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Class A shot noise limited operation is achieved in an Electrically Pumped Vertical External Cavity Laser, opening the way for integration of such peculiar noiseless laser oscillation in applications where low power consumption and footprint are mandatory. The quantum well active medium is grown on InP substrate to enable laser oscillation at telecom wavelengths. Single frequency class A operation is obtained by a proper optimization of the cavity dimensions ensuring at the same time a sufficiently long and high finesse cavity without any intracavity filtering components. The laser design constraints due to electrical pumping are discussed as compared to optical pumping. The intensity noise spectrum of this laser is shown to be shot-noise limited leading to a relative intensity noise of -160 dB/Hz for 3.1 mA detected photocurrent.

Semiconductor lasers have emerged as the most widespread lasers in most fields of applications. This success is linked to the high density of states within semiconductor materials, which leads to compactness, robustness and low power consumption when it is combined with electrical pumping. In several areas such as coherent communications and microwave photonics, low intensity noise lasers are mandatory [1]. An interesting and reliable option is to make the semiconductor laser operate in the so-called class A dynamical regime by increasing the photon lifetime inside the cavity to turn it higher than the population inversion lifetime [2,3]. In this regime the laser relaxation oscillations vanish leading to an effective relative intensity noise limited by the shot noise, i.e., the quantum noise. This property is of major importance as the intensity noise variance becomes proportional to the CW output optical power, and not to its square as in other lasers. Accordingly, the signal-to-noise ratio (SNR) of any system where such laser is implemented continues to increase as the laser output power is increased, as opposed to standard class B lasers where the SNR is fixed by the laser RIN level whatever its output power. Increasing the photon lifetime can be achieved by increasing significantly the laser cavity length and/or its finesse. Vertical External Cavity Surface Emitting Lasers (VECSELs) are the ideal device to obtain such properties [4-7] as they are by essence not subject to propagation losses that might forbid class A oscillation. Accordingly, Optically-Pumped VECSELs (referred as OP-VECSELs), when operated in single frequency, have been shown to provide Relative Intensity Noise (RIN) levels as low as -165 dB/Hz over a frequency range of typically 100 MHz to 22 GHz [8]. To date, however, electrically pumped shot noise limited class A VECSELs (EP-VECSELs) at 1.5 µm have never been reported in the literature, mainly due to the additional optical losses related to the use of doped semiconductors and also to the difficulty in achieving uniform electrical injection on such large areas [9,10]. Despite these technological challenges, such EP-VECSELs at 1.5 µm would open up new avenues in low noise applications where turn-key, compact and energy efficient lasers are required.

In this paper, we report for the first time to our knowledge the realization of an EP-VECSEL at telecom wavelength optimized for class A operation at shot noise levels.

The EP-VECSEL includes a gain mirror structure optimized at 1550 nm wavelength. The structure, depicted in Fig. 1, is composed of an InP-based active region surrounded by two semiconductor Distributed Bragg Reflectors (DBRs) with different reflection coefficients. The bottom DBR comprises 21.5 AlAs/GaAs pairs leading to a high reflectivity of ≥ 99.5%, whereas the top DBR comprises 6.5 GaInAlAs/InP pairs to reach a reflectivity of 70%. This arrangement enhances the effective optical gain and minimizes the optical losses introduced by the thick n-doped InP current spreading layer [10]. Besides, the active medium is composed of two n doped InP cladding layers, 7 compressively strained GaInAlAs QWs , and a p++/n++ InAlGaAs circular tunnel junction (TJ) which ensures electrical and optical confinement. The aperture size of the active medium is thus defined by the TJ whose diameter is equal to 20 µm. All materials were grown by MOVPE epitaxy on InP and GaAs substrates. Due to lattice mismatch, this GaAs based DBR has been bonded to the InP based active layer according to the wafer fusion technique [11,12]. Furthermore, the anode gold layer allows to increase the reflectivity of the bottom DBR as well as to improve the thermal conductivity facilitating the dissipation of the thermal heat released by the device to the copper substrate.

