Intermodal strong coupling and wideband, low-loss isolation in silicon

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Abstract: We demonstrate wideband strong coupling between two photonic bands via electrically-driven acousto-optic scattering. Based on this system, we demonstrate a non-magnetic, low-loss (< 1 dB) and broadband (59 GHz 10 dB isolation bandwidth) optical isolator. © 2023 The Author(s)

1. Introduction

Strong coupling enables a diverse set of applications that include optical memories, non-magnetic isolators, photonic state manipulation, and signal processing. To date, controllable strong coupling in integrated platforms has been realized in high-Q optical resonators [1–3], which features limited operation bandwidth due to the characteristic linewidths of cavity modes. Alternatively, strong coupling between photonic bands can lead to wideband integrated photonic functionalities. Among various coupling mechanisms including optical nonlinearities and electro-optics, optomechanical coupling stands out as a promising candidate for its ability to drive indirect interband transitions, which gives rise to wideband nonreciprocity [4]. So far, wideband nonreciprocal acousto-optic modulators have already been realized in silicon waveguides [5, 6], but their inefficient coupling rates limit the mode conversion efficiency, and thus limit their usage as practical low-loss isolators.

Here, we demonstrate strong interband coupling between two photonic bands in a multi-mode silicon waveguide. The coupling is mediated by electrically driven phonons via photelastic scattering process. Our system allows us to observe a full Rabi-like energy exchange cycle between two waveguide modes. When tuned to full energy conversion, our system unlocks a series of photonic functionalities, including optical modulators, routers, and filters. In particular, we experimentally implement a single sideband suppressed-carrier acousto-optical modulator (AOM) with pump suppression ratio > 55 dB and insertion loss of 2.08 dB. By reconfiguring our device, we also demonstrate a frequency-neutral low-loss (< 1 dB) isolator that demonstrates > 10 dB isolation over a 59 GHz bandwidth.

2. Results

Our device is fabricated on an AlN-on-SOI platform using a CMOS foundry process. The device composes of a triple-pass silicon optomechanical waveguide and a piezoelectric interdigital transducer (IDT) positioned on a suspended AlN/Si layer (Fig. 1a). Under the microwave drive at frequency Ω0/(2π) ≈ 3.1 GHz, the angled IDT excites phonons towards the optomechanical region, and enables the acousto-optic scattering process between the symmetric (mode 1) and anti-symmetric optical mode (mode 2) in each ridge waveguide. In order to boost the coupling efficiency of the system, we extend the active interaction region by integrating eight IDT units into a multi-pass spiral waveguide (Fig. 1b). Two mode multiplexers are added into the system to couple in and out the optical modes selectively.

When injecting power P1 in the symmetric mode, we expect the optical output power of mode 1 as P1 out = P1 in cos²(βL0/v1 L) (red), and mode 2 as P2 out = P1 in sin²(βL0/v1 L) (blue). Here v1 is the group velocity of the optical mode, and L0 is the length of an active region. This is reminiscent of typical Rabi oscillation systems, as the power in each optical mode oscillates as a function of the enhanced intermodal coupling rate |bg|, which is the product of the phonon field amplitude b and the acousto-optic coupling rate g. We observed this Rabi-like energy exchange in Fig. 1c, where we control the acoustic field amplitude through the applied RF power P RF.

By configuring our system to operate at the full energy conversion point, we demonstrate an acousto-optic modulator (AOM) and an optical isolator. The AOM is characterized by measuring the frequency resolved optical...
output as a function of RF frequency Fig. 1d, which features the high modulation efficiency of $\sim$2.08 dB (red for targeted Stokes sideband), good single-sideband selectivity (SSB) of 32.1 dB (purple for unwanted anti-Stokes sideband) and large pump suppression ratio of 55.3 dB (blue for pump residue), comparable to the commercial fiber AOMs. The optical isolator is studied through an optical transmission measurement in Fig.1e, which demonstrates a 10 dB isolation bandwidth of 59 GHz and a peak isolation contrast of 13 dB. The minimum insertion loss is -0.74 dB, which is only limited by the optical propagation loss.

Fig. 1. a/b, Cross-section/Top view cartoon of the device fabricated in an AlN-on-SOI platform. c, The Rabi-like energy exchanges between the symmetric mode (red) and the anti-symmetric mode (blue). d, The output power of the acousto-optic modulator, which consists of the pump residue (blue), Stokes (red), and unwanted anti-Stokes (purple), are respectively measured as a function of the RF frequency. e, A direct optical transmission measurement demonstrates a 10 dB isolation bandwidth of 59 GHz and minimum insertion loss of -0.74 dB.

3. Conclusion

We demonstrate strong coupling between two photonic bands in a silicon waveguide. The efficient mode conversion of this system enables the demonstration of an efficient AOM and a wideband, low-loss optical isolator.

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