Semiconductor Optical Amplifiers in a non-linear Mach-Zehnder Interferometer

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Semiconductor Optical Amplifiers (SOAs) are widely used as non-linear elements for optical data processing. For optimal use, high values of the phase change should accompany low changes in gain. The gain itself should be as high as possible. The relation between these two effects is described by the linewidth enhancement factor (α-factor). Here a method is proposed to unambiguously determine it on-chip. The method uses an integrated SOA in a Mach-Zehnder Interferometer with unequal power distribution. The MZI output depends on the gain saturation and the phase shift, due to self-phase modulation. Analyzing this signal gives information about the α-factor.

Introduction

Semiconductor Optical Amplifiers (SOAs) are playing a significant role in optical integrated circuits. A number of their advantages, such as a wide gain spectrum and possibilities of integration with other devices, are making them very attractive not only for amplifying the signal, but also for optical data processing, like in wavelength converters, where SOAs provide cross-phase modulation [1].

The non-linear behavior of a SOA originates from carrier depletion at high optical input powers. This changes both the gain and the refractive index (and thus the optical phase) in the SOA. For optimal use of these SOAs in non-linear applications, high values of the phase change should accompany low changes in gain. The relation between these two effects is described by the linewidth enhancement factor, or α-factor. Determining this parameter for a SOA in an optical integrated circuit is important for evaluating and optimizing the SOA design.

In the present paper we propose a method to unambiguously determine the α-factor. This method uses an integrated SOA in a Mach-Zehnder interferometer (MZI), (see fig.1). The input coupler is unbalanced, so that power differences over the branches of the MZI are obtained. The output of the MZI then depends both on the gain saturation and on the phase shift, due to self-phase modulation, in the SOA. Analyzing this output signal therefore gives direct information on the α-factor.

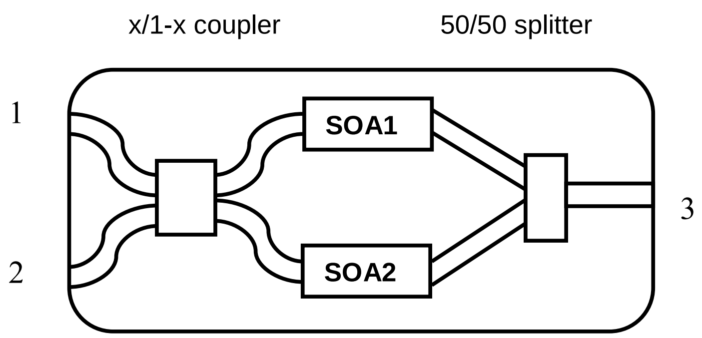

Fig. 1. Schematic layout of the MZI with the unbalanced coupler.

Description of the method

The relationship between gain saturation and non-linear phase shift can be written as [2]:

$$G_1(P) = G_0 \cdot \exp(-\frac{2 \cdot \Delta\Phi_{NL}(P)}{\alpha}), \tag{1}$$

where G_0 – is the gain of the SOA in the unsaturated regime (gain is expressed in cm^{-1}),
$G_1(P)$ and $\Delta\Phi_{NL}(P)$ – are the gain in the saturated regime and consequently induced non-linear phase shift for a certain input power P.

In order to determine the α-factor (being an *effective α-factor*), the non-linear phase shift and gain saturation have to be determined.

For the small-signal region (when both amplifiers are working in the unsaturated regime), the overall gain (G_S) of the MZI structure for two different paths can be written as

$$G_{S1\to3} = \frac{G_0}{2} - G_0 \cdot \sqrt{x(1-x)} \cdot \sin(\Delta\Phi_L) \tag{2}$$

and

$$G_{S2\to3} = \frac{G_0}{2} + G_0 \cdot \sqrt{x(1-x)} \cdot \sin(\Delta\Phi_L), \tag{3}$$

where x – is the coupling factor of the input coupler,
$\Delta\Phi_L$ represents the linear phase shift resulted from differences in the MZI branches.

Similarly, the overall gain of the combiner structure for the large-signal region (one of the amplifiers works in the saturated regime) (G_L) can be written as:

$$G_{L1\to3} = \frac{G_1(1-x)}{2} + \frac{G_0 x}{2} - \sqrt{G_0 G_1 x(1-x)} \cdot \sin(\Delta\Phi_L - \Delta\Phi_{NL}) \tag{4}$$

and

$$G_{L2\to3} = \frac{G_1(1-x)}{2} + \frac{G_0 x}{2} + \sqrt{G_0 G_1 x(1-x)} \cdot \sin(\Delta\Phi_L + \Delta\Phi_{NL}). \tag{5}$$

Using equations (1) – (5), the effective linewidth enhancement factor can be obtained from measurement results.

