A new design of ECLD for compact atomic clocks

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***Abstract*— Cold atom clocks would take great benefits of microgravity environment. In Relation with the compact clock developments, we work on miniature laser-cooling optical benches. In this article we describe a new design of compact external cavity laser diode, which exhibits up to 80 mW at the output of the ECLD for a diode current of 100 mA and a line width of about 150 kHz.**

I. Introduction

The interest of microgravity environment operation for cold atom clocks is not to demonstrated yet. Several space clock projects are developed in Europe and USA [1][2]. One of the main difficulties of such setup is to reduce the size of the optical bench necessary to cool the atoms. In laboratory experiments these optical benches are typically 90 x 60 cm large and contain more than fifty components, and so it is very difficult to make them compatible with space specifications or with onboard constraints.

In relation with the development of compact cold atom clock HORACE [3], we have started a study about the design of compact and reliable cold atom optical bench. The expected bench size is a A4 format (29,7 x 21 cm), so about 10 times smaller than a laboratory bench. To reach this goal, two directions are studied: simplification of the bench architecture, and design of small optical functions thanks to new technologies as intergated optic and MOEMs. Listed functions are laser sources, frequency shift and control, intensity control and transport from optical bench to the vacuum chamber. In this article we only present the results of study about the laser source.

II. Optical Design of the ECLD

A. *Basic architecture*

The starting point of our design is the External Cavity Laser Diode (ECLD) configuration describe in [4]. This configuration uses a narrow-band dielectric interference filter as wavelength discriminator inside a 7 cm long extended cavity. These interference filters have 90% transmission and ~ 0,3 nm FWHM at near infra-red wavelengths, and are fabricated by Research Electro-Optic Corp. (REO).

One of the principal interests of this configuration is that the two tasks of wavelength selection and feedback reflection are carried-out by two different optical components: the interference filter and a 20% reflection mirror (see Figure 1).

So these two components can be aligned independently and most of all a cat's eye configuration to auto-align the cavity into the two transverse directions can be implemented. Thus, this configuration is very robust with optical misalignments, mechanical vibrations and thermal fluctuations. But on the other hand the ECLD is very sensitive to optical feedback and stray light and then a -35dB optical isolator has to be added at the ECLD output to prevent from backscattering light. With a laser diode SDL 5422 (P~150 mW with I = 150mA) the Typical ECLD output power is about 50mW (with I = 100mA) power and decreases to 40mW after the optical isolator.

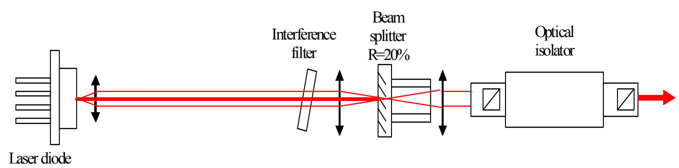

Figure 1. ECLD configuration describe in [4]. Emitting wavelength is selected thanks to the interference filter and feedback light is provided by a 20% reflection mirror in a cat's eye configuration.

B. *Our design and how does it work ?*

The principle idea of our design is to use the empty space inside the external cavity to add some useful optical components, as the optical isolator, which is a large size component. Obviously, a usual optical isolator inside the cavity blocks the return path of the beam to the diode and so the inside cavity losses are too large and prevent the emission on an extended cavity mode. Thus our optical isolator is a custom made isolator by Optic For Research (OFR) and the value of the Faraday angle is fixed to +28°. Polarization selectors are a polarizer at the input and a polarization beam splitter (PBS) at the output. The rotation angle between the transmission axis of the polarizer and the transmission axis of the PBS is -28° (see Figure 2). This angle value is chosen to set the ratio of the power transmitted and reflected by the PBS, as we will see below.

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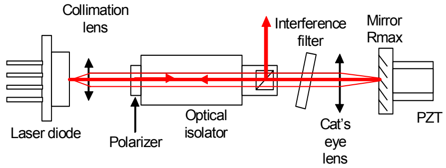


Figure 2. ECLD scheme of our ECLD configuration. The customized optical isolator acts as a circulator. For the forward beam, the circulator is like a R=68%/T=32% beam splitter. For the intra-cavity backward beam the transmission of the circulator is 100%. For the stray light coming to the ECLD output the transmission of the circulator is 0%.

