Non-linear behavior in quantum-well polarization converters

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The application of strain in quantum-wells leads to polarization dependence in their absorption characteristics. Material containing compressively strained quantum-well layers (such as used in the POLarization based Integration Scheme, POLIS) shows enhanced interaction with the TE polarization. Devices fabricated on such material are affected by the polarization dependence as well. For slanted side-wall polarization converters this leads to different effective conversion lengths for the TE and TM polarization. Simulations show that the polarization dependent absorption affecting these devices is saturable and therefore power dependent. The simulations have been confirmed by measurements on experimental devices.

Quantum well polarization converters

Slanted sidewall polarization converters operate on the principle that the light, applied at the input, is forced into two hybrid polarization states [1]. These hybrid states are linear combinations of the main polarization states TE and TM. The fraction of TE polarized light and TM polarized light in the two hybrid modes is dependent on the angle at which the two hybrid modes are placed with respect to the TE and TM polarization. This angle can be influenced by the angle of the slanted sidewall and the width of the converter waveguide.

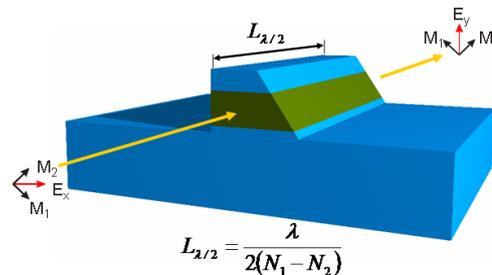$$L_{\lambda/2} = \frac{\lambda}{2(N_1 - N_2)}$$

Figure 1: A slanted side-wall polarization converter

One tilted mode is dominantly polarized parallel with the slanted interface, while the second tilted mode is polarized perpendicular to that interface. Both tilted modes experience different propagation constants and dephase while propagating through the converter waveguide. At the end of the polarization converter light in the tilted modes is forced back in the TE and TM polarization. The fraction of light in both polarization states is determined by the phase difference the light gained while propagating in the tilted modes. The coupling between the two orthogonally polarized modes, which occurs in the polarization converter, can be described by means of the coupled mode theory.

Some applications require the slanted side-wall polarization converters to be fabricated on quantum-well material. This, for example, is the case in the POLIS (POLarization based Integration) scheme in which the polarization dependence of the material is used

for active/passive integration [2]. In these applications the quantum-well layer is part of the converter's waveguide region and it will therefore interact with the light passing through the converter. Depending on the wether the waveguide is pumped or not, the TE-polarized light is either amplified or absorbed.

The absorption of light, leads to the generation of free carriers. This two consequences. The first consequence is that, because of the limited number of states available in the quantum-well, the absorption is quickly saturated. This effect is enhanced by the fact that the free carriers are not removed from the well by means of an externally applied field. The other consequence is that the free carriers affect the refractive index of the material and therefore influence the operation of the converter. Both effects have been investigated by means of a computer model and were confirmed by measurements on experimental devices, of which the results are discussed in the remaining part of this paper.

Modeling of the devices

The model of the quantum-well polarization converters is based on the coupled mode theory. The coupled mode theory applies to a large class of mode interactions, when there are two guided modes with sufficient phase synchronism to allow a significant exchange of energy. Therefore, one can neglect all other modes and obtain simple coupled wave equations to describe the interaction between these modes [3].

For the polarization converters under consideration, the coupled mode equations are given below. The equations have been written as a set of four real differential equations, representing the power and phase of both polarizations. In these equations the variables κ, α and δ represent the coupling constant, the TE attenuation and the phase mismatch respectively. The rate equations were solved by means of a traveling wave model.

$$\frac{dP_{TE}(l)}{dl} = 2\kappa\sqrt{P_{TE}(l)P_{TM}(l)}\sin(\psi(l)-\phi(l)) - 2P_{TE}(l)\alpha \tag{1}$$

$$\frac{dP_{TM}(l)}{dl} = 2\kappa\sqrt{P_{TE}(l)P_{TM}(l)}\sin(\phi(l)-\psi(l)) \tag{2}$$

$$\frac{d\phi(l)}{dl} = -\kappa\sqrt{\frac{P_{TM}(l)}{P_{TE}(l)}}\cos(\phi(l)-\psi(l)) + \delta \tag{3}$$

$$\frac{d\psi(l)}{dl} = -\kappa\sqrt{\frac{P_{TE}(l)}{P_{TM}(l)}}\cos(\phi(l)-\psi(l)) - \delta \tag{4}$$

Incorporating the saturable quantum-well losses for the TE polarization can easily be done by replacing the factor α_{TE} in eq. 1 with the differential equation in eq. 5 that describes the amplification/absorption in the quantum well. The changes in phase caused by the fluctuating carrier density are accounted for by adding eq. 6, to the appropriate phase equation. The carrier density itself is represented by eq. 7.

$$\frac{dP_{TE}}{dl} = \frac{1}{v_g}\left[\frac{g(N)P_{TE}}{1+\varepsilon P_{TE}} - \alpha_{int}P_{TE}\right] \tag{5}$$

$$\frac{d\phi}{dl} = -\frac{1}{2v_g}\left[\alpha_N g(N) - \alpha_T\frac{g(N)P_{TE}}{1+\varepsilon P_{TE}}\right] \tag{6}$$

$$\frac{dN}{dl} = \frac{1}{v_g}\left[-\frac{N}{\tau_s} - BN^2 - CN^3 - \frac{g(N)P_{TE}}{1 + \varepsilon P_{TE}}\right] \tag{7}$$

The results of the simulations with this model are shown in figures 2(a) and 2(b). Figure 2(a) shows the response of a partial polarization converter with TE losses for increasing power, while TM polarized light is applied at the input. Figure 2(b) shows the response of the same converter, but with TE polarized light applied at the input. In the first figure we can see an increase in the ratio between the amount of TE and TM polarized light. This can be explained by the fact that as the quantum-well saturates, more light is available for conversion and thus more TE polarized light appears at the output. The response of the second figure can be explained by the fact that for low power, the TE polarized light is converted as well as absorbed. As the power increases, the absorption saturates. More light is converted, but more TE light is present at the output as well.

