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Voltage-controlled slow light in an integrated semiconductor structure with net gain

Filip Öhman, Kresten Yvind, and Jesper Mørk

COM•DTU, Department of Communications, Optics and Materials, NanoDTU, Technical University of Denmark,
Oersteds Plads, Building 345v, DK-2800 Kgs. Lyngby, Denmark
fo@com.dtu.dk

Abstract: We demonstrate the use of coherent population oscillations (CPO) to realize a monolithically integrated semiconductor device which allows voltage controlled tuning of the group velocity corresponding to a phase shift of up to 55 degrees at a frequency of 10 GHz. By combining sections of slow and fast light, corresponding to absorption and gain, we demonstrate control of both the slow-down factor and the signal amplitude, which is important for applications as true-time delay in microwave photonics. The physics of CPO is discussed in relation to electromagnetically induced transparency (EIT). In particular, we demonstrate and explain the possibility of achieving transparency when using the effect of CPO despite the fact that it relies on only a partial saturation of an absorption line.

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References and links

1. Introduction

During the past few years several experiments have shown the possibility of controlling the speed of light in various media [1-10]. The fundamental demonstrations [1] of light slow-down in an ultra-cold atomic cloud of Na atoms employed the effect of Electromagnetically Induced Transparency [11, 12] (EIT), whereby an applied pump field induces a change in the dispersion of the refractive index of the medium, and thereby the group index. Illustrated in Fig. 1 for a three-level ladder scheme, the pump photon energy is chosen resonant with the two upper levels 2 and 3 and due to Rabi oscillations and the associated shifts of the (dressed) levels, the absorption line of the 1-2 transition is split in two. The corresponding change of the dispersion of the refractive index implies a positive group index at the 1-2 transition frequency while at the same time strongly reducing the absorption. A different physical effect, Coherent Population Oscillations (CPO), also illustrated in Fig. 1, was used in an important demonstration of the feasibility of achieving light slow-down in a solid-state material at room temperature [2]. In this case the interference of a pump and probe signal exciting a continuum of transitions leads to coherent oscillations of the populations in the continuum at the pump-probe beat frequency [2,9]. This, in turn, changes the refractive index dispersion seen by the probe due to wave mixing effects [13].

The effects of EIT and CPO differ fundamentally in that EIT involves a quantum mechanical interference effect between the electronic state wave functions, while for CPO the coherence is assured by the interference of the external laser beams. This leads to a profound difference between the two schemes with respect to the influence of the relaxation processes of the medium. For EIT the width of the spectral dip is thus given by dephasing rates characterizing the coherence of the transitions and in order to obtain a large index slope and thereby a large group index, it is usually required to cool the medium to very low temperatures. In contrast, spectral features for the CPO case are determined by the carrier lifetime [2], which may be relatively long, even at room temperature. Furthermore, EIT requires a medium with discrete states, whereas CPO works for media with a continuum structure, like semiconductors [4, 5, 9]. Another important difference between the two schemes relate to the level of absorption. In the case of EIT the absorption of the 1-2 transition can be nearly cancelled by the destructive interference between the different transition paths, the residual absorption being proportional to the dephasing rate of the 1-3 coherence [14]. In contrast the CPO effects relies on saturating the medium, see Fig. 1, and only approaches zero for very large control intensity, in which case the index modulation also approaches zero. Thus, while the CPO effect may lend itself more readily towards realistic applications using solid-state devices, such as semiconductors, because of the independence of decoherence effects of the medium, the issue of the large residual absorption is a fundamental problem that needs to be solved. In this paper we propose a solution to this problem and demonstrate an integrated semiconductor device which achieves large phase delays at microwave frequencies, while allowing control of the amplitude of the signal and even achieving net gain.
Fig. 1. Level diagrams and typical examples of susceptibilities for electromagnetically induced transparency (EIT, left column) and coherent population oscillations (CPO, right column) versus detuning frequency. The level schemes (upper row) illustrate the choice of control and probe photon energies, $\hbar \omega_{co}$ and $\hbar \omega_{pr}$, for the two schemes of excitation. Below, the imaginary and real parts of the susceptibilities are depicted, with dashed lines showing the susceptibilities for zero control signal. The probe frequency is normalized with respect to the 2-1 dephasing time for EIT and with respect to the carrier lifetime for CPO.

