

Studies on Device Performance of Optical Filters and Semiconductor Lasers for Optical Communications

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学 位 論 文 要 旨

ABSTRACT

Semiconductor lasers and optical waveguide filters are key devices in optical communication systems. The former are the most important light sources in the transmitter side, while the latter are essential for wavelength-divisions-multiplexing (WDM) switching networks. Further improvement of performance of the devices contributes to further development of the communication systems. In this regard, two methods capable of designing optical waveguide filters for any desired spectral response have been proposed. Both methods were based on approximating the reflection coefficient to the Fourier transform of the corresponding spatial variation of the effective refractive index, which was then translated into variation of either the corrugation depth or width. One method was based on modulating the depth of the corrugation structure, while the other modulated the corrugation width. Two numerical examples to design two- and four-rejection band filters were given. On the other hand, two important physical properties affecting performance of laser diodes have been analyzed, namely the optical gain and the quantum noise. The optical gain was analyzed based on an infinite-order perturbation approach. The analysis is based on the semiclassical density matrix analysis. Forms of the expansion orders of the gain coefficient were shown. The reported gain formulation led to the approximated reported forms in the corresponding approximation limits. Computer simulation of gain was given. Based on the numerical results, (1) simple mathematical forms of gain were proposed, and (2) accuracy of approximating the infinitely expanded gain to finite ones was examined, so that limit of application of the recent third-order approach was investigated. Analysis of quantum noise was based on a time-analysis approach. A new method was proposed to construct the Langevin noise sources of the photon and carrier numbers, and then time integration of their noise-driven rate equations was carried out. The real time fluctuations of the photon number, carrier number and output power, as well as their dependence on the injection current were shown. The high-frequency spectrum of quantum noise was then obtained applying the fast Fourier transform (FFT) technique and was found to fit well the spectrum calculated by applying the conventional frequency-analysis approach. The proposed model can be considered as a good basis to analyze mode-competition and feedback noise in semiconductor lasers.

1. DESIGN METHODS OF OPTICAL CORRUGATED WAVEGUIDE FILTERS

1.1. Introduction

Waveguide filters can be designed by periodically or aperiodically perturbing a suitable waveguide parameter.¹⁻³ We propose simple analytical methods to design optical corrugation waveguide filters characterized by either varied depth and constant depth, or varied width and constant depth. The basis of the designing techniques is a combination of the effective index approach, the Fourier transform and the F-matrix method. By applying the proposed methods, it is possible to yield the filter corrugation profile required to attain any desired spectral response characteristics.

1.2. Approximate Definition of the Reflection Coefficient

The considered waveguide is a planar type having a surface corrugation along the propagation z -axis with a pitch of almost $\lambda_0/2n_{eff}$, where λ_0 is the filter center frequency and n_{eff} is the effective refractive index, Fig. (1-1). The averaged core thickness is \bar{d} . By assuming propagation of only the fundamental mode of TE polarization, the propagated field in the waveguide is described by

$$E(y, z, t) = [U(z)e^{-j\beta z} + V(z)e^{j\beta z}]F(y)e^{j\omega t} \quad (1-1)$$

where $U(z)$ and $V(z)$ are the amplitudes of the forward and backward propagating waves, the normalized function $F(y)$ describes the field distribution in the y -direction determined in the nonperturbed (uniform) limit, and $\beta = k_0 n_{eff}$ is the propagation constant in the z -direction. Substituting Eq. (1-1) into the Maxwell's equations, leads to the next definition of variation of the effective refractive index

$$\Delta n_{eff}(z) = \int_{-\infty}^{\infty} [n(y, z) - n_i] |F(y)|^2 dy \quad (1-2)$$

where $i=1$ and 2 corresponds to the core and cladding regions, respectively. The variation $\Delta n_{eff}(z)$ is then proved to approximately determine the corresponding spectral variation of the reflection coefficient

$$r(\beta) = \frac{V(-L/2)}{U(-L/2)} = -j \frac{2\pi}{\lambda} \int_{-L/2}^{L/2} \Delta n_{eff}(z) e^{-2j\beta z} dz \quad (1-3)$$

Then getting an arbitrary profile of $r(\beta)$, $\Delta n_{eff}(z)$ is determined by means of the inverse Fourier transform IFT . The variation $\Delta n_{eff}(z)$ is then translated to variation of the corrugation depth $\Delta d(z)$ by applying Eq.(1-2).

