

al.,<sup>8</sup> who found that for the specific case of  $\omega/h = 0.101$  and  $t/h = 0.011$ , the microstrip with a circular-edged strip will

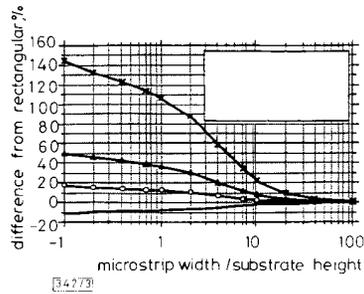


Fig. 3 Conductor power loss

$t = 10 \mu\text{m}$   
 —○— 60° —x— 30°  
 —▲— 45° ——— circular

have 15% less conductor loss than the microstrip with rectangular edges. For the same configuration, the present technique predicts a 10.7% decrease in loss for a circular cross-section.

**Conclusion:** Microstrip conductor loss can be calculated quickly by a perturbation method which includes the effect of strip edge shape. The work of Lewin and Vainshtein has been extended here to implement the technique on microstrip. The required stopping points in the loss integrations have been found here for a variety of trapezoidal strip edges. Loss calculations have been done for these and other edges, and it is apparent that the edge shape has a significant effect on the

conductor loss. Although results here tend to overestimate the effect owing to breakdown of the approximations, conductor loss due to edge shape increases as the edge shape gets sharper and the strip gets narrower or thicker.

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#### References

- LEWIN, L.: 'A method of avoiding the edge current divergence in perturbation loss calculations', *IEEE Trans.*, 1984, **MTT-32**, pp. 717-719
- VAINSHTEIN, L. A., and ZHURAV, S. M.: 'Strong skin effect at the edges of metal plates' in Russian, *Pisma Zh. Tekh. Fiz.*, 1986, **12**, pp. 723-729; English translation in *Sov. Tech. Phys. Lett.*, 1986, **12**, (6), pp. 298-299
- VON KOPPENFELS, W., and STALLMAN, E.: 'Praxis Der Konformen Abbildung' (Springer-Verlag, Berlin, 1959), pp. 207-209
- GRADSHTEYN, I. S., and RYZHIK, I. M.: 'Table of integrals, series, and products' (Academic Press, Inc., San Diego, 1980), p. 58
- BARSOTTI, E. L., KUESTER, E. K., and DUNN, J. M.: 'A simple method to account for edge shape in the conductor loss in microstrip'. MIMICAD Technical Rep. No. 2, University of Colorado, Boulder, Colorado, 1990
- BARSOTTI, E. L., KUESTER, E. K., and DUNN, J. M.: 'A simple method to account for edge shape in the conductor loss in microstrip', to be published
- KOBAYASHI, M.: 'Longitudinal and transverse current distributions on microstrips and their closed-form expression', *IEEE Trans.*, 1985, **MTT-33**, pp. 784-788
- CHRYSSOMALLIS, M., SIAKAVARA, K., and SAHALOS, J. N.: 'A study of open thick microstrip: the hybrid quasistatic approximation', *Canadian Journal of Physics*, 1989, **67**, pp. 747-752

## COMBINED HIGH POWER AND HIGH FREQUENCY OPERATION OF InGaAsP/InP LASERS AT 1.3 $\mu\text{m}$

*Indexing terms:* Semiconductor lasers, Optical communications

A simultaneous operation of a semiconductor laser at high power and high speed was demonstrated in a buried crescent laser on a P-InP substrate. In a cavity length of 300  $\mu\text{m}$ , a maximum CW power of 130 mW at room temperature was obtained in a junction-up mounting configuration. A 3 dB bandwidth in excess of 12 GHz at an output power of 52 mW was observed.

A combination of high power and high speed operation of a 1.3  $\mu\text{m}$  wavelength laser is very desirable in a number of applications such as long-haul wide-band optical fibre communication. The very high power capability also offers increased reliability since usefully large amounts of power can be obtained with the laser 'idling' at a fraction of its maximum capability.<sup>1</sup> It has been established that certain laser structures such as buried crescent (BC) on P-InP substrate<sup>2,3</sup> and double channel planar buried heterostructure (DCPBH) lasers<sup>4</sup> are capable of delivering a CW optical power in excess of 100 mW and can be operated reliably over thousands of hours.<sup>1</sup> The general approach for obtaining high output power is based on the following: the use of long laser cavity, the application of low reflectivity coating to the laser output facet and the adoption of junction-down mounting configuration and efficient heat sinking. A combination of all these techniques has led to a CW output power of 200 mW.<sup>5</sup>

