a sample in Fig. 2. One sample with an imperfect moulding shows a large decrease in light output power at 100mA. This type of degradation will be suppressed by improving the moulding processes.

The devices and modules also showed stable operating characteristics during temperature cycling tests. No failure was observed even for the pigtail-type laser module over 1000cycles ranging from –40 to 70°C (one cycle per 2h) and without controlling the humidity. The adhesion of the plastic is sufficient even for the fibre. These results for environmental tests indicate that the modules satisfy some of the authorised criteria; for example, operation for 5000h at 85% and 85°C and 500cycles from –40 to 70°C, although the number of samples tested is small.

From these results, it can be concluded that the simple laser modules described in this Letter are practical and low cost optical sources for optical fibre transmission systems. They will start the new stage of laser module fabrication technology for optical fibre transmission systems.

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# True carrier lifetime measurements of semiconductor lasers

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*Indexing terms: Carrier lifetime, Laser variable measurement, Semiconductor junction lasers*

Differential carrier lifetimes of semiconductor lasers are obtained directly from the device impedance measurements. This new technique gives accurate lifetimes down to low bias currents, at which correct lifetimes are an order of magnitude higher than those obtained by a commonly used optical technique. Correct lifetimes reconcile the results of early PL studies and suggest much higher carrier concentrations.

Differential carrier lifetime is a very important characteristic of semiconductor lasers. It allows the estimation of the carrier concentration in the active layer of the laser diode, which permits analysis of the recombination processes in the active layer media. In most carrier lifetime studies, an optical response measurement technique [1 – 4] was used. In this Letter, we present a new technique based on pure electrical measurements of the laser impedance. We will also show that the commonly used optical technique needs correction.

The equivalent circuit of a semiconductor laser diode in the small-signal regime below threshold is shown in the inset of Fig. 1. The active layer is essentially an RC circuit with a characteristic time equal to the differential carrier lifetime [5, 6]. Taking into account a series resistance $R_s$, introduced by contacts and cladding layers, and a bonding wire inductance $L$, we have a circuit with a total impedance of

$$Z(\omega) = j\omega L + R_s + \frac{R_d}{1 + j\omega\tau_d} \qquad (1)$$

where $\tau_d = R_dC$ and $R_d$ is the static differential resistance of the *p-n* junction. This model does not take into account leakage paths and blocking structure capacitances. Samples used in this work were buried heterostructure InGaAsP 1.3μm lasers with a bulk active layer, including trenches 5μm from each side of the mesa, which effectively reduce parasitic blocking layer capacitance to a low level.

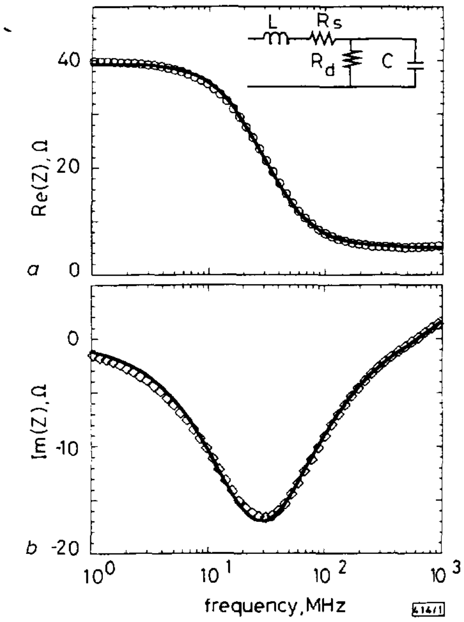

**Fig. 1** *Measured real and imaginary parts of laser impedance; I = 1mA*

*a* Real impedance
*b* Imaginary impedance
O measured values
——— fit to data
Inset: equivalent circuit
Fitting parameters: $R_d$ = 34.3Ω, $R_s$ = 5.1Ω, $L$ = 0.4nH, $\tau_d$ = 5.47ns

The impedance of the laser diode was measured as a function of frequency using an HP 8753D network analyser and then fitted to eqn. 1. Plotted in Fig. 1*a* is the real part of the device impedance at a bias of 1mA and a fit to the real part of eqn. 1. The fitting parameters are also given. In the low frequency (DC) limit, the real part of the diode impedance is $R_d$ + $R_s$, whereas at high frequencies, it drops to $R_s$. At low currents, the differential resistance is high. The impedance changes with frequency by several orders of magnitude. As the bias current increases, the value of $R_d$ decreases as ~$I^{-1}$ and becomes very small at high currents. This fact sets a limitation on the technique. In the present work, carried out at room temperature, the laser has a threshold current of 16mA. The differential resistance, even at biases close to threshold, was large enough so that the value of the differential carrier lifetime could be measured with high accuracy. This pure electrical technique gives a very high signal to noise ratio even for applied powers as low as –60dBm, which was used to ensure a small-signal excitation regime at low bias currents.

A similar analysis can be applied to the imaginary part of the impedance. Experimental data and fit are presented in Fig. 1*b*, providing a value of differential carrier lifetime and estimation of the bonding wire inductance. The values of differential carrier lifetime and differential resistance, extracted by fitting the real and imaginary parts of eqn. 1, are within 5% of each other over the entire current range, indicating consistency of the equivalent circuit.

