

Gain switching characteristics of quantum well laser by using SPICE simulator

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Gain switching phenomena of quantum well (QW) lasers diode is described by using a SPICE equivalent circuit model, which is based on the three-level rate equations. Effects of gain switching frequency, some laser diode parameters and dc and rf drive conditions on the full-width half maximum (FWHM) of gain switched pulses are investigated. It is shown that FWHM of pulses decrease as the rf current increased, at a constant frequency. However, the FWHM of pulses increases as the dc bias is increased. FWHM decreases also for small value of gain compression parameter whereas the variation in carrier lifetime in the well does not significantly affect the FWHM of generated pulses. It is also shown that as the frequency is increased, FWHM start to increase.

(Received August 9, 2007; accepted August 23, 2007)

Keywords: Quantum well (QW) laser, SPICE simulator, Gain switching

1. Introduction

Semiconductor lasers have numerous applications in data processing and communications. In these applications, any system designer requires an equivalent circuit model of semiconductor lasers to construct the laser and driver circuits to carry out applications that involve both electronic and optical components. Electrical equivalent-circuit models for optical components are useful as they allow existing, well developed circuit simulators to be used in the design and analysis of optoelectronic circuits. Such models for the quantum well (QW) laser are now starting to appear, both the transmission line form [1], and in the lumped-element form [2-7]. These models are all based on the rate equation, which describes rate change between the carrier density and photon density. Then, the carrier density and photon density are converted to current and voltage representations, respectively. The input current (carrier) and output voltage (light) from a two port equivalent model. The input port can be connected to driver circuits, and output port can be coupled through fiber or free space to receivers circuits for the simulation of the over all signal transmission. The rate equations used in [2-5] are of the one level variety in that they describe only the interaction between the bound states of the QW and the photon population. In [1], [6] and [7] the laser models are based on a two-level rate-equation representation of carrier dynamics within the laser, i.e., one equation describes the continuity of carrier charge in the QW, while another performs the same function for carriers in the separate-confinement heterostructure (SCH). Carriers are considered able to exchange directly between continuum states of the SCH and bound states of the QW.

A further improvement in the description of carrier dynamics may results from incorporating within the circuit model the effect of the so-called gateway states [8]. In [9] three level rate equations which include, in their

characterization of charge dynamics; the role of gateway states at the quantum well was used. The equivalent circuit model [9] is versatile in that it can be used for both small-signal and large-signal analyses.

In this paper, we show for the first time gain switching characteristics of QW laser diode using SPICE equivalent circuit model of ref [9]. 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 [10]. 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.

In this work, pulse width dependence on applied dc and rf current, gain compression factor (ϵ), and spontaneous coupling factor (β) are determined.

2. Equivalent circuit model QW laser diode

A schematic representation of the dynamical processes occurring within a QW laser possessing states is given in Fig. 1. In the figure, I_i is the current injected into the SCH layer from the n-type cladding, the τ_n 's are time constants for spontaneous (radiative and nonradiative) recombination processes in each of the three regions of the device (SCH, QW, gateway (G)), τ_D is a transit time constant, computed from charge control theory, which relates to carriers which traverse the SCH by ambipolar diffusion [11], and exit into the gateway states, is the ambipolar capture time constant for carriers transferring from gateway states to the QW bound states, while τ_{ESC} is the corresponding time constant for the inverse process of escape via thermionic emission, τ_G is a time constant associated with the lifetime of carriers in the gateway states [12].

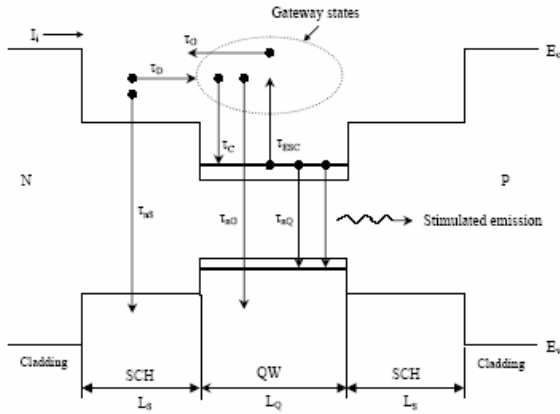


Fig. 1. Schematic of the dynamical processes occurring within the QW laser.

