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MECHANISM OF CENTRAL WAVELENGTH TUNING OF THE SOLITONS FORMED IN A PMFL WHEN VARYING THE TOTAL ATTENUATION IN THE CAVITY OR WHEN CHANGING THE PUMP POWER

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Pe baza observațiilor experimentale raportăm varierea lungimii de undă centrală cu până la 18 nm a solitonului fundamental obținut intr-un PMFL (laser pe fibra optică cu un cuplaj pasiv al modurilor), la simpla aplicare a unei atenuări suplimentare într-o anumită poziție în cavitatea laser, sau prin varierea puterii de pompaj. Depinzând de configurația cavității şi de setarea polarizației în cavitate, efectul variației lungimii de undă centrale este în stransă corelație cu stabilitatea solitonică. In aceeasi configurație a cavității laser se pot observa două spectre solitonice în acelasi timp, unul la 1544 nm şi altul la 1557 nm, existența lor fiind posibilă pentru anumite setari ale polarizației şi pentru un interval ingust al puterii de pompaj. Totodată, am dedus pe baza rezultatelor experimentale că dependența stabilității solitonice de lungimea de undă este corelată cu lungimile de undă favorabile formării solitonilor stabili, astfel spectrul dual discutat mai sus se formează la aceleaşi lungimi de undă la care stabilitatea solitonică prezintă maxime.

We report on the experimental observation a central wavelength tuning with up to 18 nm of the fundamental soliton in a passively mode-locked fiber ring laser (PMFL) when applying an extra attenuation in a certain position in the laser cavity, or by varying the pump power. Depending on the cavity configuration and the polarization setting the effect of central wavelength tuning is tightly correlated to solitonic stability. In the same configuration of the laser cavity two solitonic spectra can be observed in the same time, one at 1544 nm and the other at 1557 nm, their existence being possible for certain polarization settings and for a narrow range of the pump power. In the same time we obtained experimentally that the dependence of the solitonic stability on the wavelength is correlated to the wavelength favorable to the solitonic state formation, thus the dual solitonic spectrum discussed above is formed at the wavelengths for which the soliton has maximum stability.

Key words: solitons, passively mode-locked soliton fiber laser

Acronyms used: EDFA - Erbium Doped Fiber Amplifier
SESAM- SEmiconductor Saturable Absorber Mirror

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1. Introduction

Solitary wave generation is a generic property of many nonlinear dynamic systems and has been widely investigated [1-3]. Optical solitons, due to their theoretical importance and potential practical applications in optical communication and signal processing systems, have attracted special attention [4-7].

Optical solitons have also been observed in the passively mode-locked fiber lasers [8-10], where all cavity components, such as the gain medium, the output coupler, the saturable absorber, and the type of fiber used for their connection, affects the detailed dynamics of the formed solitons. Various passive mode-locking techniques, such as the nonlinear loop mirror method [11,12], the nonlinear polarization rotation (NPR) technique [13-15] and the semiconductor saturable absorber method [16,17], have been used to generate ultra-short pulses.

Independent of the concrete mode-locking techniques it was found that the soliton operation of all lasers exhibited a common feature, namely, under strong pumping power multiple-soliton pulses are always generated in the laser cavity, and in the steady state all the solitons have exactly the same pulse properties: the same pulse energy and pulse width when they are far apart. The latter property of the solitons was called the soliton energy quantization effect [18].

In a cavity where the nonlinear polarization rotation technique was used to mode-lock the laser, it was shown experimentally that by simple adjustment of the polarization controllers of the laser, the central wavelength of the mode-locked pulses can be continuously tuned. A tuning range of up to 6 nm can be achieved at 1550 nm. The tuning ability and the existence of two discrete tuning ranges are found to be results of the combined effect of the polarizer and the cavity's birefringence. The combination of a polarizer and the cavity birefringence forms a linear periodic-wavelength filter [19].

In this article we report, on behalf of the experimental observations, the possibility of continuous variation of the central wavelength of the solitons by a simple adjustment of the pumping power or by introducing an extra attenuation in the passively mode-locked laser cavity. We also show that the wavelengths for which solitons can be directly generated are connected to the characteristic of the soliton stability described with the aid of a band-pass filter of 10 nm wide, accordable on the whole range of wavelengths of the amplifier.

