Assuming \( N = eV/\hbar \omega \), where \( N \) is the carrier density, \( J \) is the current, \( e \) is the electron charge, \( V \) is the volume of the active layer, and \( B_0 \) is the effective recombination coefficient, \( \Diamond \hbar \omega N \) is proportional to \( \Delta \gamma \Delta N \). Therefore, the temperature dependence of the modulation characteristics would be improved in a TDR mirror coated laser.

Fig. 4 shows the square of resonance frequency \( f^2 \), measured using the relative intensity noise (RIN) measurement, against temperature for both a constant power of 5mW and a constant current of 30mA. As expected, the \( f \) for a TDR mirror coated laser is less temperature insensitive than that for a conventional HR coated laser. This is attributed to the less temperature insensitive \( \hbar \omega N \) characteristics as shown in Fig. 3 in spite of the decrease of photon lifetime with temperature due to the decrease of mirror loss. These modulation characteristics are favourable for practical applications as well as temperature insensitive threshold current and differential quantum efficiency operation as shown in Fig. 1.

In conclusion, we have measured the net gain of SL-QW lasers with conventional HR coating and TDR mirror coating. It is found that the observed high \( T_c \) in an SL-QW laser with TDR mirror is attributed to the temperature insensitive net gain, resulting from the decrease of mirror loss or the increase of facet reflectivity with temperature. Less temperature dependence of the modulation characteristics is measured in a TDR mirror coated laser.

**High-power figure-of-eight laser for soliton transmission experiments**

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*Indicating terms: Fibre lasers, Ring lasers, Nonlinear optical loop mirrors*

The Letter reports on a modified figure-of-eight laser constructed with a 70% output coupler inside a nonlinear amplified loop mirror generating single nearly transform-limited pulses (1.3ps) per high-power roundtrip (<3SW). This laser is a convenient source of soliton pulses for propagation experiments in standard telecommunication fibres.

Figure-of-eight lasers (FSL) [1], comprising a passive loop and a fibre amplifier in a nonlinear amplified loop mirror (NALM) [2], are convenient sources of pico- and femtosecond soliton pulses. Generally Er-doped fibres used in FSL have sufficient gain to support tens or even hundreds of first-order solitons, randomly spaced and exiting the laser at the cavity roundtrip period [3]. Once pulse formation has been established, the laser gain must be greatly reduced, so that a stable single pulse is produced per roundtrip. Because the peak power of the soliton is clamped [4], the light extracted from the passive loop of the laser through a coupler has relatively low power, requiring additional external amplification for soliton transmission in standard fibres. In this Letter we describe the performance of a modified figure-of-eight laser (MFSL) capable of producing higher-power transform-limited output pulses, adequate for soliton propagation experiments in standard telecommunications fibre (STF).

The configuration of the MFSL is similar to that of the conventional laser, but instead of having a 10-70% output coupler spliced in the passive loop, here the output coupler is placed in the NALM, between the amplifier and fibre F, as illustrated in Fig. 1. The filter (FP) is used to allow for wavelength tuning and to suppress sideband generation which arises through periodic amplification of the solitons [5]. The main output port (output 1) follows the amplifier in the clockwise direction. An additional output (output 2) is available, providing pulses before amplification. For the beam circulating clockwise in the NALM in the steady-state regime, the pulse suffers strong amplification, large loss (output coupling) and SPM in the long fibre. The counterpropagating pulse suffers little or negligible SPM, large loss and then is strongly amplified. As long as the resulting gain of the combination of the amplifier and the passive coupler is sufficiently high, the extra loss can be tolerated by the laser, and solitons are formed. This is achieved at the expense of the number of soliton pulses generated per roundtrip. In the MFSL operating in the steady state, if the loss in fibre F and in polarization controller PC1 is neglected, the differential phase shift for the two counterpropagating components in the active loop is \( \Delta \phi = L \beta_2 (G - \alpha \gamma - P_2 \alpha) \), where \( L \) is the length of fibre F, \( G \) is the single-pass gain in the amplifier and \( P_2 \) is the power of the pulses entering the NALM after the 3dB coupler. The power at output 1 is given by \( P_1 = P_2 \alpha \), and since \( P_2 = P_0 \epsilon \), the single-pass gain can be found through the ratio \( G = F/P \). The product \( G (1-\alpha) \) gives the net gain in the active loop before the interference in the 3dB coupler. As long as the amplifier can provide sufficient gain, the output coupler can be chosen to have large \( \alpha \), and thereby high...
optical powers can be removed from the cavity. If the fraction of the power coupled out of the cavity is increased, the gain $G$ also has to be increased correspondingly in order to maintain the same intracavity power, keeping constant the product $G(1-a)$ and the differential phase shift. As a consequence, increasing the value of $a$ from 0.3 to 0.5, 0.7 or 0.85 leads to an output power increase of 2.3, 5.4 or 13.2 times, respectively. Note that having the output coupler immediately after the amplifier allows for extracted power much greater than that circulating on average as a fundamental soliton in the laser.

