Time delay generation at high frequency using SOA based slow and fast light

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Abstract: We show how Up-converted Coherent Population Oscillations (UpCPO) enable to get rid of the intrinsic limitation of the carrier lifetime, leading to the generation of time delays at any high frequencies in a single SOA device. The linear dependence of the RF phase shift with respect to the RF frequency is theoretically predicted and experimentally evidenced at 16 and 35 GHz.

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References and links
1. Introduction

Slow and fast light (SFL) is becoming a wide research field driven by an extensive effort to implement this new technology in real applications [1]. In this context, SFL based devices have today to meet numerous criteria in addition to the usual slow-down factor. Among these criteria, one can quote continuous, easy, and reliable control of the induced delays, bandwidths reaching the GHz range, small footprint, high speed configurability... [2, 3, 4, 5]. With these constraints in view, Coherent Population Oscillations (CPO) in Semiconductor Optical Amplifiers (SOA) constitute one of the most promising approaches, in particular for the processing of optically carried microwave signals [6, 7, 8]. Indeed, many of these systems require a tunable delay line whose bandwidth-delay product is modest compared to that needed for data buffering optically carried microwave signals [6, 7, 8].

Several criteria, such as parallel programmable filtering, TTD operation implies a perfectly proportional evolution of the phase $\phi$ of the microwave signals with respect to their frequency $f$, $\phi = 2\pi f \tau$, over $[f_{\text{op}} - B_{\text{inst}}/2, f_{\text{op}} + B_{\text{inst}}/2]$. Moreover, tuning the delay is equivalent to tuning the slope $\frac{\phi}{\tau}$ (as illustrated in Fig. 1(a)). These stringent requirements are mandatory in microwave photonics systems in order for instance to synchronize and coherently recombine broadband signals [11, 12, 13].

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The generation of a tunable TTD can be broken down in two stages. First, a tunable delay \( \tau \) is generated over \([f_{op} - B_{\text{inst}}/2, f_{op} + B_{\text{inst}}/2]\) (as illustrated in Fig. 1(c)). The microwave phase \( \phi \) is then linear with respect to the microwave frequency: \( \phi = 2\pi \tau f + \phi_0 \). When \( \tau \) is tuned, \( \phi_0 \) varies. Slow and fast light devices are well suited to realize this function. Second, in order to realize a TTD unit, a tunable phase shifter is needed in order to adjust the phase bias \( \phi_0 \) (see Fig. 1(b)). For a given delay \( \tau \), a fixed phase shift \( -\phi_0 \) must be added over \([f_{op} - B_{\text{inst}}/2, f_{op} + B_{\text{inst}}/2]\). TTD is then obtained, i.e., \( \phi = 2\pi \tau f \) over \([f_{op} - B_{\text{inst}}/2, f_{op} + B_{\text{inst}}/2]\) (as illustrated in Fig. 1(a)). The tunable phase shifter can be easily realized by separate carrier tuning [14]. This method consists in tuning the phase of the optical carrier, which is single-sideband modulated by the microwave signal. The microwave signal is then straightforwardly phase shifted. A demonstration of this concept has been conducted in [15] using Stimulated Brillouin Scattering (SBS) in a 20-km long fiber. In this example, SBS is used for both the phase shift and the delay, but at the cost of the very long switching time associated with the propagation through 20 km of fiber.

The realization of a tunable TTD integrated device is highly desirable for embedded systems (airborne systems or satellite communications) and for the next generation of radars which will require distribution to several hundreds of radiating elements. In this context, Coherent Population Oscillations (CPO) are promising for practical integrated devices because they enable to control slow and fast light in a solid-state device at room temperature, and do not require a precise laser wavelength. However, the first demonstrations in ruby [16] and alexandrite [17] crystals offered narrow instantaneous bandwidths, smaller than 100Hz and 1kHz, respectively. CPO in a Semiconductor Optical Amplifier (SOA) are a further step towards applicability [6]. Indeed, the carrier lifetime \( \tau_s \) is in the nanosecond range, which suits the requirements in terms of instantaneous bandwidth and high speed reconfigurability. Moreover, the component uses low power, has a small size (\( \approx 1 \text{ mm} \)), and the delays can be electrically controlled. Furthermore, recent works show the compatibility of SOA with microwave photonics systems in terms of noise and non-linearities [18, 19, 20, 21, 22]. However, when used for TTD generation, CPO have an intrinsic limit in terms of operating frequency range. In a SOA, the operating frequency cannot exceed few hundreds of MHz [10].

