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HIGH-POWER AL-FREE ACTIVE REGION ($\lambda = 852\text{nm}$) DFB LASER DIODES FOR ATOMIC CLOCKS AND INTERFEROMETRY APPLICATIONS

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ABSTRACT

Atomic clocks will be used in the future European positioning system Galileo. Among them, the optically pumped clocks provide a better alternative with comparable accuracy for a more compact system [1]. For these systems, diode lasers emitting at 852nm are strategic components. The laser in a conventional bench for atomic clocks presents disadvantages for spatial applications. A better approach would be to realise a system based on a distributed-feedback laser (DFB). We have developed the technological foundations of such lasers operating at 852nm. These include an Al free active region, a single spatial mode ridge waveguide and a DFB structure.

The device is a separate confinement heterostructure with a GaInP large optical cavity and a single compressive strained GaInAsP quantum well. The broad area laser diodes are characterised by low internal losses ($<3\text{cm}^{-1}$), a high internal efficiency (94%) and a low transparency current density ($100\text{A}/\text{cm}^2$). For an AR-HR coated ridge Fabry Perot laser, we obtain a power of 230mW with $M^2=1.3$.

An optical power of 150mW was obtained at 854nm wavelength, 20°C for AR-HR coated devices. We obtain a single spatial mode emission with $M^2=1.21$ and a SMSR over 30dB, both at 150mW.

DFB Lasers at 852.12nm, corresponding to the D2 caesium transition, were then realised with a power of 40mW, 37°C for uncoated devices. The SMSR is over 30dB and the $M^2=1.33$ at 40mW.

Furthermore, the preliminary results of the linewidth obtained with a Fabry Perot interferometer give a value of less than 2MHz.

1. INTRODUCTION

Single frequency and spatial single mode diode lasers emitting at 852nm are strategic components for systems such as atomic clocks (positioning systems for navigation, in space atomic clock like Galileo or Pharao (cold atom), measurement of fundamental constants), or interferometry applications. We have developed the technological foundations of lasers at 852nm to address these different applications.

In a conventional bench for atomic clocks, the laser source is a Fabry-Perot laser diode, which is placed in an external cavity laser configuration to provide the

single frequency emission behaviour and the essential low line-width. However, with this configuration, limited power typically only a few milliwatts is achieved, which is not sufficient to fulfil the atom cooling requirements. Furthermore this technique presents difficulties for spatial applications owing to the precise requirements of the optical alignment and the mechanical stability. A system based on a single-frequency and spatial single mode diode laser providing both low line-width and higher power is a better approach for this application.

With the aim to develop such a device, we have developed laser structures emitting at $\lambda=852\text{nm}$, using an aluminium free active region. Lasers in the InGaAsP/GaAs material system are characterised by a much better reliability [2,3] than AlGaAs-based devices. This factor is important for high power and spatial applications. Atomic clock need a single frequency laser, so we have developed a distributed feedback laser structure (DFB). Another advantage of the aluminium-free system is the easier implementation of epitaxial regrowth compared to an AlGaAs-based system. This is a particularly important issue for the fabrication of a single frequency and single spatial mode operation with a distributed feedback laser structure, based on the epitaxial regrowth concept.

2. LASER STRUCTURE

2.1 Epitaxial structure

The laser wafer was grown by metal organic vapour phase epitaxy (MOVPE) on an n-type doped (100) GaAs substrate. The device under study is a separate confinement heterostructure (SCH) with a GaInP large optical cavity (LOC, total thickness $\sim 1\mu\text{m}$) to provide low optical losses and a compressive-strained GaInAsP quantum well (8nm). An intentional lattice mismatch in the quantum well causes a reduction of the hole effective masses, and thus reduces the valence band density of states. Strain separates the light and heavy hole sub-bands by up to several $k_B T$ such that under compressive strain the heavy hole band is uppermost. As a result, the emission is transverse electric (TE) and the TM radiative recombination rate is strongly

reduced. The confining layers consist of p and n doped AlGaInP. Figure 1 shows the laser structure.

