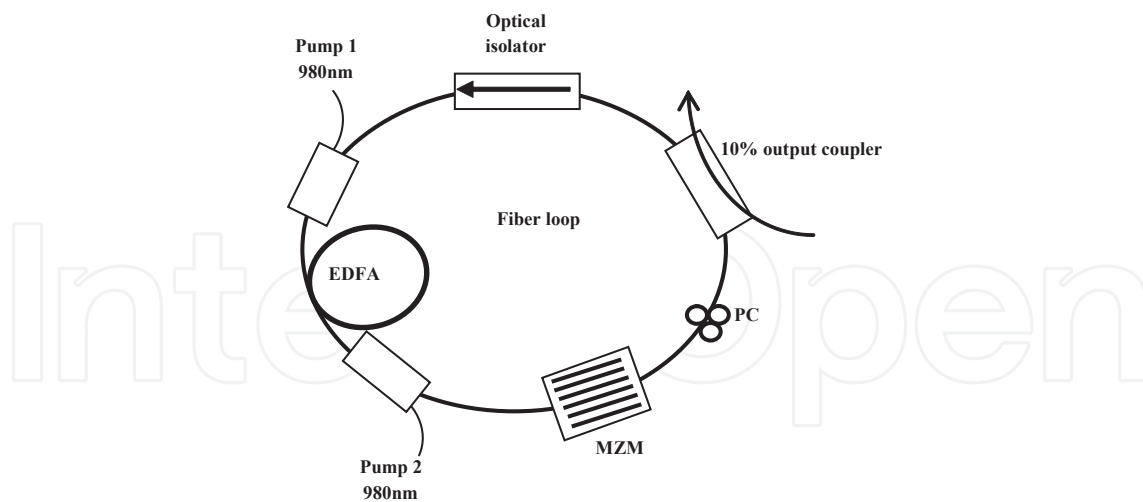
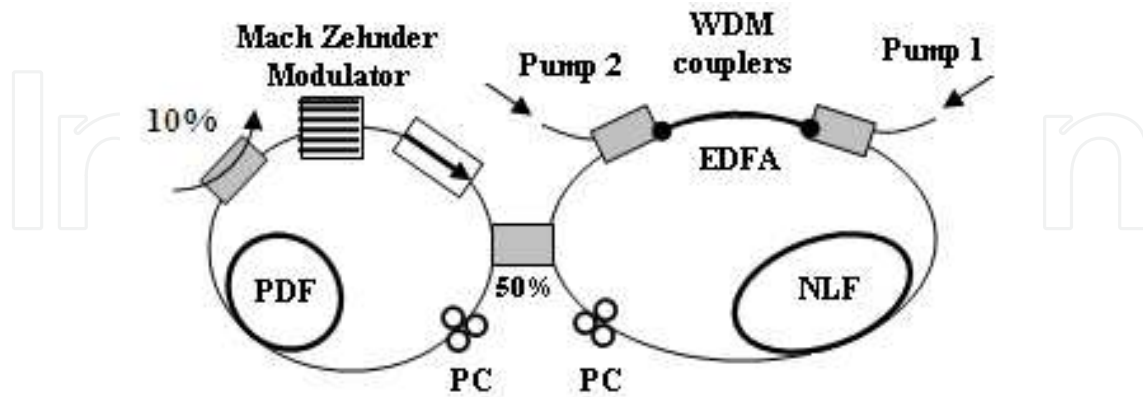


Figure 12. Actively mode locked ring fiber laser.

Aiming to profit at the same of the two configurations advantages: a rather low width and a sufficiently high repetition rate of pulses, new prospects and configurations of fiber lasers, using both the passive and active mode locking techniques, have been proposed. This new generation of pulses generator is called hybrid type mode locked fiber laser [20]. Fig. 13

shows hybrid type mode locked fiber laser using both a machZehnder modulator to actively mode lock the cavity and a non linear amplifying loop mirror to passively mode lock the cavity.



**Figure 13.** Hybrid type mode locked 8FL.

Being 90% made of fiber; light propagation through a fiber laser can be modeled by the Split Step Fourier Method.

## 5. Split step fourier method

Light propagation within optical fiber may be expressed by the Generalized Non Linear Schrödinger Equation (GNLSE) as follow:

$$\frac{\partial A}{\partial z} + j\frac{1}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial T^3} + j\frac{\beta_4}{24} \frac{\partial^4 A}{\partial T^4} + \frac{\alpha}{2} A = j\gamma |A|^2 A \quad (5)$$

$\beta_2$  and  $\beta_3$  are the second and the third order dispersion terms,  $\alpha$  is the attenuation coefficient of the fiber,  $T$  is the related time given by  $T=t - z/v_g$  where  $z$  and  $v_g$  are the longitudinal coordinate and the group velocity corresponding to the central wavelength  $\lambda$  and  $\gamma$  is the nonlinear parameter of the fiber given by  $\gamma=2\pi n_2/\lambda A_{eff}$ .  $n_2$  is the non linear refractive index and  $A_{eff}$  is the effective area of the fiber. When studying the propagation into an EDFA, the GNLSE become:

$$\frac{\partial A}{\partial z} + j\frac{1}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial T^3} + j\frac{\beta_4}{24} \frac{\partial^4 A}{\partial T^4} + \frac{\alpha - g}{2} A = j\gamma |A|^2 A \quad (6)$$

The gain of the Erbium Doped Fiber Amplifier (EDFA) can be estimated as  $G=\exp(gl)$  where  $l$  is the length of the doped fiber and  $g$  the gain coefficient.