The F-matrix method is applied to get more accurate description of $r(\beta)$ corresponding to the calculated profile $\Delta d(z)$. We assume that the corrugated region is divided into N thin parallel sections in the z -direction. Length and core width of the i th ($i=1, \dots, N$) section are $l^{(i)} = z^{(i+1)} - z^{(i)}$ and $d^{(i)}$, respectively.

The field distribution $F(y)$ is assumed constant through the guiding region, while $\beta^{(j)}$ and the optical impedance $Z^{(i)} = k_o \sqrt{\mu_o / \varepsilon_o} / \beta^{(i)}$ suffer variation due to surface corrugation. The reflection coefficient can be expressed more accurately by

$$r(\beta) = \frac{A+B/Z^{(N+1)} - [C+D/Z^{(N+1)}]Z^{(o)}}{A+B/Z^{(N+1)} + [C+D/Z^{(N+1)}]Z^{(o)}} \quad (1-4) \quad \text{with} \quad \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_{i=1}^N \begin{bmatrix} \cos(\beta^{(i)}l^{(i)}) & jZ^{(i)}\sin(\beta^{(i)}l^{(i)}) \\ j/Z^{(i)}\sin(\beta^{(i)}l^{(i)}) & \cos(\beta^{(i)}l^{(i)}) \end{bmatrix} \quad (1-5)$$

1.3. Proposed Design Method of Waveguide Filters Having Depth-Varied Corrugation

Using the above results, we propose a method to design corrugated waveguide filters that correspond to any desired spectral response $r(\beta)$. First, the desired profile $r_o(\beta)$ is specified. Then using *IFT* of Eq. (1-2), the approximated profile of $\Delta n_{eff}(z)$ is obtained, which is then translated to variation of the corrugation depth $\Delta d(z)$. The approximated spectral response $r(\beta)$ is then calculated more accurately by applying Eq. (1-4), and is then compared to the expected profile $r_o(\beta)$. Good fit between both profiles is obtained by either modifying the initial setting $r_o(\beta)$ or modulating the designed profile $\Delta d(z)$.

1.4. Design Method of Waveguide Filters Having Width-Varied Corrugation

Realization of the above designed depth profile may be difficult, so we propose here a technique to transform to a width-varied corrugation structure while the depth is kept constant based on the F-matrix analysis. Another design technique modulating the width is then proposed. First, the continuous variation of the corrugation depth is transformed to the corresponding square variation. Then the profile is transformed to another equivalent profile $\Delta d'(z)$ obtained by nullifying the negative $\Delta d(z)$ -values and doubling the positive ones. Each section having positive $\Delta d(z)$ is then transformed to three subsections characterized by either of two widths $p^{(i)}$ or $q^{(i)}$, two corrugation depths Δd_i or 0, two propagation constants β_i or β , respectively while the pitch is kept constant, i.e.,

$$\beta_i p^{(i)} + \beta (2q^{(i)} + \ell^{(i+1)}) = \pi \quad (1-6)$$

By equating the F-matrix of each section to the multiplication of those of the transformed subsections, the widths $p^{(i)}$ or $q^{(i)}$, are determined and $r(\beta)$ is calculated in the F-matrix analysis.⁴

The proposed technique to design the varied-width corrugation waveguide filter follows the same steps of the last method, except that (1) the width profile $P^{(i)}$ is calculated from the depth one $\Delta d(z)$, and (2) the modulation is applied to the width profile rather than the depth one.

Figure (1-2) shows application of both methods to design a four-rejection-band *AlGaAs* filter. As shown, good fit is obtained between the desired characteristics and the calculated ones.

