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Abstract: The authors report a comparison of the self-pulsing characteristics of two types of semiconductor laser. They show that the self-pulsing frequency of the DFB laser is decoupled from the resonance frequency. They discuss the various characteristics, their significance in relation to optical synchronisation, and use the results to suggest a possible explanation for the mechanism for self-pulsation in the DFB laser.

1 Introduction

Self-pulsation in the lasing emission of laser diodes is often observed. The light output from self-pulsing laser diodes consists of a train of relatively short ($\leqslant 100$ ps) pulses, although the laser is only DC biased. The repetition rate of these pulses is dependent on the laser bias current, but generally is of the order of 1 GHz. Early work [1] interpreted this pulsation as being caused by absorbing regions or centres associated with poor crystal quality. As growth and fabrication techniques improved self-pulsation was observed less frequently (particularly for InGaAsP lasers).

Recently, two distinct types of self-pulsing InGaAsP laser diode have attracted significant attention for use as optical clock regenerators in communications systems [2, 3, 4, 5]. The most popular arrangement [2, 4, 5] uses a multisection geometry with one section biased as a saturable absorber to obtain controllable self-pulsation. We call this type of self-pulsing laser the intracavity absorber self-pulsing (IASP) laser because there is a saturable absorber within the laser cavity. The alternative approach [3] uses a multisection DFB laser with all sections biased above threshold to obtain the self-pulsation, by means of a mechanism which does not involve saturable absorption [6, 7]. We call this type of self-pulsing laser the DFB self-pulsing (DFBSP) laser. In order to determine the suitability of these two types of self-pulsing laser for application to synchronisation/clock extraction, it is necessary to compare their characteristics, bearing in mind the requirements for optical synchronisation. Additionally it is important to understand the mechanism by which the DFB laser is self-pulsing.

In this paper we compare the relative intensity noise (RIN) and optical spectra of DFBSP and IASP lasers. We present new data on the behaviour of the self-pulsing frequency with bias current. We show that the self-pulsing frequency of the DFBSP laser (f_{DFBSP}) does not always exhibit the increase with current which is characteristic of the IASP laser. We compare this variation with that expected of the relaxation oscillation or resonance frequency (f_r). We show that the self-pulsing frequency of the DFB laser is decoupled from the resonance frequency. Additionally, we show that when the DFB laser is self-pulsing, the damping factor and the resonance frequency are larger than expected. We also present data on the optical spectra of both types of self-pulsing laser and show that for the case of the DFBSP laser the self-pulsation is associated with a longitudinal mode instability. We discuss these various characteristics, their significance in relation to optical synchronisation, and use the results to suggest a possible explanation for the mechanism for self-pulsation in the DFB laser.

2 Experimental

RIN and optical spectra were measured using a HP 71400C Lightwave Analyser and an Ando AQ-6310B Optical Spectrum Analyser, respectively. The DFB laser

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was a three-electrode GRINSCH-SL-MQW (graded index separate confinement heterostructure, strained-layer multiquantum well) device (with no built-in phase shifts) operating at 1.55 μm. The laser is fibre-pigtailed in a package with a silicon chip-carrier bias T, a peltier cooler and a built-in 65 dB optical isolator. The lasing threshold current (I_{th}) is 63.6 mA at 21°C with all sections connected together. Self-pulsation in the light output can be observed when the front and back sections are biased with one constant current source, and the centre section is biased with a separate constant current source. The lengths of the front, centre and back sections are 0.5, 1.0 and 0.5 mm, respectively. Self-pulsation occurs above lasing threshold for a range of bias currents; front and back current ($I_f + I_b$) = 38–60 mA and centre current (I_c) = 46–59 mA [8].

