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Ultrafast Dynamics Effect in Presence of Different Pulse Width in Semiconductor Optical Amplifier

تأثير الحركيات السريعة في وجود نبضات ذات عرض مختلف في المضخم شبه الموصل البصري

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Abstract

The dynamics that occur in bulk semiconductor optical amplifier (SOA) like gain and phase dynamics in presence of pulses in subpicosecond and picosecond range are studied numerically. If the passing pulse through SOA in the femtosecond range, the ultrafast effects presented by the compression of gain, phase will appear and as a result, the recovery of them will be fast comparison with the pulse width in the picoseconds range which suffers from slow recovery. The dependence of the studied of the gain and phase on the pulse width was clear and the ultrafast effects present in this paper like spectral hole burning (SHB) and carrier heating (CH) and its effects on pulse chirp are studied extensively.

الخلاصة

تمت دراسة الحركيات التي تظهر في المضخم شبه الموصل البصري عدديا مثل حركية الكسب والطور في وجود النبضات ضمن مدى البيكوثانية والفيمتوثانية. إذا كانت النبضة التي تمر خلال المضخم ضمن مدى الفيمتوثانية فان التاثيرات السريعة المتمثلة بأنضغاط الكسب والطور ينتج عنها استرداد سريع للكسب والطورمقارنة بالنبضات ضمن مدى البيكوثانية التي تعاني من الاسترداد البطيء . ان اعتماد المعاملات المدروسة على عرض النبضة كان واضحا والتاثيرات السريعة مثل SHB و CH وتاثيراتها على chirp للنبضة تم دراستها.

1. Introduction

Gain compression that is caused by CH and SHB effects becomes more importance in many applications [1]. It takes into account the importance of gain dynamics on the picoseconds to subpicosecond time scale in SOA.

When the bit-rates is lower, the experienced gain will be achieved by interband carrier recombination lifetime but in the case the signal rates is higher when the input signal pulses become very short, (pulse width in the order of the intraband relaxation times), then the gain of the amplifier gets modulated because of the intraband effects. The later effects include the carrier heating (CH),spectral hole burning (SHB) and the gain of the amplifier will be influenced by these effect [2]. To describe the ultrafast dynamic in a SOA, one can express a multicomponent system which contains three subsystems that compose ensemble of unified dynamic. These may be identified be the electrons in the conduction band, holes in the valence band, and the lattice which characterized by a hierarchy of relaxation times in which the inter subsystem relaxation times are longer than the intra subsystem relaxation times. For time intervals long enough for quasi-equilibrium to be established, temperatures of subsystems can be different and also, mean the systems temperatures are different. If the time scales greater than 10^{-12}s then the three subsystems temperatures will be taken equal. The case of equal temperature is common in semiconductors theory. Therefore, on the femtosecond time scale, the temperature difference between carriers and the lattice becomes important for dynamic response of SOA. So, rate equations must be modified in SOA to take into account gain nonlinearities that include temperature dependence. In other word, the carrier temperature is a considered as a dynamic variable [3].

High bite-rate larger which composed from very short pulse propagated through SOA requires taking into account the ultrafast dynamics (intraband effect) and this cause problem of how to model the above dynamics [2]. So many approaches add these effects to compression factors; they include all the nonlinear effects which occur due to passing a short pulse through SOA [4,5]. The effects on chirp and phase that take place as a result of gain compression [6]. In [7], one of parameter that cause the gain compression and its effects on the phase and chirp are studied. It is presented the effect of wavelength at constant pulewidth, i.e. it is interested of dependence the recovery dynamics gain on the wavelength. Our model depends on the integrated gain equation for both cases: interband and intraband effects, also, The dependence of the gain compression on the pulse width was presented and the spectral hole burning (SHB) and carrier heating (CH) that occur due to passing a short pulse through SOA and its effect on pulse chirp and phase are studied extensively.

