Research of Frequency Characteristics and Temperature Drift Power Quantum-Well Lasers

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Abstract. In the following paper results of AFC (amplitude-frequency characteristics) and PFC (phase-frequency characteristics) and temperature drift studies as well as of time delay of CW and impulse signals in QW InGaAs lasers with CW output power more than 1W at direct modulation are given. It is demonstrated, that power QW lasers can potentially surpass their low-power analogues and DH lasers on one of the major parameters – product of the maximum modulating frequency (bandwidth) and output modulated RF power. The developed analytical mechanism considers QW power lasers’ working features in a static and dynamic mode and enables us to calculate AFC, PFC, their temperature drift and delay of modulating signals with a sufficient for engineering calculations accuracy.

1. Introduction

In a modern radar, communication and radio-astronomy it is the equipment on the basis of nanophotonics that is increasing in its application possessing significant advantages in comparison to the traditional electronic one[1]. Nanophotonic equipments usually apply to realization of transferring pathes of the big capacity low-power DH lasers with direct or external modulation with the subsequent strengthening the modulated optical signal by semi-conductor or fiber optical amplifiers. However optical amplifiers have efficiency of approximately 10 % [2]. Meanwhile modern quantum-well (QW) power lasers have efficiency of 70 % and more [3]. In order to realize high-power transmitting paths of nanophotonic equipment the low-power heterolasers - with direct or external modulation and with the following amplification of the modulated optical signal by semiconductor or fiber-optical amplifiers - are utilized. Therefore it is an issue of great interest to estimate potential frequency characteristics and AFC and PFC temperature drift of QW power lasers with wavelengths of 0,85 - 1,05 μm, which correspond to maximum quantum efficiency of modern photodetectors modulated directly with a radio-frequency signal. However, nowadays only frequency characteristics and their temperature drift of low-power DH lasers of various types have been well-studied under direct modulation with a radio-frequency signal [4-6]. This is due to a much greater complexity in construction of a dynamic model of QW power lasers, as it is necessary to simultaneously take into consideration a lot of parameters, neglecting of which facilitated considerably the analysis of low-power lasers. In addition, experimental check seems problematic, because of significantly greater influences of parasitic elements of the equivalent circuit of power lasers themselves as well as their modulator circuits.

2. AFC and PFC of QW power lasers

By solving total system of the rate equations and implementing the multifactorial analysis of time dependences of QW power lasers’ internal parameters from table 1, analytical expressions for calculation AFC and PFC in a wide frequency range have been received in explicit form. Results of modeling for a power single-mode InGaAs QW SCH "internal" laser at low-signal modulation (up to 70 %) of AFC and PFC at various relations of bias currents to a threshold current are presented in
Fig. 1 (a) and (b) respectively. In order to perform a quantitative check of the calculation method offered, the experimental results, received for QW power lasers with similar resonator length $L = 3\, \text{mm}$, with the bias current ratio $I/I_\text{th}$ and working temperature at the continuous operating mode, were used (these results are shown in [7]). The results utilized confirm sufficient correspondence to the theory: the maximal deviation does not exceed 15%. As these experimental results were received by measuring the level of relative noise of the RIN laser without a modulating signal, they reflect potential dynamic properties of power heterolasers without the influence of the circuit parasitic elements.

**Table 1. QW SCH Characteristics of LD structures**

| Parameter                        | Symbol | Value                     | Unit |
|----------------------------------|--------|---------------------------|------|
| Forbidden bandwidth              | $h_\nu$| 1.16-active area of a 1.42-wave guide of 1.8-emitters | eV   |
| Active area volume               | $V_a$  | $2.96*10^{-15}$          | m$^3$|
| Resonator length                 | $L$    | 3000                      | Mm   |
| Resonator width                  | $W$    | 100                       | μm   |
| Confinement factor               | $\Gamma$| 0.008-0.01               | -    |
| Mirror reflectivity 1            | $R_1$  | 0.05                      | -    |
| Mirror reflectivity 2            | $R_2$  | 0.95                      | -    |
| Intrinsic loss                   | $\alpha_i$| 0.34                     | cm$^{-1}$|
| Differential gain                | $g_0$  | $1.32*10$                 | m$^3$/c|
| Nonlinear gain suppression       | $\varepsilon$| $7.0*10^{-23}$ | m$^3$|
| Effective carrier lifetime       | $\tau_{\text{eff}}$| $1.5*10^{-9}$ | S    |
| Photon lifetime                  | $\tau_p$| $25.5*10^{-12}$         | s    |
| Transparency density             | $N_t$  | $8.0*10^{-23}$           | m$^{-2}$|
| Characteristic temperature       | $T_\text{eo}$| 110                     | °K   |
| Threshold current                | $I_{\text{th}}$| 430                     | mA   |
| Drive current at output power 6 W| $I_n$  | 7000                      | mA   |
| Differential quantum efficiency  | $\eta_d$| 1000                     | mW/mA|

Fig. 1 Analytical solutions of AFC (a) and PFC (b) of QW SCH InGaAs "internal" power laser, without parasitic elements, at various relations of bias currents to a threshold current $I/I_\text{th} = 1.67, 8.73 \text{ and } 18.56$ respectively at low-signal (up to 70%) modulation and the temperature of $+20^\circ\text{C}$.  

