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OPTICAL PULSE SELF-COMPRESSOR COMBINED THE NONLINEAR COUPLER WITH BACKWARD RAMAN FIBER AMPLIFIER

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Abstract. *Based on the nonlinearity of the nonlinear optical coupler (NOC) and the amplifying capacity of the backward Raman fiber amplifier (PBRFA), a new optical system to compress the optical pulse (optical pulse self-compressor: OPSC) is proposed. Using the expressions describing relationship between output intensities from both output ports and input one of NOC and the expression describing the amplification of the PBRFA, the compressing process of the optical pulse propagating through OPSC is simulated. The results show that the peak of optical pulse will be enhanced and the duration of optical pulse will be reduced significantly, and the shape of input pulse is completely compressed with certain efficiency. It means the optical pulse is self-compressed without the external pump pulse.*

I. INTRODUCTION

There are many techniques interested and used to compress the optical pulse as the amplitude passive modulation, the mode-locking, the intra-cavity saturation absorption-amplification [1, 2], the stimulated Raman backscattering in plasma [10–29], etc. The operating principle of all mentioned techniques is based on the nonlinearity in the optical medium under the interaction of the intense laser beam [2,9,10,15,19]. In the early 1970 s, Stolen and Ippen [30] demonstrated Raman amplification in optical fibers. By the early part of 2000 s, almost every long-haul (typically defined ∼300 km to 800 km) or ultralong-haul (above 800 km) fiber-optic transmission system uses Raman amplification [13], and there are many works interested in the stimulated Raman backscattering in fiber [6–8]. As the operating principle of the pumped backward Raman amplification, the longer pulse propagating along the opposite direction of the signal pulse is necessary. So, the classical pulse compressing system always needs two optical pulses, one of them plays the role of the pump source and second one plays the role of the signal.

In our previous work [3], the nonlinear optical coupler has been proposed and the nonlinearity appeared in the transfer efficiency-input intensity characteristic. Due to the nonlinearity of the nonlinear optical coupler, the output pulse selection at two ports is found out, i.e. when the powerful signal is propagated through one port, meanwhile the weak signal will propagate through second port in the conditional intensity density. The intensity reducing at second port of NOC can be seen as the phenomenon appeared in the saturation absorption medium. Thus, the combination of the nonlinear optical coupler (NOC) with the pumped backward Raman fiber amplifier (PBRFA) will become a system to compress the optical pulse.

In this paper, we propose the configuration of the optical pulse self-compressor (OPSC) based on NOC and PBRFA. The simulated results will be presented to confirm the pulse self-compression possibility of the proposed OPSC.

II. THEORETICAL BASICS

II.1. Intensity selection and pulse shortening of NOC

The NOC is consists of one linear optical fiber and Kerr fiber, which is illustrated in Fig. 1 [3, 4]. The operating principle of NOC is similar to linear optical coupler except the Kerr effect in nonlinear fiber [8]. Since the Kerr effect, the transfer coefficients at two ports of NOC depend on input intensity, which are given as following [4]

$$\begin{aligned} \eta_{lin} &= \left[\frac{C^2}{\frac{\omega^2\varepsilon_0^2 n_{nl}^4 I_{in}^4}{16}+C^2}\sin^2\left(l_{cpl}\sqrt{\frac{\omega^2\varepsilon_0^2 n_{nl}^4 I_{in}^4}{16}+C^2}\right)\right] \\ (1-\eta)_{nonlin} &= \left[1-\frac{C^2}{\frac{\omega^2\varepsilon_0^2 n_{nl}^4 I_{in}^4}{16}+C^2}\sin^2\left(l_{cpl}\sqrt{\frac{\omega^2\varepsilon_0^2 n_{nl}^4 I_{in}^4}{16}+C^2}\right)\right] \end{aligned} \tag{1}$$

where, ω is the signal frequency, ε_0 is electric permeability, I_{in} is the input intensity, $\eta_{lin} = I_{out,in}/I_{in}$ is transfer coefficient of linear fiber, $(1-\eta)_{nonlin} = I_{out,nonlin}/I_{in}$ is the transfer coefficient of nonlinear fiber (see Fig. 1), n_{nl} is the nonlinear coefficient of refractive index of nonlinear fiber, l_{cpl} is the coupling length, and C is the linear coupling coefficient, which depends on the radius of fiber, separation distance between two fibers, refractive index, and signal wavelength [5].

