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Slow-light: Fascinating physics or potential applications?

Slow and fast light in quantum dot based semiconductor optical amplifiers

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Abstract

Recent progress in the field of quantum dot/dash based semiconductor optical amplifiers (SOAs) for slow and fast light is discussed. Room temperature fast light has been obtained in InAs/InP QDash based SOAs by means of coherent population oscillation and four wave mixing (FWM) effects. Typical optical delays amount to 55 ps at 2 GHz. Growth optimization of the QDashes allowed us to achieve high modal gain, leading to very similar performances, e.g. gain and FWM efficiency, to those of a bulk SOA. A novel approach based on linear spectrograms is also introduced to measure the phase shift induced by wave mixing in an SOA. ***To cite this article: A. Martinez et al., C. R. Physique 10 (2009).***

Résumé

Lumière lente et lumière rapide dans les amplificateurs optiques à semi-conducteurs à base de boîtes quantiques. Les progrès récents dans le domaine des amplificateurs optiques à semi-conducteurs (SOA) à base de boîtes/batônnets quantiques pour la lumière lente et rapide sont discutés. Une lumière rapide à température ambiante a été obtenue dans des SOA à batônnets quantiques InAs/InP par les phénomènes d'oscillation cohérente de population et de mélange à quatre ondes (FWM). Des valeurs typiques de retards optiques de 55 ps ont été obtenues à une fréquence de 2 GHz. L'optimisation de la croissance des batônnets quantiques permet d'obtenir un gain modal élevé, conduisant à des performances presque identiques, en termes de gain et d'efficacité FWM, à celles d'un SOA à matériau massif. Une nouvelle approche basée sur la technique des spectrogrammes linéaires est également introduite pour mesurer le déphasage induit par le mélange d'ondes dans un SOA. ***Pour citer cet article : A. Martinez et al., C. R. Physique 10 (2009).***

Keywords: Slow light; Semiconductor optical amplifier; Quantum dot; Nonlinear effects; Coherent population oscillation

Mots-clés : Lumière lente ; Amplificateurs à semi-conducteurs ; Boîte quantique ; Effets non-linéaires ; Oscillation cohérente de population

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1. Introduction: group velocity control in semiconductor optical amplifiers

Controllable optical delays based on group index modification in guided wave devices have recently received much attention [1–3]. Indeed, slow and fast lights are attractive for many applications, such as optical buffers for telecommunication [1,4,5], or control of optically carried microwave signals. Slow light schemes are based on the modification of the waveguide and/or material dispersion [1]. The former method can be implemented using periodic structures like two-dimensional photonic crystals or Fabry–Perot resonators. Material dispersion can be changed using various methods such as electromagnetic induced transparency, nonlinear effects in optical fibers like stimulated Brillouin scattering, or by changing the gain or the absorption spectrum of semiconductor devices via wave mixing [1,3].

Although the maximum achievable delays via wave mixing are modest for optical buffer applications [6,1], these compact delay lines exhibit a great potential for microwave photonic applications where signal processing of radio-frequency signals is performed in the optical domain. Slow and fast lights have indeed been used for phased array antennas [7], where the direction of a beam can be steered [8] without introducing beam distortion and without resorting to mechanical means that limit the speed of the system; tuneable microwave notch filter at 20 GHz for broad band access networks [9]; and optoelectronic processing functions for defense applications [10,11].

Control of the group-velocity in guided wave devices is achieved by exploiting wave mixing in semiconductor optical amplifiers, i.e. coherent population oscillation (CPO) [12]. CPO and FWM arise from the beating of an intense pump with a weak probe beam (or with a modulation sideband) within the semiconductor nonlinear material that generates a carrier density pulsation [12,1], which in turn modifies the refractive index seen by the optical beam. Population pulsation is also responsible for four wave mixing: the temporal index variation generates two four wave mixing signals [12,13], i.e. FWM signal 1 and FWM signal 2 [13]. The interaction modifies the nonlinear susceptibility of the material, thereby altering the dispersion relationship experienced by the light [1].

Modification of the material dispersion is of paramount importance since strong carrier confinement in low dimensional material systems can allow the achievement of compact optical delay lines at room temperature.

