

Frequency Mode Locking in Erbium Doped Fiber Laser

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Abstract:

In this research, may insert of all the effects, such as dispersion, nonlinear, gain factor associated with the pumping pulse , attenuation and others in the conclusion the general equation for the propagation of the optical fiber through the laser resonator. In addition, the introduction of the effect of mode locking process using frequency modulation in order to get a stream ultrashort pulses. Selecting an suitable frequency modulated pulses achieved the stream could reach the stage of stability according to a certain number of trips round-trip (RT), since the highest frequency accompanied by a number less than the RT. On the other hand, the increase in R adversely affect the output pulses stream. The interval time between resulted pulses is inversely proportional to frequency modulated. stream pulses can be stable in the energy and pulse width with RT appropriate. increase factor β_2 contribute to stability of pulses energy while β_3 did not show any effects. The effect of the pumping energy represent of the g_0 worker showed that resulting energy increases with increases this factor. Pulse width T_0 initial and factor T_2 and modulated depth representing of their effects change method the oscillation of the factors resulting pulses.

Keywords: fiber laser, mode mocking, erbium.

1. Introduction

Interest in ultrashort optical pulse sources is rapidly growing due to the wide range of emerging areas where subpicosecond pulses are providing new advances. Mode locked fiber lasers are reliable, compact and cost- effective sources of stable subpicosecond pulses. Fiber lasers offer a set of properties suitable for the generation of ultrashort pulses through mode locking techniques, either active or passive [1]. A simple and powerful approach for understanding the basic dynamical behavior of a laser is based on a rate equation model, in which simple balance equations for the total number of atoms undergoing a transition and the total number of photons created or annihilated are written. For a more-refined treatment of laser dynamics based on either a semiclassical or a full-quantum electro dynamic approach, which may account for certain phenomena such as dynamical laser instabilities, laser coherence and photon statistics [2].

Many optically pumped lasers have a gain medium consisting of rare earth or transition metal ions doped into an insulating dielectric solid. These are termed solid state lasers, and include laser erbium [3]. The gain of erbium doped fiber lasers (EDFLs) depends on many parameters such as erbium-ion concentration, amplifiers length, core radius, and pump power [4]. Many of the properties of a laser can be determined from a rate-equation model for the populations of the laser levels and the number of photons in the laser cavity [5]. All laser cavities share two characteristics that complement each other: 1) they are basically linear devices with one relatively long optical axis and 2) the sides parallel to this axis can be open, not enclosed by reflecting material as in a microwave cavity [6]. The most common types of laser cavity is known

as the Fabry–Perot cavity, which is made by placing the gain medium in between two high-reflecting mirrors. In the case of fiber lasers, mirrors are often butt-coupled to the fiber ends to avoid diffraction losses [7].

In the Fabry–Perot laser cavity The light makes two passes through the gain medium per round-trip (RT). Laser system consists of a set of mirrors and a gain medium. The gain medium is an optical amplifier which coherently amplifies light passing through it. The mirrors may be curved or planar and together make up the laser cavity or resonator. The cavity is aligned so that light reflects back and forth again and again, passing along the same path every time [8]. The mirrors of the laser keep photons from escaping completely, By making the mirrors partially transmitting, some of the photons are allowed to escape. They constitute the output laser beam. The intensity of the output laser beam is determined by the rate of production of excited atoms, the reflectivities of the mirrors, and certain properties of the active atoms [6]. Alignment of such a cavity is not easy since cavity losses increase rapidly with a tilt of the fiber end or the mirror, where tolerable tilts are less than 1° . This problem can be solved by several methods, including use fiber gratings as mirrors [4].

In this papers gives derivation of basic wave equation, followed by the theory of pulse propagation in dispersive optical medium. Moreover, the discussion of amplification in fibers, the physics of frequency mode locking, and the required numerical analyses will presented.

2.Modeling of Fiber laser with Mode locking

The rate equations provide a simple and intuitive, yet accurate, picture of the behavior of lasers. In the most simplified form, the increase

in photon number within the laser cavity is balanced by the decrease in the population difference between the upper and lower laser levels [9]. The EDFL can be modeled using the propagation and rate equations for a homogeneous two-level laser medium. Optical pumping creates the necessary population inversion between the two energy states, which in turn provides the optical gain (peak gain) $g_p = \sigma(N_2 - N_1)$, where σ is the transition cross section and N_1, N_2 are the atomic densities for the lower and upper energy levels of the two-level system [4].

In general, the local gain coefficient g_p is a function of optical frequency due to the limited optical bandwidth. It is also a function of optical power because of the saturation effect, which can be expressed as [5]

$$g_p = \frac{g_0}{1 + (\omega - \omega_a)^2 T_2^2 + P_{ave} / P_{sat}} \quad (1)$$

where g_0, T_2, P_{sat} represent the maximum small signal gain, the dipole relaxation time, and the saturation power, respectively and ω is the optical frequency, ω_a is the atomic resonance frequency. The equation

$$P_{ave} = \frac{1}{T_m} \int_{T_m/2}^{T_m/2} |A|^2 dt \quad (2)$$

represents the average power passing through the gain medium (for mode locked laser), where T_m is the spacing between adjacent pulses and is inversely related to the repetition rate of the system [10]. To simplify the discussion, let ($\omega = \omega_a$) we obtain [7]

$$g_p = \frac{g_0}{1 + P_{ave} / P_{sat}} \quad (3)$$

The nonlinear Schrodinger equation (NLSE) is the fundamental mathematical device for analyzing nonlinear pulse propagation in fibers[11]. If the slowly varying amplitude A of the optical pulse is normalized in such a way that $|A|^2$ represents optical power, the NLSE for a standard optical fiber has the form [12]

$$\frac{\partial A}{\partial z} - \sum_{m=0}^{\infty} \frac{j^{m+1}}{m!} \beta_m \frac{\partial^m A}{\partial t^m} = -\frac{\alpha}{2} A + j\gamma |A|^2 A \quad (4)$$

