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Application of laser matter interaction for generation of small-sized materials

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Abstract

Syntheses of nano particles have drawn considerable interest in the recent past because of their ability to offer superior properties to those of bulk materials. Reduction in the size of the materials can be performed with great precision via laser–matter interaction. We focus here on following two promising schemes: (a) selective ablation of thin films via high power laser interferometry and (b) manipulation of atomic trajectories via dipole force, to generate the small-sized materials in the form of ordered arrays of required configuration. Some of our preliminary investigations on both techniques are also presented.

Keywords: Laser–matter interaction

1. Introduction

The advent of lasers four decades ago, followed by tremendous development in the range of lasers in terms of optical spectrum, power and quality, has played a crucial role in unearthing the fundamental concepts as well as improving the precision in device fabrication and in measurement. Whenever matter is illuminated with the laser radiation, the electromagnetic energy gets converted into mechanical, thermal, electronic as well as into another electromagnetic wave with different configuration. The form of the conversion of energy depends on the incident radiation as well as the properties of the medium; accordingly the material under consideration undergoes modification. Moreover, with careful choice of the medium, laser and the environment, one can engineer altogether new materials with the desired properties. It is this particular application which is giving a lot of hope particularly for its application towards optical communication (Chatterjee and Pawlowski, 1999) and quantum computing (Cirac and Zoller, 2000) with speeds much larger than present day electronics devices. In order to achieve speeds of the order of more than 10 Gb/s one requires ultrafast optical switches, detector, modulators and tunable arrays of diode lasers. This can be achieved by utilizing the properties of quantum confinement (Alvisatos, 1996) by reducing the dimensions of suitable materials. Reduction in the size of the materials can be performed with great precision via laser–matter interaction. Therefore, the focus in this paper is on following two schemes to manipulate the materials to dimensions of the order of nanometer using lasers:

1. Selective ablation of thin films via high power laser interferometry.
2. Manipulation of atomic trajectories via dipole force.

Both these lithography schemes do not require any material mask and produce ordered arrays of small-sized materials in a single step. Some of our preliminary investigations based on the above schemes are discussed in this paper.

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1.1. Selective ablation of thin films via high power laser interferometry

This technique is based on modifying the surface morphology to the order of tens of nanometer sizes by selective ablation of material using laser. This may find its application in the fabrication of optocoupler (Kubota and Takeda, 1989), laser arrays (Qu et al., 2002) and other optoelectronic devices (Korn et al., 1990; Krauss et al., 1998). The technique is very general and is applicable to any kind of material. In this technique, thin films of metals, semiconductors, polymers or any other complex compound can be ablated selectively by illuminating it with interference pattern formed by high power laser. This results in the ablation of materials in the region of maximum intensity (bright fringe) leaving the area of minimum intensity (dark fringe) unaffected. The periodicity of the grating so formed will depend on the spatial frequency of the interference pattern. The width of the line depends on the laser intensity and damage threshold of the material of the thin film. This can be explained with the help of Fig. 1. Fig. 1a is a typical interferogram from a Michelson interferometer recorded on to a CCD camera. The intensity distribution of this interference pattern is shown in Fig. 1b with the line marked for the damage threshold. From the figure it is clear that the thin film exposed to the intensities above the damage threshold will be ablated leaving behind the rest of the material unaffected and thus by changing the intensity of the laser the writing width can be controlled. By using multiple exposure of the thin films at different orientations one can generate desired two-dimensional tiny arrays of the materials. This technique is a single step with the advantage of having on line control on the configuration of the nano structures simply by modifying the interference pattern. There are a few reports of using laser interferometry for writing polymide lines by selectively ablating thin films (Phillips and Sauerbrey, 1993 and references therein).

