Multimode add-drop multiplexing by adiabatic linearly tapered coupling

Maxim Greenberg, Meir Orenstein

EE Dept. , Technion - Israel Technology Institute, Haifa 32000, Israel
meiro@ee.technion.ac.il

Abstract: Multimode multiplexing can potentially replace WDM for implementing multichannel short reach interconnects. Multiple optical modes can thus be exploited as the channels for transferring optical data, where each mode represents an independent data channel. The basic building block of the system is a Mode Add/Drop which can be implemented based on adiabatic power transfer. We propose a new scheme for realization of such adiabatic mode add drop with a predefined coupling profile, and demonstrate it by employing a linearly decreasing coupling coefficient along the propagation length. Realization using Silicon-On-Insulator (SOI) platform is discussed **-** which offers the possibility of direct integration of the optoelectronic circuitry with the Si processor.

OCIS codes: (130.3120) Integrated optics devices; (230.7370) Waveguides

References and links

1. D. A.B. Miller, "Rationale and Challenges for Optical Interconnects to Electronic Chips," Proceedings of the IEEE **88**, 728-749, (2000).
2. S. Berdague and P. Facq, "Mode division multiplexing in optical fibers," Appl. Opt. **21**, 1950-1955,(1982).
3. Y. Yadin and M. Orenstein, "Parallel optical interconnects over multimode waveguides," 15th Annual Workshop on Interconnections Within High Speed Digital Systems Santa Fe, NM (2004).
4. R.W.C. Vance and J.D. Love, "Asymmetric adiabatic multiprong for mode-multiplexed systems," J. Electr. Lett. **29**, 2134-2136, (1993).
5. K. Y. Song, I. K. Hwang, S. H. Yun, and B. Y. Kim, "High performance fused-type mode-selective coupler using elliptical core two-mode fiber at 1550 nm," IEEE J. Photonics Technol. Lett. **14**, 501–503, (2002).
6. E. Narevicius, "Method and Apparatus for Optical Mode Conversion," WO 03/100490 A1, 28.05.2003 (pending).
7. B. Jalali, P.D. Trinh, S.Yegnanarayanan, F.Corppinger, "Guided-wave optics in silicon-on-insulator technology," IEEE Proc-Optoelectron **143**, 307-311, (1996).
8. W. K. Burns, A.F. Milton, "Mode Conversion in Planar-Dielectric Separating Waveguides," J. Quantum. Electron. **11**, 32-38, (1975).
9. A.F. Milton, W.K. Burns, "Tapered Velocity Couplers for Integrated Optics: Design," Appl. Opt. **14**, 1207-1212, (1975).
10. D. Marcuse, Chapter 3 in " Theory of Dielectric Optical Waveguides," Sec. Ed., Academic Press, Boston San Diego, New York, 1972 .
11. A.F. Milton, W.K. Burns, "Mode Coupling in Tapered Optical Waveguide Structures and Electro-Optic Switches," IEEE Trans. Circuts Syst. **26**, 1020-1028, (1979).
12. A. Yariv, "Coupled-Mode Theory for Guided-Wave Optics," J.Quantum. Electron. **9**, 919-933, (1973).
13. T. A. Ramadan, R.Scarmozzino, R. M. Osgood, "Adiabatic Couplers: Design Rules and Optimization," J. Lightwave Technol. **16**, 277-283, 1998.

#8697 - $15.00 USD Received 8 September 2005; revised 1 November 2005; accepted 2 November 2005

1. Introduction

Massive Optical interconnects are facilitated by including a method of multiplexing many parallel channels into a single physical channel (waveguide) for efficient input-output [1]. Since WDM may be too expensive for very short reach interconnects, we explore a novel direction: Mode-Division-Multiplexing (MDM) as a feasible route [2]: multiple optical modes are exploited as the channels for transmitting optical data, where each mode represents an independent data channel. Yet another option is a stochastic mode combination for a data channel, and employing a MIMO architecture as presented in [3]. A basic building block of MDM is a Mode Add/Drop Multiplexer (MADM) which can upload/download a signal to/from the selected mode of the multimode waveguide, which serves as an optical data bus. We were strict in keeping the communications system integrity by selecting a scheme where the bus dimensions and number of channels are kept constant, which is not a common methodology for adiabatic design schemes (e.g., [4]). A common feature of devices for multiplexing (directional coupler [5], grating assisted coupler, adiabatic power converter [6]) is that a mode synchronism (β-crossing) between the bus mode and added mode is realized within the interaction region.