Fig. 1 illustrates the RIN spectrum of the DFB laser biased at $I_c = 55.4$ mA and $I_f + I_b = 51.6$ mA when the

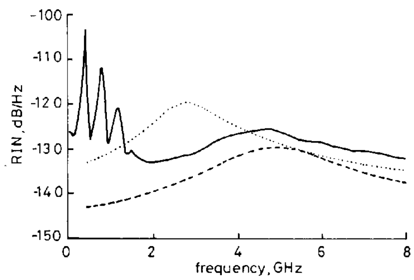

Fig. 1 *RIN spectrum of the DFBSP laser when self-pulsing at I_c = 55.4 mA and $I_f + I_b$ = 51.6 mA*

——— $I_f + I_b = 51.6$ mA, $I_c = 55.4$ mA
.... $I_{Total} = 90$ mA
------- $I_{Total} = 130$ mA

laser is self-pulsing. The self-pulsation fundamental peak is clearly visible at 358 MHz along with three harmonics. Note, however, the presence of a distinct broad feature at 4.7 GHz; this is the modulation resonance frequency. Also shown by dashed lines are RIN spectra for two values of the total current ($I_{Total} = I_f + I_c + I_b$) when the laser is not self-pulsing. It is clear from Fig. 1 that there is a dramatic increase in the RIN when the laser is self-pulsing. The increase is most pronounced at low frequencies (where the self-pulsation is), however there is also ~5 dB increase in the RIN at higher frequencies in the region of the resonance frequency and beyond. RIN spectra have been recorded for a range of I_{Total}. A single mode rate equation analysis yields a RIN fitting formula to describe the noise behaviour around the resonance frequency

$$\mathrm{RIN}\,(f) = A\,\frac{f^2 + (\gamma/2\pi)^2}{(f^2 - f_r^2)^2 + (\gamma/2\pi)^2 f^2} \tag{1}$$

where f is the frequency, A a constant, and γ the damping factor [9]. Fig. 2*a* shows f_r^2 against $I_{Total} - I_{th}$ and Fig. 2*b* shows γ against $I_{Total} - I_{th}$, obtained from fitting eqn. 1 to the experimental data. In Fig. 2*a*, f_r^2 varies approximately linearly with current as expected from the simplified expression

$$f_r^2 = C(I - I_{th}) \tag{2}$$

where C is related to the differential gain, I is the current, I_{th} is the threshold current, and assuming a linear power-current relationship above threshold [10]. We note that this expression is derived for a single-section device. For comparison we have included in Fig. 2 (square) points

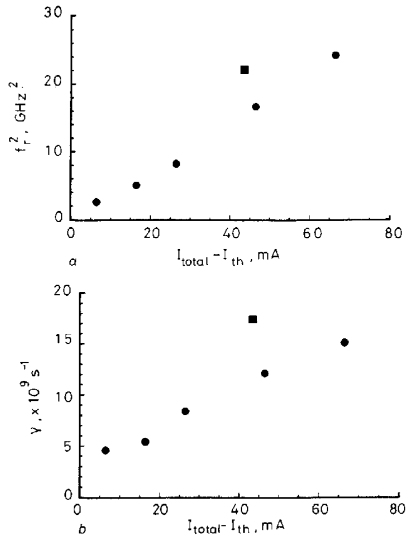

Fig. 2 *Variation of (a) f_r^2 and (b) γ with $I_{Total} - I_{th}$ for the DFBSP laser*

■ Self-pulsing spectrum, derived from Fig. 1

corresponding to the self-pulsing spectrum of Fig. 1, by adding $I_f + I_b$ and I_c to obtain a value for I_{Total}. This is justified since the current densities in all sections of the device will be approximately the same for the two biasing arrangements. At the point where the laser is self-pulsing in Fig. 2*a*, f_r^2 is larger than expected. The value for f_r^2 when self-pulsing is 22.1 GHz^2 while the value corresponding to the non-self-pulsing point at $I_{Total} - I_{th}$ = 45 mA is 16.6 GHz^2. Similarly, the value for gamma at the point where the laser is self-pulsing in Fig. 2*b* is also higher than expected from the simplified expression

$$\gamma = D(I - I_{th}) \tag{3}$$

where D is related to the photon lifetime in the cavity and the differential gain [11]. This result demonstrates that the pulsation is not caused by under damping of the cavity.