Experimental results

The MZI structure was realized in the InGaAsP/InP material system, for use at a wavelength of 1.55 μm. All epitaxial layers for the unbalanced MZI structure were grown by Low-Pressure MetalOrganic Vapour Phase Epitaxy (LP-MOVPE) [3]. The SOA active layer consists of 120 nm thick InGaAsP layer (λ_{gap}=1.55 μm) embedded between two InGaAsP layers (λ_{gap}=1.25 μm). The active layer stack was butt-joint to an InGaAsP (λ_{gap}=1.25 μm) layer for the passive by procedure described in [4]. The ridge waveguides were etched employing an optimized CH_4/H_2 etching process and an O_2 descumming process [5]. The waveguides in the circuit have a width of 3 μm, while the etching depth is 100 nm into the quaternary waveguide layer. For the couplers, MultiMode Interference (MMI) devices were chosen.

The described above technique was applied for the structure shown in fig. 1. For this device, the coupling factor *x* of the unbalanced coupler was measured to be *0.17*. By sweeping the input power at the ports 1 and 2 over a large range, and measuring the output power at the port 3, the overall gain of the MZI structure was determined. In the first experiment, a current of 180 *mA* was applied to the SOA in each branch. The measurement results are presented in figure 2 *a*). The measured values of gain in a small-signal and large-signal region are:

$$G_{S1\to3} = -9.7dB,$$
$$G_{S2\to3} = -4.9\ dB,$$
$$G_{L1\to3} = -8.2dB,$$
$$G_{L2\to3} = -7.3\ dB.$$

(the large-signal values correspond to the input power of -2.2 *dBm*). Negative values for the gain are caused by the losses in the fiber-chip coupling and in the MMIs.

Equations (2) – (5) are solved using the obtained linear phase shift $\Delta\Phi_L = 0.73\ rad$ and the non-linear phase shift $\Delta\Phi_{NL} = 1.3\ rad$. The unsaturated and saturated (at –2.2 *dBm* input power) gain is expressed in linear units 0.431 (-3.7 *dB*) and 0.152 (-8.2 *dB*) respectively. From equation (1), the linewidth enhancement factor is calculated to be 2.5.

In the second experiment, the applied current was increased to 200 *mA*. The measurement results are presented in figure 2 *b*). In this case

$$G_{S1\to3} = -10.4\ dB,$$
$$G_{S2\to3} = -3.8\ dB,$$
$$G_{L1\to3} = -7.6\ dB,$$
$$G_{L2\to3} = -7.3\ dB.$$

(the large-signal values correspond to the input power of -2.2 *dBm*). Using the same approach, the calculated values of the linear phase shift $\Delta\Phi_L = 1.0$ *rad,* and of the non-linear phase shift $\Delta\Phi_{NL} = 1.51$ *rad*. The linewidth enhancement factor is calculated to be 3.

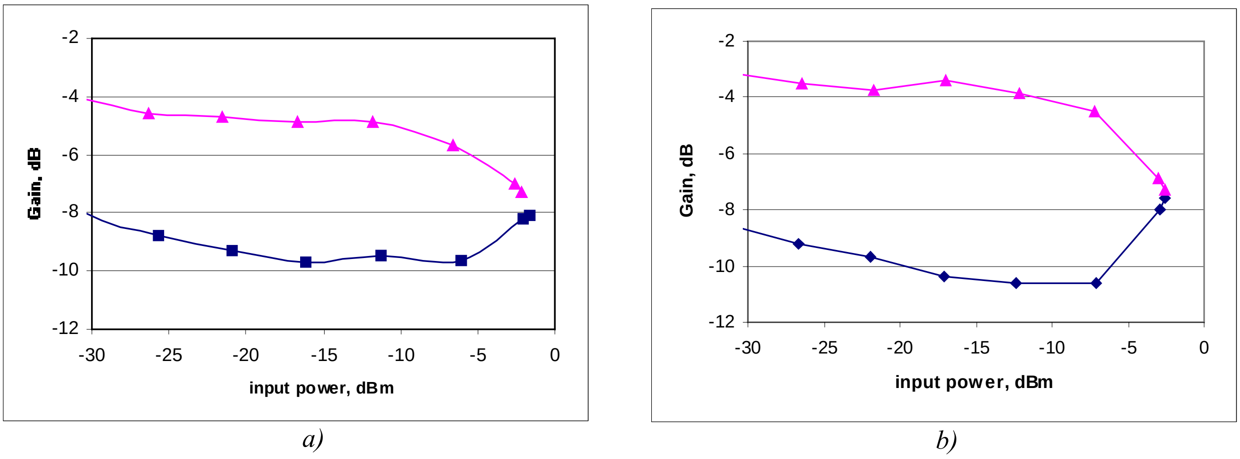

Fig. 2. Overall gain of the MZI structure as a function of the input power in port 1 (dark line) and in port 2 (light line). a) Bias current 180 mA, b) Bias current 200 mA.

Conclusions

We have presented and demonstrated a method to determine the linewidth enhancement factor of Semiconductor Optical Amplifiers, integrated in photonic circuits. The described method allows to evaluate the non-linear behavior of SOAs.

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