The SSFM consists on transforming the GNLSE as the sum of linear and nonlinear operators:

$$\begin{aligned} \frac{\partial A}{\partial z} &= (\hat{D} + \hat{N})A \\ \hat{D} &= -\frac{\alpha}{2} + j\left(-\frac{1}{2}\beta_2 \frac{\partial^2}{\partial T^2} - \frac{\beta_4}{24} \frac{\partial^4}{\partial T^4}\right) + \frac{\beta_3}{6} \frac{\partial^3}{\partial T^3} \\ \hat{N} &= j\gamma|A|^2 \end{aligned} \tag{7}$$

The SSFM relies on that propagation in each segment of the optical fiber is divided in three steps: two linear and one non linear steps (see Fig. 14). The nonlinear step is inserted between the two linear steps [21-22].

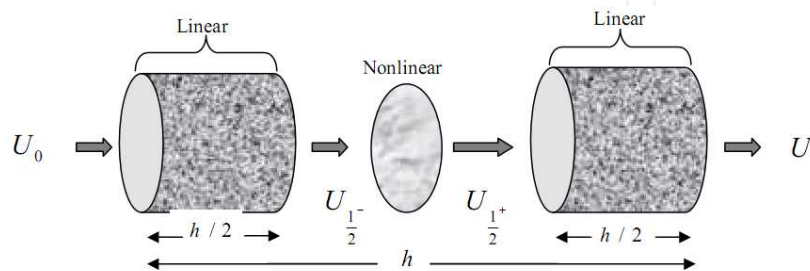


Figure 14. Principle of Split Step Fourier Method SSFM.

So, linear and nonlinear effects are supposed to be applied in the whole segment of the fiber. The linear operator is used in the frequency area and the non linear one is used in time area.

$$\begin{aligned} \hat{D} &= -\frac{\alpha}{2} + j\left(\frac{\beta_2}{2}\omega^2 - \frac{\beta_3}{6}\omega^3 - \frac{\beta_4}{24}\omega^4\right) \\ U_{\frac{1}{2}^-} &= A\left(z + \frac{h}{2}, T\right) = FT^{-1}\left(\exp\left(\frac{h}{2}\hat{D}\right)FT\left(A(z, T)\right)\right) ; A(z, T) = U_0 \\ &= \exp\left(\frac{h}{2}\hat{D}\right)U_0 \\ U_{\frac{1}{2}^+} &= \exp\left(\int_z^{z+h} \hat{N}\left(U_{\frac{1}{2}^-}\right)dz\right) ; U_1 = FT^{-1}\left(\exp\left(\frac{h}{2}\hat{D}\right)FT\left(U_{\frac{1}{2}^+}\right)\right) \end{aligned} \tag{8}$$

FT is the Fourier transform.

## 6. Erbium doped fiber amplifier

The EDFA is based on a two-level  $Er^{3+}$  system assumption that is usually adapted to model erbium-doped fiber amplifiers. The lifetime transition from level  $^4I_{11/2}$  is of the order of microseconds for silicate hosts. Therefore, it is reasonable to neglect the population density  $N_3$  in the rate equations description. A two-level system approximation is used in this case. Under the assumption of the normalized population densities  $N_1$  and  $N_2$  at the ground and

metastable energy level,  ${}^4I_{15/2}$  and  ${}^4I_{13/2}$  populations are calculated by numerically solving the rate and propagation equations [23]:

$$\begin{aligned} \frac{\partial N_2(z,t)}{\partial t} &= -\frac{1}{A_{eff}} \sum_{n=1}^N \left\{ \Gamma_n \left[ (\sigma_n^e + \sigma_n^a) N_2(z,t) - \sigma_n^a \right] \right\} \left[ P_n^+(z,t) + P_n^-(z,t) \right] - \frac{N_2(z,t)}{\tau} \\ N_2 + N_1 &= 1 \\ \frac{\partial P_n^\pm(z,t)}{\partial z} &= u_n \left\{ \rho \times \Gamma_n \left[ (\sigma_n^e + \sigma_n^a) N_2(z,t) - \sigma_n^a - \alpha \right] \right\} P_n^\pm(z,t) + 2\rho \times \Delta\nu N_2 \Gamma_n \sigma_n^e \end{aligned} \quad (9)$$

Where the optical powers are expressed in units of number of photons per unit time,  $\tau$  is the metastable spontaneous emission lifetime,  $N$  is the number of channels taken into account in the simulation (including signals, pumps, and ASE bins),  $\rho$  is the number density of the active erbium ions,  $\alpha$  is the attenuation coefficient (which takes into account the background loss of the fiber),  $\Delta\nu$  is the frequency step used in the simulation to resolve the ASE spectrum, and  $A_{eff}$  is the effective doped area given by  $\pi b^2$ , where  $b$  is the *Er* doping radius (it is considered a uniform distribution of erbium ions in the area given by the *Er* doping radius region). The  $n^{th}$  channel of wavelength  $\lambda_n$  has optical power  $P_n(z,t)$  at location  $z$  and time  $t$ , with emission and absorption cross-section  $\sigma_n^e$  and  $\sigma_n^a$  respectively, and confinement factor  $\Gamma_n$ . The superscript symbols + and – are used respectively to indicate channels travelling in forward (from 0 to  $L_{EDFA}$ ) and backward (from  $L_{EDFA}$  to 0) directions. For beams travelling in the forward direction  $u_n=1$  and for beams in the opposite direction  $u_n=-1$ . The overlap integrals  $\Gamma_n$  between the  $LP_{01}$  mode intensity distributions doped region areas are given by:

