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Dynamic optical trap generation using FLC SLMs for the manipulation of cold atoms

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Abstract. Trapping and manipulation of cold atoms using optical potentials require the ability to generate and control a time varying light intensity distribution. Such an application demands that fast changing intensity distributions are generated, which are however free from flickering, or noise in general. Ferroelectric spatial light modulators are good candidates to achieve this because of their high refresh rate but they suffer from noise due to changes in the state of individual pixels during an animated sequence. A direct binary search based optimization routine was developed which minimizes the noise during such sequences. Filter sequences designed using this technique have been tested experimentally and the results demonstrated that flicker noise was eliminated.

1. Introduction

Atoms placed in a light field gradient whose frequency is close to an atomic resonance experience a dipole force which is proportional to the gradient of the intensity and inversely proportional to the detuning δ:

$$\mathbf{F}(\mathbf{r}) \propto \frac{\nabla I(\mathbf{r})}{\delta}. \tag{1}$$

For a red detuning ($\delta < 0$), the force is directed to high intensities, making it possible to trap atoms at the focus of a laser beam [1]. The dipole force is conservative (no spontaneous emission) and relies on photon redistribution by stimulated emission. Usual dipole traps consist of a highly focused beam or two crossing beams, in order to provide a three-dimensional confinement.

We are planning to use diffractive optics in order to generate more complex optical potentials such as time-dependent arrays of micro-traps, as a step towards the realization of a neutral-atom quantum computer [2]. The central idea is to trap ultracold atoms in a set of spots of light whose positions can be individually and dynamically changed. Quantum calculations are performed by alternately bringing atoms in different micro-traps close to each other and making them interact in a controlled way.

Many dynamical optical tweezers rely on spatial light modulators (SLM), which enable the real-time modification of phase and/or amplitude profiles of the

light beam that is used to generate the traps in such optical tweezer systems. Dynamic optical tweezers have successfully been used in many areas, a recent example is the 3D manipulation of microspheres [3].

However, our application has different requirements. First, the motion of the micro-traps should be fast and smooth, in order to avoid vibrational excitation of the atoms in the traps while still coping with the finite lifetime of atomic samples (of the order of a second). Secondly, the optical field within the individual traps has to be free from any noise or flicker which would perturb the atoms.

Ferro-electric spatial light modulators (FLC SLMs) are good candidates for the diffractive device because of their high refresh rate, up to 1000 frames per second. However, they only allow for discrete phases (0 or π) and require DC balancing, and therefore need continuous refresh, which may cause some flicker when the state of the pixels changes. Additional flicker is caused when an animated sequence of holograms is displayed on the SLM.

To reduce the amount of flicker between the frames of an animated sequence, we developed an optimization routine which for each frame of the sequence generates a phase grating corresponding to the target diffraction pattern while minimizing the number of pixels having to change their state from the previous frame. Obviously, this procedure does not provide any DC balancing over the sequence, but we found that the SLM can sustain such an imbalance on the timescale of our experiment, of the order of one second.

2. Optimization procedure

2.1. *Generating arbitrary diffraction patterns*

We use a 256×256 SLM array as a phase grating. Each pixel j generates a phase shift φ_j of 0 or π, and the phase pattern is optimized using a procedure based on direct binary search (DBS) [4, 5]. The diffraction pattern is specified by providing the intensity levels $I_{\mathrm{T},i}$ desired on a finite number of target points i.

For the design of two-level phase-only pixellated SLM patterns (filters), DBS operates as follows. Pixels j in the array are first initialized to a random distribution of $\varphi_j = 0$ or $\varphi_j = \pi$ phase values. An initial pixel phase distribution could also be obtained by other means, for example based on geometrical optics considerations [6], or by using the iterative Fourier transform algorithm [7, 8] or a genetic algorithm [9]. The intensity values I_i at the selected target points i that would be generated by this initial filter are then calculated, and an error function representing the 'distance' between these intensity values and the targets can be computed, for example:

$$\varepsilon_1 = \sum_i \left| I_{\mathrm{T},i} - I_i \right|. \tag{2}$$

A random pixel is then selected and its phase changed from 0 to π or from π to 0. The error function ε_1 is recalculated and if it is reduced, the pixel change is accepted, otherwise the pixel is reset to its previous value. The process is repeated until ε_1 falls below a preset threshold value. At that point, the residual ε_1 will be an indication of how close the intensity distribution produced by the filter we have just designed will be to the values desired at the target positions.