where $A = A(z, t)$, the nonlinear coefficient is $\gamma = \omega_o \bar{n}_2 / cA_{eff}$, ω_o is the reference frequency relative to which the slowly varying envelop approximation was made, A_{eff} is the effective mode area and $\beta_m = (\partial^m \beta / \partial \omega^m)_{\omega_o}$ are the dispersion parameters [13]. Here, we will generalized this equation so that it can be applied for EDFL. When dopants such as erbium are introduced into a fiber, all these effects of the host medium are inherited by the doped fibers and can affect the performance of EDFL. Therefore, modifications must be introduced to the standard NLSE to account for the presence of dopants [5]. The propagation of an optical pulse in a fiber is characterized by a mode propagation constant $\beta(\omega)$. The mode propagation constant $\beta(\omega)$ can be expanded in a Taylor series about ω_o to get [7]

$$\beta_f(\omega) = \beta_o + (\omega - \omega_o)\beta_1 + \frac{1}{2}(\omega - \omega_o)^2\beta_2 + \frac{1}{6}(\omega - \omega_o)^3\beta_3 + \dots = \sum_{m=0}^{\infty} \frac{(\omega - \omega_o)^m \beta_m}{m!} \quad (5)$$

where β_o is the wave number. For pulses having widths in the picosecond range, the susceptibility of the dopants can be written as[4,5]

$$\chi_a(\omega) = \frac{g_p c n(\omega)}{\omega} \frac{1}{j + (\omega - \omega_a) T_2} \quad (6)$$

$n(\omega)$ is the refractive index of the fiber core in the absence of doping, the dipole relaxation time T_2 . The relative permittivity or dielectric constant of a doped fiber is obtained by adding the contribution of the dopants to that of the undoped fiber. That is [12,6]

$$\varepsilon = n^2 + 2n\Delta n \quad (7)$$

where Δn represents the change of refractive index that defined as [4]

$$\Delta n = \bar{n}_2 |E|^2 + j \frac{\alpha}{2k} + \frac{\chi_a(\omega)}{2n} \quad (8)$$

where α accounts for the fiber loss, $k = \omega / c$.

We have added the nonlinear contribution through the \bar{n}_2 term and the effect of dopant through $\chi_a(\omega)$. The absorptive and dispersive properties of the doped fiber result from the frequency dependence of $\varepsilon(\omega)$ and $|E|^2 = |A|^2 / A_{eff}$ is the optical intensity. Substituting Eq.(8) into (7), may yields

$$\sqrt{\varepsilon} = n \sqrt{1 + \frac{2\bar{n}_2 |E|^2}{n} + \frac{j\alpha}{n k} + \frac{\chi_a(\omega)}{n^2}} \quad (9)$$

Note that α , $\bar{n}_2 |E|^2$, and $|\chi_a(\omega)|$ are much smaller than $n(\omega)$. Hence, the square root on the right hand side may be extracted using Taylor series to yield

$$\sqrt{\varepsilon} \approx n + \bar{n}_2 |E|^2 + \frac{j\alpha}{2k} + \frac{\chi_a(\omega)}{2n} \quad (10)$$

The propagation constant of the signal within the doped-fiber medium can be written as $\beta(\omega) = w \sqrt{\varepsilon(\omega)} / c$. Using the definitions of \bar{n}_2 and $|E|^2$, the second term will be $\gamma|A|^2$. The propagation constant in the undoped fiber is $\beta_f(\omega) = nw / c$. So the propagation constant will be

$$\beta(\omega) = \beta_f(\omega) + \gamma|A|^2 + j \frac{\alpha}{2} + \frac{\chi_a}{2n} \frac{\omega}{c} \quad (11)$$

Using Eq.(5), Eq.(11) will be

$$\beta(\omega) = \sum_{m=0}^{\infty} \frac{(\omega - \omega_0)^m \beta_m}{m!} + \gamma|A|^2 + j \frac{\alpha}{2} + \frac{\chi_a}{2n} \frac{\omega}{c} \quad (12)$$

owing to the finite gain bandwidth associated with $\chi_a(\omega)$, all spectral components of the pulse do not experience the same gain, a phenomenon referred to as gain dispersion [5]. Using Eq.(6), the last term in Eq.(12) will be

$$\frac{\chi_a(\omega)\omega}{2nc} = \frac{g_p}{2} \frac{1}{(\omega - \omega_a) T_2 + j} \quad (13)$$

Expanding $\chi_a(\omega)$ in a Taylor series around ω_0 , the result becomes

$$\frac{\chi_a(\omega)\omega}{2nc} = \frac{g_p}{2} \sum_{m=0}^{\infty} (-1)^m (\omega - \omega_0)^m \frac{T_2^m}{(\delta + j)^{m+1}} \quad (14)$$

where $\delta = (\omega_0 - \omega_a)T_2$ represents a detuning of the carrier frequency ω_0 of the pulse from the atomic transition frequency ω_a . Substituting Eq.(14) into (12), will give

$$\beta(\omega) = \sum_{m=0}^{\infty} \frac{(\omega - \omega_0)^m \beta_m}{m!} + \gamma |A|^2 + j \frac{\alpha}{2} + \frac{g_p}{2} \sum_{m=0}^{\infty} (-1)^m (\omega - \omega_0)^m \frac{T_2^m}{(\delta + j)^{m+1}} \quad (15)$$

For simplicity, let us also assume that the carrier frequency ω_0 of the incident pulse is matched exactly to the gain peak occurring at atomic transition frequency ω_a . So that $\delta \approx 0$ and Eq.(15) will be

$$\beta(\omega) = \sum_{m=1}^{\infty} \frac{(\omega - \omega_0)^m}{m!} \beta_m^{\text{eff}} + \gamma |A|^2 + j \left(\frac{\alpha}{2} - \frac{g_p}{2} \right) \quad (16)$$

where

$$\beta_m^{\text{eff}} = \beta_m + \frac{g_p}{2} m! j^{m-1} T_2^m, \quad m = 1, 2, 3, \dots$$

