Quantum Information Processing with Microfabricated Optical Elements

F. B. J. Buchkremer, R. Dumke, M. Volk, T. Müther, G. Birkl, and W. Ertmer

Institut für Quantenoptik, Universität Hannover, Welfengarten 1, Hannover, D-30167 Germany

e-mail: birkl@iqo.uni-hannover.de

Received September 28, 2001

Abstract—We discuss a new direction in the field of quantum information processing with neutral atoms. It is based on the use of microfabricated optical elements. With these elements versatile and integrated atom optical devices can be created in a compact fashion. This approach opens the possibility to scale, parallelize, and miniaturize configurations for quantum information processing with neutral atoms. The exploitation of the unique features of the quantum mechanical behavior of matter waves and the capabilities of powerful state-of-the-art micro- and nanofabrication techniques lend this approach a special attraction.

1. INTRODUCTION

Following the spectacular theoretical results in the field of quantum information processing of recent years [1], there is now also a growing number of experimental groups working in this area. Among the many currently investigated approaches, which range from schemes in quantum optics to superconducting electronics [2], the field of atomic physics seems to be particularly promising due to the experimentally achieved remarkable control of single qubit systems and the understanding of the relevant coherent and incoherent processes. While there have been successful implementations of quantum logic with charged atomic particles in ion traps [3], quantum information schemes based on neutral atoms [4–7] are an attractive alternative due to the weak coupling of neutral atoms to their environment. A further attraction of neutral atoms lies in the fact that many of the requirements for the implementation of quantum computation [8] are potentially met by the newly emerging miniaturized and integrated atom optical setups.

These miniaturized setups can be obtained by using different types of microfabricated structures: The trapping and guiding of neutral atoms in microfabricated **charged and current carrying** structures have been pursued by a number of groups in recent years [9–16]. A new approach to generate miniaturized and integrated atom optical systems has been recently introduced by our group [17]: We proposed the application of microfabricated **optical** elements (microoptical elements) for the manipulation of atoms and atomic matter waves with laser light. This enables one to exploit the vast industrial and research interest in the field of applied optics directed towards the development of micro-optical elements, which has already led to a wide range of state-of-the-art optical system applications [18, 19] in this field. Applying these elements to the field of quantum information processing, however, constitutes a novel approach. Together with systems based on miniaturized and microfabricated mechanical as well as electrostatic and magnetic devices, the application of microoptical systems will launch a new field in atom optics which we call **ATOMICS** for **AT**om **O**ptics with **MIC**ro-**S**tructures. This field will combine the unique features of devices based on the quantum mechanical behavior of atomic matter waves with the tremendous potential of micro- and nanofabrication technology and will lead to setups that are also very attractive for quantum information processing.

2. MICROOPTICAL ELEMENTS FOR QUANTUM INFORMATION PROCESSING

A special attraction of using microoptical elements lies in the fact, that most of the currently used techniques in atom manipulation are based on the interaction of light with atoms. The use of microfabricated optical elements is therefore in many ways the canonical extension of the conventional optical methods into the micro-regime, so that much of the knowledge and experience that has been acquired in atom optics can be applied to this new regime in a very straightforward way. There are however, as we will show in the following, a number of additional inherent advantages in using microoptics which significantly enhance the possibilities of atom manipulation and will lead to a range of new developments that were not achievable until now: The use of state-of-the-art lithographic manufacturing techniques adapted from semiconductor processing enables the optical engineer to fabricate structures with dimensions in the micrometer range and submicrometer features with a large amount of flexibility and in a large variety of materials (glass, quartz, semiconductor materials, plastics, etc.). The flexibility of the manufacturing process allows the realization of complex optical elements which create light fields not achievable with standard optical components. Another

advantage lies in the fact, that microoptics is often produced with many identical elements fabricated in parallel on the same substrate, so that multiple realizations of a single conventional setup can be created in a straightforward way. A further attraction of the flexibility in the design and manufacturing process of microoptical components results from the huge potential for integration of different elements on a single substrate, or, by using bonding techniques, for the integration of differently manufactured parts into one system. No additional restrictions arise from the small size of microoptical components since for most applications in atom optics, the defining parameter of an optical system is its numerical aperture, which for microoptical components can be as high as NA = 0.5, due to the small focal lengths achievable.

Among the plethora of microoptical elements that can be used for quantum information processing applications are refractive or diffractive microoptics, computer generated holograms, microprisms and micromirrors, integrated waveguide optics, near-field optics, and integrated techniques such as planar optics or micro-opto-electro-mechanical systems (MOEMS). Excellent overviews of microoptics can be found in [18, 19]. To our knowledge, of all these elements only computer generated holograms and phase gratings have been used in atom optics so far for guiding [20] and trapping [21–23] of atoms, while a new type of atom trap based on the near field properties of laser radiation has been proposed in [24].

In this paper we give an overview of the novel possibilities that arise for quantum information processing with neutral atoms if one employs microfabricated optical elements. We show how crucial components for miniaturized systems for quantum information processing with neutral atoms can be realized with this approach.

3. EXPERIMENTAL SETUP

Among the key elements in quantum information processing with neutral atoms are atom traps which act as storage devices for the logical qubits inscribed in the internal and external states of the atoms. A particularly simple atom trap is based on the dipole potential of a single focused red detuned laser beam. This trap has been first realized by Chu *et al.* [25] and has remained an important element ever since [26].

