Self-switching in Mach-Zehnder interferometers with SOA phase shifters

Self-Switching in Mach–Zehnder Interferometers With SOA Phase Shifters

E. A. Patent, J. J. G. M. van der Tol, J. J. M. Binsma, Y. S. Oei, E. A. J. M. Bente, and M. K. Smit

***Abstract*—A self-switching mechanism in Mach–Zehnder interferometers (MZIs) is described. The input light signal is distributed unequally over the interferometer arms using an multimode interference (MMI) coupler. In the arms, semiconductor optical amplifiers are placed as nonlinear phase shifters. Unequal intensities yield a nonlinear phase shift. The signals from the two arms are then recombined in an output MMI coupler. If an obtained nonlinear phase shift in the arms can compensate the coupler-induced phase difference between the arms, the signals are in phase at the output port. Choosing an appropriate output coupler, 2×1 and 2×2 devices can be obtained. The 2×2 and 2×1 MZIs can be used as pattern effect compensators and 2R-regenerators or low-loss combiner circuits, respectively. An active–passive integration technique is applied in order to realize the interferometric structures. Fabrication, simulation, and characterization of these devices are presented in this letter.**

***Index Terms*—Integrated optics, Mach-Zehnder interferometers (MZIs), self-switching, semiconductor optical amplifiers (SOAs).**

I. Introduction

In photonic integrated circuits, Mach–Zehnder interferometers (MZI) are widely used building blocks. These MZIs can be constructed with two connected multimode interference (MMI) couplers, creating two arms from which interfering signals are obtained. In a number of applications, semiconductor optical amplifiers (SOAs) are placed in the arms of an interferometer, playing the role of nonlinear elements. The nonlinear behavior of an SOA originates from the carrier depletion at high input optical powers. A common technique to exploit the SOA nonlinearities is cross-phase modulation, which makes use of an external optical control signal. The control signal, thus, modulates the phase of an input signal, which is equally distributed over the interferometer arms. Such a configuration can be used, e.g., for wavelength conversion [1]. Another switching technique is self-phase modulation. If the input optical signal is distributed unequally over the interferometer arms, the two SOAs are operating in different regimes: One SOA operates in the saturation regime, another SOA operates in the unsaturated regime. This introduces a phase difference between the two signals. In this way, the nonlinear phase difference between the optical signals originates from the difference in the signals' intensities. Self-switching interferometers presented in this letter can find several applications. If a 2×1 output MMI coupler is used, the resulting 2×1 MZI can be used as a low-loss optical combiner, an operation principle previously reported in [2]. While the passive 3-dB combiner transmits only a half of the input power (3 dB), the low-loss optical combiner due to the induced nonlinear phase shift and related to it constructive interference of the two signals, allows for transmission of more then 2 dB of the original signal. Choosing an appropriate 2×2 output MMI coupler, a nonlinear S-form transfer function can be obtained. Such a 2×2 MZI can redistribute noise, realizing the 2R-regeneration function. The 2×2 MZI can also be used as a pattern effect compensator, a concept previously reported in [3]. The recent measurements [4] show its compensation capabilities for signals at 10 Gb/s.

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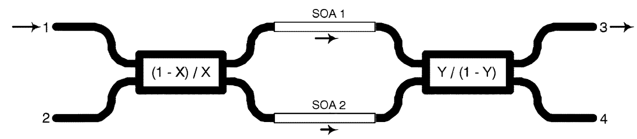
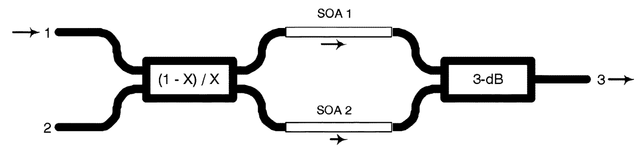


(a)



(b)

Fig. 1. Schematics of MZI-based switches with unequal power distribution: (a) 2×2 and (b) 2×1.

II. Self-Switching Principle

Two possible configurations of MZIs with unequal optical power distribution are shown in Fig. 2.