The experiments were carried out with a diode-pumped Er/Yb fibre amplifier ($D = -8$ ps/nm km, 100 m long), a 50 m dispersion-shifted fibre (DSF) $F (D = -2$ ps/nm km), a 16 m-long passive loop with standard fibre ($D = -1$6 ps/nm km), and a 2 m-bandwidth filter tuned to 1542 nm. The average dispersion of the fibre laser was $-1$ ps/nm km, and the cavity length 82 m. The gain of the amplifier was found to be sufficient to permit 85% output coupling, but to start soliton generation more easily it was convenient to use a 70% coupler. A short-length coupler was used ($-60$ cm) and was made of DSF ($D = -2$ ps/nm km). The gain was initially set to maximum, starting a multisoliton regime of operation, and was then gradually reduced so that a single soliton circulated in the cavity. Once in this regime, the laser would operate for a whole day without further adjustment. The roundtrip time of the MFBL was $-6$ times the roundtrip time of the conventional FXL, with power enhancement of approximately six times was demonstrated. The second author was supported by a fellowship from the Danish Technical Research Council and the National Agency of Industry and Trade, and the first author from the Brazilian Conselho Nacional de Pesquisas (CNPq). Overall support by the EPSRC is also gratefully acknowledged.

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References


Low-threshold mesa-etched vertical-cavity InGaAs/GaAs surface-emitting lasers grown by MOCVD

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Schematic view of MOCVD grown VCSEL

The authors have demonstrated a low threshold current of 0.33 mA and a threshold current density of 380A/cm² for MOCVD-grown InGaAs/GaAs vertical-cavity surface-emitting lasers with a pillar etched structure. The thermal characteristic of the fabricated device including thermal resistance and junction temperature rise is also discussed. Judging from this experiment, further reduction of threshold current can be expected by reducing nonradiative recombination and electrical resistance.

A slight increase in threshold current density observed in smaller devices might be caused by nonradiative recombination and excess heating in the p-mirror originating from threshold voltages higher than 2.5 V. Surface recombination velocity is examined by using the following equation [12]:

\[ J_{th} = N_v \alpha _0 \sqrt{2 V_d/r + 1/r} \]

where \(N_v\) is the number of wells, \(d\) is the well thickness, \(\alpha_0\) is the threshold current density, \(r\) is the device radius and \(t\) is the radiative carrier lifetime. The fitting curve based on the above equation determines the surface recombination velocity \(V_s\) to be \(1 \times 10^{7}\) cm/s. The improvement in surface condition by sulphide passivation [12] and reduction of electrical resistance will be helpful for further threshold reduction.

The temperature rise due to the heating at mirrors may become a crucial issue, especially in smaller devices when trying to realise ultra-low-power consumption. We show the thermal behaviour to be dependent on the device size of VCSELs. The thermal resistance is estimated by evaluating the wavelength shift with increasing electrical power. The wavelength shift as a function of the dissipated power for 6, 10 and 20μm-diameter devices was measured. The measured lasing wavelength shifts were 3, 1.3 and 0.8 A/mW, respectively. When we assume the temperature dependence of the lasing wavelength to be 1 A/K, the estimated thermal resistances are 3, 1.3 and 0.8 K/mW, respectively. They are summarised in Fig. 3 with the calculation based on the simple equation [13]:

\[ R_K = \sum \frac{T_i}{S_i} \]