

Adiabatic mode multiplexer for evanescent-coupling-insensitive optical switching

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A novel adiabatic mode multiplexer enables a 2×2 optical switch whose operation does not depend on accumulated phase due to evanescent coupling between waveguides. The adiabatic mode multiplexer has a negligible insertion loss over $C+L$ bands and modal cross talk better than -40 dB for any polarization state. Mode multiplexing is achieved by adiabatic transition from the fundamental mode of the single-mode waveguide to the higher mode of the multimode waveguide. Experimental measurement results for a device realized in silica-on-silicon technology are presented. By directly measuring the nonadiabatic transition probability, we show that the adiabatic mode multiplexer operates in the Landau-Zener regime. © 2005 Optical Society of America

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The most common solution used for optical switching in silica-on-silicon planar light-wave circuits is thermally activated Mach-Zehnder switch.¹ It consists of two 3 dB directional couplers connected by two waveguides. It is well known that directional couplers using phase-matched evanescent coupling to transfer the energy between different waveguides are sensitive to wavelength, polarization state, and fabrication changes. We have designed a novel 2×2 switch that consists of an adiabatic mode multiplexer-demultiplexer pair and a symmetric Y-branch interferometer. The adiabatic mode multiplexer (AMM) combines light from two input waveguides to either the fundamental or the first-order mode of a double-mode waveguide. The first Y branch of the symmetric interferometer splits the double-mode waveguide into two single-mode waveguide arms. At the second Y branch the waveguides are combined again into a double-mode waveguide. By applying heat on one of the interferometer arms, we are able to convert between the fundamental and the first-order modes of the double-mode waveguide. The adiabatic mode demultiplexer (AMDM) separates the fundamental and the high-order modes of the double-mode waveguide into two single-mode output waveguides. Since there is no strict condition on the accumulated phase that is due to evanescent coupling in both the adiabatic multiplexer-demultiplexer and the symmetric Y-branch interferometer, the optical switch performance is tolerant to design and fabrication parameter changes. Optical performance and design details of the switch have been reported elsewhere.^{2,3} In this Letter we focus on the operational principle and performance of the AMM, which is the key part of the new switching unit.

A mode multiplexer combines signals from multiple sources into different modes of a multimode waveguide or fiber. Currently available mode multiplexers are based on optical fiber directional couplers formed between single-mode and multimode fibers⁴ or on planar asymmetric Y splitters.⁵ Directional couplers use phase-matched evanescent coupling to transfer the energy between different modes, and

their performance is wavelength and polarization-state dependent. Multiplexers based on asymmetric Y-splitters operate over a large wavelength range. However, the finite dimension of the Y-splitter tip mixes different order modes and introduces modal cross talk as well as an additional insertion loss.

To the best of our knowledge this is the first demonstration of an AMM⁶ having a negligible insertion loss and lower than -40 dB cross talk over $C+L$ bands and state of polarization. Our device is fabricated in silica on silicon by using a 0.75% index contrast and a $6 \mu\text{m}$ height germanium-doped core.

The advantage of an adiabatic coupler is its tolerance to design and fabrication parameters.^{7,8} Adiabatic propagation requires slow effective index changes in the propagation direction that do not induce coupling between different local modes. Previously reported adiabatic couplers consist of two tapered single-mode waveguides. Adiabatic coupling was induced between the fundamental modes of these two waveguides, leading to light transfer between the waveguides. Broadband full and 3 dB couplers were fabricated and characterized.⁹ Although the adiabatic 3 dB couplers have a robust 50/50 splitting ratio, they cannot be used in optical switching applications because the uncertainty in the relative phase¹⁰ between the two output waveguides is too large. Also, the nonadiabatic coupling directly

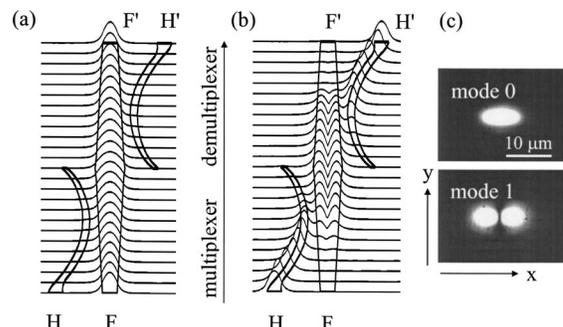


Fig. 1. Schematic device layout with modal evolution and far-field images of two modes at the end of the AMM section. Layout scale, 1:175.

