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40 dB Optical Nonreciprocal Transmission on a Silicon Chip

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Abstract

We demonstrate 40 dB nonreciprocal transmission at telecommunication wavelengths using an integrated all silicon optical diode. The nonreciprocal transmission ratio is the highest to date for CMOS compatible silicon integrated photonics.

1. Introduction

Optical nonreciprocity (ONR) is an important functionality for integrated optical communication. Recent experimental investigations have been realized using magneto-optic effect, optical nonlinearity, electro-absorption modulation, cholesteric liquid crystals, indirect interband photonic transitions and opto-acoustic effect. However they are either not CMOS compatible or requires external assistance. We recently realized an all silicon passive optical diode and demonstrated a nonreciprocal transmission ratio (NTR) of up to 28 dB (1). Based on our previous work, here we report an optical diode with an NTR of up to 40 dB which is the highest NTR experimentally demonstrated to date in silicon integrated photonics.

The schematic of our optical diode is shown in Fig. 1A–B. It consists of an add-drop filter (ADF) with asymmetric power coupling to the bus waveguides and a high-Q all-pass notch filter (NF) operating near the critical coupling regime. The NF resonance is thermally tuned to match that of the ADF through thermo-optic effect of Si (2).

The optical diode operates on the principle of optical non-linearity in high Q silicon micro-resonators (3, 4). When moderate power is fed at port I (Fig. 1A), it passes the NF without much attenuation since the resonance red-shifts away from the input wavelength. This relatively un-attenuated light is coupled into the ADF from the weakly coupled side (large gap G2) and passes unscathed into the drop port and out to port II. When the power is fed in the opposite direction (port II in Fig. 1B), it first approaches the ADF's strongly coupled side and thus red-shifts the resonance and effectively reduces the drop response. The light passes the NF and is further attenuated at its resonance. Hence, light at port II in the backward direction is strongly attenuated compared with the forward.

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2. Results and Discussion

In our previous demonstration, we realized an optical diode with 28 dB NTR at ~1630 nm. Fiber-to-chip coupling was achieved through butt coupling and suffered 10.7 dB coupling loss per facet. In this work, a number of improvements were realized to contribute to a high NTR. First, we moved the measurement platform to a vertical grating coupler configuration which allowed seamless integration of multiple devices on chip. This helps us to reduce the coupling loss to 5.8 dB per facet. Second, by optimizing the coupling gaps of the NF and the ADF, we reduced the insertion loss of the ADF and realized a strong NTR of 40 dB at ~1580 nm shown in Fig. 1C.

Fig. 2A shows the NTR for various input power levels at the device. It shows that the NTR saturates when the input power keeps increasing. This can be explained as follows. For backward transmission, input power at the ADF will red-shift its resonance further away as power increases, thus clamping the transmitted power fed to the NF. For the forward transmission, increasing the output power does not significantly red-shift the ADF response due to the weak coupling. As a result, a saturation effect is observed on the NTR.

Our previous work suffered from relatively high insertion loss due to the drop loss caused by the ADF's asymmetric coupling scheme and the fiber-to-chip coupling loss. To mitigate the losses, we cascaded an erbium doped fiber amplifier (EDFA) module with the optical diode chip so that it can provide a constant gain to compensate the drop loss and the coupling loss. A narrow band pass filter and an attenuator are placed after the EDFA so that the gain provided by the module is kept constant for both forward and backward direction. In the forward direction, light first goes through the optical diode and then into the EDFA. In the backward direction, light is first amplified by the EDFA and then enters the optical diode. In fact, the optical diode feels a disparity in input power because the backward input power is higher than the forward. In experiments with the same optical diode device at a different free spectral range, at ~ 1546 nm wavelength, the total loss is 18 dB while the NTR is 24 dB. As the EDFA gain is increased from 0 dB to 18 dB, the total loss can be compensated while at the same time, the NTR linearly increases to 36 dB (Fig. 2B). This NTR enhancement can also be attributed to the saturation effect of the ADF.

3. Conclusion

Using only silicon, we have realized a record NTR of 40 dB at an input power of ~2.5 mW. Such high ONR makes it an attractive device for future integrated photonics.

References

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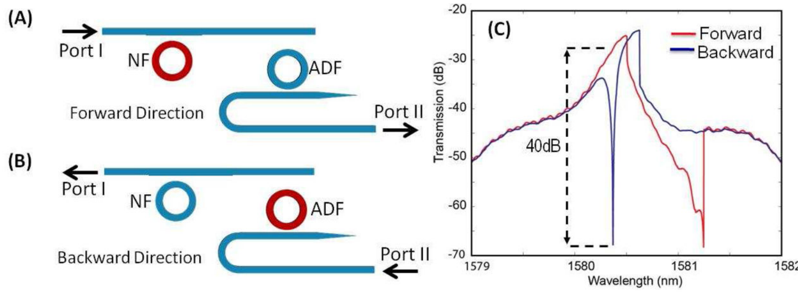

Fig. 1.
Schematic and transmission spectra of the optical diode. (A) The schematic when the optical diode is operated in the forward direction. The NF microring is drawn in red since its resonance is red-shifted. (B) The schematic when the optical diode is operated in the backward direction. The ADF microring is drawn in red since its resonance is red-shifted. (C) The transmission spectra of the optical diode in the forward and backward direction at 2.5 mW input power at the device. A 40 dB NTR is highlighted.

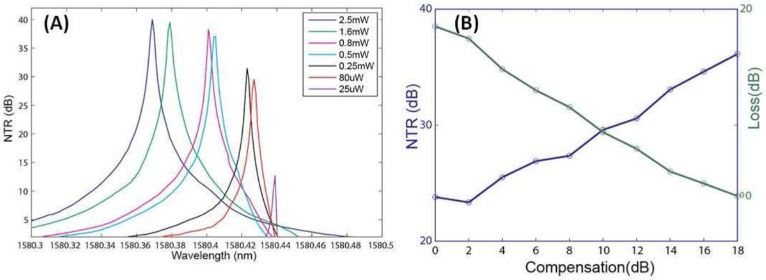

Fig. 2.

(A) NTR vs. Input Power at the device. (B) NTR and loss of the optical diode with compensation module.