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► **To cite this version:**

Paul Dumont, J.-M Danet, D Holleville, S Guerandel, G Baili, et al.. Dual-frequency VECSEL for atomic clocks using coherent population trapping. Workshop on Laser Diodes for Space Applications, Nov 2015, Palaiseau, France. 2015. <hal-01256958>

**HAL Id: hal-01256958**

**<https://hal-iogs.archives-ouvertes.fr/hal-01256958>**

Submitted on 15 Jan 2016

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# Dual-frequency VECSEL for atomic clocks using coherent population trapping

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Atomic frequency references provide high-precision stable signals, which are crucial in the most demanding applications as high bitrate communication networks, high-end inertial navigation, or satellite positioning. In this context, coherent population trapping (CPT) is an interesting technique for the development of compact atomic references [1]. It is based on the coupling of the two hyperfine ground states of an alkali atom, through excitation to a common atomic level, by two phase-coherent laser fields. In the case of Cs atomic clocks, it needs two laser fields at 852 or 894 nm with a frequency split of 9.2 GHz. One way to obtain those laser fields with low intensity- and frequency-noise is to use the dual-frequency and dual-polarization emission of an optically-pumped vertical external-cavity semiconductor laser (OP-VECSEL). This emission is induced by intracavity birefringent components which induce a controllable phase anisotropy within the laser cavity and force emission on two cross-polarized longitudinal modes.

The semiconductor active structure consists in GaAs/Al<sub>22%</sub>Ga<sub>78%</sub>As quantum wells on top of a high-reflectivity Bragg mirror. It is pumped with a high-power laser diode emitting up to 1 W at 670 nm. The 10 mm long cavity includes a birefringent YVO<sub>4</sub> plate which induces a 50 μm separation modes inside the semiconductor structure, an electro-optic crystal (MgO:SLT) to tune continuously the frequency difference, and a Fabry-Perot etalon made of a 100 μm YVO<sub>4</sub> plate. The birefringence of this etalon forces the frequency difference between the modes at 9 GHz. The whole laser cavity is mounted in a compact and thermally-stabilized casing (90 × 90 × 50 mm<sup>3</sup>).

The dual-frequency laser emission is stabilized using two separated servo-loops. First the wavelength of the ordinary polarized mode is locked onto the Cs D2 line using a saturated absorption set-up with feedback to a piezo-transducer glued on the output coupler. Then the frequency difference between the cross-polarized lines is locked on a local oscillator using electronic feedback to the intracavity electro-optic crystal. The detailed characterization of the noise properties of the laser emission is done with both servo-loops operating. The relative intensity noise (RIN) is flat from 100 Hz to 100 kHz at a level of -110 dB/Hz, limited by the pump RIN transfer to the laser. The frequency noise is limited by mechanical resonances below 1.5 kHz and by thermal fluctuations induced by the pump source above. The residual phase noise of the beatnote signal is reduced to a level below -90 dB rad<sup>2</sup>/Hz on the frequency range 100 Hz – 10 MHz [2].

The performance of this laser source is already adequate for a CPT atomic clock. The noise performance of the laser results theoretically in a clock stability of  $1.6 \times 10^{-12}$  at 1 second (Allan standard-deviation), limited by the laser RIN. This limit can be overcome using power stabilization loop and/or intensity normalization of the CPT signal [3]. We now aim at targeting a clock stability of  $3 \times 10^{-13}$  at 1 second, in order to tackle the actual performance vs size trade-off of CPT atomic clocks.

## REFERENCES

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(Retour d'un reviewer sur l'ANR : moi, je trouve ça beau ... vois ce qui peut être pertinent pour l'espace, et fais-moi rêver avec ça ...)

Les impacts du projet CHoCoLa seront être très importants car une horloge compacte ultraprécise est un élément clé pour les futures technologies numériques, mais aussi les systèmes de navigation, ou de télécommunication. En effet, tous ces défis dépendent de façon critique des références de fréquence et de temps. Des horloges précises sont ainsi nécessaires pour le traitement massif de données, le calcul haute performance, la sécurité du monde numérique, l'authentification des transactions financières, la gestion des réseaux de communication (notamment sans fils), ainsi que pour la synchronisation des références de fréquence et le rétablissement rapide des signaux GPS en situation dense (avionique/maritimes). Les débouchés au niveau du composant  $\frac{1}{2}$  VCSEL à 852 nm seront aussi très importants pour les gyroscopes ou les gravimètres ou pour les magnétomètres dans l'imagerie médicale, mais aussi dans les domaines de génération de source à haute pureté spectrale dans le domaine des THz, lidar,.... L'impact de ce projet sur les recherches futures est donc clairement avéré.