Optical and Quantum Electronics **29** *(1997) 627–638*

Effect of gain switching frequency on ultrashort pulse generation from laser diodes

MUHİTTİN SAYIN, M. S. ÖZYAZICI
Electrical and Electronics Engineering Department, University of Gaziantep, 27310 Gaziantep, Turkey

Received 5 July 1995; revised 29 October 1996; accepted 9 January 1997

In this work, the effects of gain switching frequency on ultrashort pulse generation are investigated using a model based on the multi-mode rate equations. In addition to the commonly used laser diode parameters, the key parameters corresponding to the different laser diode materials and structures are included in the model. Effects of some laser diode parameters, and d.c. and RF drive conditions on the full width at half-maximum (FWHM) of gain switched pulses are investigated for the 1–15 GHz gain switching frequency range. Multi-pulse generation and the cut-off frequency of gain switching are also determined for this frequency range. It is found that the FWHM of pulses decrease as the RF current is increased, at a constant frequency. However, the FWHM of pulses either decrease or increase as the d.c. bias is increased, depending especially on the gain compression and gain peak. As the frequency is increased, pulse widths start to decrease or increase depending on the laser diode parameters. The FWHM of pulses for shorter cavity lasers are found to be almost insensitive to the frequency. Among the parameters affecting the multi-pulse generation and cut-off, gain compression, gain constant, and d.c. and RF current amplitudes are found to be the most effective. All calculations are also carried out using single-mode rate equations and results of multi-mode and single-mode solutions are compared.

1. Introduction

Gain switching is known to be the simplest of the ultrashort pulse generation schemes, such as active and passive mode-locking, as no external cavity or careful alignment are required [1]. In this method, the gain of the laser diode is modulated by an input RF signal which results in a train of pulses at a repetition rate which is exactly the same as the frequency of the input RF signal. Gain switching pulses are essentially the first peaks of the relaxation oscillations.

A wide range of modulation frequencies can be used in gain switching, unlike in mode-locking. It has been shown that multiple pulses due to relaxation oscillations occur if the modulation frequency is too low [2, 3]. By increasing the frequency, the number of relaxation spikes appearing at the output decreases until eventually a single pulse per modulation period is achieved. This dependence on the frequency has been experimentally

0306–8919

observed in [3]. But the frequency cannot be increased above a certain value known as the 'cut-off frequency' of gain switching, after which either spontaneous emission due to d.c. bias is modulated or repetitive pulses do not have a regular shape because gain cannot follow the RF current. This cut-off frequency is conventionally defined in [3] and is different from the usual cut-off for cases of small signal modulation with d.c. bias above the threshold. It has been indicated that the high frequency gain switching characteristics of semiconductor lasers are directly related to their high-speed modulation characteristics which depend mainly on the photon lifetime and d.c. bias [4]. The same conclusion was reached in [5] for the limits of output pulse duration, which were found to be insensitive to the duration of the input electrical pulses. According to these, laser diodes with shorter photon lifetime and higher d.c. bias can be used in high frequency gain switching of laser diodes [2]. Calculations carried out in [3] show that the pulse widths increase as the frequency is increased. Conversely, theoretical and experimental results given in [6, 7] indicate that the pulse widths decrease as the frequency is increased. It has been experimentally shown that the pulse widths do not change so much in the frequency range from 0.5 to 2.5 GHz if the RF current level is adjusted to give the same average output power at each frequency [8]. Although the models used in [3, 6, 7] are similar, the results are very different, because the results given in [6, 7] are for InGaAsP lasers and those given in [3] are for AlGaAs lasers.

In this work, the parameters affecting the duration of the gain switched pulses, and the highest and the lowest ends of proper gain switching frequencies, are investigated. Unlike the previous works [3, 6, 7], confinement factor, photon lifetime and spontaneous emission factor are included in a form that can be used in the modelling of laser diodes with different structures and materials. Another difference is the form of radiative recombination, which is taken as carrier density dependent [9, 10]. With the help of these modified rate equations, it is possible to model gain switched ultrashort pulse generation from any bulk semiconductor laser (i.e. except DFB, DBR, MQW etc. devices). In addition to simulations with multi-mode rate equations, the calculations are also carried out using single-mode rate equations, even if the laser diode operates in multi-mode. The comparison of single- and multi-mode solutions will indicate the validity of using single-mode rate equations for modelling multi-mode operating laser diodes [1]. It has been shown [11, 12] that single-mode rate equations including gain compression can be used to explain multi-mode operating laser dynamics up to ~ 15 GHz for small signal modulation.

The rate equations are numerically solved using the Runge–Kutta–Fehlberg method. The standard laser diode parameters are taken for a multi-mode InGaAsP ridge-waveguide laser operating at 1.3 μm.