We have used thin films of copper (thickness $\sim 2\,\mu m$) for demonstrating the selective ablation. A thin film of copper was deposited using the pulsed laser deposition technique (Miller, 1994). The experimental set-up used for selective ablation is shown in Fig. 2. A Michelson interferometer formed with two mirrors M1 and M2 and a cube beam splitter BS was illuminated with second harmonic of Nd: YAG laser (400 mJ, in fundamental, 8 ns, beam diameter ~ 8 mm, model HYL 101, Quanta System). The interference pattern at the output of the interferometer was compressed down to a spot of diameter ~ 1.5 mm with a lens L1 and finally copper thin film T as shown in Fig. 2, was illuminated with this compressed interference pattern. The region of copper film exposed to the bright fringes was ablated leaving behind the copper lines in the dark fringe region. In this way, we could write 15 lines of copper of periodicity $\sim 20\,\mu m$. The Atomic Force Microscope (model SME-NA B, NTMDT) scan of selectively ablated copper film shown in Fig. 3 clearly confirms the formation of grating structure of the thin film. We have operated the laser much below the optimum operating conditions and hence the intensity distribution was nonuniform. Therefore the lines are of nonuniform widths. This result is very preliminary and further reduction in line width is

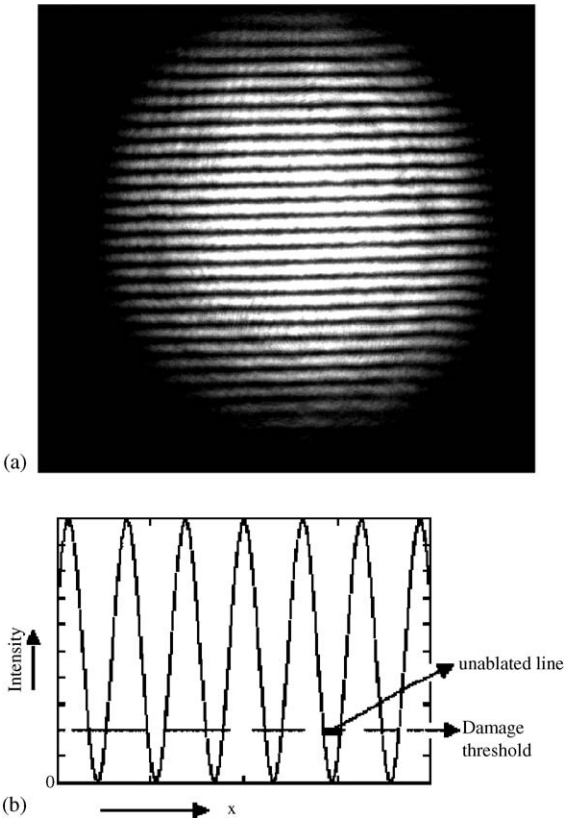


Fig. 1. (a) Interference pattern from Michelson interferometer and (b) intensity distribution in the interference pattern.

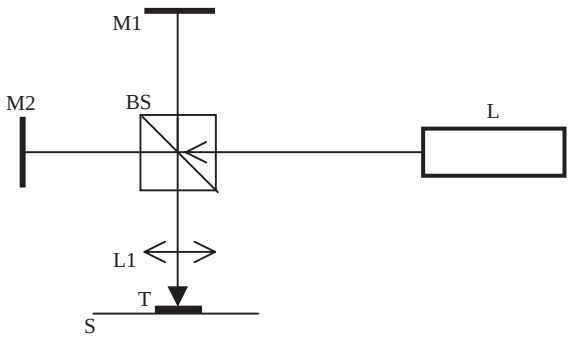


Fig. 2. Schematic of experimental set-up for selective ablation of thin film, L: Nd:YAG Laser, BS: Cube beam splitter, M1, M2: Mirrors, L1: Lens, T: Thin film, S: Substrate.

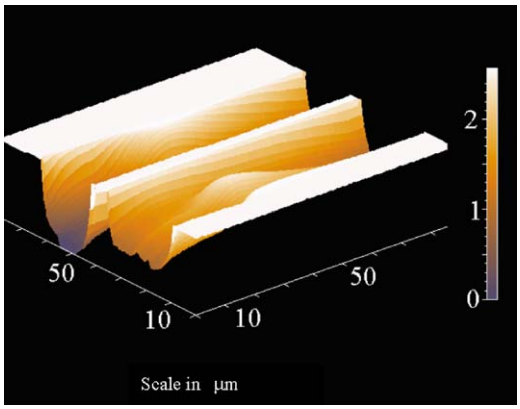


Fig. 3. AFM Scan of selectively ablated copper thin film.

possible by improving the interference pattern for fine fringes along with intensities much above the damage threshold.