It has been shown that it is possible to modify the group velocity in quantum well (QW) semiconductor optical amplifiers [14–17]. FWM and CPO were successfully used in 1.3 μm quantum well (QW) semiconductor optical amplifiers [14], yielding optical variable delays up to 160 ps at a 1 GHz bandwidth. To evaluate the potential of a slow light approach, it is customary to use the time delay-bandwidth (DBP) product as a figure of merit [5,1,18]. The results published in [14] leads to a delay-bandwidth product DBP of 160 ps GHz. Besides, slow light was also demonstrated in QW based electro-absorbers [19] where a change in the absorption spectrum is responsible for group velocity change. Moreover, investigation of monolithic integration of QW based SOAs and EAMs allowed to demonstrate the feasibility of achieving large true-time delay of ~ 61 ps at 5 GHz bandwidth [20], thus leading to a DBP of about 300 ps GHz.

Finally, spectral hole burning in QW SOA is an alternative and attractive method to achieve slow light for subpicosecond pulses [6]. A tuneable fractional delay of 1.9 ps for 700 fs pulses propagating was measured and the delay can be tuned electrically.

Owing to the three-dimensional carrier confinement [21,22], the resulting atomic-like density of states of quantum dot (QD) based materials are expected to exhibit unique optoelectronic properties compared to those of QW based devices. Modification of the material dispersion relationship using coherent population oscillation in InAs/GaAs QD SOAs has recently allowed to reduce the group index by 10% with a 13 GHz bandwidth at 1.3 μm [23], corresponding to a delay of ~ 5 ps at 13 GHz, i.e. a DBP of 75 ps GHz. In this work, the modification of the group velocity relies on a configuration that primarily involves CPO because the pump and probe beams interact in a counter-propagating scheme.

More recently, for applications at 1.55 μm, a relative phase shift of 33° at 1 GHz corresponding to optical delays of 91 ps was reported using truly three dimensionally-confined InAs/InP quantum dots by means of both CPO and FWM effects in a SOA at room temperature [24]. The DBP amounts to 91 ps GHz, illustrating a relatively low effect of the device ($L = 1.95$ mm and $i = 500$ mA) which can be attributed to a smaller optical confinement factor, compared to QW based SOA in Ref. [14].

The methods traditionally used to measure a phase shift in SOAs are either based on the so-called "phase shift experiment" that resorts to a network analyzer, or to a high speed photodiode coupled with an oscilloscope [7,23,25]. Recently, slow light in a bulk SOA was enhanced by means of optical filtering of red-shifted sideband before detection using fiber Bragg grating based notch filter [26]. Optical filtering using this method has proven successful to enhance both the optical delay as well as the slow light bandwidth. Phase shift as high as $\sim 150°$ at 19 GHz has been obtained, resulting in an optical delay of 22 ps, which implies a DBP of 418 ps GHz.

In this article, we report on the potential of InAs/InP QDash based SOAs for room temperature fast light at 1.55 μm. The first part shows how the high material gain of QDashes allows us to achieve SOAs exhibiting a very similar performance to that of bulk SOAs. We found that, despite an optical confinement factor about 40 times lower for the QDashes, the available high material gain allows us to achieve fiber-to-fiber gain and four wave mixing efficiency comparable to those of bulk SOAs. In the second part, we report on the demonstration of fast light in QDash based SOAs by electrical control of the group velocity. A microwave frequency modulated optical carrier undergoes group index variation that leads to optical delays in the range of 136 ps at 250 MHz and ~ 50 ps at 2 GHz. The optical delays measured using two different methods are very similar to those obtained in QW SOAs at 1.3 μm [14], while the current variation amounts to only a few tens of mA, compared to hundreds of mA in QW SOAs [14]. In the third part, we introduce a new method based on linear spectrogram method that permits to measure optical delays created by FWM and CPO in SOAs. This new technique allows the extraction of both the amplitude and the phase of the complex electric field at the output of an SOA. An optical delay of 60 ps is obtained at 10 GHz, which is in agreement with results published by a previous work where they used a fiber Bragg grating as an optical filter [26].

2. Comparison of nonlinear optical properties of bulk and quantum dash based SOAs

In a waveguide configuration, the interaction between pump and the active material is weighted by the optical confinement factor which is approximately 1% in quantum dashes, against 40–70% for the bulk material. Our aim is to investigate the influence of a reduction in the dimensionality of the material on the nonlinear properties of semiconductor optical amplifiers, in order to identify the material system having the highest potential for slow and fast light effects. Two material systems are investigated: a GaInAsP/InP bulk and InAs/InP quantum dash based materials.