2. Mathematical model

The multi-mode rate equations for electron density and photon density in the ith mode of gain switched laser diode can be written as:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{I}{qV} - \left(\frac{N}{\tau_{\mathrm{nr}}} + (B_0 - B_1 N)N^2 + CN^3\right) - \sum_{i=-M}^{M} S_i G_i \tag{1}$$

$$\frac{\mathrm{d}S_i}{\mathrm{d}t} = \Gamma S_i G_i - \frac{S_i}{\tau_{\mathrm{p}}} + (B_0 - B_1 N)N^2 \beta_{\mathrm{s}} D_{\mathrm{si}}(\lambda) \tag{2}$$

where M is the mode number (total number of modes is $2M + 1$), N is the electron density (cm^{-3}), t is the time (s), I is the current applied to the laser diode (A), q is the electron charge (A s), V is the volume of active region (cm^3), τ_{nr} is the non-radiative lifetime (s), B_0 ($\mathrm{cm}^3\ \mathrm{s}^{-1}$) and B_1 ($\mathrm{cm}^6\ \mathrm{s}^{-1}$) are radiative recombination coefficients, C is the Auger recombination coefficient ($\mathrm{cm}^6\ \mathrm{s}^{-1}$), S_i is the photon density in the ith mode (cm^{-3}), G_i is the gain of the ith mode (s^{-1}), Γ is the confinement factor, τ_{p} is the photon lifetime (s), β_{s} is the spontaneous emission factor and $D_{\mathrm{si}}(\lambda)$ is the spontaneous emission spectrum in the form of a Lorentzian lineshape function. The laser diode output is represented by $S_{\mathrm{t}} = \sum S_i$.

The volume of the active region is $V = Lwd$ where L, w and d are the length, width and thickness of the active region (cm), respectively.

The gain of ith mode can be written as:

$$G_i = \frac{g_0}{1 + \varepsilon_{\mathrm{c}} \sum\limits_{i=-M}^{M} S_i} [D_i(\lambda)(N) - N_0] \tag{3}$$

where g_0 is the gain constant ($\mathrm{cm}^3\ \mathrm{s}^{-1}$), ε_{c} is the gain compression parameter (cm^3), $D_i(\lambda)$ is the gain spectrum in the form of a Lorentzian lineshape function and N_0 is the electron transparency (cm^{-3}).

Various phenomena such as spatial hole burning in both longitudinal and lateral directions and spectral hole burning give rise to gain saturation [13]. Although spatial hole burning is negligibly small in high-speed InGaAsP lasers, its relative importance increases as almost the square of the cavity width [13, 14]. As a laser diode of cavity width of 5 μm is considered in this work, spatial hole burning dominates spectral hole burning and the gain compression term of the form used can be considered in modelling of gain switched pulse generation from large cavity width laser diodes up to $\sim$15 GHz [1, 11, 12]. However, if the structure is chosen, for example, as a buried heterostructure with 1–2 μm active cavity width, then it will be necessary to take spectral hole burning into account. Gain compression depends on material and geometry [15], and the estimated value of ε_{c} typically lies in the range $3\text{–}6.7 \times 10^{-17}\ \mathrm{cm}^3$ for InGaAsP laser diodes [1, 16–19], and is of the order of $10^{-18}\ \mathrm{cm}^3$ for GaAs laser diodes [17].

The confinement factor in terms of laser diode parameters is taken as:

$$\Gamma \cong \Gamma_{\mathrm{L}} \left(\frac{\left[\frac{2\pi}{\lambda_0} d \sqrt{(\eta_{\mathrm{a}}^2 - \eta_{\mathrm{c}}^2)} \right]^2}{2 + \left[\frac{2\pi}{\lambda_0} d \sqrt{(\eta_{\mathrm{a}}^2 - \eta_{\mathrm{c}}^2)} \right]^2} \right) \tag{4}$$

where Γ_{L} is the laser diode structure-dependent lateral confinement factor found from the solution of wave equations in the lateral direction, λ_0 is the central mode wavelength (cm), and η_{a} and η_{c} are refractive indices of the active region and cladding, respectively. The term inside the large parenthesis corresponds to the transverse confinement factor found from the solution of the wave equations using the transverse boundary conditions [10, 20].

Photon lifetime is written in terms of the mirror and internal losses as:

$$\begin{aligned} \tau_{\mathrm{p}} &= \frac{\eta_{\mathrm{g}}}{c_0(\alpha_{\mathrm{m}} + \alpha_{\mathrm{int}})} \\ \alpha_{\mathrm{m}} &= \frac{1}{2L} \ln \frac{1}{R_1 R_2} \\ \alpha_{\mathrm{int}} &= \Gamma\alpha_{\mathrm{a}} + (1 - \Gamma)\alpha_{\mathrm{c}} + \alpha_{\mathrm{scat}} \end{aligned} \tag{5}$$

where η_g is the group refractive index, c_0 is the velocity of light in vacuum (cm s^{-1}), R_1 and R_2 are mirror reflectivities, α_a and α_c are absorption and cladding absorption losses (cm^{-1}) and α_{scat} is the scattering loss at heterojunction interfaces (cm^{-1}).

