10Gbit/s Bias-free and Error-free All-optical NRZ-OOK to RZ-OOK Format Conversion Using a III-V-on-silicon Microdisk Resonator

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Abstract: We report the experimental demonstration of an all-optical, bias free and error-free (bit-error-rate ~10^{-12}), 10Gbit/s non-return-to-zero (NRZ) to return-to-zero (RZ) data format conversion in a 7.5µm diameter III-V microdisk integrated on top of a silicon-on-insulator (SOI) waveguide circuit.

OCIS codes: (130.3120) Integrated optics devices; (230.0230) Optical devices; (230.1150) All-optical devices.

1. Introduction

Return-to-zero (RZ) and non-return-to-zero (NRZ) are commonly used modulation formats in optical communication systems. Depending upon the size and requirements of the network, either the NRZ or RZ modulation format can be selected for use in future optical networks [1]. Format conversion from NRZ to RZ and vice-versa is important to add to the flexibility and scalability of optical networks. In the past decade, a large amount of research work has been reported on format conversion from NRZ to RZ. The reported work on NRZ-to-RZ format convertors includes all-optical e.g. [2] as well as optoelectronic e.g. [3] approaches. The majority of the investigated all-optical format convertors are based on semiconductor optical amplifiers (SOAs) while very few used other devices such as periodically poled lithium niobate waveguides, silicon waveguides and III-V waveguides. All-optical data format convertors reported so far have larger footprints and typically have a length in the range of several hundreds of micrometers to a few tens of millimeters. Larger footprints make these devices difficult to be integrated and hence less suitable for practical use. Moreover, most of these devices, mainly based on SOAs, need a dc electric bias which results in extra power consumption.

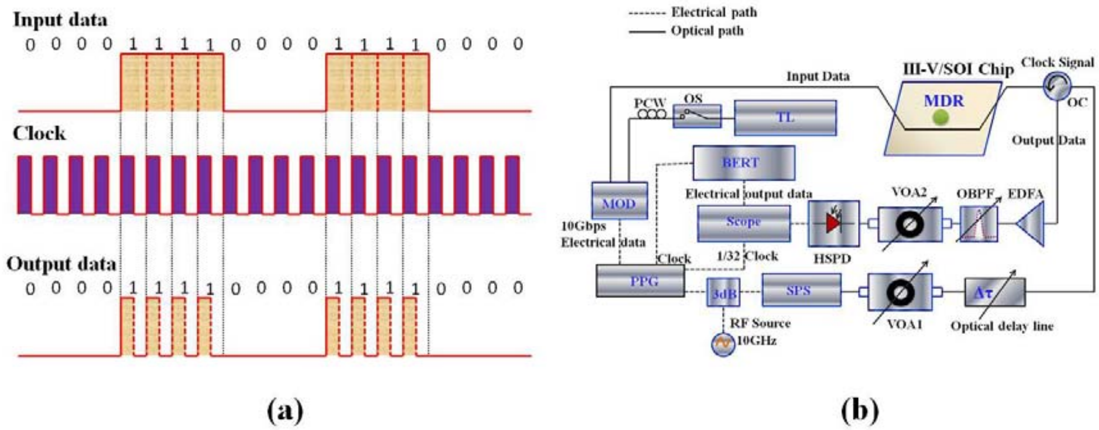
In the recent past silicon-on-insulator (SOI) technology has emerged as a promising platform for the fabrication of photonic devices due to its CMOS compatibility. All-optical devices fabricated in pure silicon rely on nonlinear effects such as four-wave-mixing (FWM), self-phase modulation (SPM), and two-photon absorption (TPA) etc., but these effects in silicon are known to be power-hungry. The NRZ to RZ format conversion has been shown to be viable on a silicon chip [2] but the total average power used was quite high (~34dBm in the silicon waveguide). The III-V-on-silicon resonant structures (such as microdisks and microrings) can be used to reduce the power consumption along with a reduction in the footprint of the device while still taking advantage of the CMOS fabrication technology to fabricate these devices [4,5]. High speed operation has been demonstrated for III-V-on-silicon resonant structures by the use of plasma dispersion effect resulting from the free carrier generation in a pump-probe configuration [6]. Here, we report the demonstration of an all-optical 10Gbit/s NRZ-OOK to RZ-OOK format conversion, without using any dc electrical bias, in an InP-InGaAsP disk of 7.5 micron diameter heterogeneously integrated on top of an SOI waveguide circuit.

2. Device fabrication

The SOI waveguide circuit as well as III-V (InGaAsP-InP) microdisk resonator are defined using 193nm deep ultra-violet (DUV) lithography. The width and the thickness of the silicon waveguide are 600nm and 220nm respectively, while the BOX (buried oxide) is 2µm thick. Grating couplers are defined in silicon to couple light in- and out of the SOI waveguide. The III-V material is bonded on top of the SOI waveguide circuit using an SiO_2 molecular bonding process resulting into a 130nm thick bonding layer. The III-V microdisk is etched such that the periphery of the microdisk overlaps with the silicon waveguide covering a width of 500nm. This overlapping section allows the evanescent coupling of the light from the waveguide to the microdisk and vice-versa. The diameter and thickness of the microdisk is 7.5μm and 580nm respectively. More details on the design as well as on the fabrication process can be found in ref. [4].

3. Theory and concept of NRZ-to-RZ conversion

Refractive index modulation caused by the free carrier generation in a pump-probe configuration can be used to change the transmission characteristics of a microdisk/ring resonator in real-time. If an optical clock is used as a pump and the optical data signal as a probe, then the format of the optical data signal can be changed from NRZ to RZ provided that the duration of the optical clock pulse is shorter than the bit duration of optical data. This is illustrated in figure 1(a).