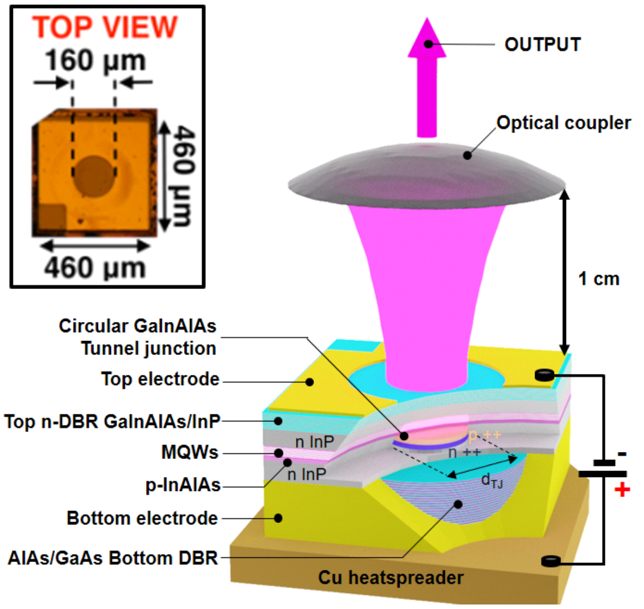

Fig. 1. Schematic of electrically pump VCSEL based quantum wells imbedded in an external high finesse cavity. MQWs: multiple quantum wells, d_{TJ}: tunnel junction diameter, DBR: Distributed Bragg Reflector.

To get rid of the relaxation oscillations, which lead to resonant excess noise, the EP-QWs-VECSEL is turned to a class A laser. This is achieved by increasing the photon lifetime, τ_p, in the cavity so that it exceeds the carrier lifetime, τ_c, in the active medium. To this aim the cavity length is set close to 1 cm, and the cavity is closed with a 99.5% reflectivity output coupler to ensure a high finesse of the overall laser cavity (see Fig. 1). In these conditions, the cavity photon lifetime is 6.6 ns, that is, higher than the semiconductor carrier lifetime at around 1 ns. The radius of curvature of the output coupler is 1 cm. The cavity length is adjusted close to the stability limit in order to match the laser waist with the 20 µm diameter of the TJ as will be discussed later. Finally, the temperature of the VCSEL structure is controlled by a Peltier thermoelectric cooler.

In VECSELs the TEM_{00} oscillation is usually ensured by the external cavity alignment. In optically pumped VECSELs, the gain profile induced by the pump beam has a Gaussian shape, or possibly top hat shape, which naturally favor TEM_{00} transverse mode oscillation. This is not the case in electrically pumped VECSELs where the inhomogeneous distribution of current density leads to a higher population inversion on the edges of the TJ than in its center [13,14], favoring high-order transverse mode oscillation even if the output mirror is perfectly aligned. This inhomogeneous gain profile can be seen on the Far-Field (FF) amplified photoluminescence on Fig. 2(a), where the output mirror has been slightly tilted in order to turn off the laser oscillation. The images on Fig. 2 have been acquired using a 640×512, 14 bit, SWIR InGaAs camera from Photonic Science. For near field measurements, a magnified intermediate image is created outside the laser and then acquired using microscope assembly with a 20× objective.

To cope with the inhomogeneous distribution of current density, the cavity length must be carefully adjusted so that the laser waist is slightly larger than the TJ radius. This is illustrated in Fig. 2 where the laser beam pattern is acquired for two situations. Close to the resonator stability limit, both near field, Fig. 2(b), and far field, Fig. 2(c), images exhibit a donut like pattern with a minimum intensity in the center [15,16]. However, when the cavity length is set a fraction of mm slightly shorter than stability limit, near field, Fig. 2(d), and far field, Fig. 2(e) acquisitions reveal TEM_{00} transverse mode oscillation. Accordingly, the TEM_{00} oscillation does not coincide with the mirror position where a maximum output power is extracted. Indeed, in this situation the diameter at the beam waist is measured to be 29 µm, i.e., higher than the 20 µm TJ diameter. Nevertheless, a pure fundamental single transverse mode emission can be achieved without an intracavity pinhole which is a positive point for power budget.

