Generating Laguerre-Gaussian Modes for Atom Trapping in a Sr Optical Lattice Clock

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***Abstract*—Aiming to improve the characterization of systematic effects in optical lattice clocks below 10^{-18}, we propose the implementation of Laguerre-Gaussian modes (LG$_{pl}$) to shape a multi-site trap in the 1D optical lattice of a Sr optical lattice clock, hence reducing the density of atoms, while preserving the advantages of 1D lattices. In this work, we demonstrate the generation of LG$_{0l}$ modes with l up to 4, and the injection of these modes into an in-vacuum optical cavity intended for the dipole trapping of atoms. Trapping depths up to $200E_r$ for an LG$_{04}$ were obtained, a priori making it possible to implement LG modes within the clock sequence. We then propose and evaluate two different methods to load atoms in a LG profile.**

***Index Terms*—Optical lattice clock (OLC); Spatial light modulator; Laguerre-Gaussian (LG) modes; diffraction grating; dipole trap; collision frequency shift.**

I. Introduction

The most accurate optical lattice clocks (OLC) have reached a systematic uncertainty on the order of 10^{-18} [1].In order to improve the evaluation of some limiting systematic effects, such as the frequency shift due to cold collisions between the trapped atoms, elaborated trapping geometries are being investigated, such as 3D lattices [2], or optical micro-tweezers [3] with single atom occupancy. The main drawback of these methods is the complexity they add to the physics package of the clock, compared to a simple 1D lattice, which can reach a high power and high mode purity with cavity enhancement. Here, we propose to use an alternative method to increase the number of trapping sites in a magic wavelength optical lattice while preserving a cavity-enhanced 1D trapping geometry. This method employs sinusoidal Laguerre-Gaussian LG$_{0l}$ transverse modes of the trapping light, with azimuthal index l, whose transverse profile is composed of $2l$ identical trapping sites per longitudinal site of the 1D lattice. Furthermore, changing l gives control over the number of trapping sites and over the distance between the sites, allowing for extra capability in characterizing systematic effects. Quantitatively, the trapping potential in a LG$_{0l}$ mode reads:

$$U_{0l}(r,\varphi,z) = -U_0 e^{\frac{-2r^2}{w^2(z)}} \cos^2\left[kz - \psi_l(z)\right] \times \left(\frac{2r^2}{w^2(z)}\right)^{|l|} \cos^2(l\varphi) \tag{1}$$

where $U_0 = \alpha_d I_0$, with α_d the atomic polarizability and I_0 the intra-cavity of the trapping light.

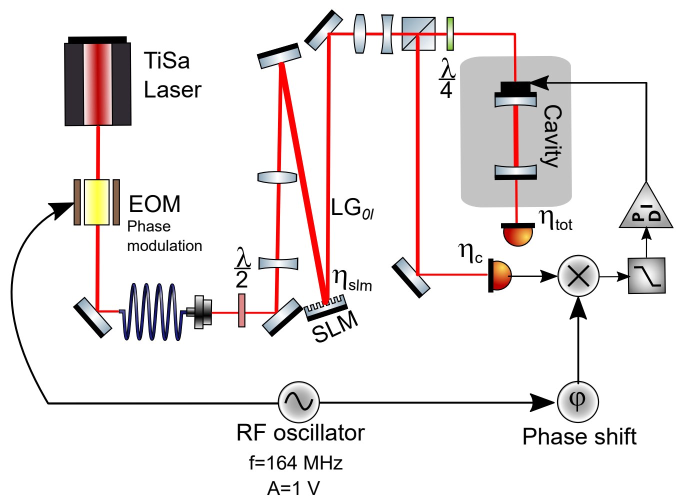


Fig. 1: Simplified setup for the generation and injection of LG modes in the in-vacuum optical cavity. EOM is the electro-optic modulator used for the phase modulation required by the PDH locking technique.

In this paper, we first present a system for generating LG profiles based on a Spatial Light Modulator (SLM), and injecting these modes in an enhancement cavity. The SLM also implements a diffraction grating to spatially separate the generated transverse profile from non-diffracted light. We compare the efficiency of the LG$_{0l}$ modes generation and cavity coupling for three different shapes of grating. Finally, we discuss the numerical and experimental implementation of two methods for loading atoms in the LG lattice, based on the trapping depths achieved with the current setup.