AlGaInP	p cladding
GaInP	optical confinement
GaInAsP	8nm quantum well
GaInP	optical confinement
AlGaInP	n cladding

Fig. 1 : Laser structure

2.2 Broad area structure

Broad area lasers with a stripe width of about 100µm were processed. Metallization on the n and p side junction was carried out and laser bars were cleaved with cavity lengths of 1mm or 2mm. To reduce current injection area, a mesa structure was formed in the stripe region of the contact layer. Individual chips were bonded in a junction-down configuration. Diodes with uncoated facets were tested to determine typical parameters such as internal efficiency, internal loss, and transparency current density. For high power CW characterisation, diodes with high reflectivity (HR) and antireflection (AR) coatings were realised.

2.3 Ridge structure

In order to obtain a spatial single mode emission, lateral confinement is provided by about 4µm wide ridge diode lasers. Figure 2 represents a schematic of the ridge laser structure. Following mirror coatings, the chips are separated using cleaving techniques and are mounted up or down on submounts.

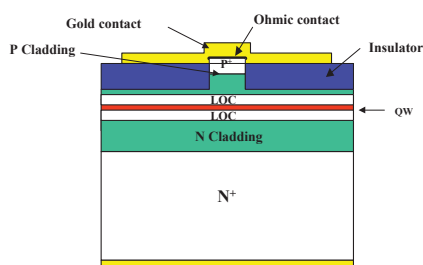


Fig. 2 : Schematic of the ridge laser structure

To obtain a spectral single mode emission, we have developed laser structure based on a distributed feedback laser structure (DFB).

2.4 DFB structure

Processing technology of the DFB is based on an identical technology to a ridge laser structure (ridge width : ~4µm). The realization of a distributed feedback (DFB) laser structure consists of three

stages : initial epitaxy, grating definition and epitaxial regrowth. The initial stage is the epitaxial growth of a structure identical to a broad area laser up to the grating layer. The grating layer, GaInAsP, is then grown followed by top layer of GaInP. The Bragg grating structure in our realisation is a second order grating with a period (Λ) of around 2500Å. The grating structure is defined by holography. The implementation of the grating structure is carried out in two steps. Step one consists of the dry etching (Reactive Ion Etching : RIE) of the GaInP/GaInAsP layers. RIE being anisotropic, an aspect ratio of 1:1 is maintained as shown in figure 3. To obtain maximum coupling efficiency an aspect ratio of 1:3 is required (cf. Fig.4). This is carried out using a wet chemical selective etch. Following the fabrication of the grating pattern, an epitaxial regrowth is carried out to grow up to the contact layer.

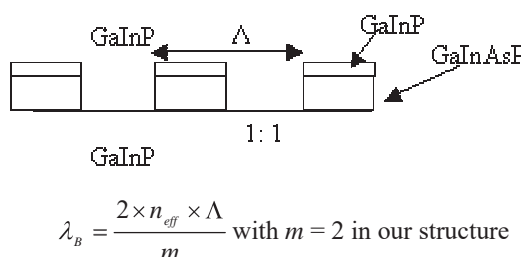


Fig. 3 : Schematic of the Bragg grating structure before wet chemical selective etch

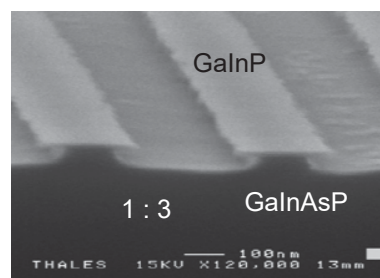


Fig. 4 : scanning electron microscope image of grating structure

3. BROAD AREA LASER RESULTS [4, 5]

Initial work was based on 100µm wide broad area lasers of different lengths with uncoated facets to determine typical parameters such as internal efficiency, internal loss, and transparency current density, which determine the quality of the epitaxial structure.

We measured low internal losses ($\alpha < 3 \text{ cm}^{-1}$), a high internal efficiency ($\eta = 94\%$) and a low transparency current density ($J = 100 \text{ A/cm}^2$).

