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# High Spectral Purity Microwave and Terahertz Oscillator

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**Abstract**— We report on the design of an ultra stable microwave/THz oscillator and on the realization and the characterization of its laser source. The tunable oscillator is expected to show below  $-150$  dB  $\text{rad}^2/\text{Hz}$  phase instability at an offset frequency of  $10$  kHz for a  $30$  GHz carrier frequency, as well as  $18$  GHz,  $100$  GHz,  $400$  GHz and  $1$  THz carrier frequencies.

**Keywords:** millimeter and sub-millimeter wave oscillator, frequency stabilization, optical to microwave conversion, THz, ultra low phase noise.

## I. INTRODUCTION

The OSMOTUS project (2012-2014) consists into the realization of two microwave/THz oscillators with a very low phase instability, below  $-150$  dB  $\text{rad}^2/\text{Hz}$  at an offset frequency of  $10$  kHz for a  $20$  GHz carrier frequency. We use the photomixing of two optical frequencies generated by a two-axis dual frequency dual polarization laser. The two laser frequencies will be stabilized on an ultra-low-expansion (ULE) cavity since they are the best resonators in the optical range [1]-[2]. This setup will transfer the exceptional stability from the optical domain to the microwave and terahertz one. Two identical setups will measure the submillimeter phase spectral purity.

## II. DUAL-FREQUENCY TUNABLE LASER SYSTEM

### A. Two-Axis Dual Frequency Laser

The dual-axis  $1550$  nm laser is pumped by a polarized and single mode  $800$  mW diode at  $980$  nm. This pump, polarized at  $45^\circ$  with respect to horizontal and vertical axes, is spatially split thanks to a birefringent  $\text{YVO}_4$  crystal, so

that the active medium is pumped by two  $2$ -mm spaced beams. The plano/concave dual axis cavity includes an active medium, one etalon and one electro-optical element per axis, and an  $\text{YVO}_4$  crystal recombining the two orthogonal polarization eigenstates (see Fig. 1). The active medium is a  $1.5$ -mm-long phosphate glass co-doped Er/Yb. The high reflectivity coating on the external face of the active medium is the input coupler M1; the internal face of the active medium has a high reflectivity coating at  $980$  nm. The resonator is closed by the output coupler M2, whose curvature had been chosen in order to facilitate the single mode operation: a good compromise is obtained with a  $4$  cm radius. The  $0.5\%$  transmission of this coupler enables the laser to operate far from the threshold, reducing favorably noises; the laser delivers a with few mW output power per axis. The single mode operation is obtained and controlled on each axis by  $40$ - $\mu\text{m}$  thick etalons with  $30\%$  reflection on each side. The rough tunability of each optical frequency is realized by tilting the etalon. We are thus able to sweep each optical frequency by steps of the  $1.7$  GHz of the free spectral range of the laser cavity; this allows the beat note to be tunable from DC to about  $900$  GHz [3]-[4].

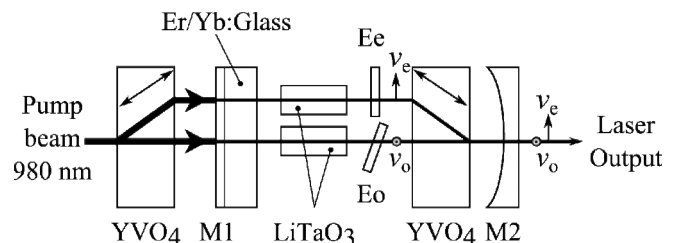


Figure 1. Two-axis dual frequency laser

The frequency of each polarization, with a measured  $(10^4/f)$  Hz/Hz<sup>1/2</sup> frequency noise spectral density, will be further stabilized on one of the resonances of a Fabry Perot cavity. The frequencies are both continuously and independently tunable thanks to the lithium tantalate (LiTaO<sub>3</sub>) electro-optic crystals, using both thermo-optic (600 MHz/°C) and electro-optic (1.1 MHz/V) effects. The measured relative intensity noise spectral density of one optical axis is displayed on the blue curve on figure 2.

### B. Amplifier System

The OSMOTUS performance requires tens of mW for the frequency stabilization, the amplitude stabilization and the beat note generation. The power fluctuations have to be stabilized in order to reduce the AM/PM couplings in the cavity and in the electronic components. Each polarization is independently amplified by a fiber system. Our amplifier system is composed of an erbium doped fiber amplifier (EDFA) and a semiconductor optical amplifier (SOA) per polarization axis (see Fig. 2).

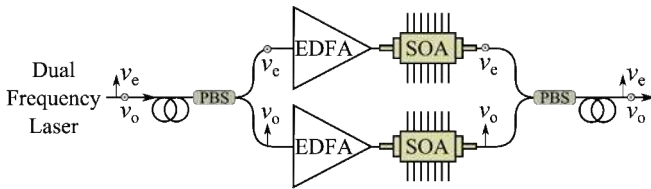


Figure 2. Amplifier system; PBS: polarization beam splitter; EDFA: Erbium doped fiber amplifier; SOA: Semiconductor optical amplifier

Since the EDFA is operated in deep saturation, it provides a constant 10 mW output power into the SOA, which is then also saturated. In that condition, the SOAs deliver a constant output power of 60 mW per polarization axis, with an amplifier system noise factor of 6 dB. Furthermore, a gain-saturated SOA decreases the intensity noise of a laser [5]. As shown on the Figure 2. the output relative intensity noise (RIN) of one axis of the dual frequency laser is reduced by 20 dB, including at the relaxation oscillation of the laser at 100 kHz, without stabilization electronics. The SOA driving currents will permit to independently stabilize the polarization amplitudes with a few hundred kilohertz bandwidth. We have checked that the amplifier system does not add any noticeable frequency noise.

