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Two Models of 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), two new optical systems to compress the optical pulse (Optical Pulse Self-Compressor: OPSC) are proposed. Using the expressions describing relationship between input and output intensities from ports of the NOC and the derived expression describing the amplification of the PBRFA, the compressing process of the optical pulse propagating through the OPSC is simulated. The results show that the peak of the optical pulse will be enhanced and the duration of the optical pulse will be reduced significantly. Consequently, the shape of input pulse is completely compressed with the certain efficiency. It means the optical pulse is self-compressed without the external pump pulse by proposing the OPSC.

Keywords: Backward Raman Fiber Amplification; Nonlinear Optical Coupler (Integrated-Optical Direction Coupler); Pulse Compression

1. 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 [3-22], 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 [2,3,8,12,23]. In the early 1970s, Stolen and Ippen [24] demonstrated Raman amplification in optical fibers. By the early part of 2000s, almost every long-haul (typically defined ~300 km to 800 km) or ultralong-haul (above 800 km) fiber-optic transmission system uses Raman amplification [6], and there are many works interested in the stimulated Raman backscattering in fiber [25, 26]. As the operating principle of the pumped backward Raman amplification, the longer pulse propagating along the opposite direction of the signal pulse is needed. So, the classical pulse compressing system always needs two optical pulses, of which one plays the role of the pump source and the one plays the role of the signal.

In our previous works [27,28], 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 the second port in the conditional intensity density. The intensity reducing at the second port of the 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 two optical pulse self-compressors (OPSC) based on the NOC and the PBRFA. The simulated results will be presented to confirm the pulse self-compression possibility of the proposed OPSC.

2. Arguments

2.1. Intensity Selection and Pulse Shortening of NOC

The NOC consisted of a linear optical fiber and Kerr fiber is illustrated in **Figure 1** [27,28]. The operating principle of the NOC is similar to the linear optical

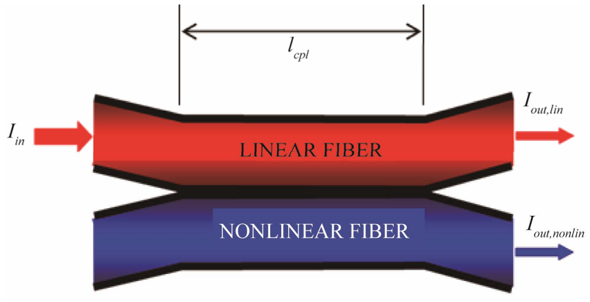


Figure 1. Nonlinear optical coupler.

coupler except for the Kerr effect in nonlinear fiber [26]. Because of the Kerr effect, the transfer coefficients η_{lin} at output linear port and $(1-\eta)_{nonlin}$ at output nonlinear port of the NOC depend on input intensity, which are given as follows [27,28]:

$$\eta_{lin} = \left[\frac{C^2}{\frac{\omega^2 \varepsilon_0^2 n_{nl}^4 I_{in}^4}{16} + C^2} \sin^2\left(l_{cpl} \sqrt{\frac{\omega^2 \varepsilon_0^2 n_{nl}^4 I_{in}^4}{16} + C^2} \right) \right]$$

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

where, ω is the signal frequency, ε_0 is the electric permeability, I_{in} is the input intensity, $I_{out,lin}$ is the output intensity from output port of linear fiber, $I_{out,nonlin}$ is the output intensity from output port of nonlinear fiber (see **Figure 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 [29].

Consider the parameters of the NOC are as follows: $C = 0.694/\text{mm}$, $n_{nl} = 1.0\times10^{-12}\ \text{mm}^2/W$, l_{cpl} = 2.5 mm. The transmittance efficiency-input intensity characteristics at two ports are simulated for the optical beam with its wavelength $\lambda = 1.5\ \mu\text{m}$, and illustrated in **Figure 2**. From **Figure 2**, we can see that, with given parameters of the NOC (*i.e.* with designed NOC), a laser signal at wavelength of 1.5 μm will be transmitted from the 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 is less than 5 × 10^{12} W/mm [27]. It means that the NOC has the property of intensity selection, which is presented in **Figure 3**. From **Figure 3**, we can see that, the considered input pulse is Gaussian, *i.e.*