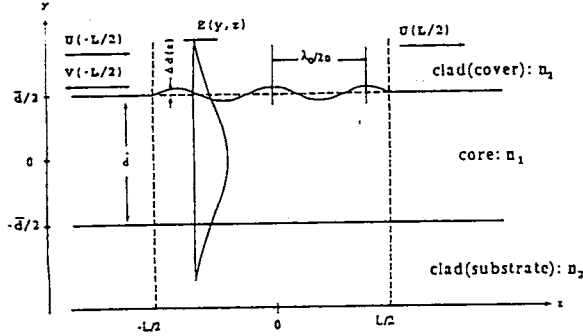


Fig. (1-1). Schematic diagram of the proposed waveguide filter

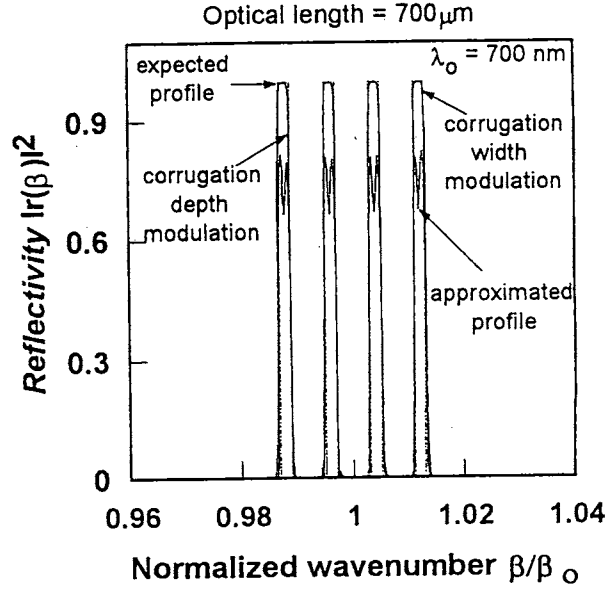


Fig. (1-2). Comparison between the expected optical spectral profile $r_o(\beta)$, the approximated profile Profile $r(\beta)$, and profiles obtained by both methods of modulating the corrugation width and depth.

2. THEORETICAL ANALYSIS OF NONLINEAR GAIN IN SEMICONDUCTOR LASERS

2.1 Introduction

In semiconductor lasers, nonlinear dependence of optical gain on laser intensity affects significantly performance of the device. Accurate analysis of gain is inevitable to improve device characteristics. The recent third-order perturbation approaches of gain are well applied in normal operation of lasers.⁵ However, their accuracy may degenerate when applying to recent and future developed lasers that are based on the microcavity structure.⁶ In the present work, we apply an infinite-order perturbation approach in terms of the field intensity to analyze gain in general. The results are checked by comparing to the previous gain analysis. Furthermore, possibility of approximating the infinite gain expansions to finite ones and the associated accuracy are examined.

2.2. Infinite-Order Perturbation Approach

In the present approach, the semi-classical density matrix analysis is applied. The electric component $E(r, t)$ of the optical field is treated classically, while the material is treated quantum mechanically where

the polarization induced by the field is given as a quantum observation of dipole moment operator R . The dynamic equation of the density matrix operator ρ including the stimulated and spontaneous transitions, the intraband relaxation and the injection of electrons is given by⁵

$$\frac{d\rho}{dt} = \frac{1}{j\hbar} [H_o - R \cdot E, \rho] - \frac{1}{2} [(\rho - \tilde{\rho})\Gamma_s + \Gamma_s(\rho - \tilde{\rho})] - \frac{1}{2} [(\rho - \tilde{\tilde{\rho}})\Gamma_s + \Gamma_s(\rho - \tilde{\tilde{\rho}})] \quad (2-1)$$

where Γ_s and Γ_{in} are for the spontaneous and stimulated emission, respectively, Λ is an operator for the carrier injection, and $\tilde{\rho}$ and $\tilde{\tilde{\rho}}$ are given by the Fermi-Dirac distributions at thermal equilibrium and quasi-equilibrium, respectively. In the present analysis, the rate equation (2-1) is solved by applying an infinite-order expansion in terms of the field intensity,

$$\rho = \rho^{(0)}(E) + \rho^{(1)}(E) + \rho^{(2)}(E^2) + \dots + \rho^{(2k)}(E^{2k}) + \rho^{(2k+1)}(E^{2k+1}) + \dots, \quad k \geq 0, \quad (2-2)$$

where the odd-orders determine the polarization and gain, while the even-ones determine the injected carrier density $N^{(0)}$ and injection current I . The gain is then infinitely expanded as

$$g_m(E_n) = g_m^{(1)} + \sum_{k=1}^{\infty} (-1)^k g^{(2k+1)} |E|^{2k} \quad (2-3)$$

