CONVERSION OF ULTRASHORT OPTICAL SOLITONS IN THE FIBRE-OPTICAL LOOP

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1. INTRODUCTION

Different types of the fibre-optical elements have been proposed and designed recently for ultra-short pulses selfswitching and ultra-fast all-optical light control. One of such constructions is so-called fibre-optical loop mirror [1] - all-fibre Sagnac interferometer based on the single-mode directional coupler with two output ports linked by long (in comparison with coupler length) single-mode fibre. In this device some effects were observed: self-switching of the ultra-short pulses in the soliton [2] and non-soliton [3] regimes of propagation; pulse shaping [4] and cross-switching [5] in the non-soliton regime.

But actually fundamental solitons (with energy and duration connected by fixed relation) haven't been described in the fibre-optical loop. Other authors varied energy of the pulses at the input of the loop without changing of the pulse duration. Here some possibilities of the conversion of the fundamental soliton in the fibre-optical loop are demonstrated: fundamental soliton selfswitching, its filtration from the background, and ultrashort pulse generation from the CW radiation due to cross-phase modulation (XPM) of this radiation by the fundamental soliton in the loop.

2. LOOP CHARACTERIZATION

Fiber-optical loop is the two-beam interferometer, in which radiation passes through the coupler then, after splitting, propagates along opposing directions in the loop fibre and at last returns back to the coupler and interferes there. One part of the radiation passes to the output of the loop the other comes back to the input fibre. The main advantage of this configuration is the separation of the process of the nonlinear interaction in the long optical fibre from the interference in the short single-mode directional coupler. It gives a lot of possibilities for varying of the working characteristics of the elements in the wide region.

After the travelling around the loop the radiations have the phase shift consisted of two parts. One part - the common linear phase shift, the same for both radiations because their optical paths are the same. The other - nonreciprocal phase shift which could exist due to the nonlinearity. One could take into account only the phase difference $\delta\varphi$ and receive the normalized transmittivity of the loop [6]:

$$\beta = \beta_0 + (1-\beta_0)\cdot SIN^2(\delta\varphi/2) \qquad (1)$$

Where $\beta_0 = (2\alpha-1)^2$ - transmittivity of the loop when one could neglect the phase difference $\delta\varphi$, α - the coupling coefficient of the coupler.

As it follows from equation (1), loop transmittivity takes on a maximal value $\beta_{max} = 1$ when $\delta\varphi = (2m+1)\cdot\pi$, and minimal $\beta_{min} = \beta_0$ when $\delta\varphi = 2m\pi$, where $m = 0, \pm1, ...$; and switching between these values is possible under varying of $\delta\varphi$.

This analysis is valid for short squared pulses with constant amplitude. For the real bell-like pulses, transmittivity varies along pulse due to varying of the $\delta\varphi$, and pulse could be broken-up or not switched fully [4]. Since optical solitons [7] are the most convenient carrier of the information in such devices due to their quasi particle propagation with constant phase along whole pulse, which makes high contrast and avoidance of the pulse break-up under switching.

Soliton passage through the loop we have described in detail in [6]. Here we concentrate our consideration on soliton filtration from the background.

There are two possibilities for the arising of the phase difference $\delta\varphi$ in the loop due to nonlinearity. The first - self-phase modulation of the nonequaled parts of the pulse propagating in the opposite direction, and the second - different phase shift of the equal counter propagated parts of the CW or quasi-CW radiation due to XPM from co propagated nonequal parts of the short pulse. Consequently at first we will discuss single soliton passage and self-switching in loop and then soliton interaction with CW or quasi CW radiation at the different wavelengths.

