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Optimization of Pump Current for Pulse Distortionless Amplification in Quantum Well Amplifiers

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Abstract-In this paper we have developed a novel method to optimize pump currents for pulse distortionless amplification in a quantum well semiconductor optical amplifier (QW-SOA). The relationship between the pump current and the maximum distance along the amplifier cavity where the input Gaussian pulse can be amplified without any distortion is proposed. For a given cavity length we have obtained an optimum pump current where the input pulse obtains high gain distortionless amplification (e.g. for a $750\mu m$ long QW-SOA, the maximum gain of distortionless amplification is $18.7dB$ when a Gaussian pulse with $1mw$ peak power and $2ps$ pulse width is applied). Also, an expression which indicates the optimum pump current as a function of the input signal peak power is presented. The dependence of the optimized pump current obtained by the proposed method on the input pulse width is analyzed and it was found that as the input pulse width increases, the optimized pump current decreases. The suitability of optimized pump current for pulse trains is discussed and it was confirmed that the pump current optimization method is suitable for the distortionless amplification of pulse trains.

***Index items*-Pump current optimization, distortionless pulse amplification, quantum well semiconductor optical amplifiers**

I. Introduction

Quantum well semiconductor optical amplifiers (QW-SOAs) have been considered to be potential candidates in the high-speed optical fibre communication system and all-optical signal processing due to wide operational bandwidth, small size and energy-efficient [1-5]. However, QW-SOAs suffer from the gain saturation, which leads to distortion when ultra-short Gaussian pulse is amplified. Distortions of pulse amplification induced by the gain saturation in SOAs have been theoretically and experimentally studied [6-10]. Some methods have been proposed to improve the gain dynamics, including optimizing the structure of SOAs [11-12], injecting the assist light [13] and doping the barrier region in QWs [14]. These measures can effectively accelerate the gain recovery of SOAs rather than totally remove the distortion of amplified output pulse.

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When a peak temporal shift exists in an amplified pulse the time interval between two peaks of the adjacent amplified pulses varies. This variation needs to be eliminated in order for the amplifier to handle the synchronous clock signal in the optical signal processing and optical fibre communication system [15-18]. It is expected that an optical amplifier amplifies the input pulse with high gain while producing no peak temporal shift. Experimental results have shown either distortionless pulse amplification or temporal pulse distortion which depends on the amplifier's construction and operating conditions. The pump current is one important factor that determines the amplifier gain and influences the distortion of amplified pulse [2]. The pump current needs to be adjusted for distortionless pulse amplification in SOA. This is because if the pump current is too high, the amplified output pulse suffers from distortion and if it is too low the amplifier gain reduces, which limits the amplification ability of the SOA. Therefore it is necessary to understand the relationship between the pump current and the amplified output pulse distortion in order to realize high gain distortionless pulse amplification in QW-SOAs. To best of our knowledge there has not been any report on using a suitable pump current to avoid distortion in an optical amplifier and also the relationship between the pump current and the peak temporal shift of the amplified pulse has not been analyzed using the detailed expression.

In this paper, we proposed a novel method of optimizing pump current for distortionless amplification. The relationship between the pump current and the maximum distance along the amplifier cavity where the amplified pulse output has no peak temporal shift is presented. The proposed formula can be employed to optimize the pump current for a given amplifier length to avoid the distortion caused by gain saturation. An optimized pump current expression is presented for the general application of input signals with different powers. The relation between the optimized pump current and the input pulse width is analyzed and the suitability of using this optimization method for pulse trains amplification is also discussed. The method provides a useful guidance for optimizing the pump current in the practical application of QW-SOAs.

II. Dynamic model of QW-SOAs

In QW-SOAs, the optical signal propagation can be modelled by the photon density and carrier density rate equations. The photon density rate equations for the input optical signal and the spontaneous emission can be expressed as [10, 19]

$$(\frac{\partial}{\partial t} \pm \upsilon_g \frac{\partial}{\partial z})S_{\nu_i}^{\pm} = \upsilon_g S_{\nu_i}^{\pm}(\Gamma g(N,\nu_i) - \alpha_0) \quad (1)$$

$$(\frac{\partial}{\partial t} \pm \upsilon_g \frac{\partial}{\partial z})E_{\nu_j}^{\pm} = \upsilon_g E_{\nu_j}^{\pm}(\Gamma g(N,\nu_j) - \alpha_0) + R_{sp}(\nu_j, N) \quad (2)$$

where, υ_g is the group velocity, $S_{\nu_i}^{+}$ and $S_{\nu i}^{-}$ are the forward and backward signals photon densities at the frequencies of the incident optical signal, $E_{\nu_j}^{+}$ and $E_{\nu_j}^{-}$ are the forward and backward photon densities due to the amplified spontaneous emission, ν_i and ν_j are the frequencies of the incident optical signal and the spontaneous emission of the optical amplifier, respectively, N is the carrier density, Γ is the optical confinement factor, g is the material gain, α_0 is the waveguide loss and R_{sp} is the spontaneous emission rate.