Molecular beam epitaxy growth of InAs quantum dots on InP (100) substrates generally leads to the formation of quantum 'dash' (QDash) nanostructures, i.e. elongated dots [27–29]. These provide a higher optical confinement factor compared to that of QDs grown on InP substrates and thus a high modal gain of lasers (48 cm^{-1} for a 9-Dash-in-a-Well layer structure), leading to a static performance similar to that of QW based lasers in terms of threshold current and quantum efficiency [30]. An optimized laser structure consisting of a stack of 6 QDash layers has in particular allowed laser emission for very short cavity lengths of 130 μm owing to the available high modal gain (typically 34 cm^{-1}) [31]. These nanostructures also exhibit very interesting properties like enhanced four wave mixing [32, 28] that have in particular allowed subpicosecond pulse generation in self-pulsating lasers at high repetition rates (> 300 GHz) [31]. It was also reported that four wave mixing efficiency in QDash SOAs exhibits a slower rate of decrease versus the pump-probe detuning [32,33].

The active layer was grown by molecular beam epitaxy on a (100) InP $n+$-oriented substrate. The layer structure consists of a 6 dot-like-in-a-well layer (DWELL) stack that is embedded between a upper p-doped and lower n-doped InP-based cladding layers [29]. The active layer was processed into buried ridge stripe (BRS) single mode waveguides (Fig. 1). The waveguide was tilted with a 7° angle and facets were AR coated leading to a residual reflectivity of about 10^{-4}. Input and output tapers (Fig. 2) ensure reduced coupling losses between the waveguide and specific lensed fibers.

Description of the experimental set-up used to determine the gain and four wave mixing efficiency can be found in Ref. [25]. A fiber-to-fiber unsaturated gain of ~ 16 dB and a saturation output power $P_{\text{o, sat}}$ of ~ 0 dBm coupled into the optical fiber are obtained at 240 mA for a 2 mm-long device. This first generation device will be used for slow and fast light experiments in the next part (part 3). Typical values of the pump and probe beams coupled into the SOA are fixed to -8.5 dBm and -18.5 dBm and the current is set to 240 mA. Both conversion efficiencies decrease with the frequency detuning due to departure from the phase matching condition of the nonlinear process (Fig. 3). The slopes of ~ -13 dB/decade are smaller than those observed in QW SOA [34] and comparable to earlier results in QDash SOAs [32]. The results are in good agreement with a recent work where a slope of ~ -10 dB/decade was obtained [33].

In order to identify the material system that exhibits the highest potential for slow light, we compared the linear and nonlinear optical properties of SOAs based on a recently optimized high modal gain QDash layer structure and a bulk active material. The lengths of the devices are 1 mm and 2 mm for the bulk [35] and QDashes, respectively. The current is adjusted to obtain the maximum gain for each amplifier. The unsaturated fiber-to-fiber gain is 29 dB for a

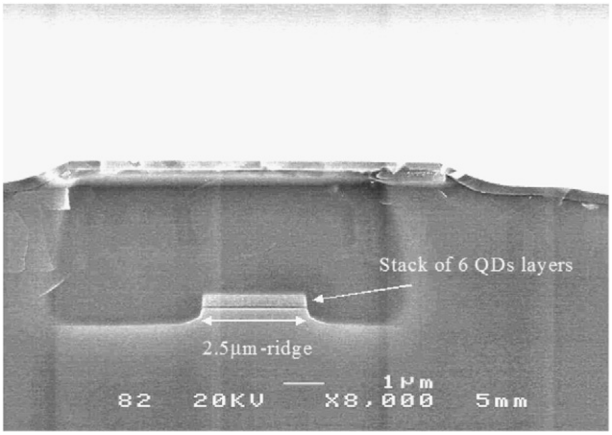

Fig. 1. Scanning electron microscopic (SEM) view of a buried ridge stripe (BRS). The layer structure is realized by GSMBE growth of Al-free QDashes and MOVPE regrowth of upper cladding.