Unfortunately, the techniques for high power operation are not always compatible with the conditions needed to obtain high frequency operation. These include the use of a short cavity to increase the corner frequency (at the same power level) and the formation of a narrow mesa to reduce the parasitic capacitance contributed by the reverse-biased blocking junction. BC lasers with semi-insulating blocking layers are

expected to have high modulation bandwidth. A 3 dB bandwidth of  $\sim 11$  GHz was reported.<sup>6,7</sup> The maximum output powers of these lasers were 30 mW or less. With vapour-phase-regrown type of lasers, even higher frequency response, 22 GHz at a power level of 15 mW was reported.<sup>8</sup> The laser structure was not specially designed for high power operation.

Efforts to combine high power and high frequency operation have been reported. A BC type laser with a Fe-doped semi-insulating (SI) current blocking layer demonstrated a 3 dB bandwidth of 6 GHz at a power level of 8 mW.<sup>9</sup> The laser used was 700  $\mu\text{m}$  long and was capable of emitting 90 mW light power in a junction-down mounting configuration.

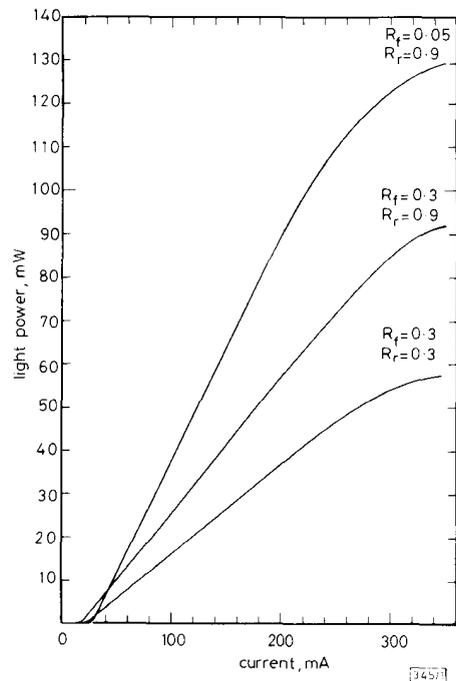
In this letter, we report on a different approach leading to a combined high power and high frequency operation of a BC laser on P-InP substrate. Medium (250-300  $\mu\text{m}$ ) to short ( $\sim 150 \mu\text{m}$ ) cavity lengths were employed to increase the corner frequency. Both narrow mesa and reduced bonding pads were employed to minimise the parasitic capacitance and junction-up mounting configuration was adopted to avoid further complication in fabrication and assembling (such as the use of polyimide). To obtain high output power, dielectric coatings were applied to the facet mirrors with specially tailored reflectivities. As a result, high power and high frequency operation were achieved simultaneously. A CW output power in excess of 130 mW was obtained in a laser of  $\sim 300 \mu\text{m}$  cavity length. A 3 dB bandwidth larger than 12 GHz at a 'safe' output power level of 52 mW was demonstrated.

The basic laser structure and fabrication process are similar to those described elsewhere.<sup>2,10</sup> A P-InP substrate was employed to facilitate high power operation.<sup>5</sup> The laser parameters, such as the active layer width and thickness, the position of the active layer relative to the blocking layers and the doping level of the layers were designed for both high power and high speed performances. The typical values of the lasers' parameters are as follows: the active layer width is 1.5-2.0, the thickness of the active layer at the centre of the crescent is 0.12-0.22, the active layer is located at or slightly above the interface between the *n*-InP and *p*-InP blocking layers, the doping level of the active layer is estimated to be

$0.3\text{--}0.9 \times 10^{18}/\text{cm}^3$ . A mesa of  $\sim 8\ \mu\text{m}$  width was etched and a bonding pad of  $100 \times 100\ \mu\text{m}^2$  was formed to reduce the parasitic capacitance.