Both the amplified signal and the noise power generated by the spontaneous emission take part in draining the carrier density hence, the carrier density rate equation can be written as [10]:

$$\frac{dN}{dt} = \frac{I}{qV} - \Gamma \upsilon_g \sum_{\nu_i} g(N,\nu_i)(S_{\nu_i}^{+} + S_{\nu_i}^{-})$$
$$- \Gamma \upsilon_g \sum_{\nu_j} g(N,\nu_j)(E_{\nu_j}^{+} + E_{\nu_j}^{-}) - AN - BN^2 - CN^3 \quad (3)$$

where, I is the injected current, q is the electron charge, V is the active region volume, A, B, and C are linear recombination coefficient, Bi-molecular recombination coefficient and Auger recombination coefficient, respectively. The material gain 'g' used in both the photon and carrier densities' rate equations can be written as [19]:

$$g(\omega) = \frac{q^2 \pi}{n_r c_0 \varepsilon_0 m_0^2 \omega L_z} \sum_{\eta=\uparrow,\downarrow} \sum_{\sigma=U,L} \sum_{n,m} \int \left| \hat{e} \cdot M_{nm}^{\sigma\eta} \right|^2$$
$$\times \frac{(f_n^c(k_t) - f_{\sigma m}^v(k_t))(\hbar\gamma)}{4(E_{\sigma,nm}^{cv}(k_t) - \hbar\omega)^2 + (\hbar\gamma)^2} \frac{k_t dk_t}{\pi^2} \quad (4)$$

where,

$$E_{\sigma,nm}^{cv}(k_t) = E_n^c(k_t) - E_{\sigma,m}^v(k_t) \quad (5)$$

$$f_n^c(k_t) = 1/(1 + \exp(\frac{E_n^c(k_t) - E_{fc}}{K_B T})) \quad (6)$$

$$f_{\sigma m}^v(k_t) = 1/(1 + \exp(\frac{E_{\sigma,m}^{\upsilon}(k_t) - E_{fv}}{K_B T})) \quad (7)$$

In the above equations, n_r is the ground refractive index, c_0 is the speed of light in free space, m_0 is the electron rest mass in free space, ε_0 and γ are the permittivity in free space and the linewidth of the Lorentzian function, respectively, L_z is the well width, $\hbar$ is the Plank constant divided by 2π, $\hat{e}$ is the polarization vector of the optical electric field, $M_{nm}^{\eta\sigma}$ are the momentum matrix elements for the material gain, E_{fc} and E_{fv} are the quasi-Fermi levels in the conduction and valence bands, respectively, K_B is the Boltzmann constant, $E_n^c(k_t)$ and $E_{\sigma,m}^{\upsilon}(k_t)$ are the band structure for the conduction and valence bands, which are obtained by solving the Schrodinger equations [20].

The spontaneous emission rate in Eq. (2) is

$$R_{sp} = \int r_{sp}(\hbar\omega) d(\hbar\omega) \quad (8)$$

where, $r_{sp}(\hbar\omega)$ is the spontaneous emission spectrum, which is given by [21]:

$$r_{sp}(\hbar\omega) = \frac{q^2 n_r \omega}{\pi\hbar c^3 \varepsilon_0 m_0^2 L_z} \sum_{\eta=\uparrow,\downarrow} \sum_{\sigma=U,L} \sum_{n,m} \int \left| M_{sp}(k_t) \right|^2$$
$$\times \frac{(f_n^c(k_t) - f_{\sigma m}^v(k_t))(\hbar\gamma)}{4(E_{\sigma,nm}^{cv}(k_t) - \hbar\omega)^2 + (\hbar\gamma)^2} \frac{k_t dk_t}{\pi^2} \quad (9)$$

