EXPERIMENTAL INVESTIGATION OF PARAMETRIC SIDEBAND AMPLIFICATION IN INJECTION LASERS

Indexing terms: Amplification, Optical modulation, Semiconductor lasers

The small-signal modulation sensitivity of an injection laser biased above threshold is increased by applying an additional pumping current, owing to parametric interaction. The theoretical amplification is compared with experimental results.

The possibility of applying a semiconductor laser not only as an optical transmitter, but also as a narrowband parametric sideband amplifier has been recently suggested by Russer *et al.*[1] In this letter, the calculated parametric gain of an injection laser will be compared with experimental results.

A monomode injection laser biased above threshold is modulated with a small-signal current at an angular frequency ω_s and with a large pumping current at an angular frequency ω_p. From the linearised rate equations,[1] the normalised modulation sensitivity $M = |S_s eV\omega_0/J_s|$ is derived, where S_s is the photon density at the angular frequency ω_s, e is the elementary charge, V is the volume of the active region, ω_0 is the small-signal modulation angular resonance frequency and J_s is the current amplitude at ω_s. Substituting the equations for the electron and photon densities and the threshold current (eqns. 6–9 and eqn. 14 in Reference 1) into the matrix system (eqns. 17*a–d* in Reference 1*), the normalised modulation sensitivity M is obtained from eqn. 18 of Reference 1:

$$M = \left|\frac{I}{T}\left[1 + j(I/T)\Omega_s + (j(1/IT)\Omega_s - \Omega_s^2)\right.\right.$$
$$\left.\left.\times\left(\frac{1-(a^2/4)\phi(\Omega_p/\Omega_s)}{1-(a^2/4)\phi^2}\right)\right]^{-1}\right| \, |[1-(a^2/4)F]^{-1}| \qquad (1)$$

where

$$\Omega_s = \omega_s/\omega_0 \qquad (2)$$

$$\Omega_p = \omega_p/\omega_0 \qquad (3)$$

$$I = (J_0/J_{th} - 1)^{\frac{1}{2}} \qquad (4)$$

$$T = \left(\frac{\tau_{sp}}{\tau_{ph}}\right)^{\frac{1}{2}} \qquad (5)$$

where J_0 is the bias current of the laser diode, J_{th} is the threshold current, τ_{sp} is the spontaneous electron lifetime and τ_{ph} is the photon lifetime.

The large-signal photon amplitude factor a,[2] due to the existence of the large pumping current amplitude J_p, is given by

$$\frac{J_p}{J_0 - J_{th}} = a[(\Omega_p^2 - \phi)^2 + \Omega_p^2(I^2/T^2)(\phi + 1/I^2)^2]^{-\frac{1}{2}} \qquad (6)$$

where

$$\phi = 2I_1(a)/aI_0(a) \qquad (7)$$

where $I_0(a)$ and $I_1(a)$ are the modified Bessel functions of order 0 and 1, respectively.

The term F is an extensive complex function of a, I, T, Ω_s and Ω_p, causing the parametric gain

$$G = |1-(a^2/4)F|^{-1} \qquad (8)$$

by suitable choice of these parameters, whereas the residual part of eqn. 1 is nearly independent of the large-signal photon amplitude factor for small values of a. For $a = 0$, i.e. no pumping current is applied, the well known small-signal modulation sensitivity of an injection laser[3] is obtained from eqn. 1. The zero condition for the imaginary part of F is given by $\Omega_s = \frac{1}{2}\Omega_p = \Omega$. Then, neglecting $1/T^2 \ll 1$, the real part of F becomes approximately

$$F_R \simeq \frac{\Omega^4(2-\phi)^2}{[\Omega^2(1-(a^2/2)\phi) - (1-(a^2/4)\phi^2)]^2} \qquad (9)$$

and maximum gain is achieved for

$$\Omega^2 \simeq \frac{\phi[2 + a^2(4 - 3\phi + \frac{1}{2}\phi^2) + a^4\phi^2(\frac{1}{4}\phi - 1)]}{2\phi + a^2(4-2\phi) - a^4\phi^2} \qquad (10)$$

Numerical computations give maximum parametric sideband amplification for pumping frequencies $\Omega_p \lesssim 2$, i.e. $\Omega_s \lesssim 1$.