For example, the first three terms have the forms

$$\beta_1^{\text{eff}} = \beta_1 + \frac{g_p T_2}{2}, \quad \beta_2^{\text{eff}} = \beta_2 + j g_p T_2^2, \quad \beta_3^{\text{eff}} = \beta_3 - 3 T_2^3 g_p.$$

with the introduction of the preceding effective parameters, we can write the propagation equation for an EDFL by replacing the corresponding parameters in the standard NLSE, i.e. Eq.(4), with the effective ones. The resulting equation will have the form

$$\frac{\partial A}{\partial z} + \beta_1^{\text{eff}} \frac{\partial A}{\partial t} - \sum_{m=2}^{\infty} \frac{j^{m+1} \beta_m^{\text{eff}}}{m!} \frac{\partial^m A}{\partial t^m} = \left(\frac{g_p}{2} - \frac{\alpha}{2} \right) A + j \gamma |A|^2 A \quad (17)$$

Eq.(17) shows how the dispersion parameters of the host fiber change because of the dopant contribution. However, the dopant induced change in the group velocity is negligible in practice. This can be done through

the following standard Galilean transformation $T = t - \beta_1^{\text{eff}} z$. Using this assumption, one may obtain

$$\frac{\partial A}{\partial z} - j \sum_{m=2}^{\infty} \frac{j^m \beta_m^{\text{eff}}}{m!} \frac{\partial^m A}{\partial T^m} = \left(\frac{g_p}{2} - \frac{\alpha}{2} \right) A + j \gamma |A|^2 A \quad (18)$$

where the two-photon contribution was added to keep the following analysis general [4,5]. In cases in which the mathematical structure of the preceding equation is paramount, it is better to recast it in normalized units.

The NLSE permits specific solution know as soliton, we introduce soliton transformations [12]

$$\xi = \frac{z}{L_D}, \quad \tau = \frac{T}{T_0}, \quad A(\xi, \tau) = \sqrt{P_o} U(\xi, \tau) \quad (19)$$

where $L_D = T_0^2 / |\beta_2|$ is the dispersion length and T_0 is the width of the input pulse. Using these transformations. Eq.(18) will be

$$\frac{\partial U}{\partial \xi} - \sum_{m=2}^{\infty} \frac{j^{m+1} \beta_m^{\text{eff}} L_D}{m! T_o^m} \frac{\partial^m U}{\partial \tau^m} = \left(\frac{g_p}{2} - \frac{\alpha}{2} \right) L_D U + j N^2 |U|^2 U \quad (20)$$

where $N^2 = L_D \gamma P_o = L_D / L_{NL}$ is the soliton order and $L_{NL} = 1 / \gamma P_o$ is the nonlinear length and P_o is the peak power [14].

The active mode-locking fiber laser is attractive because it can offer a transform limited picosecond or subpicosecond pulse trains with very high repetition rate [15]. Active mode-locking works with a periodic phase modulation, even though this leads to chirped pulses .This technique is called FM mode-locking [16]. Optical ultra short pulse sources are the most attractive block in the photonic signal processing systems. FM mode locking can be selected because the generated pulse is shorter than that in the AM mode locking scheme [7]. In order to explain FM mode-locking, we will start with its effect on a field such that [10]

$$M(U, \xi, \tau) = j \Delta_{FM} \left[\cos[\omega_m(\tau - T_s(\xi))] \right] U(\xi, \tau) \quad (21)$$

where Δ_{FM} modulation depth and $T_s(\xi)$ accounts for any detuning between the modulator and a harmonic of the cavity's repetition rate and $\omega_m = 2\pi F_m$ is angular modulation frequency [10,7]. Active mode locking requires modulation of either the amplitude or the phase of the intra cavity optical field at a frequency F_m equal to (or a multiple of) the mode spacing $\Delta\nu$ [4]. From the relation $F_m = 1/T_m$ where is T_m the round trip time, it is clear that to produce pulses much shorter than the round trip time the laser needs to oscillate at quite a few longitudinal modes simultaneously [14]. The pulse width, τ_{pulse} is approximated by T_m/M ; where, M is the total number of phase locked modes. In a real mode-locked laser, the actual pulse width depends on other factors, such as the pulse shape and the overall dispersion of the cavity [17]. Using Eq.(21) into (20), yields

$$\frac{\partial U}{\partial \xi} - \sum_{m=2}^{\infty} \frac{j^{m+1} \beta_m^{eff} L_D}{m! T_o^m} \frac{\partial^m U}{\partial \tau^m} = \left(\frac{g_p}{2} - \frac{\alpha}{2} \right) L_D U + j N^2 |U|^2 U + j \Delta_{FM} \cos \omega_m \tau U \quad (22)$$

3. Results and Discussion

The propagation of optical pulses in optical fiber is described using Eq.(4). The addition of dopant to fiber core will be modified this equation to the formula in Eq.(22), which includes the effects of dispersion and nonlinearity and the output gain coefficient due to the presence of dopant. Accordingly, using a piece of optical fiber and forming the resonator lead to solve this equation and the description laser

output. The optical pumping process is performed by a strong other pulse that is called the pump. It's effects are presented by the impact factor g_p . After that, the introducing of the mode locking concept using frequency modulation technique to get a train of short pulses that repeat according to the period of time that is inversely proportional to the frequency F_m .

Solving Eq.(22) with presence of mode locking term requires using of the split-step Fourier method (SSFM) that depends on creating a grids of frequency and of time to deal with the pulses spectrally and temporally. Accuracy of these grids control the results clearly. This equation is solved by dividing the space of length also into small sections Δz . The amount of Δz should be chosen to maximize the results and minimize the truncation and turning errors.