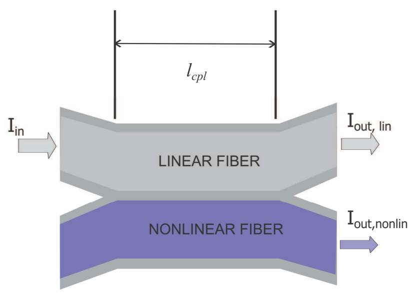

Fig. 1. Nonlinear optical coupler.

Consider the parameters of the NOC are follows: $C = 0.694$/mm, $n_{nl} = 1.0 \times 10^{-12}$ mm^2/W, $l_{cpl} = 2.5$ mm. The transmittance efficiency-input intensity characteristics at two ports are simulated for optical beam with wavelength $\lambda = 1.5\mu m$, and illustrated in Fig. 2.

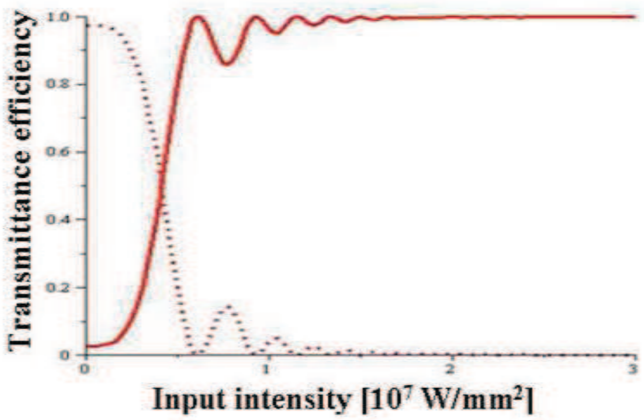

Fig. 2. The transfer efficiency through liner output port (solid) and nonlinear output port (dot) of NOC with $n_{nl} = 1.0 \times 10^{-12}$ mm$^2/W$, $l_{cpl} = 2.5$ mm vs input intensity density at $\lambda = 1.5$ μm.

From Fig. 2, we can see that, with given parameters of the NOC (i.e. with designed NOC), a laser signal at wavelength of 1.5μm will be transmitted from linear output port if its intensity density is more than about 20×10^{12} W/mm^2, meanwhile transferred to nonlinear output port if its intensity density less than 5×10^{12} W/mm^2. It means that the NOC has the property of intensity selection, which is presented in Fig. 3.

From Fig. 3, we can see that, the considered input pulse is Gaussian, i.e.

$$I_{in}(t) = I_{\max,in} \exp\left(-\ln 2 \times \frac{t^2}{\tau^2}\right) \tag{2}$$

with peak intensity density $I_{\max,in} = 4 \times 10^{12}$W/mm^2 and half-duration $\tau = 1 \times 10^{-9}$s, is split into two parts, the intense pulse, $I_{out,lin}$, with slight changing of the peak intensity density and duration, has gone out from linear output port, meanwhile the weak one, $I_{out,nonlin}$, with big reduction of both peak and duration, from nonlinear output port. It is important that the duration of weak pulse from nonlinear output port is reduced to 0.5×10^{-9} s. This property of the NOC give us an idea to set up pulse compression system consists from NOC and PBRFA (i.e. OPSC). For this OPSC, the intense pulse can be used as pumping pulse for PBRFA, and the weak shorten pulse will be amplified as the signal pulse.

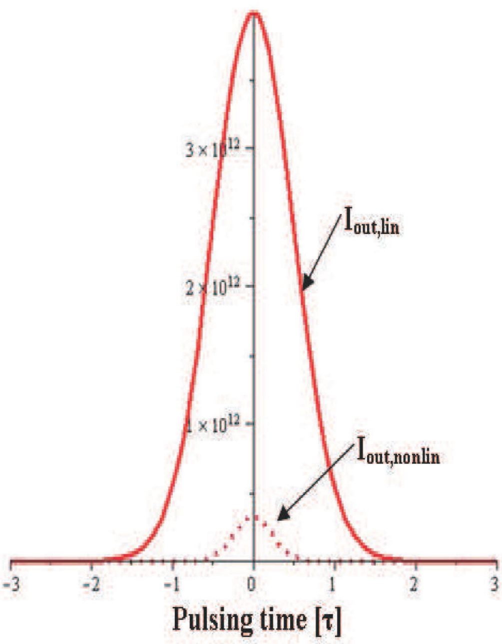

Fig. 3. Output pulses from two ports of NOC.

II.2. Operation of OPSC

Now, we propose an optical pulse compressor as shown in Fig. 4. Consider the input Stokes long pulse injected into NOC through input port (1). After propagating through NOC, the more intense pulse will go out from output port (3), which is injected into PBRFA as the pump pulse, and guided to second output port (4) along the clock-hand direction (assumed – z direction). Meanwhile, the weak and shorter pulse will go out from output port (4), which is injected into PBRFA as the signal pulse, and guided to port (3) along the opposite clock-hand direction (assumed +z direction). This pulse will be amplified by stimulated Raman backscattering [33] and go out from port (2) with slight changing.