In Fig. 1*a*, the normalised modulation sensitivity M is plotted against signal frequency Ω_s for $\Omega_p = 1{\cdot}9$, a current ratio of $J_0/J_{th} = 1{\cdot}1$ and a lifetime ratio of $\tau_{sp}/\tau_{ph} = 5000$, according to the laser diode used in the measurements. For the unpumped laser ($J_p = 0$), the ratio of maximum modulation sensitivity at $\Omega_s = 1$ to the low-frequency modulation sensitivity is about 20. With rising pumping current J_p, the modulation sensitivity peak is shifted towards lower frequencies and finally reaches a maximum amplification at $\Omega_s = \frac{1}{2}\Omega_p = 0{\cdot}95$ for $J_p = J_{p_{opt}}$, implicity given by eqns. 6 and 10. The parametric gain is nearly one order of magnitude larger in comparison with the maximum modulation sensitivity of the unpumped laser. Further increase of J_p reduces the modulation sensitivity.

For measurement of parametric sideband amplification, a

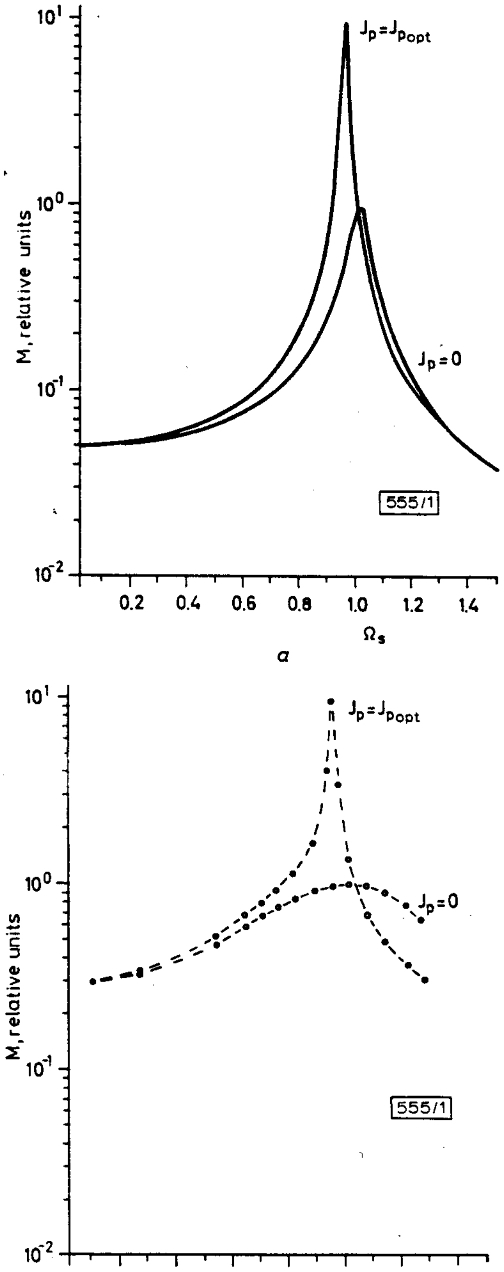

Fig. 1 *Modulation sensitivity of injection laser*

Pumped at $\Omega_p = 1{\cdot}9$ with $J_p = J_{p_{opt}}$, in comparison with the modulation sensitivity of the unpumped laser ($J_p = 0$) for a bias current $J_0 = 1{\cdot}1\ J_{th}$ and a lifetime ratio of $\tau_{sp}/\tau_{ph} = 5000$
a Theory
b Measurement

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* We regret an error in Reference 1. The terms S_p, S_p^*, N_p, N_p^* in eqns. 17*a–d* should be multiplied by the factor 1/2