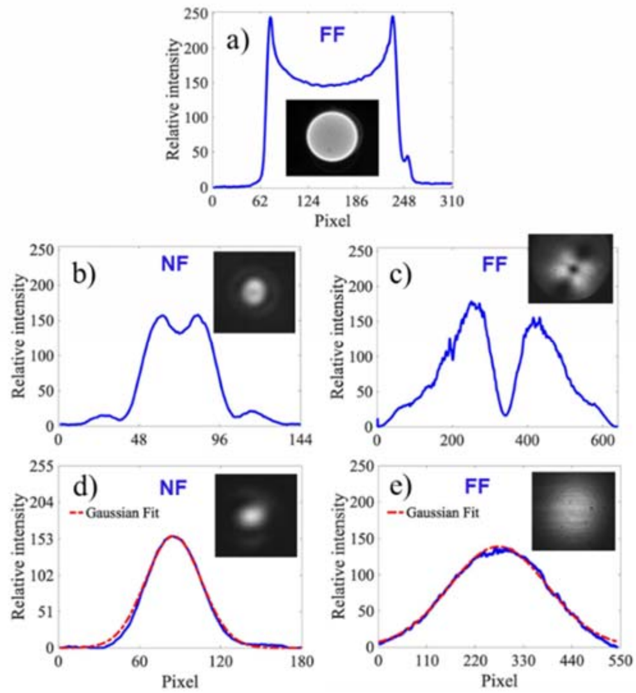

Fig. 2. Beam patterns imaged with a InGaAs camera. a) Far-field (FF) resonant amplified electroluminescence measured at a current density of 19.1 kA/cm^2. b) and c) Near-field (NF) and FF profiles of the laser beam obtained when the output mirror is positioned for maximum power extraction (60 mA pump current). d) and e) NF and FF profiles obtained for a slightly shorter cavity and exhibiting a TEM_{00} single transverse mode oscillation.

Single longitudinal mode oscillation is another issue which must be considered. According to the small diameter of the active area as compared to an optically pumped VECSEL, the radius of curvature of the output mirror was chosen to be 10 mm. This radius of curvature is found to be a good tradeoff between robust TEM_{00} oscillation, which requires a low radius of curvature, and the targeted class A operation, which in turn requires a high radius of curvature in order to ensure the stability criterion of a long linear cavity. On the other hand, a short cavity is going to favor single longitudinal mode operation. In particular, when the mirror position is adjusted below the stability limit to ensure TEM_{00} oscillation, single longitudinal mode oscillation is obtained without any intracavity étalon as shown in Fig. 3 where the laser output is analyzed over the whole device gain bandwidth using a standard optical spectrum analyzer and a Fabry-Perot interferometer with a free spectral range (FSR) of 7GHz. This shows another advantage of having the two DBRs surrounding the active region which induce an additional spectral filtering effect. Moreover, a side mode suppression ratio

(SMSR) as high as 52 dB is achieved for 60 mA pump current as reported in the right-hand side inset of Fig. 3 where the laser spectrum is now acquired with a heterodyne high-resolution spectrum analyzer (APEX AP2083A).

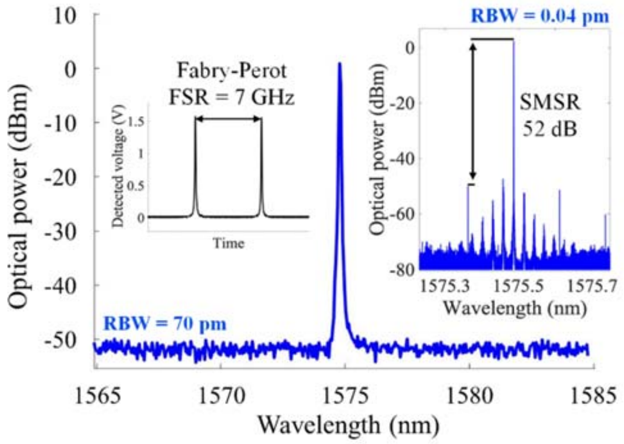

Fig. 3. Optical spectrum of the EP-QWs-VECSEL. Left hand-side inset: Fabry-Perot analysis testifying single frequency operation of the laser. Right hand-side inset: high resolution optical spectrum revealing the side mode suppression ratio of the laser.

The tradeoff regarding the cavity length and the output mirror radius of curvature is very advantageous in terms of output power budget since the lack of energy extraction imposed by TEM_{00} oscillation is counterbalanced by getting rid of an intracavity étalon which would have brought additional losses. In these conditions the laser provides 3 mW output power with single transverse and longitudinal mode oscillation. Moreover, we have checked that the laser sustains the oscillation of a single linear polarization state, meaning that the laser is perfectly single frequency. This is illustrated in Fig. 4 where the laser power versus pump current is represented together with its current vs voltage characteristic as well as the analysis of its output polarization. Pure, single frequency operation is an important aspect for reaching shot noise limited operation.

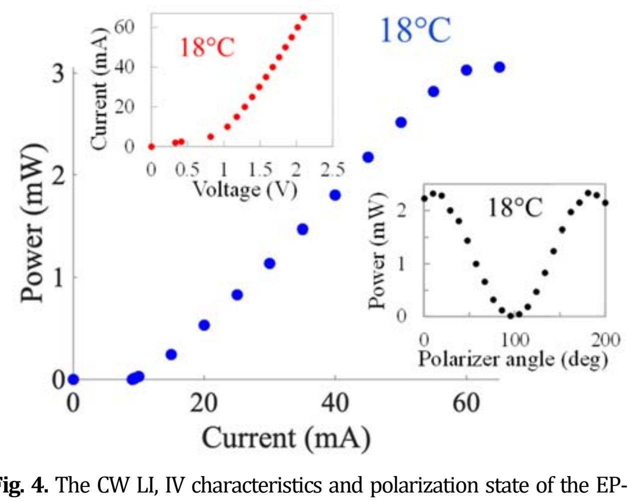

Fig. 4. The CW LI, IV characteristics and polarization state of the EP-QWs-VECSEL at 18°C.