In order to evaluate the suitability of self-pulsing lasers for optical clock extraction, it is important to understand how the self-pulsation varies with bias current. Detailed measurements of the self-pulsing frequency of the DFB laser have been made over a range of bias currents. For each bias current the value of the self-pulsing frequency (f_{DFBSP}) and its full width at half maximum (FWHM) have been recorded. Fig. 3 shows the variation of f_{DFBSP} and the FWHM of the self-pulsing frequency with current. This illustrates a range of currents for which self-pulsing is observed.When the $I_f + I_b$ is kept constant at 53.0 mA and I_c is varied from 55.3 to 56.3 mA (Fig. 3*a*), f_{DFBSP} increases as would be expected of a self-pulsation frequency [10]. At the edges of the self-pulsation current range, the FWHM is seen to increase dramatically as the pulsation dies out. The minimum FWHM is rather large as compared with that of IASP lasers [12]. For I_c held constant at 56.5 mA and $I_f + I_b$ increased from 53.2 to 55.6 mA, f_{DFBSP} decreases from 333 to 170 MHz (Fig. 3*b*), while the FWHM follows a trend similar to that shown in Fig. 3*a*. However the decrease of f_{DFBSP} with increasing current is unexpected for a self-pulsation frequency. In fact for all values of I_c, f_{DFB} decreases nonlinearly with increasing $I_f + I_b$.

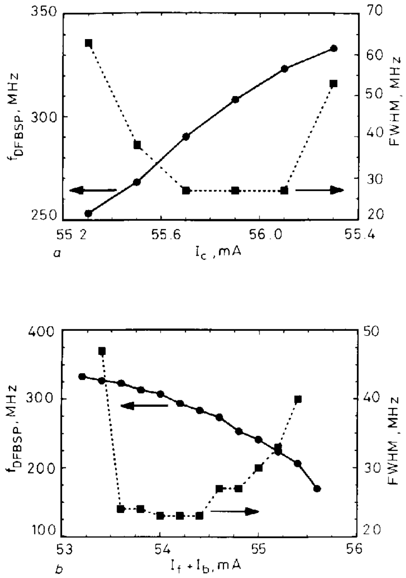

Fig. 3 *Variation of the self-pulsing frequency of the DFB laser and the FWHM of the self-pulsing frequency peak*

● f_{DFBSP}
■ FWHM

It is interesting to compare these results directly with those obtained for a typical self-pulsing laser with an intracavity saturable absorber. The IASP laser used in our experiments was a bulk two-section buried heterostructure Fabry-Perot device operating at 1.62 μm. The overall length of the device was 500 μm with a gain to absorber length ratio of 4 to 1. The threshold current of this device at 20°C was 24 mA with both sections pumped together. Self-pulsation in the light output can be observed when the gain section is biased with a constant current source and the absorber section is weakly forward biased with a contant voltage source [13]. RIN spectra and variations of self-pulsing frequency with bias current for fixed absorber section bias voltage, were recorded for comparison with the DFBSP laser.

Fig. 4 illustrates the RIN spectrum of the IASP laser operated within the self-pulsation region. From Fig. 4 the self-pulsing frequency (f_{IASP}) peak is at 500 MHz and harmonics are present right up to the sixteenth. No other features are evident in the spectrum since, for this device, the self-pulsation frequency replaces the resonance frequency [14]. In order to understand how the self-pulsing frequency of the IASP laser varies with current, f_{IASP} was recorded for fixed absorber section voltage ($V_a = 0.227$ V) over the range of gain section currents (I_g) for which self-pulsation occurs [13]. Fig. 5 illustrates the variation of f_{IASP}^2 as a function of the gain section current. Also shown is a least-squares fit to a straight line. The fit is excellent, illustrating that the self-pulsing frequency in this case follows the form expected for the relaxation oscillation frequency as in eqn. 2. Although not included in Fig. 5, it is worth noting qualitatively the behaviour of the laser at higher currents. As the gain section current is increased further (to about 94 mA) self-pulsation becomes weaker, the RIN spectrum becomes very complex and it becomes difficult to unambiguously determine a resonance for the spectrum. As the gain section current is further increased above 100 mA, self-pulsation stops completely and a conventional RIN spectrum can be seen with a distinguishable f_r. The variation of f_r^2 with gain section current in this (non-self-pulsing) region is also consistent with eqn. 2.