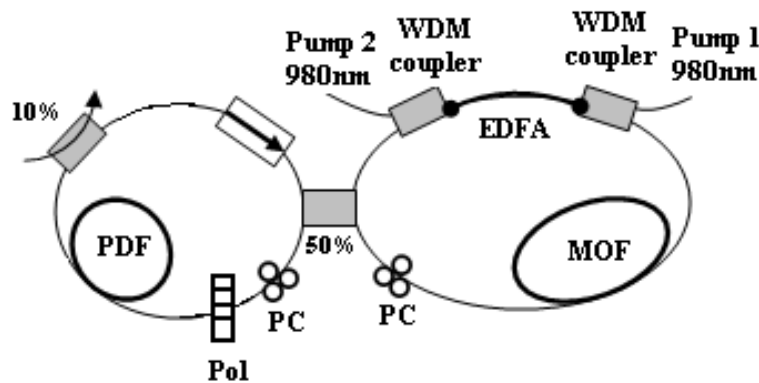
$$\Gamma_n(\nu) = \frac{\int_0^b |E(r,\nu)|^2 r dr}{\int_0^\infty |E(r,\nu)|^2 r dr} \quad (10)$$

## 7. Interaction between mode locking mechanism and non linear effects in fiber laser

Normally, when designing extremely high output average and peak power fiber laser generating ultra short pulses, the best solution that can be adopted is to enhance the non linear effects in the cavity. This can be achieved either by pumping the piece of doped fiber amplifier with a high input power rate or enhancing the SPM, XPM and FWM effects by reducing the average dispersion of the cavity and the effective area of the different fibers used. In this section, managing the pumping input powers level, the dispersion and the effective area of different microstructured optical fibers inserted into a passively and an hybrid type mode locked 8FLs, we prove that enhancing non linear effects does not lead necessarily to better results. It depends also on the type of mode locking mechanism used. The highest peak powers and the narrowest pulse widths are obtained only for specific parameters.

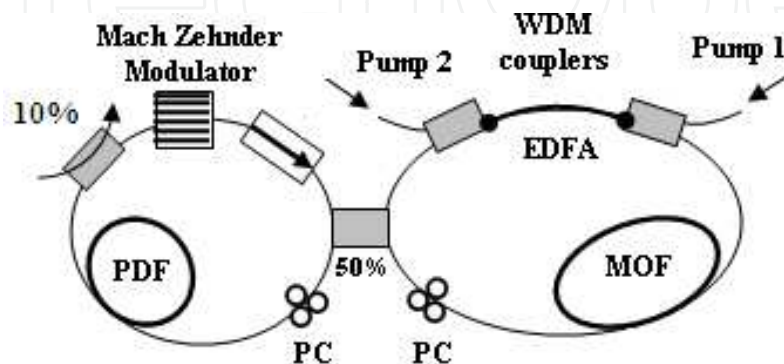
In spite of their singularities and particularities in managing linear and non linear effects, the exploitation of MOFs in laser cavities has remained a subject of research bit addressed. In fact, MOFs offer many degrees of freedom in the management of dispersion and effective area

A schematic diagram of the first passively mode locked 8FL is shown in Fig.15. It consists of two loops: a ring cavity and a non linear amplifying loop mirror NALM connected to each other through a 50% central coupler. The linear cavity is made up of 10m of PDF (Positively Dispersive Fiber:  $\beta_2=20ps^2/km$ ) having  $85\mu m^2$  as effective area and aiming to maintain balance between anomalous and normal dispersion within the 8FL, a 10% output coupler and a polarization insensitive optical isolator to ensure the circulation of light only on the clockwise direction. The NALM includes a MOF (Microstructured Optical Fiber) and a 10m EDFA (Erbium Doped Fiber Amplifier) having 0.24 as numerical aperture forward and backward pumped by two 980nm pump laser diodes coupled to the loop through two 980/1550nm WDM couplers. The  $Er^{3+}$  ions density is 700ppm.



**Figure 15.** Configuration of passively mode locked 8FL.

The second configuration, shown in Fig.16, is a hybrid type mode locked 8FL. It differs from the first one by the presence of a MZM (Mach Zehnder Modulator) as an electro-optical modulator into the linear ring cavity.



**Figure 16.** Configuration of hybrid type mode locked 8FL.

By modelling the light propagation through the various components by the SSFM (Split Step Fourier Method), we studied the influence of varying nonlinear parameters of the cavity on the output pulses shape. Light pulse propagation in the 8FL may be expressed by the NLGSE (Non Linear Generalised Schrödinger Equation) and the transfer function of the different components used [12]. The central coupler is a cross-coupler for combining or splitting the optical signal. It is bidirectional, with wavelength independent coupling, insertion loss and return loss. If we consider  $E_{in}$ ,  $E_{out}$ ,  $E_3$  and  $E_4$  respectively the input, transmitted, NALM clockwise and counter clockwise circulating light powers, after propagating into an L length loop made of EDFA and MOF, considering only the non linear effects,  $E_{3L}$  and  $E_{4L}$  are expressed as follow:

$$\begin{aligned} E_{3L} &= \sqrt{k}\sqrt{G}E_{in} \exp(jk2\pi n_2 G |E_{in}|^2 L / A_{eff}\lambda) \\ E_{4L} &= j\sqrt{(1-k)}\sqrt{G}E_{in} \exp(j(1-k)2\pi n_2 |E_{in}|^2 L / A_{eff}\lambda) \end{aligned} \quad (11)$$