2. Theory

2.1 Gain dynamic

The gain of SOA at the peak of the gain is given by [4]

$$g(w_{peak}) = g_{CDP} + g_{SHB} + g_{CH} \tag{1}$$

g_{CDP} is the contribution of interband effect while g_{SHB} and g_{CH} are the contribution of the intraband effects. The carrier lifetime τ_{CDP} is relatively long, so, the population of carrier density is not instantaneously equilibrium. For this reason, the interband dynamics which it is represented by the rate equation are speed limited to the carrier lifetime [8].

$$\frac{\partial N}{\partial \tau} = \frac{I}{qV} - \frac{N}{\tau_{CDP}} - \frac{P(z,\tau)}{E_{sat}} \tag{2}$$

Where $P(z,\tau)$ is the pulse power, I is the current which injected, V is the volume of the active region, q is the electronic charge, E_{sat} is the saturation energy. For calculating the gain at peak wavelength of interband effect from equation 1, g_{CDP} is approximated linearly as a function of the carrier density [9]

$$g = a_0(N - N_0) \tag{3}$$

where $a_0 = dg/dN$ is the differential gain coefficient. N and N_0 are the injected carrier density and carrier density needed for transparency. To find the interband dynamic represented by the rate equation, one can use equation 2 into equation 3 to obtain

$$\frac{\partial g}{\partial \tau} = \frac{g - g_0}{\tau_{CDP}} - \frac{P(z,\tau)}{\tau_{CDP} P_{sat}} \tag{4}$$

where $P_{sat}= E_{sat}/\tau_{CDP}$. The last equation represents the rate equation that describes the gain dynamic for interband only.

2.2 Integrated Gain Equation with Interband Effects

In the presence of intraband effects, there are two equations that describe the propagation through SOA [10].

$$\frac{\partial P(z,\tau)}{\partial z} = [g(1 - \varepsilon P) - \alpha]P(z,\tau) \tag{5}$$

$$\frac{\partial \varphi}{\partial z} = \frac{g}{2}(-\beta_{CDP} + \sum_x \varepsilon_x \beta_x P) \tag{6}$$

here, $\varepsilon = \varepsilon_{CH} + \varepsilon_{SHB}$ and is called gain compression, α is the internal loss, β_x is linewidth enhancement factor such that $\beta_{CDP} > \beta_{CH}, \beta_{SHB}$ [10]. These equations describe the signal power (P) and total phase (φ) for a pulse passing through SOA under fast dynamic (intraband effects).

Taking into account the condition $\alpha \ll g$ that is valid in practice and setting $(\alpha = 0)$ [11]. The last equations with interband effect only may be rewritten as

$$\frac{\partial P(z,\tau)}{\partial z} = gP(z,\tau) \tag{7}$$

$$\frac{\partial \varphi}{\partial z} = -\beta_{CDP}\frac{g}{2} \tag{8}$$

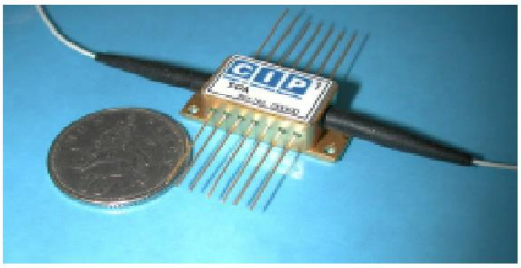
The solution of equation 7 is

$$P_{out}(\tau) = P_{in}(\tau)exp[h(\tau)] \tag{9}$$

Where $P_{in}(\tau)$ and $P_{out}(\tau)$ are the power of the input and output pulses. The integrated function $\big(h(\tau)\big)$ is defined by

$$h(\tau) = \int_0^L g(z,t)\partial z = \frac{\partial P}{P} \tag{10}$$

integrated gain that at each point of the pulse profile is represented by $h(\tau)$ and L is length of active region, the below figure present packaged and schematic SOA