As an example, figure 1 shows the result of the optimization procedure to create an array of 9 dots. The error function used was more complex than the one
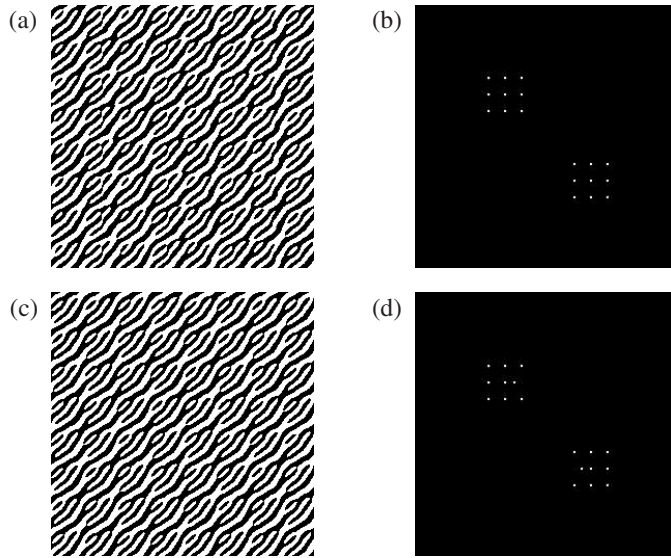
Figure 1. Frame (*a*) shows the filter calculated with DBS in order to create a diffraction pattern made of an array of 9 dots (frame (*b*)). Frame (*c*) shows the filter corresponding to a modification of that pattern, with one of the dots displaced, as it appears in frame (*d*). The two colours of the filters correspond to the two possible phase values 0 and π.

of equation (2) and was designed to favour a homogeneous illumination among the dots.

To displace the atoms, one can build an animated sequence consisting of a set of filters being sequentially displayed on the SLM. However, changing the state of the pixels induces some flicker while switching from one filter to another one. This is due to the fact that a pixel changing from one state to the other one loses its well-defined retardation effect for a switch time of about $100\,\mu s$, during which the light illuminating that pixel does not contribute to the diffraction pattern.

This flicker is reduced by minimizing the number of pixel changes between consecutive filters.

2.2. *Reducing the flicker*

To minimize the number of pixels that change between consecutive filters, we introduce a second error term, for example:

$$\varepsilon_2 = \sum_j \left| \varphi_j - \varphi_j' \right|, \tag{3}$$

where φ_j and φ_j' are the phases of pixel j for the new and the old frames, respectively. The error function ε_2 can be viewed as a measure of the distance between consecutive filters. The DBS optimization is now performed with a composite error function

$$\varepsilon = w_1\varepsilon_1 + w_2\varepsilon_2. \tag{4}$$

The weights w_1 and w_2 are chosen to balance fidelity of the intensity distribution generated and number of pixel changes.

3. Experimental results

As a test of our optimization routine, we displaced a single spot over π (generalized coordinate) along a line with a 4-frame sequence, and recorded the light power in the spot on a photodiode. Figure 2 shows (*a*) the results either when the distance between the filters is minimized, or (*b*) when it is maximized.
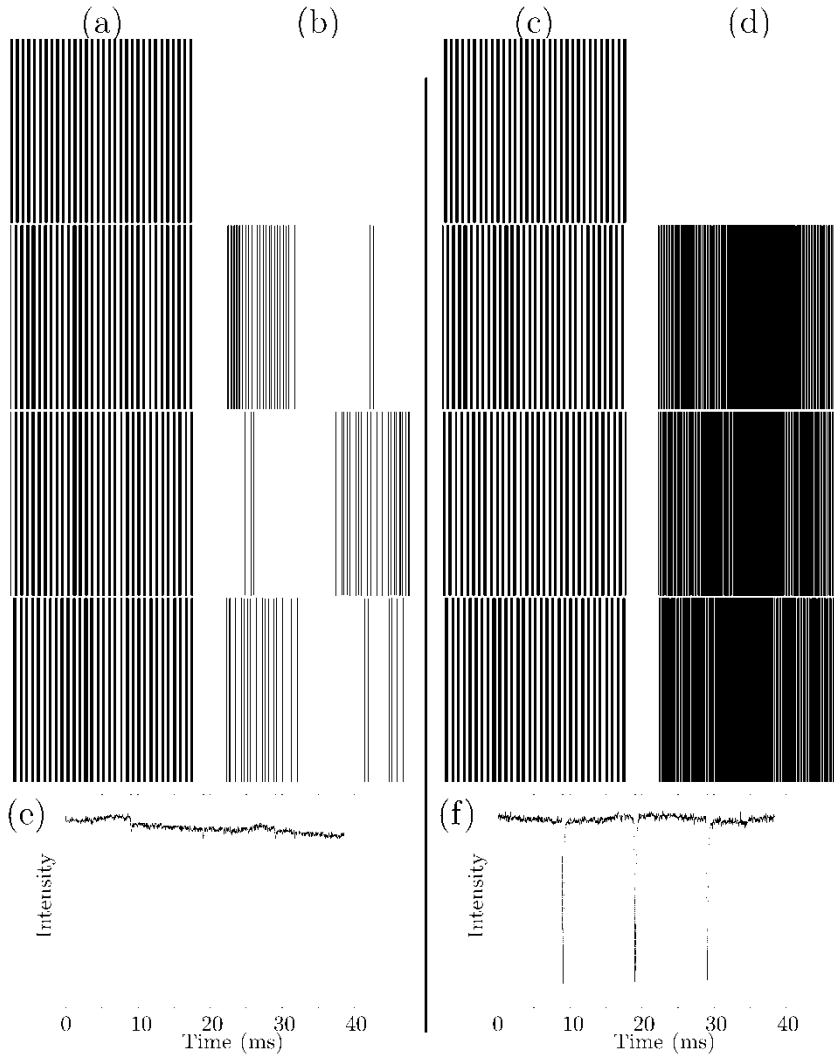