Observed values of the differential carrier lifetime disagree substantially with the results obtained using the common optical response technique. This technique is based on small-signal analysis of the rate equation for electrons [3]. The amplitude of the optical response in the small-signal regime is proportional to the carrier density variation, produced by modulation of the pumping current:

$$\delta n(\omega) = \frac{\delta I}{eV}\frac{\tau_d}{1 + j\omega\tau_d} \qquad (2)$$

The optical response curve can be fitted to this formula, allowing extraction of the differential carrier lifetime. However, the assumption that the applied current modulation depth is frequency independent may lead to a serious error [7]. Typically, signal generators have a 50Ω output impedance and do not deliver such constant amplitude current modulation. The equivalent circuit of such a signal generator is a voltage source with $r = 50\Omega$ in series. Therefore, the optical response curve must be corrected to account for a frequency dependent part of the laser impedance, and then can be fitted to eqn. 2 to extract the value of the differential lifetime.

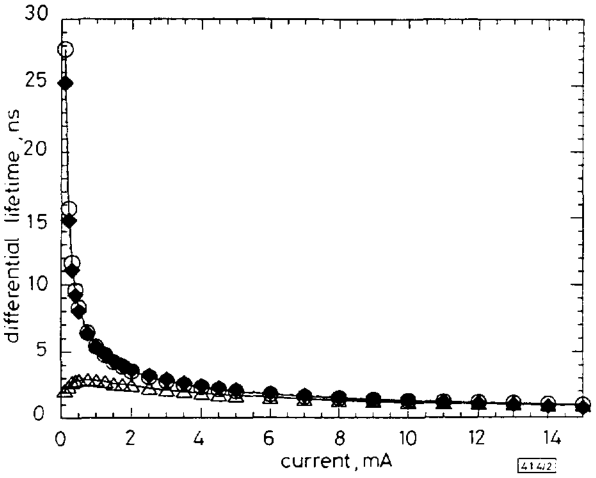

**Fig. 2** *Differential carrier lifetimes, obtained using various techniques*

—△— common optical technique
- -◆- - impedance analysis technique
—○— corrected optical technique

Fig. 2 shows the carrier lifetimes obtained using the direct impedance measurements, the common optical technique and the optical response corrected using the impedance data. The differential carrier lifetime measured using the common optical technique shows noticeable saturation and even a decrease at low pumping currents. This behaviour has been observed by previous authors (e.g. [3]). Additional recombination mechanisms were introduced to account for this effect. In contrast, the differential carrier lifetimes obtained by both the new method and the corrected optical technique do not saturate at low currents but, instead, increase rapidly with a decrease of the bias current. At 0.1mA, $\tau_d$ = 26ns. This value is in good agreement with data of photoluminescence decay studies [8], and much larger than those previously measured in active laser structures.

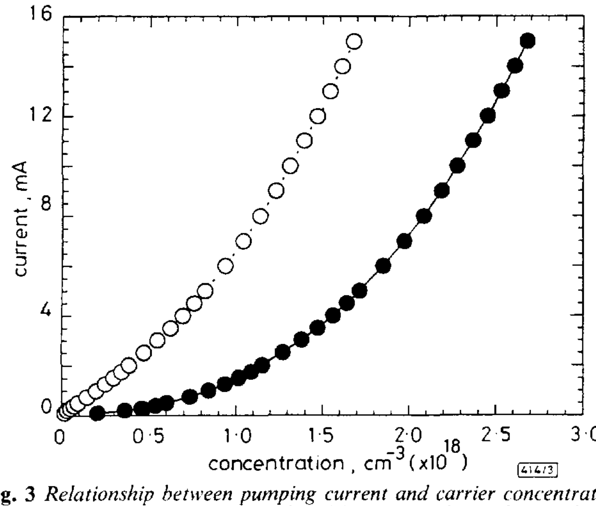

**Fig. 3** *Relationship between pumping current and carrier concentration, obtained using lifetime data, produced by commonly used optical technique and impedance analysis technique*

○ common optic technique
● impedance analysis technique

The new technique, based purely on electrical measurements, gives results very close to those produced by the corrected optical technique. This confirms the validity of the equivalent circuit, indicating an absence of parasitic elements.

The carrier density can be found by integrating the measured differential lifetime over the DC bias current [2] using

$$n(I) = \eta_{int} \int_0^I \tau_d(I_1)\, dI_1 \qquad (3)$$

The very high values of carrier lifetime at low currents show the importance of measuring $\tau_d$ down to low bias current for accurate estimation of carrier concentration. Fig. 3 shows the relationship of the carrier concentration and drive current. Using lifetime data provided by the common optical technique results in underestimation of the carrier concentration by ~$10^{18}$cm$^{-3}$ at a threshold concentration ~2.8 × $10^{18}$cm$^{-3}$. Another important result is that the new relation between the current and concentration implies considerably different recombination parameters.

In conclusion, we have presented a new technique for differential carrier lifetime measurements, based on direct analysis of the impedance of the laser diode. We have also shown that a commonly used optical response technique is incorrect and leads to errors at low bias currents. The new method is a purely electrical measurement and does not require any optical characterisation. This advantage gives the new method a wider range of applications; for example, characterisation of laser devices and structures for which optical measurements are unavailable.

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