The laser being perfectly single frequency, its Relative Intensity Noise (RIN) is analyzed for a pump current and a temperature set to 60 mA and 18°C respectively. In particular, we aim at obtaining the class A operation regime where the relaxation oscillation excess noise has completely disappeared leading to a shot noise limited oscillation. As for optical pumping the technical noise must be minimized by reducing mechanical vibrations. Accordingly, the gain structure was positioned on a Printed Circuit Board (PCB) and the probes previously used for electrical pumping were replaced by wires bonded to bridge the PCB and the laser structure. The PCB was designed to ensure a good thermal dissipation and was positioned on a Peltier thermoelectric cooler. This assembly as well as the output mirror are finally mounted within a rigid optical cage system preventing any fluctuations at low frequency. It includes four invar rods which avoid possible twist of the cavity and thermal drift of its length. As compared to optical pumping, acoustic shielding is not sufficient. Since we are probing extremely low intensity fluctuations, RIN measurements revealed that the laser is also sensitive to electrical injection noise as well as to surrounding electromagnetic radiations. In light of these observations, a low noise driver (Sandford Research System LDC502) has been employed. Moreover, all the electrical cables and connectors have been electromagnetically shielded. Finally, the laser was housed in a Faraday cage. The acoustic insulation is ensured with an absorbing layer covering the inner of the Faraday cage.

The RIN measurements from 100 kHz to 500 MHz are performed using a free space InGaAs photodiode with 1.1 A/W responsivity followed by a 51 dB gain amplifier (1 kHz - 500 MHz). The spectrum analyzer is a Rohde & Schwarz RS-FSW13. At very low frequency, i.e. below 2 MHz, the RIN spectrum reveals the current noise of the laser driver that is not filtered out by the class A laser (Fig. 5(a)). It is worthwhile mentioning that the cutoff frequency of the present laser is 20.5 MHz. Consequently, the contribution of the spontaneous emission is negligible even below the cutoff frequency proving that the excess noise usually observed below the cutoff frequency of optically pumped class A lasers is only related to the pump RIN. This behavior which was expected by Myara et al. [17] is here confirmed experimentally.

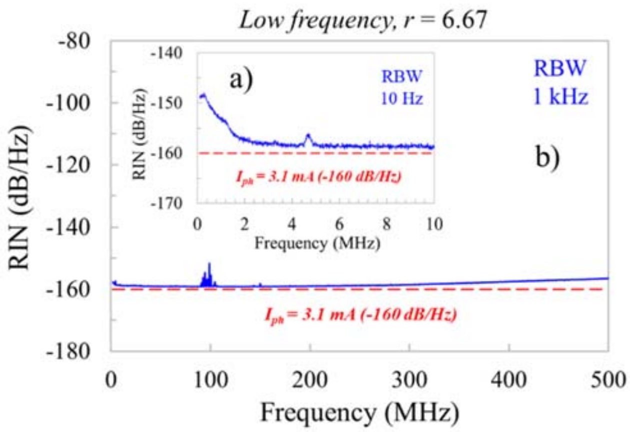

Fig. 5. RIN for 3.1 mA detected photocurrent (sweep points 10001, sweep count 100). The pumping rate, $r = I/I_{th}$, is 6.67. Red dashed lines are the relative shot-noise level for 3.1 mA detected photocurrent (-160 dB/Hz). a) RIN at very low frequency with RBW = 10 Hz , b) RIN at low frequency with RBW = 1 kHz.

In Fig. 5(b), one can notice peaks appearing from 90 to 105 MHz. They are due to the surrounding radio radiations in the FM band which are still apparent despite the shielding Faraday cage. Apart from these two regions, the laser RIN level corresponds to the relative shot noise expected at -160 dB/Hz for 3.1 mA detected photocurrent.