The spontaneous emission factor in terms of laser diode parameters is [21]

$$\beta_s = \frac{K\Gamma\lambda_0^4}{8\pi^2\eta_a^2\eta_g\Delta\lambda_s V} \tag{6}$$

where K is the spontaneous emission enhancement factor ($K = 1$ for index-guided and $K > 1$ for gain-guided laser diodes), $\Delta\lambda_s$ is the FWHM of the spontaneous emission spectrum (cm).

The gain spectrum $D_i(\lambda)$ and spontaneous emission spectrum $D_{si}(\lambda)$ are in the form of a Lorentzian lineshape function. The gain spectrum is written as

$$D_i(\lambda) = \frac{1}{1 + \left(\dfrac{2(\lambda_0 - \lambda_i)}{\Delta\lambda_g}\right)^2} \tag{7}$$

where λ_i is the ith mode wavelength (cm) and $\Delta\lambda_g$ is the FWHM of the gain spectrum (cm). The spontaneous emission spectrum is the same as the gain spectrum but $\Delta\lambda_g$ is replaced with $\Delta\lambda_s$ which is the FWHM of the spontaneous emission spectrum (cm).

The current I applied to the laser diode has both d.c. bias and RF parts and is taken as

$$I = I_b + I_{rf}\sin(2\pi f_m t) \tag{8}$$

where f_m is the gain switching frequency (Hz) and I_b and I_{rf} are bias and RF currents (A), respectively.

3. Steady-state analysis

It is necessary to make a steady-state analysis in order to find the threshold current and steady-state electron and photon densities. In steady-state all oscillations in the electron and photon densities die away, hence the change in the electron and photon densities with respect to time becomes zero. So, the left-hand sides of Equations 1 and 2 become

$$\frac{dN}{dt} = \frac{dS_i}{dt} = 0 \tag{9}$$

The threshold current of the laser diode is determined from Equation 1 by neglecting the stimulated emission term which would be very small compared with the spontaneous emission below threshold. That is:

$$I_{th} = q\,V\left[\frac{N_{ss}}{\tau_{nr}} + (B_0 - B_1N_{ss})N_{ss}^2 + CN_{ss}^3\right] \tag{10}$$

where N_{ss} is the steady-state electron density.

In order to find the steady-state electron density N_{ss}, the following assumptions are made.

(a) The applied bias current is chosen to be greater than the threshold current, because if it is below threshold lasing may cease between the pulses so that optical coherence is lost.
(b) The spontaneous emission term in Equation 1 can be neglected because stimulated emission is dominant above the threshold.

(c) The sum of steady-state photon densities is mainly determined by the main mode photon density which will be small enough to make the term $\varepsilon_c \sum S_i$ much smaller than 1.

(d) As the main contribution to the steady-state photon density comes from the main mode photon density, the gain spectrum in Equation 2 takes the value of the main mode (i.e. $D_0(\lambda) = 1$) at steady-state.

Using these assumptions in Equations 1 and 2, N_{ss} can be found as

$$N_{ss} = \frac{1}{\Gamma g_0 \tau_p} + N_0 \tag{11}$$

After calculation of the threshold current using Equation 10, rate equations are numerically solved using the Runge–Kutta–Fehlberg method. Pulse durations are calculated for I_b ranging from $1I_{th}$ to $5I_{th}$, I_{rf} from $1I_{th}$ to $10I_{th}$, and f_m ranging from 1 to 15 GHz.

The computer program calculates the durations (FWHM) of the last two adjacent pulses obtained before 8 ns after the application of the drive at $t = 0$. A total calculation range of 8 ns is chosen according to the turn on delay time which has a maximum value of 2.48 ns depending on the laser diode parameters. In order to be sure of the stability of the system, two more repetitive pulses are taken before 16 ns. These four pulses obtained before 8 ns and 16 ns are then compared to see if they have the same FWHM and amplitude, and they are shown to have the same specifications. It is also shown that the pulses reach their stable shapes after 8 ns whether the d.c. bias and RF current are applied together at $t = 0$, or RF current is applied at a certain time after which the steady-state due to the applied d.c. bias (at $t = 0$) is reached. These comparisons show that a calculation range of 8 ns is enough to obtain stable pulses at the output. In addition, the step size used in numerical calculations is adjusted according to the gain switching frequency.