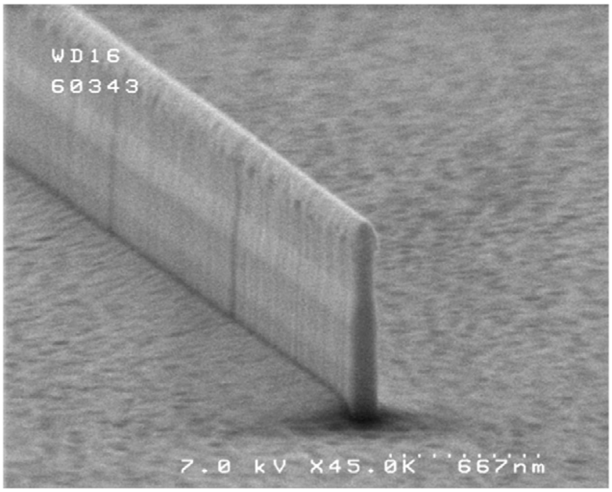

Fig. 2. SEM image of a taper defined by electron-beam lithography. The ridge waveguide tip is 0.1 µm wide.

bias current of 250 mA ($J \sim 20$ kA/cm^2), and 27 dB at 400 mA ($J \sim 13$ kA/cm^2) for bulk and QDash materials, respectively. Despite a reduction in the optical confinement factor with the dimensionality (from ~ 0.4 to 0.01), the high material gain of QDashes provides an optical gain comparable to that of bulk material for a QDash SOA twice longer than the bulk one. Nearly identical output saturation power coupled into the fiber of 10 dBm is observed.

The SOAs are biased at the same currents as in the previous paragraph. The input probe power is fixed at -16 dBm while the pump power is adjusted (between -20 dBm and 0 dBm) using a variable attenuator, the pump-probe detuning being about 100 GHz. In both material systems, FWM efficiency varies with the total output power and exhibits a maximum corresponding approximately to the output saturation power of each amplifier. For a negative detuning Δf, the decrease of FWM efficiency follows a slope of -13 dB/dec for both bulk and QDashes (Fig. 4). The decrease of FWM efficiency with the detuning is consistent with values published in previous works [33,36].

For QDash SOAs, similar conversion efficiencies are obtained at the expense of a higher bias current, which means power consumption. Nevertheless, the FWM efficiency scales with the square of the Henry factor of the SOA [13] and the maximum achievable phase shift increases with the Henry factor of the SOA when optical filtering is used [37]. Specifically engineered QDash SOAs that exhibit a high Henry factor may offer a greater potential for slow and fast light compared to bulk material. Further experiments will hence assess whether the reduction of dimensionality brings advantages to control the group velocity (slow light).

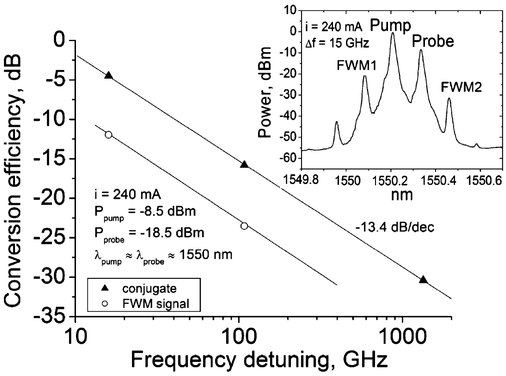

Fig. 3. Four wave mixing efficiency of the FWM signals 1 and 2 versus the pump and probe frequency detuning for a 240 mA current for a positive detuning ($\Delta f = f_{\mathrm{pump}} - f_{\mathrm{probe}} > 0$). Inset, output spectrum of the QDash SOA for a 15 GHz detuning.[1] Lines correspond to linear fits and are just a guide for the eyes.

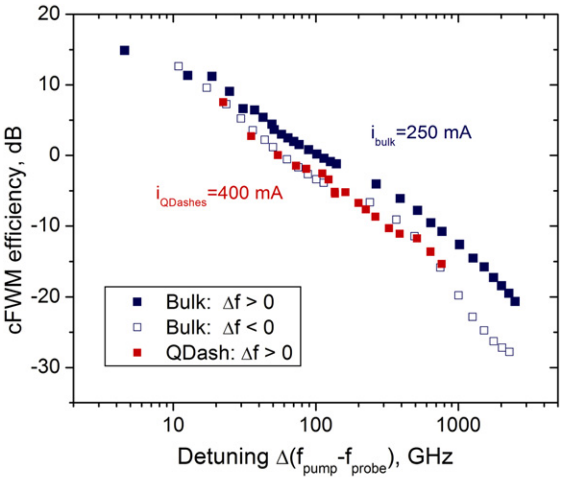

Fig. 4. Comparison between FWM efficiency of the FWM signal 1 versus pump-probe detuning for optimum powers of $P_{\mathrm{pump}} \sim -5$ dBm and $P_{\mathrm{probe}} \sim -16$ dBm in bulk and QDash materials.