2. Experimental setup

The fiber laser in EFSSpP (**E**DFA, **F**ilter, **S**ESAM, **Sp**litter and **P**olarization Control) configuration used in our experiment is schematically shown in Fig. 1. For the first part of the experiment, the band-pass filter is removed and thus the signal amplified by the erbium doped fiber amplifier (EDFA) enters into the circulator to be directed towards the semiconductor saturable absorber mirror (SESAM).

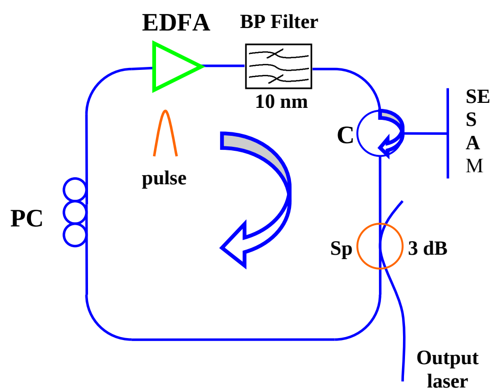

Fig. 1. Schematic of PMFL, EFSSpP configuration.
SESAM – Saturable Absorber Mirror, PC – Polarization Controller, C – Circulator

In this experiment we used a semiconductor saturable absorber mirror of the GaInNAs type to mode-lock the laser. This type of SESAM is grown by molecular beam epitaxy under molecular beam and contains 30 alternating layers of GaAs/AlAs with the purpose of realizing a GaAs/AlAs distributed Bragg reflector and a 70 Å thick $Ga_{0.64}In_{0.36}N_{0.04}As_{0.96}$ layer, quantum well positioned at an antinode of the electromagnetic field standing wave. A quarter-wavelength-thick GaAs layer is deposited on top of the quantum well to ensure that the structure is anti-resonant, thus increasing its optical bandwidth. The measurements indicated a reflectance modulation of 0.6 %, when the pulse fluency was varied from low to high values, and a saturation fluency of about 40 μJ/ cm^2[20].

At the SESAM level, the pulse suffers attenuation by reflection dependent on the incident power, thus its components of high power are attenuated more than the components of low power. After this, the signal returns into the circulator, taking the opposite direction to the entering one, more exactly towards the output coupler (Sp).

Half power of the signal is directed to the exterior, while the other half returns into the cavity. This 50% of the output power is increased and in many cases determines an imperfect coupling of the oscillation modes, visualized by the instability of spectrum. At the polarization controller level the polarization direction of the cavity can be modified in order to obtain a stable state with optimum properties. Finally, the signal reenters the erbium doped amplifier, following the same path in a cyclic way.

3. Experimental results

For relative small pump powers (10mW), the solitonic spectrum associated to the fundamental pulse looks as in Fig. 2, the red characteristic, the central wavelength being somewhere around 1556 nm. Increasing the pump power in the cavity, more solitons are created and the solitonic spectrum moves to the right towards bigger wavelengths, around 1562 nm, as it can be seen in Fig.2, the blue characteristic. Watching the sidebands with symmetric wavelengths with respect to the central ones we can notice an asymmetry and a difference between the two characteristics.

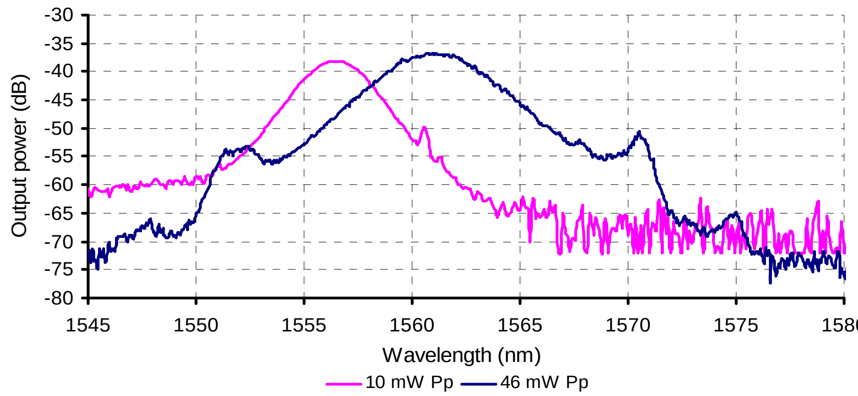

Fig. 2. Optical spectrum in PMFL, ESSpP configuration for 10 mW, respectively 46 mW optical pumping power,
ESSpP configuration – a configuration containing **E**DFA, **S**ESAM, **Sp**litter, **P**C.