$M_{sp}(k_t)$ is the momentum matrix elements for the spontaneous emission. Carrier heating effect will impose a more significant distortion on the amplified pulse. The carrier temperature change induced by carrier heating in QW-SOAs can be described by the following temperature dynamic expression [22-23]

$$\frac{dT}{dt} = \frac{1}{\partial U / \partial T}(\frac{dU}{dt} - \frac{\partial U}{\partial N}\frac{dN}{dt}) - \frac{T - T_0}{\tau} \quad (10)$$

where, U is the total carrier energy density, τ is the electron phonon interaction time and T_0 is the lattice temperature. The total carrier energy density (U) is the sum of the carrier energy densities of the conduction (U_C) and valance (U_V) bands as [24]:

$$U = U_C + U_V \quad (11)$$

where

$$U_C = \sum_n \frac{1}{\pi L_z} \int_0^{+\infty} \frac{E_n^c(k_t) - E_c}{1 + \exp((E_n^c(k_t) - E_{fc}) / K_B T)} k_t dk_t \quad (12)$$

$$U_V = \sum_m \sum_{HH,LH,SO} \frac{1}{\pi L_z} \int_0^{+\infty} \frac{E_v - E_m^v(k_t)}{1 + \exp((E_{fv} - E_m^v(k_t)) / K_B T)} k_t dk_t \quad (13)$$

E_c and E_v are the band edges of the conduction and valence bands. $\partial U / \partial T$ and $\partial U / \partial N$ in the temperature dynamics expression can be calculated through Eqs. (11) to (13). $\frac{dU}{dt}$ can be calculated by the rate of energy change induced by the simulated emission, spontaneous emission and free carrier absorption.

$$\frac{dU}{dt} = -\upsilon_g \sum_i (h\nu_i - E_g(N)) g(N,\nu_i)(S_{\nu_i}^{+} + S_{\nu_i}^{-}) +$$
$$\upsilon_g \alpha_{FC} N \sum_i h\nu_i (S_{\nu_i}^{+} + S_{\nu_i}^{-}) -$$
$$\upsilon_g \sum_j (h\nu_j - E_g(N)) g(N,\nu_j)(E_{\nu_j}^{+} + E_{\nu_j}^{-}) +$$
$$\upsilon_g \alpha_{FC} N \sum_j h\nu_j (E_{\nu_j}^{+} + E_{\nu_j}^{-}) \quad (14)$$

where, α_{FC} is the free carrier absorption coefficient.

III. Pump current optimization for distortionless pulse amplification

A. Gaussian pulse amplification in QW-SOAs

The unchirped Gaussian pulse power $P(t)$ at the input of the amplifier can be expressed as:

$$P(t) = P_{in} e^{-\frac{(t-t_0)^2}{2c^2}} \qquad (15)$$

where, P_{in} is the peak power of the input pulse, t_0 is the peak time of the Gaussian input pulse, c is the standard deviation and the full width at half maximum (FWHM) of the Gaussian pulse is given as:

$$t_f = 2.35482\, c \qquad (16)$$

The photon density S associated with the power $P(t)$ can be expressed as:

$$S = \frac{P(t)}{v_g DWh\nu_i} \qquad (17)$$

where, h is the Plank constant, D and W are the thickness and width of the active region. The input power $P(t)$ is converted into photon density at the input facet of the amplifier (i.e. at $t=0$ and $z=0$). The photon density propagates through the amplifier cavity according to the rate equations (1) and (2).

In the following analysis we assume the unchirped input Gaussian pulse is centered at $3ps$ with $2ps$ pulse width and $10mw$ peak power and the optical amplifier is a strained $In_{0.64}Ga_{0.36}As$ - $InGaAsP$ quantum well amplifier. Here, the input pulse power is comparable with the saturation power of the quantum well amplifier. The cavity length of the amplifier is $750\mu m$. The well and barrier widths are $4.5nm$ and $10nm$, respectively. The barrier with a bandgap wavelength $\lambda_g = 1.15\mu m$ is lattice-matched to the InP substrate. The other parameters used in our simulation are given in Table 1 and some of them are taken from [24].

