Self-switching in Mach-Zehnder Interferometers based on SOA phase shifters.

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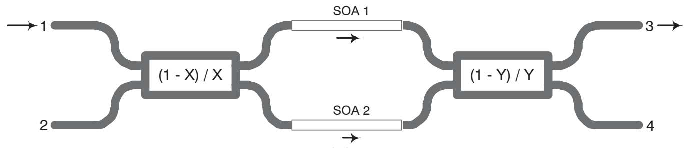
A self-switching mechanism in Mach-Zehnder Interferometers is described. The input light signal is distributed unequally over the branches where Semiconductor Optical Amplifiers are placed as non-linear phase shifters. Unequal intensities yield a non-linear phase shift. The signals from the two branches are then recombined in an output coupler. If $\pi/2$-phase shift is reached, the signals are in phase. This effect can be used in the low-loss optical combiner circuit. In this device the transmission can be improved by more then 2 dB with respect to a passive 3-dB splitter. Fabrication, characterization and performance of the combiners are presented in this paper.

Introduction

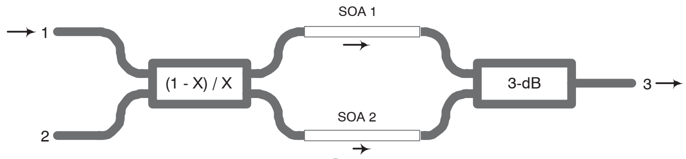
In photonic integrated circuits, Mach-Zehnder interferometers (MZI) are widely used building blocks. In a number of applications Semiconductor Optical Amplifiers (SOA) are placed in the arms of an interferometer, playing the role of non-linear elements. The non-linear behavior of a SOA originates from the carrier depletion at high input optical powers. A common technique to exploit the SOA non-linearities is cross-phase modulation (XPM), 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 (SPM). If the input signal is distributed *un*equally over the interferometer arms, the two SOAs are operating in different regimes, yielding a phase difference between the two signals.

The self-switching principle

The possible self-switching configurations in MZIs with unequal power distribution are shown in fig. 1. The optical input signal injected in one of the input ports (e.g. port 1 as shown in fig. 1(a) and fig. 1(b)), is distributed unequally over the two interferometer arms. In the high optical power arm, 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 non-linear 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 non-linear phase difference $\Delta\Phi_{NL}$ induced between the two 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 can be reached if the induced non-linear



(a)



(b)

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

phase shift compensates 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 $\Delta\Phi_{NL} = \pi$ 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 of $\Delta\Phi_{NL} = \pi/2$.

The self-switching technique can be used in a number of applications. Choosing the appropriate output coupler, the structure shown in fig. 1(a) can be used as a pattern-effect compensator [2] or 2R-regenerator. The configuration shown in fig. 1(b) is a low-loss optical combiner circuit, which operation principle was previously reported in [3]. Below, simulation and experimental results of these structures will be presented.

Design and fabrication

The interferometric structures are designed and realized in the InGaAsP/InP material system. The active-passive integration technique described in [4] is used. The active layer stack is butt-joint to an Q(1.25) layer[1] for the passive components. The SOA active layer is Q(1.55)[2] 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 low saturation powers [5]. 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, multi-mode interference (MMI) devices were chosen because of their compact design and polarization insensitivity. The unequal distribution of the input power is obtained by using a coupler with a coupling ratio of 85/15. At the output, the same type of 2×2 coupler can be used, or a 3-dB MMI splitter.

[1] Q(1.25) corresponds to the InGaAsP film layer with λ_g=1.25 μm
[2] Q(1.55) corresponds to the InGaAsP film layer with λ_g=1.55 μm

Simulation results

For the 2×2 interferometer, self-switching effects can be observed by fixing the current of SOA1 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)). In the considered structure $X = 0.15$ and $Y = 0.85$. The curves can be obtained for different input power levels. By comparing the corresponding interference curves, intensity-dependent self-switching from the destructive to the constructive interference can be seen. The simulations were performed with *Virtual Photonics Inc.* software. The results are summarized in fig. 2(a).