The three charge-continuity equations, taking into account stimulated emission, carrier and photon fluctuations are given below,

$$\begin{aligned} \frac{dN_s}{dt} &= \frac{I_i}{qV} - \frac{N_s}{\tau_{nS}} - \frac{N_s}{\tau_D} + \frac{N_G}{\tau_G} \\ \frac{dN_G}{dt} &= \frac{N_s}{\tau_D} - \frac{N_G}{\tau_G} - \frac{N_G}{\tau_{nG}} - \frac{N_G}{\tau_C} + \frac{N_Q}{\tau_{ESC}} \\ \frac{dN_Q}{dt} &= \frac{N_G}{\tau_C} - \frac{N_Q}{\tau_{ESC}} - \frac{N_Q}{\tau_{nQ}} - \frac{\Gamma v_g G(n_Q) S}{\sqrt{1 + \epsilon S}} \\ \frac{dS}{dt} &= \frac{\Gamma v_g G(n_Q) S}{\sqrt{1 + \epsilon S}} - \frac{S}{\tau_p} + \beta \frac{N_Q}{\tau_{nQ}} \end{aligned} \quad (1)$$

S is the photon population, v_g is the group velocity, Γ is the optical confinement factor, ϵ is the gain compression factor, τ_p is the photon lifetime, β is the fraction of isotropic spontaneous emission that is coupled into the lasing longitudinal mode. $G(n_Q)$ is the carrier density dependent material gain, and it is obtained from a detailed band-structure calculation using the finite-element method to solve for the conduction and valence band dispersion curves and wave functions [13]. The gain is then calculated using the k-selection rule, taking into account the intraband relaxation with the following expression:

$$G(n_Q) = a_0 + a_1 \ln(n_Q / \text{cm}^3) + a_2 (\ln(n_Q / \text{cm}^3))^2 \quad (2)$$

where a_0 , a_1 , and a_2 are constants, having, for the materials and structure under consideration, the values of $-771899.99 \text{ cm}^{-1}$, 34220.10 cm^{-1} , and -376.83 cm^{-1} , respectively. Eq. (2) can be implemented as a user-defined function in PSPICE [9].

By multiplying the active layers volume and electron charge qV , the rate equations become,

$$\begin{aligned} \tau_{nS} \frac{dI_S}{dt} &= I_i - I_S - \frac{\tau_{nS}}{\tau_D} I_S + \frac{\tau_{nG}}{\tau_G} I_G \\ \tau_{nG} \frac{dI_G}{dt} &= \frac{\tau_{nS}}{\tau_D} I_S - \frac{\tau_{nG}}{\tau_G} I_G - I_G - \frac{\tau_{nG}}{\tau_C} I_G + \frac{\tau_{nQ}}{\tau_{ESC}} I_Q \\ \tau_{nQ} \frac{dI_Q}{dt} &= \frac{\tau_{nG}}{\tau_C} I_G - \frac{\tau_{nQ}}{\tau_{ESC}} I_Q - I_Q - \frac{q \Gamma v_g G(n_Q) V_{out}}{\bar{p} \sqrt{1 + \epsilon_{out} V_{out}}} \\ q \frac{dP}{dt} &= \frac{q \Gamma v_g G(n_Q) V_{out}}{\bar{p} \sqrt{1 + \epsilon_{out} V_{out}}} - q \frac{P}{\tau_p} + \beta I_Q \end{aligned} \quad (3)$$

Here, the currents I_S , I_G , and I_Q measure the spontaneous recombination currents, qVN/τ_n , in three regions of the device, as determined by the diode elements DS, DG and DQ, respectively. Diodes are used for this purpose, rather than behavioral current elements, in an attempt to minimize the program's execution times [9]. Their usage also eliminates the requirement of placing high-value resistors in parallel with the behavioral current sources to overcome the floating node problem that would be encountered in a dc simulation. The SPICE model parameter values for the three diodes are listed in Table 1. P is the output power and it is equal to VS , and V_{out} is a nodal voltage and it is equal to $\bar{p}P$, $\bar{p}$ is a constant for converting photon population [9]. ϵ_{out} is equal to $\epsilon/V \bar{p}$.

