Switching Characteristics of SOA-based Sagnac Interferometer for Subpicosecond Pulses

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Abstract— **Semiconductor optical amplifier (SOA) is a favorable element like booster or pre-amplifier in most optical communication networks. In this paper SOA is used as nonlinear element to induce phase difference between data pulses. Switching characteristics are investigated by using a numerical method that describes the dynamic gain response of the SOA to ultrashort optical pulses. By reducing the input pulsewidth to subpicosecond regime, higher speeds and capacities for the optical telecommunications can be achieved.**

Index Terms— ***all-optical switch; semiconductor optical amplifier; Sagnac interferometer; ultrashort pulses***

I. Introduction

Increasing demand for more bandwidth and speed in modern telecommunications and therefore high bit rate applications caused to actuate the recent research into analysis of ultrashort optical pulses. One of the main characteristic of all optical networks is that information remains completely in the optical domain along the process path without opto-electrical (O/E) and electro-optical (E/O) conversions. The implementation of ultra-high speed all-optical networks requires the design and development of all-optical switches as a key communication element. These switches will perform a set of critical network processing functions such as shift register with inverter [1], address recognition [2], full adder [3] and multi/demultiplexing [4].

Sagnac interferometer is a favorable structure for the switching purpose in optical telecommunication networks. The main advantage of this interferometer compared with the other interference structures is high phase stability. The Sagnac interferometer is called with different names in publications such as terahertz optical asymmetric demultiplexer (TOAD) [5] and semiconductor laser amplifier in a loop mirror (SLALOM) [6].

SOA have been investigated for applications in all-optical processing since the devices were first realized from mid 1980s [7]. SOA nonlinearities that can be used for all-optical signal processing mechanisms are cross-gain and cross-phase modulation (XGM and XPM), four-wave mixing (FWM), polarization rotation.

In nonlinear SOA-assisted Sagnac switch, SOA is placed inside the loop in such a way that the position of the SOA can be changed with respect to the center of the loop. By this tunability desired phase can be induced to optical pulse and hence switching can be occurred.

In this paper we examine the switching characteristics of SOA-based Sagnac interferometer for subpicosecond optical input pulses. All nonlinear effects in subpicosecond are analyzed by use of the modified nonlinear Schrödinger equations (MNLSE) [8]. The model used to solve this coupled MNLSE for simulating the SOA in this circuit follows what has been presented in [9]. We investigate the manner that the performance of this switch is optimized and improved by factors such as SOA small signal gain, the switching pulses energy and width, the Sagnac loop asymmetry, and SOA length.

This paper is organized as follows: In Section 2, the principle of operation is described. In Section 3, the theory of interferometric equations and SOA modeling scheme based on modified nonlinear Schrödinger equations is introduced. In section 4, results and discussions of switching characteristics of proposed structure with improved and efficient model are presented. Conclusion is given in Section 5.

II. Principle of Operation

The schematic structure of the SOA-assisted Sagnac switch is shown in Fig. 1. The switch consists of an optical loop formed by the joint output ports of a 2×2 3-dB coupler and SOA. The position of the SOA can be displaced asymmetrically with respect to the center of loop by a distance that is equivalent to a temporal offset of $T_{asym}/2$ that can be achieved by using optical delay line (ODL). A data input light is injected into the loop through the input port and splits symmetrically to two counter-propagating pulses, (the clockwise (CW) and counter-clockwise (CCW)), of equal amplitudes. The 3-dB coupler induces a $\pi/2$ phase difference between its outputs [10]. The data (probe) signal power is small enough so that it does not excite the optical nonlinear properties of the SOA. In the absence of control (switching) pulse (at least 10 times higher power than that of the data) [1], incoming data pulse exit the switch reflection port after a time that needs for passing the switch. Without control pulse the