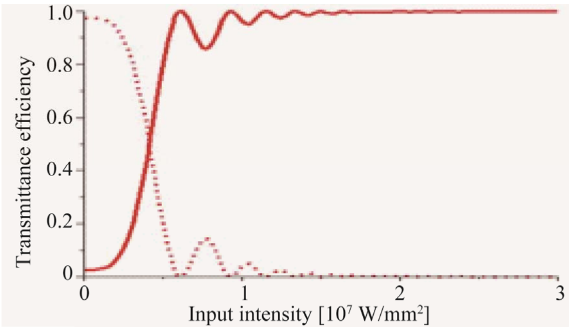


Figure 2. The transfer efficiency through liner output port (solid) and nonlinear output port (dot) of NOC with n_{nl} = 1.0 × 10^{-12} mm^2/W, l_{cpl} = 2.5 mm vs input intensity density at λ = 1.5 μm.

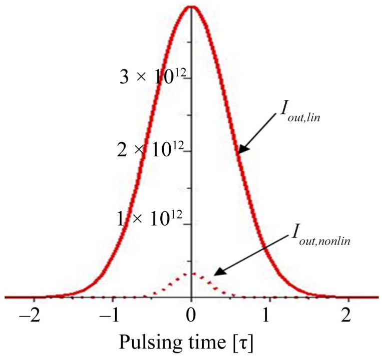


Figure 3. Output pulses from two ports of NOC.

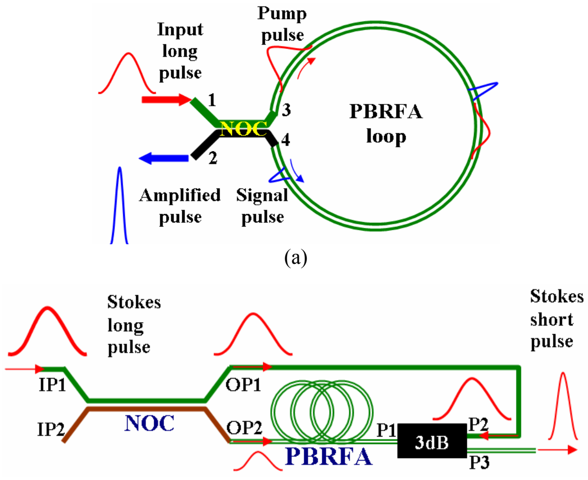
$$I_{in}(t) = I_{\max,in} \exp\left(-\ln 2 \times \frac{t^2}{\tau^2}\right) \tag{2}$$

with peak intensity density $I_{\max,in} = 4\times10^{12}\ \text{W/mm}^2$ and half-duration $\tau = 1\times10^{-9}\,\text{s}$, 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 the linear output port, meanwhile the weak one, $I_{out,nonlin}$, with big reduction of both peak and duration, from the 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 gives us an idea to set up the pulse compression system consisted of the NOC and the 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.

2.2. Configuration and Operation of OPSC

Now, we propose two models of the optical pulse compressor as shown in **Figure 4**. For first model in **Figure 4(a)**, consider the input Stokes long pulse injected into the NOC through input port (1). After propagating through the NOC, the more intense pulse will go out



(a)

(b)

Figure 4. Set-up of OPSC. (a) OSPC consist of the NOC and PBRFA loop; (b) OSPC consist of the NOC and PBRFA and 3 dB.

from output port (3), which is injected into the PBRFA as the pump pulse, and guided to the second output port (4) along the clock-hand direction (assumed − z direction). Meanwhile, the weak and shorter pulse will go out from the output port (4), which is injected into the 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 [30] and go out from port (2) with a slight changing.

For the second model in **Figure 4(b)**, a long Stokes pulse is injected into the NOC through input port (PI1). After propagating through the NOC, the more intense pulse will go out from the output port (OP1), which is injected into the PBRFA through port P2 and P1 of the 3 dB coupler as the pump pulse along −z direction. Meanwhile, the weak and shorter one will go out from the second output port of the NOC (OP2), which is injected into PBRFA as the signal pulse along +z direction. This pulse will be amplified by stimulated Raman backscattering and go out from port P3 of the 3 dB coupler.

2.3. Signal Gain of the PBRFA

For example, we derive the expression of amplified pulse for the first model. Consider the 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, 2 τ [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.

