which still might be reduced by a more sophisticated mounting technology. The room temperature threshold of 10.4 mA and the differential quantum efficiency of 72% (0.65 W/A per facet) are unaffected by the mounting, but the maximum RT output power is increased to 23 mW per facet (right part of Fig. 3), before a catastrophic optical damage (COD) of the uncoated mirrors occurs. Passivation of the mirrors should lead to significantly higher output power levels.

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bottom pn junction serves as the active or gain element. The top np junction within the top mirror stack serves as the voltage-controlled saturable absorber. This design resembles that of an integrated quantum-well detector-VCSEL in [8], where details of the structure and the fabrication can be found. The saturable absorber is biased with a voltage source, producing voltage $V_a$ in series with a variable resistor $R$ as shown in the inset of Fig. 1. A termination path is provided for any generated AC signal in the absorber.

An expanded view of the power-current ($I_p$-$L$) traces of a typical device is depicted in Fig. 2. A noticeable discontinuity in $dL/dI_p$ and a hysteresis loop are observed at threshold, indicating bistable operation. As the absorber bias voltage and resistance are varied, the hysteresis loop can be made to close as shown in the Figure, and the laser begins to self-pulsate. The transition between bistability and self-pulsation can also be explained using the absorber $I_a$-$V_a$ characteristics in Fig. 3. If $R$ and $V_a$ are adjusted so that the load line crosses the absorber $I_a$-$V_a$ three times, then bistability is observed. As the load line is tilted so that it matches the negative slope of $L$-$V_a$, more closely, the system enters a state of instability and self-pulsations commence. The typical threshold of a 25μm aperture self-pulsating laser occurs at $\approx 8.5$mA with a voltage across the active region of $\approx 3.3$V and a peak output power of $\approx 1.5$μW.

To ascertain whether self-pulsation can be achieved, the current-voltage ($I_a$-$V_a$) trace for the absorber was measured. Negative differential resistance (NDR) was obtained over a range of laser bias currents as shown by the current-voltage characteristic of a typical saturable absorber in Fig. 3a. This NDR is similar to that observed in [9], although in that work a bulk material was used as the absorber. In the following, we briefly explain the phenomenon. The absorber current is proportional to the applied electric field across the absorber junction and the optical power. When the absorber is forward biased, it behaves as a normal diode. As the absorber reverse bias increases (at the same laser bias), two competing processes affect the absorber current. The electric field across the absorber junction and the optical power. When the reverse bias voltage increases sufficiently, then the absorption decreases to point $\gamma$, bringing the absorber current back down to a mostly constant value. Thus, the strategic placement of the absorber and Fabry-Perot wavelengths. The absorber spectra for different reverse bias currents are sketched in Fig. 3b as a function of wavelength. The wavelength of the laser emission ($\lambda_{\text{lw}}$), which is fixed when the laser bias current is fixed. Point $\alpha$ indicates the amount of absorption at $\lambda_{\text{lw}}$ when $V_a = V_l$. When the reverse bias is increased to $V_a$, the absorption and hence the absorber current increase as the quantum-well absorption edge red-shifts, as shown by point $\beta$. When $V_a$ is increased sufficiently, then the absorption decreases to point $\gamma$, bringing the absorber current back down to a mostly constant value. Thus, the strategic placement of the Fabry-Perot wavelength and the quantum-well absorption edge significantly enhances the NDR, providing flexibility in the design for self-pulsations or bistability.
frequencies ranging from 1.1 to ~2GHz were also measured at other absorber voltages up to 10V, resistances ranging from 1-100kΩ, and laser bias currents 5-9mA (results not shown here).

In conclusion, we have demonstrated the first VCSEL to self-pulse using a voltage-controlled quantum-well saturable absorber. We observed negative differential resistance in the saturable absorber, which leads to self-pulsation under controllable conditions. Self-pulsation frequencies as high as 2GHz were observed with an RF linewidth (FWHM) of ~<10MHz. Such vertical-cavity devices will open up new applications for VCSELs.

