Modelling and study of all-optical demultiplexing of a 160 Gb/s OTDM signal using a QW-EAM

E.J.M. Verdurmen, M. Heck, G.D. Khoe and H. de Waardt

COBRA Research Institute, Eindhoven University of Technology

P.O. Box 513, 5600 MB Eindhoven, The Netherlands

With a numerical model of a Quantum Well Electro-Absorption Modulator (QW-EAM) we show all-optical demultiplexing based on Cross Absorption Modulation (XAM) of a 40 Gb/s channel out of a 160 Gb/s Optical Time Division Multiplexed (OTDM) channel. The model includes propagation equations to describe system related issues. The optical input power dependency of the QW-EAM is described using a phenomenological sweep-out mechanism. The absorption coefficient is calculated based on the carrier distributions in the active region and the effects of carrier heating and spectral hole burning are included. Optimum clock pulses and length active region are determined based on the model.

Introduction

The ever-growing internet traffic demands an increasing capacity of the network. High capacity Wavelength Division Multiplexing (WDM) transmission systems with a 40 Gb/s channel rate have already been successfully presented in field trials [1]. One way to reduce the cost of high capacity systems is by decreasing the number of optical sources. Therefore OTDM is proposed, which needs fewer sources by using channel rates of 160 Gb/s. The channel rates that can be achieved with OTDM are higher than the 40 Gb/s limit of the electronics. As a consequence we need all-optical techniques to handle such high channel rates. Recent achievements of all-optical functionalities by the EAM have shown the importance of the EAM as a building block for optical signal-processing [2]. In Højfeldt [3] demultiplexing of 80 Gb/s to 10 Gb/s utilizing XAM in an EAM is described. Because we expect this all-optical demultiplexing method to be suitable for higher bit rates, we developed a model to simulate this technique. Our model is based on the model of Uksov et al [4], and extended to simulate the extraction of a 40 Gb/s channel out of the 160 Gb/s OTDM data stream.

Model

The model includes an absorption coefficient, which is calculated based on a function of well carrier densities and takes into account both spectral-hole burning (SHB) and carrier heating/cooling. Instead of using a field dependency in the fermi distribution and the energy density, a phenomenological mechanism is used to describe the carrier sweep-out [3]. The sweep-out time (τ_{so}) varies from 8 ps at low carrier density to 25 ps at transparency. The complex pulse amplitudes $A(z,t)$ are slowly varying functions of z and t, and satisfy:

$$\left(\frac{\partial}{\partial z}+\frac{1}{v_g}\cdot\frac{\partial}{\partial t}\right)A(z,t)=-\frac{1}{2}\left(\Gamma(1+i\alpha_H)\cdot\alpha(z,t)+\alpha_{int}\right)\cdot A(z,t) \qquad (1)$$

where α_H is the linewidth enhancement factor, v_g is the group velocity, Γ is the confinement factor, α_{int} represents the internal loss coefficient and $\alpha(z,t)$ is the absorption coefficient. The pulse amplitudes can be written as:

$$A(z,t) = \sqrt{S(z,t)}e^{i\phi(z,t)} \tag{2}$$

where S is the photon density and ϕ is the phase of the light signal. Equation 1 leads to the following expression for the photon density in the active region, after transforming to the shifted time frame $t' = t - \frac{z}{v_g}$:

$$\frac{\partial S(z,t')}{\partial z} = -(\Gamma \cdot \alpha(z,t) + \alpha_{int}) \cdot S(z,t') \tag{3}$$

The expression used for solving the density of electrons and holes in the quantum wells are given by the balance equations for the electrons and the holes:

$$\frac{\partial n(z,t)}{\partial t} = \alpha(z,t) \cdot v_g \cdot \Gamma \cdot S(z,t) - \frac{n(z,t)-n_{eq}}{\tau_{so}(n)} \tag{4}$$

$$\frac{\partial p(z,t)}{\partial t} = \alpha(z,t) \cdot v_g \cdot \Gamma \cdot S(z,t) - \frac{p(z,t)-p_{eq}}{\tau_{so}(p)}. \tag{5}$$