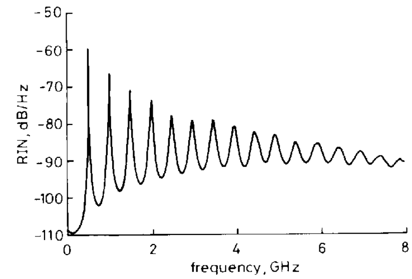

Fig. 4 *RIN spectrum of the IASP laser when self-pulsing for V_a = 0.36 V and I_g = 90.0 mA*

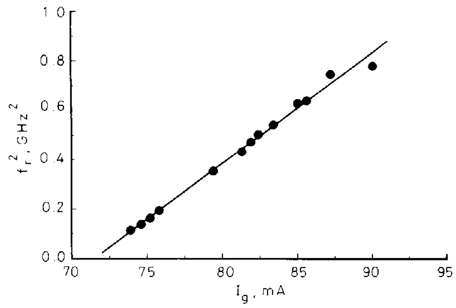

Fig. 5 *Variation of the self-pulsing frequency squared with gain section current for the IASP laser ($V_a = 0.227$ V)*

● experimental f_r^2
—— least square fit

In addition to the noise spectra described above, we have investigated the optical spectra of both DFB and IASP lasers in order to get a clearer understanding of the two types of self-pulsation. Outside the self-pulsation region, the DFB laser displays a high quality single-mode spectrum (typical side-mode-suppression ratio of >40 dB) with narrow linewidth (~1 MHz). When self-pulsing however, the spectrum is quite different. Fig. 6 illustrates the optical spectrum of the DFBSP laser for the same operating point as Fig. 1, i.e. within the self-pulsing region. Linewidth measurements at this point indicate significant broadening of the lasing mode to >100 MHz. In Fig. 6, while the laser operates primarily in a single longitudinal mode, this mode is broadened significantly, and a second mode is visible 2.2 Å away. The separation of the two modes does not correspond exactly

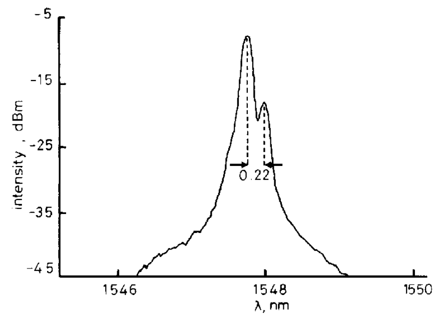

Fig. 6 *Optical spectrum of DFB SP laser when self-pulsing at I_c = 55.4 mA and $I_f + I_b$ = 51.6 mA*

to the 1.7 Å Fabry-Perot mode spacing of the device. Additionally the spectral shape does not resemble that of a chirped single mode laser. As the current is tuned out of the self-pulsation region, the subsidiary mode of Fig. 6 strengthens and takes over as the laser returns to single-mode operation. In fact, the entire self-pulsation region appears to lie along a 30 dB side-mode suppression ratio boundary in the plane of $I_f + I_b$ against I_c. Fig. 7 illustrates the optical spectrum of the IASP laser for the same conditions as Fig. 4, i.e. within its self-pulsing region. This spectrum is multimoded and each mode is strongly chirped (note shape) reflecting the large variations in carrier density occurring during the period of a pulse.

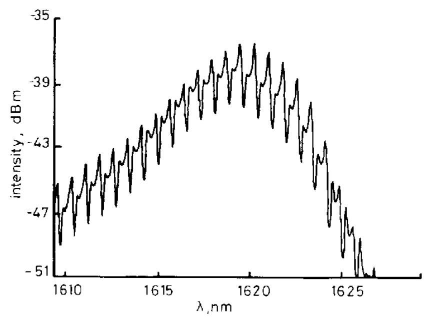

Fig. 7 *Optical spectrum of IASP laser when self-pulsing for V_a = 0.36 V and I_g = 90.0 mA*

3 Discussion

A number of interesting observations and anomalies arise when the IASP and DFBSP characteristics are compared. In this section these anomalies will be pointed out, their implications in terms of synchronisation examined, and the evidence they offer as a potential explanation of self-pulsation in the DFB laser will be elaborated upon.

The most remarkable result concerns the DFB laser. From the self-pulsation RIN spectrum in Fig. 1, the self-pulsation frequency is clearly decoupled from the resonance frequency. This is quite different from that of the IASP laser [14] where no other feature distinct from the self-pulsation frequency is observed (Fig. 4). It is also interesting that f_{DFBSP} decreases with increasing $I_f + I_b$, confirming the results reported for certain current ranges in Reference 3. On the other hand, f_{IASP} follows a dependence on current similar to that of f_r. The increased γ for the DFBSP laser proves that the self-pulsation is not caused by an undamped relaxation oscillation as proposed for IASP lasers [10].