Adiabatic devices are expected to be process robust and spectrally broadband relative to alternatives. Here we present a new recipe for building an adiabatic coupler for multiplexing into an optical bus which has a fixed structure (important in order to sustain system modularity), and different channels can be added/dropped to/from the bus in desired locations. The concept of MDM with a fixed bus is shown in Fig. 1. We dwell here with adiabatic couplers characterized by a linearly changing coupling coefficient along the propagation length. A feasible device implementation is discussed based on Silicon-On-Insulator (SOI) waveguide technology, which can be directly integrated with CMOS circuitry [7].

2. Condition for Adiabatic Operation

Adiabatic transitions were studied for the realization of mode coupling in tapered velocity couplers, Y branches and optical waveguide horns [8],[9]. The main concept of the adiabatic transition is that the power is carried by the same order "local normal mode" (of the composed structure) [10] throughout the system. Here we are employing adiabatic transitions of the type used for generalized tapered velocity coupler, i.e. the input power is carried by a fundamental mode of one waveguide (mode is referred in the text to a mode of a single waveguide in the absence of the second in contrast to local normal mode) and the output power is carried by the N^{th} order mode of the second waveguide (or vice versa). In previous reports adiabatic transitions were studied by assuming the waveguides structure (linearly tapered waveguides with constant separation, separating waveguides with constant arms width etc.)

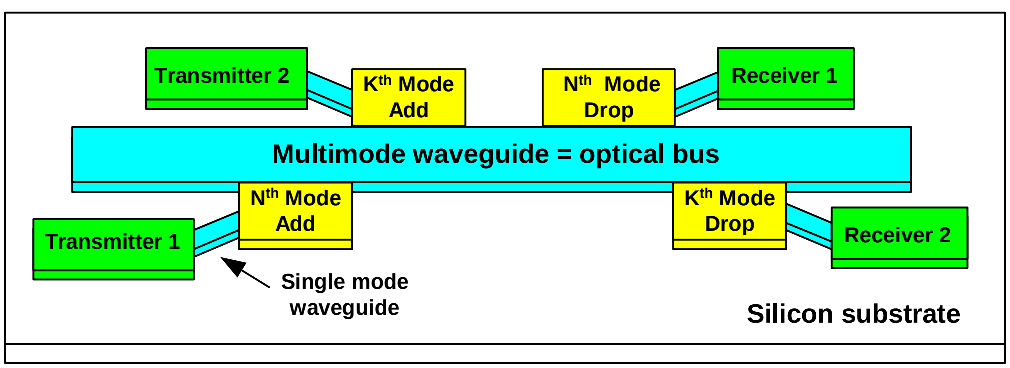

Fig. 1. Schematic chart illustrating the concept of Mode Division Multiplexing with constant optical bus.

and then the model describing the system dynamics in terms of coupling *K(z)* and propagation constant difference *Δβ(z)* (both related to the modes) was obtained. Here we propose the reverse scheme – firstly we choose the profile of coupling strength *K(z)*, than using adiabaticity we calculate the relevant propagation constant difference *Δβ(z)* and finally we translate these analytic model expressions into an actual waveguide structure. Using this scheme we are not restricted to the simple cases of constant coupling/propagation constant difference, thus more elaborated devices with better performances can be obtained.