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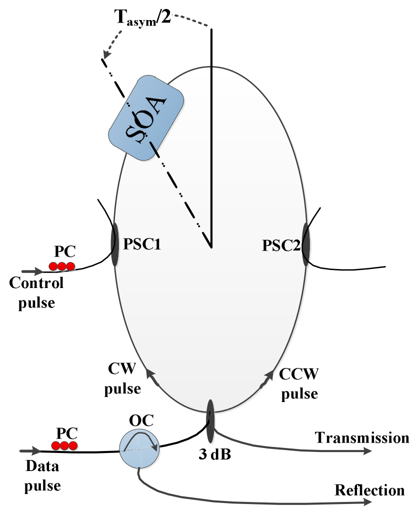

Fig. 1. The schematic structure of the SOA-assisted Sagnac switch.SOA: semiconductor optical amplifier. PSC: polarization selective coupler. PC: polarization controller. OC: optical coupler.

dynamics of the SOA remains unaltered and the two CW and CCW pulses experience the same gain and phase characteristics inside the nonlinear element (SOA) and the switch operates as a symmetric loop mirror. For switching of input data pulse to the transmission port, the control pulse can be coupled to the loop by a polarization selective coupler (PSC) together with the input data pulses to which it induces a phase shift of π between the data pulses after passing the SOA so that it can be switched at the transmission port. As the control is inserted to the structure optical properties are drastically changed since it modifies the nonlinear optical properties of the SOA. The control and data signals can be distinguished by appropriately adjusting their polarization by using polarization controllers (PC) so that they are orthogonal to each other which makes possible the insertion and extraction of the control signal in and from the loop by using two PSC1 and PSC2, respectively.

In the previous works [1, 2, and 15] the switching characteristics of the all-optical SOA-assisted switch is analyzed for picosecond control and data pulses. In this paper for the first time, we analyze the switching characteristics of SOA-assisted switch for subpicosecond pulses. For this purpose numerical simulations are carried out using the set of MNLSE that describe the interaction between the control and data pulses in subpicosecond regime as well as the normalized output power variation versus different values of relative delay between control and CW pulses.

III. Modeling

The basis for theoretically studying the switching characteristics of the SOA-assisted Sagnac switch is interferometric equations that describe its transfer function at each output ports. Transfer function is the ratio of the transmitted and the reflected to the inserted data power. The basic interferometric equations that describe the output pulses at the transmission and reflection port, can be written as [11]

$$T(t)=\frac{P_{in}}{4}\{G_{CW}(t)+G_{CCW}(t-T_{asym})-2\sqrt{G_{CW}(t)G_{CCW}(t-T_{asym})}\times\cos[\varphi_{CW}(t)-\varphi_{CCW}(t-T_{asym})]\} \quad (1)$$

and,

$$R(t)=\frac{P_{in}}{4}\{G_{CW}(t)+G_{CCW}(t-T_{asym})+2\sqrt{G_{CW}(t)G_{CCW}(t-T_{asym})}\times\cos[\varphi_{CW}(t)-\varphi_{CCW}(t-T_{asym})]\} \quad (2)$$

where $G_{CW}(t)$ and $G_{CCW}(t)$ are the SOA gain seen by the CW and CCW pulses and $\varphi_{CW}(t)$ and $\varphi_{CCW}(t)$ are the corresponding phase shifts. These two parameters are related to $\Delta\varphi_{NL}$ by

$$\Delta\varphi_{NL}=\varphi_{CW}(t)-\varphi_{CCW}(t)=-\frac{\alpha_N}{2}Ln(\frac{G_{CW}(t)}{G_{CCW}(t)}) \quad (3)$$

where α_N is the linewidth enhancement factor associated with the gain changes due to carrier depletion.

Calculation of T(t) and R(t) through (1) and (2), requires to find the gains experienced by the counter- propagating data halves. This in turn can be obtained by taking into account all nonlinear effects in the SOA for subpicosecond pulses through a set of MNLSEs which should be solved numerically. The analysis is based on central difference approximation in time domain and trapezoidal integration technique for spatial steps [8]. The forward and backward data and control optical fields with complex amplitude are determined by the following expression:

