1.5-μm DFB Lasers with New Current-Induced Gain Gratings

Christophe Kazmierski, Didier Robein, Dean Mathoorasing, Abdallah Ougazzaden, and Marcel Filoche

***Abstract*—We introduce a new concept for gratings, based on a spatial carrier modulation, induced by current for optoelectronic devices. The concept is experimentally tested on gain coupled lasers, showing predicted features as high-power, low-linewidth, and length-independent coupling length product.**

AFTER THE first demonstration of gain-coupled devices in 1988 [1] and after a lot of theoretical works (i.e., [2]–[4]) predicting their improved performance, surprisingly few realizations have been reported. The reason is probably the practical solutions for gain-grating fabrication are still limited and inflexible. There is also a special interest in the complex coupling for the control of the linewidth enhancement factor [4]. However, in that case, one should be able to adjust the amplitude and two-phase states (in-phase and anti-phase) of index and gain gratings. Two methods are used for such grating fabrication—one replaces the index modulation layer by an absorption grating [5], and another one uses active layer etching [6]. In both methods the gain/absorption modulation is strongly correlated with the embedded index grating, leading to fixed or limited combinations of the real and imaginary couplings. Moreover, usually the active layer etching is not desired, as it may decrease device reliability.

In this paper, we introduce a new kind of grating that is formed by selective current injection into the active layer following the spatial periodicity of a diffraction grating. The periodic injection creates a carrier concentration wave ripple, giving rise directly to the gain modulation in lasers or index modulation in passive waveguides. Such diffraction grating has an interesting virtual feature, meaning that this grating appears only under external stimulation by a current flow.

The principle of operation is explained in Fig. 1, which represents a 2-D simulation of the current flow using our optoelectronic device simulator DENEB [7]. The device is a bulk-laser layer stack along the light propagation direction. The current is blocked by an n-type material grating, which is added on top of the active layer and embedded by a cladding p-type material. Both n- and p-type materials may have any optical index allowed by the material family as, for example, identical ones in this case. Therefore, the value of the index-coupling constant and its phase state can be designed independently of the gain-coupling constant. As a result, it is seen in Fig. 1, that the current injection through such floating junction grating is spatially modulated. Irregularities in the spatial distribution of current on the simulated curve of Fig. 1 originate from the boundary conditions in the finite elements calculations. The calculated carrier concentration ripple in the middle of the active layer reaches 1.5×10^{17} cm^{-3}, in the case of a laser having a cavity length of 300 μm and a threshold carrier concentration of 2×10^{18} cm^{-3}. The value of the concentration ripple in actual devices will depend on the threshold carrier concentration and the grating geometry as well. In the case of the above example, the simplified relation of Kogelnik and Shank ($\kappa \cong \Gamma_{\text{grating}}\Delta n/\lambda_0 + j\Gamma_{\text{grating}}\Delta g/2$, where the index Δn and gain Δg modulation amplitudes are estimated from the established differential index and differential gain constants for bulk 1.5-μm lasers) yields a gain coupling constant estimation between 10 cm^1 and 20 cm^{-1}. The related index coupling constant, induced by the phase-amplitude coupling, is estimated here to stay in the same range below 20 cm^{-1}. This index coupling may be suppressed further by using quantum wells in the active material.

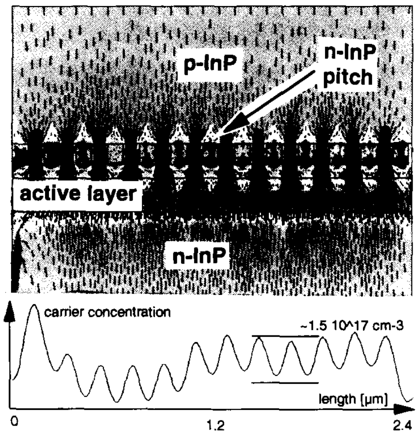


Fig. 1. 2-D simulation of current flow in GaInAsP bulk laser, showing virtual current-induced spatial carrier modulation.

If applied to passive waveguides, this concept allows the introduction of virtual index gratings, which can be turned on and off or current-tuned to a desired coupling constant without supplementary losses.

In the case of lasers, an interesting feature related to threshold carrier concentration can be predicted. Namely, as shown by David *et al.* [4], the threshold gain of a gain

Manuscript received November 1, 1994; revised January 27, 1995.
The authors are with the FRANCE-TELECOM CNET-Paris B Laboratoire de Bagneux 196, rue H. Ravera, BP107, F-92225 Bagneux, France.
IEEE Log Number 9411699.