II. Generation of Laguerre-Gaussian profiles

A Hamamatsu X13138 liquid crystal on silicon spatial light modulator (LCOS-SLM) displays a computer-generated hologram (CGH) phase mask from a grey-scale image (a value of 215 gray level corresponds to a 2π rad phase modulation). The CGH encodes the LG$_{0l}$ phase [4].

In addition to the LG mask phase, the CGH embeds a diffraction grating that spatially separates the generated mode and the non-diffracted zero order. A collimated TEM$_{00}$ laser beam at the 813 nm magic wavelength, with a radius of 2.5 mm, impinges on the SLM screen with an incident angle

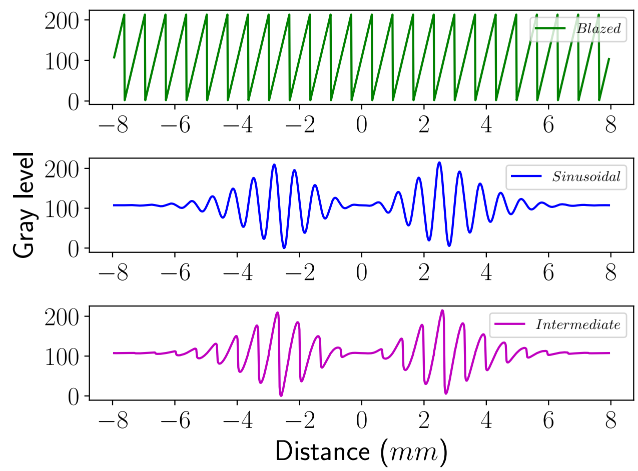
θ_{inc} less than 7 degrees. The first diffraction order takes the shape of the specific encoded LG phase. Then, this order is mode-matched to a linear cavity, which is afterward locked to the LG mode using a Pound-Drever-Hall (PDH) scheme [5], as sketched in Fig. 1.

We first consider a blazed grating that can diffract up to 90% on the first diffraction order, as reported in [6]. However, we observed that the the spatial purity is degraded when $l > 0$. We then consider a sinusoidal grating that provides a better spatial purity for LG modes with $l > 0$, but the presence of several diffracted orders degrades the diffraction efficiency. In order to combine the advantages of both gratings, we have programmed an intermediate grating, whose efficiency was compared with the two other gratings. The profile and phase masks of three diffraction gratings, are shown in Fig. 2 for $l = 2$. In addition, we examined the performance of a CGH when no diffraction grating was encoded, we observed that not only the spatial purity behaved similar to patterns issue of the blazed mask, but also compared to intermediate grating, the efficiency on the total setup was quite resembling. Then, it is more helpful to analyze the intermediate grating because it do not excite parasite higher modes in the cavity.

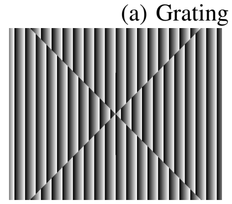
In order to characterize the potential trap depth that can be achieved with LG modes, the total efficiency (η_{tot}) of the setup was measured. This quantity is mostly limited by the diffraction efficiency of the SLM (η_{slm}) and the coupling efficiency of the modes in the linear cavity (η_c), such that $\eta_{tot} = \eta_{slm} \times \eta_c$. The measurements were made using CGHs with spatial period $T_x = 227.1\ \mu m$ (70 grooves), enough for dissociating zero and first order. We observe in Fig. 4a that the blazed grating has an efficiency η_{slm} up to 70%, decreasing slowly for higher values of the index l. The sinusoidal grating has efficiencies lower than 22% for all the LG modes, and the intermediate grating, as expected, presents efficiency values in between the other two gratings, with about 40% for the LG_{00} and decreasing down to 12% for the generation of the LG_{04} mode.

We then injected the produced LG modes into the in-vacuum optical cavity of an OLC, and locked the cavity on these modes using the PDH scheme, some modes at the cavity transmision can be seen in Fig. 3. In this configuration, it was possible to measure η_c versus the modes LG_{0l} for $l = 0, 1, 2, 3, 4$, as plotted in Fig. 4b. With the intermediate grating, we could reach the highest coupling efficiency, and with a smaller degradation of this quantity for higher l compared with the blazed grating.

