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Direct generation of Cs-based atomic clock RF interrogation signal by an optoelectronic oscillator

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Abstract—We propose to use an optoelectronic oscillator to generate the RF signal interrogation of a Cs-based RF atomic clock. In this proof-of-concept experiment, we show that the adjustment of the optical fiber length in the OEO while operating the optical carrier at 1.3 μm allows for dramatic improvement of the RF contribution to the relative frequency instability of the clock down to 2.9×10^{-14} at 1 s, a factor of 2 better than state-of-the-art RF synthesis.

Keywords—Optoelectronic oscillator, phase noise, atomic clock, Dick effect, metrology.

I. INTRODUCTION

Frequency standards find increasing applications in telecommunication systems, quantum sensing, quantum networks, global navigation satellite system (in particular Galileo next generation systems), etc. Atomic clocks based on the ground state hyperfine transition frequency of cesium 133 atoms around 9.2 GHz that currently provides the definition of the SI unit of time, enabled to build more and more accurate and stable frequency standards. Amongst them, coherent population trapping (CPT) based atomic clocks operating with a Ramsey pulsed optical interrogation sequence of the RF hyperfine transition demonstrated impressive frequency stabilities of a few 10^{-13} at 1 s and a few 10^{-15} at long-time time scales of 10 000 s [1].

However, in this pulsed interrogation scheme, the atomic clock receives only a sample of the error signal during the detection of the atomic response. The resulting loss of information makes the correction incomplete and adds an aliasing noise to the clock servo signal, called the Dick effect [2,3]. The atomic clock performance is thus very sensitive to the phase noise of the optically carried RF signal through the Dick effect with a sensitivity function depending on the characteristics of the pulsed interrogation. For this CPT clock technology, the lowest reported contribution of Dick effect has been obtained with an ultra-low noise 100 MHz OCXO followed by complex multiplication and filtering stages to end up with a low noise 4.6 GHz RF signal giving a contribution of 6×10^{-14} to the clock frequency stability at 1 s [4].

In the present paper, we present a simpler way to generate an ultra-low phase noise RF signal directly at 9.2 GHz, relying on an optoelectronic oscillator, with an optimized contribution to the clock frequency instability. In a proof-of-concept experiment, we show that the contribution of the RF signal phase noise through the Dick effect to the clock frequency instability at 1 s can be reduced below 3×10^{-14} .

II. ATOMIC CLOCK OPERATION AND EVALUATION OF THE DICK EFFECT CONTRIBUTION

The principle of operation of an atomic clock is described in the Fig. 1. It comprises a local oscillator (LO) delivering a user signal at a frequency of 10 MHz typically, an atomic resonator that provides an atomic reference transition in the GHz range, around 9.2 GHz using ^{133}Cs . A microwave synthesis provides the RF signal used for atomic interrogation from the LO. At the output of the atomic resonator, a regulation electronics generates an error signal to correct the local oscillator frequency and thus transfer the long-term stability of the atomic transition reference to the LO.

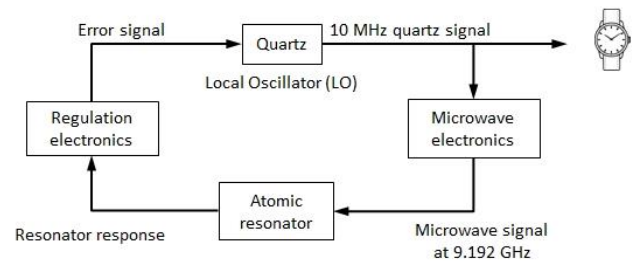


Fig. 1. Description of the principle of operation of an atomic clock and its main block functions.

The CPT phenomenon consists in employing Cs atoms as a quantum 3-level system where the first two levels are separated by the hyperfine transition that is the atomic reference (see Fig. 2). This system is illuminated with two optical frequencies resonant with the common upper level. When the two optical frequencies present a frequency difference (a “beat note”) exactly equal to the hyperfine transition around 9.2 GHz, Cs atoms are trapped in a “dark state” where they cannot absorb light. The measurement of the illuminated atoms transmission while scanning the frequency detuning of the beat note around the hyperfine transition frequency shows a narrow optical transmission line.

