Analysis, Fabrication, and Characterization of 1.55-μm Selection-Free Tapered Stripe DFB Lasers

F. Grillot, *Student Member, IEEE*, B. Thedrez, F. Mallecot, C. Chaumont, S. Hubert, M. F. Martineau, A. Pinquier, and L. Roux

***Abstract*—A new selection-free laser structure for monomode behavior based on an engineering of the stripe geometry is proposed. The structure is designed in order to eliminate facet phase effects and laser to laser variations. The effect of spatial hole burning is simulated and an enhancement of the sidemode suppression ratio (SMSR) with power is predicted and measured. Moreover, the sensitivity to technological fluctuations is theoretically analyzed. Experimentally, lasers having a 47-dB SMSR at 10 mW and an excellent homogeneity from laser to laser is obtained on a two inch wafer.**

***Index Terms*—Distributed-feedback lasers, phase-shift device, SMSR, stripe engineering.**

I. INTRODUCTION

ALTHOUGH distributed-feedback (DFB) lasers were introduced some thirty years ago, the uniform fabrication of monomode lasers with predictable spectra remains a challenge. Interference effects between the grating and the facets make the lasing properties highly dependent on cleavage plane variations as small as a part of a wavelength. To clear the fabrication process from such dependence, antireflection (AR) coatings on both facets can be used when combined to an appropriate structure such as a phase-shift laser [1]. However, in most cases, a high technological accuracy is needed to control the laser spectral characteristics and the fabrication of such structures remains a technological challenge. In this letter, a new method based on a stripe engineering approach [2], [3] is proposed and investigated in order to demonstrate "selection-free" DFB lasers that do not need spectral screening. The mode selection between the two longitudinal modes located on the edge of the stopband is obtained by a proper variation of the effective index along the laser axis. Both theoretical and experimental results on 1.55- μm AR/AR DFB lasers are reported. We show that the structure under study has a lower sensitivity to technological fluctuations than phase-shifted devices [4]. Furthermore, no spurious effect due to spatial hole burning is observed and an increase of the sidemode suppression ratio (SMSR) with the injected power is theoretically predicted and experimentally measured. Finally, a single-mode laser with a good chip to chip homogeneity and having a 47-dB SMSR at 10 mW is demonstrated.

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The authors are with ALCATEL-OPTO+, Alcatel Research and Innovation, Route de Nozay, F-91460 Marcoussis (e-mail: Frederic.Grillot@ms.alcatel.fr).

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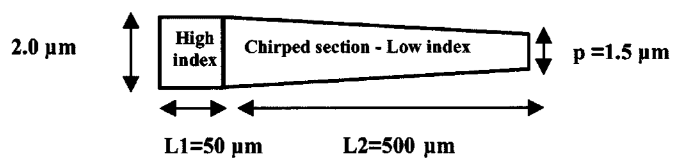

Fig. 1. Design of the device showing a 50-μm-long straight section (high index) followed by a 500-μm-long tapered stripe section (low index).

II. THEORETICAL ANALYSIS

When an antireflection coating is used on both facets, DFB lasers which have a uniform grating emit on two longitudinal modes which are symmetrically located with respect to the Bragg wavelength. Since the degeneracy between the two modes is linked to the device symmetry, a grating with antisymmetric geometry has been proposed to obtain a monomode behavior as early as 1976 [1]. A typical example was demonstrated by inserting a quarter wave section between two equal uniform DFB structures. Thus, a single-mode DFB laser with good threshold characteristics and emitting in the middle of the stop-band was predicted [1], [4]. Nevertheless, it implies the delicate control of a phase-shift technology. Another difficulty is the criticity of the phase-shift value since a small deviation from the required phase-shift can alter the single-mode behavior of the device, especially above threshold. Another approach for breaking the two modes degeneracy is to disturb the longitudinal symmetry of the grating [2], [3]. By comparison with phase-shifted devices (antisymetric grating), the laser does not lase in the middle of the stop-band, but favors one of the two longitudinal modes located on the edge of the stop-band. This approach can achieve a good selectivity of the lasing mode and if the design is appropriately chosen, no accurate control of the optical phase is required. The design that has been investigated in this letter is made of a 50- μm-long straight section ended by a 500- μm-long tapered stripe section (see Fig. 1). A uniform grating is built using conventional holographic techniques. Its optical pitch, however, varies along the device due to the dependence of the effective index with the stripe width. Because of its symmetrical shape, the tapered section alone does not allow for single-mode operation [5]. The increase of the effective index in the wider section breaks the symmetry and modifies the spectral selection. This selection technique has the key advantage to be directly usable with any standard laser manufacturing processes. Self-consistent calculations using the transfer matrix method [6] were performed to