Where  $k$  is the power splitting ratio parameter,  $G$  is the EDFA gain,  $\lambda$  is the signal wavelength and  $A_{eff}$  is the MOF effective area. For each round trip through the fiber laser, the transmitted power circulating into the ring linear cavity is:

$$\begin{aligned} E_{out} &= k\sqrt{G}E_{in} \exp(jk2\pi n_2 G |E_{in}|^2 L / A_{eff}\lambda) - (1-k)\sqrt{G}E_{in} \exp(j(1-k)2\pi n_2 |E_{in}|^2 L / A_{eff}\lambda) \\ |E_{out}|^2 &= |E_{in}|^2 G \left( 1 - 2k(1-k) \left( 1 + \cos \left( (kG - (1-k))2\pi n_2 |E_{in}|^2 L / A_{eff}\lambda \right) \right) \right) \end{aligned} \quad (12)$$

A single secant hyperbolic input pulse with  $1mW$  of peak power and  $200ps$  FWHM (Full Width at Half Maximum) is launched in the first configuration through the WDM coupler. At the beginning, we studied the output pulses shape for different EDFA pumping power levels and different MOF effective area's values. The pumping threshold is about  $300mW$ . In fact, as illustrated in Fig.17 and Fig.18 below, when increasing the pump power of the EDFA, the pulses peak power increases whereas the width decreases. However for very small effective areas like  $5\mu m^2$  and  $10\mu m^2$ , the pulse width reaches a minimum value at a specified pump power level before growing up proportionally to the laser diodes pump powers. In these cases the lowest values of the pulse width are reached respectively for  $400mW$  and  $700mW$  of pump powers.

A second approach to study the non linear effects impact in a fiber laser cavity is to use longer portion of the non linear optical fiber used. Fig.19 and Fig.20 show the output pulses peak power and width for different lengths and effective areas of MOF. The pump power delivered by each laser diode is equal to  $700mW$ .

As shown in Fig.19 and Fig.20, enhancing dramatically the non linear effects, by increasing the MOF length and decreasing its effective area, does not lead necessarily to optimal results. In fact, for each length of one selected fiber there are two optimal effective areas. The first corresponds to the one leading to the highest peak power and the second corresponds

to the one leading to the lowest pulse width and conversely. However, there is always an intermediate value of the effective area leading to a high peak and a low pulse width. For  $10m$  of MOF, the intermediate effective area is  $7.5\mu m^2$ . The peak power is equal to  $16W$  and the pulse width to  $39.7ps$ . However, the highest peak power  $18.25W$  and the lowest pulse width  $39ps$  are obtained respectively for  $5\mu m^2$  and  $10\mu m^2$  effective areas. For  $20m$  of MOF, the intermediate effective area is  $15\mu m^2$ . The peak power is equal to  $17.25W$  and the pulse width to  $38.5ps$ . However, the highest peak power  $20W$  and the lowest pulse width  $37.5ps$  are obtained respectively for  $10\mu m^2$  and  $17.5\mu m^2$  effective areas. For  $30m$  of MOF, the adequate effective area is  $15\mu m^2$ .

Thus, by reducing the mean dispersion of the cavity with an appropriate choice of the MOF optimal length and effective area, generated ultra short pulses would have the highest peak power and the lowest width.

Unlike the passively mode locked 8FL carried out above, in case of hybrid type 8FL shown in Fig.16, no input pulse is inserted in the cavity to release the cavity oscillation. The first handling aimed to study the average pulses output power fluctuation according to the pump powers of the two lasers diode for different MOF's effective areas. The MOF length and dispersion are respectively  $30m$  and  $-10ps^2/km$ . The PDF length and dispersion are respectively  $10m$  and  $20ps^2/km$  with an effective area of  $85\mu m^2$ . The electrical signal frequency injected into the MZM is  $20GHz$ . As shown in Fig.23, more the effective area is small and the pumping powers are high more the mean power of output signal is high. So, by increasing non linear effects, we increase the output pulses power.

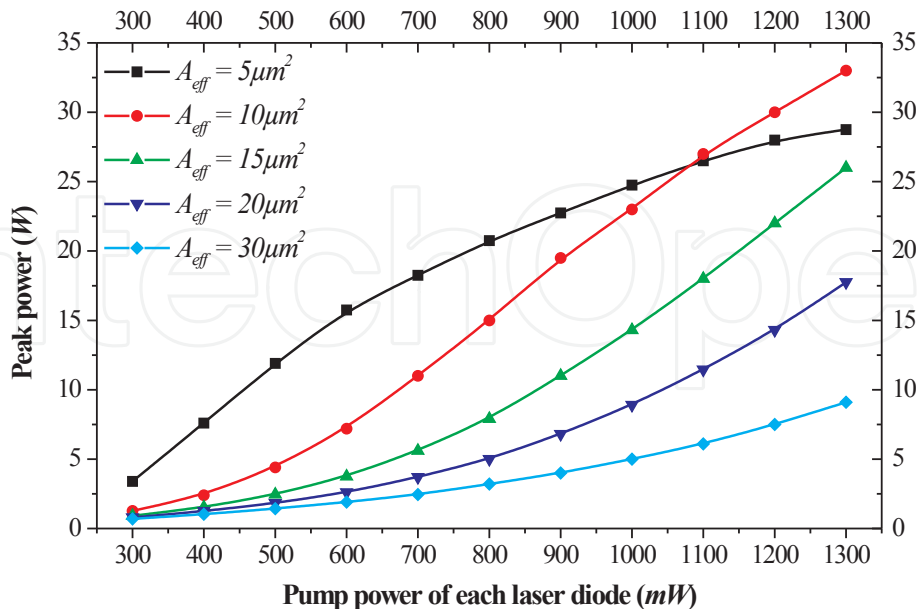


Figure 17. Peak power vs launched pump powers ( $L_{MOF}=10m$ ,  $\beta_{2MOF}=-10ps^2/km$ ).