1077–260X/95$04.00 © 1995 IEEE

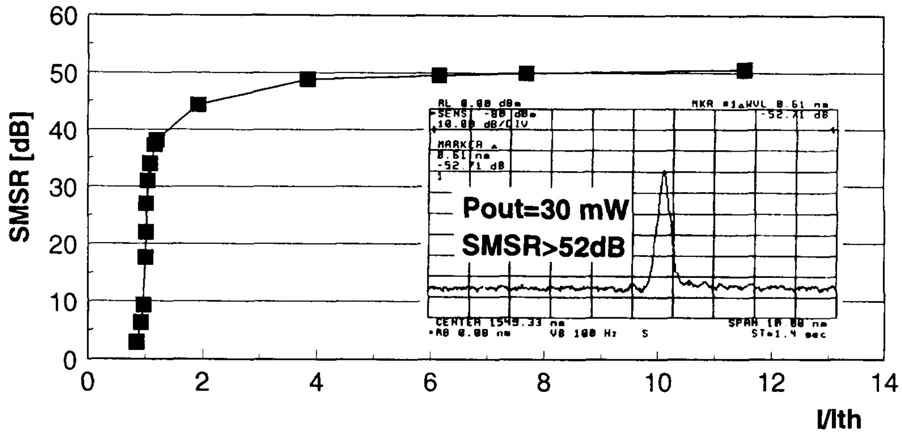


Fig. 2. Power-current variation of a 0.95/0.01 coated laser showing up to 110 mW monofrequency power. CW monofrequency spectra up to 300 mA are shown in the insert.

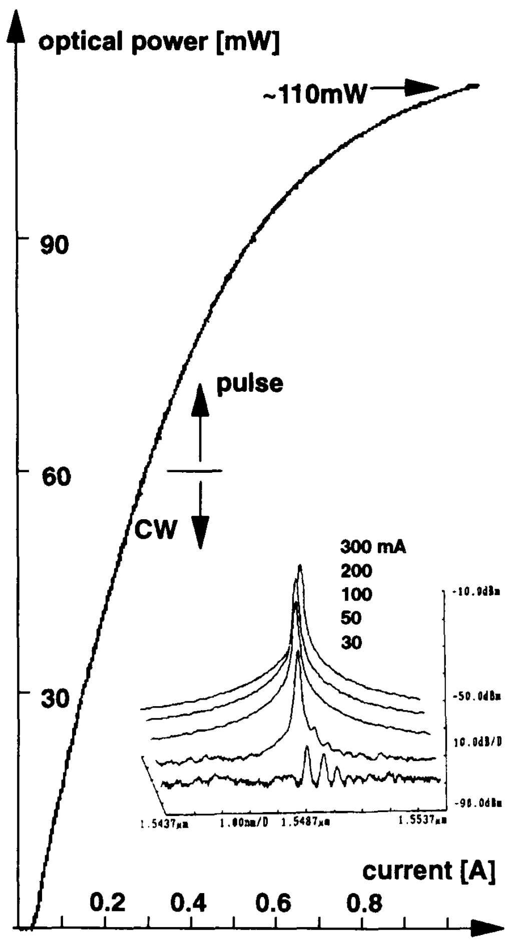


Fig. 3. Sharp SMSR rise as function of current/threshold current ratio. The spectrum shows SMSR > 52 dB at 30 mW for AR/AR coated 400-μm laser.

coupled laser is proportional to $1/(L^2\kappa_g)$ (where L is the laser length and κ_g is gain coupling constant) and, in our gratings, κ_g is proportional to the carrier concentration. This leads, in low-loss lasers, to the relation for the threshold carrier concentration $n_{\rm th} \sim 1/L$. That means that the $\kappa_g L$ product should remain independent of laser length. The same behavior is expected for the induced index coupling if it originates from carrier modulation only. This is important for low-linewidth and/or high-power lasers with the optimized coupling constant.

Up until now, our experimental work consisted in testing the grating concept. We chose a laser with a pure gain modulation without any index step layer. This seems to be difficult to realize with loss or patterned active layer gratings because of the built-in, very strong index grating. Also, the active layer consists of 1.5-μm bulk quaternary material where the carrier ripple effect is expected to be weaker than in MQW material due to an ambipolar lateral carrier diffusivity reduction with the well thickness [8].

To minimize the index difference, the gratings are fabricated using the same material (InP) alternating the same value of 1.5 $\times$ 10^{18} cm^{-3} for n- and p-type dopings. Less than 1 cm^{-1} build-in index coupling constant is expected in such structure. The layer stack is a standard 1.5-μm buried ridge structure (BRS) [9] laser holding a three-layer buried grating structure 20 nm p-InP/40 nm n-InP/20 nm p-InP close to the active layer. This structure is buried in a second p-type epitaxy step after grating and then, stripe wet etchings.