At the output of the laser diode, polarization is oriented at 0°, same as the transmission axis of the polarizer. The polarization direction is turn to +28° by the Faraday (see Figure 3). Polarizing beam splitter is oriented as the transmission axis is -28°, so 32% ($\cos^2(56°) = 0{,}32$) of the power is transmitted and 68% ($\sin^2(56°) = 0{,}68$) is reflected and constitutes the output beam of the ECLD.

Beam reflected on the mirror stays with the -28° oriented polarization and so it is totally transmitted by the PBS. Then Faraday turns the polarization to 0° and so the polarization matching of the reflected beam with the laser diode is very good.

Polarization of backscattering light which enters in the ECLD by the output is +62° oriented by the PBS after reflection in it. Then, the Faraday turns the polarization of 28° so the polarization becomes +90° oriented and so the light is totally absorbed by the polarizer.

We can determine the optical power fed back to the diode in considering transmissions and losses of the components. We have measured T=27% for the optical isolator for the forward way (32% dues to beam splitter and 85% dues to loss) and T=85% for the backward way (only loss). For interference filter T=90% forward and backward. Thus total feedback is 19% ($0{,}27\times0{,}9\times0{,}9\times0{,}85 = 0{,}19$), which is very close to the R=20% beam splitter used in [1].

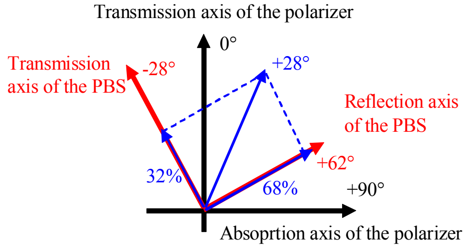


Figure 3. scheme of the polarization's orientation at the different states of the beam's propagation. Polarization is oriented at 0° (vertical axis) at the diode's output and then is totally transmitted by the polarizer. Polarization is turned to +28° through the Faraday and reaches the PBS. Transmission axis of the PBS is oriented at -28°, so the angle with the incident polarization is 56° and then 32% of the power is transmitted by the PBS and the polarization of the transmitted beam is -28° oriented. After reflection on the mirror, this backward beam goes through the PBS and is totally transmitted. Then polarization is turned to 0° by the Faraday and so is totally transmitted by the polarizer to the diode. The part of the forward beam reflected by the PBS is (-28 + 90 =) +62° oriented and contains 68% of the power.

C. *Detailed optical design*

The optical source is a TO3 packaged laser diode (SDL 5422) emitting at 852 nm up to 150mW. This diode is temperature regulated to the 0,01K level, and controlled with a very low noise current supply. Emitted elliptic beam is collimated by a C390TM-B lens (focal = 2,91 mm) from Thorlabs. The collimated beam size is about 0,6 × 1,8 mm large at $1/e^2$ of the intensity profile. Optical isolator is like already described and its windows diameter is 2 mm. The fine setting of the angle between isolator's polarizer and PBS is adjusted in maximizing the attenuation in the opposite way. Attenuation up to -35dB has been obtained. The interference filter is tilted to 6° to avoid feedback dues to backscattering light on the filter's faces. The beam is reflected to the diode by a cat's eye configuration composed of a C110TM-B lens (focale = 8 mm) and a R > 99,5% dielectric mirror placed at the focal plan of the lens. The mirror is glued on a piezoelectric transducer (PZT) which allows a displacement of about 5 µm with a voltage of 1000 Volts.

The cesium D2 line is scanned by saturated absorption method thanks to modulation of the PZT voltage. The set point is optimized with diode current and temperature, PZT voltage and position/direction settings of the isolator to minimize loss.

