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Ultralow Power Silicon Microdisk Modulators and Switches

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Abstract: We demonstrate a 4μm silicon microdisk modulator with a power consumption of 85fJ/bit. The modulator utilizes a reverse-biased, vertical *p-n* junction to achieve 10Gb/s data transmission, with 3.5V drive voltage, BER<10^{-12}, and without signal pre-emphasis. High-speed silicon bandpass switches are constructed from pairs of modulators.

1. Introduction

Communications links on high performance computers currently use electrical or directly modulated laser optical communication links that are connected to microprocessors indirectly through electrical transmission lines. In either case, powering an electrical communication line is necessary. Further, the bandwidth densities offered by multi-mode fibers do not substantially improve upon that provided by electrical transmission lines. However, optics, closely integrated with CMOS electronics has been proposed as a means for substantially improving upon the power consumption of electrical communications links [1]. Further, with silicon microphotonics, wavelength division multiplexing can readily be implemented [2] to drastically increase bandwidth density by enabling multi-terabit per second communication links that are compatible with CMOS electronics.

While many silicon modulator designs have been implemented [3-5], to date, all such devices, both resonant and non-resonant, have consumed a considerable amount of power, and, in the case of forward biased structures [3,5], required signal pre-emphasis in order to achieve data rates of 10Gb/s. Here, we demonstrate a new class of silicon microdisk modulators that utilize a vertical *p-n* junction. The vertical *p-n* junction in a 4μm diameter microdisk modulator enables sufficient modal overlap to achieve 10Gb/s reverse-biased operation with a low, 3.5V, drive voltage and without signal pre-emphasis. A bit-error-rate (BER) below 10^{-12} was demonstrated along with a measured power consumption of only 85fJ/bit (85μW/Gb/s), a new record for silicon modulators. Further, recent finite element simulations demonstrate the potential for 10fJ/bit communications with drive voltages of only 2.5V. Finally, we demonstrate the first high-speed silicon bandpass switches by coupling a pair of these modulator structures [6]. All of these devices were fabricated on a CMOS fabrication line using optical lithography.

2. Discussion and Experimental Results

A cross-sectional diagram and a scanning electron micrograph (SEM) of the fabricated silicon microdisk modulator are presented in Fig. 1a and 1b, respectively. The modulator consists of a 4μm diameter microdisk resonator with a vertically oriented *p-n* junction coupled to a pair of silicon bus waveguides. The modulator was fabricated from a

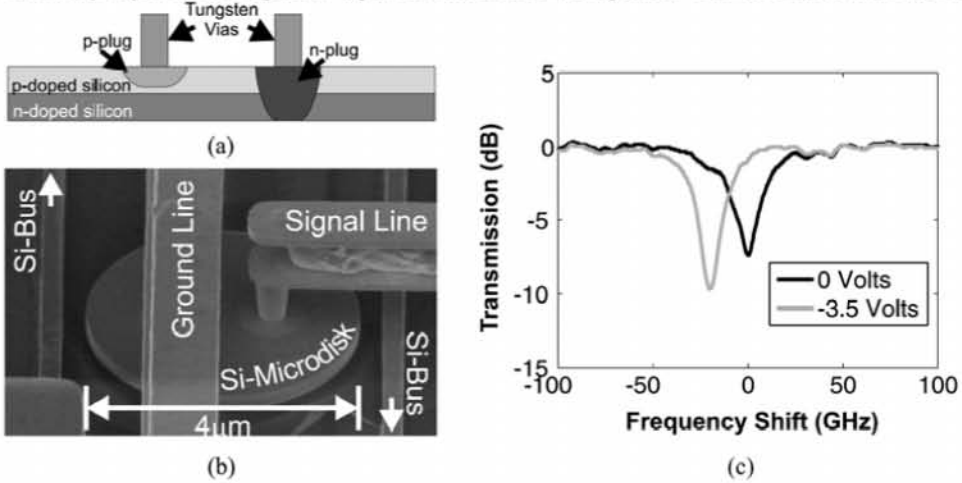
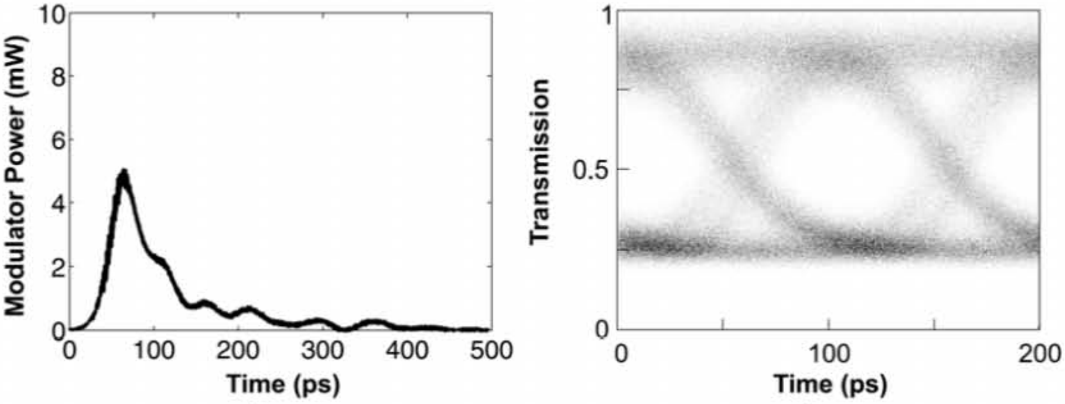


