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A tunable photonic temporal integrator with ultra-long integration time windows based on Raman-gain assisted phase-shifted silicon Bragg gratings

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ABSTRACT

A tunable photonic temporal integrator based on Raman-gain assisted phase-shifted silicon Bragg gratings is proposed and theoretically demonstrated. The proposed temporal photonic integrator is constructed using a silicon-on-insulator (SOI) π-phase-shifted Bragg grating, with a 25 V reverse bias applied to the p–i–n rib waveguide. Key feature of our design is that the length of integration time window could be widely tuned by simply changing the optical power of the pump light and could be extended to very long when the pump power is approaching lasing threshold. In addition, this scheme also has the potential for on-chip integration with other silicon photonics components.

1. Introduction

All-optical signal processing is highly desired in the fields of ultrahigh-speed telecommunications, ultrafast computing and ultrashort pulse shaping [1–5]. In the past few years, the implementation of basic signal processing functions in the optical domain has attracted considerable interests thanks to the advantages of high processing speed, low power consumption and wide operation bandwidth. A promising approach toward the implementation of all-optical signal processing is to emulate the developments in the electronic domain, i.e., to follow similar component and design strategies, using photonic technologies [6–9]. Up to now, many elementary optical signal processors such as photonic temporal differentiators [10–13], integrators [14–16] and Hilbert transformers [17–19] have been theoretically and experimentally investigated.

A temporal photonic integrator is a basic signal-processing component that performs real-time integration of an optical signal in the optical domain, which has many important applications in optical dark soliton detection [20], pulse shaping [16], optical memory [21] and photonic analog-to-digital conversion [22]. Recently, several kinds of techniques have been proposed to implement a temporal photonic integrator. A temporal integrator can be realized based on passive optical components such as Bragg fiber gratings (FBG) [23–25], a micro-ring resonator [26,27] and a time-spectrum convolution system [28]. Although the quite high bandwidth can be obtained using passive all-optical integrator, the integration time window is fixed and limited due to the loss of the cavity. In order to achieve a large integration time window, active all-optical integrators with gain compensation have been proposed and investigated. Slavik et al. reported the first experimental demonstration of all-optical integrator implemented by superimposed FBG made in Er–Yb co-doped optical fiber, and the function of this device was tested by integrating the optical pulses with time duration down to 60 ps [29]. Huang et al. proposed an optical temporal integrator based on an active Fabry–Perot cavity [30]. The operation bandwidth of 180 GHz over integration time window of 160 ns was predicted theoretically. In [31], an all-optical temporal integrator using phase-shifted distributed-feedback semiconductor optical amplifier (DFB-SOA) was numerically analyzed. By increasing injected current in the vicinity of lasing threshold, the energy transmittance and integration time window could be enhanced simultaneously. In [32], a silicon photonic integrator based on active silicon ring resonator utilizing Raman gain for loss compensation was achieved. This scheme is promising for optical integration and shows the excellent integral performance in a large input power range.

In this paper, we propose and theoretically demonstrate a silicon temporal photonic integrator based on a π-phase-shifted Bragg grating using Raman gain for loss compensation. The proposed temporal photonic integrator is constructed from a silicon-on-insulator (SOI) rib waveguide forming a π-phase-shifted Bragg grating. The performance of the temporal photonic integrator is

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numerically analyzed. An integration time window of 760 ns and an operation bandwidth of about 60 GHz are theoretically demonstrated. By simply changing the optical power of the pump light, the length of the integration time window can be widely tuned. Furthermore, the temporal photonic integrator has a potential for on-chip integration with other silicon photonics components to provide a highly integrated and scalable monolithic device. In addition, if a multiple-phase-shifted Bragg grating is introduced in our scheme, higher-order temporal integration could be simply achieved.

2. Theoretical model and operation principle

Fig.1 shows the scheme of the Raman based silicon temporal photonic integrator which is constructed from a SOI rib waveguide forming a π-phase-shifted Bragg grating. The central wavelength of pump light and signal light is 1550 nm and 1686 nm respectively. The frequency space between the pump light and the signal light is corresponding to the Raman frequency shift of 15.6 THz in silicon. Both the pump light and the signal light are located in the passband and thus can pass through the π-phase-shifted Bragg grating directly. At the out of the π-phase-shifted Bragg grating, the signal light will be amplified by the Raman gain. Fig. 2 shows the cross section of the silicon π-phase shifted Bragg grating. The Bragg grating is designed on a silicon rib waveguide which is fabricated on the (100) surface of a SOI substrate. The width of the rib waveguide is 1.5 μm, the height of the rib waveguide is 1.55 μm and the depth of the rib waveguide is 0.7 μm [33]. To reduce the optical loss caused by the two-photon absorption (TPA) induced free carrier absorption (FCA), a reverse biased p–i–n diode is fabricated in the waveguide. The separation between the edge of p and n regions is 6 μm [33].

The integration of an input signal $f(t)$ can be calculated by the convolution between $f(t)$ and the impulse response of an ideal integrator, which is the step function $u(t)$ in the time domain.

$$u(t) = \begin{cases} 1, & t \geq 0 \\ 0, & t < 0 \end{cases} \tag{1}$$

In the frequency domain, the transfer function $H(\omega)$ of the ideal integrator can be written as the Fourier transform of Eq. (1)

$$H(\omega) \propto \frac{1}{i(\omega - \omega_0)} \tag{2}$$

where ω is the optical frequency and ω_0 represents the carrier frequency of the signal. In the following, we will prove that the transfer function of our π-phase-shifted Bragg grating using Raman gain for loss compensation can be well approximated by Eq. (2).