3.SOLITON PASSAGE THROUGH THE LOOP

Let's suppose that soliton amplitude at the input port of the coupler is described by the expression: $q_0(\tau)=SECH(\tau)$ where $\tau = t/\tau_0$ - normalized on the soliton duration τ_0 time t. After the coupler and sufficiently long fiber (L - fiber length is much greater than dispersive length of the initial soliton $L_d = \tau_0^2/(\partial^2 k/\partial\omega^2)$) the new perturbed soliton with the formfactor $\varkappa_1 = (2\sqrt{\alpha}-1)$ is formed [8]:

$$q(\tau) = \varkappa_1 \cdot SECH(\varkappa_1\tau)\cdot EXP(i\varkappa_1^2\xi/2), \tag{2}$$

where $\xi = L/L_d$. This expression is valid only if $\alpha>0.25$ ($\varkappa_1>0$), otherwise the soliton is not formed and the waveform is dispersed.

As one could see, two different cases are possible. The first: $\alpha > 0.75$ or $\alpha < 0.25$ when only one soliton is formed in the loop. And the second: $0.25 < \alpha < 0.75$ when two counterpropagating solitons are formed and switching take place.Consequently we'll consider this two different cases separately.

3.1.Soliton filtering from the background ($\alpha > 0.75$)

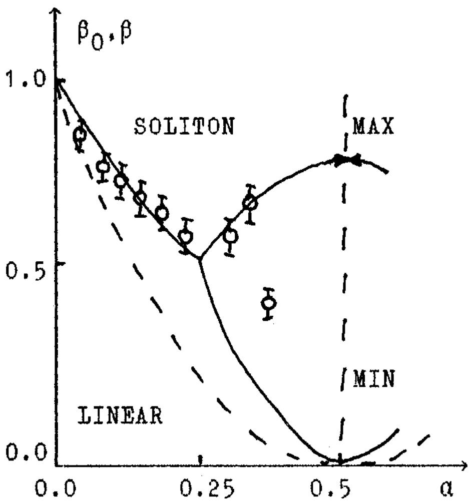
In this case the soliton forms, after the coupler, another perturbed soliton, propagating only in one direction in the loop and switching is not the case. At the loop output, immediately after the coupler, the pulse is formed: $q'(\tau) = \varkappa_1 \cdot \sqrt{\alpha} \cdot SECH(\varkappa_1\tau)$. Then, after sufficiently long fibre, the soliton $q(\tau)$ with formfactor $\varkappa=(2\sqrt{\alpha}-1)^2$ is formed. The duration T and the energy E of this soliton are connected with initial ones: $T/\tau_0 = \varkappa^{-1}$; $E/E_0 = \beta = \varkappa$. In the calculations we neglected the nonsoliton part of the radiation. It is right, when $L \gg L_d$ and the intensity of the nonsoliton radiation is critically weaker than soliton intensity.

When the α value is unsufficient for the soliton formation in "α"-channel, then soliton is formed in "1-α"-channel. So, in this case, we can exchange in all formulas α with $1-\alpha$. Besides, it is clear that for the loop all dependencies with α are symmetrical relatively to the point $\alpha = 0.5$.

It should be noted that all this formulas are independent from the loop length. It is due to the fact that soliton doesn't changes its shape and energy under propagation in the sufficiently long loop.

The dependence of the loop transmittivity on α in the linear case and for the fundamental solitons is shown in Figure 1. The linear loop transmittivity β_0 is represented by parabola. The correlation $\beta > \beta_0$ shows that the soliton transmittivity is greater than linear one even without switching. Consequently the loop filtrates valid solitons from nonsoliton background.

Figure 2 presents the intensity profile of the initial soliton on the continuous background (0.1 of the soliton amplitude) and normalized intensity of the soliton formed after the loop in the "far field" at $\alpha = 0.75$. It is also shown pulse, formed immediately after the loop. One could see that relation between intensities of the background and soliton approximately equals to initial one. But relation between energies - really registered values, is in two times greater due to increasing of soliton width. So in this case (without switching) it is possible to make contrast soliton - background higher in two times.