Figure 5 shows the optical output power and the wall-plug efficiency as a function of current at 20°C under CW operation for a 2mm long AR/HR coated laser diode. We measure a high slope efficiency (0.92 W/A) and a low threshold current (490mA), which

corresponds to a threshold current density of 245A/cm². We obtain an optical power of more than 5.5W (I= 8.5A), under CW operation at 15°C, with a maximum wall-plug efficiency of 0.45.

An optical power of more than 1.4W is obtained at 100°C (I=3.6A). The threshold current is 486mA and 686mA at 20°C and 60°C, respectively, indicating a value of T₀=116K. T₀ and T₁ are defined by :

$$I_{th}(T') = I_{th}(T) \exp\left(\frac{T' - T}{T_0}\right) \quad \eta(T') = \eta(T) \exp\left(\frac{T - T'}{T_1}\right)$$

The slope efficiency is 0.92W/A at 20°C and 0.84W/A at 60°C, respectively with a value of T₁= 436K. A power of 1.2W (I=1.7A, 15°C) is achieved at 852nm for a 2mm long device.

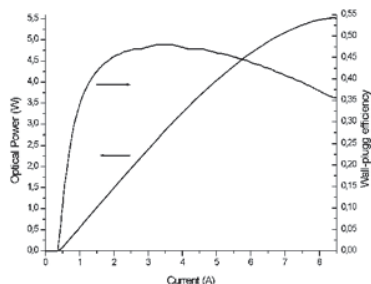


Fig. 5 : L-I and plug efficiency characteristics for a 2mm long AR/HR coated broad area laser diode

4. RIDGE LASER DIODE RESULTS [4, 5]

In order to obtain a single spatial mode emission, lateral confinement is provided by a ridge waveguide, by about 4µm wide.

Figure 6 shows the typical optical output power and the wall-plug efficiency as a function of current at 20°C for a 2mm long AR/HR coated ridge device under CW operation. We obtain a high slope efficiency (0.9 W/A) and a low threshold current (40mA). We obtain a value of T₀ = 144K (T₀ of the Ridge laser structure is similar to that of the Broad laser structure). A high optical power of 250mW is obtained at 280mA without, up to this power level, any non linearities due to higher order modes (“kink”). A maximum wall-plug efficiency of 0.40 is measured.

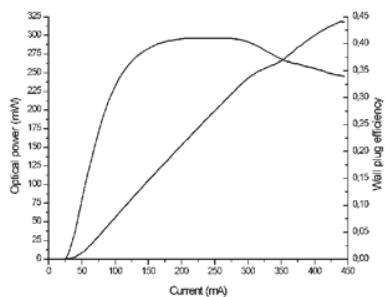


Fig. 6 : L-I and plug efficiency characteristics for a 2mm long AR/HR coated ridge area laser diode

Furthermore, we obtain the wavelength of 852nm with a high power of 145mW (I=200mA, T=15°C).

In order to investigate the brightness of our structures, we use the beam quality factor M². This factor is equal to 1 for a gaussian beam limited by diffraction. To characterise it, we measure the far field and the near field.

To determine the beam quality factor M², we can measure the near field and the far field either at 1/e² or calculate it with the second moment based on the far and near field experimental profiles. It's depend on the profiles of the fields. When fields have gaussian intensity profiles, we can calculate the M² parameter in the slow axis according the following formula:

$$M_{1/e^2}^2 = \frac{P}{4\lambda} \theta_{1/e^2} W_{1/e^2} \quad (1)$$

with λ the wavelength at the considered current, θ_{1/e²} the full divergence of the far-field at 1/e² and W_{1/e²} the full width of the near-field at 1/e².

When there are secondary lobes in the near-field and in the far-field profile, formula (1) is no longer valid. Instead, we use the generalised definition of the M² parameter based on the calculation of the second moment of the field profiles [6].

The M² parameter in the slow axis is given by :

$$M_{\sigma\sigma}^2 = 4\pi s_{x0} s_{sx} \quad (2)$$

where σ_{x0} is the second moment of the near-field intensity profile at the waist and σ_{sx} the second moment of the far-field intensity profile. Both methods were used to calculate the M² parameter. The two methods have a measurement error of ΔM²=0.1.

