On-chip mode-division multiplexing switch: supplementary material

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1. PHASE MATCHING

Asymmetric coupling regions are used in the multiplexing, demultiplexing, and mode conversion steps of the switch in order to selectively couple to particular modes. The multimode waveguides are designed to be 930 nm wide to accommodate phase-matching of the TE₁ mode with the TE₀ mode of 450-nm wide single-mode waveguides (see Fig. S1) [1]. At this combination of widths, the effective indices of the modes in their respective waveguides match with index 2.46, and so the TE₀ mode in the single-mode waveguide selectively excites the TE₁ mode in the

multimode waveguide, without also exciting the TE₀ therein, which would contribute to crosstalk. The phase-matching condition is tolerant to typical fabrication variations in waveguide width (Fig. S2). For example, an alteration of the multimode waveguide width within a 50-nm range leads to a drop of only 1% in coupling to the ring from a peak of around 9%. The peak coupling occurs at a slightly narrower width than the point of effective index matching because the mode is more delocalized, but the phase-matching is still mostly in effect. If the fundamental mode alone is present in a waveguide, it can be adiabatically tapered wider or narrower

Fig. S1. (a) Method for accessing individual modes in a multimode waveguide. A single-mode ring resonator which is properly phase-matched to the bus waveguide will drop the TE₁ channel, while the TE₀ channel can be adiabatically tapered into a single-mode waveguide. (b) Simulated effective index of 250-nm tall Si waveguide as a function of width. The phase-matching condition is met when the index for TE₀ in the single-mode waveguide (point A) matches that of TE₁ in the multimode bus waveguide (point B). The TE₀ signals can adiabatically taper to the same width as the multimode bus waveguide (point C) and back.

Fig. S2. Sensitivity of phase-matching to width for coupling between TE₀ mode in 450 nm waveguide and TE₁ mode in 930 nm waveguide. The simulation shows a large tolerance for fabrication variations in width dimensions of waveguides.

without disturbing the mode. The adiabatic taper length used is 95 μm .

Propagation of modes in multimode waveguides in principle should not lead to significant mode mixing, even with typical sidewall roughness. From coupled-mode theory, the period of a spatial perturbation can lead to coupling between modes with different propagation constants (i.e. different index) [3]. This relation is given by

$$\frac{2\pi}{\Lambda} = \Delta\beta = \frac{2\pi}{\lambda} \Delta n \quad (1)$$

where Λ is the spatial period of the perturbation, $\Delta\beta$ is the propagation constant difference, and Δn is the refractive index difference of the modes. Rearranging, we obtain the period

$$\Lambda = \frac{\lambda}{\Delta n} \quad (2)$$

For telecom wavelengths and index differences on the order of those in Fig. S1(b) (vertical separation between modes), the period is about 5 μm . However, typical waveguide sidewall roughness has a correlation length of 50-100 nm with magnitude on the order of 2-5 nm. [4,5]. Thus the unwanted coupling between modes through this mechanism is inefficient.

2. COUPLING PARAMETERS

The coupling gaps between the rings and waveguides are chosen to meet the critical coupling condition $\kappa = \kappa' + \alpha$, where κ and κ' are the add and drop port coupling constants, respectively [2]. To enable 10 Gbps operation, κ and κ' are also optimized for a bandwidth of 16 GHz per ring, although this narrows when rings are in series. The coupling gaps, calculated by the eigenmode expansion method based on the waveguide geometry, are listed in Table S1. The racetrack ring resonators used for the (de)multiplexers have radii of 16 μm and coupling lengths (L_c) of

Table S1. Coupling gaps

Coupling Region	Gap (nm)
TE1 MM to SM ring – Add port	210
TE1 MM to SM ring – Drop port	220
TE0 SM to SM ring – Add port	250
TE0 SM to SM ring – Drop port	260
Switching Ring – Add port	190
Switching Ring – Drop port	200

Fig. S3. Simulated mode transmission for adiabatic linear taper of width of multimode silicon waveguides. All modes rapidly reach high transmission when taper lengths exceed several micrometers. In (a), a taper from 1.41 μm width to 1.85 μm is 99% efficient in just 4 μm , while in (b), from 1.85 μm to 2.4 μm , this efficiency is reached by 6 μm .

5.9 μm , at which the crosstalk is minimized due to the phase-matching. The switching rings have 8.6 μm radii and 1.2 μm coupling lengths, for half the circumference of the multiplexing rings.

3. SCALING CONSIDERATIONS

Expanding the number of mode and wavelength channels supported by the switch allows for further expansion of bandwidth. For increasing the number of wavelength channels beyond the two demonstrated, an additional switching ring is needed per mode such that the total number of switching rings follows $m \cdot n_\lambda$, where m is the number of modes, and n_λ is the number of wavelengths. This is also the total number of channels, because each channel is switched individually by a dedicated ring. Scaling to more modes requires conversion rings to phase-match to each multimode waveguide width. The number of conversion rings is $3(m-1)$, which is independent of the number of wavelength channels. The number of rings passed through by channels does not change when scaling to more wavelengths or modes.

The adiabatic taper length needed for sufficiently low crosstalk can be greatly reduced in future switch designs. Simulations show that when linearly tapering width from a multimode waveguide with three modes to a waveguide with four, more than 99% of each mode is preserved in the proper channel with a taper length as short as 4 μm (Fig. S3(a)). For a taper of a four-mode waveguide to a five-mode waveguide, only 6 μm is required (Fig. S3(b)). Non-

linear tapers, such as parabolic profiles, may optimize this further. The 95 μm taper used in our demonstration can be reduced in the length dramatically, and for several mode channels, taper length should not be a dominating concern for area.

Thus the total area depends predominantly on the number of rings and scales at most linearly with the number of modes.

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