Table 1. SPICE parameters for the diodes which model the spontaneous recombination currents.

Diode	IS (A)	N	RS (Ω)
DS	6.66×10^{-15}	2	0.45
DG	4.57×10^{-16}	2	15
DQ	1.208×10^{-13}	2	10

The equivalent circuit representation of the three level rate equations is shown in Fig. 2. The elements labeled G are behavioral current sources, and those labeled E are behavioral voltage sources. Time derivative terms are shown $G1$, $G4$, and $G7$. The currents $I(VIS)$, $I(VIG)$, and $I(VIQ)$ represents the currents I_S , I_G and I_Q . As indicated in Fig. 2 the spontaneous recombination times, as represented by capacitors in the subcircuits, are taken as constants. This means that carrier concentration dependent processes, such as radiative and Auger recombination, are not accounted for. In practice, however, above threshold the regional carrier densities, particularly in the QW, do not vary appreciably, so the constant values for the τ_n 's used here can be viewed as appropriate average values.

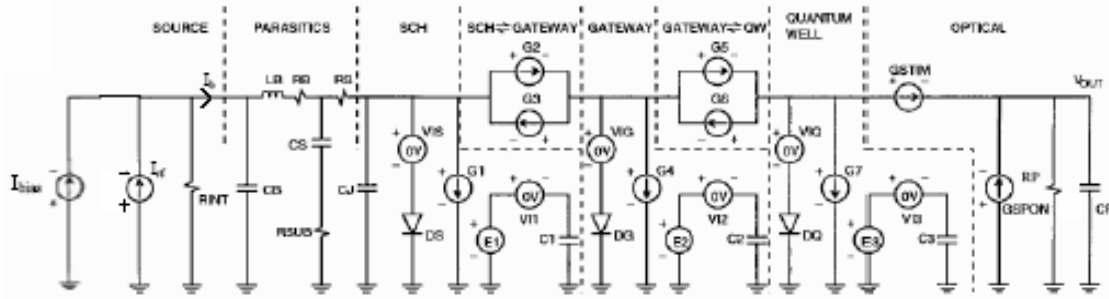


Fig. 2. SPICE equivalent circuit representation of the three level rate equations. $C1=\tau_{ns}$, $C2=\tau_{nG}$, $C3=\tau_{nQ}$, $G1=I(VI1)$,

$$G2=\frac{\tau_{nS}}{\tau_D} I(VIS), G3=\frac{\tau_{nG}}{\tau_G} I(VIG), G4=I(VI2), G5=\frac{\tau_{nG}}{\tau_C} I(VIG), G6=\frac{\tau_{nQ}}{\tau_{ESC}} I(VIQ), G7=I(VI3), G8=I(VI4), G9=I(VI5), G10=I(VI6), G11=I(VI7), G12=I(VI8), G13=I(VI9), G14=I(VI10), G15=I(VI11), G16=I(VI12), G17=I(VI13), G18=I(VI14), G19=I(VI15), G20=I(VI16), G21=I(VI17), G22=I(VI18), G23=I(VI19), G24=I(VI20), G25=I(VI21), G26=I(VI22), G27=I(VI23), G28=I(VI24), G29=I(VI25), G30=I(VI26), G31=I(VI27), G32=I(VI28), G33=I(VI29), G34=I(VI30), G35=I(VI31), G36=I(VI32), G37=I(VI33), G38=I(VI34), G39=I(VI35), G40=I(VI36), G41=I(VI37), G42=I(VI38), G43=I(VI39), G44=I(VI40), G45=I(VI41), G46=I(VI42), G47=I(VI43), G48=I(VI44), G49=I(VI45), G50=I(VI46), G51=I(VI47), G52=I(VI48), G53=I(VI49), G54=I(VI50), G55=I(VI51), G56=I(VI52), G57=I(VI53), G58=I(VI54), G59=I(VI55), G60=I(VI56), G61=I(VI57), G62=I(VI58), G63=I(VI59), G64=I(VI60), G65=I(VI61), G66=I(VI62), G67=I(VI63), G68=I(VI64), G69=I(VI65), G70=I(VI66), G71=I(VI67), G72=I(VI68), G73=I(VI69), G74=I(VI70), G75=I(VI71), G76=I(VI72), G77=I(VI73), G78=I(VI74), G79=I(VI75), G80=I(VI76), G81=I(VI77), G82=I(VI78), G83=I(VI79), G84=I(VI80), G85=I(VI81), G86=I(VI82), G87=I(VI83), G88=I(VI84), G89=I(VI85), G90=I(VI86), G91=I(VI87), G92=I(VI88), G93=I(VI89), G94=I(VI90), G95=I(VI91), G96=I(VI92), G97=I(VI93), G98=I(VI94), G99=I(VI95), G100=I(VI96).$$