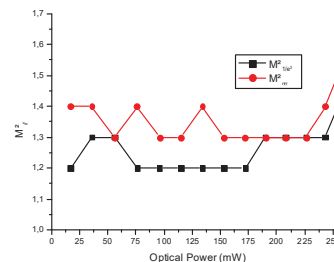


Fig. 7 : Evolution of parameter M² with optical power in the slow axis of a 2mm long AR/HR coated device

The M² parameter is very stable with the increasing current until I=280mA (P=230mW) where a higher order mode appears (cf. figure 7). This evolution corresponds to the increase in refractive index in the center of the ridge waveguide due to temperature increase (thermal lensing) and photon-density increase (spatial hole burning). Usually the method M²_{1/e²}

overestimates the beam spatial quality because of the Gaussian approximation of the mode profiles.

For the laser shown in figure 6, a good beam quality M^2 ($M^2_{1/e^2} = 1.3$ and $M^2_{\sigma\sigma} = 1.3$) is obtained at 280mA and 230mW under continuous wave operation at 20°C.

5. DFB LASER DIODE RESULTS

In order to obtain a spectral single mode emission, we have developed a distributed feedback (DFB) ridge laser structure, by about 4µm wide.

5.1 Emission at 854nm : 150mW optical power [7]

The Bragg grating period is iteratively investigated, allowing the desired wavelength to be obtained. With a grating period of ~2600Å, good results are demonstrated at $\lambda = 854$ nm.

Figure 8 shows the optical output power and the wall-plug efficiency as a function of current at 20°C under CW operation for a 2mm long AR-HR coated laser diode. We measure a high slope efficiency (1.05 W/A), a low threshold current (80mA).

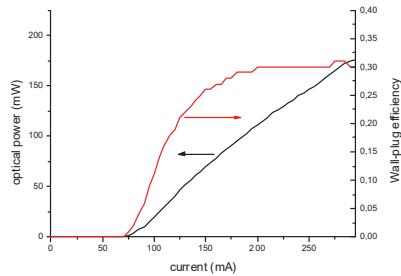


Fig. 8 : L-I and plug efficiency characteristics 2mm long AR-HR coated DFB laser diode

We obtain an optical power of more than 150mW ($I = 260$ mA) with a side-mode-suppression-ratio (SMSR) over 30dB. Figure 7 shows the emission wavelength. At a power of 153mW, the laser wavelength is 854.3nm.

Figure 9 shows the emission spectrum. At a power of 153mW, the laser wavelength is 854.3nm. We obtained single frequency behaviour at 20°C and a difference of 40dB between the Bragg peak and the gain peak. On the Bragg peak we notice the presence of slight shoulder (see insert of fig. 8) that we assume to be a secondary mode (the wavelength difference between the shoulder and the Bragg peak is around 0.4Å corresponding to the difference between two modes). The side-mode-suppression-ratio (SMSR) between the Bragg peak and the shoulder is 30dB. Furthermore, we obtained a difference of 50dB between the Bragg peak and the Bragg peak base.

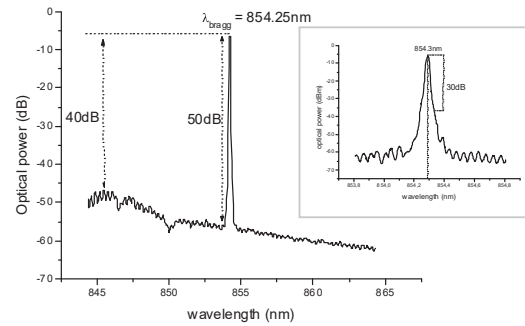


Fig. 9 : Optical spectrum showing lasing at 852nm, $T = 20^\circ\text{C}$, $I = 260$ mA, $P = 153$ mW for 2mm long AR-HR coated device

In figure 10 this SMSR is plotted as a function of the optical power. It should be noted that even up to 153mW optical power the SMSR is around 30dB.