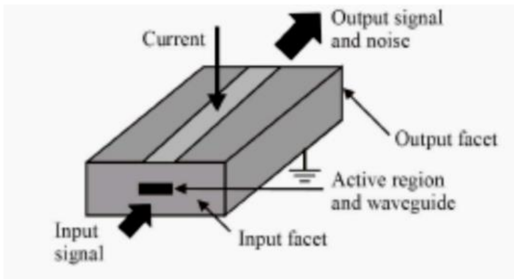


Figure 1: SOA fully packaged (left), and SOA schematic (right) [12].

total phase change for the pulse propagating through SOA may be obtained by integrating equation 8

$$\varphi_{out}(\tau) - \varphi_{in}(\tau) = -\frac{1}{2}\beta_{CDP}h(\tau) \tag{11}$$

where $\varphi_{in}(\tau)$ and $\varphi_{out}(\tau)$ are the phase of the input and output pulses . A time dependent phase change leads to a variation in optical frequency of the pulse. The instantaneous variation in frequency, known as the frequency chirp (Δv) is given by

$$\Delta v(\tau) = -\frac{1}{2\pi}\frac{d\varphi}{d\tau} = \frac{\alpha}{4\pi}\frac{dh}{d\tau} \tag{12}$$

To find the integrated gain equation needed for calculating output power, phase, and chirp, then equation 4 is integrated over the amplifier length and use $\partial P = gP\, \partial z$, yields

$$\frac{\partial}{\partial \tau} h(\tau) = \frac{h_0 - h(\tau)}{\tau_c} - \frac{P_{in}(\exp(h(\tau)) - 1)}{E_{sat}} \tag{13}$$

where $h_0 = g_0 L$ that is sometimes denoted G_0 represent the value of the integrated gain at $(\tau = 0)$. The last equation does not take into account ultrafast dynamics but only slow dynamics represented by interband effect. Equation 13 is solved numerically to obtain $h(\tau)$. After that, it possible to find phase, chirp, and gain by using equations 11, 12, and 13 respectively. The general form of the input power that it used in this work is [13]

$$p_{in}(\tau) = \frac{E_{in}}{\tau_0 \sqrt{\pi}} e^{\frac{\tau^{2n}}{\tau_0^{2n}}} \tag{14}$$

where n is a positive number that controls the degree of edge sharpness. For $n = 1$, the pulse is Gaussian while $n = 2$, the pulse is super Gaussian and τ_0 is the half width (at $1/e$ intensity point). In practice, it is customary to use the full width at half maximum (FWHM) denoted in almost (τ_p) in place of τ_0 . The two are related as $\tau_p \approx 1.665\,\tau_0$.
To consider intraband process, equation 1 must be modified in the form

$$\frac{\partial g}{\partial \tau} = \frac{g_0 - g}{\tau_{CDP}} - \frac{g}{E_{sat}} \frac{P}{1 + \varepsilon P} \tag{15}$$

Taking into account that the suggested gain (g) occurring in equation 15 that is $\left(g/\left(1 + \varepsilon P(z,\tau)\right)\right)$ [14]. Then, the equation 7 that describe power change in SOA may be written $\partial P(z,\tau)/\partial z = g\, P/(1 + \varepsilon P)$ at neglecting α and using approximation $1 + \varepsilon P \approx 1/1 - \varepsilon P)$ from Taylor series. So, the equation that describes power change in SOA under intraband effects consideration can be reformulated as

$$\frac{\partial P}{\partial z} = \frac{gP}{1 + \varepsilon P}$$

Now, taking the integration over SOA length of equation 15, yields

$$\frac{\partial}{\partial \tau} \int_0^L g dz = \frac{\int_0^L g_0 dz}{\tau_{CDP}} - \frac{1}{\tau_{CDP}} \int_0^L g dz - \frac{1}{E_{sat}} \int_0^L \frac{gP}{1 + \varepsilon P} \partial z \tag{16}$$

