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A Silicon Optical Transistor

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Abstract

We demonstrate an all-optical transistor with the modulated output signal simultaneously having an output/input ratio > 3 dB and ON/OFF ratio > 20 dB. The microring based device is ultra-compact and CMOS compatible.

1. Introduction

Interconnected electronic transistors are the building blocks of logic systems that form one of the core infrastructures of our society. To be scalable, an optical transistor must be cascable, and provide signal gain, logic level restoration and input/output isolation [1]. To be practical, it is preferred to offer in-plane input/output, small footprint and compatibility with CMOS technology. However, almost all previous proposals or demonstrations of optical logic devices fail to meet both sets of criteria. In this work, we demonstrate an all-silicon optical transistor that meets all those requirements (Fig. 1).

Analogous to the source, gate and drain of an electronic transistor, the three ports of the optical transistor are labeled as *feed*, *gate* and *through* (Fig. 1A). The feed port is a source of photons; the gate port provides an optical signal that can control the feed signal; and the through port is the output of the device. An optical transistor is realized using an asymmetrically coupled add-drop filter (ADF) and cascaded notch filter (NF), critically coupled to the feed waveguide. The dominant nonlinearity used in the device is the thermo-optic effect.

2. Results and Discussion

Fan *et al.* has demonstrated that the optical power inside the add-drop filter (ADF) microring is higher when light of identical power is coupled from the bus waveguide with a smaller gap (*e.g.* the gate waveguide), than from a bus waveguide with a larger gap (*e.g.* the feed waveguide) [2]. Hence, a weak power at the gate (strong coupling to the microring) of the ADF can appreciably alter the resonance of the ADF ring, even if relatively high power exists at the feed (weak coupling to the microring). Fig. 1B shows the transmission spectra

for both gate ON and OFF. With the gate ON (the gate wavelength is set to a different longitudinal mode from the feed for the resonator), the resonance of the ADF is shifted to match with λ_f causing a moderate drop of the feed power before it enters the NF. This reduced power will be further attenuated significantly by the NF, which is at the critical coupling condition. With the gate OFF, feed power at λ_f will not be attenuated by the ADF since the ADF ring resonance is away from λ_f . Consequently, the feed power is high enough to induce nonlinearity in the NF ring, thus avoiding the critical coupling condition and suffering only a minor attenuation. An ON/OFF ratio of 21.80 dB (> 150 times) is observed at λ_f (Fig. 1B). Simultaneously, a gain of 3.26 dB, defined as the ratio of the through power at logic 1 (gate OFF, the blue curve at λ_f in Fig. 1B) to the gate power at ON state for an inverter, is achieved. Thus our device can achieve fan out, *i.e.* the output can control two or more subsequent optical transistors. Since the output transitions from high to low (logic 1 to logic 0) when the gate power goes from low to high (logic 0 to logic 1), this device operates as an inverting transistor.

The optical transistor is tolerant to the wavelength and power fluctuations that may occur in practical systems. The device maintains an ON/OFF ratio higher than 12 dB within ± 20 pm changes in wavelength for both feed and gate ports (Fig. 2A and Fig. 2B). The device can also operate under different feed powers (Fig. 2C) for the same gate power which can result in controllable gain (Fig. 2D) and ON/OFF ratio (Fig. 2E).

To investigate switching operation, we sweep the gate power upward and downward to characterize the power transfer characteristic of the optical transistor. A sharp transition with a narrow hysteresis loop is observed (Fig. 3A). The through port output dependence on the sweeping direction is due to the bistability of the microrings. By operating beyond the hysteresis region, one can digitally switch the optical transistor ON and OFF by changing the gate power (Fig. 3B). An input power variation of ~ 2 dB at the gate results in a strong modulation with ~ 18 dB On/Off ratio at the through port. This logic level restoration function is analogous to a CMOS buffer in electronics which is used to restore and amplify a degraded signal.

3. Conclusion

To our best knowledge, no previous all-optical device has demonstrated such performance and tolerance. The all-silicon optical transistor proposed and demonstrated has many characteristics of its electronic analog and promises to be a stepping stone for future optical signal processing.

References

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Fig. 1. Schematic and characteristics of the all-silicon optical transistor
 (A) The schematic of the add-drop filter (ADF) with asymmetric coupling. (B) Transmission spectra of the optical transistor with gate OFF (in blue) and ON (in red) at a feed power of 1.4 mW and gate power of 0.19 mW. The error bars are the standard deviations extracted from multiple measurements.

Fig. 2. Wavelength and feed power tolerance of the optical transistor

(A) ON/OFF ratio vs. feed wavelength detuning when the feed power is detuned from 1587.700 nm. (B) On/Off ratio vs. gate wavelength detuning for identical power settings in (A) with the gate wavelength now detuned from 1570.220 nm. The error bars are the standard deviations extracted from multiple measurements. (C) The through port spectra with increasing feed power plotted with a y-axis offset. The feed power for (I) to (V) is about -3.25 dBm, -2.25 dBm, -1.25 dBm, -0.25 dBm and 0.75 dBm respectively. The gate power is at -5.75 ± 0.14 dBm. (D) Plot of gain vs. feed power for (C). (E) Plot of ON/OFF ratio vs feed power for (C).

Fig. 3. Power transfer characteristic and switching of the optical transistor

The error bars indicate the standard deviations of the data points. (A) The hysteresis loop of the through power vs. the gate power. The cyan curve is obtained by sweeping up the gate power, and the pink curve is obtained by sweeping down the gate power. (B) Switching of the optical transistor.