In spite of the absence of any physical index gratings, the obtained as-cleaved lasers exhibited nice single frequency behavior (i.e., side-mode suppression ratio SMSR typically in the range 35–50 dB) in the whole range of tested lengths between 180 μm up to 1 000 μm from the same wafer. This clearly confirms the expected presence of virtual carrier gratings.

Then, the lasers with cavity length above 350 μm were generally antireflection coated to check for a possible onset of the bimode lasing behavior, characteristic of the index coupled devices. Lasers, having cavity shorter than 350 μm and coated on the both facets, did not often lase because of too high

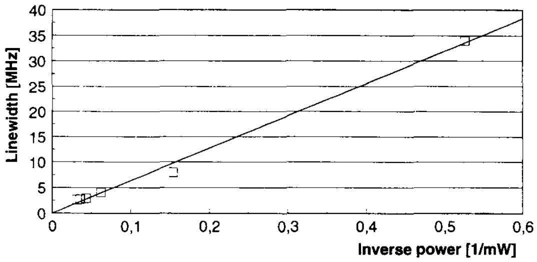


Fig. 4. Linewidth-inverse power variation showing neither rebroadening nor floor or offset up to 30 mW output per facet for AR/AR 800-μm laser.

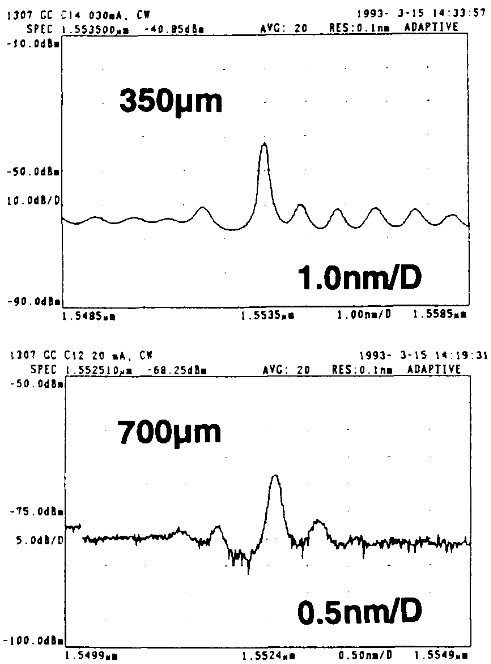


Fig. 5. Comparison between the near-threshold spectra for 350- and 700-μm devices, confirming the length independent coupling.

mirror losses, likely due to a relatively low coupling constant. We tested side mode suppression ratio SMSR on 0.001/0.001 AR/AR coated devices. Excellent mode rejections above 45 dB were generally found in the range of coated device lengths. In Fig. 2, we show a typical current-SMSR variation for a 400-μm AR/AR coated device with SMSR reaching over 52 dB at 30 mW output. The lack of the bimode behavior for AR/AR devices and a very sharp SMSR rise observed at threshold are characteristic of the gain coupling.

High-power operation is obtained with one high reflectivity facet. In Fig. 3, we show a 940-μm laser with 0.95/0.001 coatings, reaching over 60 mW (CW) at 300 mA DC, and then 110 mW (pulse) single frequency power.

Fig. 4 represents the linewidth versus inverse power curve of a 800-μm AR/AR coated device. Neither linewidth rebroadening nor floor or offset are observed up to 30-mW optical output per facet. Those features are consistent with the spontaneous emission factor decrease predicted for gain coupled lasers. The minimum linewidth is 2.6 MHz, which remains a good value for a 1.5-μm bulk active layer.

Finally, we attempted to check the kL product as a function of length. In Fig. 5, we show two near-threshold spectra of 350- and 700-μm AR/AR coated lasers. The spectra are nearly identical in shape in spite of a mode-spacing change, due to the device length. A small stop-band is noticed and it is likely, due here, to the current induced index modulation. Its two-times smaller value for two-times longer lasers is consistent with the invariant κL product.

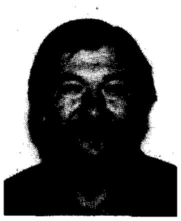
In conclusion, we introduced a new kind of diffraction gratings based on periodic carrier injection which leads to virtual spatial modulation of carrier density for index and/or gain coupling in optoelectronic devices. The concept is applied to the fabrication of gain coupled 1.55-μm lasers, showing such features as a high-single-frequency power, low-linewidth, and length-independent, coupling-length product. Using such gratings, the control of the index coupling and the gain coupling phase state should be obtained without active layer patterning. Moreover, the virtual feature of the grating may lead to new devices with on/off switching of the diffraction coupling.

ACKNOWLEDGMENT

The authors wish to thank G. Le Mestreallan and A. Lambert for their technical assistance, and to J.-C. Bouley for encouragements and critical reading of the manuscript.