(a) (b)

Fig. 1. (a) Illustration of format conversion from NRZ to RZ and (b) Schematic of the experimental set-up used for the format conversion. OS: Optical Switch, MDR : Microdisk Resonator

If the wavelength of the data signal is chosen to be on- resonance then in the absence of the clock pulses, the data signal will be coupled into the microdisk. In the presence of the clock pulses, free carriers will be generated resulting in a blue shift of the resonance and the data will become off-resonance for the duration of the pulses. Therefore, the data output is high only when the level of the input data as well as that of the clock are high. This results into conversion of a NRZ-OOK signal into a RZ-OOK signal.

4. Experiments and Results

The transmission resonance characteristics of the microdisk resonator are found by scanning the wavelength of a continuous wave (CW) tunable laser. Two azimuthal mode resonances, one at 1550.1nm and another at 1580.9nm are found. To perform the format conversion experiment, the optical data and the optical clock is chosen to be at 1580.9nm and 1550.1nm respectively. The sketch of the experimental set-up used is drawn in figure 1(b). A 10Gbit/s NRZ-OOK optical data signal is generated using an electric pulse pattern generator (PPG), an electro-optic $LiNbO_3$ modulator (MOD) and a tunable laser (TL). The use of polarization controlling wheels (PCWs) ensures that the generated optical data is TE polarized. To generate the optical clock signal, a short pulse source (SPS) is used. It is driven by the same RF source, using a 3dB RF splitter, which drives the PPG. The optical clock has a repetition rate of 10GHz has and a pulse width (FWHM) of ~8ps. A variable optical attenuator (VOA1) is used to regulate the output power of the optical clock. An optical delay line is used to synchronize the optical clock with the optical input data. The output data is collected at the drop-port of an optical circulator (OC) and is amplified using an L-band erbium-doped fiber amplifier (EDFA). An optical band pass filter (OBPF) follows the EDFA to suppress the ASE noise. A variable optical attenuator (VOA) is used to control the input power to the high-speed photodiode (HSPD) connected to the scope. For the bit-error-rate measurements, the electrical output data from the scope is fed to a bit-error-rate tester (BERT). The average power of the input optical data and the optical clock in the SOI waveguide is estimated to be ~ -2 and +1 dBm respectively.

The 10 Gbit/s NRZ-OOK input optical data waveform consisting of alternate 1s and 0s and the optical clock are shown in figure 2(a) and 2 (b) respectively. In figure 2(b), the pulse width looks much wider than its actual width (FWHM~8ps) due to the limited bandwidth of the photodiode (~30GHz). Figure 2(c) shows the format converted optical data output pattern. The 1 bit of the optical output data occupies a time slot of ~50ps although the clock duration is much shorter than this time slot. This is due to the slower dynamics of the photo-generated carriers in the microdisk. For the system performance measurements, the optical input data signal is changed to a PRBS pattern of length 2^7-1. Figure 2(d) shows a part of the waveform of the format converted PRBS signal from NRZ-

OOK to RZ-OOK. Figure 2(e) shows the BER measurement curves of the input NRZ-OOK and the output RZ-OOK data. The eye diagrams corresponding to input NRZ and output RZ data are also shown in the same figure. It is to be noted that the BER measurements for the input NRZ data are performed by keeping it off-resonance of the microdisk. An error free (BER~10^{-12}) format conversion is achieved with a power penalty of 3.6 dB. The power penalty is because of the ASE noise added due to the amplification of the format converted signal. The amplification is required for the format-converted signal because it has half the power of the original signal due to the basic procedure and principle of the format conversion involved here.

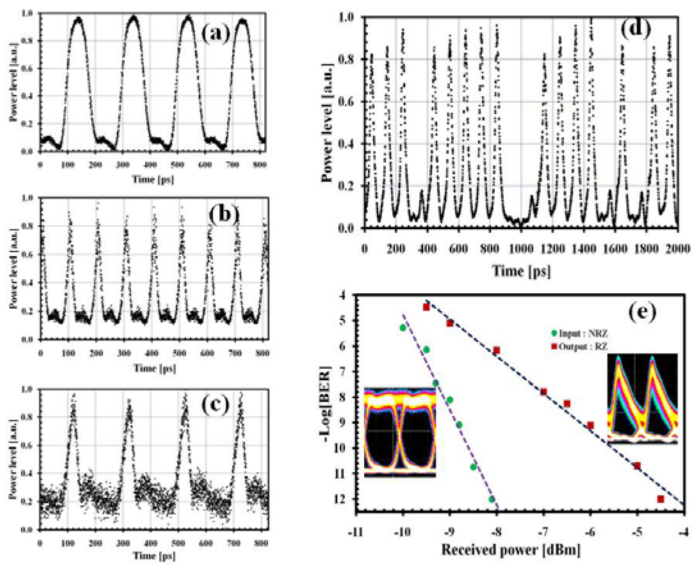


Fig. 2. (a) Input optical data 1010…., (b) Optical clock, (c) Output optical data, (d) PRBS2^7-1 data output (e) System performance

5. Conclusions

We have demonstrated an error-free and bias-free 10 Gbit/s NRZ-OOK to RZ-OOK format conversion in an ultra-small III-V-on-silicon microdisk completely processed in a CMOS pilot line. The format conversion is achieved with a moderate power penalty and relatively low average power consumption. The demonstrated format convertor has the potential of integration with other active and passive on-chip devices.

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