For calculating $h(\tau)$, substitute about $gP\partial z$ occurring in left hand side (third term) from equation 16 and using $\int_{P_{in}}^{P_{out}} \partial P/P = h(\tau)$ instead of $\int_0^L g dz$ occurring in left hand side (second term). Thereafter, the above equation will be written in new formula

$$\frac{\partial h(\tau)}{\partial \tau} = \frac{1}{\{1 + \epsilon P_{in} \exp(h(\tau))\}} \left[\frac{h_0}{\tau_{CDP}} - \frac{1}{\tau_{CDP}} h(\tau) - \varepsilon \left\{ \exp\left(h(\tau)\right) - 1 \right\} \frac{dP_{in}}{d\tau} - \left\{ P_{in} \exp\left(h(\tau)\right) - 1 \right\} \left(\frac{\varepsilon}{\tau_{CDP}} + \frac{1}{E_{sat}} \right) \right] \tag{17}$$

Equation 17 represents integrated gain equation in presence of intraband effects. It is solved numerically by suitable method, fourth order Runge-Kutta method is used in this work. The clear compression gain and phase ensure that there is importance to take into account the intraband effects included in $h(\tau)$.

3. Results and Discussion

3.1 Without ultrafast dynamics

The parameters that used in our simulation are : saturation energy $(E_{sat} = 5.68 pJ)$, $(\tau_{CDP} = 200 ps)$, $(\varepsilon_{SHB} = 0.35W^{-1})$, $(\varepsilon_{CH} = 0.7W^{-1})$, $(L = 1mm)$, and $(\beta_{CDP} = 5)$ [10, 15].

Figure 2 shows the material gain in dB and m^{-1} respectively versus normalized time τ/τ_p at using equations 4 and 8. It does not takes into account the ultrafast dynamics parameters represented by CH and SHB. There is no compression gain and phase. This behavior is expected because there no contribution from ultrafast dynamics parameters in the used equation. As a result, the recovery gain was large in both cases (small and large width pulses).

Even if short pulses were presence, the gain compression is not occurring, so, the recovery phase is long and there is no positive chirp. The causes of these are relevant with wave propagation equations 7 and 8 that neglect the contributions of gain compression factor represented by CH and SHB. These considerations interpret why, the compression factors must be taken into account in the equations that specify wave propagated in SOA. The obtained results were in good agreement with [16, 2]. Figure 5 (right) shows the chirp versus normalized time τ/τ_p at using equation 12. This equation is used for both two cases (inerband and intraband effect) but the difference between them is the integrated gain $h(\tau)$ that may be used as: without and with ultrafast dynamics equations 13 and 17 respectively.

3.2 With ultrafast dynamics

Figure 3 shows the material gain in dB and m^{-1} and phase versus τ/τ_p at using equations 17 and 11. These take into account the ultrafast dynamics that includes CH and SHB. It may be noted that there is a compression gain for small pulse width. As a result, the recovery gain will be short and shorter depending on pulses width.

Figure 4 shows the material gain in dB and m^{-1} and phase versus τ/τ_p at using equation 17 and 11. The recovery gain and phase depend on the pulse width. When the pulse is large $(10ps)$, there is no effect of ultrafast dynamic and as a result, the recovery is large. The ultrafast dynamic starts to appear when the pulse width small and when reaches to femtosecond range $(1ps)$, the sense of ultrafast dynamics is clear intesively and therefore, the gain and phase compression appears exclusively.

Figure 5 (left) shows the chirp for different pulse width versus τ/τ_p. In case of large pulse width, there is no positive chirp while in the case of small pulse width then there is positive chirp in addition to negative chirp as shown in Figure 5(right).