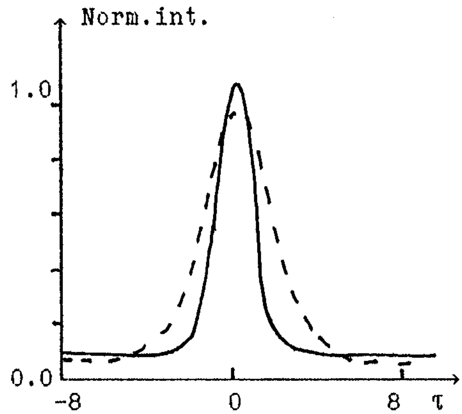


Fig.1: Loop transmittivity vs α.
Fig.2: Soliton envelope before and after the loop (α=0.75).

3.2.Fundamental soliton switching in the loop ($0.25 < \alpha < 0.75$)

In this case the counterpropagating solitons are formed in the loop and interferes in the coupler at the output. When $\alpha \neq 0.5$ the solitons amplitudes in the loop are different and the solitons phase difference exists and we have to take into account this phase difference. Solitons phase difference $\delta\varphi$ is expressed as (see (2)):

$$\delta\varphi = 2 \cdot (2\alpha - \sqrt{\alpha} + \sqrt{1-\alpha} - 1) \cdot \xi \qquad (3)$$

The dependence $\beta(\alpha)$ is nonmonotonous and more complicated then in the "nonswitching" regions due to the length dependence of the $\delta\varphi$. The maximal and minimal values of the β may be calculated (with taking into account conditions for the $\delta\varphi$) by the expression:

$$\beta(\alpha) = E/E_0 = \alpha\cdot(2\sqrt{\alpha}-1) + (1-\alpha)\cdot(2\sqrt{1-\alpha}-1) \pm$$
$$\pm \sqrt{\alpha(1-\alpha)}\cdot(2\sqrt{\alpha}-1)\cdot(2\sqrt{1-\alpha}-1)\cdot I \qquad (4)$$

where $I = \int\{SECH((2\sqrt{\alpha}-1)\tau')\cdot SECH((2\sqrt{1-\alpha}-1)\tau')\}d\tau'$. Upper sign in (4) corresponds to maximal β, lower - to minimal. The results of calculations are presented at Figure 1 at $0.25<\alpha<0.75$ and at Figure 3.

It should be noted that there is one singular point at β_{max} curve. When α exactly equals to 0.5 the same portions of the initial pulse energy propagated in both directions, their nonlinear phase shifts equals and $\delta\varphi=0$. Consequently $\beta_{max}=\beta_{min}=0$.

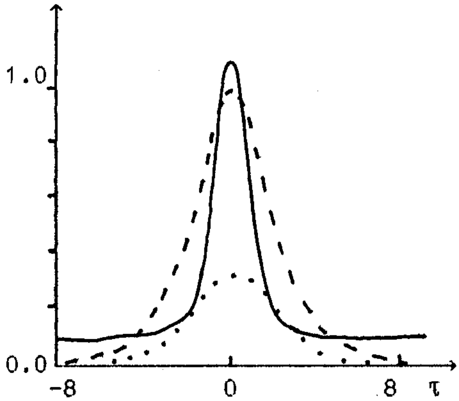


Fig.3 Soliton envelop before and after the switching (α=0.45)

The loop transmittivity depends on the phase difference $\delta\varphi$ which varies with the input solitons energy variation. The energy and time duration of the fundamental soliton are connected by the relation: $ET = CONST$ [7]. When the energy varies, the time duration and dispersive length of the soliton varies too. So, under fundamental soliton energy variation at the input of the loop, the normalized length of the loop $\xi = L/L_d$ and phase difference $\delta\varphi$ varies too. But when $\delta\varphi$ varies the loop transmittivity changes between maximal and minimal value and i.e. the self switching could take place.

The ratio of the maximal and minimal β gives the switching contrast $K = \beta_{max}/\beta_{min}$ which could be achieved at given α. The contrast K is maximal near the point $\alpha = 0.5$. In this region the parameters of the solitons, formed in the loop, are close to each other. So the envelops of the solitons are practically the same and switching with high contrast could be achieved.

