Time-Domain Computation of the Linewidth Enhancement Factor in Multi-Quantum-Well Semiconductor Optical Amplifiers

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ABSTRACT

The linewidth enhancement factor (LWEF) of a semiconductor optical amplifier (SOA) drastically affects the coherence of the amplified beam. Its measurement, however, is complicated due to its sensitivity to the underlying SOA parameters. As practical SOAs are mostly based on multi-quantum-wells (MQWs), this paper aims to introduce a robust algorithm that can be used to compute the time variation of the LWEF of an MQW-SOA. The attained simulation results are confirmed with experimental findings.

INTRODUCTION

The linewidth enhancement factor (LWEF) of a semiconductor optical amplifier (SOA) is a measure of the refractive index fluctuations in its active medium, which distort the coherence of the amplified optical beam [1]. A high LWEF has been shown to heavily degrade the signal quality in optoelectronic devices, such as frequency-swept lasers [2-3], where SOAs are used as the master component. Due to the involved experimental procedure of measuring the LWEF [4-5], a systematic computational algorithm is of great interest for an accurate estimation of the LWEF. Here, we offer a computationally straightforward procedure for evaluating the time variation of the LWEF through the solution of the rate equations for the carrier and the photon densities in the overall active region, and also within each identical quantum-well.

MODEL

The LWEF is a ratio of the variations of the real and imaginary parts of the electric susceptibility against the carrier density

$$\alpha = -\frac{\partial\left(Re\left\{1+\chi+\dfrac{\dfrac{Ne^2}{m\varepsilon_0}}{{\omega_0}^2-\omega^2-i\Omega\omega}\right\}\right)\Big/\partial N}{\partial\left(Im\left\{1+\chi+\dfrac{\dfrac{Ne^2}{m\varepsilon_0}}{{\omega_0}^2-\omega^2-i\Omega\omega}\right\}\right)\Big/\partial N}$$

(1) N: *Carrier density*, χ: *Background susceptibility*

m: *Electron mass*, ω: *Ang. frequency*, ε_0: *Permittivity*

ω_0: *Ang. transition frequency*, e: *Unit charge*

where the transition linewidth Ω depends on the carrier lifetime τ_c and the collision time T_c

$$\Omega = (1/\tau_c) + (1/T_c) \quad (2)$$

In an MQW-SOA, the carriers are mostly confined in the wells. Thus the carrier lifetime and the carrier collision time are computed based on the carrier density within the QWs as $\tau_c = 1/(A + BN_{QW} + C{N_{QW}}^2 + D{N_{QW}}^{4.5})$, $T_c = K/N_{QW}$

A: *Defect coefficient*, N_{QW}: *QW carrier density*

B: *Radiative coefficient*, C: *Auger coefficient*

K: *Collision constant*, D: *Leakage coefficient*

Equations 1-2 are functions of the carrier density within the QWs. Therefore, the rate equations for the active medium and the QWs are solved concurrently as they are coupled to each other

$$\frac{dN}{dt} = \frac{\xi_{in} I}{eV} - \frac{N}{\tau_c} - \Gamma G_{ac}(\omega)S \quad (3-4)$$

$$\frac{dS}{dt} = \Gamma G_{ac}(\omega)S - \frac{S}{\tau_p} + \frac{N}{\tau_r}, \ \tau_p = \frac{n_r L}{c}, \ \tau_r = \frac{1}{BN_{QD}}$$

$$\frac{dN_{QW}}{dt} = \frac{\Pi_{in} I}{eV_{QW}} - \frac{N_{QW}}{\tau_c} - \Gamma_{QW} G_{QW}(\omega) S_{QW} \quad (5-6)$$

$$\frac{dS_{QW}}{dt} = \Gamma_{QW} G_{QW}(\omega) S_{QW} - \frac{S_{QW}}{\tau_p} + \frac{N_{QW}}{\tau_r}, \Pi_{in} = \frac{\xi_{in}\zeta}{M}$$

$$G(\omega) = \frac{(N - N_{th}) \times \left(\frac{\lambda^2}{8\pi\tau_r}\right) \times \left(\frac{\Omega}{2\pi}\right)}{(\omega - \omega_0)^2 + \left(\frac{\Omega}{2}\right)^2} \quad (7)$$

S: *Photon density*, N: *Carrier density*, I: *Pump current*

Γ: *Optical confinement factor*, V: *Volume*, L: *Length*

G: *Small signal gain*, λ: *Wavelength*, c: *Speed of light*

ξ_{in}: *Injection efficiency*, τ_p: *Photon lifetime*

Π_{in}: *QW injection efficiency*, n_r: *Refractive index*

ζ: *QW carrier confinement ratio* $(0 < \zeta < 1)$

N_{th}: *Threshold carrier density*, M: *Number of QWs*

An accurate model for computing the LWEF as a time-invariant constant was developed by Vahala et al. [4]. Fig. 1 shows the steady state value of the time-dependent LWEF versus frequency attained by following the outlined procedure, and the frequency variation of the time-independent LWEF based on the experimentally confirmed analytical formulation by Vahala et al. [4]