As we have chosen medium to short cavity lasers, in favour of high frequency operation, rather than the long cavity ones ( $\sim 700\ \mu\text{m}$ ) usually employed in high power operation, the key for a combined high power and high frequency operation is to obtain the maximum output power. In contrast to the conclusions drawn from long lasers,<sup>3,5</sup> a high reflectivity coating on the rear facet and a low reflectivity coating on the front facet are equally important. It has been confirmed that the effect of mirror coating on the maximum output power depends strongly on the internal loss  $\alpha_i L$  of the laser (compared with mirror loss  $L_i(1/R_f R_r)$ ). For high internal loss factor,  $\alpha_i$ , and/or long cavity length,  $L$ , the effective way to increase the maximum output power is the application of a low reflectivity (LR) coating on the front facet.<sup>3,5</sup> A high reflectivity (HR) coating on the rear mirror can only improve the output power by a small fraction ( $\sim 10\%$ ). However, the HR coating becomes increasingly important when the product  $\alpha_i L$  is small which is usually the case for medium and short cavity lasers. In some cases of short cavity lasers, a low enough coating on the front mirror may even cause a decrease in maximum output power. Therefore, an optimising of mirror reflectivities with respect to the cavity length and internal loss is of crucial importance.

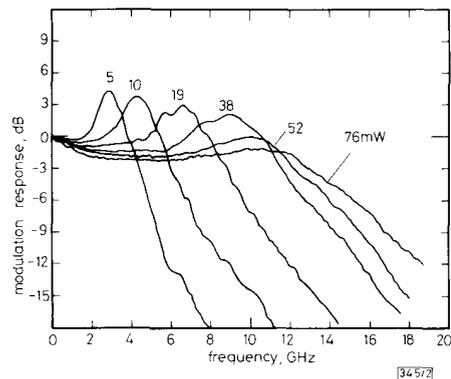
In our medium cavity length ( $\sim 300\ \mu\text{m}$ ) lasers, with LR/HR coatings on the front and rear facet, respectively, the typical room temperature CW output power is  $\sim 100\ \text{mW}$ . The best example is the following. A laser of  $300\ \mu\text{m}$  cavity length emitted a CW optical power of  $P_0 = 58\ \text{mW}$ . When the rear facet mirror was coated to  $R_r = 0.9$ , the maximum power was increased to  $91\ \text{mW}$  ( $1.57P_0$ ). A further coating on the front facet mirror to  $R_f = 0.05$  resulted in an optical power of  $130\ \text{mW}$  ( $2.24P_0$ ). Light output against current characteristics of this laser with different coatings are plotted in Fig. 1. When cavity length increases further, the LR coating makes a major contribution to the power increase. However, for short cavity lasers (e.g.,  $L \sim 150\ \mu\text{m}$ ), HR coating plays a major role. A detailed theoretical and experimental study will be presented elsewhere.



**Fig. 1** Light against current characteristics of a buried crescent laser with different mirror reflectivities

$L = 300\ \mu\text{m}$

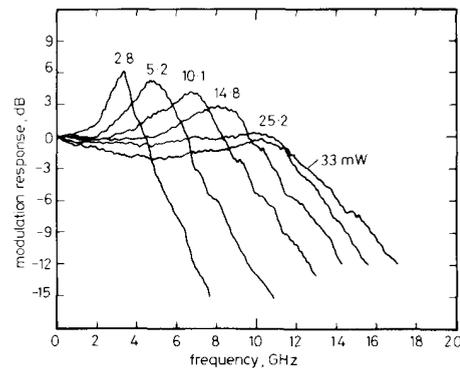
Fig. 2 shows the modulation characteristics of a  $300\ \mu\text{m}$  long laser. A 3 dB bandwidth of over 12 GHz at an output power of  $52\ \text{mW}$  was demonstrated. The maximum power of the laser was  $101\ \text{mW}$ . For short cavity lasers, the maximum power becomes smaller. The frequency response of a  $150\ \mu\text{m}$  long laser is shown in Fig. 3. The laser was coated to  $R_f = 0.18$  and  $R_r = 0.9$ . The maximum output power was  $54\ \text{mW}$  and a 3 dB cut-off frequency of 12 GHz at an output power of  $33\ \text{mW}$  was observed.



**Fig. 2** Frequency response of a medium cavity laser

$L = 300\ \mu\text{m}$

The mirror reflectivities are  $R_r = 0.9$ ,  $R_f = 0.05$ , the threshold current is  $28\ \text{mA}$ , the maximum power is  $101\ \text{mW}$



**Fig. 3** Frequency response of a short cavity laser

$L = 150\ \mu\text{m}$

The mirror reflectivities are  $R_r = 0.9$  and  $R_f = 0.18$ , the threshold current is  $17\ \text{mA}$ , the maximum power is  $54\ \text{mW}$

In conclusion, for medium to short cavity BC lasers, an optimisation of laser parameters and mirror reflectivities leads to a combined high output power and high frequency capability. A maximum CW power of  $130\ \text{mW}$  and a 3 dB bandwidth of 12 GHz at a  $52\ \text{mW}$  optical power level were demonstrated in a junction-up mouting configuration. The idea is also applicable to other laser structures.