II.3. Signal gain of PBRFA

Consider PBRFA is a single-mode fiber with length L. The signal pulse from port (4) is injected at $z = 0$ and travels in the $+z$ direction (along opposite clock-hand direction), while the pump pulse from port (3) with peak power,$P_{\max,p}$[W], and duration, 2τ [s], is injected at $z = L$ and propagates along – z direction (along clock-hand direction). Let α[dB/km] be the loss coefficient of the signal and let g [m/W] and A[m^2] denote the Raman gain constant and the effective Raman cross section, respectively.

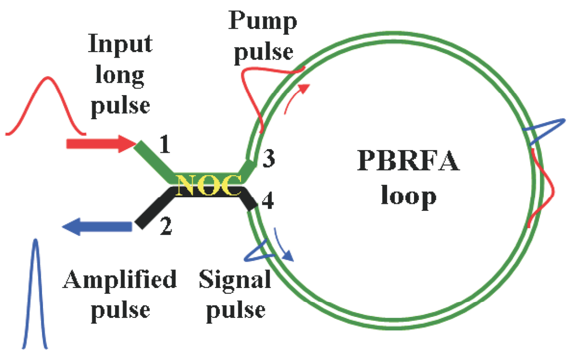

Fig. 4. Set-up of OPSC.

In order to simplify the problem, we assume that pump energy depletion is negligible, and the duration of pump pulse (intense pulse) is long enough considerable as CW, comparing to duration of signal pulse (weak pulse). Because the signal pulse travels along opposite direction of the pump pulse, the interaction length is $L_{int} = v_g\tau[m]$, which is chosen to be the length of the PBRFA's fiber, where $v_g$is the group velocity of pulse. At every point of this interval, $z_i = v_g t_i$ (or t_i) the pump amplitude is considered as

$$P_p(z_i) = P_{\max,p} \exp\left(-\ln 2 \times \frac{(z_i - L_{int})^2}{L_{int}^2}\right) \exp\left[\alpha_p\left(z_i - L_{int}\right)\right] \quad (3)$$

Similar to that of work of Lin and Stolen [31], the signal gain obtained from the pump pulse is given by

$$G(z_i) = \exp\left[\frac{gP(z_i)z_i}{A}\right] \quad (4)$$

However, at every point the signal pulse has the propagation loss $e^{-\alpha_s z_i}$. Hence the net gain is given as

$$G(z_i) = \exp\left[\frac{gP(z_i)z_i}{A} - \alpha_s z_i\right] \quad (5)$$

As shown in Fig. 3, the pump pulse is more longer than the signal pulse, so in distance increment, $\Delta z = v_g\tau_s$, where τ_s is the duration of signal pulse, the gain coefficient is considered to be constant, i.e. $G\left(\Delta z_i\right) \approx G\left(z_i\right)$, and the signal is enhanced by factor $G(z_i)$, that means the output signal pulse after propagating through Δz_i can be expressed as [32]

$$P_{out.s}(t, \Delta z_i) \approx G(z_i)P_{in,s}(t) + n(z_i) \quad (6)$$

where, $n\left(z_i\right)$ is the quantum noise at point z_i [21], $P_{in,s}(t)$ is the input signal pulse injected into the increment Δz_i.

We assume the loss and quantum noise are small negligible, using (5) and (6), we have

$$P_{amp}(t, L_{int}) = P_{in,s}(t)\prod_{i=1}^{N} G(z_i) = P_{in,s}(t)\prod_{i=1}^{N}\exp\left[\frac{gP(z_i)z_i}{A}\right] \tag{7}$$

where $N = \tau_p/\tau_s \approx \tau/\tau_s$.

The signal pulse travels along the opposite direction of the pump pulse, the shape of its can be expressed as

$$P_{in,s}(z_i) = P_{\mathrm{max,s}}\exp\left(\text{- ln2}\times\frac{(L_{in,s}-z_i)^2}{L_{in,s}^2}\right) \tag{8}$$

where $L_{in,s} = v_g\tau_s$.

After replacing the length argument z_i by the time argument$t$, and substituting (3), (8) into (7), we have

$$P_{amp,s}(t) = P_{max,s}\exp\left(-\ln 2\times\frac{(\tau_s-t)^2}{\tau_s^2}\right)\prod_{i=1}^{N}\exp\left[\frac{gv_gt_iP_{max,p}}{A}\exp\left(-\ln 2\times\frac{(t_i-\tau)^2}{\tau^2}\right)\right] \tag{9}$$

which describes the shape of the amplified pulse propagated through PBRFA only.