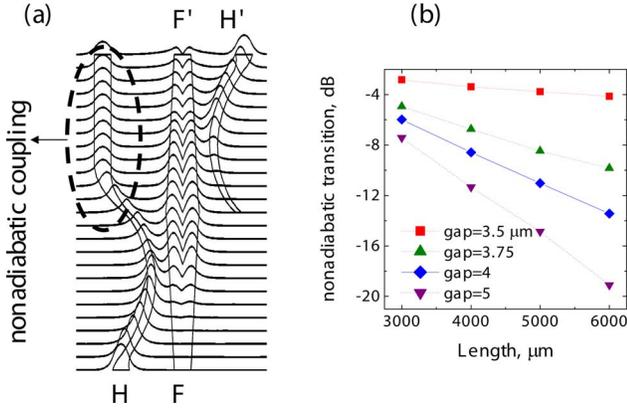


Fig. 2. (Color online) (a) Light propagation in the AMM and the AMDM with a minimal-gap size of $5 \mu\text{m}$. Owing to the nonadiabatic coupling, some of the light remains in the add waveguide. (b) Uncoupled optical power in the add waveguide as function of device length.

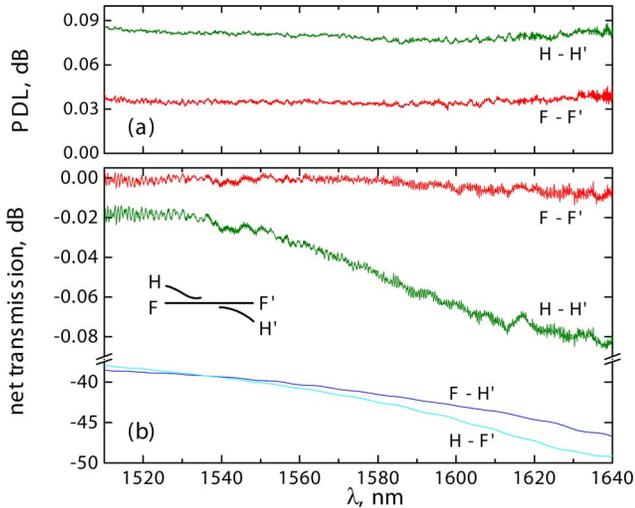


Fig. 3. (Color online) Measured insertion loss and PDL over wavelength.

influences the optical performance, introducing additional cross talk in the switching unit.

In Figs. 1(a) and 1(b) we present a schematic layout of the AMM with the optical power evolution along the propagation direction. To simplify device characterization, we built a full coupler consisting of the AMM followed by the AMDM. As one can see in Fig. 1(b), the AMM transfers light injected into port H to the first order mode of the central bus waveguide, whereas light injected into the F port of the AMM [see Fig 1(a)] remains in the fundamental mode of the bus waveguide. Light propagation is reversed in the AMDM part of the full coupler [see the demultiplexer region in Figs. 1(a) and 1(b)]. The fundamental mode of the bus waveguide exits the F' port, while the first-order mode of the bus waveguide exits as the fundamental mode of the H' port of the AMDM. The AMM consists of two tapered waveguides. The bus (double-mode) waveguide width increases with distance, from 6 to $12 \mu\text{m}$. The adjacent single-mode (add) waveguide width reduces gradually from 6 to $2 \mu\text{m}$. In the minimal-gap region the effective refractive index curves of the first-order

mode of the bus and the fundamental mode of the add waveguides cross, and the effective indices become equal, $n_H = n_F = n_0$. Because of the coupling between the waveguides, the degenerate isolated waveguide modes form two local modes with an effective refractive index separation, Δn , that is dependent on the interaction strength. During adiabatic propagation the fundamental mode of the add and the first-order mode of the bus waveguides evolve into the first-order mode of the bus and the fundamental mode of the add waveguides, respectively. Nonadiabatic coupling between the local modes reduces the mode multiplexing efficiency. Some of the light injected into the fundamental mode of the add waveguide remains in the same waveguide and does not couple to the first-order mode of the bus waveguide. This light is guided to the output facet and detected by our experimental setup [see Fig. 2(a)]. It is important to note that the uncoupled light stays in the add waveguide and is not transferred to the fundamental mode of the bus waveguide. Consequently, the nonadiabatic transition contributes only to the insertion loss of the AMM and not to the cross talk.

As was suggested earlier,⁹ the nonadiabatic coupling in adiabatic couplers should follow the Landau-Zener (LZ) expression¹¹ for the nonadiabatic transition probability. In our case the nonadiabatic transition probability is given in terms of effective refractive indices by

$$P_{\text{NA}} = \exp\left(-\frac{\pi k \Delta n^2}{2(|n'_F| + |n'_H|)}\right) = \exp\left(-\frac{\pi k \Delta n^2 \Delta L}{2(|\Delta n_F| + |\Delta n_H|)}\right), \quad (1)$$

where Δn is the difference between the effective refractive indices of the two local modes; n'_F and n'_H are the rates of change in the effective refractive index of the fundamental and the first-order modes of isolated add and bus waveguides in the vicinity of the minimal gap region. The effective index change rate can be approximated by a ratio between the change in effective index, Δn_F and Δn_H , over an interval ΔL . As it

