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Integrated SOA-MZI for pattern-effect-free amplification

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An integrated Mach-Zehnder interferometer using self-switching, capable of reducing the saturation induced pattern effect, is reported. The device functionality is shown for 10 Gbit/s, and BER measurements show an improvement of up to 7 dB of the input power dynamic range.

Introduction: A serious restriction on the linear operation of semiconductor optical amplifiers (SOAs) is caused by the gain saturation effect. At high optical powers, carrier depletion takes place, which consequently reduces the optical gain. In optical networks this can lead to waveform distortion, commonly referred to as the pattern effect [1]. The gain becomes dependent on the bit pattern. At longer bit times it shows up as a higher gain on the leading edge of a pulse.

In this Letter we report an integrated device (pattern-effect compensator) that compensates for the unwanted pulse form distortion that is characteristic for semiconductor optical amplifiers. Furthermore, because the compensation counteracts the effect of saturation, the device can replace an optical amplifier, and offer an extended input power dynamic range with a gain comparable to that of a single SOA.

Device concept: The interferometric suppression of the pattern effect was shown in [2], realised with a commercially available all-active Mach-Zehnder interferometer (MZI)-based structure. There, asymmetry in the operation of the interferometer was created by different bias currents. In the device presented in this Letter, the interferometer arms are equal, but the optical signal is distributed unequally over the arms. The advantage of this approach is that the interferometer can be operated closer to the balance (i.e. bias conditions are similar in both arms) making it more stable and broadband (the operation becomes less wavelength dependent). The pattern-effect compensator is shown schematically in Fig. 1.

Fig. 1 Schematic of MZI-based pattern-effect compensator with unequal distribution of input optical signal

The unequal distribution of the input optical signal is achieved by using a 2×2 multimode interference (MMI) coupler with a coupling ratio of 85/15. The output coupler used in the circuit is a 2×2 MMI 50/50 coupler. In the configuration shown in Fig. 1, the optical signal injected into the port 'in' is distributed unequally over the interferometer arms. Furthermore, a phase difference of $\pi/2$ is induced between the two signals by the input MMI coupler. Ideally, SOA 2 is working in the unsaturated regime and does not induce any nonlinear phase shift. Similarly, the leading part of an optical pulse injected into the SOA 1 is amplified with an unsaturated gain. Thus, the total phase difference at the output equals π across the leading edge, because the output MMI coupler also induces an additional phase difference of $\pi/2$. As a result, destructive interference for the output signal is obtained.

After the amplification of the leading part of the pulse, SOA 1 enters the saturation regime. Therefore, the waveform distortion and a nonlinear phase shift caused by change in the refractive index will take place. If the induced nonlinear phase shift is equal to π , the two signals from the interferometric arms will interfere constructively in the output coupler.

The net effect is that the leading part of the distorted pulse experiences a lower transmittance (no nonlinear phase shift is present, and incomplete destructive interference due to the unequal power levels in the output coupler leaves some signal still present at the output of the device), whereas the trailing part of the pulse experiences a higher transmittance (nonlinear phase shift is present due to the carrier depletion, yielding constructive interference). In this way, the pulse distortion can be compensated for.

The idea of a pattern-effect compensator based on the self-switching principle was initially verified using a fibre-based interferometric

structure, previously reported in [3]. Although it clearly showed the compensation capabilities, the major problem of the fibre-based structure was instability. This problem has been avoided here by integration.