When α=0.45 the maximal switching contrast equals to $K\approx30$. To observe at this α the soliton selfswitching between m-th maximum and minimum the normalized loop length must equal $\xi \approx 30\cdot m\cdot\pi$. In this case the selfswitching would be observed for the solitons with energy relation $K_0 \approx 1 + 1/(4m)$. These relations are received from (3) and (4). When m=1 then $\xi \approx 100$ and $K_0 \approx 1.25$, and when m = 5 then $\xi \approx 500$

and $K_0 \approx 1.05$. So, when the loop length is equal $L = 500L_d$, one can sort with contrast $K \approx 30$ solitons with initial energy difference only about 5%. The real loop length L is about 100 ÷ 200 meters for the solitons with duration of about 100 fs.

We have done some experiments on the fundamental soliton transmission through the fibre-optical loop based on the fused tapered coupler [6]. At Figure 1 experimentally measured transmittivity and at Figure 4 the dependence of the time duration of the formed after the loop solitons are shown . Good agreement between experiment and numerical estimations confirms correctness of the theoretical model.

4.SOLITON INTERACTION WITH CW RADIATION IN THE LOOP

When $\alpha = 0.5$ (the symmetrical coupler) the amplitudes of the counter propagated radiation equals each other and $\beta = 0$, i.e. the radiation returns back to the input fiber. Nonreciprocal phase shift could arises under interaction of CW radiation (wavelength λ_1) with the short pulse (λ_0), propagating in the loop in one direction. Due to XPM this pulse leads to additional phase shift $\delta\varphi$ to the CW radiation propagating in the same direction. The optimal pulse for modulation is soliton due to its constant form.

If soliton duration is shorter than loop round trip time the phase distortion in the counter - propagating wave will be negligible. If the loop length is sufficiently short, then phase modulation of the CW radiation will not transform to the amplitude one. In this case to calculate output signal we can take into account only phase correlation. This situation could be realized by using spectral-selective coupler with coupling coefficient varying with wavelength: $\alpha_0(\lambda_0) = 1$, $\alpha_1(\lambda_1) = 0.5$. Under these conditions pulse is formed from the CW radiation and its intensity envelop is described by the following expression:

$$I(\tau) = I_1 \cdot SIN^2(\delta\varphi(\tau)/2) \qquad (5)$$

where I_1 - initial intensity of the CW radiation; and

$$\delta\varphi(\tau) = (\eta\cdot\gamma)\cdot\int_{\tau-\gamma}^{\tau} SECH^2(\tau')\, d\tau' \qquad (6)$$

where $\eta=4\pi n_2 I_0 L/\lambda_1$; $\gamma=\Delta L/\tau_0$; n_2 - nonlinear refracted index; I_0 - peak intensity of the soliton, L - loop length; $\Delta=(1/u_0-1/u_1)$; $u_{0,1}$ - group velocities at the wavelengths λ_0 and λ_1. The formed pulse is of minimal duration and maximal intensity at the conditions: $\eta=\pi$ and $\gamma=0$:

$$I(\tau) = I_1 \cdot SIN^2(\pi \cdot SECH^2(\tau/2)) \qquad (7)$$

These conditions are satisfied when $u_0 = u_1$ and $L = L_d \cdot \pi \cdot (\lambda_1/\lambda_0)/2$. When the parameter η grows, formed pulse is splitted to some peaks. When $\gamma \neq 0$ then pulse amplitude decreases and duration grows due to soliton sliding with respect to CW radiation. Asymptotical (at high γ) dependence of the peak intensity I and FWHM time duration T are connected with initial ones by the following expressions ($\eta = \pi$):

$$I/I_1 \simeq (\pi/\gamma)^2 \ ; \ T/\tau_0 = \gamma - 0.884$$

Optimal conditions of the pulse formation ($\gamma = 0$) could be obtained under interaction of the soliton in the negative dispersion region with the CW radiation in the positive dispersion region of the single-mode fiber. Let us suppose that soliton with duration 200 fs at the wavelength 1.6 μm ($L_d \simeq 80$ cm). Let's suppose that group velocities of the soliton and CW radiation at 1.064 μm are the same. In this case modulation is optimal ($\eta = \pi$) at the $L \simeq 80$ cm.