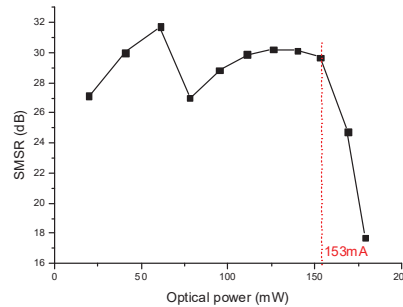


Fig. 10 : Variation of SMSR as function of optical power ($T = 20^\circ\text{C}$)

Monitoring the wavelength emission with respect to the pumping current and the temperature is a necessary approach to access the wavelength of 852.12nm corresponding to the caesium transition (D2 line).

The gain peak wavelength and the Bragg wavelength dependences on temperature are linear with a slope of about 0.3nm/°C and 0.06nm/°C respectively. The Bragg wavelength depends on the effective index variation with the temperature.

The gain peak wavelength increases in current with the same slope as the ridge Fabry-Perot lasers (0.012nm/mA) whereas the Bragg wavelength evolution in current has a slope of 0.002nm/mA. The gain peak dependence in current is based on mode jumps around the maximum of the gain curve, whereas the Bragg wavelength is again linked with the effective index variation with current (and therefore temperature)

The low evolutions of the Bragg peak wavelength with the temperature and the current are typical of DFB laser and it's a further proof of the single longitudinal

mode (SLM) behaviour reached thanks to the grating structure.

At 153mW (I=260mA), both near and far fields in the slow axis are gaussian-shaped with respective full widths at 1/e² of 8µm and 9.2° respectively, corresponding to a single spatial mode emission with a beam quality parameter $M^2_{1/e^2}=1.29$ and $M^2_{\sigma\sigma}=1.51$ (cf fig.11).

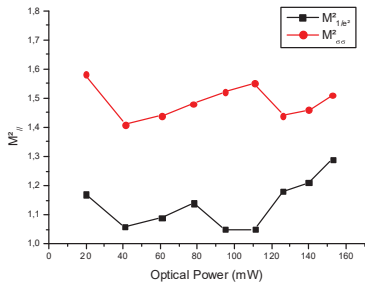


Fig. 11 : Evolution of parameter M² with optical power in the slow axis of a 2mm long AR/HR coated device

5.2 D₂ line emission : 852.12nm [7,8]

The further optimization of the grating period results in emission of 851nm wavelength. This allows now to obtain the D₂ line by temperature and current adjustment. We have obtained the D₂ line at 36.9°C. We measure (CW, 20°C) a high slope efficiency (0.44 W/A) and a low threshold current (46mA) for an uncoated laser. We measure (CW, 36.9°C) a high slope efficiency (0.4 W/A) and a low threshold current (52mA) for an uncoated laser (cf fig.12).

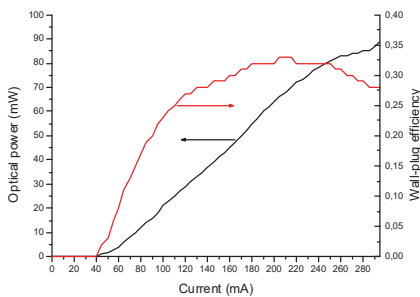


Fig. 12 : L-I and plug efficiency characteristics 2mm long uncoated DFB laser diode

Figure 13 shows the emission spectrum at 36.9°C, 140mA, 40mW. The laser wavelength is 852.12nm (corresponding to the caesium transition) and the SMSR is over 30dB.

Furthermore, we obtained a difference of 50dB between the Bragg peak and the Bragg peak base.

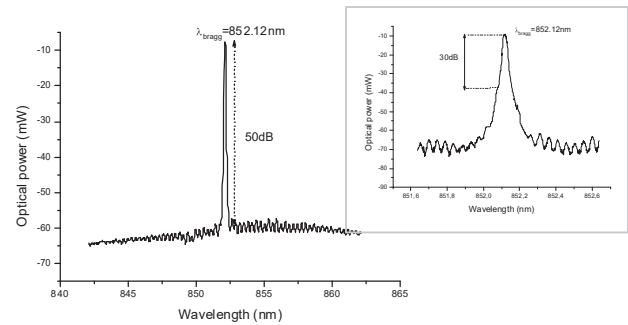


Fig. 13 : Optical spectrum showing laser emission at 852.12nm, T=36.9°C, I=140mA, P=40mW for 2mm long 4µm wide uncoated device

At 37mW (I=140mA, 20°C and CW), both near and far fields in the slow axis are gaussian-shaped with respective full widths at 1/e² of 6µm and 13.2°, corresponding to a single spatial mode emission with $M^2_{1/e^2}=1.3$ and $M^2_{\sigma\sigma}=1.5$. Figure 14 shows the near field and the far field (36.9°C) with respective full widths at 1/e² of 6µm and 13.8°.