The optical input signal injected in one of the input ports [e.g., Port 1, see Fig. 1(a) and (b)], is distributed unequally over the two interferometer arms. In the high optical power arm,[1] the SOA is operating in the saturation regime, causing changes of both the gain and the refractive index as a function of optical power. Consequently, this induces a nonlinear phase shift of the optical signal. In the low power arm, the SOA is operating in the unsaturated regime, so both the gain and the refractive index are constant. As a result, optical signals of different intensities lead to a nonlinear phase difference $\Delta\phi_{\mathrm{NL}}$ induced between the two interferometer arms. Furthermore, there is a phase difference of $\pi/2$ rad between two optical signals at the output ports of 2×2 couplers. This suggests that the maximum transmission signal from Port 1 to Port 3 can be reached if the induced nonlinear

[1]With $X < 0.5$, the high optical power arm is the one with the SOA1

phase shift compensates for the coupler-induced phase difference. The two signals from the MZI arms are then in phase, yielding an optimum recombination. For the structure shown in Fig. 1(a), the required phase shift is $\Delta\phi_{\rm NL} = \pi$ to compensate for both 2×2 couplers. The structure shown in Fig. 1(b) with a 3-dB splitter at its output requires a phase shift $\Delta\phi_{\rm NL} = \pi/2$.

If $Y = X$ (as in the case of the 2×2 device presented in this letter), the expression for the output power can be written as

$$\begin{aligned} P_{\rm out} = &\left(\sqrt{X(1-X)} \cdot e^{(G-\Delta G)L/2)}\right)^2 \\ &+ (\sqrt{X(1-X)} \cdot e^{\rm GL/2})^2 - 2X(1-X) \\ &\cdot e^{\rm GL} \cdot e^{-\Delta {\rm GL}/2} \cdot \cos\left(\frac{\alpha \cdot \Delta{\rm GL}}{2}\right) \qquad (1) \end{aligned}$$

with G the gain of the unsaturated SOA2, $G-\Delta G$ the gain of the saturated SOA1, α the effective alpha factor, which is the relation between changes in gain and the nonlinear phase shift, and L the SOA length. The first two terms are the transmitted signals through separately biased SOA1 and SOA2. The third term of the equation is the interference between the two signals. If no nonlinear phase shift is induced ($\Delta\phi_{\rm NL} = \alpha\Delta{\rm GL}/2 = 0$), the output power has a minimum value. If $\Delta\phi_{\rm NL} = \pi/2$, the output power is equal to the sum of the two transmitted signals through separately biased SOA1 and SOA2. Finally, when $\Delta\phi_{\rm NL} = \pi$, the output power reaches its maximum value: Constructive recombination of the two signals is achieved.

