Analysis of the stable two-mode operation of a 4-sections semiconductor laser for THz generation by photomixing

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***Abstract*— The stable two-mode operation of a 4-sections semiconductor laser emitting at 1.55 μm is demonstrated and analysed. The two-mode operation only depends on the current feed in the Bragg section. We interpret this special behaviour by the presence of a saturable absorber within the structure. An original model based on Lamb's theory which take into account of a saturable absorber equation is developed in order to confirm our hypothesis. The characterization of the two-mode laser operation exhibits the possibility of terahertz (THz) wave generation by photomixing using this device.**

***Index Terms*— Two-mode operation, 4-sections lasers, Lamb's theory, photomixing, terahertz .**

I. INTRODUCTION

IN this paper, we report on a 4-sections laser structure able to operate continuously in a two-mode regime for photomixing THz applications. This solution was already explored at shorter wavelengths with LT-GaAs photodevice as rectifiers. We consider here the later case but apply at the 1.55 μm wavelength in order to take benefit of the future ultrahigh bandwidth uni-traveling carrier photodiodes [1] or of newly developed THz photoconductor from ion-implanted InGaAs [2], [3].

We have experimentally characterized the stable two-mode operation of the 4-sections semiconductor DBR laser and we propose here a physical explanation to this uncommon behavior. Indeed, theoretical studies of semiconductor laser dynamic have well illustrated only recentlythe possible multimode behavior of semiconductor lasers [4]–[6] just like it has long been observed experimentally. But a stable two-mode operation has never been predicted with laser parameters consistent with existing technologies. This is in accordance with a strong coupling between longitudinal modes of a semiconductor laser that is partly related to the ultrashort intraband-relaxation time ($\approx$ 100 fs). We thus postulate the origin of this stable two-mode regime outside the usual laser model, namely by considering that a parasitic saturable absorber had been accidentally brought by the implanted areas used for insulation between the various laser sections. We discuss this hypothesis in depth by means of the classical Lamb theory of two-mode lasers [7].

II. THE 4-SECTIONS DBR LASER

The device is a classical 3-sections DBR laser (gain, phase and Bragg sections) with an additionnal integrated amplifier section. The Semiconductor Optical Amplifier (SOA) and the gain section are built with the same 6 InGaAs quantum wells (QW) epilayer while phase and distributed Bragg reflector (DBR) sections are obtained after etching and localized regrowth processes [8]. Optical gain is provided by the current I_{Gain} in the multiple QW. The laser beam is filtered by the DBR that imposes the emission wavelength (λ_{Bragg}) owing to the injection current I_{DBR}. The phase section inserted between gain and DBR sections allows a fine tuning of the emission wavelength by the electro-optical modification of the effective index through the current I_{ϕ}. Each section is electrically insulated from its neighbour using electron implantation on a few μm length area. The SOA section is bended and AR coated at its end to reduce simultaneously the beam divergence and drastically kill any optical feedback towards the DBR. A high reflectivity coating is deposited on the rear facet to increase the photon lifetime in the 3-section DBR laser. Complete performances (16 nm tunability and 55 mW output power) of this device are described in details elsewhere [8].

III. EXPERIMENTAL SET-UP

The experimental set up starts from a Suss PM5 Prober that allows to simultaneously supply the different currents to the laser and to couple the optical output of front and rear facets using specific microlens [9]. The main advantage of the selected configuration is to show that the two-mode operation doesn't require the SOA section. Indeed, we measured a two-mode laser operation on both sides (rear and front facet) of the device whatever the value of the SOA injected current I_{SOA}, especially for $I_{\mathrm{SOA}} = 0$ mA. The major conclusion of this primary experiment was to reject the hypothesis of an imperfect antireflection coating at SOA end facet. Such a reflection would have cause the 4-sections DBR laser to behave as a coupled cavity device that is well known to operate frequently in two-mode regime. The occurrence of a stable two-mode regime should thus be ascribe to the 3-sections DBR only, the SOA section contribution being assumed subsequently to be a perfectly linear amplifier.

