1. Discussion on optical losses

We discuss below the optical losses present in our experimental demonstrations with silicon photonic single-sideband modulator chip. The packaged SiPh modulator chip is operated in conjunction with external erbium-doped fiber amplifiers (EDFAs) and a frequency doubler to produce an optical Raman signal at 780nm for the cold-atom system. The laser system uses a single master/seed laser at 1560 nm as seen in Fig. S1. For demonstration of state-selective detection, the modulator is driven at 1.644 GHz at 1560 nm. The doubled 780nm signal is used to form a magneto-optic trap (MOT). The laser supplies ~0 dBm of optical power followed by an EDFA with 16 dB gain to compensate for the 15 dB insertion loss of the silicon chip. This translates to a coupling loss of ~7.5 dB/facet (input and output) to the silicon chip. There is an additional on-chip loss of ~2-3 dB in the active modulators with -4.7 dB peak conversion efficiency in the single-sideband modulator. This yields approximately -7 dBm of side-band optical power which is further amplified to 20 dBm as input to the doubler. Consequently, there is a few milli-watts of optical power (780nm) at the output of the doubler to probe the atom system.

Fig. S1. Detailed experimental schematic for state-selective detection with single-sideband (SSB) modulator chips showing all optical losses and conversion efficiencies in line to rubidium atoms. We make use of erbium-doped fiber amplifiers (EDFAs) to compensate for the high optical insertion loss (IL) of the packaged silicon photonic chip.

We have since fabricated devices with both silicon and silicon nitride (SiN) inverse-taper couplers with coupling losses as low as ~2 dB/facet (reduction from the 7.5 dB/facet used in the experiments). With successful packaging of these new devices, we can reduce the amplifiers needed.

2. Optical power handling of waveguides

A key consideration of our photonic chip design is the ability to handle the required optical powers. Early on, we determined a requirement for 1mW of optical power in the output fiber of each channel of the modulator. There are many sources of loss from input fiber to output fiber. This includes fiber to chip coupling, propagation loss in the waveguide and loss in the doped regions of the modulator. It also includes intrinsic ‘losses’, such as the need to split light to 4 channels, and the theoretical maximum conversion efficiency of -4.7 dB. For this reason, relatively high
optical power, potentially up to 1 Watt, is required at the input. At high optical powers the transmission of silicon waveguides becomes non-linear. The high optical powers generate two photon absorption (TPA), which increases proportional to the square of the intensity. This in turn creates free carriers which produce free carrier absorption (FCA). To account for this, we conducted high power optical testing of waveguides similar to those used in the modulator. This is shown in Fig. S2(A), where measured output power is plotted as red circles for various input powers up to 400 mW. The data is seen to deviate from linear absorption (dashed black line), and is fit to a model of TPA + FCA (blue curve) in order to extract the relevant material parameters. These parameters are then used to estimate the transmission through our photonic chip as a function of input power and as a function of fiber to chip coupling. This is shown in Fig. S2(B). For poor fiber to chip coupling, very high powers are required to achieve 1 mW output from each channel of the chip. However, since much of the light is lost in coupling, there is no significant non-linear absorption. By reducing fiber to chip coupling, we can dramatically reduce the required input power. At a coupling of 1 dB/facet, we require less than 100mW input to achieve 1mW output (yellow curve). From Figure S2(B), it is clear that at 1mW output power there is not significant non-linear absorption in any of the cases plotted. From the yellow curve, we can see that non-linear absorption does become more apparent when trying to achieve higher output powers, and the output power begins to saturate around 6-7 mW.

Fig. S2. Optical power handling of 600nm wide silicon ridge waveguide. (A) Measured output power versus input power of a silicon waveguide and (B) simulated output of the photonic chip at high optical inputs for several different fiber to chip coupling efficiencies.

One step taken to improve power handling was the use of silicon nitride when coupling onto the chip. Silicon nitride does not have two photon absorption at a wavelength of 1550nm and can therefore handle higher powers than silicon. Therefore, we couple onto the chip into a silicon nitride waveguide. For a four-channel chip, the power is then split four ways using silicon nitride multi-mode interference splitters before transitioning to silicon. This way the power is already reduced by a factor of 4 before entering silicon. Further increase in optical power handling can be achieved using techniques such as applying a reverse-bias to the waveguides to sweep out free carriers generated by TPA.

