R and inductance L of the laser discharge for every time instant. Combining these relationships for four adjacent time instants we can determine the values of R and L for the time period covering the four adjacent time instants. Scanning the entire time region of the laser discharge the time histories of the resistance R and inductance L of the laser discharge are revealed. These are shown in Fig. 3.

The time dependence of these electric quantities (R, L) shows strong variations in the formation phase of the discharge (first 45 ns). The resistance R (Fig. 3) of the laser discharge drops exponentially from a very high value to a low value. This is attributed to electron avalanche multiplication during the formation phase.

The inductance L of the laser discharge shows an abrupt high peak which is attributed to the temporary plasma constriction [4]. This is due to the attractive electromagnetic forces (Laplace force) because of the parallel motion of the electrons. The following expansion of the plasma is caused by the finite time required for the electric field to penetrate into the plasma. This is due to the well-known skin depth effect [5, 6]. This phenomenon is described by the equation

$$\nabla^2 \mathbf{E} - \mu_0 \frac{\partial}{\partial t}(\sigma \mathbf{E}) = 0 \qquad (3)$$

which is derived through Maxwell's equations. This diffusion-like equation for the electric field in a plasma is the basis of inductance. Finally, after the formation phase of the discharge, the inductance and resistance of the laser discharge experience in the main phase small fluctuations around constant values.

Conclusion: In this work a simple and accurate method for determining the time dependent resistance and inductance of a laser discharge is described. This method uses only the voltage across the laser channel and the current which flows through the laser discharge. The method is independent of the type of electric circuit used and the circuits electrical parameters are not required. The differential equation governing the laser discharge is very simple and we use only the values of the voltage across the laser discharge, the current and its first derivative.

The resistance and inductance of the laser discharge vary strongly in the formation phase of the discharge while in the main phase they fluctuate around constant values. The time dependence of the resistance and inductance are consistent with the physical restrictions arising from the processes taking place in a gas discharge. This consistency confirms that the calculated values of the resistance and inductance are the real values. This method can be applied not only in laser systems but in any gas discharge used in electronic instruments.

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Experimental demonstration of modulation bandwidth enhancement in distributed feedback lasers with external light injection

Xue Jun Meng, Tai Chau and Ming C. Wu

The frequency response of a semiconductor distributed feedback (DFB) laser under optical injection locking has been studied experimentally. It is shown that strong injection locking is very effective at increasing the relaxation oscillation frequency of DFB lasers. Bandwidth enhancement as high as 3.7 times has been achieved for the first time.

Introduction: Semiconductor lasers are key components for advanced broadband telecommunication networks and fibre-based RF photonic systems [1]. Semiconductor distributed feedback (DFB) lasers operating at 1.3 and 1.55 μm wavelength are the most suitable light sources for digital and analogue fibre optic systems. At present, the bandwidths of most commercially available DFB lasers are in the range of several gigahertz. In the past decade, much effort has been made to increase the bandwidth of DFB lasers, however, this usually results in more complex fabrication processes and increased costs. Recently, an alternative scheme has been proposed for significantly increasing the relaxation oscillation frequency of semiconductor lasers using external optical injection. Several theoretical simulations predicting bandwidth enhancement have been reported [2 – 4]. Previously, optical probing technique has been employed to verify the theoretical prediction indirectly [5]. Bandwidth measurement using direct microwave intensity modulation, which is essential for most practical applications, has not been reported. In this Letter, we report the experimental characterisation of the frequency response of injection-locked DFB lasers using direct current modulation. Significant bandwidth enhancement has been observed. The relaxation oscillation frequency has been increased by as much as 3.7 times using strong optical injection.
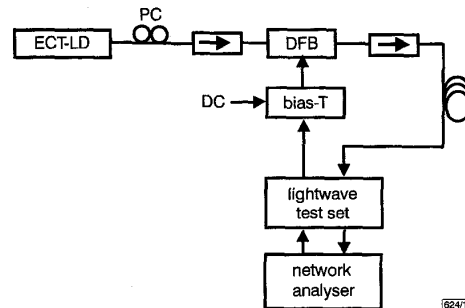

Fig. 1 *Experimental setup*

PC: polarisation control; ECT-LD: external cavity tunable laser diode; DFB-LD: distributed feedback laser diode

Experiments: The experimental setup is shown in Fig. 1. A commercial external-cavity tunable laser diode (ECT-LD) at 1.55 μm is used as the master light source. Its linewidth is < 200 kHz. The CW light from the ECT-LD is injected into the slave laser through a polarisation controller and an optical isolator. The slave laser is a 1.55 μm single-longitudinal mode DFB laser diode with threshold current $I_{th} = 23$ mA. The relaxation oscillation frequency of the free-running laser is 4.1 GHz at 40 mA. The frequency response of the directly modulated DFB laser is characterised by a network analyser (HP 8510) with a lightwave testset (HP 83420A). The bandwidth of the measurement system is 20 GHz.