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## References

- OSHIBA, S., MATOBA, A., HORIKAWA, H., KAWAI, Y., and SAKUTA, M.: 'Reliability of 1.3  $\mu\text{m}$  V-grooved inner-stripe laser diodes under high-power operation', *Electron. Lett.*, 1986, **22**, (8), p. 428
- IMANAKA, K., HORIKAWA, H., MATOBA, A., KAWAI, Y., and SAKUTA, M.: 'High power output, low threshold, inner stripe GaInAsP laser diode on a p-type InP substrate', *Appl. Phys. Lett.*, 1984, **45**, (3), p. 282
- HORIKAWA, H., OSHIBA, S., MATOBA, A., and KAWAI, Y.: 'V-grooved inner-stripe laser diodes on a p-type substrate operating over 100 mW at 1.5  $\mu\text{m}$  wavelength', *Appl. Phys. Letters*, 1987, **50**, (7), p. 374
- KOSZI, L. A., TEMKIN, H., PRZYBYLEK, G. J., SEGNER, B. P., IVAPHOLTZ, S. G., BOGDANOWICZ, C. M., and DUTTA, N. K.: 'High power operation of InP/InGaAsP double-channel planar buried-heterostructure lasers with asymmetric facet coatings', *Appl. Phys. Lett.*, 1987, **51**, (26), p. 2219
- OSHIBA, S., HORIKAWA, H., MATOBA, A., KAWAHARA, M., and KAWAI, A. Y.: 'High power output over 200 mW of GaInAsP/InP VIPS-LD'. 10th IEEE Int. Semiconductor Laser Conf., Kanazawa, Tokyo, 1986, pp. 148-149
- ZAH, C. E., CANEAU, C., MENCAL, S. G., FAVIRE, F., and LEE, T. P.: 'High-speed 1.3  $\mu\text{m}$  GaInAsP p-substrate buried-crescent lasers with semi-insulating Fe/Ti-doped InP current blocking layers', *Electron. Lett.*, 1988, **24**, (11), p. 695
- CHENG, W. H., POOLADDEJ, J., HUANG, S. Y., BUEHRING, K. D., APPELBAUM, A., WOLF, D., RENNER, D., HESS, K. L., and ZEHR, S. W.: '1.3  $\mu\text{m}$  InGaAsP buried crescent lasers with cobalt-doped semi-insulating current blocking layers grown by metalorganic chemical vapor deposition', *Appl. Phys. Lett.*, 1988, **53**, (14), p. 1257
- OLSHANSKY, R., POWAZINK, W., HILL, P., LANZISERA, V., and LAUER, R. B.: 'InGaAsP buried heterostructure laser with 22 GHz bandwidth and high modulation efficiency', *Electron. Lett.*, 1987, **23**, (W16), p. 839
- HORIKAWA, H., WADA, H., MATSUI, Y., YAMADA, T., OGAWA, Y., and KAWAI, Y.: 'High-power and high-speed semi-insulating blocked V-grooved inner-stripe laser at 1.3  $\mu\text{m}$  wavelength fabricated on p-InP substrates', *Appl. Phys. Lett.*, 1989, **54**, (12), p. 1077
- OOMURA, E., HIGUCHI, H., SAKAKIBARA, Y., HIRANO, R., NAMIZAKI, H., SUSAKI, W., IKEDA, K., and FUJIKAWA, K.: 'InGaAsP/InP buried crescent laser diode emitting at 1.3  $\mu\text{m}$  wavelength', *IEEE J. Quantum Electronics*, 1989, **QE-20**, (8), pp. 806-814

## ON THE CRAMER-RAO BOUND OF FINITE-LENGTH CEPSTRUM SPECTRAL ESTIMATORS

*Indexing terms: Speech recognition, Spectral analysis*

Spectral estimators based on finite-length cepstrum modelling are useful in several applications. The Cramer-Rao lower bound of the asymptotic variance of their logarithmic spectral estimates can be obtained in explicit form. This does not depend on the specific underlying spectrum.