In order to detect multi-pulsing and cut-off frequency of gain switching, the shapes of the two repetitive pulses obtained before 8 ns are examined. It is assumed that the output is multi-pulsed if it contains a secondary unwanted peak generated during an electrical pulse period such that the amplitude of this secondary peak is greater than 5% of the main pulse. If the amplitudes of the two subsequent pulses differ by more than 5% of the larger one, then the cut-off is assumed to have been reached. These tolerances are chosen to avoid obtaining sharp minimum and maximum gain switching frequency values. In addition to these limitations, the output is also examined to see whether it is modulated or not. It is observed that modulation is unavoidable at high d.c. bias and low RF current, as expected.

In numerical calculations, the standard laser diode parameters are taken for a 1.3 μm InGaAsP ridge-waveguide semiconductor laser. These parameters are shown in Table I.

4. Results

Single-mode and multi-mode solutions are calculated from the numerical solution of Equations 1 and 2, with the single-mode solution corresponding to the case when $M = 0$. Although more than 20 modes exist under the gain spectrum which has an FWHM of 32.5 nm, it is found that only five modes can overcome the threshold and oscillate (for $L = 200$ μm). The number of oscillating modes decreases to one or three depending on the drive conditions when the laser diode length is decreased to 100 μm.

In Figs 1 to 6, the maximum frequency is taken as 6 GHz, because almost all of the solutions lie in the 1–6 GHz range as a result of the low d.c. bias and RF current values

TABLE I Standard parameters used for 1.3 μm InGaAsP ridge-waveguide semiconductor lasers

Parameter	Symbol	Value	Unit
Non-radiative lifetime	τ_{nr}	10×10^{-9}	s
Radiative recombination coefficient	B_0	0.6×10^{-10}	$cm^3\ s^{-1}$
Radiative recombination coefficient	B_1	1.1×10^{-29}	$cm^6\ s^{-1}$
Auger recombination coefficient	C	4.0×10^{-29}	$cm^6\ s^{-1}$
Optical gain coefficient	g_0	3.15×10^{-6}	$cm^3\ s^{-1}$
Electron transparency density	N_0	1.1×10^{18}	cm^{-3}
Gain compression parameter	ε_c	3.0×10^{-17}	cm^3
Operating wavelength	λ_0	1.3×10^{-4}	cm
FWHM of gain spectrum	$\Delta\lambda_g$	32.5×10^{-7}	cm
FWHM of spontaneous emission spectrum	$\Delta\lambda_s$	87.8×10^{-7}	cm
Length of active region	L	200×10^{-4}	cm
Thickness of active region	d	0.2×10^{-4}	cm
Width of active region	w	5×10^{-4}	cm
Absorption loss	α_a	30	cm^{-1}
Cladding loss	α_c	30	cm^{-1}
Scattering loss	α_{scat}	45	cm^{-1}
Lateral confinement factor	Γ_L	0.5	–
Active region refractive index	η_a	3.51	–
Cladding region refractive index	η_c	3.22	–
Group refractive index	η_g	4	–
Mirror reflectivities	$R_1,\ R_2$	0.32	–

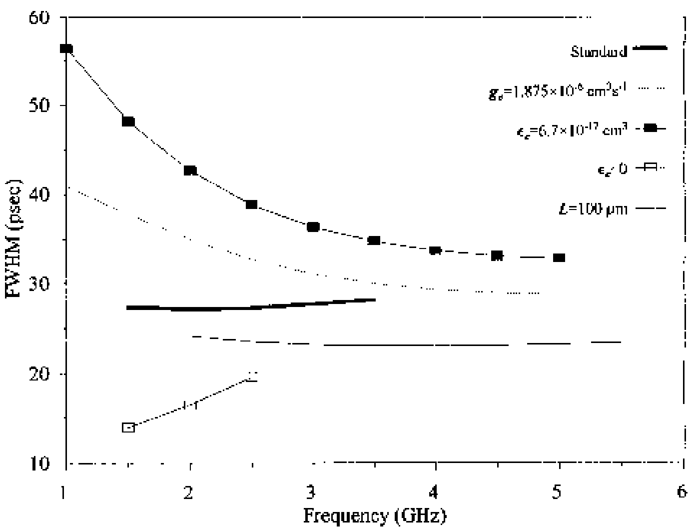

Figure 1 Variation of FWHM of pulses with frequency when $I_b = 2I_{th}$ and $I_{rf} = 5I_{th}$ (multi-mode solution).

used. Figure 1 shows the effect of gain switching frequency on the output pulse durations, obtained using multi-mode rate equations, when the laser diode is driven at $I_b = 2I_{th}$ and $I_{rf} = 5I_{th}$. As can be seen from the graphs, higher gain compression and lower gain behaviours are similar; higher duration optical pulses are obtained than in the standard case.