The obtained forms of the general expansion order $g^{(2k+1)}$, $k \geq 0$, of the gain coefficient is

$$g^{(2k+1)}(E^{2k+1}) = \frac{\xi^{k+1}}{V_I^k} \frac{\omega}{\hbar \tau_{in} n_I} \sqrt{\frac{\mu_o}{\epsilon_o}} \chi \int_{E_s} \frac{|R_{ab}|^{2(k+1)}}{\hbar^{2k}} \frac{g_{cv}(\hbar\omega_{ba}) [f_c(\hbar\omega_{ba}) - f_v(\hbar\omega_{ba})] \left(\frac{2(\tau_c + \tau_v)/\tau_{in}}{(\omega - \omega_{ba})^2 + 1/\tau_{in}^2} \right)^k d(\hbar\omega_{ba}) \quad (2-4)$$

τ_c and τ_v are the intraband relaxation time in the conduction and valence bands, while τ_{in} is for the polarization relaxation. $\xi^{(2k+1)}$ is the $(2k+1)$ th-order of the power confinement ratio in the active region.

When assuming plane-wave fields, the gain expansion (2-3) can be summed up and lead to the next reported formulas in approximation limits of homogeneous and inhomogeneous gains broadening,

$$g(E) \approx g^{(1)} \left/ \left[1 + \frac{2(\tau_c + \tau_v)\xi\tau_{in}|R_{ba}|^2}{\hbar^2} |\overline{E}(t)|^2 \right] \right. \quad (2-5)$$

Which fits the form by Suematsu and Yamada⁷ and Yariv.⁸

$$g(E) \approx g^{(1)} \left/ \sqrt{1 + \frac{2(\tau_c + \tau_v)\xi\tau_{in}|R_{ba}|^2}{\hbar^2} |\overline{E}(t)|^2} \right. \quad (2-6)$$

Which is reported by Yariv⁸ and Agrawal⁹ in a single mode operation by an unperturbed technique.

2.3. Computer Simulation of Gain

As numerical examples, *AlGaAs* semiconductor lasers at room temperature are considered. The assumption of $\tau_c = \tau_v = \tau_{in}$ is used. The linear gain $g^{(1)}$ is calculated via Eq. (2-4) when $k=0$ as functions of the injected carrier density $N^{(0)}$. By assuming the laser be vibrating at the frequency

corresponding to the peak $g^{(1)}$, the higher orders of the gain coefficient $g^{(2k+1)}$, $k \geq 0$, are then calculated. They are plotted as functions of $N^{(0)}$ in Fig. (2-1). The calculated data of the infinite expansion orders of the gain coefficients are fitted by the following simple linear functions of $N^{(0)}$ around the peak of $g^{(1)}$

$$g^{(1)} \approx a^{(1)} \xi^{(1)} \left\{ N^{(0)} - N_g^{(1)} - h^{(1)} \hbar [\omega - \omega_o]^2 \right\} \quad (2-7)$$

$$g^{(2k+1)} \approx 4^k \xi^{(2k+1)} / [V^k (1+k)] a^{(1)} |R|^{2k} (\tau_{in}/\hbar)^{2k} \left\{ N^{(0)} - N_g^{(2k+1)} \right\} \quad , \quad k \geq 1, \quad (2-8)$$

where h , $N_g^{(1)}$, $N_g^{(3)}$, $N_g^{(5)}$, etc., are fitting parameters. These fitting relations are plotted in Fig. (2-1) by dashed lines. The $(2k+1)$ th order of the confinement factor $\xi^{(2k+1)}$, $k \geq 0$, is determined in Fabry-Perot lasers as

$$\xi^{(2k+1)} = \left[(2k+1)! / 2^k k! (k+1)! \right]^2 \xi_y^{(2k+1)} \quad (2-9)$$

where ξ_y is the confinement factor in the y-direction.