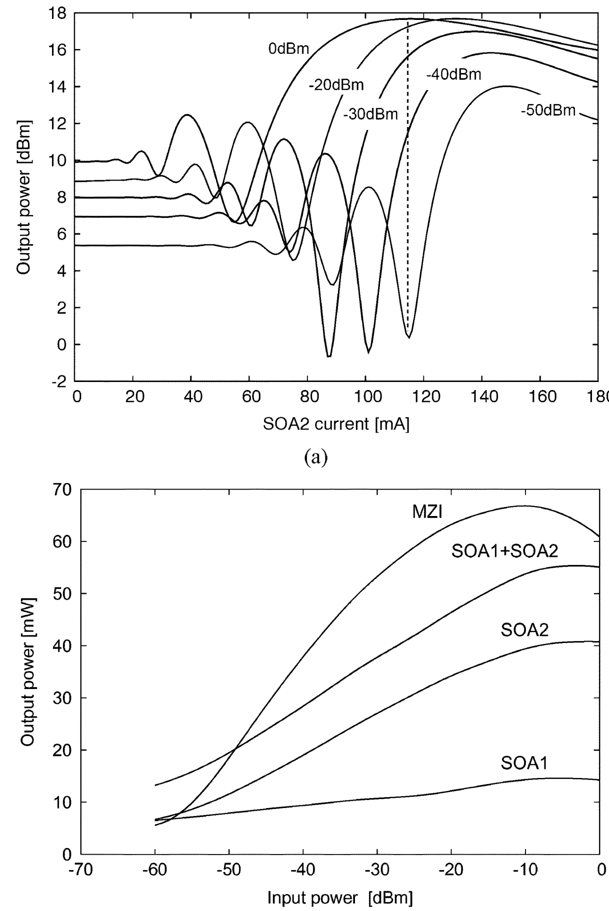
III. Design and Fabrication

The interferometric structures are designed and realized in the InGaAsP–InP material system. The active–passive integration technique described in [5] is used. The active layer stack is butt-joint to a $Q(1.25)$ layer (an InGaAsP layer with $\lambda_g = 1.25\ \mu$m) for the passive components. The SOA active layer is a $Q(1.55)$ layer with a thickness of 120 nm, sandwiched between two $Q(1.25)$ layers. The passive waveguides in the circuits have a width of 3 μm, and are 100 nm etched into the quaternary layer. The geometry of the passive waveguides is optimized for low propagation losses in the bends. The SOA waveguides are 2 μm wide, also etched 100 nm into the quaternary layer. The geometry of the SOA-waveguide was optimized for a high photon density in the active layer, which is advantageous for nonlinear effects. The SOAs have a length of 1000 μm. The ridge waveguides were etched employing an optimized CH_4–H_2 reactive ion etching process alternated by an O_2 descumming process. For the couplers, MMI devices were chosen because of their compact design and polarization insensitivity. The unequal distribution of the input power is obtained by using an unbalanced MMI coupler with a coupling ratio $X = 0.15$. It has a length of 724 μm with a width of 10 μm. The 3-dB MMI splitter, used at the output of the 2×1 MZI, has a length of 115 μm with a width of 10 μm. At the output of a 2×2 MZI, couplers of different ratios can be used, depending on the application. For the configuration studied in this letter, a coupler with $Y = 0.15$ with a length of 234 μm is used.

IV. Simulation Results

For the 2×2 interferometer, self-switching effects can be observed by fixing the current of SOA1 at 140 mA in the high optical power arm, while sweeping the current of SOA2, and detecting the optical power at the output Port 3 [see Fig. 1(a)]. The curves can be obtained for different input power levels. By comparing the corresponding interference curves, intensity-dependent self-switching from destructive to constructive interference can be seen. The simulations were performed with the VPItransmissionMaker software. The results are summarized in Fig. 2(a).

It is clearly seen that the curves in Fig. 2(a) depend on the optical power. For an SOA2 current of about 120 mA, a switching from interference minimum to interference maximum is observed. The transmission curves obtained by sweeping the input power and detecting the output power are presented in Fig. 2(b). In order to illustrate the self-switching effect in the interferometer, the transmission was calculated biasing each SOA separately (curves "SOA1" and "SOA2") and adding these two curves together. The resulting curve "SOA1 + SOA2" is plotted without taking into account the induced phase shift. The contribution of the interference is obvious from comparing this curve with the curve "MZI."



(a)

(b)

Fig. 2. (a) Calculated interference curves for input powers $-50 - 0$ dBm and (b) transmission curves for only SOA1, SOA2, sum of these two and the full MZI.

V. Experimental Results

Prior to the transmission measurements, we have determined the working point of the interferometer by choosing the right bias conditions. For the optimal operation of the devices based on self-switching, the two bias currents are not

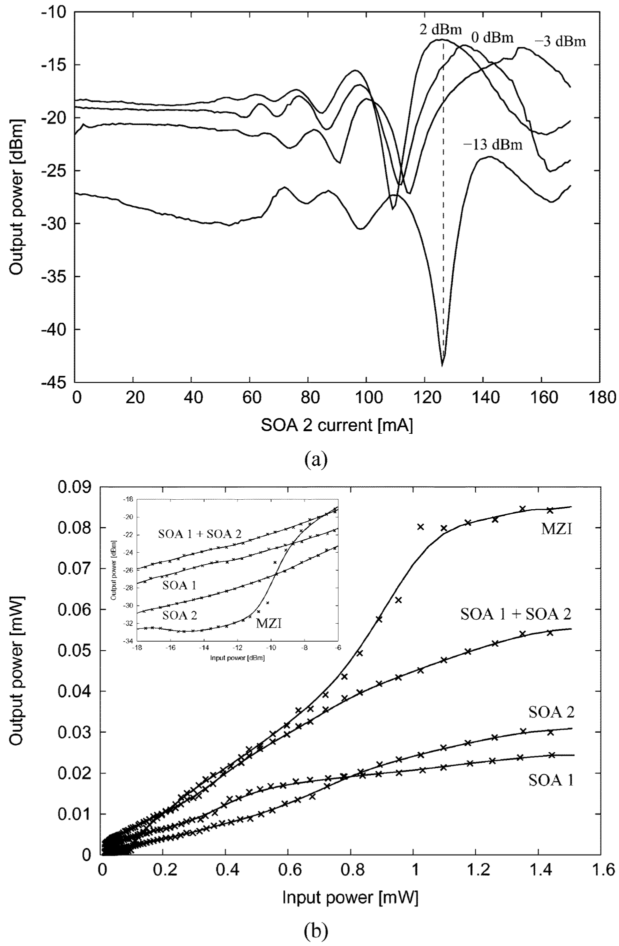


Fig. 3. (a) Measured interference curves and (b) transmission curves of the 2×2 MZI. Input and output power are the ones in the fiber. The inset shows in decibel scale the low-power behavior of the MZI.

necessarily equal. One explanation for this is the asymmetry in the arms caused due to technological reasons. The working point is determined by fixing the current of the SOA in the high optical power arm (SOA1), and scanning the current of the SOA2. The measurements are repeated for different input powers [Fig. 3(a)]. In the experiment, the SOA1 bias current is 140 mA. The measurements are performed at $\lambda = 1550$ nm.