Table 1
QW-SOA Modelling parameters [10, 19]

Symbol	Description	Value
n	Background refractive index	3.67
α_{FC}	Free carrier absorption cross-section	$0.5\times10^{-21}m^2$
Γ	Confinement factor	0.025
N_0	Transparent carrier density	$1.2\times10^{24}m^{-3}$
τ	Electron phonon interaction time	$1ps$
α_0	Waveguide loss	$1000m^{-1}$
A	Linear recombination	$2\times10^{8}s^{-1}$
B	Bi-molecular recombination	$6\times10^{-16}m^3s^{-1}$
C	Auger recombination	$8\times10^{-41}m^6s^{-1}$
W	SOA width	$1\mu m$
D	SOA thickness	$24.5nm$

Figure1 shows the evolution of the input pulse shape at different distances along the amplifier cavity when the input current is $300mA$. Figure 1 clearly shows that the amplified pulse becomes asymmetric due to the gain saturation. The leading edge obtains higher amplification than the tailing edge, which leads to the peak temporal shift. When the distance is approaching the length of the amplifier cavity, the peak temporal shift becomes larger. In general, there exists a maximum distance Z_m along the amplifier cavity where the amplified pulse waveform has no temporal shift (i.e. it is also centered at $3ps$). In this example, we have analyzed the amplified pulse waveforms at different distances and found that $Z_m = 300\mu m$ when the pump current is $300mA$.

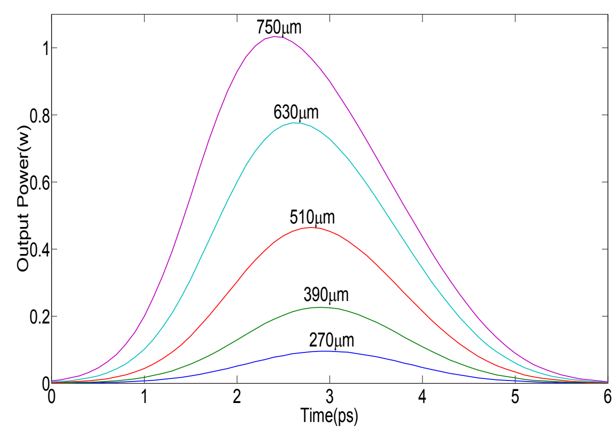

Fig. 1 Evolution of an unchirped Gaussian input pulse inside a quantum well semiconductor optical amplifier

B. Pump current relation function

The pump current determines the initial carrier density along the amplifier cavity before the optical signal amplification. The carrier density distribution determines the maximum distance along the amplifier cavity where the amplified pulse waveform has no temporal shift. In order to control the pump current for distortionless pulse amplification, we have obtained the following relationship between the pump current I and the maximum distance Z_m :

$$I = ae^{bZ_m} + ce^{dZ_m} \quad (0 < Z_m \le L, b \le 0, d \le 0) \qquad (18)$$

where, L is the length of the amplifier cavity, a , b , c and d are the coefficients of the above pump current formula and can be determined by the properties of QW-SOA and the input pulse. The curve fitting method is adopted to obtain these coefficients based on the above dynamic model of QW-SOAs. In order to make sure of the calculation accuracy and also save the computation time, we have obtained Z_m for 11 different values of the pump currents ranging from $50mA$ to $300mA$. Table 2 shows the simulation results.

Table 2
Data for the coefficient calculation

Group	Pump current I (mA)	Maximum distance Z_m (μm)
1	50	592.5
2	75	485.1

3	100	427.5
4	125	392.1
5	150	367.5
6	175	350.6
7	200	337.5
8	225	325.1
9	250	315
10	275	307.1
11	300	300

Since the relation between the pump current and the maximum distortionless distance along the amplifier cavity needs to be explored, the value of the pump current should satisfy the condition $L > Z_m$. Based on the data given in Table 2, the coefficients of Eq. (18) are obtained using the MatLAB curve fitting tool kit. Figure 2 and Table 3 show the fitting results. Figure 2 clearly indicates that the proposed Eq. (18) can give a good description of the relationship between the pump current and the maximum distortionless distance along the amplifier cavity.

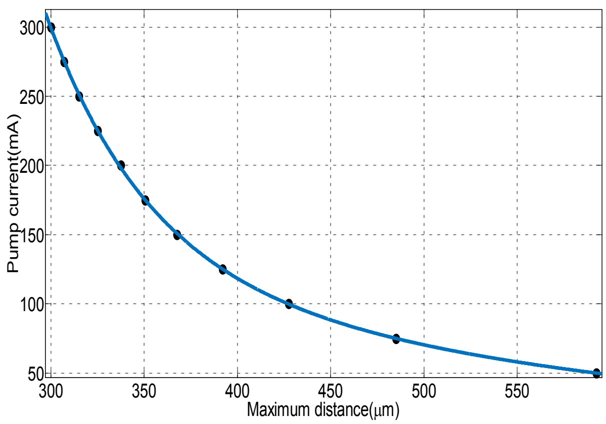

Fig. 2 Variations of the pump current with maximum distance Z_m.