To solve the equation on the resonator, it means resolved back and forth using the same division Δz so that we can reach the required RT. This means that the equation will be solved thousands of times using the step Δz on the resonator length L . Accordingly, the calculations require too much time every time up to more than 6 hours. This effect prevents us from using larger numbers of RT. To emphasize here that this may cause an increase in the truncation and turning errors.

Table (1) illustrates the values of coefficients used in the operation, which will consider as constant through all shapes resulting figures unless otherwise indicated.

Table (1) : Simulation parameters [17,16].

Symbol Paramete r	Value	Symbol Paramete r	Value
γ	0.0012 $1/w.m$	β_2	$-1.4 \times 10^{-26} s^2/m$

g_0	0.8 $1/m$	β_3	$30 \times 10^{-41} s^3/m$
E_s	1 nJ	α	0.21/m
T_2	50ns	λ_c	1550 nm
T_0	100 ps	L	4 m
Δ_{FM}	0.4	R_{HR}	0.99
F_m	20 MHz	R_{OC}	0.5
$T_s(\xi)$	0		

Fig.(1) represents a pulse shape using different numbers of RT. It is evident from the figure that the input pulse is such that will be faced to the deformation once its movement inside the resonator due to the generated stimulated radiation and presence the mode locking. With increasing RT the pulse begins deform, then make lobes and breaking to form a stream of ultrashort pulses. The energies of these pulses begin to oscillation with the increase in RT until it reaches the stabilization case. On the other hand, the distance between these short pulses also be oscillatory until to lock on the distance $T_m = 1/F_m$. However continue to move through the resonator after a short time, we will get a stream of regular pulses with the same energy and the time interval between them.

Fig.(2) represents stream of generated pulses for several cases of F_m R and a number of RT. It is clear that increasing RT leads to breaking the pulse to a train of pulses, the power of these pulses and the interval between them tend to stability with increase RT. With increased R we note confusion incidence in the behavior of the resulted stream, and this is attributable to increasing the percentage of the reflected pulses energy inside the resonator. The fact that $R = 50\%$ makes high regularity

of pulses by interval F_m . With increased R , its regularity becomes disturbed and the pulses are generated outside this interval of time and therefore, the power output will be less. From the other hand the generated pulses will be shifted increasingly with a decrease of F_m and therefore, it means the difficulty in obtaining steady stream at small F_m only after a large number of RT. The opposite happens at large F_m . The small values F_m has caused irregular stream of pulses that represents existence of pulses outside the intervals of the relationship $T_m = 1/F_m$. This irregular can be removed with increased RT and reduce R to the limits of 50%. Therefore the irregular output at small RT that is well-known in the laser subject is linked to both the RT and R and the frequency of mode locking technique. These three factors are essential control in the work of the laser to generate the required pulses.

Fig.(3) represents a stream of generated pulses with RT and different F_m . It is evident from the figure that the breaking rate with increases of F_m and tendency to stabilization of stream pulses with increased RT. For certain value of the RT, we note that the stream is not symmetrical but rather varies by value of F_m . The difference is the lack of stability of the stream and separated time the intervals. Where we see that the stream at $F_m = 25\text{MHz}$ stabilizes at $\text{RT} = 500$, whereas the frequency $F_m = 20\text{MHz}$ causes the partial stability of for the stream at $\text{RT} = 1000$ and less than that for the least frequencies. In the stream summary the Fig.(2) and (3) the possibility to controlling pulses generated by identifying each of the F_m and RT and the reflectivity with the steadying of all the other operators factors. Each pulse, generated in a

resonator will cause a stream of the pulses within the limits of the original pulse (ps). After a short period of time, a steady and stable stream of the ultrashort (fs) pulses will generate.

Fig.(4) represents a form of ultrashort pulses, which are generated at the center of the initial input pulse at the times $T_m = \pm n/F_m$ where $n = 0, \pm 1, \pm 2, \pm 3, \pm 4$. The upper left corner represents the case $n = -4$ and lower right represents the case $n = 4$ respectively. All the blue lines represent the shape of the pulses at different RT until it reaches the final step using $RT = 250$. It is clear that the generated pulses change in shape and power with increase of RT and whenever the greater RT, the value tends to stability. Note that, the pulse center will be at $(200, \dots, 150-, 200-)$ ps and this refers to position of the pulse a related of to the center of initial proposed pulse. The pulses and by its proximity to the initial pulse center position will begin to emergence faster than the distant pulses, but with increase RT all that tends to stability, in particular using an appropriate values for R and RT.