At microwave frequencies, the RIN is measured using a second bench including a fibered photodiode (cutoff 22 GHz) and a RF amplifier (100 MHz - 20 GHz) of 50 dB gain. The spectrum analyzer is a Rohde & Schwarz RS-FSW26. For all our measurements, the Power Spectral Density (PSD) of the noise floor, i.e. when the photodiode is in the dark, is kept at least 7dB below the measured PSD when the laser beam illuminates the photodiode. Due to the fiber coupling losses and to the slightly lower photodiode efficiency at this frequency range, the measured photocurrent is now 1.48 mA. This theoretically leads to a relative shot noise level of -157 dB/Hz (Fig. 6). As expected, the RIN measured from 150 MHz to 20 GHz sticks to this quantum noise floor, proving that the laser operates in the class A regime. It is worthwhile mentioning that the tiny peak at 14.92 GHz, appearing 6.3 dB above the relative shot noise level, corresponds to the beating between the oscillating mode and the amplified spontaneous emission lying in the two adjacent non-lasing modes. This peak might be removed if needed by inserting a buffer reservoir mechanism based on two-photon absorption or second harmonic generation cavity [18]. Finally, let us mention that we have also investigated VCSEL structures including tunnel junctions of 50 µm and 75 µm diameters. Even though, their oscillation in an external cavity was successfully obtained, they were less suitable for realizing a shot noise limited laser. Indeed, perfect single transverse and longitudinal mode was difficult to obtain without inserting intracavity elements such as clear aperture and/or étalon, leading to additional losses degrading the cavity finesse. As a result, their noise characteristics were less satisfactory as compared to the 20 µm diameter TJ structure reported here. Nevertheless, the structures with larger TJ could find interesting openings in high power but less demanding applications in terms of noise level.

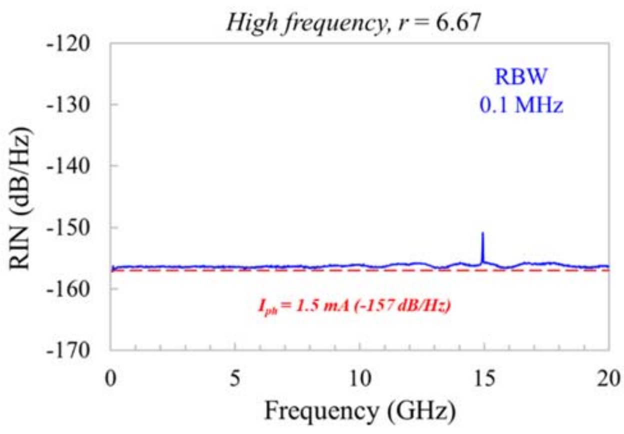

Fig. 6. High frequency RIN for 1.48 mA detected photocurrent (RBW = 0.1 MHz, sweep points 10001, sweep count 100). The pumping rate, r = I/I_{th}, is 6.67. Red dashed line is the relative shot-noise level for 1.48 mA detected photocurrent -157 dB/Hz.

In conclusion, we report here on the first electrically pumped shot noise limited class A laser operating at telecom wavelength. The VCSEL active medium includes GaInAlAs quantum wells grown on InP and pumped through a tunnel junction ensuring efficient current confinement. Homogeneous pumping implies a relatively small tunnel junction, which in turn rules the cavity design. We show that the class A shot noise limited operation relies on a cautious optimization of the cavity design and in particular on the control of its transverse modes. Moreover, a careful electromagnetic shielding was necessary in addition to the common acoustic shielding. In these conditions, the laser RIN spectrum exhibits a maximum RIN level of -145 dB/Hz between 100kHz and 2 MHz. Above 2 MHz, the RIN sticks to the quantum limit relative shot noise level, that is, -160 dB/Hz and -157 dB/Hz for a measured photocurrent of respectively 3.1 mA (1 kHz - 500 MHz) and 1.48 mA (100 MHz - 20 GHz).

These results pave the way to the integration of shot noise limited lasers into real systems. Indeed, class A operation is here achieved with a 1 cm long laser cavity. The electrical pumping brushes aside cumbersome optical-pumping assembly, making the overall laser fits a butterfly package commonly used for edge emitting lasers. Moreover, in such a housing, the electromagnetic shielding would be obviously fulfilled. Moreover, as far as field applications are targeted, the power consumption is an important aspect. The electrical power consumption has been here drastically reduced. Indeed, a 3 mW shot noise limited coherent optical beam at 1.5 µm was achieved with 120 mW pump power. This contrasts with optical pumping where the same optical beam characteristics would require typically 4-5 W electrical pump power. Direct electrical injection opens other interesting perspectives such as easy active noise reduction below the laser cutoff frequency, that is in the region where inherently some excess noise remains. Possible light squeezing, which was not conceivable with optical pumping, is another interesting future research issue offered by such an electrically pumped class A laser.

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Disclosures. The authors declare no conflicts of interest.

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