Following Milton and Burns [11] we investigate the adiabatic transition using local normal modes expansion. The evolution equations for the amplitudes of two local normal modes in a z non-uniform optical waveguides structure are:

$$\frac{dA_j}{dz} = \frac{1}{2(X^2(z)+1)}\frac{dX}{dz}A_i - j\beta_j(z)A_j \qquad (1)$$

$$\frac{dA_i}{dz} = -\frac{1}{2(X^2(z)+1)}\frac{dX}{dz}A_j - j\beta_i(z)A_i \quad . \qquad (2)$$

A_i is the amplitude of the dominant local normal mode – comprised predominantly from the fundamental mode of the single mode waveguide at the input and a prescribed Nth mode of the multimode waveguide at the output. A_j is related to the complimentary local normal mode. $\beta_i(z)$, $\beta_j(z)$ are the propagation constants of the local normal modes, $X=\Delta\beta(z)/2|K(z)|$ with $\Delta\beta = \beta_{add} - \beta_N$ being the difference between propagation constants of the fundamental mode and Nth high-order mode of the corresponding waveguides; *K(z)* is a coupling coefficient calculated for the modes. The equations have an analytical solution if $dX/dz=\gamma[\Delta\beta_{i,j}2(X^2(z)+1)]$, where γ is the adiabaticity indicator such that the maximal power converted to the local normal mode *j* is $P_{j,max}/P_{i,0}\approx 4\gamma^2$ with $P_{i,0}$ the launched power in local normal mode *i*. Expansion of $\Delta\beta_{i,j}=\beta_i-\beta_j= 2|K(z)|(X^2(z)+1)^{1/2}$ from conventional coupled modes theory [12] yields the following system description:

$$dX/dz = 4\gamma\left|K(z)\right|\left(X^2(z)+1\right)^{3/2}. \qquad (3)$$

X is the most important engineering design parameter of the device. In the limit $X\to\pm\infty$, the local normal modes of the structure become the modes of the constituent waveguides; $X=0$ describe a situation of synchronism, i.e. $\Delta\beta=0$. The length required for *X* to evolve from $-\infty$ to $+\infty$ is the length of the device.

Equation (3) defines the required relation between *Δβ(z)* and *|K(z)|*, which in turns defines the waveguides structure. Choosing a *z* independent coupling *K(z)=const* [11] - the *Δβ(z)* which satisfies Eq. (3) is not realizable since $X\to\pm\infty$ requires $\Delta\beta\to\pm\infty$ which can not be obtained in real structures. One way to solve this problem is by concatenating the segment with constant coupling to another segment with exponentially decreasing coupling and constant *Δβ* [13]. However we propose an alternative way for achieving $X\to\pm\infty$, by applying *z* dependent coupling, with $K(\pm L)=0$ (overall device length is *2L*). The condition $K(\pm L)=0$ is realizable by separating the waveguides far enough (in our case a number of microns).

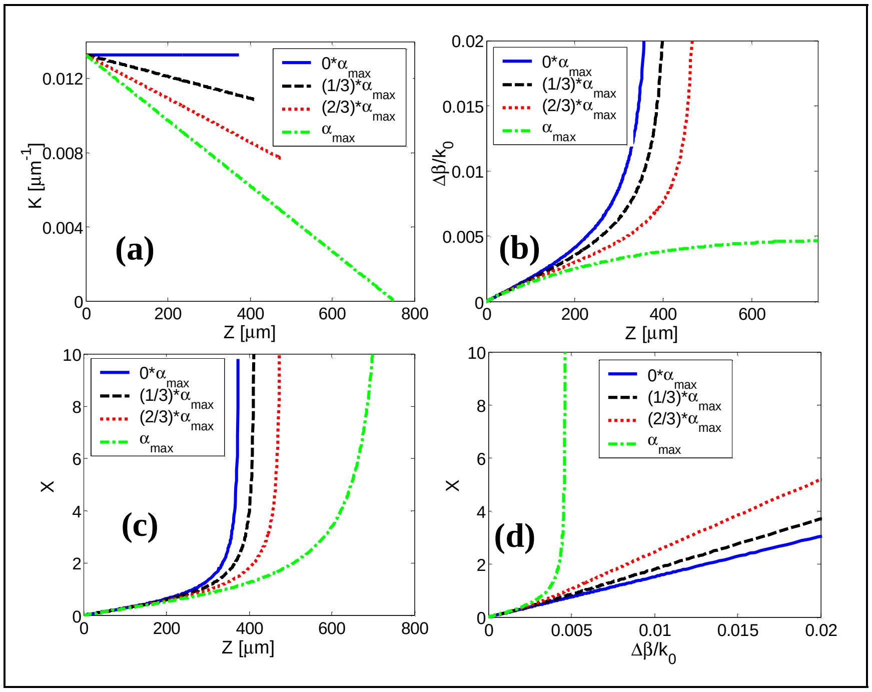

Fig. 2. (a) Coupling strength $K(z)$, for different α.. (b) Corresponding $\Delta\beta(z)$ for different α. $\Delta\beta(L)$ is finite only for $\alpha = \alpha_{max}$. (c) $X(z)$ for different α. (d) $X(\Delta\beta)$ for different α.