1.2. Manipulation of atomic trajectories via dipole force

Manipulation of atomic trajectories in presence of near resonant optical field is coming up because of its potential application towards direct deposition of neutral atoms onto a substrate resulting in feature size of sub −100 nm (Ashkin, 1994; Ryytty and Kaivolta, 2000). This atom lithography technique offers the advantage of creating two- and three-dimensional complex structures without using any physical mask. An atom in a radiation field experiences two kinds of forces (Cohen-Tannoudji et al., 1992). The radiation pressure force results from absorption, followed by random spontaneous emission of photons. The magnitude of this force is limited by the rate of spontaneous emission and saturates as the laser intensity increases. This dissipative spontaneous force is responsible for laser cooling (Dalibard et al., 1992). The second kind of force is called the gradient or dipole force, which originates from the interaction of induced dipole moment with nonuniform light distribution (Cohen-Tannoudji, 1992). The magnitude of this force depends on the intensity gradient and the amount of detuning from the atomic resonance frequency. This dipole force can modify the trajectories of atoms and with the careful choice of the parameters it can lead to focused spots of atoms of the order of tens of nanometers (Gupta et al., 1995). In this way an atomic beam can be deposited to the dimensions of the order of nanometers. Theoretical limit of focused spot of the atomic beam using dipole force has been reported to be 1 nm (Helseth, 2002).

There have been experimental reports on this technique of atom lithography using atomic beams of sodium (Timp et al., 1992), chromium (Sandoghadar et al., 1997; Gupta et al., 1995), aluminum (McGwan et al., 1995), and cesium (Salomon, 1987) in the presence of dipole forces. The configuration used so far is a thermal atomic beam of required material, incident transverse to the standing wave field of a laser, as shown in Fig. 4, detuned to the resonance transition. The periodic gradient in the intensity acts as the series of lenses to focus the atomic beam with periodicity $\lambda/2$; λ being the wavelength of laser. In this scheme one- and two-dimensional periodic arrays of atoms have been deposited with array width of the order of nanometer (Sandoghadar et al., 1997; Gupta et al., 1995). The modification of trajectories of CS_2 molecules in the focused region of near resonant laser via dipole force has also been reported (Zhao et al., 2000).

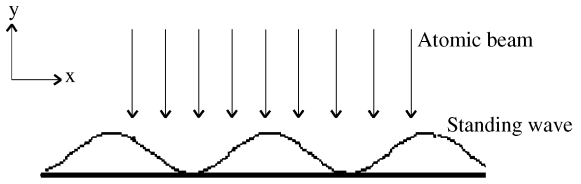


Fig. 4. Schematic of standing wave configuration for the focusing of atomic beam.

Following semiclassical treatment the expression for the dipole force is given by Scholten et al. (1999)

$$\vec{F} = \frac{-\hbar\Gamma^2\Delta\vec{\nabla}(I/2I_{\text{sat}})}{\Gamma^2(1+I/I_{\text{sat}})+4\Delta^2}, \tag{1}$$

where Γ is the natural line width, Δ is the detuning factor, I is the laser intensity and I_{sat} is the saturation intensity.

Eq. (1) is computed for the trajectories of rubidium thermal (17 m/s) and super thermal (1700 m/s) collimated monoenergetic atomic beam for the transition $5^2S_{1/2}$–$5^2P_{3/2}$ corresponding to a wavelength of 780 nm for various intensities of laser. The detuning parameter was chosen to be 200 MHz.