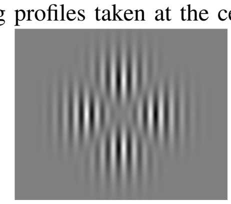
Likewise, we characterized the evolution of η_{tot} with l, which represents the ratio between the power coupled to the optical cavity and the incoming power on the SLM, as can be seen in Fig. 5. Comparing the resulting η_{tot} for all the gratings, we conclude that the sinusoidal grating has to be discarded as an option for the proposed new trap geometry, because it presents a total efficiency lower than 15%. Due to the higher coupling of the modes issued from the intermediate pattern, η^I_{tot} (purple data) is only 10% below η^B_{tot} (green data) for $l = 0$. Besides, this difference decreases when l increases down to 2.7% for the LG_{04} mode. Consequently, because of the similar η_{tot} for $l = 3, 4, ...$ of both gratings, we conclude that they can be used for the creation of a Laguerre-Gaussian lattice.



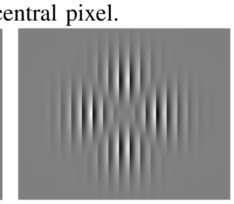
(a) Grating profiles taken at the central pixel.



(b) CGH using a blazed grating.

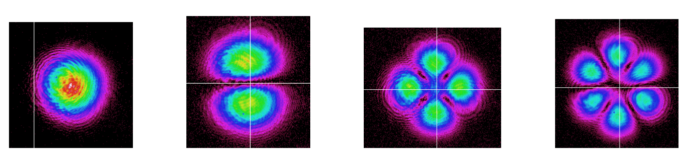


(c) CGH using a sinusoidal grating.

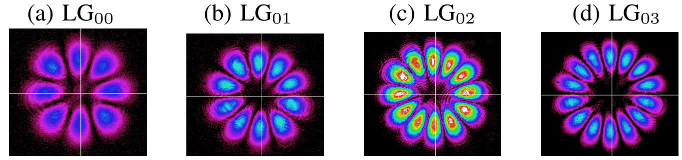


(d) CGH using an intermediate grating.

Fig. 2: Grating profiles along the horizontal axis for the three diffraction gratings, and computer-generated holograms for the three diffraction gratings with a spatial period of $T_x = 662.5\mu m$ or 24 grooves. Note that sinusoidal and intermediate grating suffer a damping, the reason is that the SLM is a phase modulation only device, and for achieving a pure mode, a complex amplitude modulation had to be made as it is explained in [7]. Also, this kind of damping was tried with a blazed grating, but the efficiency of diffraction was low than when no CAM was used, and the resulting shape was not a pure LG mode.

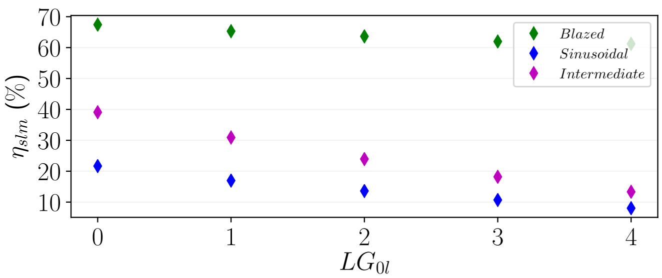


(a) LG_{00} (b) LG_{01} (c) LG_{02} (d) LG_{03}

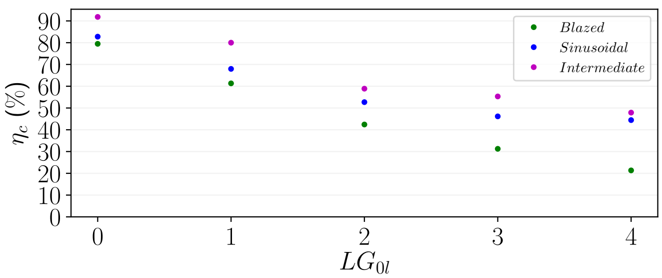


(e) LG_{04} (f) LG_{05} (g) LG_{06} (h) LG_{07}

Fig. 3: Laguerre-Gaussian modes observed at the cavity transmission when the cavity was locked with the PDH.



(a) SLM diffraction efficiency.