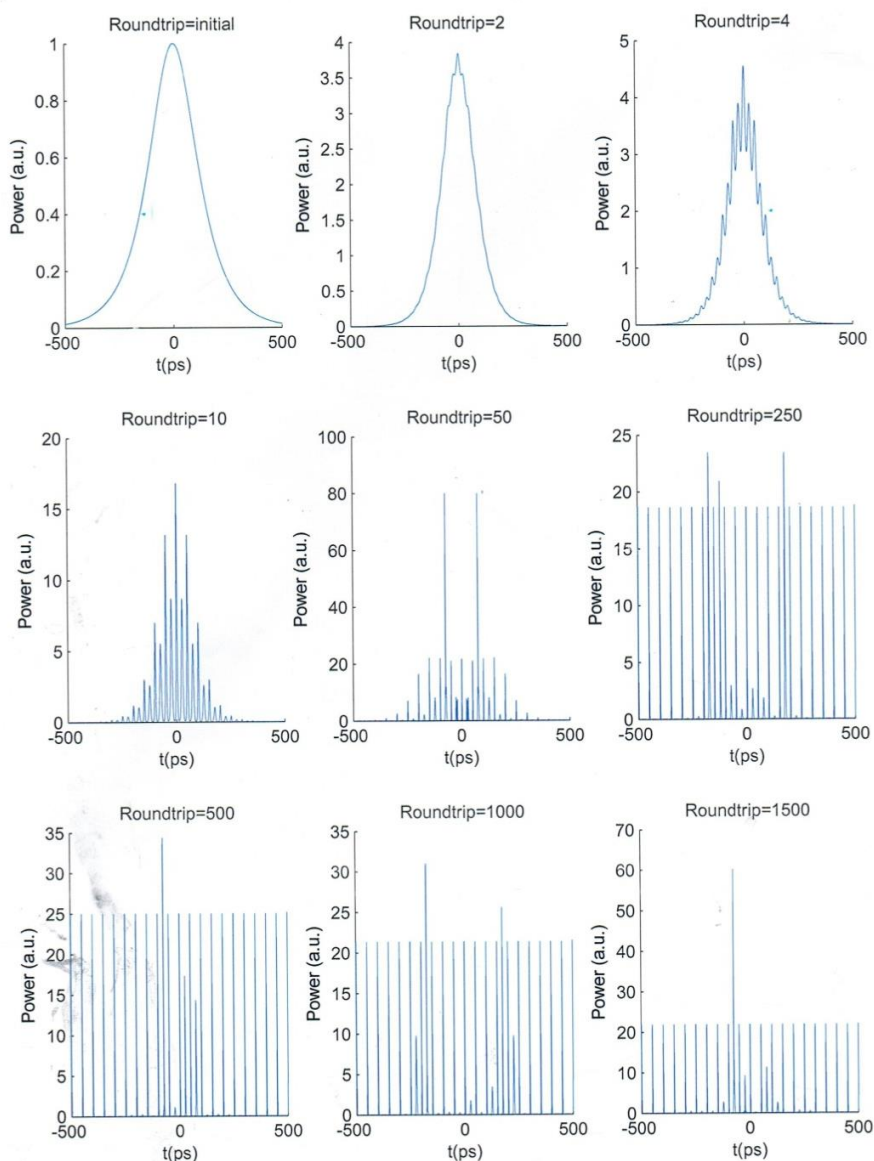


Fig.(1): The evolution of pulse with roundtrip, where pulse is segmentation into many ultrashort roundtrip pulses with a time interval $T_m = 1/F_m$. Here $F_m = 20\text{MHz}$.