Recently, research has been conducted in order to increase the operating frequency in slow and fast light devices based on SOAs. Promising results have been obtained for phase shifters: higher frequencies can be reached either by filtering out the red shifted side band of the signal at the output of the SOA [23] or by forcing the CPO mechanism to be efficient beyond the inverse of the carrier lifetime [24]. These techniques have been shown to be quite reliable for inducing tunable RF phase shifts at a given RF frequency, i.e., without any specific relation between the induced phase shift and the frequency. However, the achievement of TTD at a frequency higher
Fig. 2. Principle of integrated delay generator using UpCPO in a SOA. An optically carried RF signal, at a high RF frequency $f_{op}$, propagates through the SOA. A second optically carried RF signal, at a low RF frequency ($f_{cpo}$ < a few GHz), induces CPO. The modal gain $g$ is then modulated at $f_{cpo}$. The gain modulation at $f_{cpo}$ generates then two optically carried RF signals at $f = f_{op} - f_{cpo}$ or $f = f_{op} + f_{cpo}$. The CPO effect is controlled by the average gain $< g >$ (through the current or the input optical power), which permits to control the delay $\tau$ of the RF signal at $f$.

than the intrinsic limit in SOA remains till now a challenging issue.

In this paper, we show how Up-converted Coherent Population Oscillations (UpCPO) enable to get rid of this intrinsic limitation of the carrier lifetime, leading to the generation of time delay at any high frequencies in a single SOA device. In a first part, we explain the principle and derive the theory. In a second part, we experimentally evidence the generation of tunable delays induced and controlled by UpCPO at 16 and 35 GHz.

2. Principle and theory of UpCPO

Our idea to generate tunable delays at high frequency, i.e., beyond the limit imposed by the carrier lifetime, is to combine CPO and cross gain modulation (XGM). XGM already allows to up-convert microwave signals for radio-over-fiber applications [25]. Here we show that up-converting CPO by XGM enables to optically generate a signal at high frequency and to control its delay at the same time. The principle is described on Fig. 2. Before the SOA, the intensity of a laser is modulated by a microwave signal at a high RF frequency $f_{op}$. The RF spectrum and the oscillogram of this RF signal, after photodetection, are displayed on the left column of Fig. 2. A second optically carried RF signal, whose RF frequency, $f_{cpo}$, is lower than the carrier lifetime, generates CPO. The modal gain is then modulated at $f_{cpo}$. The CPO effect is controlled by the average gain $< g >$, as represented on the oscillogram of the gain in Fig. 2(b). The gain modulation at $f_{cpo}$ generates two optically carried RF signals at $f_{op} + f_{cpo}$ and $f_{op} - f_{cpo}$. After
The optical intensity is then given by \( \frac{1}{2} |E|^2 = U_1 + M_{\text{cpo}} e^{-i2\pi f_{\text{cpo}} t} + c.c., \) under small modulation depth approximation. \( U_1 \) is the DC component of the intensity, \( M_{\text{cpo}} = \frac{1}{2} (E_0 E_{-1}^* + E_1 E_0^*) \) is the beat-note term at frequency \( f_{\text{cpo}}. \)

