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Published in:
Proceedings of the 22nd European Conference on Optical Communication

Publication date:
1996

Document Version
Publisher's PDF, also known as Version of record

First detailed analysis of nonlinear directional coupler biased at transparency showing ultra fast all-optical signal processing

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Abstract - A novel approach to ultra fast signal processing at high bit rates is presented. It is shown that demultiplexing at 160 Gbit/s is possible in a nonlinear semiconductor directional coupler (NLDC) operating at transparency.

Introduction - Optically controlled switching devices will play an important role in future high capacity OTDM and WDM networks. Previously all-optical signal processing has been performed by four-wave mixing using Kerr-effects in fibre [1] and ultra fast nonlinearities in semiconductor devices [2]. Furthermore, band-filling effects have been used in semiconductor laser amplifiers in an interferometric structure [3]. However, four-wave mixing is inherently polarisation dependent and the techniques relying on band-filling effects suffer from the relative long carrier life time.

In this paper we present a novel approach to simple, ultra fast and polarisation independent signal processing at high bit rates. This is achieved by combining the propagation in a nonlinear directional coupler (NLDC) with the dynamics of nonlinearities in semiconductors biased at transparency. By operating at transparency the band-filling effects are avoided.
It is shown by a detailed model that the α-parameter for carrier temperature changes is a figure of merit for the device. Furthermore, demultiplexing at 160 Gbit/s with an extinction ratio of 18 dB for a pump pulse energy of 3 pJ is possible.

Configuration - The InGaAsP ridge waveguide NLDC structure under study is shown schematically in Fig. 1. The straight waveguide coupling section is biased to transparency (where no net band-to-band transitions take place) for the particular wavelength used. The coupler is fabricated by Tele Danmark R&D and is characterised by the following parameters: an effective index difference of 0.127, waveguide separation of 2.5 μm, internal loss of 1000 m^{-1}. The signal and pump pulses are launched into the NLDC as shown in Fig. 1. To allow separation of signal and pump pulses at the output of the coupler two different schemes can be employed. Either different wavelengths or orthogonal polarisations for signal and pump pulses.

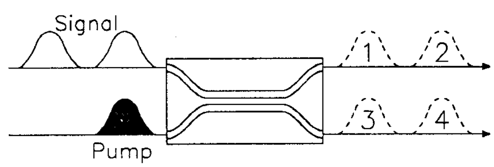

Fig.1: The NLDC shown schematically. Two signal pulses are launched into one waveguide while one pump pulse is launched into the other waveguide. At the end of the NLDC four signal pulses with different pulse energies can be detected.

Simulation of propagation - The propagation of the signal pulse and the pump pulse in the NLDC is simulated employing both a beam propagation method (BPM) and a method based on coupled mode theory (CMT). The two models have been implemented to verify the results by comparison. The propagation can be described by the following equation:

$$\frac{dE(z,t)}{dz} = LE(z,t) + RE(z,t)$$

Here $E(z,t)$ denotes the electric field as a function of both time, t, and the axis of propagation, z. The operator L expresses the linear effects (linear part of the refractive index distribution, dispersion and loss) while the nonlinear effects are accounted for by the operator R through the response function, $h(t)$:

$$R = \int_{-\infty}^{+\infty} h(t-t')|E(z,t')|^2\,dt' \quad ; \quad h(t) = h_{TPA}(t) + h_{CH}(t)$$

The dominating nonlinearities at transparency are caused by two photon absorption (TPA), h_{TPA}, and by carrier heating (CH) mediated by free carrier absorption, h_{CH} [4].

Nonlinearities at transparency - Semiconductor components based on band-filling effects (carrier density changes) cannot be used at high bit rates due to the large recovery time related to spontaneous recombinations (approx. 1 ns). Band-to-band transitions do not occur for energies below half the bandgab but the required nonlinear effects are only obtained for very large peak powers due to the inefficient non-resonant processes taking place [5]. It is therefore interesting to exploit the nonlinear effects that occur at transparency. Here no net change of the carrier density takes place, but rather changes in the shape of the carrier distribution occur due to carrier heating. Such structural changes are associated with a very short recovery time, less than 1 ps.

The influence on the transmission and the change of phase from two photon absorption (TPA) and carrier heating (CH) is determined by simulation of a pump/probe experiment where the probe pulse is incident with a time delay, τ, relative to the pump pulse.
Fig. 2a shows the relative transmission of the probe as a function of the delay time between the pump and the probe. The curves show the contributions from the two nonlinear effects for different FWHM-widths of the pump and the probe. Both TPA and CH results in a reduction of the transmitted probe field as both effects involve absorption of probe photons. For pulses with a width of 0.2 ps the change in transmission due to two photon absorption is observed as a peak at τ = 0 ps since TPA is an instantaneous effect. For the 0.2 ps-curve the contribution from CH becomes dominant for values of τ larger than 0.1 ps. The influence from TPA decreases compared to CH as the pump width increases and for the 2 ps-curve CH is dominant for all values of τ.
Fig. 2b shows the change of phase for the probe. Here TPA and CH result in opposite contributions to the change of phase. TPA reduces the phase as can be seen from the 0.2 ps-curve at $\tau = 0$ ps. Again the effect from CH is dominant for values of τ larger than 0.1 ps and results in a positive change of phase. As for the transmission, the influence from CH is dominant for a width of 2 ps. It can thus be concluded that the nonlinearities at transparency are dominated by CH for pulse widths of 2 ps or larger.