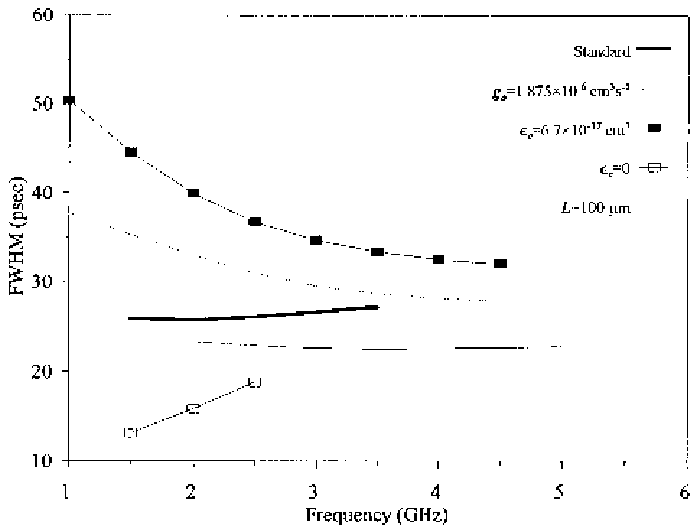

Figure 2 Same drive conditions as for Fig. 1 but single-mode solution.

On the other hand, the laser diode without gain compression gives the shortest pulses of those cases investigated in this work. The FWHM of output of laser diodes with higher gain compression and lower gain decreases as the frequency is increased as in [6, 7]. The laser diode without gain compression exhibits the opposite behaviour, similar to the results given in [3], the FWHM of pulses increases as the frequency is increased. In addition, the

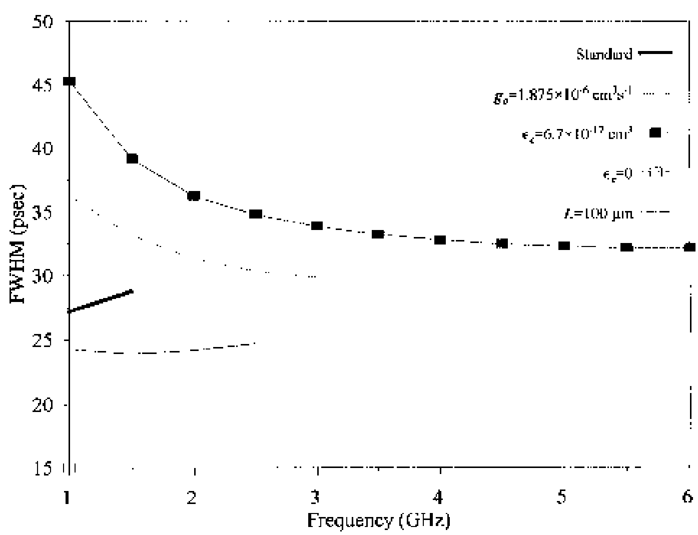

Figure 3 Variation of FWHM of pulses with frequency when $I_b = 1.2I_{th}$ and I_{rf} is changed from $1I_{th}$ to $7I_{th}$ to find minimum duration pulses (multi-mode solution).

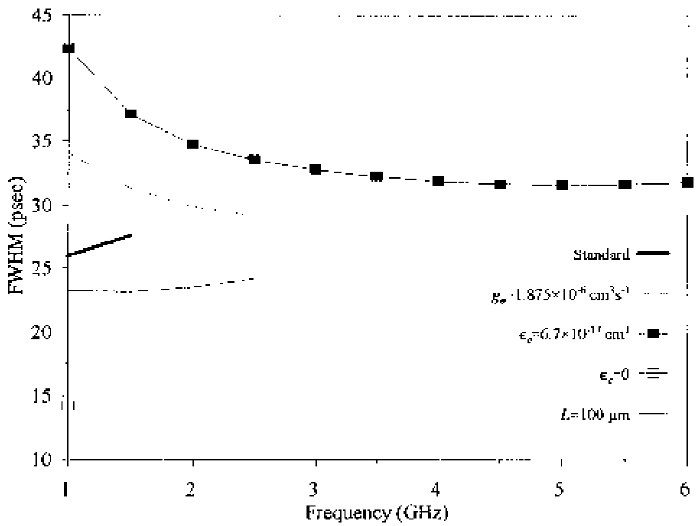

Figure 4 Same drive conditions as for Fig. 3 but single-mode solution.

pulsewidths of the shorter cavity laser diodes are found to be almost insensitive to the variations in gain switching frequency.