The DFB laser under test is biased at 40 mA ($\simeq 1.75\ I_{th}$) and the output power is 1.2 mW. Using the modified delayed self-homedyne (MDSHM) scheme suggested by Esman *et al.* [6], which measures the linewidth of the laser using small signal modulation at 450 MHz, stable injection locking can be determined by observing the reduction in linewidth of the slave laser [7].

Fig. 2 shows the parameter ranges for stable injection locking expressed in terms of the injection ratio and the detuning frequency between the master and the slave lasers. Stable injection locking is observed in the region bounded by the two solid curves:

the top curve is the Hopf bifurcation boundary and the bottom curve is the lock-unlocking boundary described in [4].
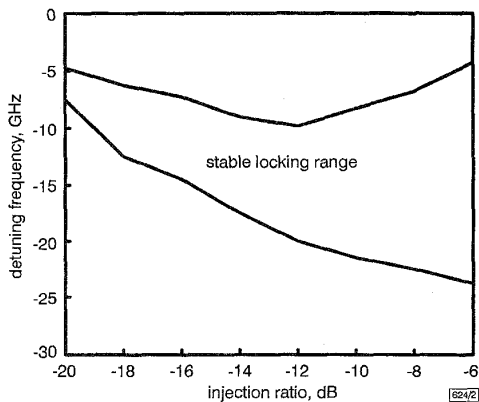

Fig. 2 *Parameter range for stable injection locking*

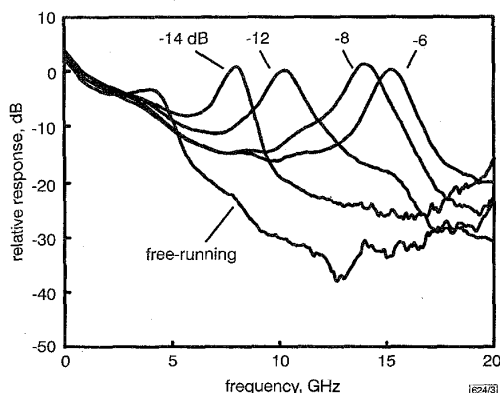Parameter range expressed in terms of injection ratio and detuning frequency

Fig. 3 *Frequency responses of DFB laser for various injection ratios as well as free running case*
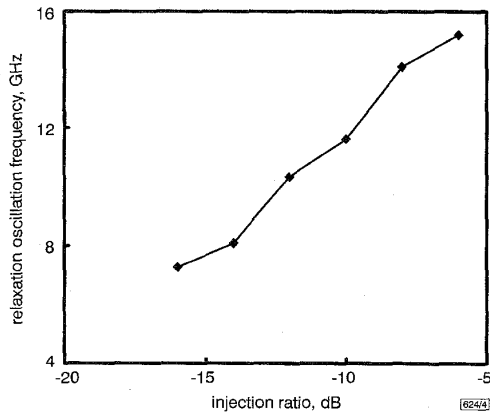
Detuning frequency: –12.5 GHz

Fig. 4 *Relaxation oscillation frequency against injection ratio for injection-locked DFB laser*

Detuning frequency: –12.5 GHz

Fig. 3 shows the relative frequency responses of the DFB laser for four different injection ratios. The response of the free-running laser is also plotted in the same graph for comparison. The relaxation oscillation frequency of the laser increases steadily with the optical injection ratio. A resonant frequency as high as 15.2GHz has been achieved at an injection ratio of –6dB. This result agrees very well with the theoretical prediction [2]. During the test, the detuning frequency is fixed at –12.5GHz, which is well within the stable injection locking range and more than 2.5GHz away from

the Hopf bifurcation boundary. The dip in the frequency response before the relaxation oscillation frequency results from the electrical parasitics of the laser. It can be suppressed by reducing the area of the top contact pad.

Fig. 4 shows the variation in relaxation oscillation frequency against injection ratio. The increase in relaxation oscillation frequency (1.7 times) is evident even for weak optical injection (injection ratio = –14dB). With strong optical injection, enhancement by as much as 3.7 times has been observed. This is the largest bandwidth enhancement ever achieved experimentally in injection locked DFB lasers.

Conclusions: In conclusion, the frequency response of distributed feedback (DFB) lasers under various optical injection levels has been experimentally characterised and compared with that of a free running laser. It is shown that the relaxation oscillation frequency of the DFB laser increases dramatically under strong optical injection locking. Bandwidth enhancement as high as 3.7 times has been demonstrated for the first time.

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High temperature operation of II-VI ridge-waveguide laser diodes

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Ridge-waveguide laser diodes based on beryllium chalcogenides have been realised. An extremely large temperature coefficient (T_0 = 330K at room temperature) allows device operation up to temperatures of 413K. Lateral monomode emission is obtained with a ratio between the vertical and the lateral far field pattern of, for example, 1.2:1 for a stripe width of 1μm.