For a π-phase-shifted Bragg grating, the forward and backward waves can be described by the following transfer matrix [31]

$$\begin{bmatrix} A_f(L) \\ A_b(L) \end{bmatrix} = T_\Sigma \begin{bmatrix} A_f(0) \\ A_b(0) \end{bmatrix} = T_1 T_\varphi T_2 \begin{bmatrix} A_f(0) \\ A_b(0) \end{bmatrix} \tag{3}$$

where A_f and A_b denote the amplitudes of forward and backward waves in the grating respectively. The transfer matrixes T_1 and T_2 can be given as

$$T_1 = T_2 = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) + i\frac{\sigma}{\gamma}\sinh(\gamma l) & i\frac{k}{\gamma}\sinh(\gamma l) \\ -i\frac{k}{\gamma}\sinh(\gamma l) & \cosh(\gamma l) - i\frac{\sigma}{\gamma}\sinh(\gamma l) \end{bmatrix} \tag{4}$$

where k is the coupling coefficient of the grating, $\sigma = 2\pi n_{eff}(1/\lambda - 1/\lambda_B) - ig_{net}/2$ is the detuning from the Bragg wavelength λ_B, n_{eff} is the efficient refractive index in the silicon grating, g_{net} is the net gain of Stokes light in the grating, $l = L/2$ is the half of the grating length and $\gamma = \sqrt{k^2 - \sigma^2}$. The transfer matrix of phase-shifted sub-section T_φ can be obtained as

$$T_\varphi = \begin{bmatrix} \exp(i\varphi/2) & 0 \\ 0 & \exp(-i\varphi/2) \end{bmatrix} \tag{5}$$

For a transmissive π-phase-shifted Bragg grating, the transfer function can be calculated as [31]

$$H(\omega) = \frac{A_f(L)}{A_f(0)} = \frac{1}{T_{\Sigma,22}} = \frac{1}{i\frac{k^2}{\gamma^2}\sinh^2(\gamma l) - i[\cosh(\gamma l) - i\frac{\sigma}{\gamma}\sinh(\gamma l)]^2} \tag{6}$$

The lasing threshold gain gth is determined by the condition of $T_{\Sigma,22}(\omega_0) = 0$, which means if the net gain of the Stokes light g_{net} is quite close to gth, the transfer function $H(\omega)$ can be written as follows:

$$H(\omega) \approx \frac{1}{T_{\Sigma,22}(\omega_0) + T_{\Sigma,22}`(\omega_0)(\omega - \omega_0)} \propto \frac{1}{\omega - \omega_0} \tag{7}$$

Thus, the silicon Raman π-phase-shifted Bragg grating can be employed as a type of active photonic temporal integrator.

To achieve the enough optical gain, we introduce the stimulated Raman scattering in the grating. It is well known that the Raman frequency shift in silicon is 15.6 THz, which means if the wavelength of pump light is 1550 nm, then the wavelength of Stokes light will be about 1686 nm. Although the linear loss in silicon at wavelength of 1.3–1.7 μm is small, the TPA induced FCA can significantly reduce the Raman amplifying due to the relatively long free carrier lifetime [33]. However, if a reverse biased p–i–n junction is imbedded in the silicon waveguide, the carrier lifetime will decline with the increase of reverse bias. For instance, the carrier lifetime could reduce to ~1.0 ns with a reverse bias of 25 V [33].

The optical power of pump light and Stokes light in the silicon waveguide can be described by the following equations [33,34]:

$$\frac{\mathrm{d}}{dz}I_P(z) = \left[-\alpha_P - \frac{\beta}{A_{eff}}I_P(z) - \frac{\sigma_P \beta \tau_{eff}}{2E_P {A_{eff}}^2}{I_P}^2(z) \right] I_P(z) \tag{8}$$

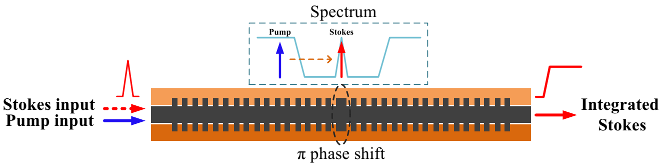

Fig.1. The scheme of the Raman-gain assisted silicon photonic temporal integrator.

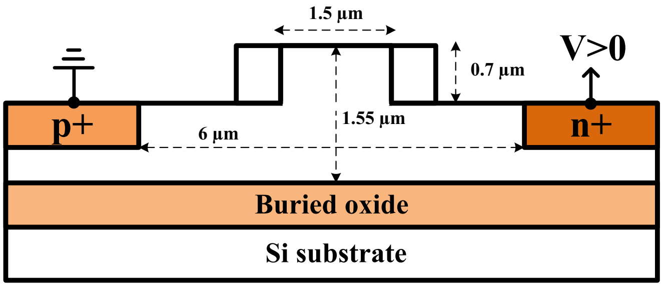

Fig.2. The cross section of the π-phase-shifted silicon Bragg grating.