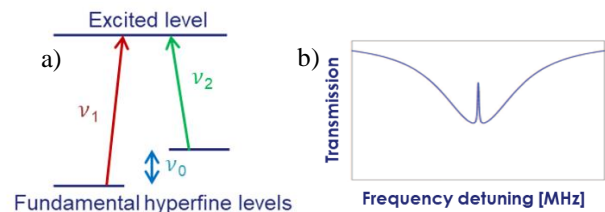


Fig. 2. Description of the Coherent Population Trapping (CPT). a) atomic levels and optical frequencies involved. b) transmission peak generated in the absorption profile when the frequency difference (beat note) between the two optical frequencies is tuned around the hyperfine transition frequency.

This CPT line is quite insensitive to the environment. For the atomic clock operation, it is used to generate an error-correction signal of the RF interrogation to lock it on the atomic transition and thus to stabilize the LO generating the RF. The interrogation can be performed with a continuous optical intensity to produce a CPT peak with a linewidth in the kHz range with a remaining sensitivity to optical power, called light-shift effect, which is detrimental to the long-term stability performance.

More interestingly, a Ramsey pulsed interrogation [5], generating interference patterns, enables to produce fringes of narrower linewidths down to the range of one hundred Hz with a reduced sensitivity to light-shift. A typical interrogation sequence is described in Fig. 3. The atoms are illuminated by laser pulses of duration T_i carrying the two optical frequencies. A first pulse pumps the atoms into the dark state. The atoms evolve then freely in the dark for a Ramsey duration T_R . The second pulse with a different LO phase creates a new dark state that interferes with the previous one. After a delay τ_d from the start of a pulse, the optical signal is detected and averaged for a time τ_m . The rest of the second pulse prepares the atoms in the new dark state for the next sequence. For an optimized CPT signal, the interrogation sequence parameters are typically $T_i = 2$ ms, $T_R = 4$ ms, $\tau_d = 20$ μ s and $\tau_m = 25$ μ s. The cycle duration T_C is defined as $T_i + T_R$.

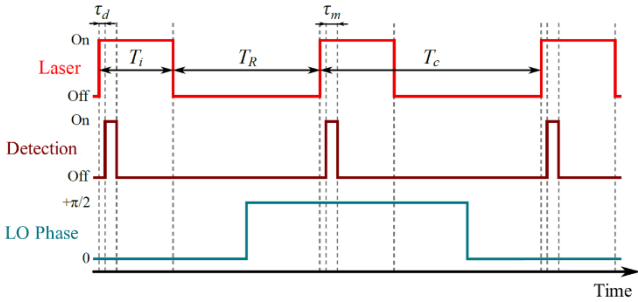


Fig. 3. Ramsey interrogation sequence for clock error signal generation. See text for details. Durations τ_d and τ_m are deliberately exaggerated for reading.

As already discussed, the pulsed interrogation suffers from the Dick effect [2], related to the temporal sampling of the atomic signal. The noise induced by the Dick effect, produced with an interrogation sequence of period T_C contributes to the relative frequency instabilities of the clock. This contribution with an interrogation duration τ can be written as:

$$\sigma_{y,Dick}^2(\tau) = \frac{1}{\tau} \sum_{m=1}^{\infty} \left(\frac{g_m}{g_0} \right)^2 S_y \left(\frac{m}{T_C} \right), \quad (1)$$

where $S_y(f)$ is the Power Spectral Density (PSD) of the relative frequency noise of the local oscillator and coefficients g_0 and g_m are calculated from the sensitivity function $g(t)$ associated to the atomic interrogation temporal sequence. Starting from an optically carried RF with a given phase noise PSD $S_\varphi(f)$, one can calculate the PSD of the relative frequency noise of the local oscillator with:

$$S_y(f) = \frac{f^2}{\nu_0^2} S_\varphi(f), \quad (2)$$

where ν_0 is the RF carrier frequency. Regarding the sensitivity function, it can be evaluated numerically using simplifying assumptions [3], using the time parameters of the interrogation, as well as on the relaxation time of the hyperfine coherence and relaxation time of the optical excited level. Fig. 4 represents the ratio $(g_m/g_0)^2$ for the values of the parameters given above. Interestingly, one can observe that the ratio collapses at the harmonics of the frequency $1/\tau_m$. We can also observe that the sensitivity function is pondering more the phase noise for low offset frequencies, i.e. typically below 1kHz et filtering the phase noise for high offset frequencies, i.e. beyond 10 kHz.