The spontaneous emission coupled into the lasing mode is accounted for via the current source $GSPON$. The stimulated photon emission is determined by the current source $GSTM$, the photon lifetime is modeled via RP , and the time derivative of the photon population is related to CP .

$$GSTM = \frac{q\Gamma v_g G(n_Q) V_{out}}{\bar{p}\sqrt{1 + \varepsilon_{out} V_{out}}} \quad (4)$$

$$RP = \frac{\tau_p \bar{p}}{q}, \quad CP = \frac{q}{\bar{p}} \quad (5)$$

SPICE may converge to a solution where V_{out} becomes negative. To avoid this unphysical condition, V_{out} is limited to be positive by using $LIMIT$ function [9]. Source, package and internal parasitic element can be added to the equivalent circuit [14]. Referring to Fig. 2, $RINT$ is the internal resistance of the source, CB , LB , and RB are the capacitance, inductance, and resistance associated with the bond wire, respectively, CS is a lumped element representation of all the capacitance from the top metallization to the substrate outside the ridge, $RSUB$ is the substrate resistance in series with CS , and RS is the sum of contact, ridge, lower cladding, and substrate resistances [1]. Usage of the circuit components is made with the values tabulated in Table 2.

Table 2. Parasitic values used in the simulations.

Parameter	Value	Unit
RINT	50	Ω
CB	0.1	pF
LB	0.2	nH
RB	0.1	Ω
CS	1.6	pF
RSUB	1.5	Ω
RS	4	Ω

Length of SCH L_S is 300 nm, the longitudinal dimension L_L of the QW is 300 μm , the ridge width is 2.5 μm , and width of the QW is 8 nm. The other model parameters used in simulation are given in Table 3.

3. Results and discussion

The SPICE program has been run for the parameter values given in the Table 3. Under these conditions, the laser diode has a threshold current I_{th} of 10.5 mA and corresponding I_{bias} current is 38 mA as shown in Fig. 3.

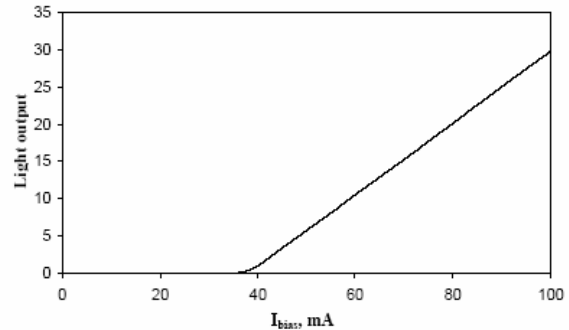


Fig. 3. Light-current ($L-I_{bias}$) characteristics of QW laser diode.

Fig. 4 represents the variation of the FWHM of the generated pulses, with and without gain compression, as a function of the applied dc bias current for the same parameter values. The applied rf current is adjusted at each dc bias current to obtain the minimum pulse duration. Fig. 4 clearly demonstrates the effect of the gain compression parameter on the pulse width of the generated pulses. At a fixed dc bias current of $I_b=I_{th}$, the laser diode with gain compression produces an optical pulse having a duration of 26 ps. If the phenomenon of gain compression was not present, 19 ps optical pulses at the same value of the dc bias current would have been produced under the otherwise identical conditions. Hence, due to gain compression, the pulse width broadens. It should also be

mentioned that there is a maximum value of dc bias current that can be applied to the laser diode without obtaining a double pulse. For the parameter values used, the maximum dc bias current which can be applied to the laser diode is calculated $1I_{th}$. The dc bias current level will be different if the standard parameter values given in Table 3 are changed. Results shown in Fig. 4 indicate that, the pulse width decreases if the applied dc bias current is decreased. The same variation in the FWHM of the pulses with dc bias has been shown in [10] for the case where gain compression is taken into account.