(b) LG modes coupling efficiency.

Fig. 4: Efficiency of conversion to the LG modes and coupling efficiency to the lattice cavity.

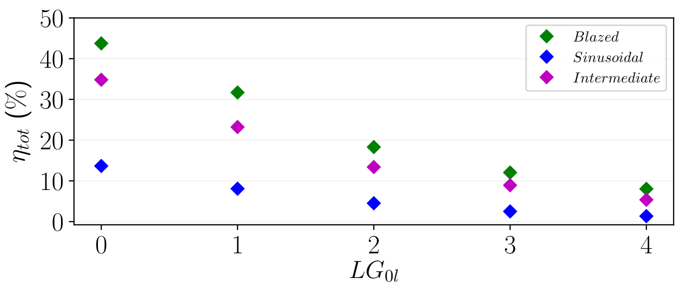


Fig. 5: Total efficiency of the setup.

III. LG lattice loading methods

We report in Table I the maximum depth U_m of the trapping potential for different mode numbers l. It decreases when l increases, due to the fact that the total intensity, hence U_0, decreases when the total efficiency decreases, but also from the fact that, according to equation (1), the depth at the bottom of a maximum of intensity maximum decreases with l for a given value of U_0. We observe that the trap depth U_m with $l = 4$ is still suitable for the clock interrogation part of the clock sequence.

However, loading the atoms usually requires a larger trap depth. This is especially true with the optical drain loading technique [8] in which the atoms are directly loaded from the first stage MOT (461 nm), by pumping the atoms to the metastable triplet states using 689 nm and 688 nm lasers overlapped with the optical lattice. We therefore identify two possible

LG_{0l}	η_{tot} (%)	U_0 (E_r)	U_m (E_r)
0	43.8	1095	1095
1	31.7	792	291
2	18.3	457	123
3	12.1	302	67
4	8.0	200	39

TABLE I: Trapping depths achievable with the modes LG_{0l}, for $l = 0, 1, 2, 3, 4$ when using a blazed grating. $-U_m$ is the minimum of the function given in equation (1). Is is expressed in recoil energies E_r associated with the absorption of a lattice photon. It assumes a typical trap depth of 2500 E_r that can be obtained in a $TEM_{0,0}$ configuration without the LG generation setup.

loading techniques:

(A) *Transferring atoms from the 1st stage MOT to the LG_{0l} lattice.*

With the drain technique, the large decrease of U_m with increasing values of l yields a rapid loss in the number of trapped atoms, given that the latter scales like $U_m^{1.5}$. However, this effect is mitigated by the fact that the LG mode has a larger area as l increases. All in all, we expect that the number of atoms that can be trapped in a LG_{04} mode is 43% of the number of atoms that can be trapped in a TEM_{00} mode with the same U_0. Taking in to account the mode generation efficiency η_{tot}, it could be possible to trap in a LG_{04} mode up to 10% of the atoms that would be trapped in a TEM_{00} mode. Monte Carlo simulation will be conducted to confirm this result, and to determine the optimal size for the drain lasers.

(B) *Transferring atoms from a TEM_{00} lattice to an LG_{0l}.*

Another possibility would be to trap and cool the atoms in a powerful TEM_{00} lattice, and then to modify the lattice profile to an LG_{0l} mode. The in-vacuum optical cavity locking represents the main challenge for this method: as the TEM_{00} and the LG_{0l} modes are resonant with the cavity at different frequencies, this method requires to switch the correction signal of the cavity lock from one point to the other in a time interval no larger than 1 ms. This can be achieved with digital electronics and a pre-calibration of the required set points.

IV. Conclusions

We have realized a system for the generation of Laguerre-Gaussian modes exploiting the features of three diffraction gratings encoded on an SLM. The coupling of $LG_{0,l=0,1,2,3,4}$ with the in-vacuum optical cavity was also reached with high efficiency, being the intermediate grating the one exposing a better spatial purity. The blazed and the intermediate gratings proved to be the good candidates for creating the new lattice, and then being implemented at least in the interrogation stage of the clock.

The next step will involve the experimental demonstration of trapped atoms in the new geometry. Finally the clock spectroscopy, will allow is to study the systematic uncertainty associated with cold collisions and lattice light shift effects in the LG geometry.

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