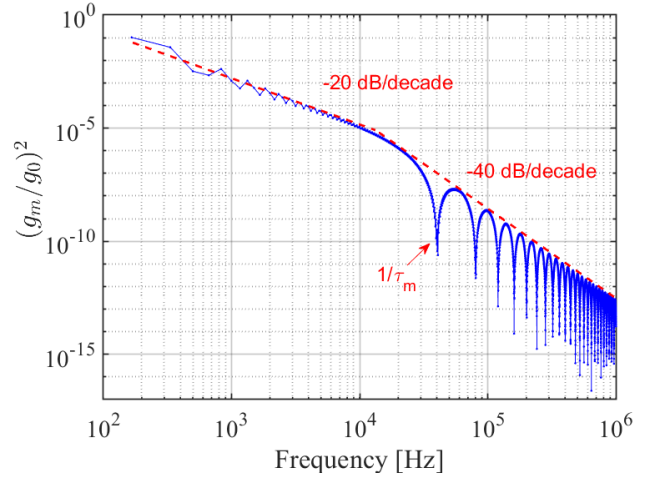


Fig. 4. Ratio of the coefficients from the Dick effect sensitivity function. The red dotted asymptotes give the different frequency regimes.

III. OPTOELECTRONIC OSCILLATOR

OEOs have proved their ability to generate GHz range RF signals with ultra-low phase noise at low offset frequencies [6]. The OEO resonator, corresponding to a closed-loop microwave photonic link as sketched in Fig. 5, exhibits a quality factor, which scales linearly with the optical fiber length. At first order, increasing the fiber length improves the OEO phase noise at low offset frequencies. Thanks to low propagation loss of optical fibers, one can implement km-long optical delay lines in the OEO to reach record phase noise performances at low offset frequencies [7]. Such architecture could therefore be particularly interesting as a source for the generation of the 9.2 GHz interrogation RF signal for a CPT clock.

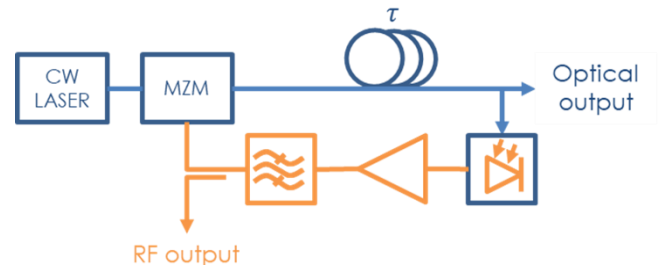


Fig. 5. OEO setup. MZM: Mach-Zehnder Modulator.

However, the optimization of the OEO phase noise performances is not as straightforward. First, increasing the fiber length reduces the mode spacing, which makes the RF oscillation frequency selection more difficult (i.e. sharp bandpass filter) and degrades the OEO spectral purity with strong spurious peaks induced by non-oscillating modes.

From the phase noise point of view, the close-to-carrier improvement is ultimately limited by the optical carrier frequency noise, which is converted into RF phase noise due to dispersion of the optical fiber [8].

The OEO architecture and phase noise requirements are designed following (1), and more precisely the ratio $(g_m / g_0)^2$. First, the lowest offset frequency to consider is given by the cycle rate $1/T_c$, 166 Hz for the parameters given previously. Besides, as discussed, the ratio collapses at the harmonics of the frequency $1/\tau_m$, in our case 40 kHz. If one adjusts the fiber length so that the mode spacing matches this frequency, the high spurious level of OEOs will intrinsically not be taken into account in the Dick effect. In other words, the optimal resonator length is 5 km, and the OEO can remain in a single loop, as the clock sensitivity function naturally filters out the contribution of non-oscillating modes.

We then used a model [8] to adjust the phase noise of an OEO with respect to clock application. Because of the fiber frequency dispersion, the laser frequency noise is converted into timing jitter and thus microwave phase noise. This effect is particularly sensitive in long fiber OEOs. Although one could use dispersion-shifted fiber at 1.55 μm , we believe it is more interesting to operate at 1.3 μm wavelength where standard optical fibers dispersion is almost null, while keeping on using a compact distributed feedback (DFB) semiconductor laser and efficient Mach-Zehnder modulators (MZM).