$$\left[\pm\frac{\partial}{\partial z}+\frac{1}{v_g}\frac{\partial}{\partial t}\right]A^{\pm}(t,z)=\left\{\begin{aligned}&\frac{i}{2}\beta_2\frac{\partial^2}{\partial t^2}-\frac{\gamma}{2}-\left(\frac{\gamma_{2p}}{2}+ib_2\right)I(z,t)+\frac{1}{2}g_N(\tau)\times\\&\left[\frac{1}{f(\tau)}+i\alpha_N\right]+\frac{1}{2}\Delta g_T(\tau)(1+i\alpha_T)\\&-i\frac{1}{2}\left.\frac{\partial g(\tau,\omega)}{\partial\omega}\right|_{\omega_0}\frac{\partial}{\partial\tau}-\frac{1}{4}\left.\frac{\partial^2 g(\tau,\omega)}{\partial\omega^2}\right|_{\omega_0}\frac{\partial^2}{\partial\tau^2}\end{aligned}\right\}A^{\pm}(t,z) \quad (4)$$

where, $A^{+}(t,z)$ and $A^{-}(t,z)$ are the forward and backward time domain complex envelope functions of an optical pulse and $I(z,t)=\left|A^{+}(t,z)\right|^2+\left|A^{-}(t,z)\right|^2$ corresponds to the optical power. In (4), the temporal variation of the complex envelope function is very slow compared with the cycle of an optical field (slowly varying envelope approximation). β_2 is the group velocity function, γ is linear loss, γ_{2p} is the two-photon absorption (TPA) coefficient, $b_2(=\omega_0 n_2/cA)$ is the instantaneous self-phase modulation term due to the ultrafast nonlinear refraction (UNR), ω_0 is the center angular frequency of input light, n_2 is the Kerr effect coefficient, c is the velocity of light in vacuum, $A(=wd/\Gamma)$ is the effective area (w and d are width and thickness of active region, and Γ is confinement factor), $g_N(\tau)$ is the saturated gain due to carrier depletion [12], $f(\tau)$ is the spectral hole burning (SHB) function [13], α_N and α_T and are the linewidth enhancement factors associated with the gain change due to carrier depletion and carrier heating (CH), $\Delta g_T(t)$ is the resulting gain change due to CH and TPA [14]. Finally, we have

$$\left.\frac{\partial g(\tau,\omega)}{\partial \omega}\right|_{\omega_0} = A_1 + B_1[g_0 - g(\tau,\omega_0)]$$
(5)

$$\left.\frac{\partial^2 g(\tau,\omega)}{\partial \omega^2}\right|_{\omega_0} = A_2 + B_2[g_0 - g(\tau,\omega_0)]$$
(6)

$$g(\tau,\omega_0) = g_N(\tau,\omega_0)/f(\tau) + \Delta g_T(\tau,\omega_0)$$
(7)

where, A_1 and A_2 are the slope and curvature of linear gain at ω_0, and B_1 and B_2 are constants describing changes in these quantities with saturation [14]. The gain spectrum of an SOA can be approximated by the following second-order Taylor expansion in ω.

$$g(\tau,\omega) = g(\tau,\omega_0) + \Delta\omega \left.\frac{\partial g(\tau,\omega)}{\partial \omega}\right|_{\omega_0} + \frac{(\Delta\omega)^2}{2}\left.\frac{\partial^2 g(\tau,\omega)}{\partial \omega^2}\right|_{\omega_0} \tag{8}$$

We have used the parameters of a bulk SOA (InGaAsP/InP, double heterostructure) at the wavelength of 1.55 μm for the simulation. The length of the SOA is assumed to be 500 μm. We have obtained all the results with a propagation step Δz of 500/256 μm.

IV. Results and Discussion

In our simulation, for the first time, we consider all nonlinear effects to calculate carrier dependent nonlinear gain for switching purpose. For this purpose, we use the $sech^2$ data and control pulses with 200 fs full width at half maximum (FWHM), input data pulse energy of 1 fJ, control pulse energy of 100 fJ, and the loop asymmetry time of 7.5 ps. The dependency of normalized output power (T(t)/(R(t) + T(t))) to different values of time delay between control and CW pulses is investigated. We examine variation of normalized output power by scanning through each related parameter, while keeping constant the other parameters. The concerned parameters are: g_0 (small signal gain), switching/control energy, control pulse width, and SOA length. These fixed values were selected are: (unless other quantities are stated in figure's legend): g_0 = 110 cm^{-1}, E_{cntrl} = 100 fJ (switching energy), T_{cntrl} = 200 fs (control pulse width), and L = 500 μm (SOA length).