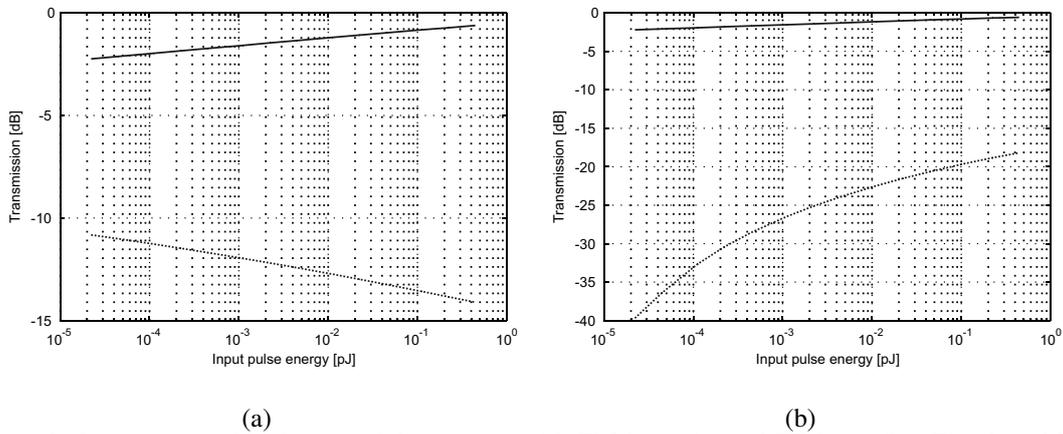(a)   (b)

Figure 2: Lossy conversion for a partial converter with TM input (a) and TE input (b). The dotted lines represent TM polarized light, the solid lines TE polarized light

Experimental verification of the model

To verify the results obtained with the simulations on the quantum-well polarization converters, measurements have been performed on experimental devices. The test structures consisted of a waveguide, connected to a polarization converter which was cleaved through the middle. The waveguide was used to couple the light in the polarization converters. By the cleaving of the converters both polarization states at the output could be monitored without suffering from waveguide losses. A schematic overview of the mea-
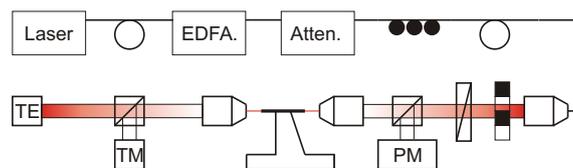

Figure 3: A schematic overview of the measurement setup, TE and TM indicate detectors for that polarization, PM is a power meter

surement setup is shown in figure 3. It consists of a tunable CW laser, coupled to an EDFA to provide enough power to saturate the quantum-well layer. The amount of power sent into the device under test is regulated by a computer controlled attenuator and was continuously monitored by a free space power meter. The polarization of the light applied to the input waveguide was set to TM with an external polarizer, to prevent absorption in the waveguide. After having passed through the teststructures, the polarization states of the light are separated by means of a polarization beam splitting cube. The light in both polarization states is then monitored by two free space detectors.

In the measurements, the input power of the polarization converter was swept over a large range, while the polarization of the output light was continuously monitored. This measurement has been performed for several lengths of polarization converters fabricated on material containing a quantum-well, as well as on material containing no quantum-well. The results of these measurements are shown in figures 4(a) and 4(b). In these figures the ratio of the TM polarized light over the TE polarized light is shown.

With increasing power, this ratio should not change, if the operation of the polarization converter is not influenced by absorption or index changes. This is the case for converters fabricated on bulk material (figure 4(a)). For the converters fabricated on quantum-well material, the ratio between the amount of TM and TE power decreases; indicating an increase in the amount of TE power, a decrease in the amount of TM power or both at the same time. This implies that the absorption of TE polarized light is saturated.

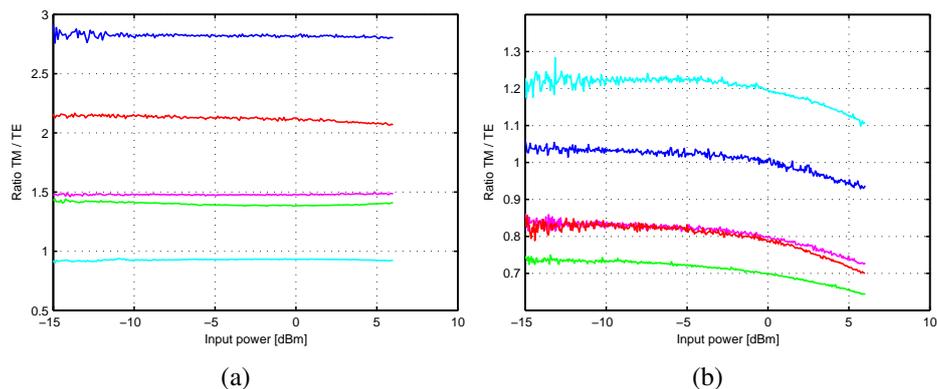(a)   (b)

Figure 4: Power dependence of a polarization converter on bulk material (a) and POLIS material (b). The different lines correspond to converters of different lengths

Conclusions

We have shown that the saturability of the absorption in quantum-well polarization converters leads to power dependent behavior of the converters. With increasing input power, the effective conversion length of the converter changes and the behavior of the device approaches the behavior without no absorption.

References

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