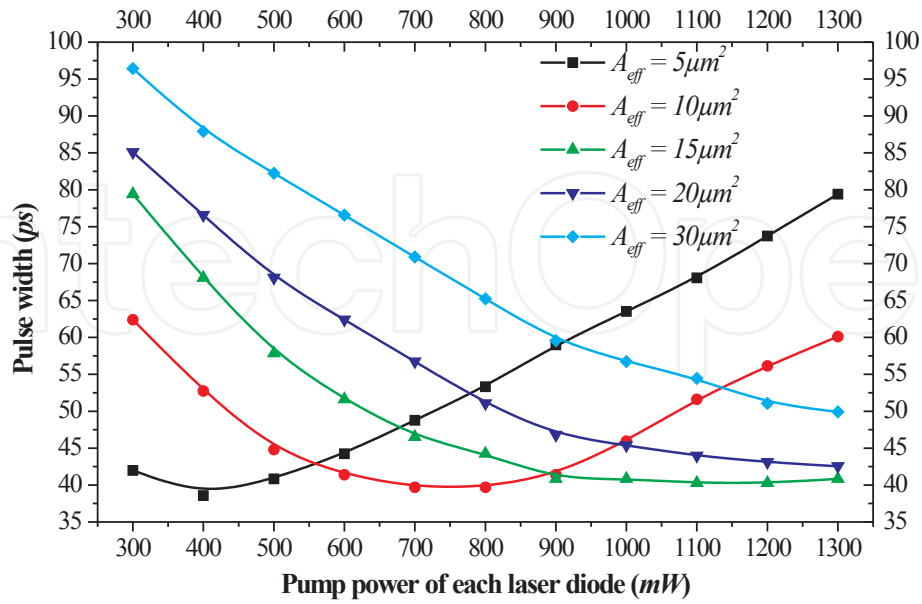


Figure 18. Width vs launched pump powers ( $L_{MOF}=10m$ ,  $\beta_{2MOF}=-10ps^2/km$ ).

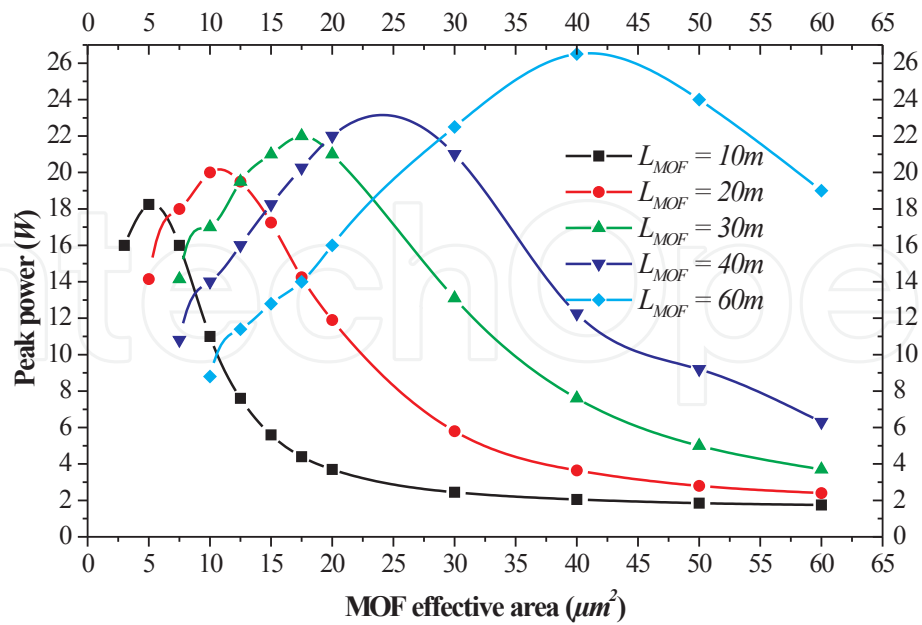


Figure 19. Peak power vs MOF's effective area and length.



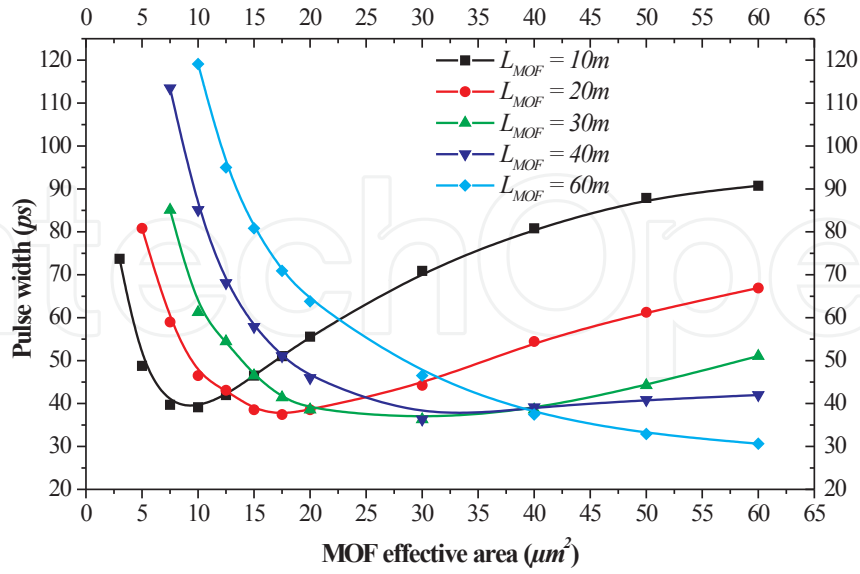


Figure 20. Width vs MOF's effective area and length.

About pulses shape depending on group velocity dispersion, Fig.21 and Fig.22 show that the best results correspond to MOF having negative chromatic dispersions.