During all experiments, the working temperature was controlled owing to a thermoelectric cooler and stabilized within a few hundredth of Kelvin. The optical output was fed in an optical spectrum analyzer. The injection current was limited for each section of the device in order to avoid any destructive damage, namely $I_{\mathrm{SOA}_{\max}} = 150$ mA, $I_{\mathrm{Gain}_{\max}} = 100$ mA, $I_{\mathrm{DBR}_{\max}} = 50$ mA, $I_{\phi_{\max}} = 30$ mA.

IV. Measurement results

When increasing I_{DBR} from 10 mA to 50 mA, we observed a succession of very different spectral behaviors of the 4-sections DBR laser (see Fig. 1). Transition from stable monomode generation to stable two-mode generation were registered together with their reverse transition. This was obtained while keeping all other parameters constant ($T =$ 300 K, $I_{\mathrm{SOA}} = 100$ mA, $I_{\mathrm{Gain}} = 80$ mA and $I_{\phi} = 0$ mA). More precisely the laser is strictly monomode everywhere excepted for I_{DBR} close to 30 mA and to 40 mA. Usually the tuning process performed by I_{DBR} is to put in coincidence the Bragg maximum reflection and a Fabry-Pérot (FP) mode of the 3-sections laser. This behavior was observed with I_{DBR} increasing from 10 mA to 30 mA with a continuous singlemode tuning of the output from 1.550 μm to 1.554 μm over three FP mode hopping; the spacing between adjacent modes being $\delta\nu \approx 100$ GHz in this structure. Similar features were obtained for 30 mA $< I_{\mathrm{DBR}} <$ 40 mA and for $I_{\mathrm{DBR}} >$ 40 mA.

To the contrary, around $I_{\mathrm{DBR}} \approx 30$ mA and $I_{\mathrm{DBR}} \approx$ 40 mA, a stable two-mode laser operation is measured, the two modes being separated by $\delta\nu \approx 100$ GHz, with balanced powers. This two-mode laser operation must be first attributed to the filtering of the DBR that roughly select two adjacent FP modes. We confirmed this assumption when observing that the two lasing modes at $I_{\mathrm{DBR}} \approx 30$ mA where just shifted of $\delta\nu \approx 100$ GHz from the two lasing lasing modes at $I_{\mathrm{DBR}} \approx 40$ mA.

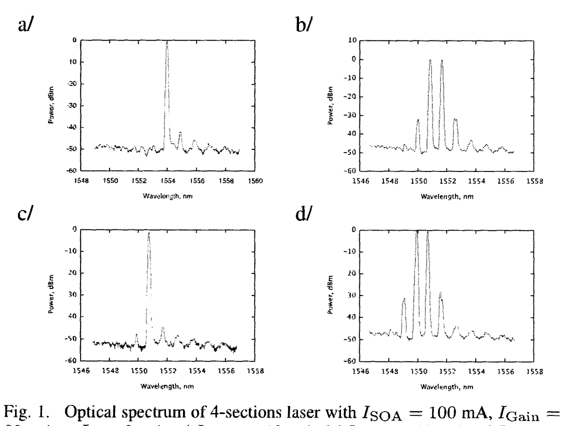

Fig. 1. Optical spectrum of 4-sections laser with $I_{\mathrm{SOA}} = 100$ mA, $I_{\mathrm{Gain}} =$ 80 mA et $I_{\phi} = 0$ mA. a/ $I_{\mathrm{DBR}} = 10$ mA; b/ $I_{\mathrm{DBR}} = 30$ mA; c/ $I_{\mathrm{DBR}} =$ 35 mA; d/ $I_{\mathrm{DBR}} = 40$ mA