An important property of the solitons is their forming and moving towards the wavelength for which the cavity has maximum gain. This happens because in the fight for existence between the photons of different wavelengths, the ones with wavelengths closer to the one corresponding to the maximum gain of the cavity have bigger chances to maintain themselves in the cavity, being regenerated faster than the attenuations suffered along the cavity. Thus, the maximum soliton power will correspond to a wavelength close to the one associated to the maximum density of photons.

In experiments conducted in this paper we used an amplifier whose active wavelength is of 2 m, the concentration of erbium in the doped fiber being low. The amplifier is pumped by a semiconductor laser of 980 nm wavelength and maximum power around 110 mW.

The total gain is then defined as follows:

$$G = \frac{P_{s,out}}{P_{s,in}}, \quad (1)$$

where $P_{s,in}$, respectively $P_{s,out}$ are the input, respectively output powers.

Gain saturation of the erbium doped amplifier is a common feature within laser and amplifier systems, which can be interpreted as a gain decrease with increasing signal power. This is due to the fact that more signal photons are required for gain when the signal increases. Obviously, the gain saturation can appear sooner or later with respect to the distance traveled by the signal inside the erbium doped fiber.

If we consider that the erbium doped fiber spans along the z axis and it is homogenous, having a gain coefficient denoted with g_0 and constant on all the length L, the total gain of an amplifier of length L is given by equation (2) [21], if no area of the fiber enters into saturation.

$$G = \exp\left(\int_0^L g_0 dz\right) = \exp(g_0 L)\ . \qquad (2)$$

For choosing a frequency of the useful signal close to the atomic transition frequency, the dependence of the gain coefficient on the incident power can be written as in equation (3) [21]

$$g = \frac{g_0}{1 + \frac{P}{P_s}}, \qquad (3)$$

where P is the signal power and P_s is the saturation power.
Therewith, the amplifier gain depends also on the wavelength of the input signal.

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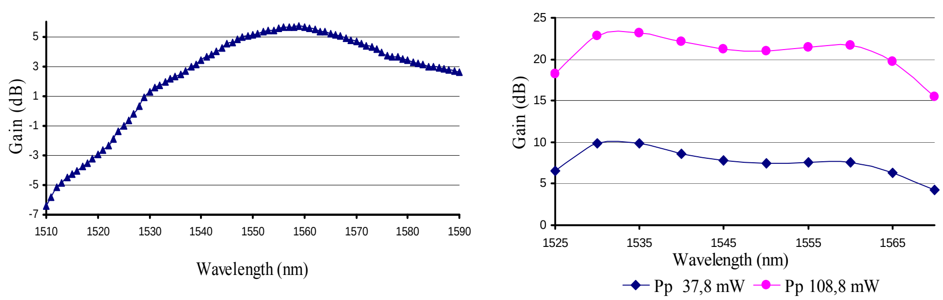
In Fig. 3 it is shown the dependence of the total gain of the amplifier with respect to the wavelength of the input power for constant input power.



(a) (b)

Fig.3. EDFA gain depending on wavelength for 1 dBm input power and 49,6 mW pumping power (a), and -30 dBm input power and 37,8 respectively 108,8 mW pumping power (b).

The gain characteristic for the amplifier is illustrated in Fig.3, where we can observe a difference of the optical gain with respect to the wavelength and the pump power. In case (a) the input power is quite high and thus the amplifier is almost saturated, while in case (b) the input power is low and thus the amplifier does not get into saturation. We can observe that the maxima of gain vary from one case to the other: for (a) the maximum being around 1560 nm, while for (b) around 1532 nm.

We define the tipping effect of the gain characteristic of the amplifier as the change of the maximum optical gain at high input powers or high pump powers. By simply varying the input power in the amplifier and not modifying the pump power, the maximum gain can move from one wavelength to another. This change in the gain characteristic of the amplifier is sensed by the solitons through changing the central wavelength.

In the case of this amplifier the change takes place between 1532 nm and 1557 nm and when the output power of the amplifier exceeds a certain threshold. At its turn, the output power of the amplifier depends on the pump power and the input power. The solitonic state is influenced by the angle made by the tangent to the gain characteristic in the point of central wavelength and the horizontal axis.

A variation of the wavelength with 6 nm has been observed by the simple growing of the pump power from 10 mW to 46 mW as it can be seen in Fig. 2. The effect of wavelength variation with respect to the pump power has been observed indifferent to the presence in the cavity of a single soliton or more. For certain settings of the PC at the same pump power we can obtain one soliton or more. It was experimentally observed that for the same polarization direction in the cavity, the central wavelength measured either for one soliton or for two is the same. This proves that the changing of the wavelength property has to do with the amplifier and not with the intensity or other features of the pulse.