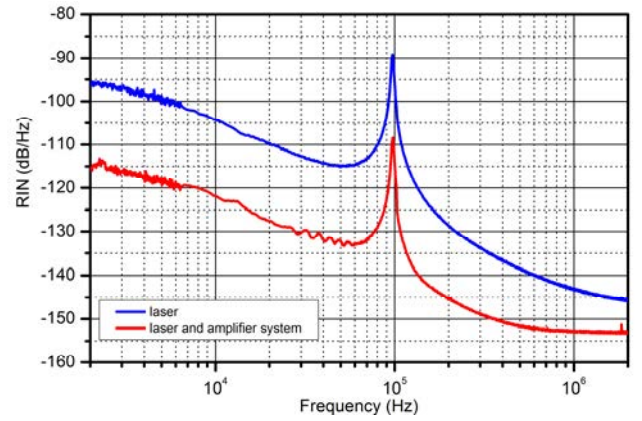


Figure 3. RIN of laser and laser with amplifier

### III. STABILIZATION AND MICROWAVE/THZ GENERATION

The two optical frequencies of the laser described above will be stabilized onto two resonances of one Fabry-Perot cavity with the Pound-Drever-Hall scheme. The cavity spacer is made with an ultra-low expansion ceramic (ULE). The cavity is placed in vacuum. This is today the best relative dimensional stability compact resonator, limited by the thermal fluctuations of the spacer and of the mirrors [6]-[9]. The two laser frequencies sense the same cavity length fluctuations so that the best possible relative frequency stability of the beat note is limited by the relative dimensional stability and by the shot noise of each polarization. For a 10 GHz beat note, the beat note frequency noise should be limited by the optical shot noise. For a 1 THz beat note, the cavity stability should limit the beat noise phase noise at 10 Hz offset frequency to  $-90$  dB rad<sup>2</sup>/Hz.

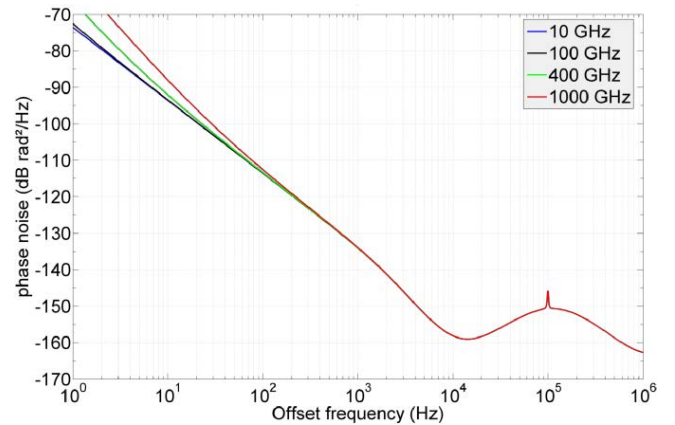


Figure 4. Expected phase noise of ultra stable oscillator

A 75% fraction of the beam transmitted by the cavity is used to stabilize the amplitude of the laser, and a 25% fraction is sent on a polarizer and a photomixer for optical to millimeter wave conversion. In the submillimeter frequency range the photomixer is an optimized UTC photodiode. The AM/PM conversion is a known limiting factor to the

stability of some optical resonators [10]. A first coupling is the opto-thermal conversion in the cavity: the power fluctuations are absorbed by the mirrors and thus induce fluctuations of the cavity length by dilation of the mirrors and by index modification with temperature. In our setup, this effect will be made negligible at a 1 Hz frequency offset by stabilization of the optical carrier at the  $8.10^{-9}/\text{sqrtHz}$  level, already demonstrated out of loop. Static biases on the frequency stabilization error signal could give AM/PM couplings: we predict to correct for these by tuning the offsets of the error signals. Photodiodes and amplifiers also give AM/PM couplings at levels of about 10 rad/W; these couplings should be negligible with our level of amplitude stability.

#### IV. CONCLUSION

The system will be tunable from DC to THz by steps of 1.5 GHz, which is the free spectral range of the ULE cavity. Two laser/cavity systems are on development. Their phase noise performance will be evaluated by beat note of the two millimetre or THz outputs. At a 10 GHz beat note frequency, our system should have state of the art phase noise performance both at 1 Hz and 10 kHz offset frequencies. Furthermore, the phase noise of the sub millimetre carrier is relatively independent of its carrier frequency: at 18 GHz, 100 GHz, 400 GHz, 1 THz, we hope to exceed the state of the art. At 400 GHz, we use uni-travelling-carrier photodiode (UTC-PD). At 30 GHz, we expect to obtain -80 dB rad<sup>2</sup>/Hz at 1 Hz offset frequency, and below -150 dB rad<sup>2</sup>/Hz at 10 kHz offset frequency.

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