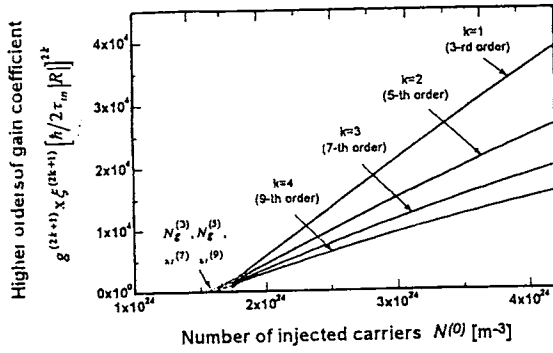


Fig. (2-1). Plot of $g^{(2k+1)}$, $k=1,2,3,4$, as functions of $N^{(0)}$. The dashed lines plot the fitting relations (2-7) and (2-8).

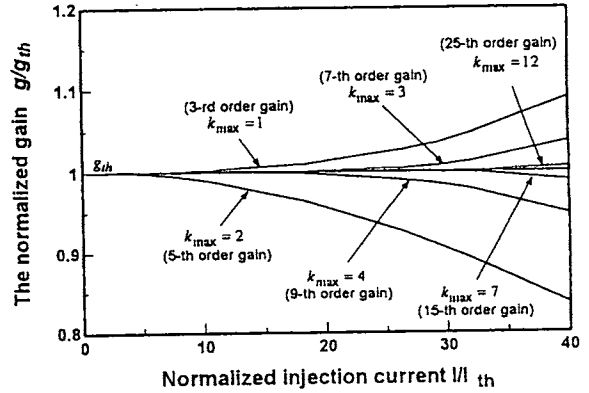


Fig. (2-2). Plot of 3rd, 5th, 7th, 9th, 15th, 25th-order gain expansions. The third-order gain is accurate at low I , while its accuracy degenerates as I increases.

Here we examine the possibility of approximating the infinite-order gain by finite expansions. The lasing power $|\overline{E}|^2$ is determined by applying the oscillation condition, $g(E)=g_{th}$, as function of the injection current I . Then the gain $g(E)$ is calculated via Eq. (2-3), using Eqs. (2-7) and (2-8), by truncating the expansion up to different higher orders. The obtained data are compared to the infinite gain in Fig. (2-2). The results indicate that: up to current of to 2.5 times its threshold I_{th} , i.e., convenient lasers, the gain suppression is represented well by the third order with accuracy of 0.2 %. At

higher current, higher orders of the gain expansion has to be included in order to get accurate analysis.

3. ANALYSIS OF INTENSITY FLUCTUATION AND QUANTUM NOISE IN SEMICONDUCTOR LASERS

3.1. Introduction

Fluctuations on output of laser diodes limit their performance in application systems. Analysis of the intensity fluctuations and the associated noise is theoretically done by numerical integration of the rate equations driven by correlated noise sources for photon and carrier numbers. However, there was no clear method to construct these correlated noise sources, except that by Marcuse.¹⁰ Analysis of noise based on this time approach was also lacked. In this work, we present a theoretical model and computer simulation to analyze the intensity fluctuation. The model can be considered as a correct basis to analyze the mode-competition and feedback noise. We present a new technique to construct the correlated photon and carrier noise sources. Furthermore, we newly analyze the quantum noise based on the direct time approach and compare the results to the frequency approach of noise.¹¹

3.2. Theoretical Model

The conventional Langevin noise-driven rate equations of the photon number $S(t)$ and carrier number $N(t)$, which account for their fluctuations due to their quantum nature are

$$\frac{dS}{dt} = \left[a\xi \left(\frac{N}{V} - N_g \right) - G_{th} \right] S + \frac{N}{\tau_s} C + F_s(t) \quad (3-1) \quad \frac{dN}{dt} = -a\xi \left(\frac{N}{V} - n_g \right) S - \frac{N}{\tau_s} + \frac{I}{e} + F_e(t) \quad (3-2)$$

The Langevin noise sources $F_s(t)$ and $F_n(t)$ are Gaussian random variables with zero mean, and are δ -correlated. Numerical integration of the stochastic differential equations (3-1) and (3-2) requires defining forms of $F_s(t)$ and $F_n(t)$. We devised a new technique to generate these correlated noise sources. The basis is to define the carrier random source $F_n(t)$ using its variance, and then make orthogonality between $F_n(t)$ and a built fluctuation function $\{F_e(t) + kF_s(t)\}$ using a suitable k -value. The quantum intensity noise is calculated in terms of the RIN using the time-fluctuation of the output power $P(t)$.