The transmission measurement results for the bias conditions $I_{\mathrm{SOA1}} = 140$ mA and $I_{\mathrm{SOA2}} = 127$ mA are summarized in Fig. 3(b). It can be seen that the device shows a nonlinear transfer function, which implies its applicability for 2R-regeneration. The results agree qualitatively with Fig. 2(b). It can be seen that for very low input powers, the output signal of the interferometer is lower then the sum of output signals detected for separately biased SOAs. The nonlinear phase shift in this power range is negligible. For higher input powers (above 0.7 mW), the effect of the interferometer becomes stronger, the output signal becomes larger then the sum of the two separately transmitted signal, and the maximum improvement of the transmission is then 1.9 dB. Based on (1), assuming that the obtained nonlinear phase shift at maximum improvement is π, the effective α-parameter can be calculated, and in this experiment is found to be around four.

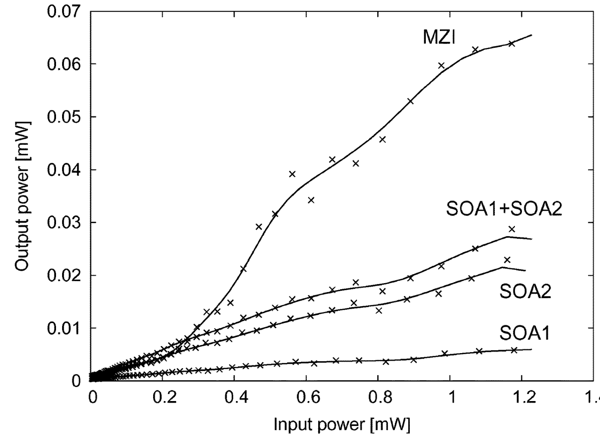


Fig. 4. Measured transmission curves of the 2×1 MZI.

For the 2×1 interferometer in Fig. 1(b), the situation is different. The device must operate symmetrically with respect to the input Ports 1 and 2. A nonlinear phase shift of $\pi/2$ is needed. The required switching is then not from the destructive to constructive interference, but from the middle state to constructive interference. The working point determined for this device is $I_{\mathrm{SOA1}} = 120$ mA and $I_{\mathrm{SOA2}} = 117$ mA. The results are presented in Fig. 4.

The maximum improvement of the transmission "MZI" with respect to the "SOA1 + SOA2" is in this case larger then 2 dB.

VI. Conclusion

Self-switching in SOA-based MZIs with unequal distribution of input optical signal is presented. Using 1000-μm SOAs, large nonlinearities were observed, leading to a phase shift of π for optical powers below 1.5 mW (in the incoupling fiber). The self-switching can be used for 2R-regenerators, pattern effect compensators, and low-loss optical combiner circuits.

References

[1] C. Janz, B. Lavigne, F. Poingt, I. Guillemot, F. Gaborit, B. Dagens, D. Chiaroni, and M. Renaud, "Low-penalty 10 Gbit/s operation of polarization-insensitive Mach–Zehnder wavelength converters based on bulk-tensile active material," in *Tech. Dig. Opt. Fiber Comm. (OFC'98)*, San Jose, CA, Feb. 22–27, 1998, pp. 101–102.

[2] J. J. G. M. van der Tol, R. G. Broeke, and X. J. M. Leijtens, "Low -loss integrated optical combiner based on semiconductor optical amplifiers," in *SAFE*, Veldhoven, The Netherlands, Nov. 2000.

[3] E. A. Patent, J. J. G. M. van der Tol, N. Calabretta, and Y. Liu, "A pattern effect compensator," in *Proc. IEEE/LEOS Symp. (Benelux Chapter)*, Brussels, Belgium, Dec. 2001, pp. 233–236.

[4] E. A. Patent, J. J. G. M. van der Tol, M. L. Nielsen, J. J. M. Binsma, Y. S. Oei, J. Mørk, and M. K. Smit, "Integrated pattern effect compensator based on self-switching," in *Proc. 11th Eur. Conf. Int. Opt. (ECIO 2005)*, Grenoble, France, Apr. 6–8, 2005.

[5] J. J. M. Binsma, M. van Geemert, F. Heinrichsdorff, T. van Dongen, R. G. Broeke, and M. K. Smit, "MOVPE waveguide regrowth in InGaAsP/InP with extremely low butt joint loss," in *Proc. IEEE/LEOS Symp. (Benelux Chapter)*, Brussels, Belgium, Dec. 2001, pp. 245–248.