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Invited Paper

Optical-biased modulator employing a single silicon micro-ring resonator

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ABSTRACT

We propose and experimentally demonstrate an optical-biased modulator employing a single silicon micro-ring resonator. By adjusting optical bias, the micro-ring modulator is capable of generating several modulation formats, namely, on–off keying, binary phase shift keying and reversed on–off keying, at the speed of 0.4 Gbit/s with extinction ratio higher than 5 dB. Compared to the previous reported bias control approaches, the optical bias proposed in this study is a novel mechanism, which can be easily conducted without complicated integrated structures or redundant electrical devices. Meanwhile, optical bias can also effectively protect the vulnerable integrated silicon devices from possible damage induced by high direct current voltage.

1. Introduction

Integrated silicon optical modulator, which has long been a focus of the scientific community, is vitally important as one of the main functional elements for the future optical interconnection system [1]. Remarkable progress in silicon modulators is achieved in recent years, such as ultra-high speed silicon modulator [2], ultralow power consumption silicon modulator [3] and integrated silicon modulator with novel structures [4]. In previous researches, several approaches were proposed to control the bias of integrated modulators, such as using micro-heaters [5], tuning the signal's wavelength [6] and employing electrical bias [7]. Among the methods mentioned above, the employment of micro-heater on a silicon modulator greatly adds to the complexities during the fabrication process while tuning the signal wavelength may cause trouble in the high speed wavelength division multiplex (WDM) communication systems. Furthermore, as the most commonly used method at the present, electrical bias relies on some electrical devices such as bias tee to accomplish bias control in integrated modulators, which seriously impedes the all-optical integration and causes the system to be bulky. Meanwhile, because most integrated optical devices are extremely vulnerable to high voltage, the voltage of DC bias must be carefully adjusted or it can induce serious damage to the integrated optical modulators.

In this letter, we propose and experimentally demonstrate an optical-biased modulator employing a single micro-ring resonator (MRR). We can obtain non-return-zero on–off keying (NRZ-OOK), binary phase shift keying (BPSK) and reversed NRZ-OOK signals at fixed wavelength in a single MRR modulator by adjusting the power of a continuous wavelength (CW) as the bias. The fundamental physics of the optical bias is the optical induced thermal effect, which causes the red shift of resonance in the MRR [8]. Compared to the previous methods of altering bias in the integrated silicon modulators, the employment of optical bias neither requires additional integrated structures such as micro-heaters nor depends on external electrical devices such as bias tee. Meanwhile, the optical bias can protect the modulators completely from potential harm induced by high DC voltage. Hopefully, the optical manipulation of the modulator bias proposed in this study can overcome most disadvantages of previous methods. With ultra-small footprint, the optical-biased modulator can also reduce the interconnect systems complexity and pave the way of all-optical integrated modulator as a novel way of on-chip optical manipulation.

2. Operation principle

Fig. 1 gives an overview about the working principle of optical-biased modulator. Assume that the wavelength of input continuous wavelength (CW) light is aligned with the MRR resonant wavelength. Meanwhile, another CW light whose wavelength is aligned with another resonant wavelength acting as the optical bias. When no optical bias is applied, the transmission of through port of MRR is positively varied as the voltage applied on the MRR is increased, due to the plasma dispersion effect induced by

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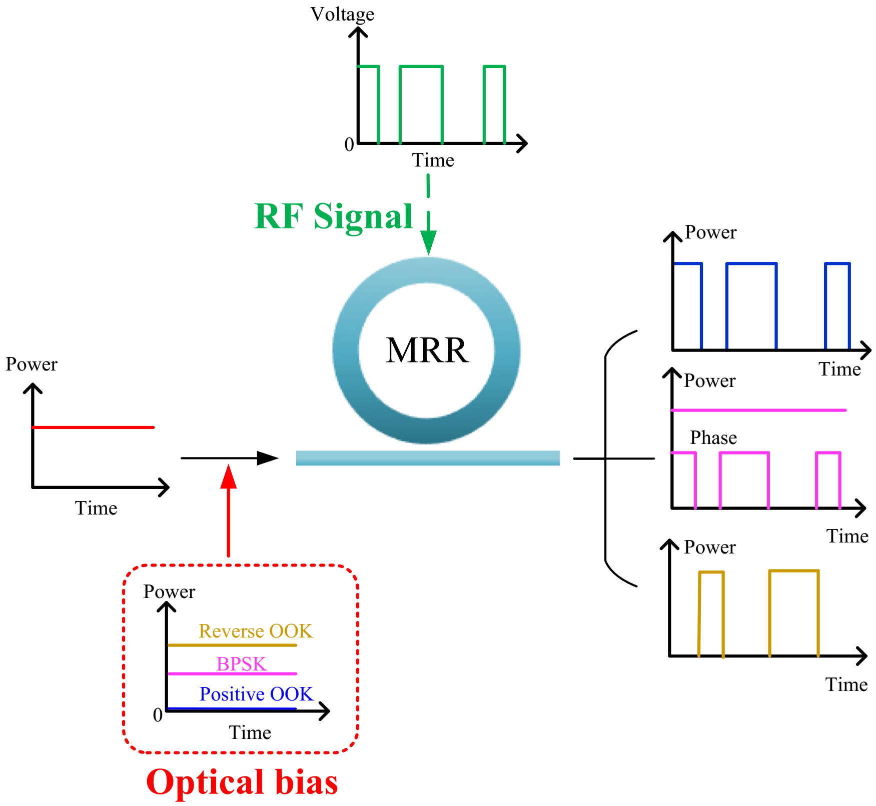