To have the shape of the output amplified pulse from port (2) of the NOC, we must combine (1) with (9). Firstly, resolving (1) to find out $P_{\max,s}$, τ_s and $P_{\max,p}$; secondly, substituting them into (9) to find out $P_{amp,s}(t)$; finally, using (1) again to find out the output amplified pulse. In the simulating process, we can replace the intensity P by the intensity density: $W = P/A$ [W/m^2], then (9) can be rewritten as follows

$$W_{amp,s}(t) = W_{max,s}\exp\left(-\ln 2\times\frac{(\tau_s-t)^2}{\tau_s^2}\right)\prod_{i=1}^{N}\exp\left[gv_gt_iW_{max,p}\exp\left(-\ln 2\times\frac{(t_i-\tau)^2}{\tau^2}\right)\right] \tag{10}$$

II.4. Simulation of self-compression process

All NOC's parameters are given as that in Section II.1. The input signal pulse parameters are as follows:$W_{\max,in} = 1.0\times10^{12}W/m^2$, $\tau = 1\times10^{-6}$ s. The PBRFA parameters are as follows:$g = 1.0\times10^{-13}$ m/W, $v_g = 2\times10^8$ m/s [34], and $L_t = v_g.\tau =$ 200 m.

For given above parameters, the shorten pulse is simulated (Fig. 5), and compared with the input pulse (Fig. 6). From Fig. 5 can see that, the duration of optical pulse is shorten to about$2\times10^{-8}s$, i.e. about 10^2times shorter, meanwhile, its peak intensity density is enhanced to $1.3\times10^{13}W/m^2$.

Let $E = \int_{-\infty}^{+\infty} W(t)dt = \tau W_{\max}\sqrt{\frac{\pi}{\ln 2}}$ be the energy density and the ratio of input pulse to amplified pulse, $\eta_{energ} = E_{in}/E_{amp}$ be energy transfer efficiency. Let $F = W_{\max}/2\tau$ be defined as the pulse "force" and $\eta_{comp} = F_{amp}/F_{in}$ as the compression efficiency.

Then, from Fig. 5 we can see that although the energy transfer efficiency reaches 13% only, which means the energy density of pump pulse is not changed in good agreement

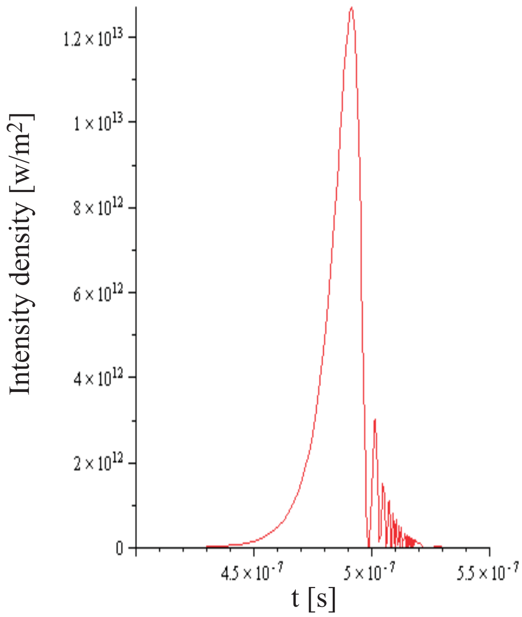

Fig. 5. Shorten pulse.

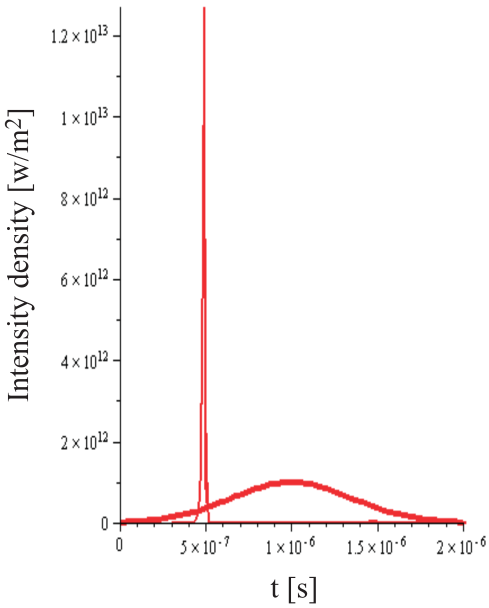

Fig. 6. Comparison of input pulse with shorten pulse.

with our approximation, but the duration of the amplified pulse is significantly reduced, about 10^{-2} times shorter. Additionally, the force, F_{amp}, of the amplified pulse increases up to 0.65×10^{21}, more bigger than that, F_{in}, of input pulse, 0.5×10^{18}. It means, the self-compressing efficiency for our model, η_{comp}, is very high about 1.3×10^{3} (see Table 1.).