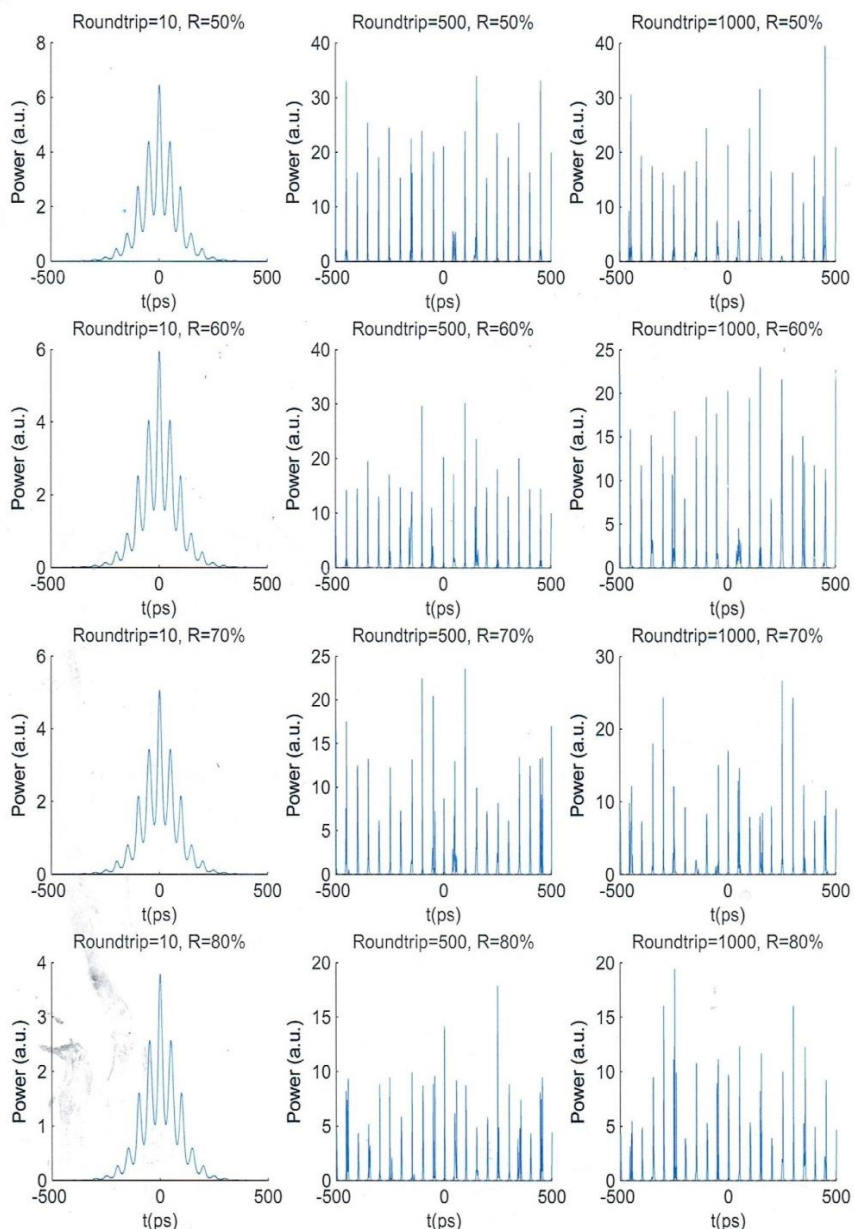
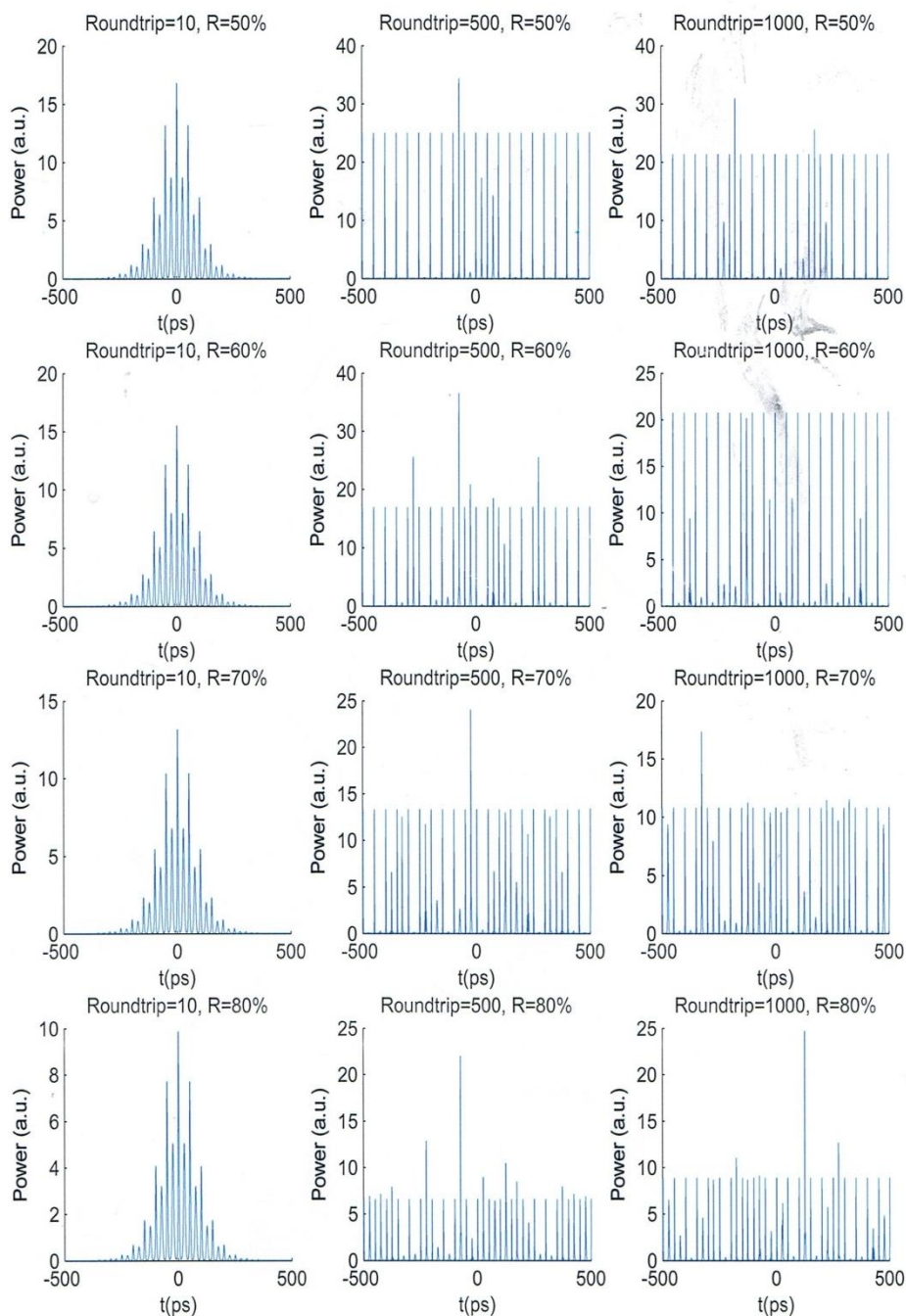
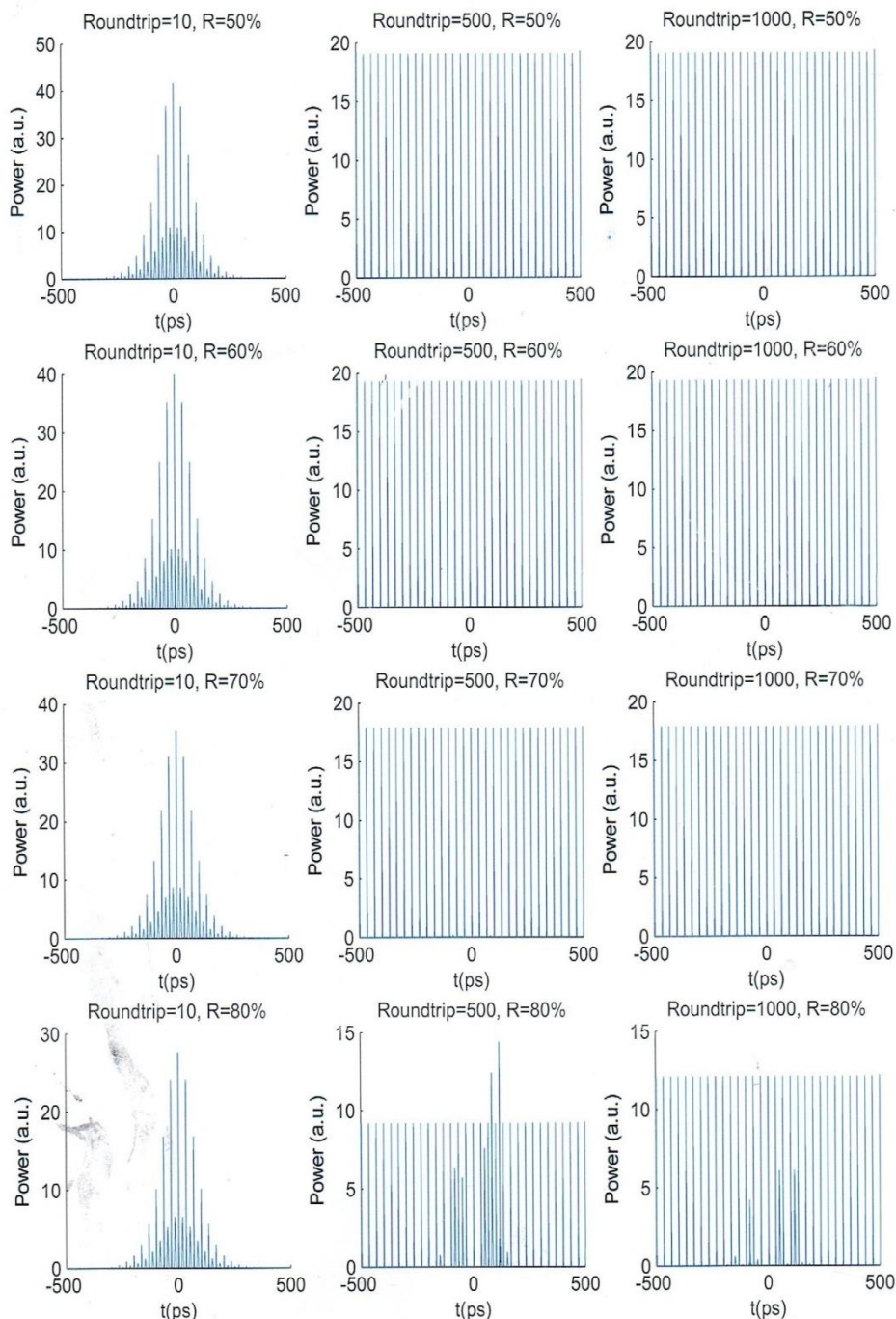