3. Adiabatic Coupler with Linearly Decreasing Coupling Strength

Here we analyze the second half of the transition $0<z<L$ (starting at the β crossing point), while the first half ($-L<z<0$) can be designed similarly. We restrict the coupling z dependence to be linear – i.e. $K(z)=K_0-\alpha z$. (The analysis of polynomial coupling will be published elsewhere.) Substituting into (3) and integrating, with the initial condition $X(z=0)=0$, we obtain

$$X^2(z) = \frac{16\gamma^2\left(K_0 z - \frac{\alpha z^2}{2}\right)^2}{1-16\gamma^2\left(K_0 z - \frac{\alpha z^2}{2}\right)^2} . \tag{4}$$

The related $\Delta\beta(z)$ is obtained from $\Delta\beta(z)=2|K(z)|*X(z)$. The condition $X(L)\rightarrow\pm\infty$ implies zeroing of the denominator and the length of the device is obtained from the solution of the quadratic equation:

$$z^2 - \frac{2}{\alpha}K_0 z + \frac{1}{2\alpha\gamma} = 0 , \tag{5}$$

and is given by

$$L(\alpha) = \frac{K_0}{\alpha} \pm \frac{1}{2}\sqrt{\frac{4K_0^2}{\alpha^2} - \frac{2}{\alpha\gamma}} , \tag{6}$$

where the solution with the '–' sign is the physical solution. The condition on non-negative discriminant translates to a bound on maximum α:

$$\frac{4K_0^2}{\alpha^2}-\frac{2}{\alpha\gamma}>0 \quad \Rightarrow \quad \alpha \le 2\gamma K_0^2 = \alpha_{\max}\,. \tag{7}$$

Figure 2(a) shows a number of linear coupling shapes for different values of α and Figs. 2(b) and 2(c) depict the related $\Delta\beta(z)$ and $X(z)$ dependences. For $\alpha=\alpha_{max}$ the length of the transition is $L(\alpha_{max})=(2\gamma K_0)^{-1}$ and $K(z=L)=0$. The requirement $X(L)\to\infty$ is satisfied for finite value of propagation constants difference

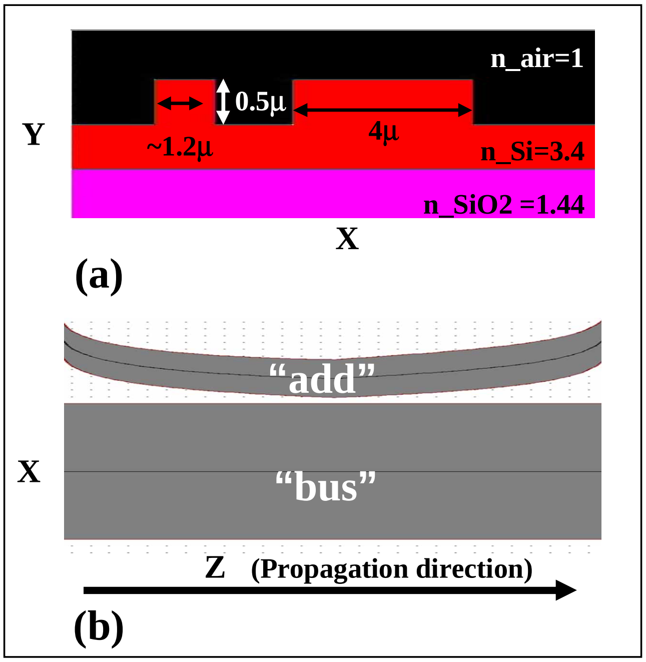

Fig. 3. (a) The x-y crossection of the SOI waveguides. (b) The x-z layout of the optical Mode Add/Drop.