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c.w. laser diode with $\tau_{sp}/\tau_{ph} = 5000$ and a maximum permissible current ratio of $J_0/J_{th} = 1{\cdot}1$ was used in a setup shown in Fig. 2. The signal frequency Ω_s and the pumping frequency Ω_p are generated by sweep oscillators. A large pumping current is achieved by a t.w.t. power amplifier. Damage to the frequency sources, caused by mismatching and frequency mixing in the oscillators, is prevented by two isolators and a 20 dB attenuator. Signal and pumping amplitudes are guided by a directional coupler to the spectrum analyser, which is switched to a *p–i–n* detector diode for light-output measurement. The laser diode is mounted on a copper heatsink and cooled by a levelled Peltier element. For current measurements, the impedance of the laser is supposed to be small in comparison with the 50 Ω matching resistor, which is integrated into the heatsink, together with the a.c. and d.c. blocks. A transistorised constant-current source supplied by a storage battery delivers the bias current.

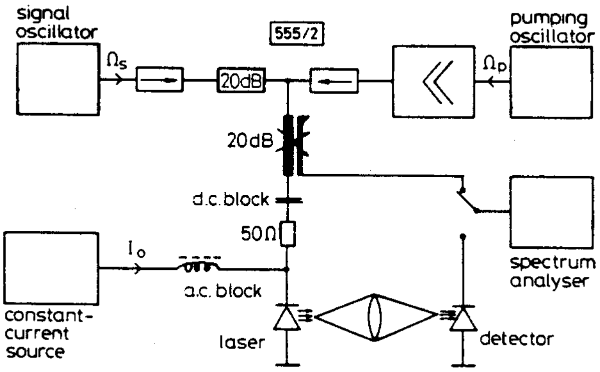

Fig. 2 *Schematic of experimental setup for measuring parametric sideband amplification in injection lasers*

Measured parametric sideband amplification is shown in Fig. 1*b* for $\Omega_p = 1{\cdot}9$. Although the maximum modulation sensitivity at $\Omega_s = 1$ of the unpumped laser ($J_p = 0$) is only three times the low-frequency value, the parametric gain of the pumped laser attains one order of magnitude in relation to the peak value of the umpumped laser. Corresponding to theory, maximum amplification is attained for $\Omega_s = \frac{1}{2}\Omega_p$. However, a parametric gain of 20 is measured at frequency $\Omega_s \doteq \frac{1}{2}\Omega_p$ for $\Omega_p = 1{\cdot}7$, whereas computations only give low gain for this case. This effect is supposed to be due to the weak resonance maximum of the unpumped laser, caused by multimode operation and spontaneous emission[4] not being considered in the rate equations.

Applying a laser as a parametric sideband amplifier is restricted to analogue modulation by the narrow bandwidth of the modulation sensitivity maximum, which may be enlarged only by reducing the gain. This can be accomplished by decreasing the pumping current amplitude J_p from its optimum value $J_{p_{opt}}$. Bandwidth and gain, moreover, are reduced by the idler frequency $\Omega_i = \Omega_p - \Omega_s$, also appearing in the light output. For this reason, operation only with $\Omega_s \neq \frac{1}{2}\Omega_p$ is possible.

Analogous to parametric sideband amplification, a parametric sideband upconvertor should be realisable with similar gain and bandwidth behaviour.

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References

1 RUSSER, P., HILLBRAND, H., and HARTH, W.: 'Parametric sideband amplification in injection lasers'. *Electron. Lett.*, 1975, **11**, pp. 87–89
2 HARTH, W.: 'Large-signal direct modulation of injection lasers', *ibid.*, 1973, **9**, pp. 532–533
3 IKEGAMI, T., and SUEMATSU, Y.: 'Direct modulation of semiconductor lasers', *Electron. Coummun.*, 1968, **51B**, pp. 51–57
4 HARTH, W., and SIEMSEN, D.: 'Modulation characteristics of injection lasers including spontaneous emission. Pt. I—Theory' (to be published)