Fig. 2 Measurement setup for experimental evaluation of integrated pattern-effect compensator

Design and fabrication: The interferometric structure is designed and realised in the InGaAsP/InP material system. The active-passive integration technique described in [4] is used. The active layer stack is butt-jointed to a Q(1.25) layer (an InGaAsP layer with $\lambda_g = 1.25 \mu\text{m}$) 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 $3 \mu\text{m}$, and are 100 nm etched into the quaternary layer. This geometry of the passive waveguides is optimised for low propagation losses in the bends. The SOA waveguides are $1000 \mu\text{m}$ long and $2 \mu\text{m}$ wide, also etched 100 nm into the quaternary layer. The ridge waveguides were etched employing an optimised CH_4/H_2 reactive ion etching process alternated by an O_2 descumming process. For the couplers, multimode interference devices were chosen because of their compact design and polarisation insensitivity [5]. The unbalanced 85/15 MMI coupler has a length of $724 \mu\text{m}$ and a width of $10 \mu\text{m}$. At the output of the 2×2 MZI, a 50/50 coupler with a length of $489 \mu\text{m}$ is used.

Fig. 3 Eye diagrams at 10 Gbit/s for an input power of 6 dBm in fibre

- a Uncompensated waveform at working point 1
- b Compensated waveform at working point 1
- c Compensated waveform at working point 2

Experimental results: The pattern-effect compensation of the integrated Mach-Zehnder interferometer was investigated at a bitrate of 10 Gbit/s. The measurement setup used for these experiments is shown in Fig. 2. Because of high fibre-to-chip coupling losses, the required input power levels were rather high in order to detect the signal with enough power at the output. There is a certain unbalance in the MZI arms due to fabrication reasons. Therefore the bias currents in the two arms are not necessarily equal and have to be adjusted. The measurements were performed at a wavelength of 1550 nm. The optimised bias currents of SOA 1 and SOA 2 are 130 and 91 mA (working point 1), and 30 and 121 mA (working point 2), respectively.

Fig. 3a shows a distorted waveform at a bitrate of 10 Gbit/s, which is obtained by biasing only the high power arm. In this way, only one SOA ('single SOA') is operating, showing gain saturation and consequently the pattern effect. Figs. 3b and c shows the compensated waveform at two working points, as detected at the output of the MZI. As can be seen from the eye diagrams, there is a clear improvement of the optical pulses at the output of the pattern effect compensator as compared to the distorted waveform from the single SOA.

The pattern-effect compensator represents a viable alternative to an SOA if, apart from reducing the unwanted pulse distortion, it also increases the input power dynamic range and provides a comparable gain. The output power for the same input power level was measured for the single SOA and for the MZI. The output power of the MZI is 4.3 dB higher than measured with the single SOA. To compare the pattern-effect compensator with an inline SOA, the losses induced by the MMI couplers should be taken into account. Even with these extra 3.8 dB losses, the proposed integrated pattern effect compensator has a higher gain than the gain of the single SOA.

To assess the performance of the pattern-effect compensator, the receiver sensitivity at a bit error rate (BER) of 10^{-9} was measured for the distorted signal (only SOA 1 is biased) and the compensated signal at the output of the MZI (both SOAs are biased at the first working point). The measurements were performed at a bitrate of 10 Gbit/s. The results are shown in Fig. 4. From this Figure it can be seen that the input power dynamic range of the pattern-effect compensator is extended by about 7 dB with respect to the single SOA.

Fig. 4 Receiver sensitivity at $BER = 10^{-9}$ against input power at 10 Gbit/s, measured at working point 1

Conclusions: In this Letter, a pattern effect compensator based on a Mach-Zehnder interferometer with unequal distribution of the input optical signal, is presented. Its operation principle is based on the fact that the leading part of the pulse is attenuated by incomplete

destructive interference, while the trailing part of the pulse experiences a higher transmittance, owing to a nonlinear phase shift caused by carrier depletion. In this way the device compensates for the pulse distortion. The realisation of the pattern-effect compensator is based on an active-passive integration technique. The integrated pattern-effect compensator has shown its compensation capabilities for a bitrate of 10 Gbit/s. Furthermore, the input power dynamic range of this device, compared to a single SOA, is extended by 7 dB. It provides a comparable gain. Therefore, the integrated circuit operates as a pattern-effect-free optical amplifier with an extended input power dynamic range.

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