For the cavity configuration in Fig.1, without band-pass filter, it was observed the existence of a dual solitonic spectrum, as we show in Fig. 4, for certain settings of the polarization direction and a certain pump power.

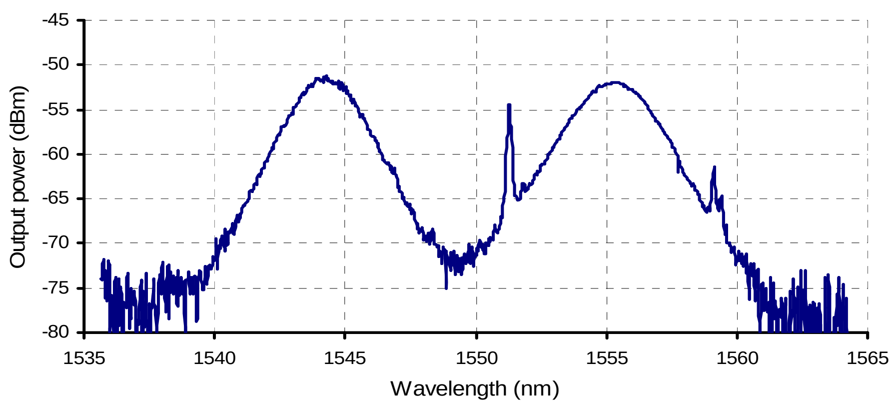


Fig.4. Dual optical spectrum of the PMFL, ESSpP configuration at 34.4 mW optical pump power,

For the same configuration of the laser cavity, if we insert a bandpass filter exactly after the amplifier (as in Fig. 1), we can draw the stability plot, for different wavelengths, for pump powers corresponding to the important points in the functioning of the laser. The four important powers are: the minimum power for which the fundamental pulse still exists in the cavity ($P_{min,las}$), the minimum power for which the laser is self-starting when starting the pump ($P_{min,stab}$), the maximum power for which the laser is self-starting when starting the pump power ($P_{max,stab}$), and the maximum power for which it is still possible to maintain the fundamental solitonic state in the cavity ($P_{max,las}$). With respect to these four pump powers, stability can be computed with the help of equation (4).

$$S = \frac{200\left(P_{\max,stab} - P_{\min,stab}\right)}{\frac{P_{\max,stab} + P_{\min,stab}}{2} + \left(P_{\min,stab} - P_{\min,las}\right) + \left(P_{\max,las} - P_{\max,stab}\right)} \quad (4)$$

The characteristic of the stability of the fundamental pulse with respect to the wavelength for EFSSpP configuration is presented in Fig. 5.

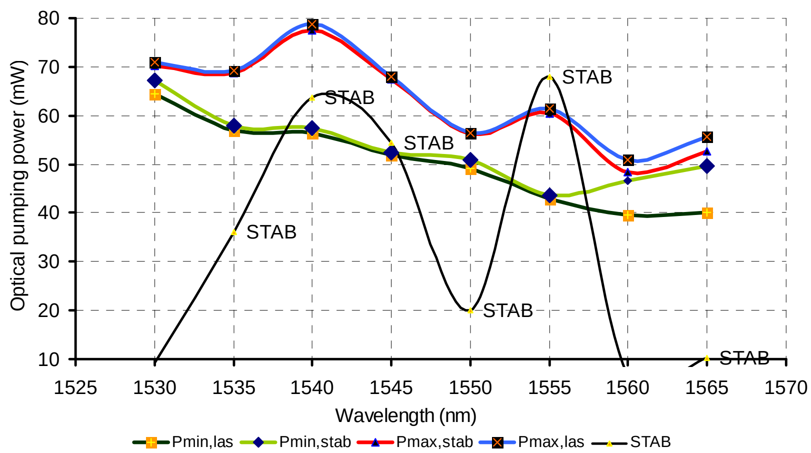


Fig. 5. The dependence of the PMFL stability - EFSSpP configuration on the central wavelength of the fundamental pulse in the range of 1530-1565 nm.