Table 3
Coefficient values and fitting effect

Coefficients	Value	Fitting effect
a	4.422×10^4	
b	-0.01845	$\begin{pmatrix}\text{Goodnees of fit} \\ \text{R}-\text{square}=0.9999\end{pmatrix}$
c	324.5	
d	-0.003183	

C. Maximum pump current for Gaussian pulse distortionless amplification

Eq. (18) describes the relationship between the pump current and Z_m. Substituting $Z_m = L$ into Eq. (18), the maximum pump current I_m for pulse distortionless amplification can be expressed as:

$$I_m = ae^{bL} + ce^{dL} \quad (19)$$

Based on the coefficients in Table 3, the maximum pump current for Gaussian pulse distortionless amplification is $29.86mA$. In order to verity the validity of this method, I_m is taken as the pump current of the amplifier. The amplified pulse output of the amplifier is shown in Fig. 3.

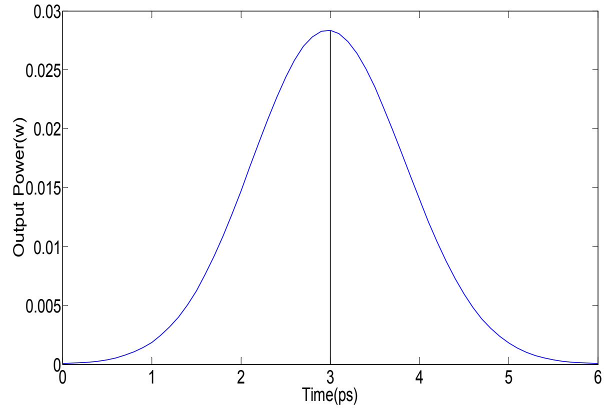

Fig. 3 Amplified output pulse at the pump current I_m

From this figure, we can conclude that the amplified pulse is centered at $3ps$ when the pump current is $29.86mA$. Let us define the peak temporal shift sensitivity parameter γ as:

$$\gamma = \frac{|t_p - t_0|}{t_0} \times 100\% \quad (20)$$

where, t_p is the peak time of the amplified output pulse waveform. Figure 4 shows variations of γ with the pump current I in the vicinity of the optimized pump current $I_m = 29.86mA$. As the figure clearly shows when $28.5mA < I \le I_m$ there is no temporal shift. As I increases within $I_m < I \le 31mA$, γ increases to less than 2.2%. This simulation result shows that the above proposed method can be used to optimize the amplifier pump current so that a distortionless amplified output pulse can be obtained with minimal sensitivity.

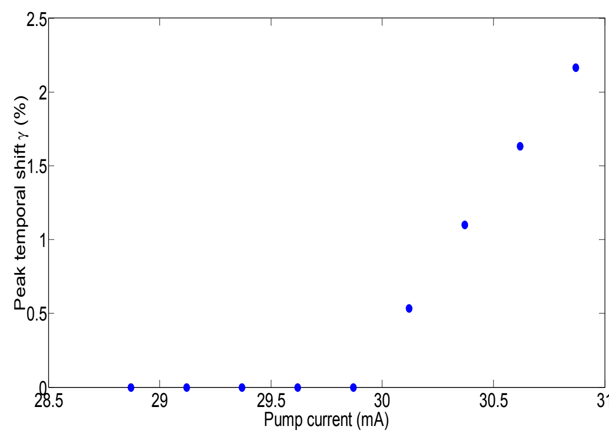

Fig. 4 Variations of γ in the vicinity of $I_m = 29.86mA$

Furthermore, using the above method, we have obtained the optimized pump currents and amplifier gains for different applied input peak powers ranging from 1mW to 10mW. Table 4 lists the values of optimized pump currents and the corresponding gain values for distortionless amplification at different input peak powers.