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References


Upconversion-induced variations in gain-spectra of 1.48μm pumped erbium-doped fluoride fibre amplifier

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Indexing terms: Fibre amplifiers, Erbium-doped fibre amplifiers

Upconversion-induced variations in gain-spectra as large as ~1.3dB are observed in a 1.48μm pumped erbium-doped fluoride fibre amplifier, when gains at 1540 and 1560nm are kept equal to each other at different multiwavelength input powers. A novel model that takes upconversion into consideration well explains the experimental results.

Introduction: Erbium-doped fibre amplifiers (EDFAs), either erbium-doped silica fibre amplifiers (EDSFAs) or erbium-doped fluoride fibre amplifiers (EDFFAs), are key devices in 1.5μm band wavelength-division multiplexed (WDM) transmission and routing networks. EDFAs in particular, offer the advantage of gain flatness over EDSFAs [1 – 3]. The gain spectrum of the EDFAs in a network must be kept constant to stabilise system performance when either or both of the number of channels and the optical power launched into the EDFAs change [1, 4]. Several studies have reported that the gain-constant characteristic of EDSFAs is due to the strength of the homogeneous-gain-saturation effect [4 – 6].

This Letter shows, to our knowledge for the first time, that a typical EDFAs cannot, in a WDM configuration, offer gain-constant control at the same level as an EDSFAs. When gains at 1540 and 1560nm were kept equal to each other at different multiwavelength input powers, the gains in the signal wavelengths from 1540 and 1560nm of the EDFAs varied by ~1.3dB. A model of the population densities of the energy levels, which accounts for the upconversion processes, is proposed, and is found to successfully explain the measured variations in gain-spectra of EDFAs.

Experiment: Gain of a commercially available typical erbium-doped fluoride fibre (EDFF) was measured in a WDM configuration. The core-composition, Er³⁺-concentration and length of the EDFAs were ZBLAYLN [3]. 1000w-ppm, and 7.4m, respectively. The gain of an aluminium co-doped erbium-doped silica fibre (EDSF) with the same Er³⁺-concentration and a length of 18m, was also measured for comparison. Both EDFAs (EDFF and EDSF) were forward pumped by a 1.48 μm laser diode.

Three signal lights with wavelengths of 1540.1, 1551.3, and 1560.1μm, and the same optical power at each wavelength, were launched into the EDFAs. The three lights represented typical multichannel signal lights, and are called saturation lights in this Letter. The total power of the saturation lights launched into the EDFAs (Pₙ) was varied from ~26 to ~10dBm. Moreover, a probe signal light, which had a constant power of ~35dBm and wavelengths from 1522.5 to 1575.0μm, was also launched into the EDFAs in order to measure small-signal gain.

Fig. 1 shows the measured gain spectra for both EDFAs at Pₙ =-26, -22, and -17.7dBm. The measured gains are indicated by symbols and the lines were drawn by interpolation. The pump powers at the three saturation light powers launched into the EDFAs (Pₛₙ) were adjusted so that the gains at 1540 and 1560μm were kept equal to each other for the EDFAs (EDFF). Pₛₙ at Pₙ =-26, -22, and -17.7dBm for the EDFAs (EDSF) were 55.5, 67.8, and 88.8mW (42.2, 55.3, and 88.8mW), respectively.

Let the gain at a wavelength λ and saturation light power Pₛₙ be G(λ, Pₛₙ), and the gain difference between Pₛₙ and Pₛₙ be ΔG(λ, Pₛₙ), Pₛₙ = G(λ, Pₛₙ) - G(λ, Pₛₙ). Fig. 2 shows the gain differences ΔG(λ, Pₛₙ), Pₛₙ =-17.7dBm (where Pₛₙ =-26, -22dBm, -17.7dBm) in the EDFAs (EDSF) and EDFAs (EDFF).