These results may be interpreted as, the presence of the ultrafast dynamics parameters and when the pulse width is large then, the negative chirp will be produced only while the presence of the ultrafast dynamics parameters and short pulse width (approaches from femtosecond range), positive chirp will be produced in addition to the negative. In other word, if the pulse width is large, the chirp is more positive and becomes positive in the end of the leading edge and this is because the effect of intraband processes which reduce the self phase modulation on the pulse.

4. Conclusion

The ultrafast dynamics effects start in appearance when the pulses width decreases more and more to reach within the femtosecond range. The recovery gain and phase also decrease depended on pulse width. The use of integrated gain equation that includes ultrafast dynamics parameters do not affect on recovery gain or phase as if the mentioned parameters is not exist in equation. The effect starts to be clear in the case use the integrated gain equation when the pulse width be small. At femtosecond range, the effect of recovery is so short.

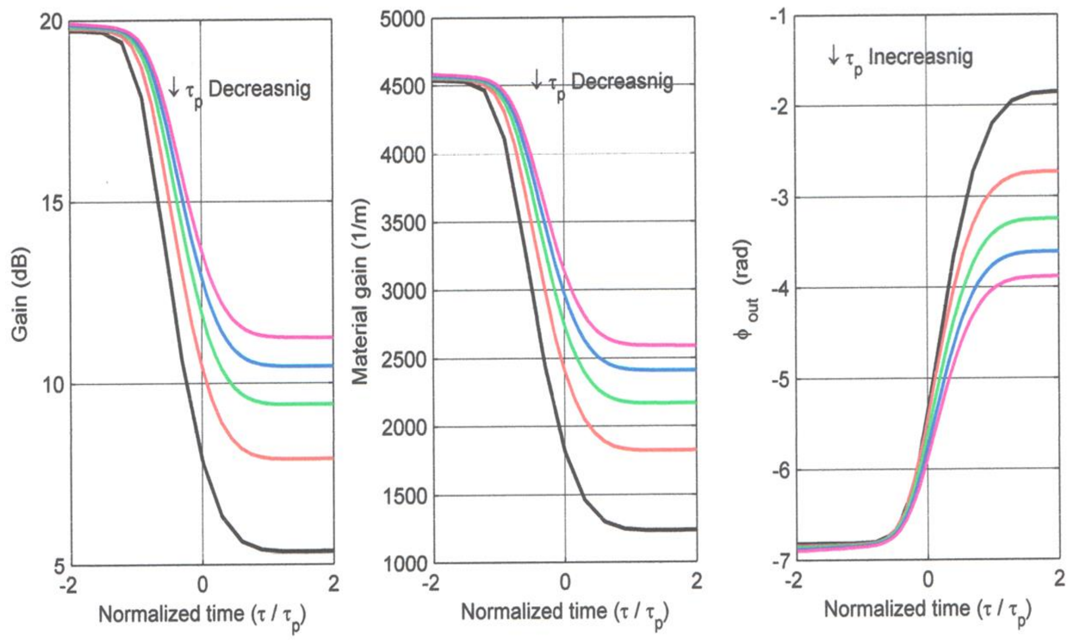


Figure 2: Gain in dB (left) , in m^{-1} (middle) , and phase shift versus normalized time under interband effect only for different pulses width, $G_0 = 25dB$. τ_p in the figures refers to the pulses width.