Figure 1 also shows how the parameters affect the maximum and minimum gain switching frequencies that can be applied to the laser diode. Multi-pulsing occurs at frequencies below 1.5 GHz for standard parameters and no gain compression cases, and 2 GHz for the short cavity case. Among the other parameters, the highest cut-off frequency is calculated to be 5.5 GHz for the short cavity case. This case corresponds to the

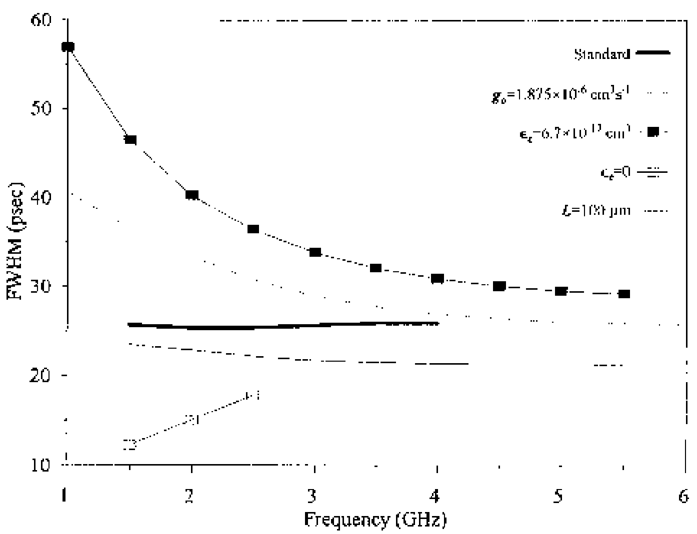

Figure 5 Variation of FWHM of pulses with frequency when $I_{rf} = 7I_{th}$ and I_b is changed from $1I_{th}$ to $2I_{th}$ to find minimum duration pulses (multi-mode solution).

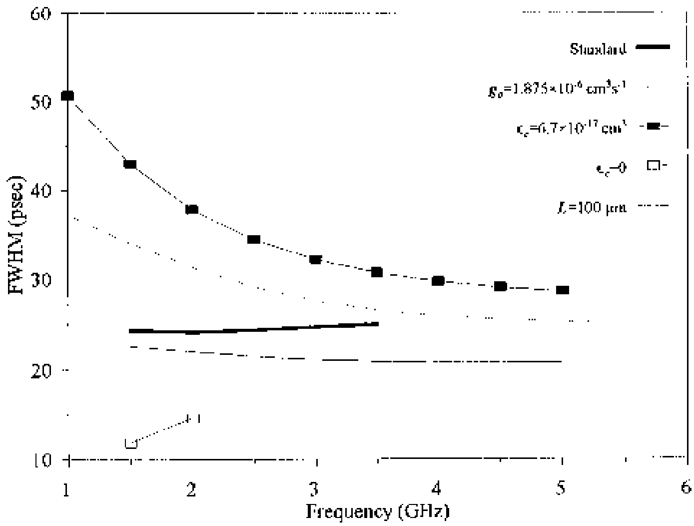

Figure 6 Same drive conditions as for Fig. 5 but single-mode solution.

reduced photon lifetime as depicted in [4]. Gain compression is also found to strongly affect the high frequency gain switching such that the laser diode with high gain compression has a cut-off frequency of 5 GHz whereas the laser diode without gain compression has a cut-off frequency of 2.5 GHz. This is because of the more stable operation of the laser diodes with high gain compression.

Figure 2 is the solution of single-mode rate equations for the same drive conditions as in Fig. 1. Although the solutions are very similar, there are two important differences between them. First, the single-mode solution gives shorter pulses than does the multi-mode solution for the same drive conditions. This difference is noticeably high at relatively low frequencies (near 1 GHz) especially for the high gain compression case ($\sim$6 ps) and low gain constant case ($\sim$3.5 ps), and decreases as the frequency increases. In general, the single-mode solution gives 2–8% lower duration pulses than does the multi-mode solution, with the smallest difference corresponding to the short cavity-length case ($\sim$2–3%). This is because the laser diode with $L = 100$ μm operates nearly single-mode. The other important difference between the two solutions is the maximum pulse repetition rates which are calculated to be almost 0.5 GHz smaller for the single-mode solution. These two differences show that the single-mode rate equations fail to explain the pulse width at low frequencies and maximum repetition rate at higher frequencies.