Table 4
Optimized pump currents and amplifier gains at different input peak powers

Peak Power (mw)	Optimized pump current(mA)	Gain(dB)
1	123.61	18.74
2	94.65	16.71
3	75.82	14.94
4	63.97	13.47
5	54.73	12.04
6	47.47	10.64
7	41.69	9.28
8	37.50	8.11
9	32.54	6.48
10	29.86	4.53

Based on the data in Table 4, we have found the following equation, through simulation, which expresses the optimized pump current I_m as a function of the applied peak input power P_{in} :

$$I_m = 82.92 \times e^{-0.6372 P_{in}} + 89.13 \times e^{-0.111 P_{in}} \quad (21)$$

Plots of Eq. (21), solid curve, and the data given in Table-4, dotted curve, are shown in Fig.5. The calculated $R-square$ of the fitting is 0.9999 , which implies Eq. (21) is a very good description of the data listed in Table-4.

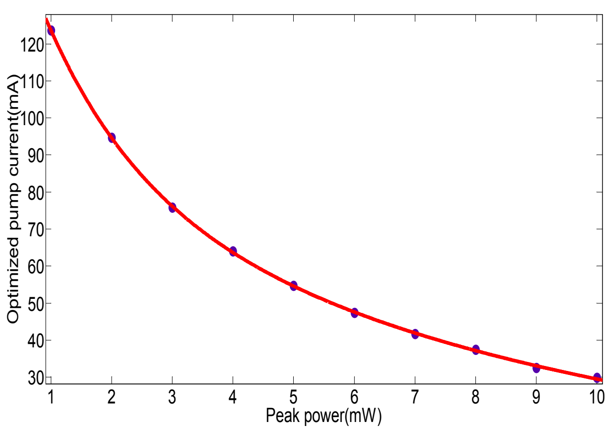

Fig. 5 Optimized pump current versus peak power P_{in} .

In the following, we explore the dependence of optimized pump current on the input pulse width. The input pulses having the peak power $5mw$ with different pulse widths ranging from $1ps$ to $3ps$ are applied to the QW-SOA and the optimized pump currents are obtained based on the above optimization method. Figure 6 shows the optimized pump current versus input pulse width.

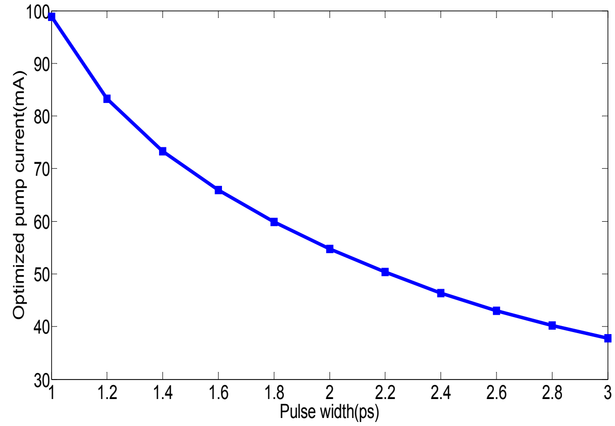

Fig. 6 Optimized pump current versus input pulse width

The figure shows that as the input pulse width increases, the optimized pump current decreases. This is because higher pulse width depletes more carrier density during the amplification process which results in a temporal shift in the pulse peak. Also, as Fig. 6 shows when the input pulse width is less than $1.6ps$, the optimized pump current increases rapidly, which indicates that for input pulses that $t_f \leq 1.6ps$ we can obtain high gain distortionless amplification.

IV. DISTORTIONLESS AMPLIFICATION OF PULSE TRAINS

In order to confirm that the proposed pump current optimization method can also be applied to pulse trains, we have applied the pump-probe technique described in [25] to investigate the gain recovery response of QW-SOAs. In doing so, a pump pulse which was centered at 3ps and had a peak power of 5mw and pulse width of 2ps was applied to the amplifier input. Then after a time delay $\Delta\tau$ the probe pulse which had similar waveform as the pump pulse but with peak power of 1mw was applied to the amplifier input. The pump current is $54.73mA$, which is the optimized value for the pump pulse (shown in Tab. 4). Figure 7 shows the gain recovery of the QW-SOA. The negative delay indicates that the probe pulse arrives before the pump pulse.