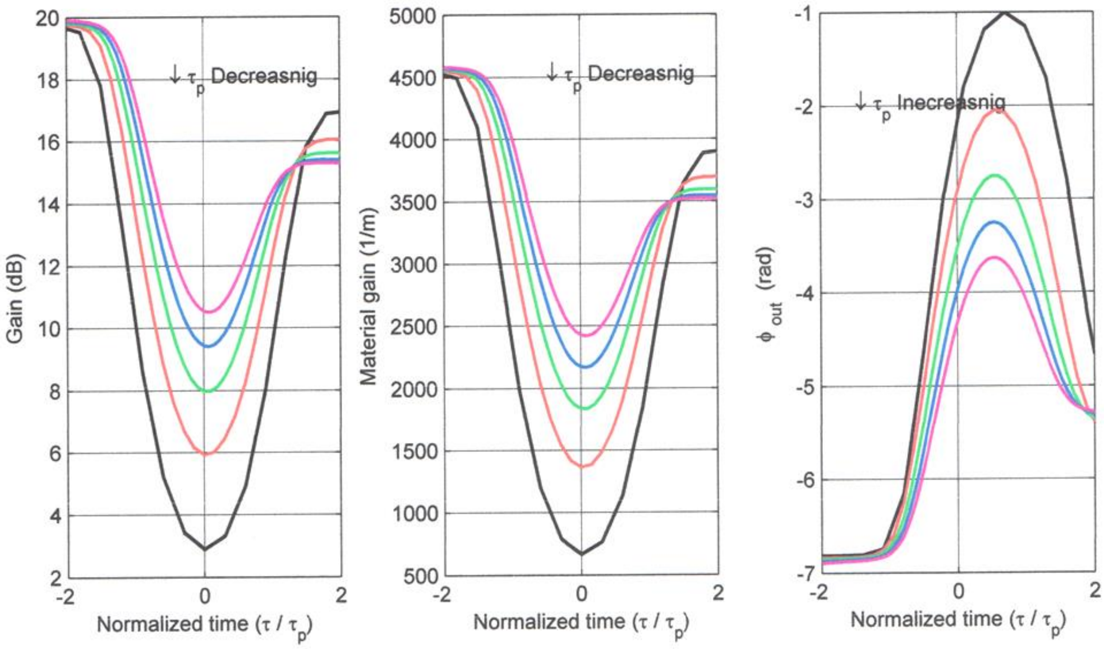


Figure 3: Gain in dB (left) , in m^{-1} (middle) , and phase shift versus normalized time under intraband Effects (ultrafast dynamics) presented by CH and SHB are taken into account for pulses width $\tau_p = 0.5, 1, 1.5, 2, 2.5\ ps$, small signal gain is $(G_0 = 25dB)$.

