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High speed response of nonlinear optical phase-shifter based on vertical micro-cavity saturable absorber

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Abstract: We present the modeling and experiment on the intensity-dependent phase shift of a nonlinear optical phase-shifter based on vertical micro-cavity saturable absorber for high-speed response. We demonstrated the 25 ps transient response with a large negative nonlinear phase shift of over −0.7 radian. Our device would enable us to control the phase of high speed optical pulses including the compensation of fiber nonlinear effects in optical domain.

Keywords: nonlinear optical device, micro-cavity, saturable absorber, pulse compression, kerr effect

Classification: Photonics devices, circuits, and systems

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1 Introduction

In recent years, the precise control of the phase of high-speed optical signals is becoming important for long-haul fiber transmission systems. In particular, fiber nonlinearities are dominant limiting factors for high-speed transmission systems of 40 Gb/s or beyond. If we realize an optical nonlinear-effect compensator, which gives us a negative phase-shift in an opposite sign of an optical Kerr effect in fibers, we will be able to compensate fiber nonlinearities.

We proposed an optical nonlinear-effect compensator [1] based on a nonlinear etalon [2]. The proposed compensator can be included in each repeater as shown in Fig. 1. The phase induced by self phase modulation (SPM) in each fiber span can be optically compensated by our device. The proposed compensator enables various applications such as the compensation of optical Kerr-effect, chirp control, and all-optical signal processing for phase modulation signals. We already reported the static response of the device [3], showing a negative phase-shift. The dynamic response is limited by the carrier recovery time of a saturable absorber.

In this letter, we report the modeling and experiment on the high-speed response of an optical nonlinear phase-shifter with a reverse bias.

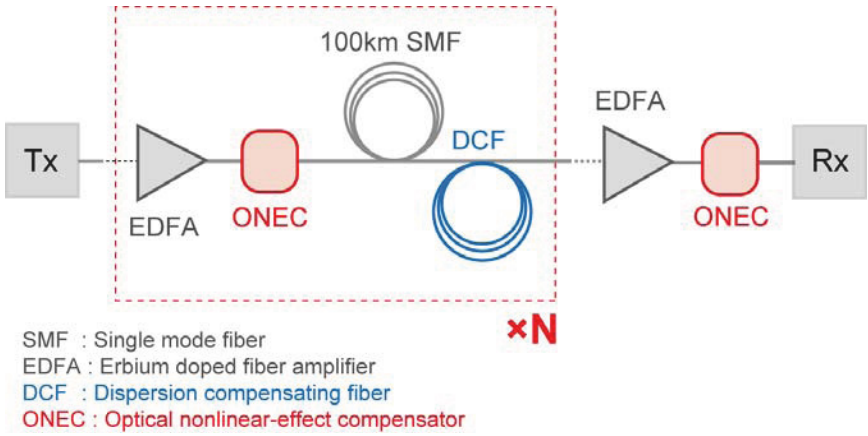

Fig. 1. Optical nonlinear-effect compensator (ONEC) for compensating fiber nonlinearlities.

2 Modeling of Optical Nonlinear Phase-shifter

Figure 2 shows the schematic of our proposed optical nonlinear phase-shifter based on a vertical-cavity saturable absorber. The density of photo-carriers generated in the saturable absorber is modulated for input signals, which

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induces an intensity-dependent refractive index change of the saturable absorber. Thus we are able to obtain the nonlinear phase shift for input signals, which is enhanced by a resonant cavity. In our previous work, we reported the dynamic response of the nonlinear phase shift for a reverse-biased 1.55 μm VCSEL, which gives a positive phase shift [4]. Also, we found either negative or positive phase shift is obtained by changing the reflectivity of a top mirror.

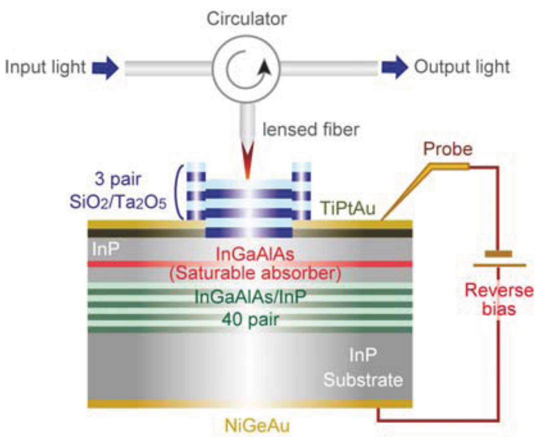

Fig. 2. Optical nonlinear phase-shifter using vertical-cavity saturable absorber.

In this work, we designed and fabricated a device consisting of 3-pair SiO_2/Ta_2O_5 (top-DBR) and 40-pair InGaAlAs/InP (bottom-DBR), and InGaAlAs QWs functioning as a saturable absorber. The top mirror was optimally designed for getting a negative phase shift. An intensity dependent negative refractive index change appears with a sign opposite to that of the optical Kerr effect in the saturable absorber, which is enhanced by a resonant vertical-cavity. An InGaAlAs saturable absorber is sandwiched by the two mirrors. We calculated the transient nonlinear phase shift depending on a carrier recovery time. The rate equation of photo-carriers and the absorption coefficient α for a saturable absorber are expressed by,

$$\frac{dN}{dt} = \eta_i \frac{P}{\hbar\omega V} - \frac{N}{\tau} \tag{1}$$

$$\alpha \approx A\,(N_0 - N) \tag{2}$$

where, N, η_i, P, V, τ, A, N_0 denote the photo-carrier density, internal efficiency, absorbed optical power, volume, carrier recovery time, absorption cross-section area, and transparency carrier density of the saturable absorber, respectively. Here, we assumed the α-parameter, which is the ratio between the variation of refractive index and absorption coefficient, is constant [4, 5]. We calculated the phase-shift of reflected light induced by the refractive index change of the absorber.