3. Room temperature fast light in 1.55 μm InAs/InP quantum dash based semiconductor optical amplifier

The potential of InAs/InP QDash based SOA for fast light has been investigated using two different methods to measure the optical group delays. The tuneable optical delays were measured through the analysis of oscilloscope time traces. A single optical beam whose optical carrier is f_o, acting as a pump, is modulated with a $LiNbO_3$ Mach–Zehnder intensity modulator. Two modulated side bands are thus generated at optical frequencies $f_o + f_m$ and $f_o - f_m$ and they will play the role of probe beams. The investigated microwave frequencies f_m were 250 MHz, 1 GHz and 2 GHz, while the applied radio-frequency power to the modulator was kept constant. The intensity modulation index is thus kept constant for all values of f_m. This is possible owing to a 10 GHz modulation bandwidth of the modulator. The signal exiting from the SOA is amplified through an erbium doped fiber amplifier (EDFA) followed by a fixed attenuator, in order to optimize scope measurements and to avoid any saturation of a high speed photodetector that would induce unwanted phase shift. The average power at the output of the EDFA is kept well below the level required for significant nonlinear effects at the origin of optical delays in fibers. A bandpass filter is used to prevent distortion of the analyzed signal. Note that the average input pump power is kept below the saturation input power of the QDash SOA (−17 dBm).

In the case of $f_m = 250$ MHz, when the current is increased from its reference value of 190 mA up to 250 mA, the sinusoidal signal moves back on the left side of the initial signal at 190 mA (Fig. 5), thus evidencing an optical advancement: fast light is observed. A maximum relative optical delay of ~ 136 ps at 250 MHz is achieved for this current variation. Similar experiments performed at 2 GHz (Fig. 5) and an SOA input power of −17 dBm yielded a maximum relative optical delay of ~ 55 ps for the same current variation. The delay-bandwidth product amounts to 110 ps GHz. This phenomenon is attributed to both coherent population oscillation and nearly degenerate FWM as previously reported in QW SOAs at 1.3 μm [14] and in QD SOA at 1.55 μm [1,24].

These optical delays are about twice as high as those obtained with 1.55 μm QD SOAs [24], and comparable to those obtained in QW SOAs at 1.3 μm based on a similar approach [14] and hence QDashes show a quantum-well like behaviour. Moreover, these delays are obtained by varying the current by only few tens of mA owing to the enhanced FWM of this material system, while for 1.3 μm QW and 1.55 μm InAs/InP QD SOAs, current variation of few hundreds of mA are required [14,24], implying a lower differential gain in these latter material systems. The reduction of the optical delays with the frequency (from 250 MHz to 2 GHz) is attributed to a reduction of the carrier lifetime [12,23].

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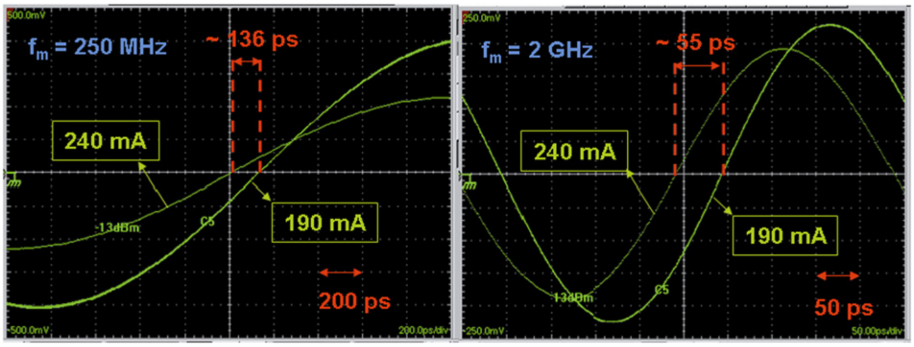

Fig. 5. Oscilloscope time traces of a modulated pump beam when the current is changed from 190 mA to 240 mA (a) at 250 MHz and (b) at 2 GHz. The SOA input power is −17 dBm.[2]

These investigations are further confirmed by a 'phase-shift experiment' method based on a network analyzer [14]. For a 2 GHz modulation frequency and a −16 dBm optical power at the SOA input, the phase of the output modulated signal experiences a relative phase variation of $\sim 45°$. The RF phase change can be converted in an optical group delay change using $\Delta\tau = (\Delta\phi/360)(1/f_m)$, $\Delta\phi$ being in degree. An optical delay variation of ~ 62 ps is deduced. This value is in fair agreement with the 55 ps determined from the oscilloscope time traces, given the different uncertainties of the two methods and the slightly different current ranges.

