Fabrication, polarisation and wavelength insensitive optical switch/attenuator based on adiabatic mode multiplexer

E. Narevicius, R. Narevich, Y. Berlatzky, J. Dieckroeger, G. Heise, G. Rosenblum, I. Shtrichman, I. Vorobeichik and S. Wang

Experimental results of an adiabatic mode multiplexer (AMM) based novel 2×2 optical switch/variable optical attenuator that consists of a symmetric Y-branch interferometer (mode converter) and adiabatic mode multiplexer/demultiplexer pair are presented. It is shown that both normally cross and bar designs have identical optical performance. Extinction ratio without thermal activation is wavelength independent. Over C-band the attenuation at -20 dB varies by less than 0.3 dB and polarisation dependent loss is less than 1 dB. It is proved that the mode converter plays a dominant role in polarisation state sensitivity at high attenuation values and can be optimised by varying interferometer arm length. Since an AMM-based switch does not require process optimisation steps it can be fabricated within a process optimised for other optical devices.

Introduction: Most planar optical switching devices are built using a Mach-Zehnder interferometer (MZI) configuration. It consists of two 3 dB couplers connected by two waveguides. Clearly, MZI-based optical switch performance is limited by the performance of the 3 dB couplers. The most compact and frequently used 3 dB coupler is the directional coupler (DC). DC operation relies on phase-matched evanescent coupling to transfer the energy between different waveguides. However directional couplers suffer from high sensitivity of splitting ratio to wavelength, polarisation state and fabrication changes [1]. There were several attempts to reduce the coupling ratio sensitivity of 3 dB couplers. Doerr *et al.* [1] suggested bending the entire DC with a constant bending radius. Jinguji *et al.* [2] proposed a wavelength insensitive coupler made of two DC couplers connected by a small optical path difference. Mizuno *et al.* [3] constructed an optical switch using this type of coupler. Shani *et al.* [4] have shown an adiabatic 3 dB coupler. The main disadvantage of these desensitisation techniques is that reduced sensitivity in splitting ratio comes at the expense of increased sensitivity of phase between the signals at the output of the coupler. In applications such as a waveguide tap the relative phase is not important, however, in MZI-based optical switches it is essential to have both low relative phase error and robust splitting ratio. Relative phase error induces unpredictable phase shift dependent on polarisation state. It is well known that a 3 dB Y-branch splitter has low error in both relative phase and splitting ratio [5]. However, it has only one input port and cannot be used to construct a 2×2 optical switch. It is possible to get around this problem by splitting a double- instead of a singlemode waveguide. Both the fundamental and first-order modes of a double-mode waveguide split on a Y-branch with a robust splitting ratio and well defined relative phase. To populate selectively fundamental and the high-order modes of the double-mode waveguide we need a mode multiplexer device. An asymmetric Y-splitter can serve as a mode multiplexer over a large wavelength range. However, a finite dimension of the Y-splitter tip (owing to fabrication resolution limits) mixes different order modes and introduces modal crosstalk that limits switch extinction ratio to -20 dB [6]. We propose to use a novel adiabatic mode multiplexer (AMM) [7] that has negligible insertion loss over C + L bands and modal crosstalk better than -40 dB [8] for optical switching. Mode multiplexing is achieved by adiabatic transition from the fundamental mode of the singlemode waveguide to the higher mode of the multimode waveguide. The advantage of an adiabatic multiplexer is its tolerance to design and fabrication parameters. AMM followed by a symmetric Y-branch splitter forms a four-port 3 dB coupler. The Y-branch splitter ensures robust splitting ratio and low phase error, whereas the AMM provides two input ports, one for fundamental and other for the first-order mode. Since optical performance of the novel switch does not depend on the design details of the AMM, it is more natural to represent our optical switch as a mode converter inserted into an adiabatic mode multiplexer/demultiplexer pair.

Here for the first time we introduce a novel optical switch based on an AMM. Because the AMM has a low polarisation and wavelength dependence, the extinction ratio of our switch is better than 30 dB over a large wavelength span. The switch can be designed to be normally cross or bar without any detrimental effect on its optical performance. The optimisation of the symmetric Y-branch interferometer (mode converter) is not difficult and is relatively insensitive to the process details. Therefore the AMM-based switch can operate as a broadband normally dark variable optical attenuator (VOA) with a very low polarisation dependent loss (PDL) and good process tolerance. We will provide experimental evidence showing that the PDL of the VOA does not depend on AMM design details.