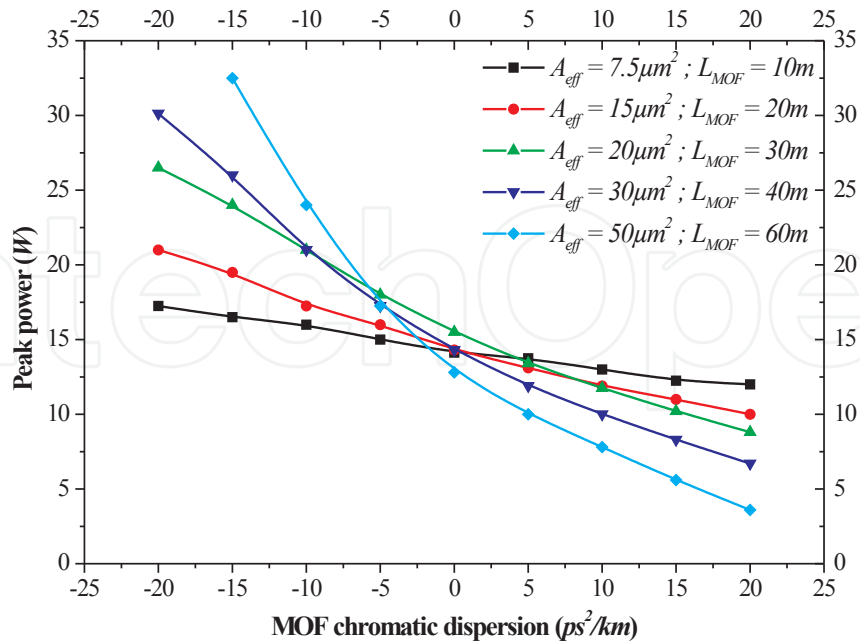


Figure 21. Peak power vs MOF chromatic dispersion.

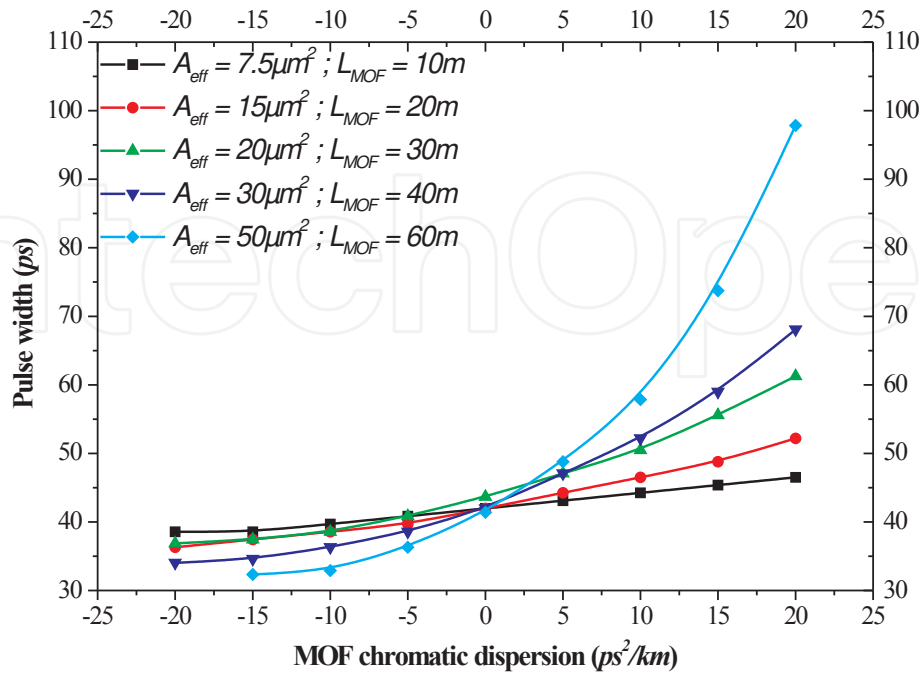


Figure 22. Width vs MOF chromatic dispersion.