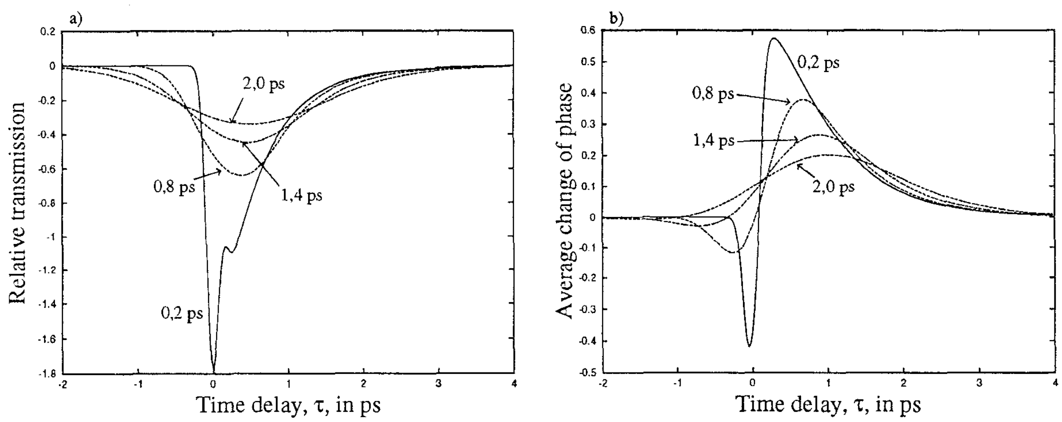

Fig.2: *a)* Relative transmission as function of time delay for a pump/probe experiment calculated for different pulse widths. *b)* The change of phase corresponding to a).

The relation between the transmission and the change of phase due to CH is included in the α_T-parameter defined as

$$\alpha_T = \frac{\partial(\mathrm{Re}\{\chi\})/\partial T}{\partial(\mathrm{Im}\{\chi\})/\partial T}$$

where χ is the material susceptibility and T is the temperature of the carrier electron distribution. The influence of the α_T-parameter is illustrated in Fig. 3a that shows the energy in pulse 2, E_2, and 4, E_4, as a function of the pump pulse energy. The curves are normalised with the total energy launched into the coupler. The figure represents two sets of curves corresponding to $\alpha_T = 3$ and 12. For $\alpha_T = 3$ coupling is not prevented, i.e. the main part of the energy is still coupled ($E_4 > E_2$). But if α_T is increased to, e.g., 12 coupling can be prevented. Therefore, it is obvious that an increase in α_T results in an improvement of the coupling characteristics. This means that α_T acts as a figure of merit for the coupler. For a low value of α_T, the nonlinear loss associated with a change of the carrier temperature is too high relative to the index change.

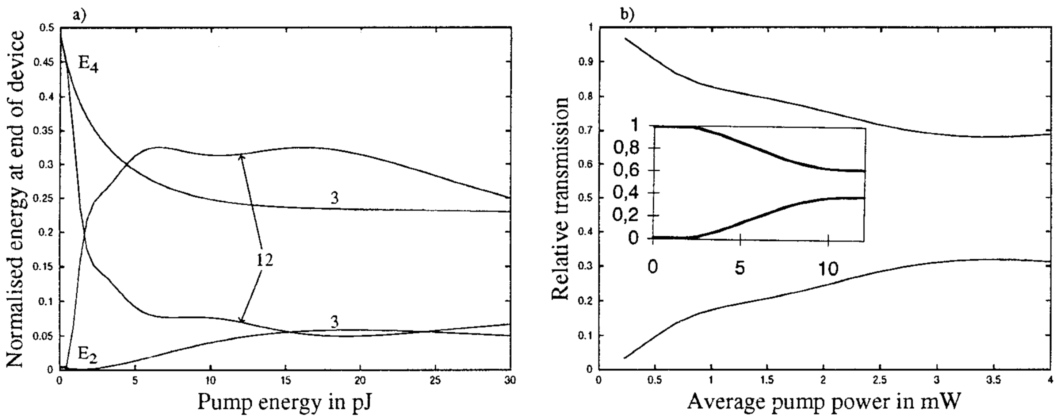

Fig.3: *a)* Coupling characteristics for different values of α_T. The energy in each waveguide is normalised to the total energy launched into the coupler. *b)* Calculated coupling characteristics for the configuration used by Davies et al. The experimental results are shown as an insert.