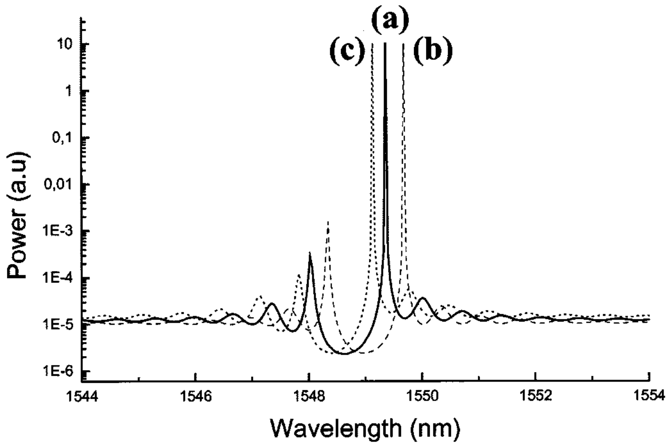

Fig. 2. Superimposition of three calculated spectra: (a) Solid line: $p = 1.5$ μm corresponding to the initial case (design of Fig. 1) $\lambda = 1549.36$ nm; SMSR at 10 mW = 45 dB; $\Delta\lambda = 1.3$ nm. (b) Dashed line: Tip width $p = 1.7$ μm; $\lambda = 1549.68$ nm; SMSR at 10 mW = 39 dB; $\Delta\lambda = 1.3$ nm. (c) Dotted line: Tip width $p = 1.4$ μm; $\lambda = 1549.13$ nm; SMSR at 10 mW = 49 dB; $\Delta\lambda = 1.3$ nm.

predict the spectral behavior. Variations of the effective index, of the confinement factor and of the grating strength, were taken into account. The spatial hole burning effect was simulated by truncating the devices into small constant carrier density regions. The lasing conditions were then self-consistently found for any input current. Once the carrier density and index profiles were determined, the spectrum was finally calculated. In Fig. 2, a simulation at 10 mW of the optical spectra [solid line (a)] corresponding to the design of Fig. 1 is depicted. As predicted by the theoretical analysis, the laser is strictly monomode and emits on the edge of the stop-band. The calculated values of the stop-band $\Delta\lambda$ and SMSR values are respectively about 1.3 nm and 45 dB. The laser response to a small variation of geometrical parameters due to technological fluctuations has also been carefully simulated. Fig. 2 shows a superimposition at 10 mW of the calculated optical spectra for three different tip widths of $p = 1.5$ μm [initial case (a)], $p = 1.7$ μm [dashed line, case (b)] and $p = 1.4$ μm [grey solid line, case (c)]. If the width of the tip varies from 1.5 to 1.7 μm [case (b)], a small red shift of the emitting wavelength which does not exceed 0.32 nm (from 1549.36 to 1549.68 nm) is predicted by the simulation tool, while the stopband value remains equal to 1.3 nm. Although a small decrease of the SMSR of 6 dB is also calculated, the single-mode character is not affected under such a variation since the SMSR remains equal to 39 dB at 10 mW. Even when the width of the tip is reduced to 1.4 μm [case (c)] no degradation is observed since the calculated values of the stop-band $\Delta\lambda$ and SMSR are respectively about 1.3 nm and 49 dB even if a 0.2 nm small blue shift of the emitting wavelength is again predicted (from 1549.36 to 1549.13 nm). The overall phase-shift δ induced by a variation of the tip width in the tapered long stripe section has also been calculated