Complementary investigations were directed in the vicinity of previously observed stable two-mode conditions. At $T =$ 300 K and $I_{\mathrm{DBR}} = 30$ mA we varied the gain current and phase current in conjunction in order to maintain a strict two-mode operation with equal optical intensities on both modes. Results are given in Fig. 2a. It is observed that a stable two-mode operation is always possible as soon as I_{Gain} exceeds the laser threshold value. An increase of I_{Gain} is accompanied by a decrease of I_{ϕ} of exactly the same value since slopes of -1 are observed on the guidelines. This shows that the efficiency in index modulation of the phase section is exactly the same that the one of the gain section. Overall behavior depicted in Fig. 2 thus corresponds to a perfect locking on two given adjacent FP modes by simply keeping the sum $I_{\mathrm{Gain}} + I_{\phi}$ constant. In more details the 4-sections DBR laser is locked on the two modes $\lambda_1 = 1549.96$ nm and $\lambda_2 = 1550.77$ nm when $I_{th} < I_{\mathrm{Gain}} < 45$mA and it is locked on $\lambda_1 = 1551.21$ nm and $\lambda_2 = 1551.98$ nm when 45 mA $< I_{\mathrm{Gain}} < 80$ mA. The $I_{\phi} <$ 30 mA current limit gives the corresponding limited range of locking and requires a mode hopping around $I_{\mathrm{Gain}} \approx 45$ mA.

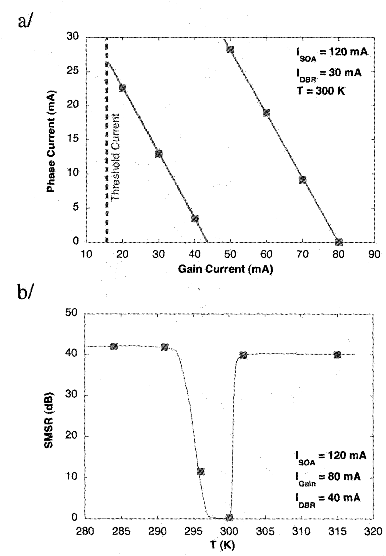

Fig. 2. a/ Observed stable two-mode operation with equal intensities for each mode as a function of gain and phase currents. Squares are some of the observed conditions while lines are guide to the eye between them.
b/ Side mode suppression ratio (SMSR) measured as a function of device temperature.

Another characteristic was obtained by measuring the side mode suppression ratio (SMSR) of the 4-sections DBR laser as a function of temperature. Result is given in Fig. 2b with laser parameters of $I_{\mathrm{DBR}} = 40$ mA, $I_{\mathrm{Gain}} = 80$ mA and $I_{\mathrm{SOA}} = 120$ mA. The higher the SMSR the most singlemode the 4-sections DBR. It was observed during experiments that uncertainties in the figure are pretty well represented by the size of square symbols. As seen, the 4-section DBR is highly singlemode almost everywhere except in a small temperature range around the room temperature. At this point, the SMSR is shown to change from 40 dB to 0 dB in less than 5 K when increasing the temperature and the reverse behavior is obtained in 2 K when increasing T from 300 to 302 K. In between, a stable two-mode behavior (SMSR $<$ 3 dB) is obtained within a range of ≈ 3 K in temperature. When referring to known values of the refractive index sensitivity with temperature in InP materials [10], this range corresponds to an overall modification of the guided mode refractive index of about $6\,10^{-4}$ within the 4-sections DBR laser. Although it is awfully stable when it occurs, the two-mode operation thus requires a quite precise set of values for laser operating parameters in order to be observed.

V. MODEL

The hypothesis to validate is that a saturable absorber may transform a 'usual' bistable semiconductor laser in a two-mode one. The most simple theory of two-mode laser comes from Lamb theory [7] and involves only simple differential equations of time to describe the dynamical intensity evolution and predict the occurrence of a two-mode regime. It differs from the usual rate equations commonly used for semiconductor lasers for which numerous typical parameters are known [11].

A. Lamb's model of the two-mode laser with saturable absorber

The existence of a stable two-mode operation implies particular coupling conditions between these modes [7]. Lamb's seminal analysis starts from two coupled ordinary differential equations describing the time evolution of mode optical intensities I_1 and I_2

$$\frac{dI_1}{dt} = (\alpha_1 - \beta_1 I_1 - \theta_{12} I_2)\, I_1 \qquad (1)$$
$$\frac{dI_2}{dt} = (\alpha_2 - \beta_2 I_2 - \theta_{21} I_1)\, I_2$$

where the α_i are unsaturated net gain and where β_i and θ_{ij} are self- and cross-saturation coefficients. It is thus straightforward to show that steady state two-mode solutions in intensity are