Comparison with experimental results - The calculated coupling characteristics of the device have been compared to experimental results by Davies et al. [6] for a bulk semiconductor coupler. This coupler is characterised by a index difference of 0.2, internal loss of 5000 m^{-1} and waveguide separation of 2 μm. The experimental (shown as an insert) and calculated results are shown as Fig. 3b where the energy in the two waveguides are normalised so that the sum is 1.

Good agreement between the two figures is seen. Both sets of curves approach 0.4 and 0.6 asymptotically. It is furthermore noticed that the necessary pump power for the calculated results is lower than for the experimental results. This is ascribed to differences in the coupler structure as well as uncertainties in the material parameters. In addition, the insertion losses are not known. Both curves illustrate that coupling cannot be prevented for the used configuration. Davies et al. ascribe the poor coupling characteristic to high losses which is in agreement with the conclusion drawn from our model.

Routing and demultiplexing - In the following the ability of the coupler to perform routing and demultiplexing is investigated. The routing performance of the coupler can be analysed from the coupling coefficients $R_{3,1}$ and $R_{4,2}$, while demultiplexing capability is investigated through $R_{1,2}$ and $R_{3,4}$. The four coupling coefficients are defined as ratios between the energies of the four pulses shown at Fig. 1. The coefficients are calculated as functions of the pump energy and are shown in Fig. 4. The calculations are made for the configuration realised by Tele Danmark R&D, a signal width of 2 ps and $\alpha_T = 12$. Time slots are fixed at twice the pump pulse width.

The coefficient $R_{3,1}$ is seen to be independent of the pump energy for pump widths of 3 and 5 ps. This means that the nonlinearities introduced by the pump in the time slot before the signal do not influence trailing pulses. Therefore, $R_{3,1}$ is constantly 21 dB corresponding to total coupling. This is essential for a pump controlled switch since the pump is not allowed to have any influence on the coupling of the following signal pulse. The advantage of operating at transparency is that $R_{3,1}$ is constant for even very high bit rates.
$R_{4,2}$ varies from complete coupling (21 dB) at no pump energy to approximately -6 dB for a pump energy at 6 pJ. This ratio is not considered sufficient for practical purposes thus it can be concluded that the component is inadequate for routing performance without further optimisation.

In order to study the component used for demultiplexing the energy ratio between pulse 1 and 2 ($R_{1,2}$) and between pulse 3 and 4 ($R_{3,4}$) are shown in Fig. 4b as a function of pump energy analogous to Fig. 4a. From this figure it can be seen that $R_{1,2}$ is 8 dB for a pump energy at 6 pJ while $R_{3,4}$ becomes -18 dB for a pump energy at 3 pJ. The requirement to this ratio is approximately 20 dB for demultiplexing and is fulfilled for the energy ratio $R_{3,4}$. As it is possible to obtain a ratio at -18 dB for pump widths of both 3 and 5 ps, demultiplexing is possible at a bit rate of 160 Gbit/s.

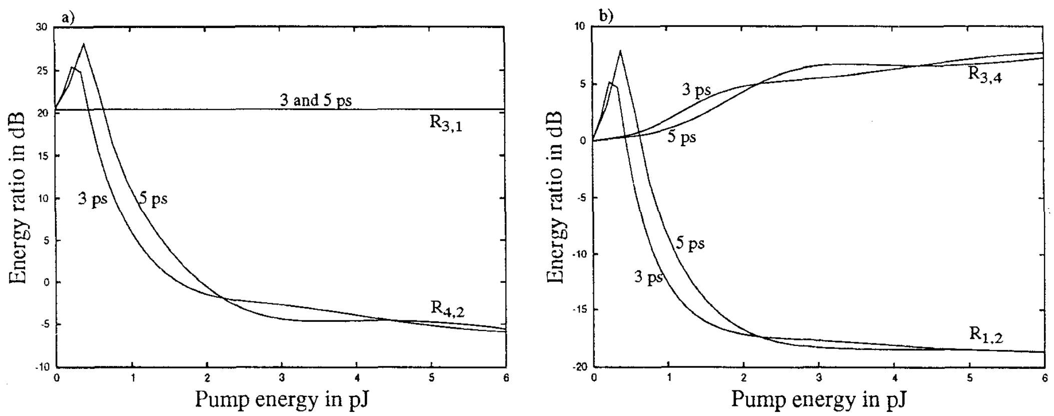

Fig.4: *a)* Energy ratios for routing for pulse widths of 3 and 5 ps. *b)* Energy ratios for demultiplexing for pulse widths of 3 and 5 ps.

Conclusion - We have presented the first detailed theoretical analysis of a novel approach to ultra fast signal processing using nonlinearities at transparency. It is shown that the α-parameter for carrier temperature changes is a figure of merit for the device. In addition, demultiplexing at 160 Gbit/s with an extinction ratio of 18 dB for a pump energy of 3 pJ is shown possible. The results show the prospect of such devices for use in future communications systems where high bitrates are expected.

Acknowledgments - We thank K. Stubkjær and B. Mikkelsen for helpful comments and discussions.

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