$$\delta = \int_0^{L_2} dz |\Delta n_{\mathrm{eff}}(z)|. \tag{1}$$

Equation (1) corresponds to the variation of the optical length in the tapered section of length L_2. $\Delta n_{\mathrm{eff}}(z)$ describes the variation of the effective index along the tapered stripe and is zero on the large section. When the width of the tip increases from 1.5 to 1.7 μm (and decreases from 1.5 to 1.4 μm, respectively) the variation of the optical length within the tapered section is, respectively, equaled to $\delta \approx 2\lambda/3$ ($\delta \approx \lambda/3$, respectively). The variation of the optical length in the laser cavity are significant compared to the wavelength, yet in opposition to phase-shifted devices, they do not induce any degradation on the laser spectral behavior. This demonstrates the possibility to conceive a facet-phase independent monomode structure emitting on the edge of the stopband and having a low dependence on technological fluctuations.

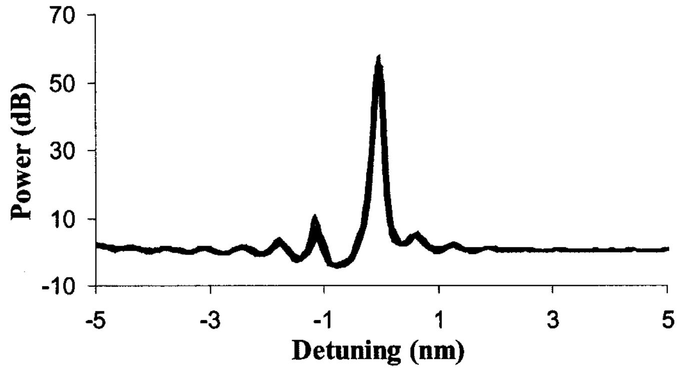

Fig. 3. Superimposition of twelve measured spectra at 10 mW versus the Bragg detuning. SMSR = 47 dB; $\Delta\lambda = 1.1$ nm.

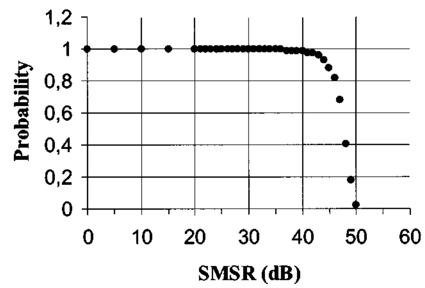

Fig. 4. Probability to reach a minimum side mode suppression ratio (SMSR) versus the SMSR for a set of 75 tested lasers at 10 mW.

III. Technology and Experimental Results

The laser is a buried ridge stripe (BRS) with proton implantation. The vertical structure has already been published in details [7]. The active stack is made of six strained layer multiquantum wells (SL-MQWs) surrounded by two confinement layers. The grating is defined in a quaternary layer localized over the active region. In a similar way as for conventional DFB lasers, a standard holographic process is used to fabricated a single pitch grating over the full wafer. Moreover, to avoid undesirable reflections, an antireflection coating in the range of 10^{-4} was deposited on each facet. In Fig. 3, the optical spectrum at 10 mW corresponding to a set of twelve lasers are reported versus the normalized Bragg detuning. A very good agreement with calculated spectra (see Fig. 2) is obtained. The measured stop-band is about $\Delta\lambda = 1.1$ nm and is very closed to the calculated value. A very reproducible value of the emission wavelength is also demonstrated from laser to laser with a standard deviation as low as 0.15 nm at 10 mW, measured under probe tests on three bars of 25 lasers chosen randomly on a 2-in wafer. In Fig. 4, the SMSR distribution is plotted. These measurements