The balance equation for the energy density in the absorbing region is:

$$\frac{\partial u_i}{\partial t} = S \cdot v_g \cdot \alpha(z,t) \cdot E_i^0 - \frac{u_i - u_{Li}}{\tau_{ui}} - \frac{u_i}{\tau_{so}} \tag{6}$$

where i=c,v refers to the conduction and valence band respectively. The other variables in the above mentioned equations are: n and p represent the local electron and hole densities, n_{eq} and p_{eq} are the local electron and hole densities in equilibrium, E_i^0 is the energy of the generated electrons (i=c) or holes (i=v) and τ_{ui} represents the energy relaxation time. The energy of electrons (holes) relaxes to the energy at lattice temperature: u_{Li}. The absorption coefficient is calculated as a function of the well carrier densities, and takes into account both spectral-hole burning and carrier heating/cooling. By not describing the field, electro-absorption effects are not included [5]. Therefore the absorption changes are induced by band-filling only. The absorption coefficient is expressed as:

$$\alpha = \alpha(z,t) = \frac{\alpha_0}{1 + \varepsilon_{sup} \cdot S(z,t)} \cdot (1 - f_c(\varepsilon_{Fc}, E_c^0, T_c) - f_v(\varepsilon_{Fv}, E_v^0, T_v))) \tag{7}$$

where α_0 is the unsaturated absorption coefficient, and f_c and f_v are the fermi distributions characterized by Fermi levels (ε_{Fi}), temperatures (T_i) and kinetic energy of the generated carriers (E_i^0). The term ε_{sup} is the absorption suppression factor due to SHB. The equations that describe the dynamics of the Fermi levels and the temperature are given by the balance equations for carriers and their energy in the absorbing region (see equations 4-6). In quantum well (QW) absorbers the photo-generated carriers are confined in the QW in the direction of the external field, so the field will not heat the carriers in the QW. Therefore we may neglect the influence of the field on carrier temperature dynamics. The carrier density and the energy density can be described as:

$$n_i = N_I \cdot F_{1/2}\left[\frac{\varepsilon_{Fi}}{k_B T_i}\right] \tag{8}$$

$$u_i = \frac{3}{2} \cdot k_B \cdot T_i \cdot N_I \cdot F_{3/2}\left[\frac{\varepsilon_{Fi}}{k_B T_i}\right] \tag{9}$$

where $F_{1/2}$, $F_{3/2}$ are the Fermi-Dirac integral of the order 1/2 respectively 3/2. N_i (i=c,v) is the effective density of states:

$$N_i = 2 \cdot \left(\frac{m_i k_B T_i}{2\pi\hbar^2} \right)^{3/2}. \tag{10}$$

Simulation Results

In this section we present the simulation results of demultiplexing a 40 Gb/s channel out of a 160 Gb/s OTDM signal, using the model described in the previous section. An incoming 160 Gb/s signal at $\lambda_1 = 1553.6$ nm (4 channels, 40 Gb/s each) and a 40 GHz optical clock signal at $\lambda_2 = 1548$ nm are injected into the EAM. For 160 Gb/s, the switching window for demultiplexing must be at least 6.25 ps. To optimize the switching window, the transmission properties have been investigated by sending a CW signal co-propagating with a 40 GHz clock-signal. The incremental step in the simulation is $dz = 10\mu$m. In Fig. 1 it

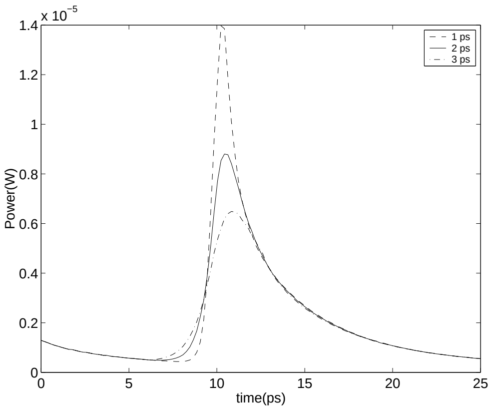

Figure 1: *The switching windows corresponding to the 1, 2 and 3 ps FWHM clock signal. CW = 0 dBm and is co-propagating with the clock-signal. Length active region EAM is $L = 150\mu m$.*

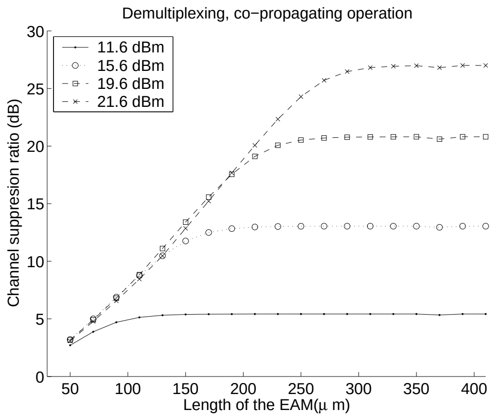

Figure 2: *The dependence of the channel suppression ratio on the length of the active region of the EAM. The results are shown for four different average clock-powers.*