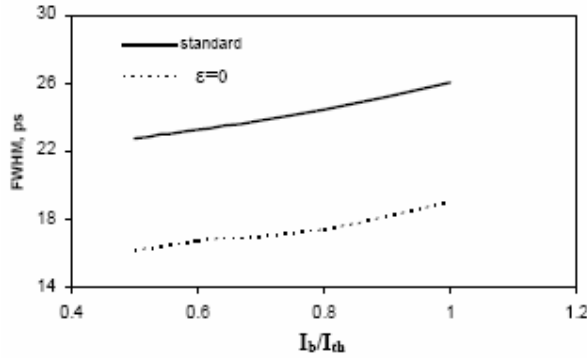


Fig. 4. Variation of the FWHM of pulses with dc bias current.

Table 3. Model parameter values used in the simulation.

Parameter	Value	Unit
τ_{ns}	1	ns
τ_{nG}	1	ns
τ_{nQ}	0.35	ns
τ_D	48.3	ps
τ_G	1	ps
τ_C	0.18	ps
τ_{ESC}	200	ps
τ_P	3.02	ps
Γ	0.019	
v_g	7.5×10^7	ms^{-1}
ϵ_P	6.3×10^{-8}	
$\bar{p}$	3.03×10^{-8}	W
β	1×10^{-4}	
C_J	140	fF

Fig. 5 shows the variation of FWHM as a function of applied rf current. For this case dc current is adjusted at each rf current to obtain the minimum pulse duration. The effect of gain compression on the pulse width can clearly be seen from Fig. 5. There is a maximum value of rf current that can be applied to the laser diode without

achieving multi-pulsing. The maximum value of rf current is found to be $9 I_{th}$ with and without gain compression. In both cases, the FWHM of the pulses decrease as the rf current is increased as in [15]. For, say, $I_{rf}=I_{th}$, the pulse widths are 42.38 ps for $\epsilon=0$ and 47.64 ps for the gain compression case. The broadening of the pulse due to gain compression is considerable.

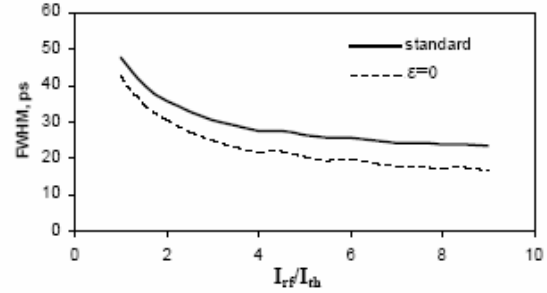


Fig. 5. Variation of the FWHM of pulses with rf current.

Some of the parameters, which are structure and design dependent, are varied from their standard values given in the Table 3 to investigate their effect on pulse width. Carrier lifetime τ_{nQ} in the well can be changed slightly. The effect of changing the value of τ_{nQ} from 0.35 ns to 0.23 ns on FWHM of the pulses is shown in Fig. 6 as a function of dc bias both with and without the gain compression parameter. As can be seen in figure, the variation in τ_{nQ} does not significantly affect the FWHM of the generated pulses. However, it does affect the threshold current. For $\tau_{nQ}=0.23$ ns, the threshold current is found 12.16 mA.

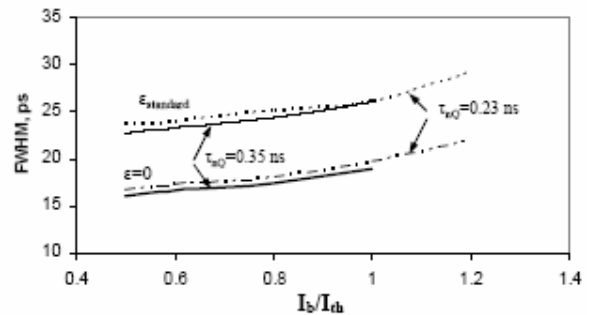


Fig. 6. Effect of the variation of carrier lifetime τ_{nQ} on the FWHM of pulses.