Experimental results: We present a schematic layout of the AMM-based switch in Fig. 1 with the optical power evolution along the propagation direction in the thermally activated ON state. Light injected into the F port of the AMM splits at the first Y-junction, resulting in two waves with equal amplitude and phase. Local heat changes the phase of the wave travelling in the waveguide under the active heater by $\pi/2$. After the second Y-junction recombines the two waves we have an antisymmetric first-order mode that goes into an adiabatic mode demultiplexer (AMDM) and emerges from it in port H′ as a symmetric mode. In the case where no power is applied to the heater, mode conversion does not occur and light injected into the F port exits the F′ port of the AMDM. Since F and F′ ports of the switch in Fig. 1*a* are on opposite sides, this configuration is normally cross. In Fig. 1*b*, F and F′ ports are on the same side, hence this configuration is normally bar. As we shall show below both configurations have the same optical performance. The possibility of having either normally bar or cross configurations can save crossing stages in some large count switching matrix architectures. AMM is a robust device with excellent optical performance that does not depend on polarisation state, wavelength and fabrication changes. Optical switch polarisation and wavelength sensitivity comes predominantly from the mode converter, i.e. a symmetric Y-branch Mach-Zehnder interferometer (YMZI). Heise and Narevich [9] have shown that the polarisation dependence of a YMZI can be described by two parameters, state of polarisation (SOP) rotation at the Y-branch and waveguide birefringence at the YMZI arms. Moreover, the authors illustrated that YMZI performance can be always optimised by varying the YMZI arm length. The optimisation procedure was shown to be robust over different wafers. Having optimised the YMZI we can use it in conjunction with the adiabatic mode multiplexer to construct a low PDL VOA. This result is important since it implies that no process optimisation steps are used to obtain low PDL in a VOA. Consequently, AMM-based switch/VOAs can be fabricated within the same process optimised for other optical devices, such as arrayed waveguide gratings (AWGs).

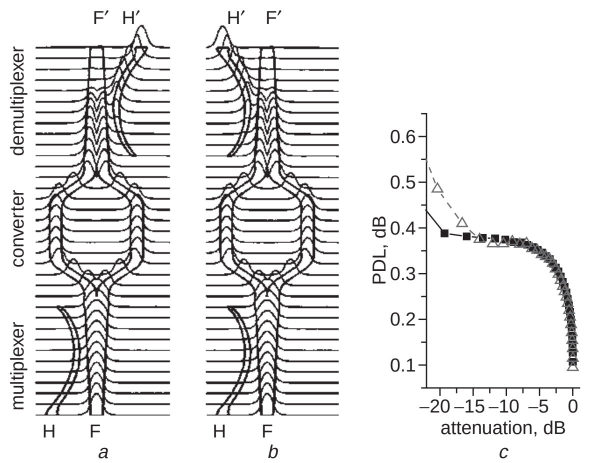

Fig. 1 *Schematic device layout with optical power evolution in normally cross and bar configurations*

Layout scale is 1 : 257.
a Normally cross configuration
b Bar configuration
c Measured polarisation dependent loss against attenuation in normally cross (full squares) and bar (empty triangles) devices

We show measurement results for a typical VOA with optimised PDL in Figs. 1 and 2. Over C-band the attenuation at -20 dB varies by less than 0.3 dB (Fig. 2*a*) and PDL at that attenuation by less than 0.25 dB

(Fig. 2*b*). PDL is below 1 dB for attenuation values up to 20 dB for both normally bar and cross switches (see Fig 1*c*). Our AMM-based switches were fabricated in silica PLC on silicon wafer using plasma enhanced chemical vapour deposition (PECVD). The refractive index contrast in the germanium-doped core is approximately 0.75%. Interferometer arms are 6×6 µm waveguides. Directly above the waveguide there are 180 nm-thick TiW heaters. Heat-insulating trenches reduce the power needed to operate the VOA. We illustrate that the optical performance of the switch/VOA does not depend on the AMM design details in Fig. 2*c*. We measured PDL values against attenuation for non-optimised (YMZI arm length of 2 mm instead of 3 mm) switches with different AMM length. As one can see the attenuation curves are virtually independent of this parameter. It shows again that AMM operation does not depend on accumulated phase owing to evanescent coupling between waveguides and AMM does not contribute to the PDL sensitivity of the AMM-based switch/VOA.