The computed trajectories of thermal beam (room temperature) of rubidium in standing wave at intensities 1 and 10 W/m^2 for blue detuning are shown in Figs. 5a and b, respectively. At higher intensities atoms are more tightly focused with better contrast. Results for a super-thermal beam at atomic velocity 1700 m/s are shown in Fig. 6. Results are similar to that of a thermal beam with improved contrast at higher intensity (Fig. 6b). Super-thermal beam has to travel a distance longer by two orders of magnitude before being focused compared to that of thermal atomic beam. This confirms that interaction time required for the focusing at any given intensity is constant and is independent of velocity of the atom. From Figs. 5 and 6 it is obvious that at lower intensity the atomic beam has to travel a larger distance, in other words the interaction time with the field are required to be large. Interaction time required for the atomic beam for focusing at various intensity are listed

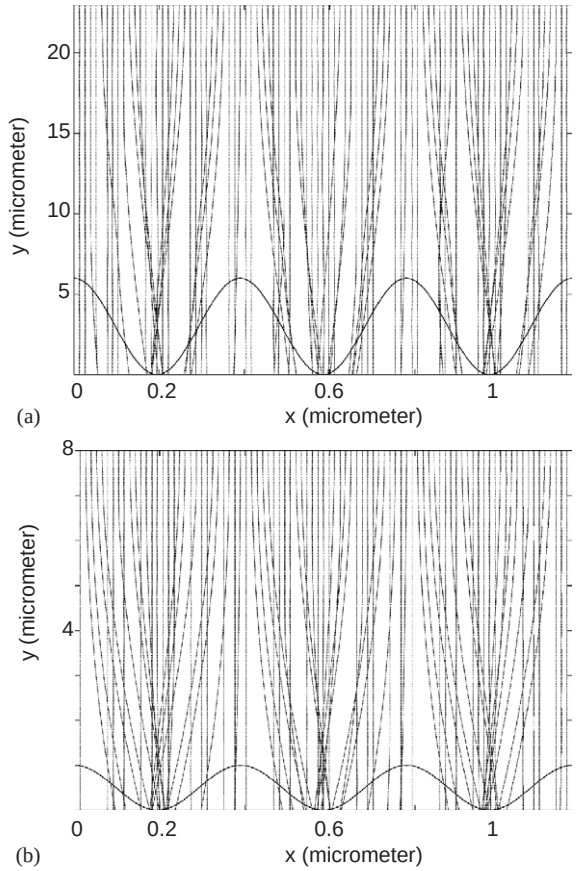


Fig. 5. Trajectories of initially collimated rubidium thermal atomic beam at intensity: (a) $I_o = 1\,\mathrm{W/m^2}$ and (b) $I_o = 10\,\mathrm{W/m^2}$. Intensity field is as shown in the bottom of the figure.