Fig.(2): The segmentation process into ultrashort roundtrip pulses for different values of roundtrip and R where
a) $F_m = 10\text{MHz}$, b) $F_m = 20\text{MHz}$ and c) $F_m = 30\text{MHz}$.



To be continued



To be continued

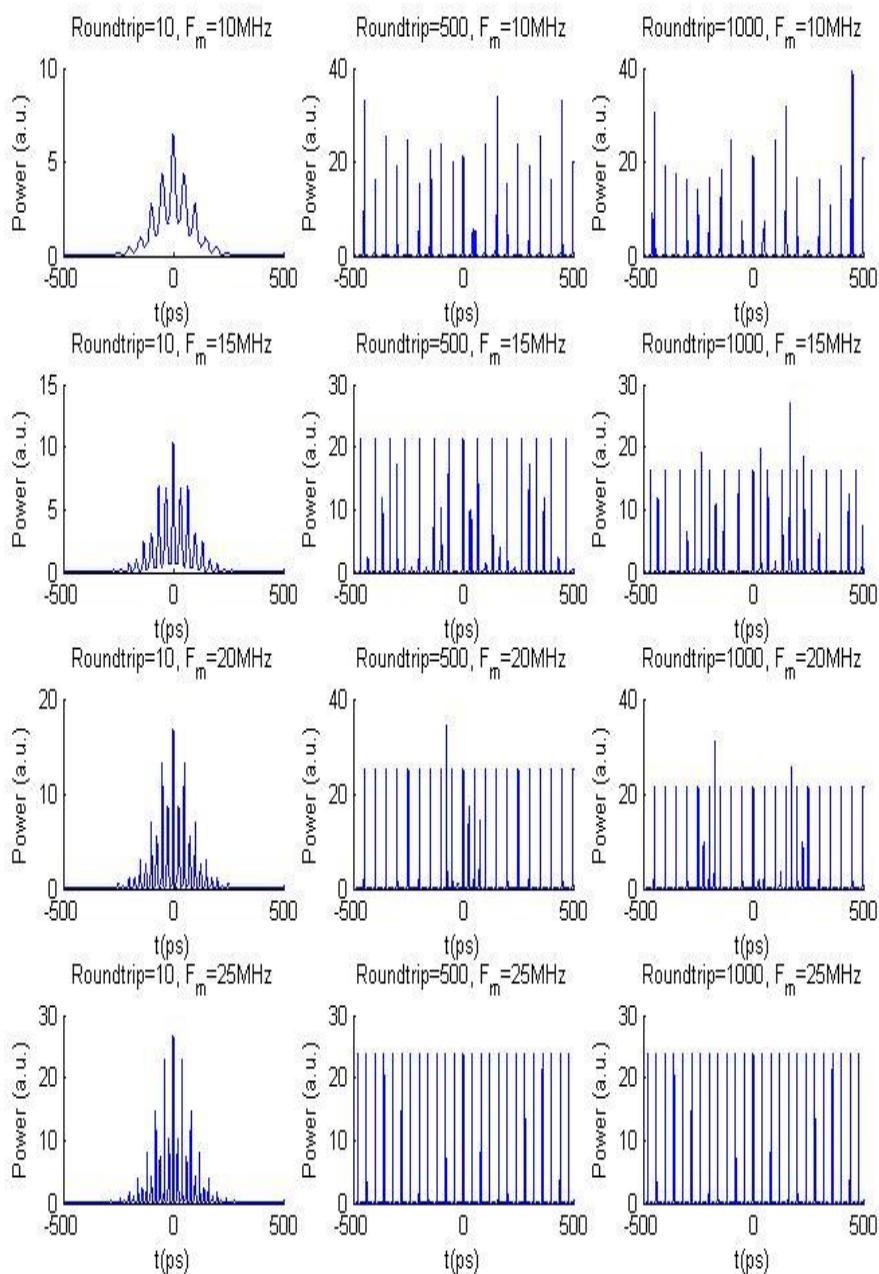


Fig.(3):The segmented process into ultrashort roundtrip pulses
for different values of F_m and roundtrip using $R = 50\%$.