3.3. Numerical Simulation

The numerical integration was performed applying the 4th order Runge-Kutta algorithm using a time interval of 10 ps for *AlGaAs* lasers. The fluctuated power $P(t)$ under CW operation is shown in Fig. (3-1). The amplitude of the fluctuation decreases with increasing the current I . The high-frequency spectrum of *RIN* is calculated for the power fluctuations using the fast Fourier transform, and is

compared in Fig. (3-2) to that calculated by the conventional frequency analysis.¹² Both characteristics are in good fit.

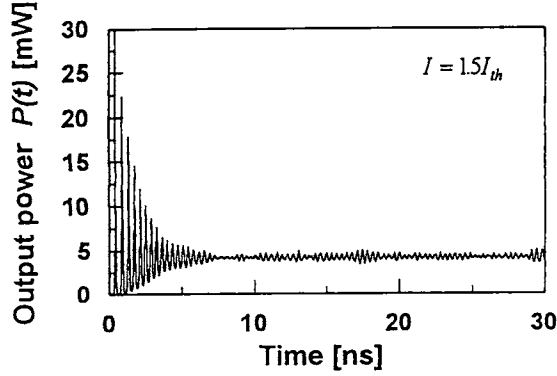


Fig. (3-1). The time fluctuation of the output power at injection current $I = 1.5 I_{th}$.

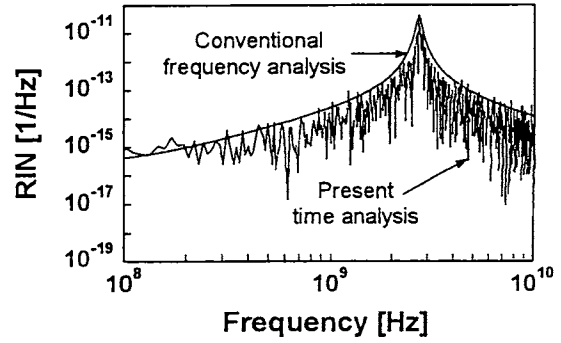


Fig. (2-2). Comparison between RIN using the time and frequency approaches.

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学位論文審査結果の要旨

提出された論文や資料に基づき、平成11年7月28日に第1回審査委員会、平成11年8月5日に口頭発表(英語)と最終審査を行った。

本論文は、光通信や光エレクトロニクスにおける基本デバイスに関する2種の課題を研究したものである。

光フィルタは光ファイバ通信での波長多重方式において、合波器や分波器となるデバイスである。これまで、光フィルタの設計は、素子の構造や屈折率分布を定めてから伝搬特性を解析する方法であり、設計できる特性に一般性がなかった。本研究では、最初に要望される特性を与え、それを周期的に変化する導波路幅の振幅や周期を変調して、要望される特性を実現する設計方法を提案し、その理論解析例も示した。

半導体レーザは光ファイバ通信などの各種光エレクトロニクスにおける発光源である。発振動作中の半導体レーザでは、光電界によりレーザ利得が飽和している。レーザ動作は、量子統計学の一手法である密度行列を用いて解析され、光電界の3次摂動項までを考慮して、利得飽和効果が解析されていた。しかし半導体レーザの微少化が進むと、注入電子密度レベルが増加するので、3次摂動項まででは飽和効果の解析が不十分になる。本研究では、高次摂動項の一般的形式を見つけだし、無限次摂動項までの級数和によって、飽和効果を正確に求める方法を示した。また、級数和を有限で打ち切った場合の適用範囲についても検討した。

本論文の研究は、基本的な理論解析から始め、その成果は当該分野での技術開発に貢献できるものである。したがって、博士(学術)の学位を受けることに値するものと判定した。