$\Delta\beta(z=L)=\sqrt{2}K_0$. Since we are interested in coupling to the Nth mode, we have to impose $\beta_{N+1}<\beta_{add}<\beta_{N-1}$ in order to eliminate cross-talk to other high-order modes; it can be achieved by choosing K_0 so that $\beta_{N+1}<\beta_N \pm\sqrt{2}K_0<\beta_{N-1}$.

For $\alpha<\alpha_{max}$ the requirement $X(L)\to\infty$ translates to infinite propagation constants difference $\Delta\beta(z=L)\to\infty$, which can not be implemented in real devices. Nevertheless, the coupling shapes with intermediate values of α are sufficient for practical purposes to obtain a large but finite value of X in the end of the transition.

We analyzed a system supporting only two local normal modes thus no direct information on the crosstalk to other high-order modes is obtained. However it is plausible that the crosstalk to other modes is smaller than the mode-conversion between local normal modes i and j – which are the highly interacting local normal modes (their propagation constants difference is minimal – in the region of maximal coupling). This assumption is verified using numerical simulation of the device.

4. Mode Add/Drop Implementation

We present the design of an adiabatic MADM based on SOI structure from a fundamental mode of a waveguide (add) to the third-order mode of a multimode waveguide (bus)

#8697 - $15.00 USD Received 8 September 2005; revised 1 November 2005; accepted 2 November 2005

supporting five modes (Fig. 3(a)). The design parameters are $\gamma=0.05$ (corresponding to *-20dB* conversion between local normal modes *i* to *j* which is a limit crosstalk value to other modes in the system), and minimal waveguide separation WS=0.2μm. Following our scheme, to implement a real device we should translate the mathematical profiles $|K(z)|$, $\Delta\beta(z)$ to actual waveguides parameters. As discussed above we retain the bus constant allowing only changes in the width and relative position of the add waveguide. $\Delta\beta$ depends only on the ridge width of the add waveguide (RWA); the coupling strength depends mainly on the spacing between the waveguides (WS) and weakly on RWA, thus for simplicity we omit the later dependence. Employing a mode-solving module we calculate the dependence $\beta_{add}(RWA)$ and β_3 of the multimode waveguide (Fig. 4(a)) and obtain $RWA(\Delta\beta)$. Subsequently we calculate $K(WS)$ for a constant width add waveguide ($RWA(\Delta\beta=0)$). Combining the required $|K(z)|$, $\Delta\beta(z)$ from the above analytical model and $WS(K)$, $RWA(\Delta\beta)$ yields the structural parameters $WS(z)$ and $RWA(z)$.

For the linear *z* dependence of the coupling strength, achieving large values of *X* is accompanied by a rapid change of the structural parameter *WS(z)* resulting in coupling to radiation modes In our closed form formulation, we did not take into account these radiation modes. As a result a loss will be experienced in the input part of the device. In contrast to the large *WS(z)* depedence, *RWA* changes only by 10-20% and adiabatically throughout the structure so that the loss induced by *RWA* change (less than 1%) can be neglected. We simulated the full-length device and observed a loss of ~-1.5dB. This loss can be eliminated by choosing a more complex *z* dependence of the coupling strength. However, a simpler approach is to shorten the device to achieve a finite *X* which is sufficiently large for the