REFERENCES

[1] Y. Luo, Y. Nakano, and K. Tada, "Facet reflection independent single mode longitudinal oscillation in GaAlAs/GaAs distributed feedback laser equipped with a gain coupling mechanism," *Appl. Phys. Lett.*, vol. 55, pp. 1606–1608, 1989.
[2] K. Kudo, J. I. Shim, K. Komori, and S. Arai, "Reduction of effective linewidth enhancement factor α_{eff} of DFB lasers with complex coupling coefficients," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 531–534, 1992.
[3] X. Pan, B. Tromborg, H. Olesen, and H. E. Lassen, "Effective linewidth enhancement factor and spontaneous emission rate of DFB lasers with gain coupling," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 1213–1215, 1992.
[4] K. David, J. Buus, and R. G. Baets, "Basic analysis, of AR-coated, partly gain-coupled DFB lasers: The standing wave effect," *IEEE J. Quantum Electron.*, vol. 28, pp. 427–433, 1992.
[5] K. Tada, "Gain-coupled DFB lasers," in *Tech. Dig. OFC/IOOC'93*, San Jose, CA, Feb. 21–26, 1993, invited paper ThB1, p. 160.
[6] H. Lu, G. P. Li, and T. Makino, "Spectral linewidth reduction in partly gain-coupled 1.55-μm strained multiple quantum-well distributed feedback laser," *Appl. Phys. Lett.*, vol. 63, pp. 589–591, 1993.
[7] M. Filoche, C. Kazmierski, and E. Caquot, "Numerical analysis of the interface recombination effects on leakage current for InP/InGaAsP buried ridge stripe lasers," in *Tech. Dig. 3rd Int. Conf. Indium Phosphide Rel. Mater.*, Cardiff, Wales, UK, paper M.P12, Apr. 8–11, 1991.
[8] H. Hillmer, A. Forchel, and C. W. Tu, "An optical study of the lateral motion of two-dimensional electron-hole pairs in GaAs/AlGaAs quantum wells," *J. Phys.: Condens. Matter.*, vol. 5, pp. 5563–5579, 1993.
[9] N. Bouadma, C. Kazmierski, and J. Semo, "Over 245 mW 1.3-μm BRS laser diode on n-substrate fabricated by the RIBE technique," *Appl. Phys. Lett.*, vol. 59, pp. 22–24, 1991.



Christophe Kazmierski was born in Gdansk, Poland, on June 17, 1950. He received the M.Sc. degree in physical electronics from the Warsaw Polytechnic School, in 1973.

Since 1973, he has studied the liquid phase epitaxy for GaP light emitting diode applications. In 1981, he joined the Thomson Central Laboratory of Research, Orsay, France. He has been engaged in research on GaInAsP–InP semiconductor lasers and photodiodes. More specifically, he studied the acceptor diffusion into InP, heterointerface band discontinuities by CV methods, and photoluminescence imaging methods for laser material characterization. He came to the National Center of Telecommunication Research (CNET)-France Telecom, Bagneux, France, in 1987, where he joined the semiconductor laser team. He has been working on the design and technology of quantum-well high-speed lasers and optoelectronic devices for OEIC's. Presently, he heads the department of semiconductor sources, which is engaged in research on laser optical sources and laser-based photonic circuits for multiwavelength and/or high-speed communication systems.

Mr. Kazmierski is the author and coauthor of over 60 papers in III-V semiconductor research area.

Didier Robein was born in Alger, Algeria, on April 5, 1961. He received the high level technician degree from University of Paris XI, Orsay, France, in 1983, and the engineer degree from the Conservatoire National des Arts et Métiers, Paris, France, in 1992.

He joined the Center National d'Etudes des Télécommunications, Bagneux, France, in 1984. He has been engaged in semiconductor compounds epitaxial growth by MOVPE for photonics and was particularly involved in semi-insulating materials studies and components integration.

Dean Mathoorasing was born in Curepipe, Mauritius, on October 22, 1963. He graduated from École Nationale Suprieure des Télécommunications in 1989.

He started working on high-frequency mixers for receivers at the Observatoire de Meudon, before joining France Telecom, National Center of the Telecommunication Research (CNET), Bagneux, France, in 1990, where he is involved in high-speed laser characterization.

Abdallah Ougazzaden was born in Casablanca, Morocco, on March 15, 1960. He received the M.Sc and Ph.D. degrees from Paris 7 University, in 1986 and 1990, respectively.

Since 1986 he has been working on the development of MOVPE reactors and material growth for semiconductor laser at the National Center of Telecommunication Research (CNET-France Telecom), Bagneux, France.

Marcel Filoche, photograph and biography not available at the time of publication.