The optical spectrum (Fig. 6) clearly shows that a second mode is involved in the self-pulsation process in the DFB laser. A double-moded spectrum has also been observed by Mohrle, *et al.* [7], but no attempt was made to explain the origin of the second mode. As pointed out earlier, this subsidiary mode is not a Fabry-Perot mode as the spacing would be 1.7 Å for the 2 mm cavity length, and more Fabry-Perot modes should be visible because of the weak grating (coupling factor $K = 9\ cm^{-1}$). Additionally, the mode is not the other DFB mode because of the measured 2.2 Å spacing (which is much smaller than the DFB stop band). Further investigations will be necessary in order to clarify this anomaly.

Concerning application to synchronisation, there are a number of important points. First, the minimum measured FWHM in this work for f_{DFBSP} (20 MHz) is very large compared with IASP lasers [12]. This means that a larger amount of optical power will be required for optical clock extraction. Since f_{DFBSP} is only observed over a narrow range of bias currents (see also Reference 7), it appears to be more difficult to obtain self-pulsation in DFB lasers, compared with lasers with intracavity saturable absorbers. The decoupling of f_{DFBSP} from f_r observed in this work will limit the upper speed attainable for synchronisation. Finally, the weaker harmonics observed in this work will certainly limit its use in relation to harmonic synchronisation [15].

It must be emphasised that the observations of Reference 6 do not include a resonance in the noise other than the self-pulsation frequency. Indeed the pulsation frequency involved is much greater than the relaxation frequency of typical semiconductor lasers. A very recent analysis [16] has suggested dispersive Q-switching as the mechanism for the pulsation observed in Reference 6.

The cause of this self-pulsation in DFB lasers biased above threshold is still an open question. Clearly the pulsation is different from that of IASP lasers [6, 7], and does not undamp the relaxation oscillation (see Figs. 1 and 2*b*). In fact, the pulsation reported in this paper is over an order of magnitude lower in frequency than the modulation resonance. As a result, it is postulated that this pulsation is governed by carrier rather than photon dynamics. In the theoretical work of Schatz [17], an instability resulting from spatial hole burning in DFB lasers is proposed, such that a cavity may support two stable asymmetric carrier (and photon) distributions. We propose that the self-pulsation in DFB lasers can arise from a dynamic interchange of carriers between these distributions, and the time period associated with this interchange is carrier diffusion limited. The increased damping of the photon dynamics may result from the damped response of the carriers resulting from diffusion, while the f_r increase may be caused by a reduced effective carrier lifetime brought about by the carrier interchange. Furthermore, if we define $\Delta I = I_c - (I_f + I_b)$, then f_{DFBSP} increases (or decreases) as ΔI increases (or decreases) as shown in Fig. 3*a* (or Fig. 3*b*). As ΔI can be related to the carrier concentration gradient between the sections, the dependence of f_{DFBSP} on ΔI is consistent with the proposed mechanism. Nevertheless, alternative types of self-pulsation in DFB lasers may have to be considered to explain reported results of self-pulsation frequencies greater than the resonance frequency.

4 Conclusion

We have presented results on the characteristics of self-pulsing DFB and intracavity saturable absorber lasers. We have compared the characteristics of these two distinct types of self-pulsing laser with each other, and with those of similar self-pulsing lasers in the literature. We have reported the first observation of self-pulsation in the light output of a diode laser at a frequency which is different from the modulation resonance frequency. We show that there is an enhancement in the resonance frequency and the damping factor of the DFB laser when it is self-pulsing. We have presented the results of measurements of the self-pulsing frequency with current, and conclude that for the IASP laser the variation is as expected of the resonance frequency, while for the DFB laser it is not. A mechanism for the self-pulsation in multisection DFB lasers has been proposed based on asymmetries in the carrier numbers in the sections and a dynamical interchange between them. Furthermore, this mechanism must be strong enough to decouple the self-pulsation from the relaxation oscillation.

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