For drawing the characteristic in Fig. 5, the polarization direction was optimized in all measurements. It was noticed that for many of the inferior points of the plot (***$P_{min,las}$*** and ***$P_{min,stab}$***) the optimum polarization direction, set with the aid of PC, is the same. This denotes an increased stability of this particular configuration of the laser cavity. The same conclusion is drawn from the fact that the difference between the two pumping powers (***$P_{min,las}$*** and ***$P_{min,stab}$***) is relatively small. The existence of the dual solitonic spectrum shown in Fig. 4, requests the existence of an optimum and stable cavity, inside which the reflections should be minimized and the birefringence small.

The characteristic of the stability changes if we insert an extra attenuation in the laser cavity. The four power levels being influenced differently, besides changing the power ratio between the two local maxima of the stability plot, there can also appear variations of the central wavelengths. The extra attenuation in the cavity laser determines a growth of the minimum power for which the fundamental pulse self-starts ($P_{min,stab}$). In most cases the minimum power for which there still exists a pulse in the cavity (Pmin,las) is not influenced in the same way as the level of minimum power for which the fundamental pulse self-starts, because the power of pulse is correlated with the saturation fluency of the absorber. Inserting this extra attenuation causes frequently an instability of the solitonic spectrum, fact that also results from the increased difference between the $P_{min,las}$ and $P_{min,stab}$ characteristics. In Fig. 6 it is presented the case in which an extra attenuation (of 1-2 dB) is introduced before the EDFA, the configuration of the cavity remaining unchanged (EFSSpP).

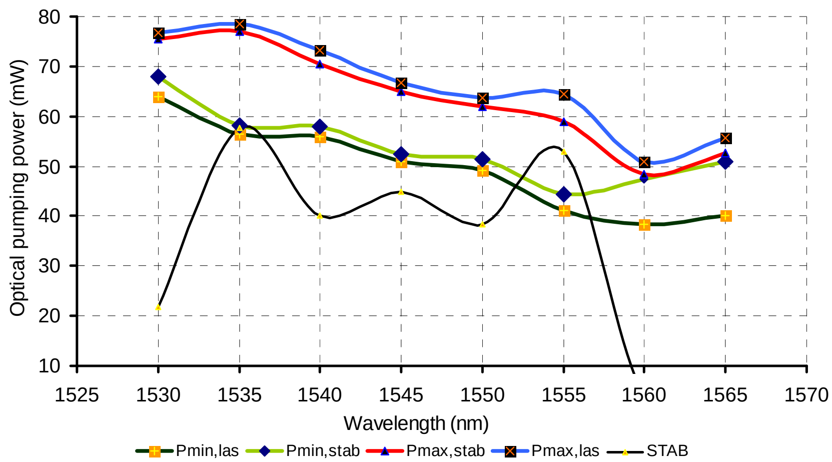


Fig. 6. The dependence of the PMFL stability - EFSSpP configuration on the central wavelength of the fundamental pulse in the range of 1530-1565 nm, a loss of 1-2 dB being intentionally inserted before EDFA.

It can be noticed that the wavelength with the maximum stability moves towards 1532 nm, where the gain of the amplifier takes the maximum value. This happens because the input power decreases due to the attenuation introduced before the EDFA and thus, even if the pumping power is relatively increased, the amplifier is not saturated.

3. Conclusions

The solitons existence is a phenomenon very complex in the fiber laser due to multiple effects that appear. After the existence of the hysteresis of the pumping power was experimentally proved, the existence of more types of hysteresis can be detected. The way in which every element in the cavity interacts with the optical signals and the weight of the forces that determine the mode-coupling is difficult to explain entirely, many of the effects observed in the cavity being still at the level of assumption.

The main conclusion resulted from the analysis of various experiments on PMFL is that the equilibrium between the gain characteristic of the amplifier and the optimum of the solitonic spectrum is the one that generates the multiple effects over the stability, the pulse performances and its characteristics. The change in wavelength of the fundamental soliton with up to 18 nm, by simply varying the attenuation, is possible due to the existence of two areas of high solitonic stability, separated by a barrier well defined in the range of the amplifier's gain.

The stability characteristic was plotted with the aid of a band-pass filter of 10 nm wide, continuously accordable in the amplifier's wavelength range. For certain configurations of the laser cavity, according to the stability characteristic drawn by varying the central wavelength, we can remark the appearance of a dual spectrum centered on 1544 nm and 1557 nm. Its existence is according to the stability plot obtained by varying the wavelengths with the aid of a band-pass filter continuously accordable. Therewith, another property of the solitons created in PMFL is proved experimentally, their formation in the points of maximum stability. These properties are extremely important in the construction of sources of ultra-short pulses with high repetition and optimization rate.

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