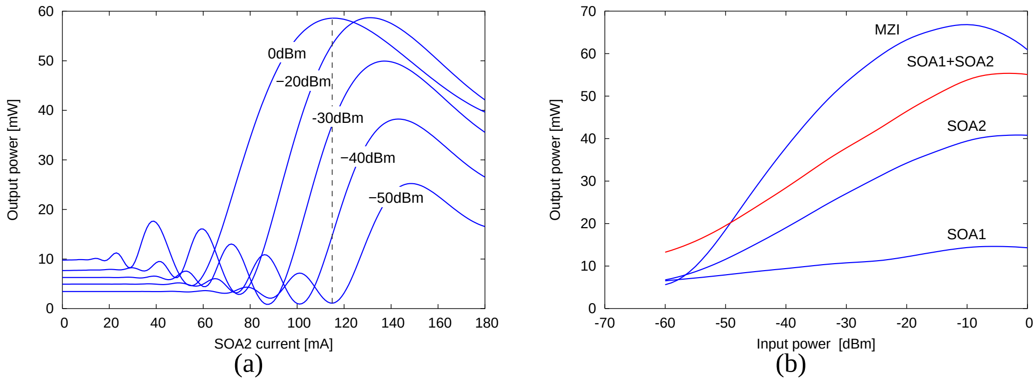


Figure 2: Calculated interference curves for input powers -50 dBm - 0 dBm (a) and transmission curves for only SOA1, SOA2, sum of these two and the full MZI (b).

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 the latest with the curve ”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, for that a non-linear 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.

Experimental results

The measurement setup, developed for characterization of the interferometers, is equipped with polarization maintaining fibers. The polarization stability is an important issue as the SOAs are optimized for the TE-polarized optical signals. The input and output signals are detected at the same time, so ambiguities in interpretations of the results (e.g. due to temperature drifts) can be avoided. At the output, a tunable bandpass filter is used in order to filter out the ASE noise generated by the SOAs. Prior to the transmission measurements, it is important to determine the working point of the interferometer by choosing the right bias conditions. It can be seen from fig. 2(a) that for the optimal self-switching, the two bias currents are not necessarily equal. One of the reasons for that is the minimum power level, for which the SOA in the low power arm is operating in the unsaturated regime. Another reason is that due to technological reasons the two SOAs are not exactly identical. 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 second SOA (SOA2). The measurements are repeated for different input powers (fig. 3(a)). In the experiment SOA1 bias current is 140 mA. The measurements are performed at λ=1550 nm.

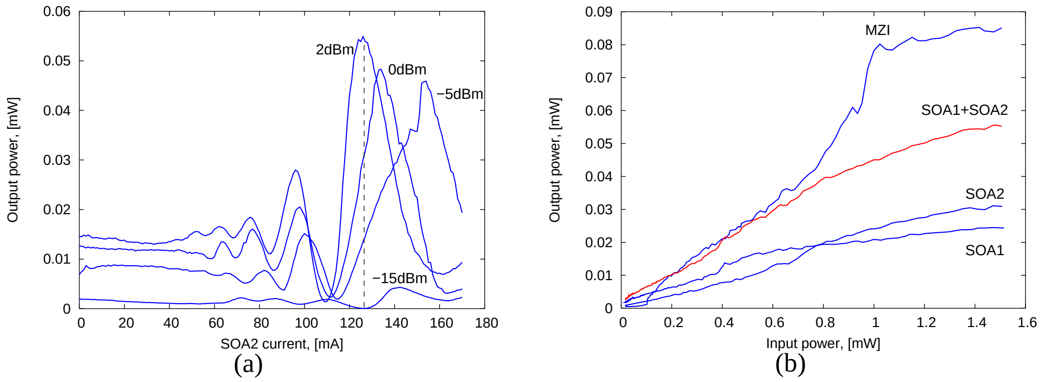


Figure 3: Measured interference curves (a) and transmission curves (b). Input and output power are the ones in the fiber. The fiber-to-chip coupling losses are not taken here into account.

The transmission measurement results are summarized in fig. 3(b). The results agree qualitatively with the simulations. It can be seen that for low input power range, output signal of the interferometer is equal to the sum of output signals detected for separately biased SOAs. Thus, the non-linear phase shift is negligible. However, for higher input powers (above 0.7 mW), the effect of the interferometer becomes stronger, and the maximum improvement measured is 1.9 dB.

Conclusions

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

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