In conclusion, we have demonstrated the potential of InAs/InP QDash SOA for room temperature fast light at 1.55 μm. Maximum optical tunable delays up to ~ 55 ps at 2 GHz are achieved when the current is changed by only few tens of mA, attributed to the enhanced FWM efficiency of the quantum dashes. Future work on optimized QDash SOA structures should demonstrate even higher delays owing to the higher available gain and FWM conversion efficiency.

4. New approach based on linear spectrogram to measure optical delays in semiconductor optical amplifiers

We mentioned in the introduction that optical filtering has been found to enhance both the maximum attainable phase shift as well as the bandwidth of slow light induced effects [26]. Following these results, we introduce here a new method based on linear spectrogram [37–39] that allows one to measure the complex electric field, i.e. the phase as well as the amplitude of the electric field, using a simple configuration that requires neither a high speed photodiode nor a network analyzer. This technique uses a time-dependent element to gate the input signal and then spectrally resolve the input signal. This method builds a time–frequency distribution of the input signal from which the original complex electric field is obtained. The functional form of a spectrogram is given by:

$$S(\omega,\tau) = \left| \int_{-\infty}^{+\infty} E(t)G(t-\tau)\exp(-i\omega t)\,\mathrm{d}t \right|^2 \tag{1}$$

$E(t)$ is the complex electric field at the output of the SOA and $G(t-\tau)$ relates to the delayed gate function. The method relies on a two-dimensional blind deconvolution similar to that of a frequency resolved optical gating algorithm [37] where $G(t)$ can take any form, i.e. a sine wave for our purpose.

This approach offers a direct mean to rapidly evaluate the potential, in terms of optical group delays, of various SOAs based on different types of active layers. This method allows to select the best SOAs before the implementation of the experiment using a fiber Bragg grating as the optical filter. The linear spectrogram method can also allow the extraction of the phase amplitude coupling factor of SOAs [40] that plays a major role in the slow and fast light effects [26].

The experimental set-up is illustrated in Fig. 6. An external tunable cavity laser plays the role of the pump at 1.55 μm (Fig. 6). A $LiNbO_3$ based Mach–Zehnder modulator (MZM) is driven with a 10 GHz modulation frequency

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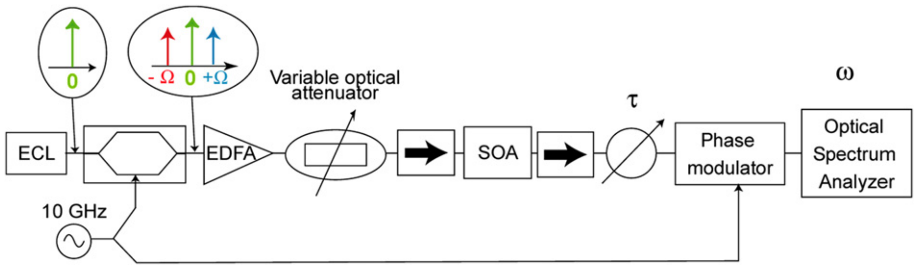

Fig. 6. Experimental set-up of the linear spectrogram method used to measure the phase advance/time delay.

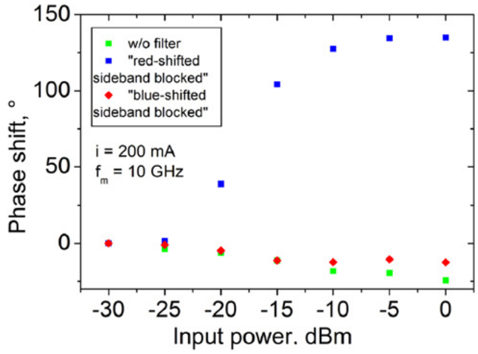

Fig. 7. Measured phase shift versus the input optical power for 10 GHz modulation frequency extracted from the linear spectrogram method.

and generates two sidebands in the frequency domain that act as probe beams. The complex electric field $E(t)$ at the output of the SOA is gated through a gate function $G(t-\tau)$, where τ is a relative programmable delay. The gate function is determined by an electro-optic phase modulator that exhibits the advantage of a large operating wavelength range compared to an electroabsorption modulator [38,39]. It also has a much simpler transfer function, i.e. a pure phase modulated signal, that allows for a faster convergence of the algorithm compared to an electro-optic Mach–Zehnder modulator that contains both amplitude and phase modulation [39]. The variable attenuator allows to adjust the input optical power in the input fiber (fiber before the SOA) from −30 dBm up to 0 dBm.