Analytical approximation is good for estimations but is not valid when loop length is not sufficiently short and one have to take into account dispersive evolution of the CW radiation due to the XPM phase. To receive more realistic results computer simulation have been done. Figure 4 shows results of this simulation.

Very interesting feature of the generated pulse is the practically linear chirp within all pulse at the loop lengths $L/L_d \simeq \pi/4$. At the longer length the chirp becomes lower and curved in the central part of the pulse. When the chirp is linear through all pulse, it could be effectively compressed without any wings [9]. Compressed pulse at the loop length $L \simeq L_d \cdot \pi/4$ is shown at Figure 4.

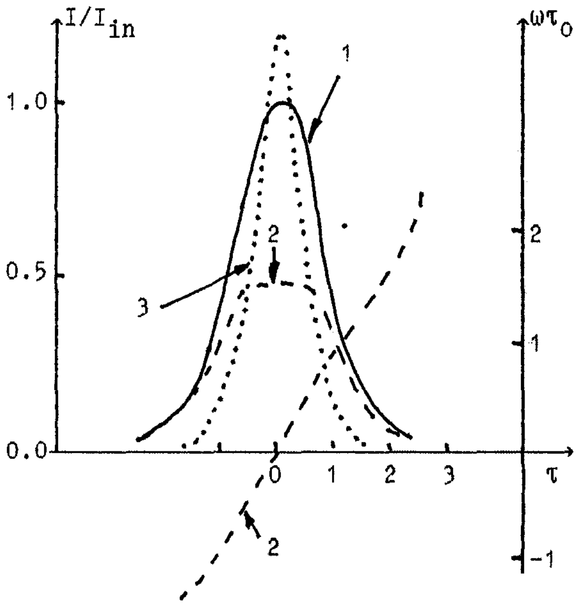


Fig.4 Soliton (1), generated pulse (2), and compressed pulse (3) at $\gamma=0$, $\eta \simeq \pi$. Dashed line - pulse chirp.

When the intensity of the CW radiation is greater than soliton intensity it is necessary to take into account XPM by CW radiation to soliton. But at the loop length about $L/L_d=\pi/4$ the parameters of the formed pulses are approximately the same as at low intensity radiation.

5.CONCLUSIONS

All the results mentioned above are connected with the fiber-optical loop mirror - Sagnac interferometer based on a single coupler. By using two or more couplers one could receive more complicated device in which could be realized another types of the fundamental soliton conversion and radiation handling. In Mach-Zehndor interferometer [1], for example, there are two couplers and two fiber arms and it is possible to form dark or programmable ultrashort pulses from the CW radiation under soliton XPM.

REFERENCES

1. N.J.Doran and D.Wood, Optics Letters, 13, 56 (1988)
2. K.J.Blow, N.J.Doran and B.K.Nayar, Optics Letters, 14, 754 (1989)
3. N.J.Doran, D.S.Forrester and B.K.Nayar Electronics letters, 25, 267 (1989)
4. K.J.Smith, N.J.Doran and P.G.J.Wigley Optics Letters, 15, 1294 (1990)
5. M.C.Farries and D.N.Payne Appl. Phys. Letters, 55, 25 (1989)
6. E.A.Zakhidov, F.M.Mirtadzhiev, D.V.Khaidarov, A.V.Kuznetsov and O.G.Okhotnikov Kvantovaya Electronika (Moscow), 18, 333, (1991)
7. A.Hasegava and F.Tappert Appl. Phys. Letters, 23, 142 (1973)
8. J.Satsuma and N.Yajima Progr. Theor. Phys. Suppl., 55, 284 (1984)
9. W.J.Tomlinson, R.H.Stolen and C.V.Shank JOSA B 1, 139, (1984)