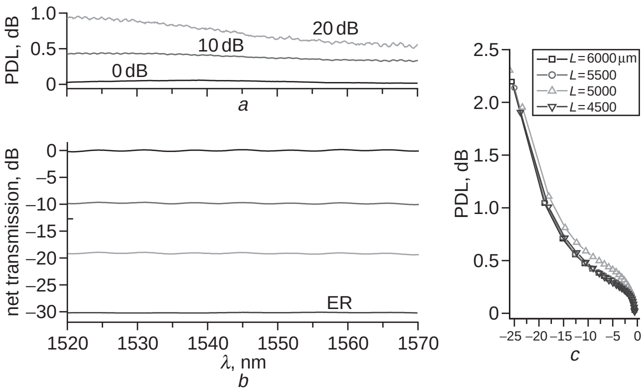

Fig. 2 *Measurement results*

a Measured PDL against wavelength at different attenuation values
b Wavelength dependence of different attenuation levels and switch extinction ratio
c PDL against attenuation for different AMM lengths

Conclusion: We have presented a novel AMM-based switching unit/VOA. It consists of a mode converter and adiabatic mode multiplexer/demultiplexer pair. We show that the mode converter alone is responsible for the polarisation state sensitivity at high attenuation values. The mode converter can be easily optimised by varying the Y-branch interferometer arm length. We provide experimental evidence that the AMM design details do not affect PDL behaviour. The AMM-based switch/VOA does not require process optimisation and can be fabricated within the same process parameters optimised to produce other optical devices such as AWGs.

18 September 2005
Electronics Letters online no: 20063322
doi: 10.1049/el:20063322

E. Narevicius, R. Narevich, Y. Berlatzky, G. Rosenblum, I. Shtrichman, I. Vorobeichik and S. Wang (*OpTun Inc., 3350 Scott Blvd., Santa Clara, CA 95054, USA*)

E-mail: enarevicius@yahoo.com

J. Dieckroeger and G. Heise (*OpTun GmbH, Otto-Hahn Ring 6, Building 31, D-81739 Munich, Germany*)

References

1 Doerr, C.R., Cappuzzo, M., Chen, E., Wong-Foy, A., Gomez, L., Griffin, A., and Buhl, L.: 'Bending of a planar lightwave circuit 2 × 2 coupler to desensitize it to wavelength, polarization, and fabrication changes', *IEEE Photonics Technol. Lett.*, 2005, **17**, pp. 1211–1213
2 Jinguji, K., Takato, N., Sugita, A., and Kawachi, M.: 'Mach-Zehnder interferometer type optical waveguide coupler with wavelength-flattened coupling ratio', *Electron. Lett.*, 1990, **26**, pp. 1326–1327
3 Mizuno, T., Takahashi, H., Kitoh, T., Oguma, M., Kominato, T., and Shibata, T.: 'Novel Mach-Zehnder interferometer switch with high extinction ratio over a wide wavelength range', *Opt. Lett.*, 2005, **30**, pp. 251–253
4 Shani, Y., Henry, C.H., Kistler, R.C., Kazarinov, R.F., and Orlowsky, K.J.: 'Integrated optical adiabatic devices on silicon', *IEEE J. Quantum Electron.*, 1991, **27**, pp. 556–566
5 Doerr, C.R.: 'Planar lightwave devices for DWM' *in* 'Optical fiber telecommunications IVA' (San Diego Academic Press, 2002), pp. 427–428
6 Silberberg, Y., Perlmutter, P., and Baran, J.E.: 'Digital optical switch', *Appl. Phys. Lett.*, 1987, **51**, pp. 1230–1232
7 Narevicius, E.: 'Method and apparatus for optical mode division multiplexing and demultiplexing', WO 03/100490 patent pending
8 Narevicius, E., Narevich, R., Berlatzky, Y., Shtrichman, I., Rosenblum, G., and Vorobeichik, I.: 'Adiabatic mode multiplexer for evanescent coupling insensitive optical switching', *Opt. Lett.*, 2005, **30**, pp. 3362–3364
9 Heise, G., and Narevich, R.: 'Simple model for polarization sensitivity of silica waveguide Mach-Zehnder interferometer', *IEEE Photonics Technol. Lett.*, 2005, **17**, p. 2116