$$I_{1\mathrm{SS}} = \frac{\alpha_1 - (\theta_{12}/\beta_2)\,\alpha_2}{(1-C)\,\beta_1}, \qquad I_{2\mathrm{SS}} = \frac{\alpha_2 - (\theta_{21}/\beta_1)\,\alpha_1}{(1-C)\,\beta_2} \qquad (2)$$

where

$$C = \frac{\theta_{12}\theta_{21}}{\beta_1\beta_2} \qquad (3)$$

is a dimensionless coupling factor that was shown by a perturbation analysis to dictate the existence of the stable two-mode operation. If $C > 1$, *i.e.* in the case of strong coupling, only singlemode operation is possible and the laser is bistable. This is the case expected for semiconductor lasers.

For stable two-mode operation, $C < 1$ is required. In practice an additional physical process must be invoked to reach this condition. This is easily obtained with a saturable absorber having a saturation characteristic similar to the gain medium [12]. In other words, if we suppose a non-dispersive saturable absorber a convenient modification of Eqs. (1) is to include characteristics terms of saturable absorber optical mode intensity $-(\gamma - \epsilon(I_1 + I_2))$:

$$\frac{dI_1}{dt} = (\alpha_1 - \gamma - (\beta_1 - \epsilon)\, I_1 - (\theta_{12} - \epsilon)\, I_2)\, I_1 \qquad (4)$$
$$\frac{dI_2}{dt} = (\alpha_2 - \gamma - (\beta_2 - \epsilon)\, I_2 - (\theta_{21} - \epsilon)\, I_1)\, I_2$$

thus leading to a new coupling coefficient that must be less than 1 for possible stable two-mode operation with a saturable absorber

$$C' = \frac{(\theta_{12} - \epsilon)\,(\theta_{21} - \epsilon)}{(\beta_1 - \epsilon)\,(\beta_2 - \epsilon)} < 1 \qquad (5)$$

When combined with the obvious constraint that coefficients in Eq. (4) must all be positive, it yields

$$\min(\beta_1, \beta_2, \theta_{12}, \theta_{21}) > \epsilon > \frac{\beta_1\beta_2}{\theta_{12} + \theta_{21} - \beta_1 - \beta_2}\;(C - 1\,) \qquad (6)$$

Provided that the condition Eq. (6) is validated, a bistable laser with a saturable absorber may switch to a stable two-mode laser.

B. Numerical estimation of bistable to two-mode operation

Numerical calculations were conducted using the typical parameters of a multi-quantum well semiconductor laser, *i.e.* a material gain $g = 4000\ \mathrm{cm}^{-1}$, at a polarization current of 10 mA above threshold, and a photon cavity lifetime of $\tau_p = 1$ ps. The adjustment between single mode Lamb's theory and classical laser rate equations provided the numerical values of the linear gain and the self-saturation coefficients to be used in our model: $\alpha = 7.5\,10^{-2}\ \mathrm{ps}^{-1}$ and $\beta = 7.2\,10^{-6}\ \mu\mathrm{m}^3\mathrm{ps}^{-1}$. Since our experimental device of interest operate on two spectrally close modes, we assumed $\alpha_1 = \alpha_2 = \alpha$ and $\beta_1 = \beta_2 = \beta$ in Eqs. (4). Starting from a naturally bistable laser with $C = 1.2$, we chose $\theta_{12} = 0.9\beta$ and $\theta_{21} = 1.33\beta$ as illustrating parameters. Then, Eq. (6) yields a corresponding range for the self-saturation of the saturable absorber that is $0.9 > \epsilon/\beta > 0.857$.

Experimental observations of Fig. 1 have shown that the two-mode operation depends on the DBR current value. It comes from the spectral dependence of the end mirror reflectivity provided by the DBR, the center wavelength of which being roughly driven linearly by I_{DBR}. In the framework of our model, this has been accounted for by variations in linear gains ($\alpha_i - \gamma$ terms in Eqs. (4)) so that their sum remains constant. This is a simple method to translate the effect of the DBR without trying to model exactly its transfer function that is out of the scope of the present work. This yields a 'relative detuning' parameter that can explore extensively the tuning practical possibilities of our true device.