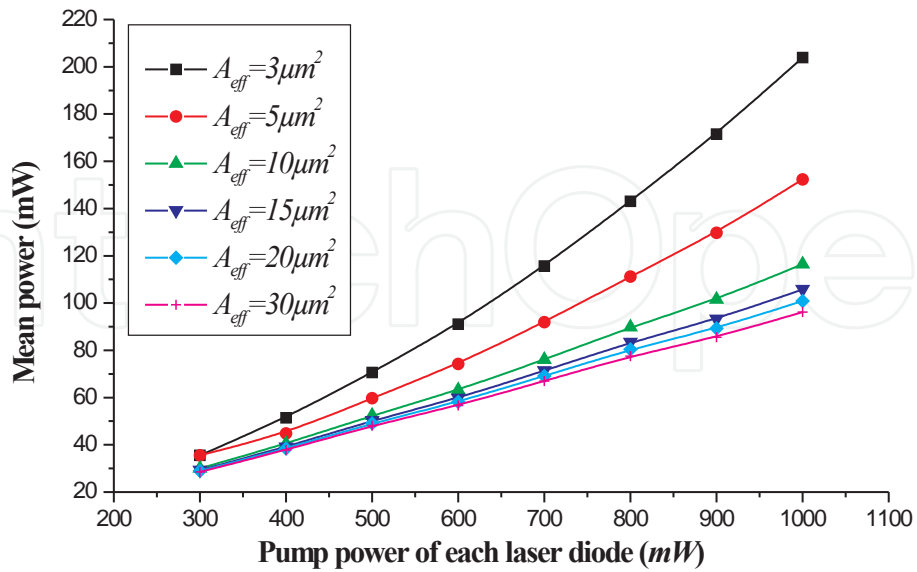
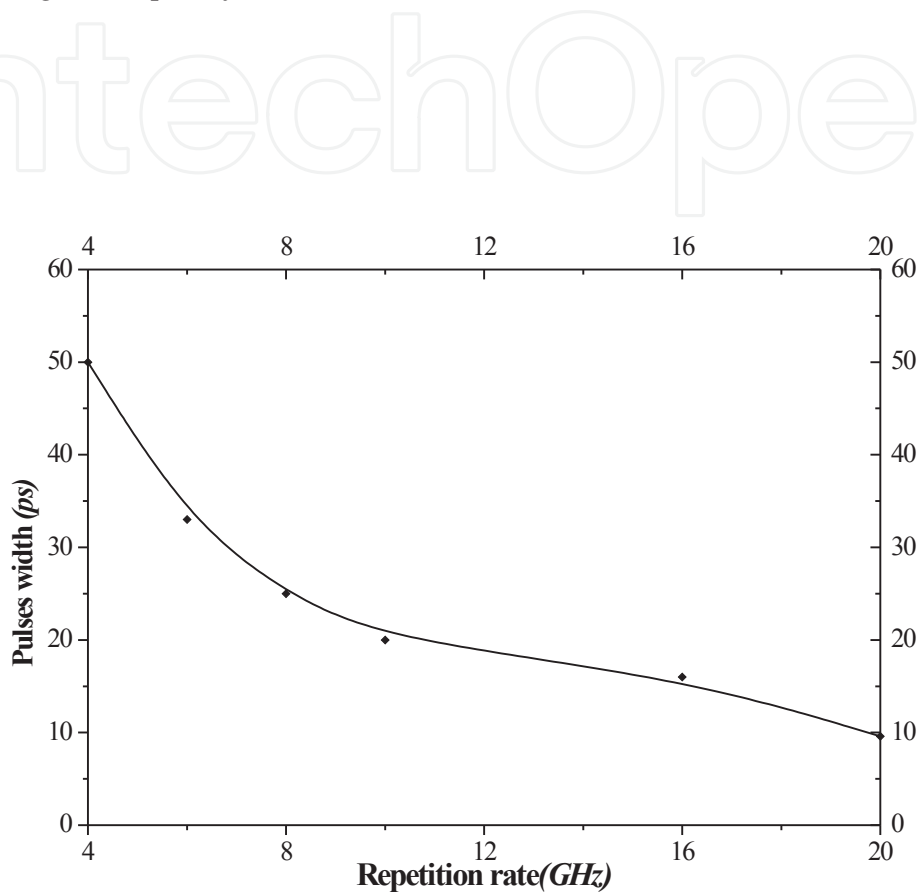


Figure 23. Mean power vs launched pump powers.

The repetition rate and the width of output pulses are fixed by the electro-optical modulator characteristics.

The repetition rate of pulses depends directly on the frequency of the electrical signal injected into the MZM. Fig.24 illustrates the variation of the width of output pulses according to the electrical signal frequency.



**Figure 24.** Width vs Repetition rate.

Fig.25 shows hybrid type output pulses with a repetition rate of 20GHz. The second handling aimed to study the average pulses output power fluctuation from a hybrid type 8FL according to non linear effects by varying the length and the effective area of the MOF.

Curves shown in Fig.26 illustrate that more the MOF is long and its effective area is small more the exit power of the laser is significant. However, a significant increase of the MOF length and the effective area leads to a fast power fall. We can also notice that for all different MOF's lengths there is a particular value of the effective area leading always to the same result. In this case, it corresponds to  $12\mu m^2$ . At the end, we studied the hybrid type 8FL behaviour when decreasing the average chromatic dispersion of the cavity. Contrary to passively mode locked 8FL, the maximum values of exit power, for a hybrid type 8FL, are reached for normal dispersion of the MOF  $\beta_{2MOF} > 0$  (see Fig.27).

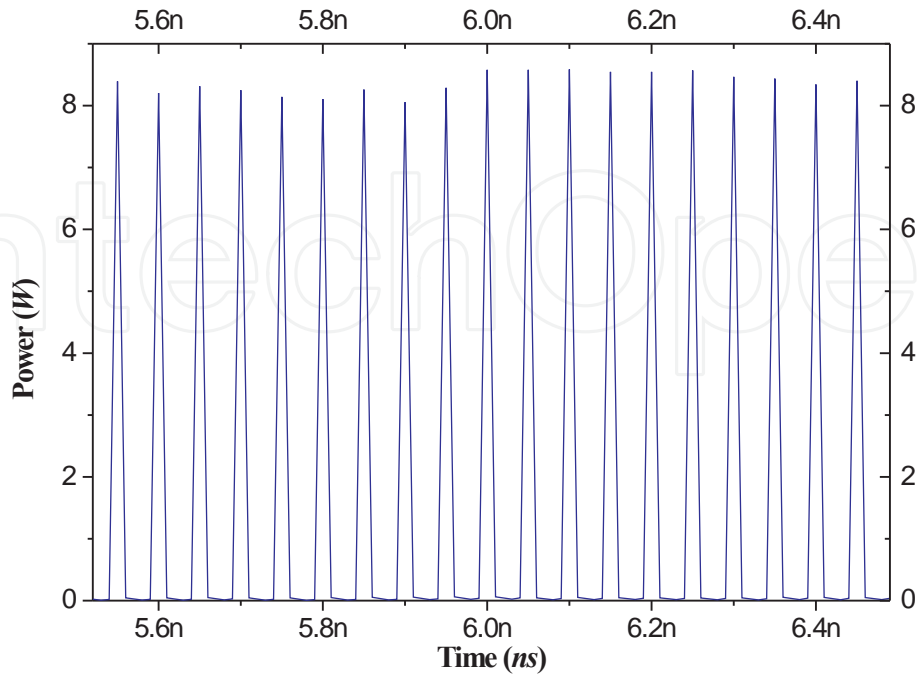


Figure 25. GHz hybrid type 8FL output pulses.