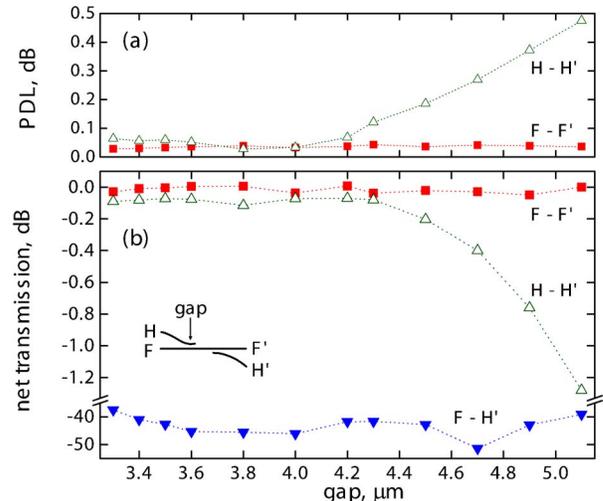


Fig. 4. (Color online) Measured insertion loss and PDL as a function of minimal gap.

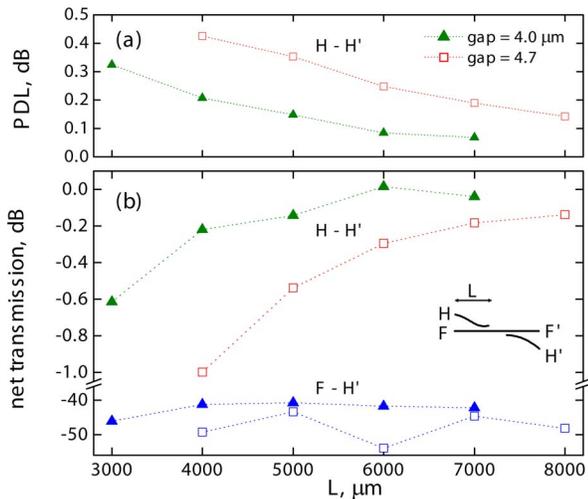


Fig. 5. (Color online) Measured insertion loss and PDL as a function of device length.

is evident from Eq. (1) the unwanted nonadiabatic coupling probability can be reduced by making the device longer so that the local perturbation is weaker. Alternatively, the local mode separation, Δn , can be increased by making the interaction between waveguides stronger (for example, by reducing the minimal-gap dimension). We have measured the nonadiabatic transition probability by monitoring the light that emerges uncoupled in the add waveguide [see Fig. 2(a)]. As is expected on the basis of the LZ formula, the nonadiabatic transition probability is linear (on a logarithmic scale) as a function of AMM length, which is proportional to the length interval ΔL . As one can see from Fig. 2(b), the slope of the nonadiabatic transition probability increases when the minimal-gap dimension is reduced.

As we have mentioned above, the adiabatic power transfer process does not depend on the exact amount of phase accumulated during propagation, and consequently it is not sensitive to small changes in the effective refractive index. Both wavelength- and polarization-dependent loss (PDL) measurements show in Fig. 3, there is no considerable effect on the optical performance of our device. In the HH' path of the full coupler, light injected into the H port of the AMM is transferred to the first-order mode of the bus waveguide and subsequently guided to the H' port of the AMDM. The HH'-path insertion loss of the AMM and the AMDM is better than 0.05 dB (per multiplexer), and the PDL is less than 0.1 dB (full coupler) in C+L bands. Figure 4 shows that AMM and AMDM optical performance is very stable in the minimal-gap range of 3.3–4.3 μm . It illustrates again that adiabatic AMM is not sensitive to the exact amount of coupling between the two waveguides. For a gap size larger than 4.4 μm the insertion loss and the PDL of the AMM and the AMDM start increasing owing to weaker coupling between waveguides that reduces the local mode separation, Δn . Nonadiabatic coupling between weakly separated local modes can be reduced by making the device longer and the rate of change in

effective indices, n'_F and n'_H , smaller. This is illustrated in Figs. 5(a) and 5(b), showing that the insertion loss and the PDL of the AMM and the AMDM decrease with increasing device length. The AMM and the AMDM with a smaller separation between local modes (larger gap of 4.7 μm) matches the optical performance of the large-separation device (smaller gap of 4.0 μm) at a larger device length. Finally, consider the FF' channel of the AMM and the AMDM. Light injected in port F exits the AMM as the fundamental mode of the central waveguide. The fundamental mode of the central waveguide is strongly confined and not affected by the adjacent waveguide. Consequently the FF' path does not have any additional insertion loss or PDL as compared with a straight reference waveguide. Also the isolation between the fundamental and the high-order modes of the central waveguide as measured in FH' or HF' paths is usually better than -40 dB. Both FF'- and FH'-path optical performance is virtually independent of wavelength (see Fig. 3) and design parameters such as minimal gap (see Fig. 4).

We have presented a novel adiabatic mode multiplexer (AMM) having excellent optical performance over a wide range of design and fabrication parameters. An AMM and AMDM pair was used to construct a broadband 2×2 switch and a variable optical attenuator that does not suffer from imperfections of phase-matched evanescent-coupling-based switching devices.

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