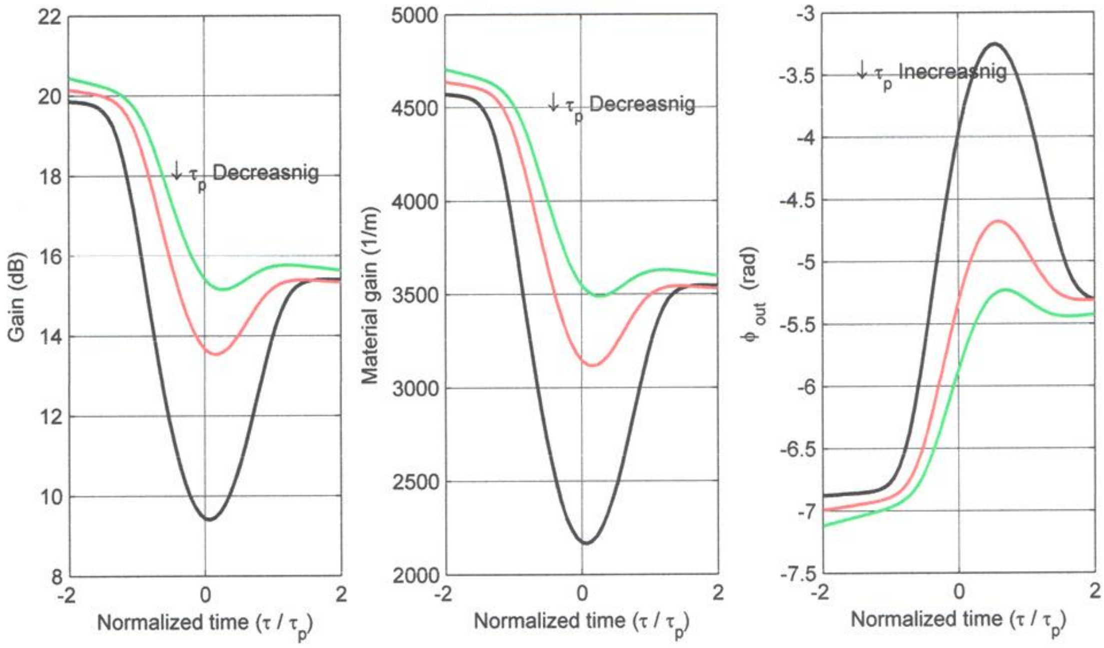


Figure 4: Gain in dB (left) , in m^{-1} (middle) , and phase shift versus normalized time under intraband Effects (ultrafast dynamics) like (CH and SHB) are taken into account for pulses width $\tau_p = 1, 4, 7\ ps$, small signal gain is $(G_0 = 25dB)$.

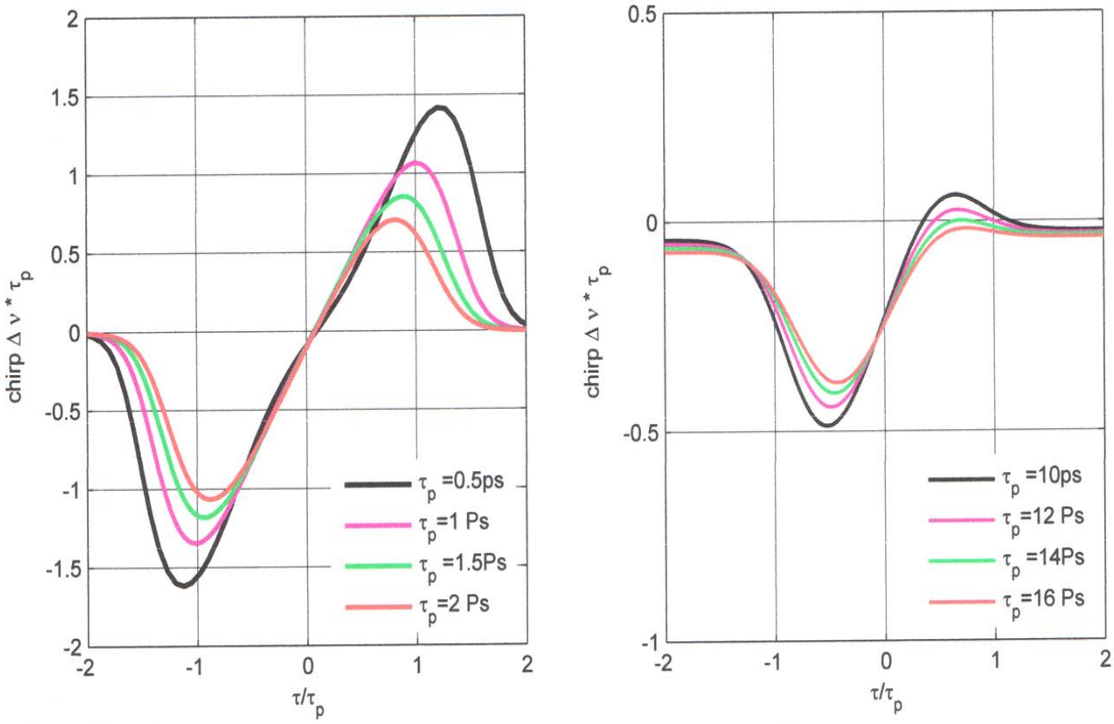


Figure 5: (left) frequency chirp versus normalized time under intraband Effects (ultrafast dynamics) like (CH and SHB) are taken into account for pulses width $\tau_p = 0.5, 1, 1.5, 2\ ps$ and (right) for $\tau_p = 10, 12, 14, 16\ ps$. Intraband effects are taken into account , small signal gain is ($G_0 = 25dB$).

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