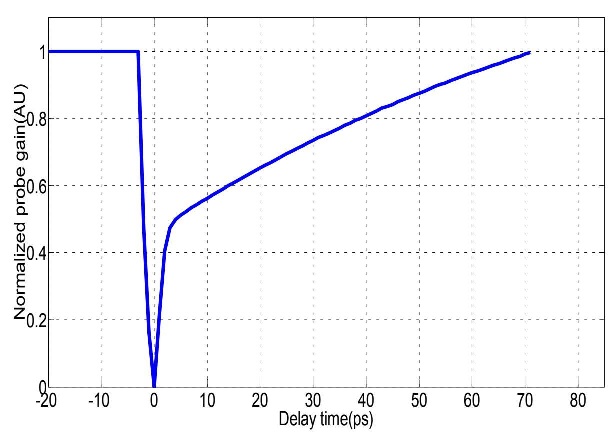

Fig. 7 Gain recovery of the QW-SOA

In Fig. 7, the normalized probe gain is defined by [25]

$$\overline{G} = \frac{G - G_{SAT}}{G_F - G_{SAT}} \tag{22}$$

where, G_{SAT} is the saturated gain, G_F is the gain at the full recovery. From this figure, it can be seen that the gain response of the QW-SOA includes the fast recovery process (around $3ps$) induced by carrier heating and the slow recovery process. The gain recovery time (i.e. the time needed for the amplifier gain to recover to 90% of its full recovery) for this amplifier was 53ps. We have applied to the amplifier input a 14GHz pulse train (where each pulse had the same waveform and peak power value as the above mentioned pump pulse) with the optimized pump current of $54.73mA$. The time interval between two adjacent pulses of the pulse train is more than the gain recovery time. Figure 8 shows the amplified pulse train waveform. As the figure clearly shows no distortion is observed in the amplified output waveform and the peak of each pulse in the pulse train remains centered at $3ps$. Also, all amplified output pulses have the same magnitude.

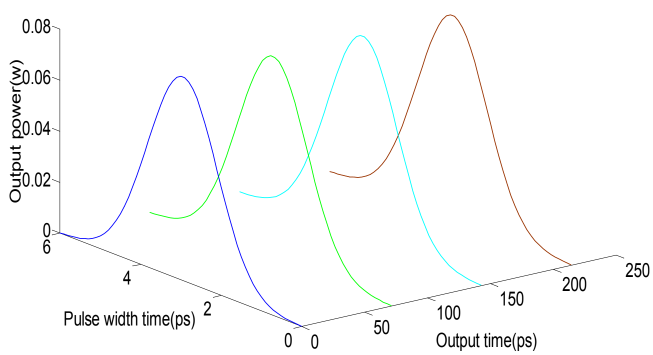

Fig. 8 A 14 GHz pulse train amplification at the optimized pump current.

Figure 9 shows the amplified output pulse train for a 28 GHz pulse train (having the same parameters as those of 14GHz pulse train). In this case, the time interval between two adjacent pulses is less than the gain recovery time. Again, the amplified output waveform is distortionless and each pulse peak is centered at 3ps however, a gradual reduction in the magnitude of each amplified pulse has been observed which is due to the slow gain recovery. Based on the results shown in Figs. 8 and 9, it can be concluded that the above pump current optimization method can also be applied to pulse train to obtain distortionless amplification.

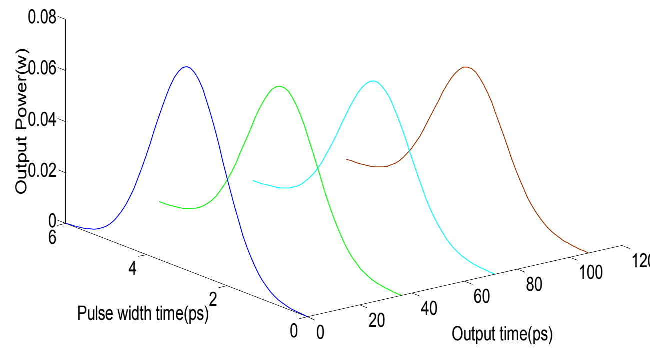

Fig. 9 Pulse trains amplification with the optimized pump current at $28GHz$

IV Conclusions

This paper presents a novel method of controlling pump current for distortionless amplification in QW-SOAs. A formula which relates the amplifier pump current with the maximum distance along the amplifier cavity where the amplified pulse is distortionless (i.e. Z_m) is proposed. For a given QW-SOA length, the formula can be used to obtain the optimum amplifier pump current. Also a formula is proposed which expresses the optimum pump current as a function of the input signal power. Variations of the optimized pump current with the input pulse width are explained. Also, the distortionless amplification of pulse trains using the optimised pump current is discussed. This method can provide an effective guidance for choosing a suitable pump current to realize the distortionless amplification in the practical application of QW-SOAs.

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