Fig. 2 depicts the effect on the normalized output power versus time delay between CW and control pulses for different small signal gain values. A negative time delay means that the CW data pulse lags behind the control pulse, and a positive time means that CW data pulse is ahead of the control pulse. The normalized output power can be called switching window. In accordance with experimental switching window [15] the shape of the normalized output power is asymmetric. The sharp peak in zero time delay is due to subpicosecond nonlinear effects especially SHB. For the case of g_0 = 130 cm^{-1}, the nonlinear effects are further excited and extra sharp peak is predicted due to the more powerful nonlinearity. The asymmetric normalized output power is due to the propagation time of the pulses in the SOA (equivalent to finite length of SOA) that limits the minimum achievable width of the normalized output power. Especially for the case of g_0 = 110 cm^{-1}, the leading part of the normalized output power has a rise time of several fs, because the control pulsewidth is 200 fs. The trailing part of the normalized output power has a fall time of 13 ps, i.e. twice the transit time for a 500 μm long SOA, as already reported in [1]. However for the cases of g_0 = 130 cm^{-1} and g_0 = 90 cm^{-1}, the effects of nonlinear phenomena is higher and lower than g_0 = 110 cm^{-1}, respectively. At the last point the extinction ratio for g_0 greater than 110 cm^{-1} is approximately 21.5 that are larger than previous work in subpicosecond. For higher g_0 the main windows of the normalized output power is shifted to the left-hand side of the time delay axis. It means that longer time difference between CW and control pulses the maximum switching in transmission will be occurred.

Fig. 3 shows the influence that the control pulse energy (switching energy) has on the normalized output power. The appropriate switching (normalized output power larger than 0.9) is occurred when a differential phase shift of π induced between the counter-propagating data pulses. For this purpose the control (switching) energy should be appropriate. If control is lesser than proper amount the switching is incomplete and full constructive interference does not occur at the transmission port (E_{cntrl} = 50 fJ in Fig. 3). Besides, for E_{cntrl} = 1 pJ we can

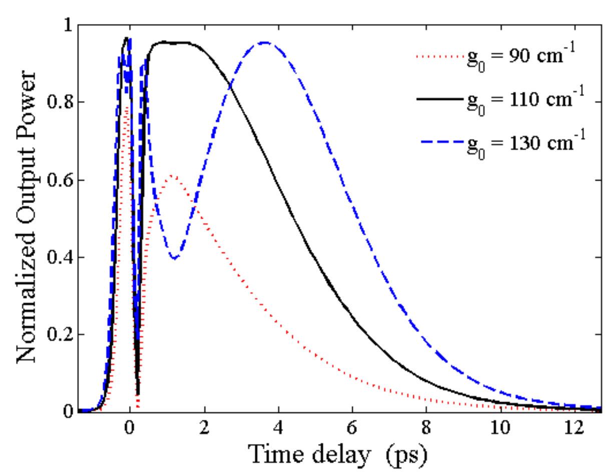

Fig. 2. Normalized output power variation vs. time delay between CW and control pulses for different small signal gain values.

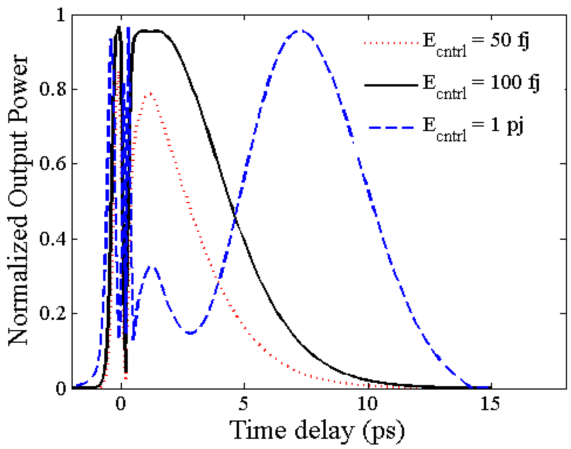

Fig. 3 Normalized output power variation vs. time delay between CW and control pulses for different values of control pulse energy.

reach perfect switching (maximum extinction ratio) but because of further excitation nonlinear effects, the extra peaks can be seen in near zero time delay.