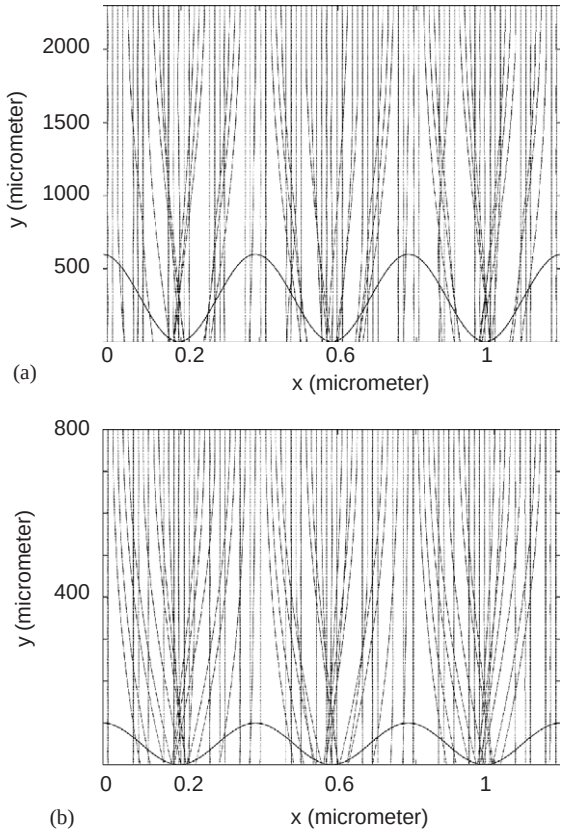


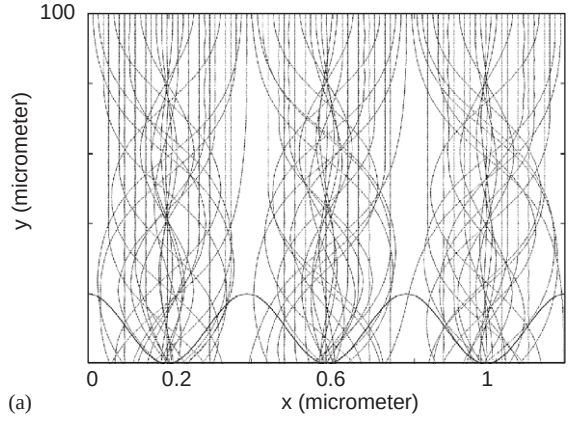
Fig. 6. Trajectories of rubidium super-thermal atomic beam at intensity, $I_o = 1\,\mathrm{W/m^2}$ and $10\,\mathrm{W/m^2}$.

Table 1
Focussing time at various intensities of laser beam

Intensity ($\mathrm{W/m^2}$)	Focusing time (μs)
0.1	2.93
1.0	1.35
10.0	0.47

in Table 1. If the atomic beam is allowed to travel further, multiple focusing of the beam is observed as shown in Figs. 7a and b. At higher intensities (Fig. 7b) the trajectories of the beam after first focus is confined around the minima of the field. Therefore after the first focus, substrate location is not very critical at higher intensities and atomic beam can be deposited with very good contrast.

The periodicity of this atom lithography technique for standing wave configuration is always limited to $\lambda/2$. Therefore, there is a need to work on some new configurations in terms of atomic beams as well as laser field for dipole force so as to reduce the periodicity below $\lambda/2$. We propose a new configuration of using square arrays of atomic beams (matrix of micro-ovens) in presence of gaussian intensity distribution ($\mathrm{TEM_{00}}$ mode) of laser to reduce the periodicity of focused spot. We have computed the trajectories for such configuration and generated the two-dimensional focused pattern of arrays where the atomic beam and laser are counter propagating. The cross section ($z-x$ plane) of collimated arrays of atomic beam used for computation is as shown in Fig. 8, where the periodicity of atomic beam is 2 μm and the diameter of each beam is 1 μm with the atoms located symmetrically in it. The atomic beam is taken to be propagating along y axis and that of laser beam along $-y$ axis. The atoms are launched at a Rayleigh distance with respect to beam waist ($w_0 = 50\,\mu\mathrm{m}$) of laser. The peak laser intensity at the center of the beam waist is chosen to be I_{sat} ($16.5\,\mathrm{W/m^2}$) for rubidium transition under consideration. The trajectories were computed for red detuning ($\Delta = -200\,\mathrm{MHz}$). The final location of the atoms after traveling a distance of 800 μm in the laser beam is shown in Fig. 9. It clearly shows the compression of the arrays by an order of magnitude around the center of the laser beam resulting in periodicity less than 100 nm with final



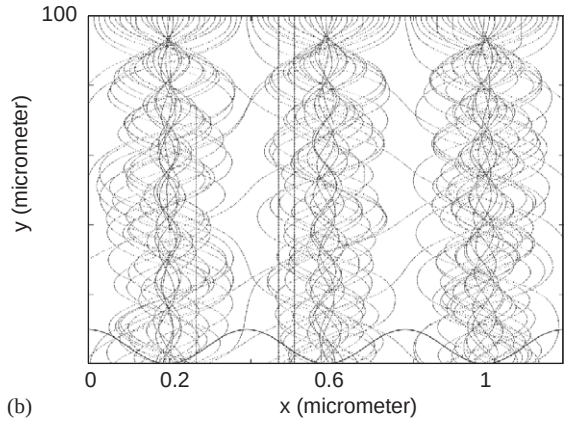


Fig. 7. Multiple focusing of rubidium thermal atomic beam at, $I = 1$ and $10\,W/m^2$.