Earlier experiments [9] have demonstrated an electrically and optically controllable delay in a single waveguide electro absorber (EA) at high modulation frequency (more than 15 GHz). The EA acts as a saturable absorber and slow light is achieved by CPO, which in this case can also be described by a time varying absorption induced by the intensity modulated signal [9]. The maximum achievable delay is thus limited by the carrier lifetime, and the large residual absorption in the device further limits the achievable delay and introduces substantial losses to the signal. While the existence of a fundamental limitation in terms of a finite delay-bandwidth product is common for both CPO [9, 15] and EIT [15,16], the loss-limitation of the CPO effect is a main issue that may limit applications. In order to solve these problems we here suggest to 1) combine the EA with an amplifying element, a semiconductor optical amplifier (SOA), to compensate for the loss and 2) concatenate several EA-SOA pairs in order to increase the absolute value of the controllable time or phase delay. While the counteraction of the loss using an amplifier seems a trivial solution, the effect on the delay is not. It has been shown that an SOA introduces an advancement of the phase, corresponding to the effect of fast light [3,9], thus counteracting the effect of the EA. The achievement of a net, sizable, phase change thus relies on a careful choice of the operating conditions of the SOA and the EA. We show below that this is indeed possible and besides resulting in net gain it also allows control of the amplitude of the output signal. In addition, the cascading of several alternating gain and absorber sections allows a reduction of noise.

We believe this device structure represents a viable route for the use of slow-light effects for a number of practical applications, such as phased-array antennas and microwave filters, while benefiting from standard semiconductor fabrication technology.

The paper is structured as follows: After the introduction of the physical effects and the motivation of the work in this section, we present the device structure and discuss the
experimental technique. After that the main experimental results of phase and amplitude control are shown and discussed by comparison with modeling results. The model is next employed to investigate the potential of the device. The conclusions are summarized in the final section.

2. Results and discussion

2.1 The device and the experimental setup

The fabricated device, shown in Fig. 2 in a schematic and in an actual photo, employs an optical ridge waveguide structure that is angled 7 degrees relative to the cleaved facets, in order to further reduce the reflections into the waveguide from the anti reflection coated facets. The electrode on top of the waveguide is divided into sections. The length of the SOA and EA sections are 545 and 120 μm, respectively. The active material is in this case the same for all sections and consists of five 7.0 nm thick, compressively strained, InGaAsP quantum wells, in a strain compensated structure. For more design flexibility it is possible to employ an additional etch and re-growth step during fabrication in order to have different active material with for example different band gaps in the amplifying and absorbing sections.

![Waveguide schematic](image)

Fig. 2. The device under investigation. Schematic (top) and photo (bottom) of the examined device consisting of concatenated semiconductor optical amplifiers (SOA) and electro absorbers (EA).

The experimental characterisation of the phase delay in the device is based on the measuring technique of Bigelow et al. [2, 9, 17]. In short, a weak sinusoidal intensity modulation is imposed on a CW laser beam. After passing through the device under test the signal is measured in the time domain using an oscilloscope and the phase and amplitude of the modulated signal is measured relative to a reference beam using a network analyzer. The reference beam has traversed the same path as the measured signal but with the operation parameters set to achieve the background refractive index. In practice the reference measurement is done at low input power and zero reverse bias of the absorber, i.e. where the saturation of the sections and the additional delay are small. The reference can also be measured with all sections biased at transparency where the phase shift is independent of the input power. The results when using the two different reference measurements are very similar and zero bias is chosen for easier measurements. The wavelength of the signal beam is 1555 nm in order to be just above the absorption edge of the EAs at zero bias voltage. The polarization is optimised for maximum absorption in the EAs using a polarization controller since the device has not been fabricated for polarisation independent operation. The signal is launched into and collected from the waveguide of the device by tapered fibers. The coupling losses are estimated to about 3 dB. The bias current to the first and second SOA are 80 and 30 mA, respectively. These bias points are chosen for optimising the phase shift. The operation parameters varied during the measurements are the bias voltage on the EAs, which is the same for both EAs, and the optical input power.