Fig. 1. Overview about the working principle.

external voltage [9]. In this case, the CW light is positively modulated by electrical frequency (RF) signal. Thus positive NRZ-OOK signal can be obtained, as the blue waveforms show. When we add an optical bias, the input light will heat the high quality factor (Q) MRR remarkably owing to its strong resonance phenomenon. Meanwhile, significant red-shift of the initial transmission spectrum is generated due to the large thermo-optic coefficient in silicon. In this way, the transfer function of the modulator, i.e., the transmission of the MRR at the resonant wavelength with different external voltages, can be altered to obtain different signal formats. Via choosing the power of optical bias properly, we expect the modulator to be capable of generating both BPSK and reversed NRZ-OOK signal, as the waveforms in pink and brown color show respectively.

To verify the feasibility of the optical bias, we calculate the red-shift of the MRR transmission spectrum under different optical bias power. In the calculations, we believe that the thermal effect caused by high power light is the dominant phenomenon under these circumstances, despite the fact that the free carriers generated from two photons absorption may induce blue shift when the heating just starts [10]. According to theoretical model of optical induced thermal effects in the high-Q micro-cavity community, the red-shift response of the MRR can attain a steady red-shift state finally under given optical power. The Eqs. (1) and (2) gives the relationship between the input optical power and the corresponding amount of red-shift [8].

$$0 = I_h \frac{1}{\left(\frac{\lambda_p - \lambda_r}{\Delta\lambda/2}\right)^2 + 1} - K\Delta T \tag{1}$$

$$\lambda_r = \lambda_0(1 + a\Delta T) \tag{2}$$

where I_h is the optical power that heats the cavity λ_P, λ_0 and λ_r represent the input wavelength, the cold cavity resonance-wavelength and resonance wavelength after red-shift respectively, α is the temperature coefficient of resonance-wavelength, ΔT is the temperature difference between mode volume and the surrounding, K (J/s °C) is the thermal conductivity between the cavity mode volume and the surrounding. For a given pump light with the wavelength fixed at the cold cavity resonance-wavelength, one stable solution of ΔT for Eq. (1) can be calculated, inducing a stable red-shift of the resonance described as Eq. (2). In the calculations, we assume that Q factor of the MRR is 15,000 with the resonant wavelength of 1550 nm, indicating a resonance width of 0.1 nm, the temperature coefficient of resonance wavelength is $5.34{*}10^{-5}$ (1/°C) and thermal conductivity is 3.81(J/s °C). The red shift of the MRR dependent on the optical bias power is shown in Fig. 2. It should be noted that the high optical power coupled to the waveguide will cause the two photon absorption (TPA) and generate excessive free carriers. These free carriers may induce free carrier dispersion (FCD) and free carrier absorption (FCA). The FCD will contribute to the modulation, which may only alter the external voltage applied in the modulation. Meanwhile, the FCA will result in nonlinear loss, which will increase the insertion loss of the modulator and can be compensated by optical amplifier. Therefore, both FCD and FCA will not have serious impact on the performance of the modulator. In addition, due to the external voltage, the free carriers will be swept out and the lifetime of the free carriers will be very short comparing to the modulation speed. Thus, we believe that the nonlinear effect induced by the high power will not significantly affect our experiment results.

We can see that, the red-shift caused by thermo-optic effect can be as large as 0.42 nm when the optical bias power reaches 10 dBm. Meanwhile, the red-shift is continuously varied with the optical bias power. Furthermore, with the help of the plasma dispersion model in silicon, the transfer function of the MRR modulator under different optical bias powers can be