Fig. 4 shows the dependence of the normalized output power on the control pulse width. As this parameter is increased, the main window is shifted to the left time delay and its size is also reduced. This behavior can be understood through the fact that larger control pulsewidth results in reduction of SOA length that CCW can be amplified. Decrease of SOA amplification length for CCW pulse, causes the effect of SOA length on the trailing part of the normalized output power to be reduced and consequently main window will be narrower. The maximum window shift is also the result of reduction of SOA amplification length for CCW pulse. By increasing control pulsewidth, the CCW pulse doesn't have enough time to be in maximum amount of window and will face with saturated SOA that cause CCW not to be amplified. Similar to previous cases extra peaks near the zero time delay, shown in inset, are the result of more excited nonlinear effects.

The normalized output power window variation vs. time delay between CW and control pulses for different values of the SOA length is shown in Fig. 5. This figure indicates that if

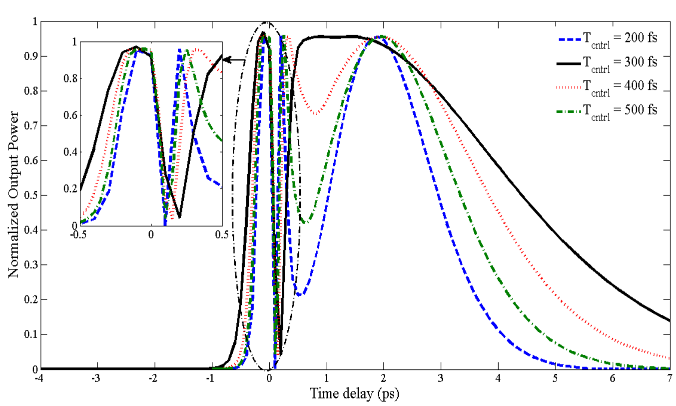

Fig. 4. Normalized output power variation vs. time delay between CW and control pulses for different values of control pulsewidth.

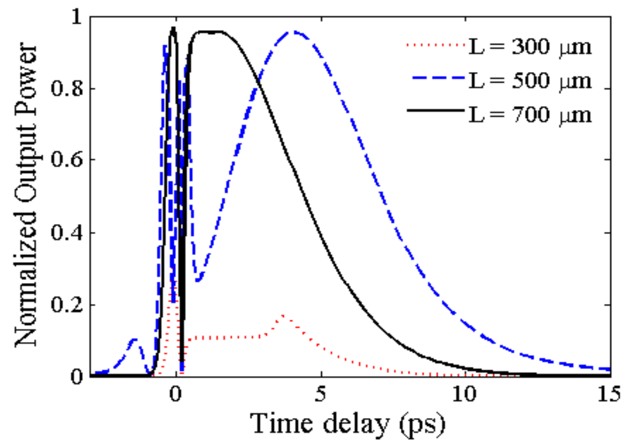

Fig. 5. Normalized output power variation vs. time delay between CW and control pulses for different values of SOA length.

the SOA length is lower than proper length, the maximum extinction ratio will not be achieved. Besides, for the case of greater length (L = 700 μm) the curve is shifted to the right and the control pulse is more delayed with respect to the CW pulse. The physical meaning of this behavior is that since under this condition the CCW pulse needs more time to arrive at the required phase difference respect to the CW pulse.

V. CONCLUSION

We investigated the switching characteristics of an all optical SOA-assisted switch. For this purpose, a comprehensive numerical simulation have been carried-out using the all nonlinear effects that describes the interaction between the signal pulses in the switch as well as the output power variation caused by changing time delay between CW and control pulses. The effects of control pulse characteristic and structural parameters on the power of switching port were studied. In the results, we have shown the optimum condition to extract maximum switching output power.

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