3. Discussion on bandwidth of silicon single-sideband modulators

We measure the 3dB optical bandwidth of our silicon Mach-Zehnder modulators used in all the atomic physics experiments to be ~1.13 GHz for a modulator length of 1.55mm (see Fig. S3). These were lumped-element p-n junction modulators. We have since improved the frequency response of these modulators by using travelling-wave segmented electrode designs. By periodically attaching the capacitive p-n junction to a high impedance travelling-wave electrode, both the impedance and velocity matching can be achieved simultaneously to increase the bandwidth. We see more than 4 times greater bandwidth from the new design to be ~5 GHz. This frequency response was measured with no reverse DC bias applied to the modulator. We expect even greater bandwidth when a reverse bias is applied, as this increases the depletion region within the doped modulator and reduces capacitance.
Fig. S3. Optical frequency response of silicon Mach-Zehnder modulators. The current modulators have a measured optical 3dB bandwidth of ~1.13 GHz for a modulator length of 1.55mm (blue curve). These packaged devices were used for all the atomic physics experiments. New generation of travelling-wave electrode silicon Mach-Zehnder modulators have an improved optical bandwidth of ~5 GHz at 1560nm (past the ~4 GHz requirement for this atom system) shown as the red curve.

4. Packaging of single-sideband modulator chips

To demonstrate practical application of this silicon photonic chip to an atom interferometry system we must package the chip with both electrical and optical interfaces. A cross-section of the packaging geometry is illustrated in Fig. S4. Due to the significant number of electrical I/O required for thermo-optic, electro-optic and photodiode elements in a four-channel modulator chip seen in Fig. S5(A), we implemented a packaging scheme based on a 280-pin count ceramic pin grid array (CPGA). Additionally, this package provided a significantly large die cavity which allowed for placement of both the photonic chip and a fiber array substrate side by side. Direct wire-bonding from the photonic chip to the package would have resulted in very long wire-bonds with potential for shorting and damage. Therefore, an electrical interposer was designed. This was a silicon chip matched to the package die cavity dimensions. The interposer contained a single gold metal layer which routed signals from the package to pads near to the photonic die. Automated wire-bonding was implemented to bond the photonic chip to the interposer and the interposer to the package. Images of a chip after wire-bonding are shown in Fig. S5(B).

Fig. S4. Cross section of the packaging scheme implemented. Packaging incorporates an optical fiber v-groove array (VGA), DC signals (wire-bonds), RF signals from printed-circuit board (PCB), interposer to the silicon photonic die, and ceramic pin grid array (CPGA) package (in black).

While this is suitable for low frequency signals, package and interposer would not be suitable for the high frequency RF signals required to drive the modulator. For that reason, an additional printed circuit board was designed to introduce RF signals. This board featured smp connections, surface mount RF bias tees and co-planar RF waveguides.
This PCB can be seen in Fig. 3 of the main text. The board was characterized by wire-bonding two boards together and measuring RF transmission from one board to the second. It was found to have approximately 4 GHz bandwidth, which is suitable for the frequencies required on this project. The board is attached to the CPGA using a thermally conductive, electrically insulating epoxy. After attachment, wire-bonding is used to route the RF signal from the PCB to the RF pads on the photonic die.

Once a die has been fully packaged electrically, optical packaging is done in a custom packaging setup. For single-channel chips an 8-count fiber array is used for packaging. For four-channel chips a 20-count fiber array is used. As a result of differences in the thickness of the photonic die substrate and the fiber array substrate, additional pieces of silicon and pyrex are used to adjust the heights of each. The silicon photonic die is placed on a silicon shim prior to wire-bonding. An appropriate pyrex shim is then chosen in order to match the height of the fiber array to that of the photonic die as closely as possible. Ideally, when the fiber array is properly aligned to the photonic die, there should be a gap on the order of 10 microns between the fiber array and the shim below it. UV cure epoxy is applied to this gap and subsequently cured. During the curing process the epoxy shrinks by ~1%, causing the fiber array to be pulled downward. We've found that if the layer of epoxy is much greater than 10 microns this shrinkage will cause a significant reduction in optical coupling from fiber to photonic die. Additional epoxy is applied to the interface between the photonic die and fiber array. This provides an index matching effect which reduces loss at this interface and provide additional mechanical support. Lastly, UV cure epoxy is used to attach the fibers to the edge of the ceramic package for additional strain relief.

**Fig. S5. Four-channel single-sideband modulator chip.** (A) Micrograph image of fabricated 4-channel single-sideband modulator chip with 8mm-by-8mm footprint. (B) Top view of a four-channel silicon photonic die following automated wire-bonding. (C) Side view of the same die showing the silicon shim below the die.

During alignment of the fiber array, an alignment waveguide loop on the chip is used to monitor fiber to chip coupling. This alignment waveguide connects the first and last fiber in the array, such that a laser can be transmitted through the chip and monitored for alignment and curing. It was noted that the transmission through this alignment loop was approximately -17dB prior to curing of the epoxy. The epoxy was cured overnight, and the transmission was observed to improve to approximately -16dB. Propagation of light within the alignment loop contributes approximately 1dB of loss, so we estimate a fiber to chip coupling of -7.5 dB.
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