Figure 1. (a) Cross-sectional diagram of the microdisk modulator highlighting the vertical p-n junction and method of contact. (b) A scanning electron micrograph of the fabricated 4μm diameter microdisk modulator and (c) the optical spectra of the microdisk with no bias and a 3.5V reverse bias applied. The center wavelength of the unbiased resonance is 1578nm.

silicon-on-insulator (SOI) wafer with an initial 250nm silicon layer thickness and 3μm of buried oxide. The modulator geometry was defined with an ASML Deep Ultra-Violet (DUV) laser scanner and silicon etch. Contact to the *p-n* junction was made with tungsten vias connected to highly doped p+ (B) and n+ (P) plugs. The modulator operates on the free-carrier-effect in silicon [7] and a reverse-biased voltage serves to modulate the depletion width of the vertical *p-n* junction and thereby modify the modal index, and resonant frequency of the microdisk. In this manner, all contacts are kept within the interior of the microdisk enabling a hard outer silicon wall of the microdisk to be maintained. This is in contrast to all previously demonstrated silicon microring modulators and it is this hard outer wall that enables maximum confinement of the whispering gallery mode and the realized 2μm bend radius to be achieved without inducing radiation loss. Further, the use of a vertical *p-n* junction maximizes the overlap of resonator mode with the depletion width, enabling sufficient changes in the resonant frequency to be achieved with low reverse-biased voltages. The optical responses of the modulator with no applied bias and with a 3.5V reverse-bias voltage applied are presented in Figure 1c. With a 3.5V reverse bias, a frequency shift of -20GHz is achieved. This frequency shift is sufficient to provide 8dB of extinction between the two states. Further, this extinction ratio can readily be improved upon by removal of one of the bus waveguides and tuning in the coupling coefficients to match the losses in the modulator. However, the use of a pair of bus waveguides leaves free the option for using one of the guides as a power bus and, this extinction is sufficient for achieving good contrast in the modulated output.



(a) (b)

Figure 2. The switching energy of the modulator at a drive voltage of 3.5V was measured using electrical time domain reflectometry to be 340fJ. The modulator power consumption for a 3.5V voltage step as a function of time is plotted in (a). It is important to note that the energy/bit is one-fourth the switching energy for a non-return-to-zero (NRZ) data format since power is only consumed for 0-to-1 transitions. Therefore, the energy/bit is 85fJ. Shown in (b) is an eye-diagram for the modulator with a 10Gb/s NRZ data format with a PRBS pattern length of 2^{31}-1. The bit-error-rate (BER) was measured to be less than 10^{-12} for a pattern length of 2^{15}-1 and 10^{-9} for a pattern length of 2^{31}-1. The modulator was driven directly from the 1.8V output of the PRBS generator with no amplification or pre-emphasis. Due to the high impedance of the device, the voltage realized across the junction was ~3.5V.

To determine the dynamic performance of the modulator, it was driven directly with the 1.8V output of a 10Gb/s non-return-to zero (NRZ) pseudo-random bit-stream (PRBS) generator with no signal amplification or pre-emphasis. An eye-diagram for the modulator with a 10Gb/s NRZ data format and a PRBS pattern length of 2^{31}-1 is presented in Figure 2b. The bit-error-rate (BER) was measured to be less than 10^{-12} for a pattern length of 2^{15}-1 and 10^{-9} for a pattern length of 2^{31}-1. The increased error rate at longer pattern lengths is believed to be due to a combination of thermo-optic effects and the low received power level resulting from poor fiber-to-chip coupling.