In the same way, we consider a second laser modulated by a microwave signal at \( f_{\text{op}}. \) The field is then composed of the optical carrier of complex amplitude \( F_0 \) and two sidebands of complex amplitudes \( F_2 \) and \( F_{-2}. \) The optical intensity is then given by \( \frac{1}{2} |F|^2 = U_2 + M_{\text{op}} e^{-i2\pi f_{\text{op}} t} + c.c., \) under small modulation depth approximation. \( U_2 \) is the DC component of the intensity, \( M_{\text{op}} = \frac{1}{2} (F_0 F_{-2}^* + F_2 F_0^*) \) is the beat-note term at the frequency \( f_{\text{op}}. \)

The operating frequency \( f_{\text{op}} \) is assumed to be larger than the inverse of the carrier lifetime, so that the carrier density and the modal gain \( g \) of the SOA can be considered to be modulated at \( f_{\text{cpo}} \) only. Consequently we introduce: \( g(z,t) = g(z) e^{-i2\pi f_{\text{cpo}} t} + c.c., \) where \( <,> \) holds for the time average. \( g_{\text{cpo}} \) is deduced from the resolution of the carrier rate equation [10]:

\[
g_{\text{cpo}} = \frac{-<g> + M_{\text{cpo}}/U_s}{1 + U_s/2\pi f_{\text{cpo}} \tau_s},
\]

(1)

where \( \tau_s \) is the carrier lifetime and \( U_s \) the saturation intensity.

Consequently, the following propagation equations can be derived, under small signal conditions:

\[
\frac{dM^+_{\text{signal}}}{dz} = (\Gamma <g> - \gamma) M^+_{\text{signal}} + \Gamma g_{\text{cpo}} \left[ \frac{1}{2} (M^R_{\text{op}} + M^B_{\text{op}}) + \frac{i\alpha}{2} (M^R_{\text{op}} - M^B_{\text{op}}) \right],
\]

(2)

\[
\frac{dM^-_{\text{signal}}}{dz} = (\Gamma <g> - \gamma) M^-_{\text{signal}} + \Gamma g_{\text{cpo}}^* \left[ \frac{1}{2} (M^R_{\text{op}} + M^B_{\text{op}}) + \frac{i\alpha}{2} (M^R_{\text{op}} - M^B_{\text{op}}) \right],
\]

(3)

where \( \gamma \) holds for the internal losses; \( \Gamma \) is the confinement factor; \( \alpha \) is the linewidth enhancement factor, introduced to model the index-gain coupling induced by the carriers. \( R \) (resp., \( B \)) denotes the optical intensity resulting from the beat-note between the optical carrier \( F_0 \) and the red-shifted (resp., blue-shifted) sideband at \( f_{\text{op}}: M^R_{\text{op}} = F_0 F_{-2}^* \) (resp., \( M^B_{\text{op}} = F_2 F_0^* \)). \( M^+_{\text{signal}} \) and \( M^-_{\text{signal}} \) denote the signals created by UpCPO at \( f_{\text{op}} + f_{\text{cpo}} \) and \( f_{\text{op}} - f_{\text{cpo}}, \) respectively. \( g_{\text{cpo}}^* \) is the complex conjugate of \( g_{\text{cpo}}. \)

The parameters of the SOA are set at the same values as in [10]. Most of these parameters are extracted from simple measurements, as described in [10]. For this model of UpCPO, the only additional input parameters are the linewidth enhancement factor (\( \alpha = 4.5 \)) and the chirp parameter of the modulator (0.72). Indeed, the up-conversion reveals the index-gain coupling induced by the carriers (see Eq. 3) and it is then sensitive to the input values of \( M^R_{\text{op}} \) and \( M^B_{\text{op}}. \) The results of the simulations will be discussed in the following part.
3. Experimental demonstration of tunable delays by UpCPO

In our experiments, we used a commercially available SOA (InP/InGaAsP Quantum Well Booster Amplifier from COVEGA). The length of this SOA is 1.5mm and the quantum well active area cross-section is evaluated to be 0.06µm². This SOA is not specifically optimized for slow and fast light. Higher delay-instantaneous bandwidth products could be expected with custom SOA designs.