Figure 3 shows the variation of FWHM of laser output with frequency, calculated using multi-mode rate equations, when $I_b = 1.2I_{th}$ and I_{rf} changes from 1 to $7I_{th}$ to find the optimum RF current level that gives minimum FWHM pulses. All minimum FWHM values in this figure are obtained at $I_{rf} = 7I_{th}$ which implies that FWHM of pulses decrease as the RF current is increased [3, 7, 8, 22, 23]. Although the graphs in Figs 1 and 3 show similar behaviour, comparison of these figures shows that multi-pulsing frequencies are shifted towards the lower frequencies. Another result is related to the maximum repetition rate such that, when d.c. bias is decreased maximum repetition rate also decreases. The only exception to this case is the high gain compression case at which threshold current is

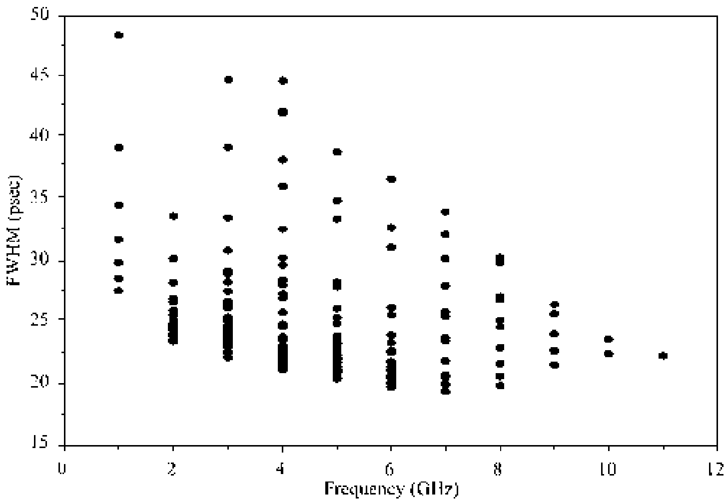

Figure 7 Possible solutions of multi-mode rate equations (FWHM values) obtained at different frequencies when I_b changes from 1 to $5I_{th}$ and I_{rf} changes from 1 to $10I_{th}$ (both with $1I_{th}$ steps).

largely affected by RF current level. Figure 4 is the single-mode case of Fig. 3 in which 1–7% lower FWHM values are obtained for the single-mode case. As for Figs 1 and 2, the maximum repetition rate is found to be smaller for the single-mode solution.

Figure 5 shows frequency versus FWHM for $I_{rf} = 7I_{th}$ and I_b changes from 1 to $2I_{th}$ using the multi-mode rate equations. The d.c. bias level is adjusted to give minimum duration pulses, and it is observed that all minimum FWHM values are obtained at $I_b = 2I_{th}$ which implies that the FWHM of pulses decrease as the d.c. bias is increased [2, 3, 7, 8, 23]. The only exception is the high gain compression case for which minimum duration pulses are obtained at $I_b = 1I_{th}$ as theoretically and experimentally verified in [1]. Comparison of Figs 1 and 5 shows that ($I_b = 2I_{th}$ for both) multi-pulsing frequencies are shifted towards the lower frequencies when RF current is increased. A similar comparison between Figs 3 and 5 ($I_{rf} = 7I_{th}$ for both) shows that the minimum gain switching frequency is decreased as the d.c. bias is decreased.

Figure 6 shows the single-mode solution case at the same drive conditions as for Fig. 5. The single-mode solution gives 2–11% shorter duration pulses than does the multi-mode case.

Figure 7 shows the possible FWHM values obtained over a frequency range of 1–15 GHz using standard parameters and multi-mode rate equations when I_b changes from 1 to $5I_{th}$ and I_{rf} changes from 1 to $10I_{th}$, both with $1I_{th}$ steps. All FWHM values are smaller than 50 ps, with the shortest duration obtained at 7 GHz (at $I_b = 5I_{th}$ and $I_{rf} = 10I_{th}$) as 19.56 ps. The cut-off frequency of this laser diode in this drive current range is 11 GHz with a pulse duration of 22.4 ps. This cut-off frequency will be changed if d.c. bias and RF current are changed. It should be kept in mind that when the standard parameters are changed, cut-off frequency will also be changed. The shortest duration pulses at each frequency are obtained at maximum drive level as expected. The pulses with peak power smaller than 5 mW, and being modulated in the case with high d.c. bias and relatively low RF current are not shown in this graph. It can be seen from the graph that maximum

FWHM range occurs at 4 GHz at which FWHM values of 20 to 45 ps are possible to obtain by choosing the proper d.c. bias and RF current. This feature of the laser diode makes it versatile in applications which require variable pulse widths.

5. Conclusions

The results obtained from the model can be summarized as follows.

(a) Minimum and maximum gain switching frequencies are affected by laser diode parameters as well as drive conditions in the following ways.

 (i) Minimum gain switching frequency decreases with decreased d.c. bias or increased RF current. Laser diodes with higher gain compression or lower gain can be gain switched at lower frequencies.

 (ii) Maximum repetition rate increases with increasing d.c. bias. Laser diodes with short cavities or high gain compression have higher maximum repetition rates. Maximum repetition rate is smaller for the laser diodes which do not exhibit gain compression.