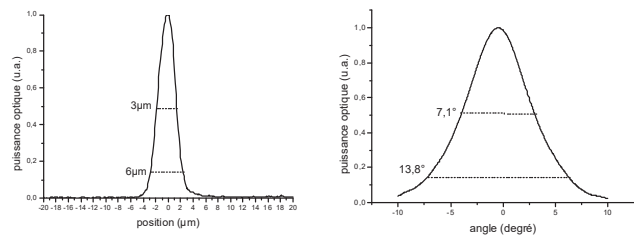


Fig. 14 : near and far fields for a 4µm wide 2mm long uncoated DFB laser diode at 852nm wavelength

6. DFB LINEWIDTH MEASUREMENTS AT 854nm

A Fabry-Perot interferometer (FPI, FSR=150MHz, resolution of 750kHz), as shown in figure 15 was used to measure the linewidth of our DFB laser. In the FPI, there are two optical isolators, that prevent a beam return towards the laser. The latter would create a cavity which could disrupt the measurement of the linewidth. In this configuration, the λ/2 plate is required to optimize the polarization of isolator (Faraday effect).

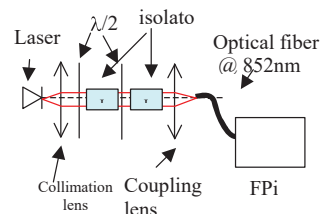


Fig. 15 : Schematic of the linewidth measure with a Fabry-Perot interferometer.

Figure 16 shows a single peak of the interferometry graph together with its lorentzien fit. We obtain a low linewidth value of 1.3MHz at an optical power of 111mW ($T=20^{\circ}\text{C}$). At 40mW we obtain a linewidth value of 1.9MHz.

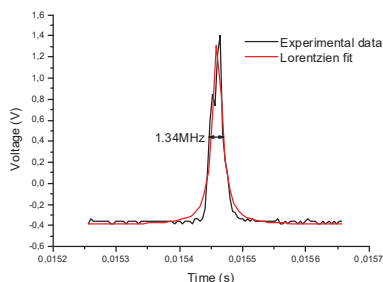


Fig. 16 : Interferogram and its Lorentzian fit with the Fabry-Perot interferometer and a Lorentzian fit ($P=111\text{mW}$)

7. CONCLUSIONS

We have demonstrated very stable single frequency (SMSR over 30dB : 40dB between Bragg and gain peaks, 50dB between Bragg peak and Bragg peak base) in optical power but also in temperature. We obtain indeed a SMSR around 30dB up to 80°C . The Bragg wavelength evolution in current has a slope of $0.002\text{nm}/\text{mA}$. The Bragg wavelength evolution in temperature has a slope of $0.06\text{nm}/^{\circ}\text{C}$. The low value of Bragg wavelength evolutions in current and temperature are characteristic of a DFB laser structure. Furthermore we have demonstrated very stable single mode lasers ($M^2 < 1.5$) with a high optical power. An optical power of 150mW was obtained at 854nm wavelength for AR-HR coated 2mm long around $4\mu\text{m}$ wide devices.

With a pitch adjustment we have demonstrated lasers at 852.12nm wavelength (D2 caesium wavelength) by temperature adjustment at 36.9°C for uncoated 2mm long devices. At this temperature, we have obtained a power of 40mW (140mA), a threshold current of 52mA and a slope efficiency about $0.4\text{W}/\text{A}$.

So we have demonstrated a very stable DFB laser suitable for Caesium pumping.

To our knowledge this is the first demonstration of an Al free laser diode for Cs pumping at 852nm.

These performances can be improved by the facet appropriate coating. Our following work will concentrate on reliability studies.

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