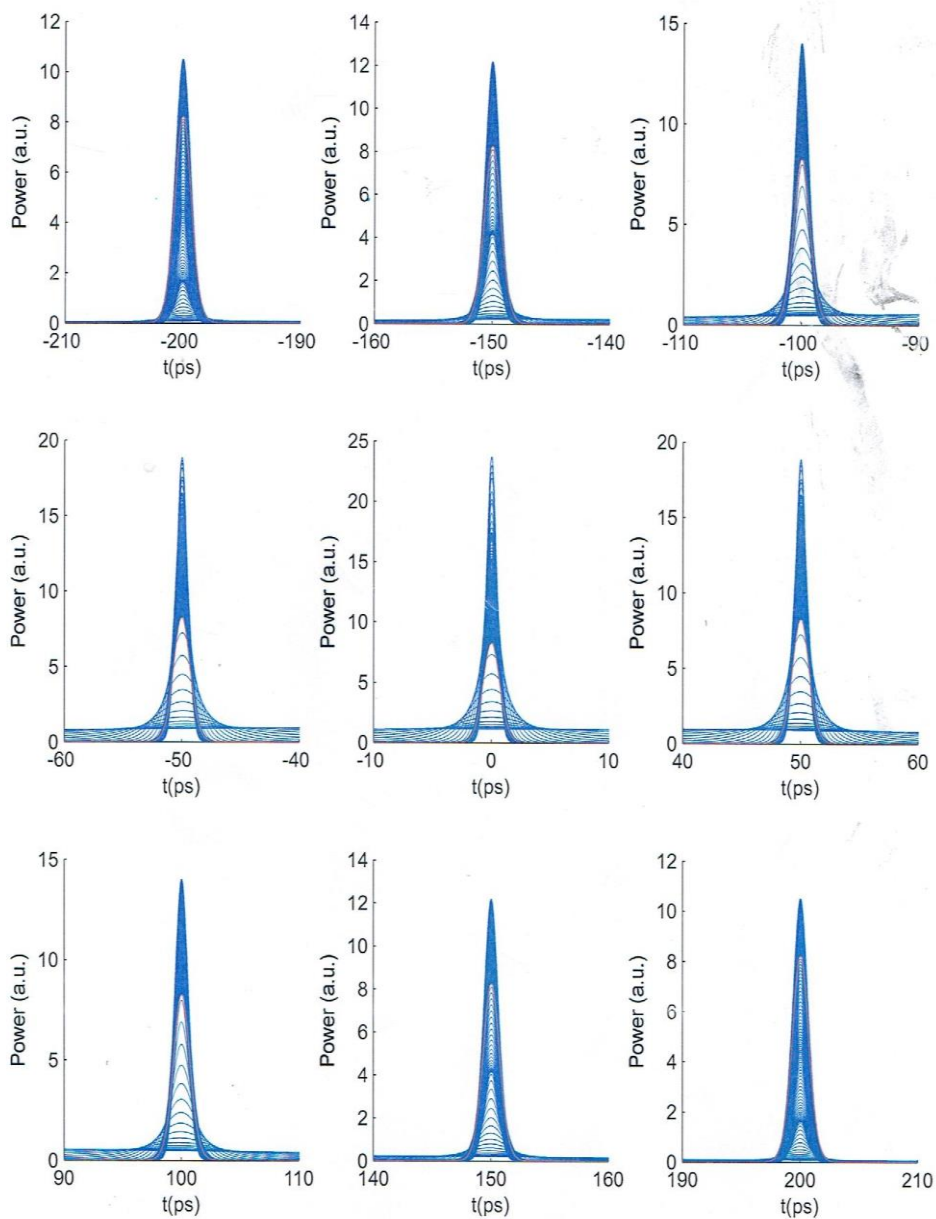


Fig.(4): The ultrashort roundtrip pulses that generate at the positions $0, \pm 50, \pm 100, \pm 150, \pm 200 \text{ ps}$ for many roundtrip, where the red line represents the final result.

4. Conclusion

In conclusion, the stream of ultrashort pulses is affected by R , RT and F_m , when the largest F_m will require the smallest RT . The pump power will affect the gain g_0 , so the resulted stream is much affected by the pump power. The presence of β_2 may be altered by the behavior of resulted power and energy. The other parameters β_3 , T_0 , T_2 and Δ_{FM} do not explain an important features on the resulted ultrashort pulses in terms of pulse duration and pulse energy.

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الخلاصة

في هذا البحث , تم ادخال جميع التأثيرات مثل : التشتت , اللاخطية , عامل الربح المرتبط بنبضة الضخ , التوهين وغيرها في استنتاج المعادلة العامة للانتشار في الليف البصري خلال مرنان الليزر. بالإضافة لذلك تم ادخال تأثير عملية اقفال النمط باستخدام تضمين التردد بغية الحصول على سيل نبضات فائقة القصر.

باختيار مناسب لتردد التضمين فأن سيل النبضات المتحقق يمكن ان يصل الى مرحلة الاستقرار وفق عدد معين من رحلات الذهاب – العودة (RT) , حيث ان التردد الاعلى يرافقه عدد اقل من (RT) . من جانب اخر , فان زيادة R تؤثر سلباً على سيل النبضات الناتج. ان الفاصلة الزمنية بين النبضات الناتجة تتناسب عكسياً مع تردد التضمين. سيل النبضات يمكن ان يكون مستقر في الطاقة وعرض النبضة مع (RT) مناسبة. زيادة العامل β_2 تسهم في استقرار طاقة النبضات في حين ان β_3 لم يظهر اي تأثيرات. تأثير طاقة الضخ المتمثلة بالعامل g_0 بينت

ان الطاقة الناتجة تزداد مع زيادة هذا العامل. عرض النبضة الاولي T_0 والعامل T_2 وعمق التضمين تتمثل تأثيراتها بتغيير اسلوب التذبذب لعوامل النبضات الناتجة.