The second parameter which is changed from its standard value is the value of β , that is, the spontaneous emission into the mode. The effect of a decrease of β , from 10^{-4} to 10^{-5} on the pulse width is shown in Fig. 7 where it is seen to decrease the pulse width. At a fixed dc bias current of $I_b=I_{th}$, the width is decreased from 26 ps to 22.89 ps with gain compression and from 18.98 ps to 16.52 ps without gain compression. This shows that the variation in the value of β affects the pulse width of the pulses generated by gain switching.

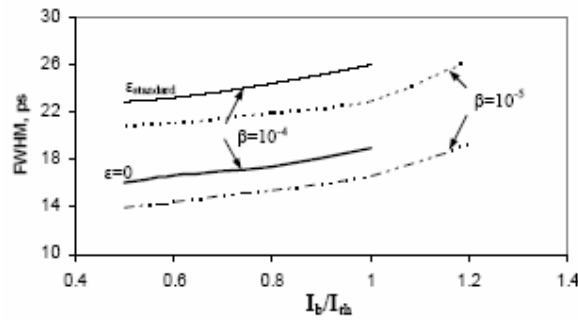


Fig. 7. Effect of the variation of spontaneous coupling factor β on FWHM of pulses.

Effect of gain switching frequency on pulse width is given in Fig. 8 when the laser diode is driven at $I_b=1.12I_{th}$ and $I_{rf}=4I_{th}$. The FWHM of output of laser diodes increases as the frequency increased with and without gain compression. This figure also shows how the parameters affect the maximum and minimum gain switching frequencies that can be applied to laser diode. Multipulsing occurs at frequencies below 1.5 GHz for standard parameters and no gain compression cases. The highest cut-off frequency is calculated to be 4.5 GHz for standard parameters. Gain compression is also found to strongly affect the high frequency gain switching such that the laser diode with no gain compression has a cut-off frequency of 3 GHz. This is because of the more stable operation of the laser diodes with high gain compression.

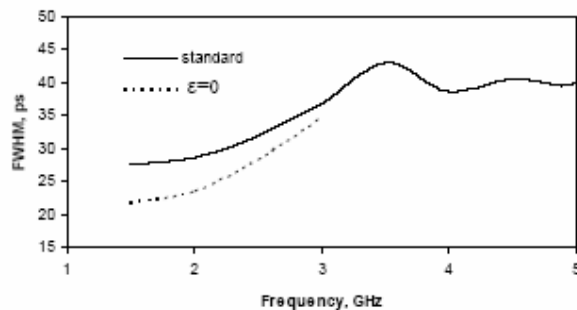


Fig. 8. Effect of the gain switching frequency on the FWHM of pulses.

Fig. 9 shows the output peak power with rf current for standard parameters case and for no gain compression. As it is expected, the output power increases with increased rf current in both cases. High power pulses with short durations are the best ones for light wave communication systems since bandwidth and attenuation are directly related to the pulses used in this systems.

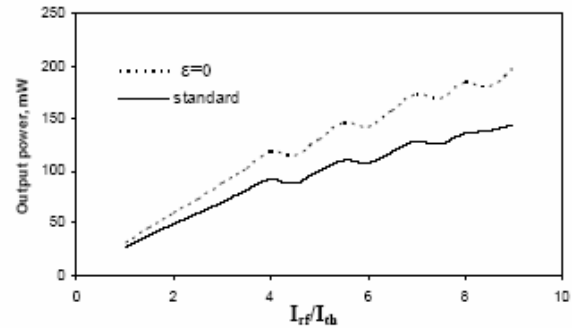


Fig. 9. Variation of output peak power with rf current.

4. Conclusions

The generation of picoseconds pulses by gain switched using SPICE simulator has been discussed. Several conclusions can be drawn from the simulation results. First of all, the main limitation for obtaining short pulses is gain compression parameter. The pulse width broadened due to gain compression. It has been found that the carrier lifetime τ_{nQ} in the well has little effect in gain switching. It is clear from the simulation that the spontaneous emission factor β will affect the width of the generated pulses. In order to have shorter pulses, the laser diode structure should be designed so as to give rise to a small β . It is also found that pulse width increases as the frequency is increased.

In conclusion, in order to achieve shorter pulse widths the following are required: small value of spontaneous emission factor, and a laser diode which has a small gain compression effect.

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