Moreover, optical filtering is implemented through digital filter in the algorithm calculation which avoids the need of a very narrow band notch filter. The radio frequency source used to control the EOPM is the same as for the MZM.

The bulk SOA (characterized in part 3) is biased at 200 mA to obtain a fiber-to-fiber gain of about 27 dB at 1.55 µm. When no optical filtering is used, the transmitted signal through the SOA experiences a negative delay, i.e. a phase advance which is representative of fast light. Blocking of the red shifted sideband is found to enhance the optical delay by a factor of 6 in a bulk SOA compared to the unfiltered scheme when the input power increases from −30 dBm up to 0 dBm (Fig. 7), demonstrating phase delay of 135° at 10 GHz, close to the seven fold improvement measured in a bulk SOA using a network analyzer and a fiber Bragg grating [26]. This improvement is attributed to the influence of the refractive index dynamics [26]. When the blue-shifted sideband is blocked, slow light is observed but no significant enhancement of the phase shift is observed because the influence of the refractive index dynamics is partially compensated.

This method exhibits the advantages of offering a powerful mean to investigate the potential of SOAs based on different type of active layers prior to the physical implementation of the optical filter.

5. Conclusion

1.55 µm InAs/InP quantum dash based SOAs can be used as compact optical delay lines operating at room temperature. Typical maximum achievable delay amounts to 50 ps at a few GHz when the group velocity is electrically tuned. Growth optimization of QDashes allowed to obtain comparable four wave mixing efficiency to that of bulk SOA. A new method based on linear spectrogram method allowed one to measure the complex electrical field at the output of an SOA, i.e. both the phase and the amplitude of the electric field. Optical filtering using signal processing in our method is found to enhance both the slow light related effect phase shift and the optical bandwidth, in agreement with experiments using fiber Bragg grating as an optical filter [26].

Future work will include the investigation of the potentially high achievable Henry factor of specifically band gap engineered QDash based SOA to enhance the maximum phase shift.