IV. EXPERIMENTAL RESULTS

As a proof of concept, we assembled an OEO with 5 km of standard G.652 optical fiber operating at 10 GHz. The operation frequency is set by the RF filter ($Q \sim 3000$). The laser is a DFB semiconductor laser emitting 100 mW at 1319 nm with low relative intensity noise (RIN), and low frequency noise. The MZM exhibits a V_π at 10 GHz of 6.2 V and insertion loss of 4 dB. The other components are equivalent to the one used in former work [8]. We measured the RF phase noise with a Rohde and Schwarz FSWP-26 signal analyzer from 100 Hz up to 1 MHz, with a 1% resolution bandwidth and 1000 correlations at 100 Hz.

Fig. 6 shows the OEO phase noise PSD. One can see that the spurious peaks are well located at harmonics of 40 kHz. The phase noise values at 100 Hz and 1 kHz are -105 dBc/Hz and -133 dBc/Hz respectively, close to the phase noise sensitivity of the bench as suggested by the trace thickness. Reaching such phase noise level at 100 Hz using an OCXO-based frequency synthesis would require a PSD level of -165 dBc/Hz at 10 MHz oscillation frequency or -145 dBc/Hz at 100 MHz assuming perfect frequency multiplication. When using this experimental phase noise to evaluate the OEO RF phase noise contribution in the CPT clock noise budget, the Dick effect contribution at 1 s is 2.9×10^{-14} , a factor of 2 improvement with respect to state-of-the-art RF synthesis for this interrogation [4]. Yet our simulations predict even lower phase noise levels at low offset frequencies, when assuming that the laser frequency noise contribution is negligible. In order to understand this discrepancy, further characterizations must be performed, including laser frequency noise and baseband RIN to RF phase noise coupling due to the photodiode used at 1.3 μm . We also observed a small and slow MZM bias drift during the phase noise measurement time (several minutes), which can eventually affects the phase noise.

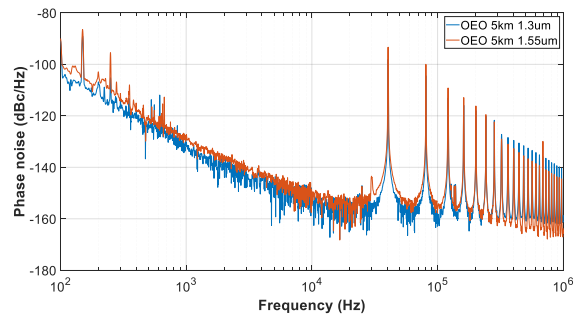


Fig. 6. OEO phase noise spectrum with a 5 km optical delay line. (blue : optical carrier at 1.3 μm ; red: optical carrier at 1.55 μm)

In order to highlight the advantage of the operation wavelength, we performed phase noise measurements at 1.55 μm replacing only the DFB laser and the MZM, and trying to keep the cardinal performances (e.g. RIN, frequency noise, V_π , and photodiode sensitivity) equivalent for both components as much as we could. Results are also shown in Fig. 6: the phase noise is degraded by 5 dB due to the contribution of the dispersion in the phase noise. This leads to an increase of the Dick effect contribution at 1 s to 4.6×10^{-14} , which remains yet better than the microwave synthesis solution. The phase noise level in the 100 Hz - 1 kHz band is consistent with our simulations. Above 1 kHz, the phase noise is larger than expected, likely due power saturation in the RF path as the photodiode sensitivity and the MZM V_π are better at 1.55 μm . However, given the sensitivity function shape (see Fig. 4), the largest impact of the RF phase noise in the overall Dick effect contribution on the clock stability is located in the 100 Hz - 1 kHz band.

V. CONCLUSION AND PERSPECTIVES

We experimentally showed that OEOs offer a simple solution to generate the interrogation RF signal for Cs-CPT clocks under proper design. Using 5 km of optical fiber with a carrier wavelength at 1.3 μm , the Dick effect contribution on the clock stability at 1 s integration time is as low as 2.9×10^{-14} .

According to our simulations, there is room for improvement. Further work includes the characterization of the component at 1.3 μm (DFB RIN and AM to PM coupling through the photodiode, frequency noise) for full understanding and finer optimization of the OEO phase noise. Of course, the OEO frequency must match the ground state hyperfine transition at 9.2 GHz using a dedicated RF filter (currently under design), before being locked to this transition. Recent PLL work on OEOs suggests that this should be feasible [9].

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