Our setup is presented in Fig. 3. A first laser is modulated at low frequency $f_{\text{cpo}} < 2.5$ GHz. A second laser, at a different wavelength, is modulated at a higher frequency, which corresponds to the operating frequency $f_{\text{op}} > 10$ GHz. The wavelengths of the lasers are $\lambda_1 = 1548.59$nm and $\lambda_2 = 1547.03$nm. We have chosen the laser wavelengths close to the maximum gain of the SOA, and the wavelength difference $\Delta\lambda$ which corresponds to 195GHz has been chosen larger than the targeted operating frequency range (here 35GHz, limited by the modulator), but small enough for the two channels to undergo the same optical gain. The first channel is dedicated to the electrical to optical conversion of the signal at the operating frequency $f_{\text{op}}$. It is composed of a laser diode (DFB from JDS Uniphase) and a z-cut LiNbO$_3$ Mach Zehnder intensity modulator (MZM), working up to 40GHz. This modulator has a chirp rate of 0.72 GHz. The second channel, composed of a directly modulated laser diode (Alcatel LMI), optically converts the RF signal which is at a low RF frequency $f_{\text{cpo}}$, and which induces the CPO effect. The optical power of the two channels are balanced, and the input RF modulation rates are respectively 0.14 at 16GHz and 0.33 at 1GHz. The total input optical power into the SOA is 13.3dBm. In the SOA, the gain modulation induced by CPO is seen by the second channel, and UpCPO signal is created by XGM at $f_0 - f_{\text{cpo}}$ and $f_0 + f_{\text{cpo}}$. The phase of these signals is experimentally analyzed thanks to a Vector Network Analyzer. Actually, in the experimental set-up, the VNA emits at the frequency $f : f_{\text{op}}$ is emitted by an independent RF generator. $f_{\text{cpo}}$ is generated by difference between $f$ and $f_{\text{op}}$. After the photodiode, the electrical spectrum
Fig. 4. The figures (A.1) and (A.2) respectively represent the typical simulated and measured phase shifts induced in the SOA by usual CPO with respect to the RF frequency. By adjusting the current from 42 mA to 200 mA, the delays are tunable from 0 to 380 ps, over an instantaneous bandwidth of 320 MHz. The operating frequency range is limited to the instantaneous bandwidth. The figure (B.1) represents the simulated phase shift induced in a SOA with respect to frequency, by combining XGM and CPO, around an arbitrarily high frequency \( f_{op} \). (B.2) and (B.3) represent the corresponding measured phase shift at \( f_{op} = 16 \text{GHz} \) and \( f_{op} = 35 \text{GHz} \), respectively. By adjusting the current from 80 mA to 599 mA, delays are tunable from 0 to 89 ps, over an instantaneous bandwidth of 1.2 GHz. Here we experimentally show that UpCPO enable the operating frequency to reach 35 GHz, far beyond the intrinsic bandwidth of CPO.

contents four frequencies (cf. Fig. 2(a))). However the VNA only analyses the frequency that it emits, i.e. \( f \). In the experiment, we measure the phase of this signal while \( f \) is swept. The phase reference has been chosen at high current (599 mA), where the phase is supposed to be constant versus frequency. The delays have been measured by a linear fit from the experimental data, and the instantaneous bandwidth has been defined as the maximum frequency offset for which the relative phase error between the experimental data and the linear fit is kept below 15%.

In Figs. 4(B.2) and 4(B.3), the measured RF phase shift is displayed for \( f_{op} = 16 \text{GHz} \) and \( f_{op} = 35 \text{GHz} \), respectively, while \( f_{cpo} \) is swept from 0 to 2.5 GHz. We show that the measured phase shift of the signal at \( f = f_{op} \pm f_{cpo} \) is affine with respect to the frequency, with a slope tunable with the bias current. We experimentally demonstrate a delay generator, electrically tunable from 0 to 89 ps, with an instantaneous bandwidth of 1.2 GHz, and easily reconfigurable at 16 GHz and 35 GHz.