Since one of the primary drivers in considering optical inter- and intra-chip communications networks is reducing power consumption, the required energy per transmitted bit is of equal, if not more importance, than the data rate and BER. Although the drive voltage from the PRBS was only 1.8V, the voltage realized across the p-n junction was closer to 3.5V on account of the impedance mismatch between the 50Ω line and the high impedance modulator. The power absorbed in the modulator with a voltage of 3.5V was determined by a series of small-signal time domain reflectometry measurements with step voltage inputs in ½Volt increments up to 3.5V. The total power consumption was determined by comparing the difference in the power reflected when the microwave probe was in contact with the device or in contact with an open-circuited device with probe pads. The difference between these measurements is the power absorbed in the modulator and is presented in Fig. 2a. The switching energy was then determined to be 340fJ by integrating the absorbed power. This is in close agreement with the 230fJ switching energy predicted by finite element simulations. It is important to note that the 0-to-0, 0-to-1, 1-to-0, and 1-1 transitions are all equally probable in an NRZ PRBS, and since the device has essentially no dark current (<100pA) and energy is only required to make the 0-to-1 transition, the energy/bit is ¼ of the 0-to-1 switching energy. Therefore, the average energy/bit is 85fJ.

Traditional electrical and optical interchip communication lines require on the order of 10pJ/bit (10mW/Gb/s). Here we have demonstrated the ability to generate data at 85fJ/bit (85µW/Gb/s) or approximately two-orders of magnitude less than more traditional techniques. Moreover, since the switching energy is simply CV^2, more intricate doping profiles that are limited primarily to the outer regions of the disk where the optical mode resides will reduce the capacitance and the required energy/bit even further. And while the power consumption of the laser source and the receiver have not been taken into account, it can argued that the power consumption of these components will be less than 10fJ/bit. The arguments are based on the idea that with low capacitance receivers, CMOS logic gates can be driven directly without the need for amplification [1]. As a final point, high-speed, high-order bandpass switches can be constructed from multiple modulators coupled together. An SEM of a fabricated and previously demonstrated [6] structure is shown in Fig. 3a and the filter response depicted in Fig. 3b as a function of applied forward bias along with the dynamic response of the switch demonstrating greater than 16dB extinction in the Thru port and 20 dB extinction in the Drop port with a ~2.4ns switching time (Fig. 3c).

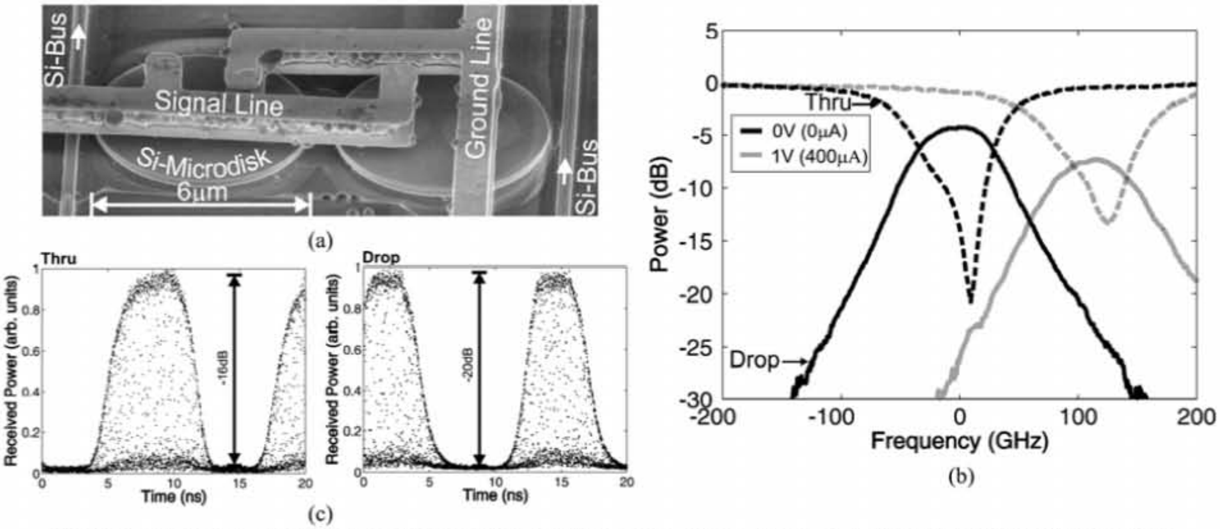


Figure 3. (a) Cross-sectional diagram of the microdisk bandpass switch. (b) The bandpass of the switch under 0V and 1V applied bias and (c) the dynamic response of the switch in the Thru and Drop ports switching 10Gb/s data. The center wavelength is 1533nm.

3. Conclusions

We demonstrate the first silicon microphotonic modulator to achieve less than 100fJ/bit. The modulator, utilizes a reverse-biased, vertical *p-n* junction to achieve 10Gb/s data transmission, with low drive voltage (3.5V), $BER<10^{-12}$, and without signal pre-emphasis. Together with high-speed, low-power, bandpass switches, microdisk modulators have the potential to form the building blocks for richly interconnected short-range optical networks such as the three-dimensional mesh networks connecting high-performance supercomputers. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

4. References

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