In order to clearly illustrate the time delay in the device the modulated signal at the output of the SOA-EA component, as measured by the oscilloscope, is plotted in Fig. 3 for different EA bias voltages. The signals are normalised to their respective mean values since an increase
in bias voltage increases the loss in the device and hence reduces the intensity of the signal for a constant input power. As the reverse voltage is increased the time delay is increased up to a maximum of about 14 ps at 1.2 V in this case. At 10 GHz this corresponds to a phase shift of about 50 degrees, more than three times higher than achieved earlier [9]. We notice that the phase change per unit device length is not larger than in [9], since the EAs, which provide the delay, only constitute a small fraction of the total device length. However, it should be emphasized, that the integration of several EA and SOA sections is necessary in order to limit the total absorption as well as the spontaneous emission noise resulting from the SOA sections.

![Graph showing transmitted intensity modulation](image)

Fig. 3. Transmitted intensity modulation showing time delay. The measured optical signal intensity is shown as a function of time for constant optical input power and three different values of EA reverse bias. The signals are normalised to their respective mean value. Two SOA-EA pairs are concatenated. The first and second SOAs are biased at 80 and 30 mA, respectively and both EA sections are biased at the reverse voltage indicated in the figure legend. The modulation frequency is 10 GHz, the optical input power is 6.8 dBm and the wavelength of the optical carrier is 1555 nm.

2.2 Microwave phase shifter based on slow light

The main experimental result of this paper is presented in Fig. 4, which shows in a double contour plot the dependence of the phase shift (coloured contour lines) and change in amplitude (black contour lines) on the input optical power and reverse bias voltage of the EAs. These results demonstrate that it is possible to achieve a sizable delay while maintaining the signal intensity, which shows that the effect of CPO can be tailored by the suggested device to result in characteristics similar to those of EIT. Perhaps more interesting, however, the results demonstrate the possibility of independent control of the signal phase shift and amplitude by varying two parameters (the input power and EA bias voltage). Such functionality is for instance of importance for the application of slow-light effects in phased-array and adaptive antennas. The possibilities for control could be further expanded by also adjusting the SOA bias currents.

The phase delay shows similar qualitative behaviour as for a single EA [9] with a distinct maximum as function of reverse bias. This maximum is due to the interplay of two effects: The absorption increases for a larger electrical field across the quantum wells due to the quantum-confined Stark effect, which increases the delay, but at the same time the rate of carrier sweep-out is increased, which reduces the delay since the carrier lifetime is decreased and the saturation power is increased. The phase delay increases monotonically with increasing optical power in the investigated range.
2.3 Modeling, cascadability and device potential

In order to investigate the potential of the proposed device and optimize the operation parameters a theoretical model has been developed based on a description of the dynamics of the EA [9] and SOA sections. The details of the model for the EA are presented in [9] and for this work we have extended the same model to also include multiple sections with absorption or gain. The gain sections model is derived using the same general assumptions as for the absorbers and the main difference is the choice of parameter values. The model is unidirectional and does not include any ASE noise.

There is a “fast light” effect in the SOAs [17-20], which is similar to the slow light in the EA but results from the saturation of the gain instead of the absorption. This leads to a temporal advancement in the SOA sections, which partially cancels the delay imposed by the EA sections. In order to achieve an overall net time delay in the SOA-EA pair it is therefore important to design the devices for proper saturation properties. The output saturation power of the amplifier sections must be higher than the input saturation power of the absorber sections. This ensures that the absorbers saturate at a lower input power than the amplifiers. The SOAs then operate in a more linear regime resulting in a limited contribution to the change in group index. Furthermore, the bandwidth of the slow and fast light effects depends on the carrier dynamics in the respective device. At the high frequency used in the measurement, the fast carrier sweep out in the EAs thus allows the slow light effect to dominate over the fast light effect, which is limited in bandwidth by the relatively long carrier recombination time in the SOAs.

It should be noted that the net change in group index in the device is quite modest. The relatively long device results in an average group index increase in the total device of a factor of two [calculated from the results in Fig. 5(a)]. This is due to the fast light effect in the long SOAs and the actual slow down factor in the EA sections are much larger (but not measured separately in this work). Moreover the residual absorption in the EAs, which constitutes a fundamental limitation to the length of a single absorber and hence the achievable delay, is...
compensated by the gain of the SOA. The net gain in the device allows several sections to be cascaded in order to increase the achievable time and phase delay, which is the important measure for microwave photonic applications like phased-array antennas.