Figure 3 (a) shows the calculated transient response of a nonlinear phase shifter for an input pulse of 25 ps with different carrier recovery times. The optical bandwidth and the sign of a nonlinear phase shift can be controlled by

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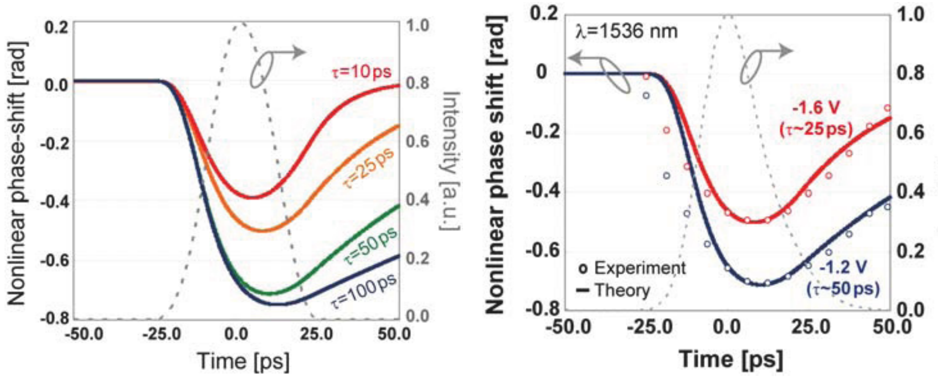
changing the reflectivity of the top mirror. We assumed the thickness of the saturable absorber is 50 nm, the design wavelength of the cavity is 1535 nm, the input spot-size is 4 μm, and the α-parameter, which is the ratio between the variation of refractive index Δn and absorption coefficient change $\Delta\alpha$, is 4 [4, 5]. For 40 Gb/s pulse signals, we need a carrier recovery time of around 10 ps.

3 Measurement



(a) (b)

Fig. 3. (a) Calculated carrier recovery time dependence of nonlinear phase-shift for 40 Gb/s signal of 13 dBm input power. (b) Measured nonlinear phase shift with reverse bias of 1.2 V and 1.6 V and for input peak power of 13 dBm.

We fabricated an InGaAlAs vertical-cavity saturable absorber based on a 1.55 μm VCSEL structure, which was grown in Corning Incorporated [6]. The device consists of 3-pair SiO_2/Ta_2O_5 (top-DBR), InGaAlAs/InP (bottom-DBR) and InGaAlAs QWs functioning as a saturable absorber. We carried out the measurement on the transient phase shift by using a pulse analyzer

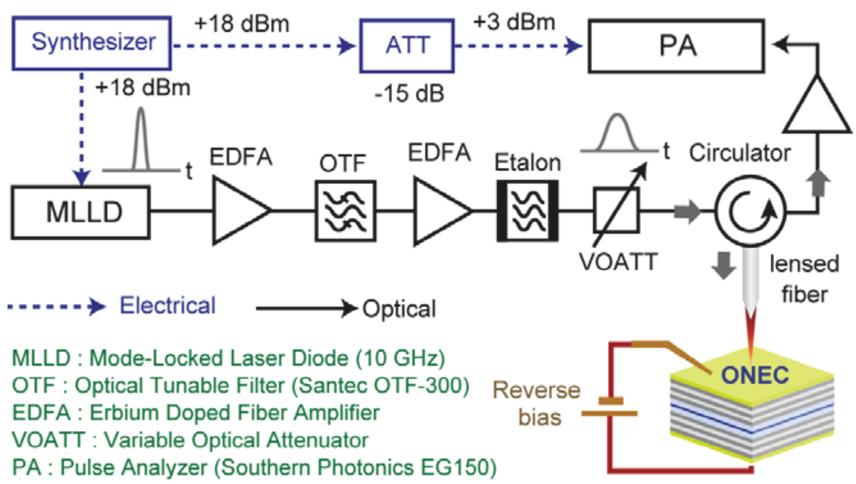


Fig. 4. Experimental setup.

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(Southern Photonics EG150). The experimental setup is shown in Fig. 4. We created 25 ps pulses, which correspond to 40 Gb/s signals, by inserting a narrow pass-band optical filter and etalon for 3 ps pulses from a tunable mode-locked laser diode. The input power is controlled by a variable optical attenuator. The insertion loss of the nonlinear-effect compensator at 1535 nm is about −8 dB, which could be reduced by reducing the number of pairs of the top mirror. Also, the coupling loss between a lensed fiber and the device is about 2.5 dB.

The measured dynamic response of the fabricated optical nonlinear-effect compensator is shown in Fig. 3 (b). We obtained a large negative phase-shift of −0.7 radian, which is large enough for compensating fiber nonlinearities. We estimated the carrier recovery time with a fitting in the rate equation analysis as about 50 ps and 25 ps for reverse biases of 1.2 V and 1.6 V, respectively. It is noted that the accuracy of phase-measurement can be guaranteed only for the main body of pulses due to the low intensity of pulse edges. The reduction of absorption recovery time below 10 ps with reverse bias would enable us to use the compensator for high bit-rate signals over 40 Gb/s.

4 Conclusion

We demonstrated the fast response of the optical nonlinear phase shift with reverse bias, exhibiting a recovery time of 25 ps. The optical bandwidth and the sign of the nonlinear phase shift can be controlled by changing the reflectivity of the top mirror. A large negative nonlinear phase shift of over −0.7 radian was observed for 25 ps short pulses. Faster response can be expected by increasing the reverse bias. The proposed concept may open up a novel technology for compensating fiber nonlinearities in optical domain.

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