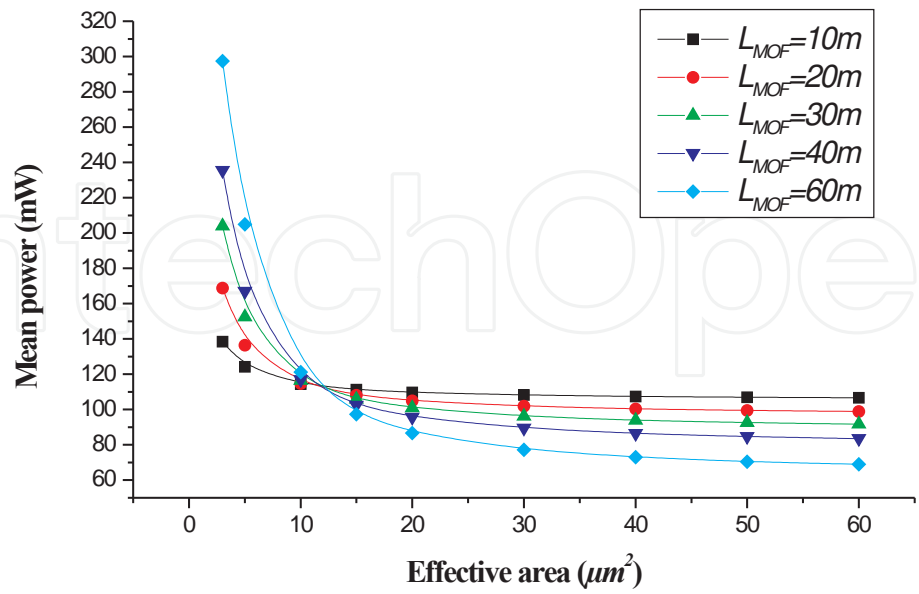


Figure 26. Mean power vs MOF length and effective area ( $\beta_{2MOF}=-10\text{ps}^2/\text{km}$ ).

Thus, increasing the average exit power of hybrid type 8FL, operating at any pulses repetition rate, can be reached by choosing a rather long MOF having small effective area and normal dispersion.

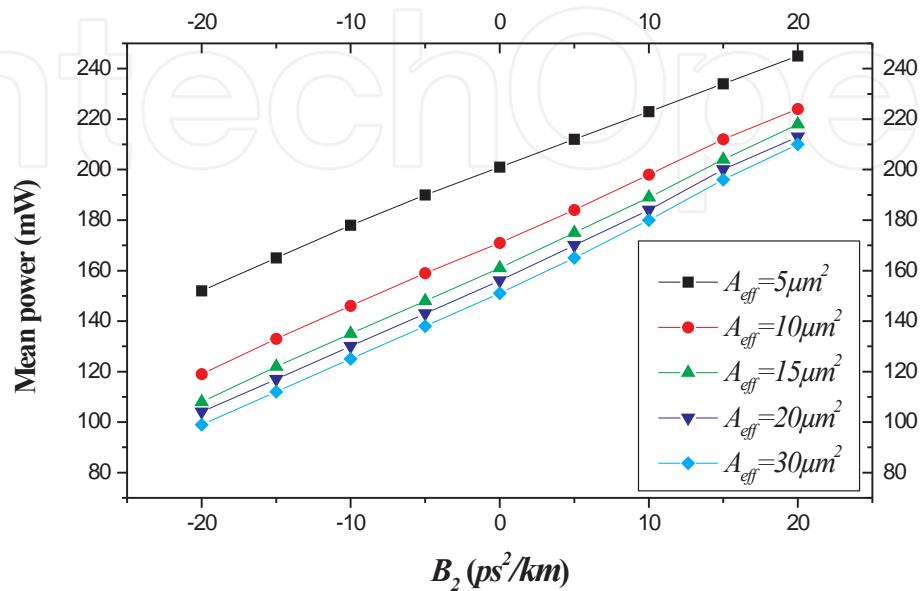


Figure 27. Mean power vs MOF chromatic dispersion.

## 8. Conclusion

We summarized different techniques used to generate ultra short pulses from a fiber laser. Using the Split Step Fourier Method algorithm to model light propagation within a loop cavity, we described some operating process of different kind of mode locked fiber lasers. We also focused on some optical components operating process used in fiber laser to passively or actively mode lock the different modes oscillating within a laser cavity. In addition, we focused on Erbium Doped Fiber Amplifier operating process. We highlighted the improvement of fiber laser performances does not depend only on the management of the non linear parameters of the cavity. In fact, it depends tightly on the mode locking mechanism used. A passively mode locked 8FL and a hybrid type 8FL do not respond the same way to non linear effects increase. In fact, in case of passively mode locked 8FL, for each length of the high non linear fiber, correspond two associated optimal effective areas: one leading to the highest peak power and one leading to the lowest pulse width. Whereas, increasing the non linear effects by using a rather long high non linear fiber having a reduced effective area leads to the best output results in case of hybrid type 8FL. Moreover, contrarily to hybrid type 8FL, reducing the average dispersion of the cavity leads necessarily to better output

passively mode locked 8FL pulses shape. In fact, this work aims to illustrate the existing interaction between non linear effects and mode locking mechanism in fiber laser.

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