(b) FWHM of laser output decreases as the frequency increases for laser diodes with high gain compression or low gain, whereas the behaviour is the opposite for laser diodes with no gain compression. The output pulse duration is almost insensitive to frequency for short cavity laser diodes.

(c) Comparison of single-mode and multi-mode solutions shows that:

 (i) the single-mode solution always gives shorter pulses, the difference between the solutions is higher for laser diodes with high gain compression or low gain, and decreases as the frequency increases;

 (ii) the difference between the solutions increases as the d.c. bias or RF current is increased;

 (iii) the maximum repetition rate calculated using single-mode rate equations is always smaller than that obtained from multi-mode rate equations.

The results given in this work explain the conflicting pulse width-frequency behaviours in [3, 6, 7]. It is found that the material and structure of the laser diode affect the FWHM-frequency behaviour of the gain switched laser diode. Among the other parameters, gain compression is the most important one that has powerful effects on this behaviour. As an example, as InGaAsP laser diodes have relatively higher gain compression compared with AlGaAs laser diodes, it is possible to obtain opposite FWHM-frequency behaviours as shown in Figs 1–6. Cooling the laser diode to increase the gain, using different device structures such as ridge-waveguide, rib-waveguide, and different types of buried heterostructure lasers, or decreasing the active region length will all result in different FWHM-frequency behaviours.

The frequency dependence of the FWHM of the gain switched pulses and the comparison of single-mode and multi-mode solutions in order to deduce whether single-mode rate equations can adequately model the gain switched pulse generation from multi-mode operating laser diodes, over a frequency range of 1 to 15 GHz are presented in this work for the first time.

References

1. M. S. OZYAZICI and M. S. DEMOKAN, *Int. J. Optoelectron.* **5** (1990) 7.
2. S. TARUCHA and K. OTSUKA, *IEEE J. Quantum Electron.* **17** (1981) 810.

3. H. ITO, H. YOKOYAMA, S. MURATA and H. INABA, *IEEE J. Quantum Electron.* **17** (1981) 663.
4. C. LIN, C. A. BURRUS, G. EISENSTEIN, R. S. TUCKER, P. BESOMI and R. J. NELSON, *Electron. Lett.* **20** (1984) 238.
5. P. M. DOWNEY, J. E. BOWERS, R. S. TUCKER and E. AGYEKUM, *IEEE J. Quantum Electron.* **23** (1987) 1039.
6. N. ONODERA, H. ITO and H. INABA, *Appl. Phys. Lett.* **45** (1984) 843.
7. N. ONODERA, H. ITO and H. INABA, *IEEE J. Quantum Electron.* **21** (1985) 568.
8. J. AUYEUNG, *Appl. Phys. Lett.* **38** (1981) 308.
9. R. OLSHANSKY, C. B. SU, J. MANNING and W. POWAZINIK, *IEEE J. Quantum Electron.* **20** (1984) 838.
10. G. P. AGRAWAL and N. K. DUTTA, *Long-Wavelength Semiconductor Lasers* (Van Nostrand Reinhold, New York, 1986).
11. J. E. BOWERS, *Electron. Lett.* **21** (1985) 1195.
12. R. OLSHANSKY, D. M. FYE, J. MANNING and C. B. SU, *Electron. Lett.* **21** (1985) 721.
13. P. A. MORTON, R. F. ORMONFROYD, J. E. BOWERS and M. S. DEMOKAN, *IEEE J. Quantum Electron.* **25** (1989) 1559.
14. R. S. TUCKER and D. J. POPE, *IEEE J. Quantum Electron.* **19** (1983) 1179.
15. H. LIU, M. FUKAZAWA, Y. KAWAI and T. KAMIYA, *IEEE J. Quantum Electron.* **25** (1989) 1417.
16. R. S. TUCKER and I. P. KAMINOW, *J. Lightwave Technol.* **2** (1984) 385.
17. D. R. HJELME and A. R. MICKELSON, *IEEE J. Quantum Electron.* **25** (1989) 1625.
18. T. L. KOCH and R. A. LINKE, *Appl. Phys. Lett.* **48** (1986) 613.
19. G. P. AGRAWAL and T. M. SHEN, *Electron. Lett.* **22** (1986) 1087.
20. D. BOTEZ, *IEEE J. Quantum Electron.* **14** (1978) 230.
21. J. C. CARTLEDGE and A. F. ELREFAIRE, *J. Lightwave Technol.* **8** (1990) 704.
22. P. PAULUS, R. LANGENHORST and D. JAGER, *IEEE J. Quantum Electron.* **24** (1988) 1519.
23. J. P. VAN DER ZIEL and R. A. LOGAN, *IEEE J. Quantum Electron.* **18** (1982) 1340.