Moreover, in Figs. 4(B.2) and 4(B.3), the phase shifts measured for \( f_{op} = 16 \text{GHz} \) and \( f_{op} = 35 \text{GHz} \) show the same behavior with respect to the RF frequency and to the current. Since the operating frequency \( f_{op} \) is assumed to be higher than the inverse of the carrier lifetime, the gain of the SOA is not modulated at \( f_{op} \). This explains that the experimental results are inde-
ependent of $f_{\text{op}}$. Fig. 4(B.1) displays the theoretical results derived from our model, and shows a very good agreement with the experimental data both at 16GHz and 35GHz (Fig. 4(B.2) and 4(B.3)). From a practical point of view, this characteristic offers a strong asset: the device is easily reconfigurable at any operating frequency $f_{\text{op}}$.

It is worth stressing out the contribution of the linewidth enhancement factor $\alpha$. Indeed, $\alpha$ is known to play a role in the SOA slow and fast light schemes involving filtering of the red sideband of the optical output [23]. Here, $\alpha$ appears in the equations (3) and (2). However, it is weighted by $M_{\text{op}}^R - M_{\text{op}}^B$, and not by $M_{\text{op}}^R$ like in the SOA slow and fast light schemes involving filtering of the red sideband of the optical output [23]. $M_{\text{op}}^R$ and $M_{\text{op}}^B$ are different because of the non-zero value of $\alpha$, but $\frac{\alpha}{2}(M_{\text{op}}^R - M_{\text{op}}^B)$ has still a small contribution compared to $\frac{1}{2}(M_{\text{op}}^R + M_{\text{op}}^B)$. The impact of the factor $\alpha$ is only the asymmetry in the curves displayed in Fig 4(B.3). Consequently, the described tunable-delay principle works with a small or even zero $\alpha$.

In order to compare the performances of CPO and UpCPO in the same component, we represent the typical simulated and measured RF phase shifts induced by CPO in the SOA with respect to the RF frequency on Figs. 4A.1 and 4A.2. To perform this measurement, we used a set-up similar to Fig. 3, except that only the first channel is connected. The MZM is directly connected to the output of the VNA. The total input optical power into the SOA is 10.0dBm. In this case, the phase reference has been taken at low current (42mA). We show that the phase is proportional to the modulation frequency only below 320MHz (at any current). The delays are tunable from 0 to 380ps by adjusting the current. However, we note that the use of a SOA greatly increases the operating frequency range compared to the first demonstrations of CPO in doped crystals.

The key figure in order to compare two tunable-delay generators is the delay-instantaneous bandwidth product, which is equal to 0.11 in both experiments displayed in Fig. 4 (with CPO or UpCPO). Consequently, we have shown that UpCPO enable to extend the operating frequency of a tunable delay line based on SOA from 320MHz up to 16GHz and 35GHz, within the same component, while keeping the same delay-instantaneous bandwidth.

We experimentally demonstrated that the operating frequency range $\Delta f_{\text{op}}$ can reach 35GHz. However, the upper limit of the operating frequency range $\Delta f_{\text{op}}$ is expected to lie beyond 100GHz. Indeed, upconversion efficiencies are linked with the SOA optical gain spectrum [26]: high upconversion efficiency is achieved as long as the input wavelengths are in the optical gain bandwidth of the SOA (about 80nm, i.e., 9THz). Consequently, the operating frequency range can potentially reach THz frequencies.

4. Conclusion

In conclusion, we have demonstrated the first integrated tunable delay generator, based on a semiconductor optical amplifier, whose operating frequency is no longer limited by the inverse of the carrier lifetime. By up-converting CPO by XGM, the operating frequency is easily reconfigurable and can reach the THz range. The instantaneous bandwidth and tunable delays are similar to those achieved by using standard CPO at low frequencies, with unique component. Such a device can be associated with an integrated phase shifter based, for example, on microrings [27] in order to realize a fully integrated TTD generator, working at high frequencies, with a high speed reconfigurability, and millimetric footprint. This work therefore suggests the possibility of TTD generators based on SOAs matching the requirement for the next generation of radars, wireless and satellite communications.
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