Table 1. Parameters of compressed pulses vs Raman gian.

g [m/W]	0.2×10^{-13}	0.3×10^{-13}	0.4×10^{-13}	0.5×10^{-13}	1.0×10^{-13}
$W_{\max}$ [W/m^2]	4.6×10^{9}	2.8×10^{12}	4.2×10^{12}	5.6×10^{12}	1.3×10^{13}
τ[s]	1×10^{-7}	0.5×10^{-7}	0.35×10^{-7}	0.12×10^{-7}	0.1×10^{-7}
F [W/m^2.s]	2.3×10^{16}	2.8×10^{19}	6×10^{19}	4.35×10^{20}	0.65×10^{21}
η_{comp}[*]	4.6×10^{-2}	5.6×10^{1}	1.2×10^{2}	8.7×10^{2}	1.3×10^{3}

$^*F_{in} = 0.5 \times 10^{18}$.

However, the shorten pulse's shape, i.e. its peak power and duration as well as compressing efficiency depend on design parameters, for example, their shape depend on the Raman gain in Fig. 7. If the Raman gain constant increases, the peak power of amplified pulses increases, meanwhile, their duration decreases.

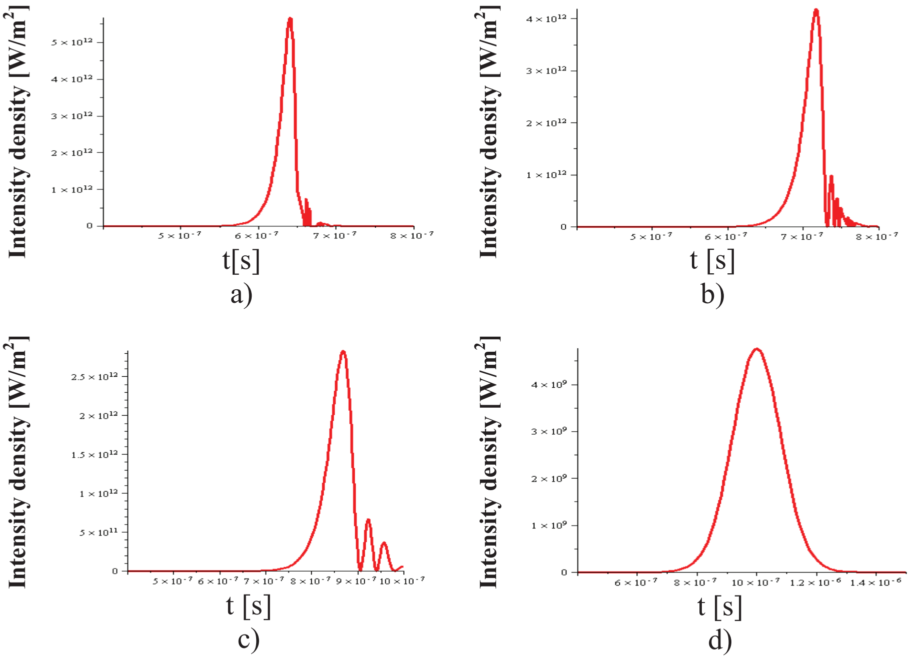

Fig. 7. Self-compressed pulses for different Raman gain: a) 0.5×10^{-13} m/W; b) 0.4×10^{-13} m/W; c) 0.3×10^{-13} m/W; d) 0.2×10^{-13} m/W.

III. CONCLUSION

Basing on the nonlinear optical coupler and the pump backward Raman fiber amplifier, the optical pulse self-compressor was newly proposed. The pulse selection at two ports of NOC is shown out by the simulation. This property is a main reason to choose output pulses from NOC as the pump and signal pulses for PBRFA. With proposed configuration of the self-compressor, the expression for the amplified pulse was introduced by some approximations. The simulated results have shown that by this configuration, the optical pulse should be self-compressed with certain efficiency, which can be enhanced by the matching conditions. However, the quality of the OPSC, especially, the compression efficiency, depends on principle parameters as the nonlinear coefficient of the refractive index, coupling length, radius of fiber core, peak intensity density and duration of input pulse, etc. Those questions will be investigated in detail in the next articles.

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