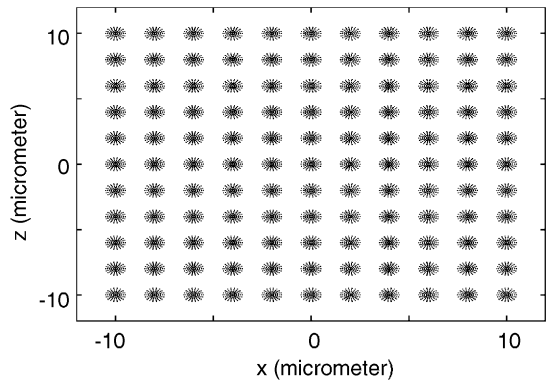


Fig. 8. Cross-section of square arrays of atomic beams.

atomic spots less than 50 nm. The astigmatism in the final pattern is because of the nonuniform gradient of intensity distribution of TEM_{00} mode. A well-collimated atomic beam is an ideal choice for such lithography. But in practice it will be extremely difficult to obtain such a well-collimated matrix of atomic beams. Therefore, we

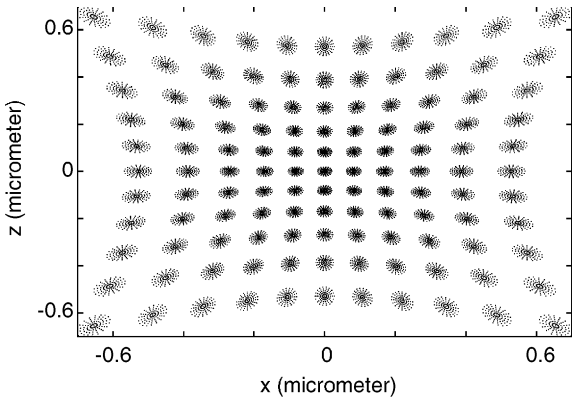


Fig. 9. Final position of atoms after interacting with TEM_{00} mode laser for collimated set of atomic beams.

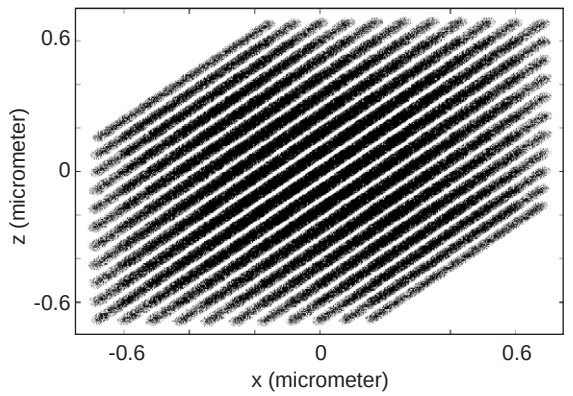


Fig. 10. Final position of the atoms from set of divergent atomic beams after interacting with TEM_{00} mode laser.

have tried to consider the effect of divergence of the atomic beam. The starting configuration of atomic beam is considered same as shown in Fig. 8, with a total divergence of each beam of 9 mrad. Final position of the atoms at a distance of 1100 μm from launching position is as shown in Fig. 10. Since the trajectories of the atom evolving at different angles is different, it results in line deposition. The separation of the lines and line width can be controlled by initial location and divergence of the atomic beam and by laser parameters.

2. Conclusion

We have performed the preliminary experiment on selective ablation and could write the copper lines of minimum width of 5 μm. In order to maintain the uniformity of the lines and to reduce the line width, the laser has to be operated at higher power. An extensive experimental work is to be taken up for various

promising materials to extend the scope of selective ablation for fabrication of optoelectronics devices.

In atom lithography technique using dipole force for standing wave configuration, the computed trajectories confirms that the location of substrate for deposition of focused beam at higher intensity is not very critical. The idea of the matrix of micro oven system for the arrays of atomic beams in TEM_{00} mode appears to be a promising lithography technique for generating periodic arrays of nano structures with periodicities much less than the wavelength. This new idea of designing such closely spaced mico-ovens delivering large number of discrete atomic beams with small divergence may be a fairy tale at this moment, but probably selective laser ablation in future may prove to be one of the promising techniques for it.

Both the techniques discussed above are relatively new. There is a need to take up the detailed studies to make them viable techniques for the generation of all together new series of periodic arrays of small materials for device applications.

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