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

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

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 **Figure 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.* $G(\Delta z_i) \approx G(z_i)$, 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, $n(z_i)$ is the quantum noise at point z_i [16,21], $P_{in,s}(t)$ 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

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

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 follows

$$P_{in,s}(z_i) = P_{\max,s}\exp\left(-\ln 2\times\frac{(L_{in,s}-z_i)^2}{L_{in,s}^2}\right) \quad (8)$$

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

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

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 $P_{\max,p}$; next, 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* with the intensity density: $W = P/A$ [W/m^2], then (9) can be rewritten as follows

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

For the second model in **Figure 4(b)**, to obtain the amplified pulse, the expression (1), (9) and (10) will be used also, but the simulation process is slightly changed, *i.e.*, firstly, resolving (1) to find out $P_{\max,s}$, τ_s and $P_{\max,p}$; secondly, multiply $P_{\max,p}$ with 1/2 (by 3 dB coupler), thirdly, substituting them into (9) to find out $P_{amp,s}(t)$; fourthly, using (1) again to find out the output amplified pulse, finally, multiply again with 1/2.

2.4. Simulation of the Self-Compression Process

All the NOC's parameters are given in Section 2.1. The input signal pulse parameters are as follows: $W_{\max,in} = 1.0\times10^{12}\ W/\text{m}^2$, $\tau = 1\times10^{-6}$ s. The PBRFA parameters are as follows: $g = 1.0\times10^{-13}\ \text{m}/W$, $v_g = 2\times10^8$ m/s [33], and $L_t = v_g\cdot\tau = 200$ m.

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

Let $E = \int_{-\infty}^{+\infty} W(t)\,\mathrm{d}t = \tau W_{\max}\sqrt{\frac{\pi}{\ln 2}}$ 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 **Figure 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 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}, much bigger than that, F_{in}, of the input pulse, 0.5×10^{18}. It means, the self-compressing efficiency for our model, η_{comp}, is very high at about 1.3×10^3 (see **Table 1**).

However, the shorten pulse's shape, *i.e.* its peak power and duration as well as compressing efficiency depend on the designing parameters, for example, their shape depends on the Raman gain in **Figure 7**.

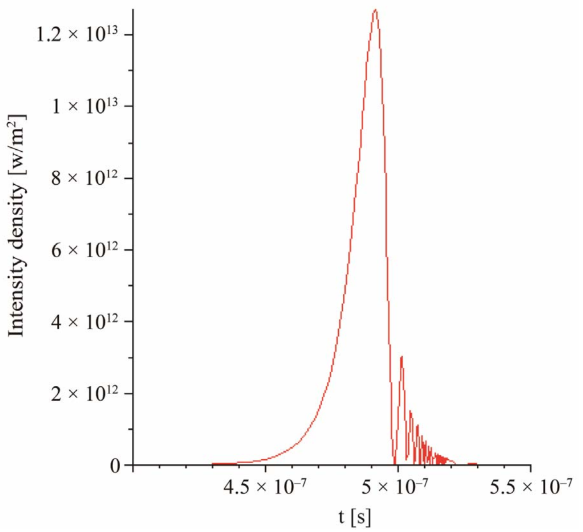


Figure 5. Shorten pulse.