III. THERMO-MECHANICAL DESIGN

The principal objective of the thermo-mechanical design was to realize a compact and reliable setup. All the optical configuration is integrated in bulk machined aluminum sole which provide a very good mechanical stability and low resonance frequencies (see Figure 4). The sole is placed on a large thermoelectric cooler which guarantee a good temperature control (typically 0,1K). The use of aluminum for the sole avoids temperature gradient. Optical alignment is not very difficult thanks to the cat's eye configuration. The orientation of the interference filter (about 6°) is set by watching the scan of the D2 line. Settings of the optical isolator are done in minimizing loss in it and in suppressing feedback influence due to backscattering on the first polarizer face. All the optical components are placed in position then screwed or glued. Total size of this feedback isolated ECLD is 65 × 99 × 37 mm (l × L × H) that is about 7 times smaller than a classical ECLD and its optical isolator.

This setup exhibits excellent insensitivity to mechanical vibrations or shocks and relative insensitivity to temperature fluctuations, which can probably be improved in adding a thermal-uncoupled cap.

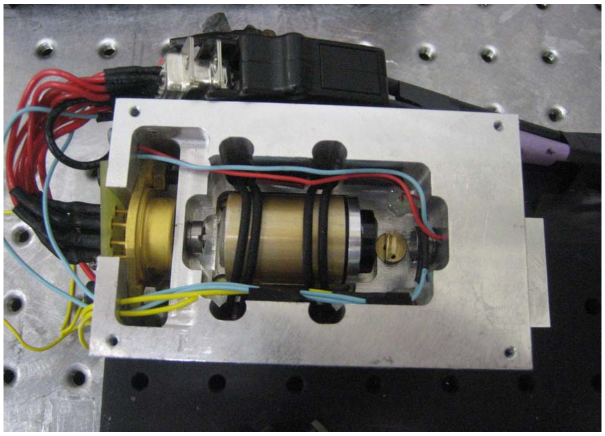
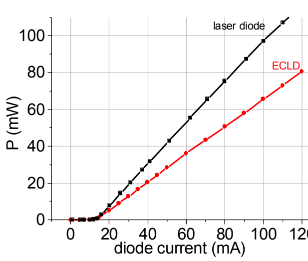


Figure 4. photography of our setup. We can see (from left to right) the TO3 laser diode, the mounted collimating lens, the optical isolator, the interference filter (on its little circular brass holder) and the cat's eye lens (partially hidden by wires). The mirror and PZT are not visible but they are at the right of the cat's eye lens, inside the sole (we can see the red and blue PZT wires). The thermoelectric cooler is hidden under the sole but blue and yellow wires of thermal sensors are visible.

IV. CESIUM SPECTROSCOPY

The output power versus diode current has been plotted and shows than about 70% of the power is extracted from the cavity (se Figure 5). Current threshold of the ECLD is about 16 mA that is very comparable to the laser diode alone. The reduction of the current threshold is not observed here, may be due to the important loss introduced by the optical isolator. Single mode emission has been obtained up to 110 mA. For greater current, emission of our setup becomes multimode, which is classical for ECLD with current greater than 7 times the current threshold. Single mode emission on the cesium D2-line has been obtained up to 75 mW at the output of the ECLD, which makes it possible to consider optical bench configuration without master/slave optical injection, which should be an important simplification of the architecture and reduction of the number of optical components.



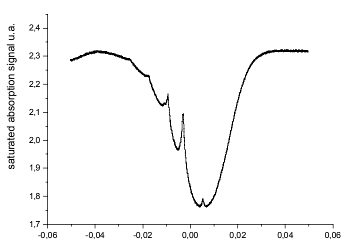


Figure 5. output power versus diode current. About 70% of the power is extracted from the cavity, allowing output power up to 75 mW. The current threshold is not reduced by the ECLD working may be due to important loss induced by the optical isolator.

Figure 6. scan of the D2 line of cesium shows spectral range without mode hop of about 2 GHz and a very good thermo mechanical stability.

A wide scan of the cesium D2-line thanks to PZT voltage shows that spectral range without mode hop of about 2 GHz is accessible that is about the free spectral range of the 7 cm long external cavity (see Figure 6). This range without mode hop is large enough to guarantee long term frequency stabilization with saturated absorption spectroscopy method.