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The potential transmission efficiency $T_{ef}$ (that equals to product of target capacity $P_o$ and resonant frequency $f_o$, i.e. $T_{ef} = P_o * f_o$) comparison of typical QW power lasers and the low-power lasers specially optimized for generation of the maximum value $f_o$ (the maximum operation speed) yields the following results. From [8] for the low-power laser we have: at $I/I_{th} = 1.8$: $T_{ef} ≈ 0.92 * 4.65 ≈ 4.3$ GHz * mW. For the power laser [7] at $I/I_{th} = 1.7$: $T_{ef} ≈ 30 * 1.14 ≈ 34.2$ GHz * mW. For the low-power laser from [9] at $I/I_{th} = 9$ we have: $T_{ef} ≈ 11 * 4.7 ≈ 51.7$ GHz * mW, for the power laser [7] at $I/I_{th} = 9$: $T_{ef} = 300 * 2.91 ≈ 873$ GHz * mW.

For the power laser with the parameters given in table 1 it is possible to assess: at $I/I_{th} ≈ 9$: $T_{ef} ≈ 3000 * 3.17 ≈ 9510$ GHz * mW, i.e. $~ 10^3$ THz * mW.

Thus, it is possible to draw the following conclusion: QW power lasers, for example InGaAs QW SCH, potentially surpass low-power analogues and DH lasers in one of the major parameters - product of the maximum modulated frequency (bandwidth) output power and radio-frequency of modulation.

3. Temperature Drift Power Quantum-Well Lasers

Owing to the solution of total system of the rate equations and the multifactorial analysis of time and temperature and bias ($S_0$, $S_0(T,I)$), $\chi(T)$, $\tau_p(T)$, $\tau_{ef}(T)$, analytical expressions for calculation AFC and PFC and their temperature drift in a wide frequency and temperature range have been received in an explicit form.

For a single mode InGaAs QW SCH "internal" power laser at low-signal modulations with no optical feedback, AFC and PFC depending on temperature, bias current and frequency will be:

$$|A(T,I,\omega)| = \frac{g_{x}(T)S_{0}(T,I)}{\chi(T)\tau_{p}(T)(1+\varepsilon S_{0}(T,I))\left(1+\frac{\varepsilon}{g_{x}(T)\tau_{ef}(T)}\right)};$$

$$\varphi(T,I,\omega) = -\arccos\left[\frac{g_{x}(T)S_{0}(T,I)}{\chi(T)\tau_{p}(T)(1+\varepsilon S_{0}(T,I))\left(1+\frac{\varepsilon}{g_{x}(T)\tau_{ef}(T)}\right) - \omega^2} \right];$$

where:

$$D = \left[\frac{g_{x}(T)S_{0}(T,I)}{\chi(T)\tau_{p}(T)(1+\varepsilon S_{0}(T,I))\left(1+\frac{\varepsilon}{g_{x}(T)\tau_{ef}(T)}\right)} - \omega^2\right]^2 +$$
\[
\Delta \tau = -\frac{\phi(T,I,\omega)}{360 \cdot f};
\]

where: \( f \) is modulation frequency.

The size of time drift \( \Delta \tau \) PFC can be expressed through the phase drift by using the formula:

Some results of mathematical modelling are given in (fig. 2) and (fig. 3). In fig. 2 there is an example of 3D amplitude surface \( A(\omega, T) \) construction, calculated by the formula (1), as functions of frequency in a range from 0 to 10 GHz and temperatures in range from +20 to +80 °C, for the laser with parameters from tab. 1 and bias current \( I = 5 \) A and \( (I / I_{th} = 10) \). In fig. 3 there is an example of 3D phase surface \( \phi(\omega, T) \) construction, calculated by the formula (2), as functions of frequency in range from 0 to 10 GHz and temperatures in range from +20 to +80 °C for the similar laser with bias current \( I = 5 \) A and \( (I / I_{th} = 10) \).

4. Conclusions

It has been shown that high-power QW lasers potentially surpass low-power analogues in one of the major parameters - product of the maximum modulating frequency (bandwidth) and output modulated RF power. Also the method of AFC and PFC calculation for QW power lasers as well as of their temperature drift at direct modulation by RF signal has been developed giving sufficient accuracy for engineering calculations. Directly modulated quantum-well high-power lasers can be applied in transmitting paths of...
nanophotonic transmitters of radio-fibre systems (RoF), including systems of the broadband wireless Internet with large coverage range (WiMAX) and open laser communication systems.

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