References

[1] C.J. Chang-Hasnain, et al., J. Lightwave Technol. 24 (12) (2006) 4642.
[2] Yoshitomo Okawachi, Mark Foster, Jay Sharping, Alexander Gaeta, Qianfan Xu, Michal Lipson, Opt. Express 14 (6) (2006) 2317.
[3] Jesper Mørk, Rasmus Kjær, Mike van der Poel, Kresten Yvind, Opt. Express 13 (20) (2005) 8136.
[4] A.E. Willner, B. Zhang, L. Zhang, L.-S. Yan, I. Fazal, IEEE J. Select. Top. Quantum Electron. 14 (3) (2008) 691.
[5] R.S. Tucker, P.-C. Ku, C.J. Chang-Hasnain, J. Lightwave Technol. 23 (12) (2005) 4046.
[6] F.G. Sedgwick, Bala Pesala, Jui-Yen Lin, Wai Son Ko, Xiaoxue Zhao, C.J. Chang-Hasnain, Opt. Express 15 (2) (2007) 747.
[7] S. Sales Maicas, F. Ohman, J. Capmany, J. Mork, IEEE Photon. Technol. Lett. 19 (20) (2007) 1589.
[8] José Capmany, et al., Nat. Photon. 1 (2007) 319.
[9] Weiqi Xue, S. Sales, J. Mork, J. Capmany, IEEE Photon. Technol. Lett. 21 (3) (2009) 167.
[10] Filip Öhman, Kresten Yvind, Jesper Mørk, IEEE Photon. Technol. Lett. 19 (15) (2007) 1145.
[11] Perrine Berger, Jerome Bourderionnet, Mehdi Alouini, Fabien Bretenaker, Daniel Dolfi, Opt. Express 17 (22) (2009) 20584.
[12] G.P. Agrawal, J. Opt. Soc. Am. B 5 (1) (1988) 147.
[13] T. Mukkai, T. Saitoh, IEEE J. Quantum Electron. 26 (5) (1990) 865.
[14] H. Su, P. Kondratko, S.L. Chuang, Opt. Express 14 (11) (2006) 4800.
[15] Piotr Konrad Kondratko, Shun-Lien Chuang, Opt. Express 15 (16) (2007) 9963.
[16] A. Uskov, C.J. Chang-Hasnain, Electron. Lett. 41 (16) (2005) 922.
[17] P. Palinginis, F. Sedgwick, S. Crankshaw, M. Moewe, C.J. Chang-Hasnain, Opt. Express 13 (24) (2005) 9909.
[18] F.G. Sedgwick, C.J. Chang-Hasnain, P.C. Ku, R.S. Tucker, IET Electron. Lett. 41 (24) (2005) 1347.
[19] J. Mørk, R. Kjær, M. van der Poel, K. Yvind, Opt. Express 13 (20) (2005) 8136.
[20] F. Öhman, K. Yvind, J. Mørk, IEEE Photon. Technol. Lett. 19 (15) (2007) 1145.
[21] A. Arakawa, H. Sakaki, Appl. Phys. Lett. 40 (11) (1982) 939.
[22] A. Asada, et al., IEEE J. Quantum Electron. 22 (9) (1986) 1915.
[23] H. Su, S.L. Chuang, Appl. Phys. Lett. 88 (6) (2006) 061102.
[24] A. Matsudaira, D. Lee, P. Kondratko, D. Nielsen, S.L. Chuang, N.J. Kim, J.M. Oh, S.H. Pyun, W.G. Jeong, J.W. Jang, Opt. Lett. 32 (19) (2007) 2894.
[25] A. Martinez, G. Aubin, F. Lelarge, R. Brenot, J. Landreau, A. Ramdane, Appl. Phys. Lett. 93 (9) (2008) 091116.
[26] Weiqi Xue, Salvador Sales, José Capmany, Jesper Mørk, Opt. Lett. 34 (7) (2009) 929.
[27] R.H. Wang, A. Stintz, P.M. Varangis, T.C. Newell, H. Li, K.J. Malloy, L.F. Lester, IEEE Photon. Technol. Lett. 13 (8) (2001) 767.
[28] S. Deubert, A. Somers, W. Kaiser, R. Schwert, J.P. Reithmaier, A. Forchel, J. Cryst. Growth 278 (2005) 346.
[29] F. Lelarge, B. Dagens, Jeremie Renaudier, R. Brenot, A. Accard, F. van Dijk, D. Make, O. Le Gouezigou, J.-G. Provost, F. Poingt, J. Landreau, O. Drisse, E. Derouin, B. Rousseau, F. Pommereau, G.-H. Duan, IEEE J. Select. Top. Quantum Electron. 13 (1) (2007) 111.
[30] G. Moreau, S. Azouigui, D.-Y. Cong, K. Merghem, A. Martinez, G. Patriarche, A. Ramdane, F. Lelarge, B. Rousseau, B. Dagens, F. Poingt, A. Accard, F. Pommereau, Appl. Phys. Lett. 89 (24) (2006) 241123.
[31] K. Merghem, A. Akrout, A. Martinez, G. Aubin, A. Ramdane, F. Lelarge, G.-H. Duan, Appl. Phys. Lett. 94 (2) (2009) 021107.
[32] A. Bilenca, R. Alizon, V. Mikhelashvili, G. Eisenstein, R. Schwert, D. Gold, J.P. Reithmaier, A. Forchel, IET Electron. Lett. 38 (22) (2004) 1350.
[33] A. Capua, et al., Opt. Express 16 (23) (2008) 19072.
[34] K. Kikuchi, M. Kakui, C.-E. Zah, T.-P. Lee, IEEE J. Quantum Electron. 28 (1) (1992) 151.
[35] J.-Y. Emery, et al., IET Electron. Lett. 33 (12) (1997) 1083.
[36] D. Nielsen, et al., Appl. Phys. Lett. 92 (21) (2008) 211101.
[37] C. Dorrer, et al., Opt. Lett. 27 (15) (2002) 1315.
[38] J.-G. Provost, et al., in: Proceedings European Conference on Optical Communication, 2005, paper Tu1.5.5.
[39] D. Reid, et al., IEEE Photon. Technol. Lett. 19 (8) (2007) 535.
[40] Jin Wang, Ayan Maitra, Chris G. Poulton, Wolfgang Freude, Juerg Leuthold, IEEE J. Lightwave Technol. 25 (3) (2007) 891.