We have also verified that our setup is well protected against stray light. Direct back reflection of the output beam to the ECLD with several reflection coefficients does not show any modification of the saturated absorption signal.

To cool, manipulate and detect atoms, laser linewidth is a very important characteristic. Thus we have also measured the linewidth of our ECLD by a heterodyne mixing against another Laser (see Figure 7). An ECLD as described in [4] is frequency stabilized on the edge of the D2 line. The 140 MHz beat-note between this laser and our ECLD is detected with a fast photodetector. This beat-note is used to frequency lock our ECLD with a bandwidth of about 10 kHz. The measured signal is presented Figure. 6 and exhibits a FWHM of the beat-note of 300 kHz. Considering that the two lasers are similar, we obtain linewidth of about 150 kHz for each of them. This measure confirms that our ECLD has all the characteristics to efficiently cool and detect atoms.

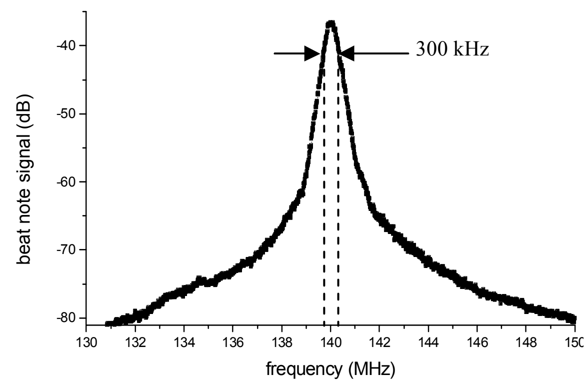


Figure 7. beat-note signal of our laser with another ECLD. This measure shows a FWHM of 300 kHz, which corresponds to linewidth of 150 kHz for each laser.

V. CONCLUSION AND OUTLOOK

We have realized a compact laser source with characteristics allowing simply use to cool and to detect cesium atoms (150 kHz linewidth and 75 mW output power). The next step will consist to assemble a complete A4 format optical bench. Several other optical functions are already developed, as compact saturated absorption setup with home made miniature cesium cells, and compact 2×6 optic fiber splitter.

In parallel, study to simplify the optical bench architecture and reduce the number of laser sources, is in progress. With the use of frequency lock and electro-optic modulator, we expect to reach architecture with only one or two laser source.

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REFERENCES

[1] P. Laurent, A. Clairon, P. Lemonde, G. Santarelli, C. Salomon, C. Sirmain, F. Picard, C. Delaroche,O. Grosjean, M. Saccoccio, M. Chaubet, L. Guillier, J. Abadie, **"**The space clock PHARAO: functioning and expected performances**",** Frequency Control Sympposium and PDA Exhibition Jointly with the 17th European Frequency and time Forum, 2003. Proceedings of the 2003 IEEE International , 2003, pp. 179 – 184

[2] S.R. Jefferts, T.P. Heavner, L.W. Hollberg, J. Kitching, D.M. Meekhof, T.E. Parker, W. Phillips, S. Rolston, H.G. Robinson, J.H. Shirley, D.B. Sullivan, F.L. Walls, N. Ashby, W.M. Klipstein, L. Maleki, D. Seidel, R. Thompson, S. Wu, L. Young, R.F.C. Vessot, A. DeMarchi, "PARCS: a Primary Atomic Reference Clock in Space"**,** Frequency and Time Forum, 1999 and the IEEE International Frequency Control Symposium, 1999., Proceedings of the 1999 Joint Meeting of the European vol 1 , 1999 pp. 141-144

[3] S. Trémine, S. Guérandel, D. Holleville, J. Delporte, A. Clairon and N. Dimarcq, "Limitations to the short term frequency stability in a compact cold atom clock", *Proceedings of the Joint IEEE International Frequency Control Symposium and Precise Time & Time Interval Systems & Applications,* Vancouver (Canada), Août 2005

[4] X. Baillard, A. Gauguet, S. Bize, P. Lemonde, Ph. Laurent, A. Clairon, P. Rosenbusch, "Interference-filter-stabilized external-cavity diode lasers", Opt. Comm., vol 266, issue 2, 2006 , pp. 609-613