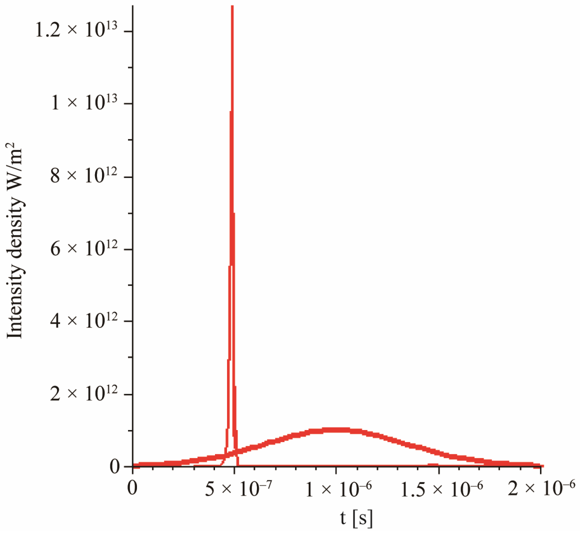
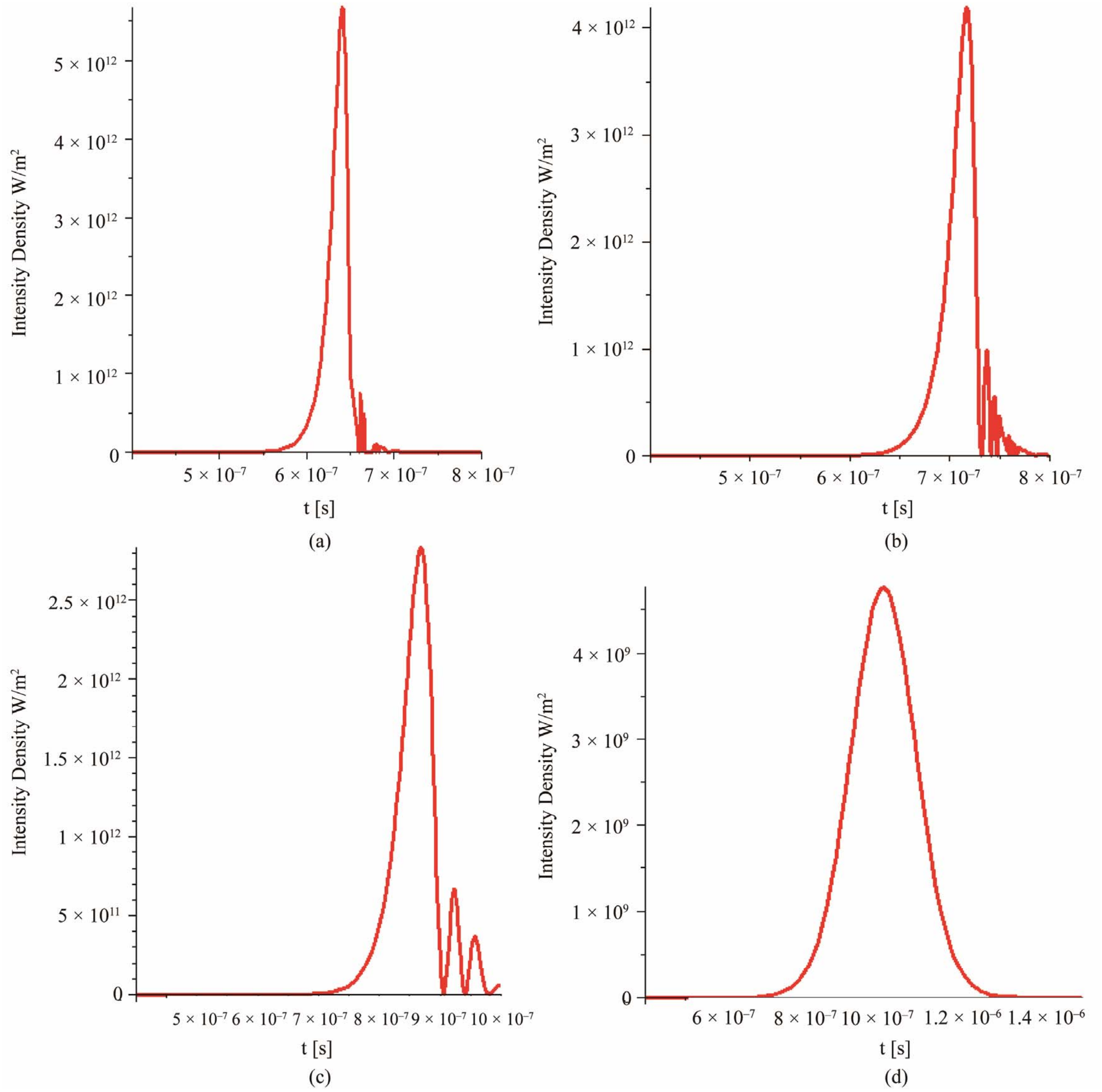


Figure 6. Comparison of input pulse with shorten pulse.



(a) (b) (c) (d)

Figure 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.

Table 1. Parameters of the compressed pulses vs the Raman gain.

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/m²]	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/m²·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}

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

If the Raman gain constant increases, the peak power of the amplified pulses increases, meanwhile, their duration decreases.

3. 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 the NOC is shown out by the simulation. This property is a main reason to choose output pulses from the NOC as the pump and the signal pulses for the 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 these configurations, the optical pulse should be self-compressed with a certain efficiency, which can be enhanced by the matching conditions. However, the quality of the OPSC, especially, the compression efficiency, depends on the 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 next articles.

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