is shown that clock-pulses of 1, 2 and 3 ps Full Width Half Maximum (FWHM) correspond to a switching window of 1.7 ps, 3.3 ps and 4.6 ps FWHM respectively. The energy of the clock-pulse is taken to be 1.1 pJ, corresponding to 16.5 dBm average power. We can deduct from Fig. 1 that the switching window becomes smaller when using shorter clock-pulses. The disadvantage of these switching windows is the large tail, which burdens the suppression of the other channels. The tail originates from the carrier sweep-out time which limits the recovery speed of the absorption. Fig. 2 shows the the channel suppression ratio for several clock-powers as a function of the length of the active region of the EAM. As expected the improvement of suppression ratio levels out when the power of the clock-pulse has decreased to a level where the absorption is no longer influenced. To obtain suppression ratios of 20 dB or higher the optimal length of the EAM is about 250 μm for an average clock-power of 21.6 dBm. A sequence of ones was used as input signal for the demultiplexer to simulate the largest influence of crosstalk after the demultiplexer. An eye-diagram of a demultiplexed signal is shown in Fig. 3. The power of the clock-pulses was 1.1 pJ. This is not enough to saturate the absorption completely, therefore the adjacent channels are still clearly visible in the eye-diagram. By increasing the power of the clock signal the suppression of the adjacent channels is improved. The relation between the channel suppression and the power of the clock signal is shown in Fig. 4. Comparing co-propagating and counter-propagating a little better performance is observed for co-propagating operation. The optimum clock-power for both operation modes is around 20 dBm. This high power is required to bleach the absorption.

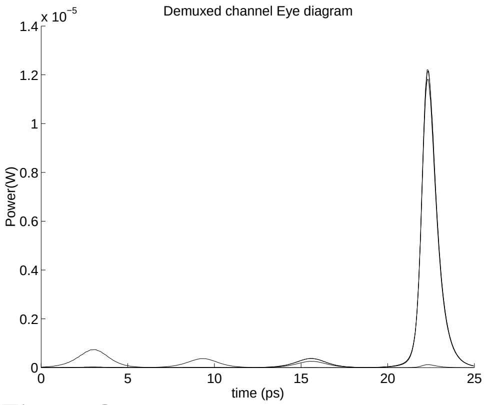

Figure 3: *Eye-diagram of the demultiplexed channel. Clock-pulses are 1.1 pJ, which corresponds to 16.5 dBm average power.*

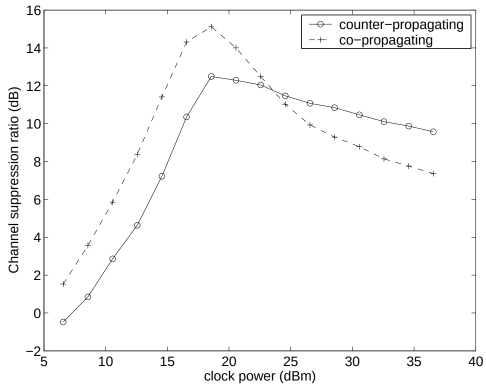

Figure 4: *Clock-power (dBm) versus channel suppression ratio (dB). Input power is 3 dBm (2 ps FWHM), FWHM clock-signal is 1ps*

Conclusions

We have studied all-optical demultiplexing based on XAM. In short, we have demonstrated demultiplexing of a 40 Gb/s channel out of a 160 Gb/s OTDM channel. We showed that for the length of the EAM $L = 150\mu m$ the optimum clock-power in terms of channel rejection is 20 dBm average power. The performance is a little better for co-propagating operation compared with counter-propagating operation. Furthermore, this model can be used to investigate other all-optical functions performed with an EAM, e.g. wavelength conversion and signal regeneration.

Acknowledgements

This research was supported by the Towards Freeband Communication Impulse of the technology programme of the Ministry of Economic Affairs.

References

[1] S. Bigo and Y. Frignac, "Multi-terabit/s WDM transmissions at 40 Gbit/s channel rate", in *2001 Digest of the LEOS Summer Topical Meetings*, 2001, pp. 2.

[2] E.S. Awad, P.S. Cho, N. Mouton and J. Goldhar, "All-optical timing extraction with simultaneous optical demultiplexing from 40 Gb/s using a single electroabsorption modulator", *IEEE Photonics Technology Letters*, vol. 15, pp. 126-128, January 2003.

[3] S. Højfeldt, "Modeling of carrier dynamics in electroabsorption modulators", PhD thesis, COM Technical University of Denmark, May 2002.

[4] A.V. Uksov, J.R. Karin, J.E. Bowers, J.G. McInerney and J.L. Bihan, "Effects of carrier cooling and carrier heating in saturation dynamics and pulse propagation through bulk semiconductor absorbers", *Journal of Quantum Electronics*, vol. 34, pp. 2162-2171, 1998.

[5] L.K. Oxenløwe, et al, "All-optical Demultiplexing and Wavelength Conversion in an Electroabsorption Modulator", *Proc. 27th Eur. conf. on Opt. Comm.*, ECOC'01 Amsterdam.