Figure 2. Sequences of 4 filters to move a single spot over π (in generalized coordinates). In sequence (*a*), the distance between consecutive filters is minimized, whereas in sequence (*c*), it is maximized (worse case scenario). Columns (*b*) and (*d*) show the difference (white for unchanged pixels and black for changed pixels) between consecutive frames of sequence (*a*) and (*c*) respectively. The recording of the power in the spot on a photodiode shows in graph (*e*) that in sequence (*a*) the flicker was practically eliminated, whereas in sequence (*c*), as it appears in graph (*f*), the power drops to less than 10% of its average value. The dotted lines indicate the transitions between the filters.

These two cases correspond to a positive w_2 or a negative w_2, respectively. It is clear that minimizing the distance between consecutive filters drastically reduces the amount of flicker.

Another trivial observation is that half the filters of sequence (*b*) are very similar to the corresponding filters of sequence (*a*), whereas the other half are almost the complementaries of the corresponding filters of sequence (*a*). Since there are always two complementary filters able to generate a given diffraction pattern, the first effect of our optimization is to select the one which is closest to the previous filter in the sequence. Adjustment of the weights w_1 and w_2 allows the amount of change between consecutive filters to be fine tuned. In this example, the relative weight w_1/w_2 was such that in sequence (*a*), only 12% of the pixels changed between filters. Allowing for a larger number of filters in the sequence would make the motion of the spot even smoother.

More generally, there is a trade-off between the efficiency, the reduction of the flicker, the fidelity and the number of intermediate frames. Although our set-up is inherently inefficient (less than 5% at our working wavelength), the important point is that the additional constraint of reducing the flicker barely reduces that efficiency. We could keep the uniformity below the percent level.

4. Conclusion

As pointed out previously, the main effect of the optimization procedure is to select for each frame the best filter out of the two complementary possibilities. There is however some room for fine tuning the process. First, the error function ϵ_1 can be tuned to control the light distribution among the target points, as in standard DBS. Second, the error function ϵ_2 and the relative weight w_1/w_2 can be tuned to favour either smoothness of the transition between consecutive filters, or faithful reproduction of the desired diffraction pattern. Finally, it is always possible to increase the smoothness of the animation by increasing the number of intermediate filters in the sequence, at the cost of a slower animation.

An additional aspect of the optimization is the choice of the initial state for the pixels. Three obvious possibilities are random pixel phase values, a constant phase across the filter and the phase values corresponding to the previous frame in the animated sequence. For the results presented here we used a random initial phase distribution since it helps to avoid false minima during the optimization and appears to yield good results. We plan further work in this area however, in particular the use of the previous frame with additional noise will be examined.

Even without further optimizations, our improved DBS algorithm features a strong decrease in the flicker and appears to be very promising for atom manipulation. The next step is to load a Bose–Einstein condensate of rubidium atoms in an array of dots and to demonstrate the manipulation of the atomic sample with minimum heating.

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