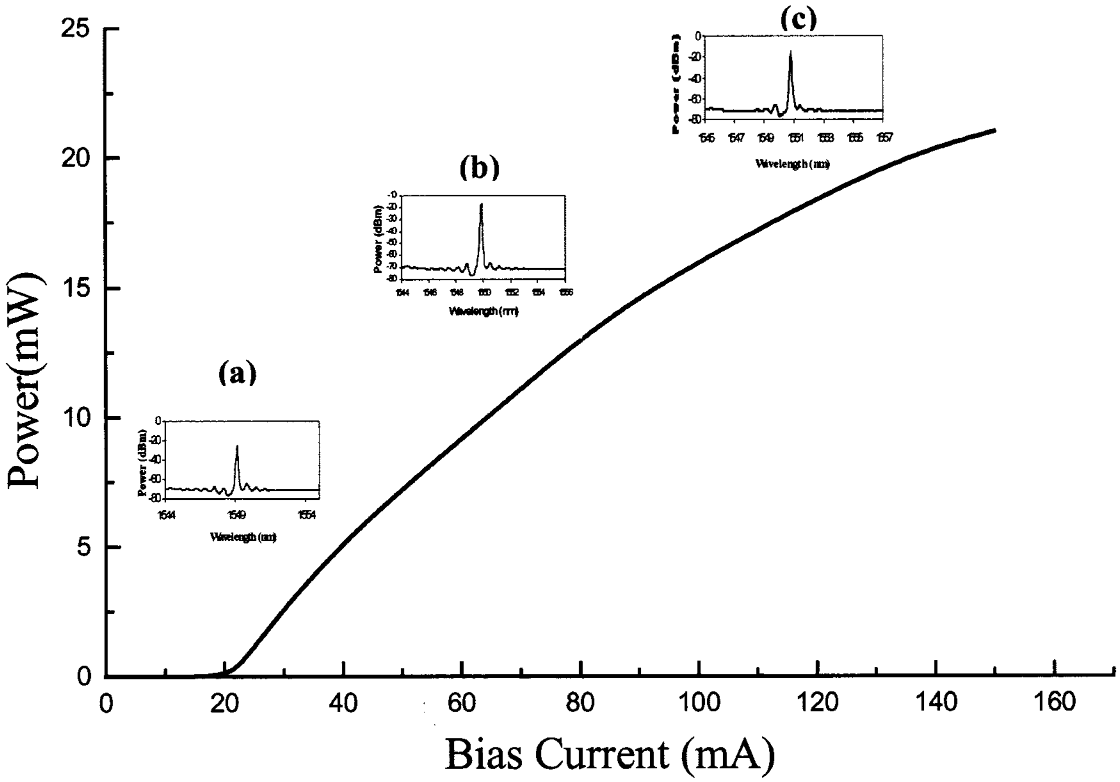

Fig. 5. Light current characteristic: Ith = 20 mA , $\eta = 0.26$ W/A. Inset: Spectra at different injected current. (a) $I = 27$ mA SMSR = 39 dB. (b) $I = 63$ mA SMSR = 47 dB. (c) $I = 116$ mA SMSR = 51 dB.

were realized for the set of 75 lasers at 10 mW and demonstrate a monomode yield of 100% and a very good SMSR uniformity with an average value of (47 $\pm$ 2) dB at 10 mW and of (50 $\pm$ 1) dB at 15 mW. These results constitute a successful demonstration of the spectral homogeneity and are of prime importance for the realization of DFB lasers bars with uniform wavelength. In Fig. 5, the light current characteristic is reported with the spectra at different power levels shown in inset. The threshold current is about 20 mA, whereas an external efficiency at threshold of 0.26 W/A has been obtained. An increase of the SMSR with the injected power is obtained throughout the whole $L(I)$ curve. The decrease of the efficiency is attributed to temperature increase, as well as to leakage current (the laser do not have blocking layers) and is not predicted by simulation. Through these results, we have demonstrated that by using an antireflection coating on both facets to eliminate facet phase effects and a variable stripe width, it is possible to conceive selection-free DFB lasers with a good reproducibility.

IV. Conclusion

We have shown in this letter that antireflection coated DFB lasers can demonstrate a high chip-to-chip homogeneity and excellent spectral behavior when combined with proper stripe engineering. Thanks to the simulation tool, a low sensitivity of such designs to technological fluctuations associated to an enhancement of the SMSR with the injected power has been demonstrated. These predictions were confirmed by the measurements and a 100% yield on three randomly chosen 25 laser bars with a 47-dB SMSR at 10 mW increasing to 50 dB at 15 mW has been obtained. These results constitute a successful demonstration of the proposed stripe engineering approach and are of prime importance for the realization of selection-free DFB lasers.

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