Numerical calculations given in Fig. 3 illustrate the expected behaviors when ϵ lie without or within the range defined by Eq. (6). On the one side (Fig. 3a), we chose $\epsilon/\beta = 0.8$ that is outside the previous range. The result is that the laser is always bistable whatever the detuning parameter should be. A mode hopping is observed when the detuning parameter becomes larger than ≈ 0.42 and the two-mode regime is observed in the vicinity of this sudden change. On the other side (Fig. 3b), we chose $\epsilon/\beta = 0.9$ within the range defined by Eq. (6). The major result is a smoothing of the transition between the two modes that let open a detuning parameter range where the laser is effectively two-mode.

This behavior is in perfect accordance with experimental observations of Fig. 1 where an increase of I_{DBR} produce a/

b/

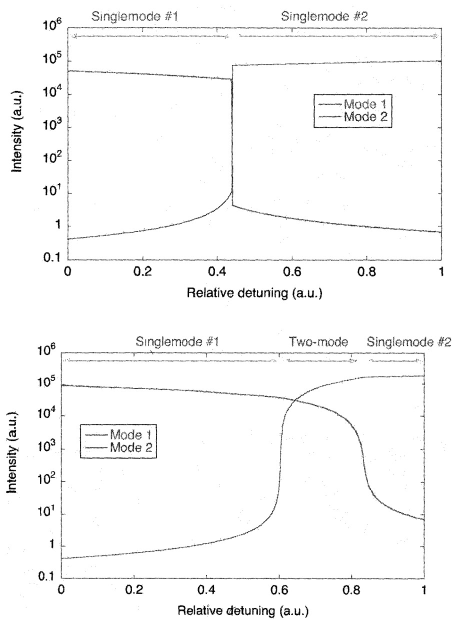

Fig. 3. Optical mode intensities obtained from Eqs. (4) as a function of the relative detuning parameter accounting for the DBR (see text), $\alpha_1 = \alpha_2 = 7.5\,10^{-2}$ ps^{-1}, $\beta_1 = \beta_2 = 7.2\,10^{-6}$ μm^{3}ps^{-1}, $\theta_{12} = 6.48\,10^{-6}$ μm^{3}ps^{-1}, $\theta_{21} = 9.61\,10^{-6}$ μm^{3}ps^{-1}. a/ $\epsilon = 5.76\,10^{-6}$ μm^{3}ps^{-1}. b/ $\epsilon = 6.41\,10^{-6}$ μm^{3}ps^{-1}.

successive occurrence and vanishing of stable two-mode operations. In order to accord in more details with experiments where the two-mode regime appears twice as I_{DBR} increases, it would have been necessary to account more than two modes in the model. Nonetheless, present calculations are demonstrative and can serve to estimate the saturable absorber parameters. It is however worth to note that the condition of Eq. (6) is quite restrictive so that it can explain that such a behavior may appear only with one technological run whereas it does not with all others. Reason should be that tiny variations in the laser gain material, in the process and/or in the absorption produced by the implanted area have occurred.

VI. Conclusion

The stable two-mode operation of a 4-sections DBR semiconductor laser has been characterized and modeled. The optical frequencies of the modes are separated by approximatively 100 GHz. This behavior is obtained with two values of the current fed in the DBR zone. In the two mode regime, the laser oscillates on two adjacent modes belonging to the Fabry-Pérot mode set. The stability of this behavior has been studied as a function of phase current and temperature. In fact such a behavior seems unlikely due to the strong coupling that exists between two close Fabry-Pérot modes.

We postulate that the two-mode regime comes from a parasitic saturable absorber inside the structure that was brought by the implantation process devoted to electrical insulation between the four different sections of the device. An analytical criterion has been established using Lamb's theory to numerically simulate the complete device using rate equations. Results are in agreement with our initial assumption and typical parameters are obtained for the saturable absorber.

These devices are expected to be used for THz waves generation at 1.55 μm by photomixing using either uni-travelling-carrier (UTC) photodiodes [1], ultrafast photoconductors [2] or by the excitation of the THz plasma waves in nanotransistors [14]. The present study may serve in the design rules to willingly build such two-mode lasers and improve them in order to produce very efficient and compact photomixing THz sources.

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