The phase shift is plotted as function of bias voltage for different input powers in Fig. 5. The left panel (a) shows the experimental result and the right panel (b) the modelling results. The model parameters are chosen to achieve a good fit to the measurements for one SOA-EA pair at the highest input power. The effect of concatenation is demonstrated by showing the results for one (dashed lines) and two (solid lines) SOA-EA pairs. The two measurements are performed on the same device. In order to measure only the influence of one pair, the second pair is biased at transparency, where the phase shift as a function of power is measured to be negligible.

Comparing Figs. 5(a) and 5(b) shows that the model in general agrees very well with the experiments in the entire bias interval examined. In the calculations, however, the phase shift at large reverse bias is predicted to be the same for one and two pairs, which does not agree with the measurements. However, this is a result of the simplified EA model, which gives an unrealistically large absorption at high reverse bias. The strong absorption in the first pair results in a phase shift in the second pair that is close to zero due to the very low input power.

Fig. 5. Comparison of experiment and theory. Measured (a) and calculated (b) phase shift as function of EA reverse bias for different input power levels. The solid and dashed lines show the results for two and one SOA-EA pair, respectively. The inset demonstrates the predicted result of concatenating several sections by showing the calculated phase shift for 1, 2, 4 and 8 SOA-EA pairs.

Comparing the phase shift for one and two pairs in Fig. 5 reveals that the phase shift is almost doubled for two pairs at lower input powers, while the additional phase shift is less substantial at higher input powers. This can be attributed to the change of the absorption in the first EA as the bias voltage is varied. At high reverse bias, where the phase shift is largest for high input power, the absorption is large and the input power into the second pair and hence the phase shift in these sections is low. At intermediate reverse bias the absorption is smaller and the phase shift in the second SOA-EA pair is larger. For very low reverse bias the delay in both EAs is small and the negative delay, or “fast light”, in the SOAs [17-19] dominates. These combined effects will shift the maximum phase shift to the bias point where the net gain of the combined SOA-EA device is unity as more pairs are concatenated. This shift can be seen when comparing the one and two pair cases in Fig. 5.
The results in Fig. 5 demonstrate that the phase shift due to slow light effects can be substantially increased by concatenating SOA-EA sections in an integrated device. As opposed to purely absorbing slow light devices [2, 3, 6], the phase shift in the SOA-EA device can thus be enlarged by increasing the device length and adding more sections. In the inset of Fig. 5 we substantiate this further by using the model to predict the phase shift and corresponding time delay for one, two, four and eight SOA-EA pairs. The bias point of the maximum phase shift is lowered as additional pairs are added and approaches the point where the net gain of the device is zero, as discussed for the experimental results. The results demonstrate that within the limits of the model, i.e., small signal modulation and no spontaneous emission noise, it is possible to achieve large adjustable phase shifts by concatenating several absorber and amplifier pairs. For the non-optimized parameters used, eight SOA-EA pairs are required in order to achieve a total adjustable phase shift of 180 degrees. However, the use of semiconductor integration technology makes such a structure practically feasible and it should be emphasized that there is ample room for optimization.

In principle the non linear absorption in the EA, which absorbs low intensity light more than high intensity light, leads to nonlinear distortions of the signal and creation of higher harmonics. The larger modulation depth seen in Fig. 3 at high voltage is for example attributed to this. Some tendencies of distortions can also be seen in Fig. 3 for larger bias voltage. This problem is expected to be worse for large modulation depth but can to some degree be counteracted by proper filtering [21]. Amplified spontaneous emission from the SOAs will limit the number of amplifier and absorber sections that can be concatenated, but the nonlinearities of the devices may be used to advantage by redistributing the noise.

3. Conclusion

We have demonstrated an integrated semiconductor structure that enables voltage controlled light slow-down with the possibility of simultaneous control of the amplitude, to the extent of even obtaining net gain. The gain provided by the SOAs counteracts the fundamental limitation of absorbing CPO based devices due to residual absorption and allows the cascading of several sections, leading to a large absolute phase shift at a microwave frequency of 10 GHz. The experimental results are well described by a theoretical model and based on the model we conclude that a cascaded device achieving a phase shift of more than 180 degrees is practically feasible. We therefore believe that the present device structure has excellent potential for applications in microwave photonics, such as phased array antennas and radars.

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