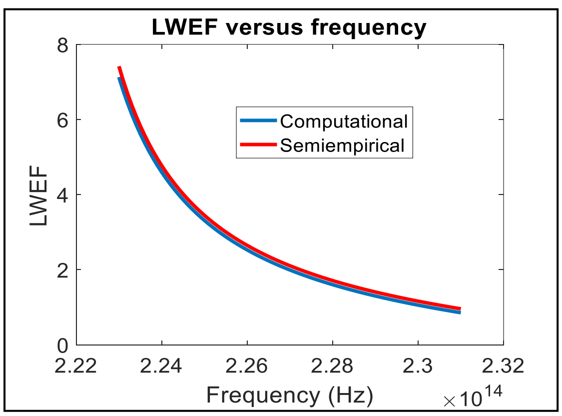

Fig. 1. Comparison of the LWEF variation versus frequency based on numerical computation and semiempirical values.

The steady state values of the LWEF are plotted against frequency in Figures 2-3 for different QW carrier densities N_{QW}, and ratios of the active region volume to the total volume occupied by the wells $\kappa = V_{active}/V_{well}$ within the operation bandwidth of lnP-lnGaAsP MQW-SOAs. The LWEF is observed to decrease with increasing values of N_{QW} and κ, confirming experimental observations [1,4].

$V_{well} = (M \times v_{well})$, v_{well}: *Single well volume*

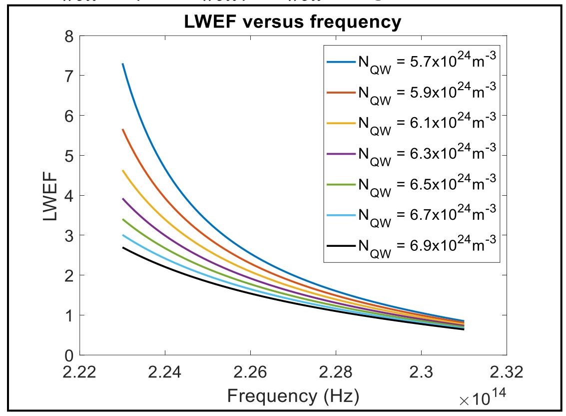

Fig. **1**. Variation of the LWEF against frequency for different carrier densities within the quantum wells.

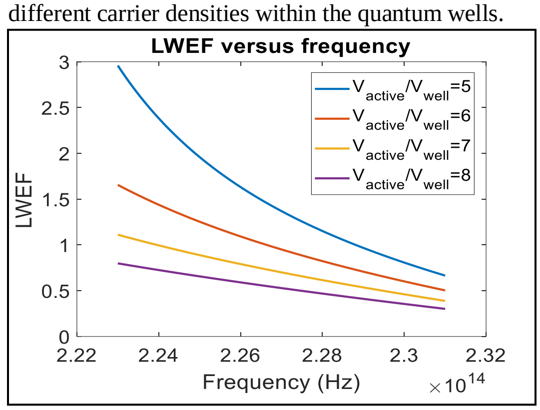

Fig. 2. Variation of the LWEF against frequency for high ratios of the active region volume to the total QW volume.

CONCLUSION

A straightforward computational procedure is outlined for estimating the LWEF of an MQW-SOA in time. The presented procedure enables fast computation of the LWEF with high accuracy and requires fewer input parameters.

REFERENCES

[1] J. Miloszewski, M. Wartak, P. Weetman, O. Hess, *Analysis of linewidth enhancement factor for quantum well structures based on InGaAsN/GaAs material system*, Journal of Applied Physics. 106, 063102 (2009)

[2] A. Sobhanan et al., *Semiconductor optical amplifiers: recent advances and applications*, Advances in Optics and Photonics. 14, 571 (2022)

[3] Aşırım, Ö.E., Huber, R., Jirauschek, C, *Influence of the linewidth enhancement factor on the signal pattern of Fourier domain mode-locked lasers*, Appl. Phys. B**.** 128, 218 (2022)

[4] K. Vahala, L. Chiu, S. Margalit, A. Yariv, *On the linewidth enhancement factor α in semiconductor injection lasers*, Applied Physics Letters. 42, 631 (1983)

[5] C. Ri, C. Kim, Y. Oh, S. Kim, *Immediate estimation of feedback factor and linewidth enhancement factor from measured self-mixing signals under moderate or strong regime*, Measurement Science and Technology. 31, 065204 (2020)