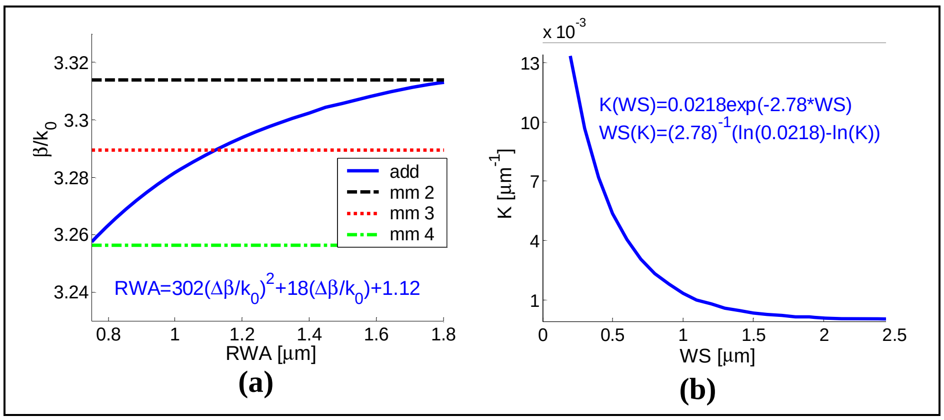

Fig. 4. (a) Propagation constants (normalized by k_0) vs. the ridge width of the "add" waveguide and propagation constants of the 2nd, 3rd, 4th modes of the "bus" waveguide (mm=multi mode). (b) Coupling coefficient between the fundamental mode of "add" waveguide and the 3rd mode of the "bus" vs. waveguide spacing. The calculation is performed at constant ridge width of the "add" waveguide.

practical case. We select *X* such that the initial power projection into any unwanted local normal mode *j* is below a prescribed value. In our device selecting $X(L)=10$, the initial crosstalk (given by $(2X)^{-2}$) is *-26dB* and the overall conversion crosstalk is smaller than *-20dB*. For simplicity we designed a device with $X(-z)=-X(z)$, thus the device length is $L_{tot}=2L=1470\mu m$, the resulting structure is shown in Fig. 3(b).

Received 8 September 2005; revised 1 November 2005; accepted 2 November 2005

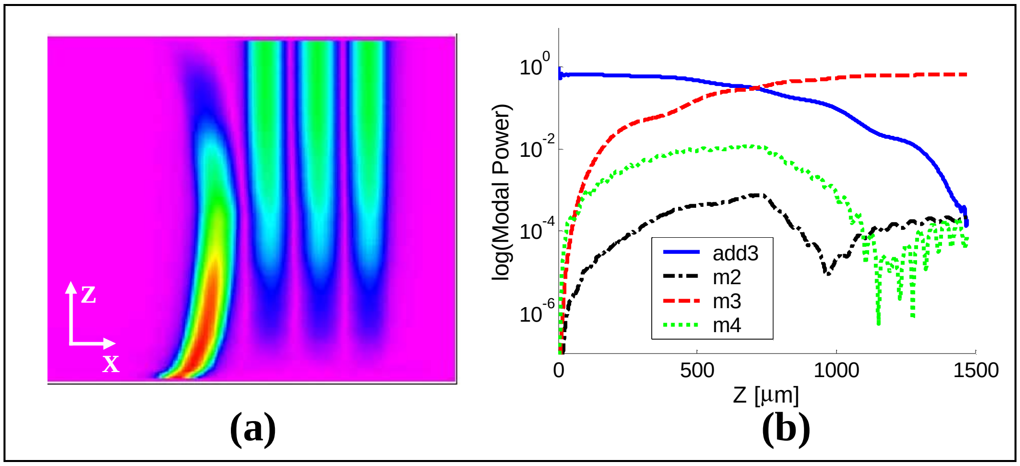

Fig. 5. (a) The propagation x-z crossection for coupling to the 3rd mode of the multi-mode waveguide (Add operation). (b) The powers at the 2nd, 3rd, 4th modes of the "bus" waveguide and the fundamental mode of the "add" waveguide.

The Mode Add performance was validated by beam propagation method simulations (Fig. 5(a)). The field intensity distribution in Fig. 5(a) is validating the operation as a Mode Add (Mode drop for the reversed initial conditions). The power of the first 3 modes of the "bus" waveguide and the launched mode in the "add" waveguide are shown in Fig. 5(b). The crosstalk to the other modes is less than -30dB.

5. Conclusion

For launching mode-multiplexed data channels into distinctive high-order modes of multimode optical waveguide, in very short-reach optical communication schemes, we presented a mode-add-drop device and novel analytical design rules derived from coupled local normal mode theory. These rules were successfully implemented in a feasible SOI waveguide structure exhibiting adiabatic add/drop multiplexing of a channel to/from the third mode of a data bus multimode waveguide. Relatively short device (less than 1.5mm) and low modal crosstalk (<-30db) were validated by simulation of the designed device. The scheme preserves the communications system integrity by maintaining as a constant both the bus dimensions and number of channels.

#8697 - $15.00 USD Received 8 September 2005; revised 1 November 2005; accepted 2 November 2005