**Introduction:** Parametric modelling of stationary random process is widely used in many engineering and statistics applications. Especially popular are rational models as the all-pole or autoregressive (AR) model and the general pole-zero or autoregressive moving-average (ARMA) model.<sup>1</sup> There also exist nonrational models of interest in a number of applications. Particularly, the model

$$S(\omega) = e^{P(\omega)} \quad (1)$$

where  $P(\omega)$  is a trigonometric polynomial of the angular frequency  $\omega$  ( $-\pi \leq \omega \leq \pi$ )

$$P(\omega) = \sum_{k=-M+1}^{M-1} c_k e^{-j\omega k} \quad (2)$$

appears in various fields, e.g., radar and sonar applications that make use of Gaussian spectra,<sup>2</sup> or the absorption spectra encountered in interferometric spectroscopy.<sup>3</sup> From a theoretical point of view, this type of model arises from the maxi-

misation of an entropy measure of the underlying random process assuming an accurate set of autocorrelation values is given.<sup>4</sup> Since the coefficients  $c_k$  of  $P(\omega)$  are the cepstral coefficients of  $S(\omega)$ ,<sup>5</sup> this type of spectral model is equivalent to consider a finite-length cepstrum.

Finite-length cepstrum spectral estimators obtained from AR (or LPC) modelling are very successful in speech processing whenever a distance between spectra has to be evaluated.<sup>6</sup> Since the AR spectral modelling involves an infinite cepstral sequence, the model underlying these distances (of Euclidean type) is no longer of AR type. Actually, it is a finite-length cepstrum model, as indicated by eqn. 1. In fact, whenever a spectral estimator involves a cepstrum windowing, it will be based on this type of modelling (see Reference 7 for another example).

In spite of the use that is being made of spectral estimators based on this type of model, the statistical efficiency of them can not be easily evaluated due to the lack of a theoretical explicit lower bound for the variance. In this letter a general expression for the asymptotic Cramer-Rao lower bound of the log spectrum is given. As will be shown, it does not depend on the specific underlying spectrum. Before finding this Cramer-Rao bound we will calculate the corresponding Fisher information matrix.

**Asymptotic Fisher information matrix of finite-length models:** Let  $x(n)$  be a zero-mean Gaussian stationary time series. Assume that measurements are available in the range  $1 \leq n \leq N$  where  $N \rightarrow \infty$ , and the cepstral parameters  $c_k$ ,  $k = 0, 1, \dots, M-1$ , are estimated from  $x(n)$ . The Fisher information matrix associated with this estimation is given by Whittle's formula (expression G.3 in Reference 8):

$$F_{ij} = \frac{N}{4\pi} \int_{-\pi}^{\pi} \frac{\partial \log S(\omega)}{\partial c_i} \frac{\partial \log S(\omega)}{\partial c_j} d\omega \quad (3)$$

where  $F_{ij}$  are the elements of the Fisher matrix  $F$ , where  $i, j = 0, 1, \dots, M-1$ .

According to the spectral model eqns. 1 and 2

$$\log S(\omega) = c_0 + \sum_{k=1}^{M-1} c_k (e^{j\omega k} + e^{-j\omega k}) \quad (4)$$

so that the derivatives involved in eqn. 3 are

$$\frac{\partial \log S(\omega)}{\partial c_i} = 2 \cos \omega i \quad i > 0 \quad (5a)$$

$$\frac{\partial \log S(\omega)}{\partial c_0} = 1 \quad (5b)$$

The Fisher matrix takes the simple form

$$F_{ij} = N\delta(i-j) \quad \text{if } i, j \neq 0 \quad (6a)$$

$$F_{00} = \frac{N}{2} \quad (6b)$$

$$F = N \begin{pmatrix} 1/2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (7)$$

which does not depend on the parameter values  $c_k$ .

**Cramer-Rao lower bound of the asymptotic log spectrum variance:** Assume  $\hat{C} = [\hat{c}_0, \hat{c}_1, \dots, \hat{c}_{M-1}]^T$  is an asymptotically unbiased estimator of the vector of  $M$  cepstral parameters of the model. The spectral estimate  $\log \hat{S}(\omega)$  obtained through eqns. 1 and 2 is also asymptotically unbiased and its asymptotic variance is bounded by the corresponding Cramer-Rao bound.<sup>9</sup>

If the estimator is efficient, this variance will approach the Cramer-Rao lower bound as  $N$ , the number of data points, tends to infinity. If it is not efficient, then var  $\{\log \hat{S}(\omega)\}$  will be strictly greater than the bound as  $N \rightarrow \infty$ .