The experimental setup that we employ for our studies of the applicability of microoptical elements to generate novel trapping structures is depicted in Fig. 1. The focal plane of a microoptical focusing component illuminated by a laser beam is transferred into the vacuum chamber with the help of two achromats ($f = 300$ mm, $D = 50$ mm) so that we can load atoms into the laser beam foci by overlapping them with a cooled atom sample prepared in a magnetooptical trap (MOT). This setup has the advantage, that the performance of the
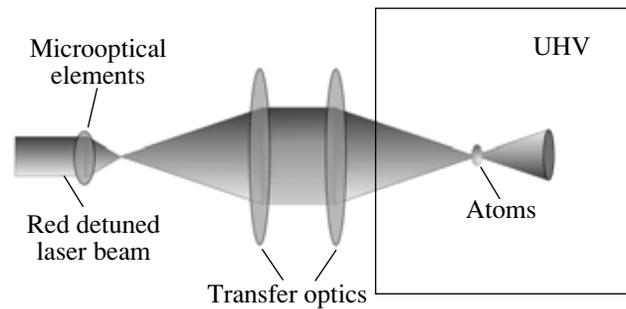

Fig. 1. Experimental setup. The light of an incoming red detuned laser beam is focused by a microoptical component and the focal plane is imaged into the vacuum chamber (UHV). Atoms are first collected in a MOT and then trapped in the refocused light field.

MOT is not disturbed by the microoptical component and that we can experiment with a variety of microoptical elements without the need to open the vacuum chamber. As a first step we have achieved a simple dipole trap by using a single lens as the microoptical component in Fig. 1 and have managed to trap approximately 10^5 ^{85}Rb atoms with a lifetime of 166 ms (Fig. 2) in a dipole trap of potential depth $U_0/k_B = -1.9$ mK (laser power $P = 50$ mW, detunig of $\Delta\lambda = 2$ nm, Gaussian waist of focus $w_0 = 15$ μm).

4. QUANTUM STATE REGISTER BASED ON ARRAYS OF DIPOLE TRAPS

A new approach arises from the application of one- or two-dimensional arrays of spherical microlenses for atom trapping (Fig. 3). Microlenses have typical diameters of ten to several hundreds of μm. Due to their short focal lengths of typically 100 μm to 1 mm, their numerical aperture can be as high as 0.5, resulting in foci whose focal size q (defined as the radius of the first minimum of the Bessel function which results from the illumination of an individual microlens with a plane wave) can be as low as $q = 1$ μm for visible laser light.

By focusing a red detuned laser beam with sufficiently large diameter with a spherical microlens array, we obtain one- or two-dimensional arrays of a large number of dipole traps (Fig. 4), in which we store multiple-atom samples [27].

For frequently used atomic species and commonly used laser sources one can easily obtain a large number (several tens to hundreds) of atom traps of considerable depth with rather moderate laser power. For typical laser parameters and 100 atom traps, the trap depth is significantly larger than the kinetic energy of the atoms achievable with Doppler cooling [17]. The low rates of spontaneous scattering that are achievable with sufficiently far detuned trapping light ensure long storage and coherence times as required for successful quantum information processing, while a strong localization of the atoms strongly suppresses heating of the atoms
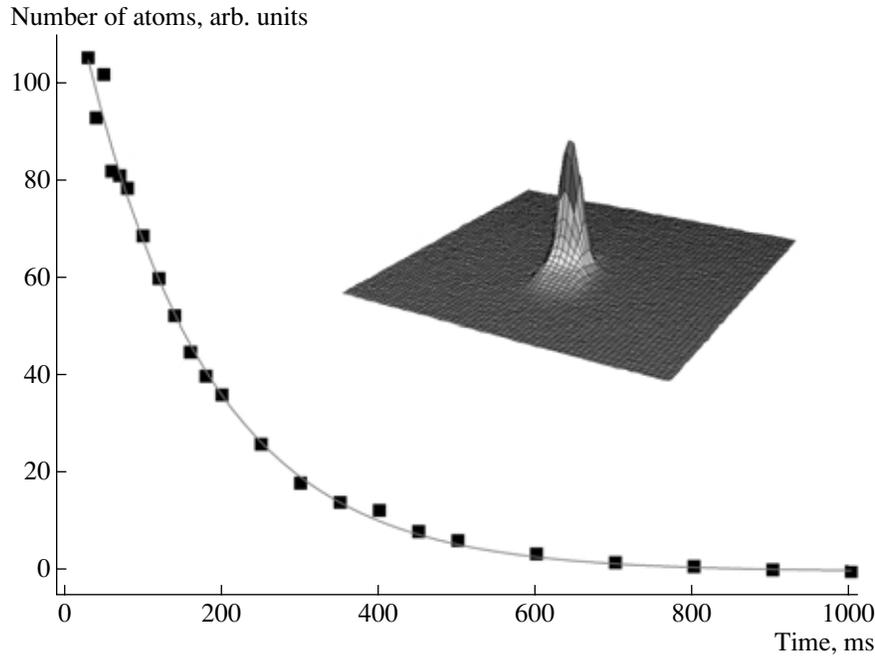
Fig. 2. Number of atoms remaining in dipole trap as a function of time. An exponential fit to the data yields a storage time of 166 ms. Inset: Density distribution of atoms in a single dipole trap obtained by using a single microlens in the setup depicted in Fig. 1.
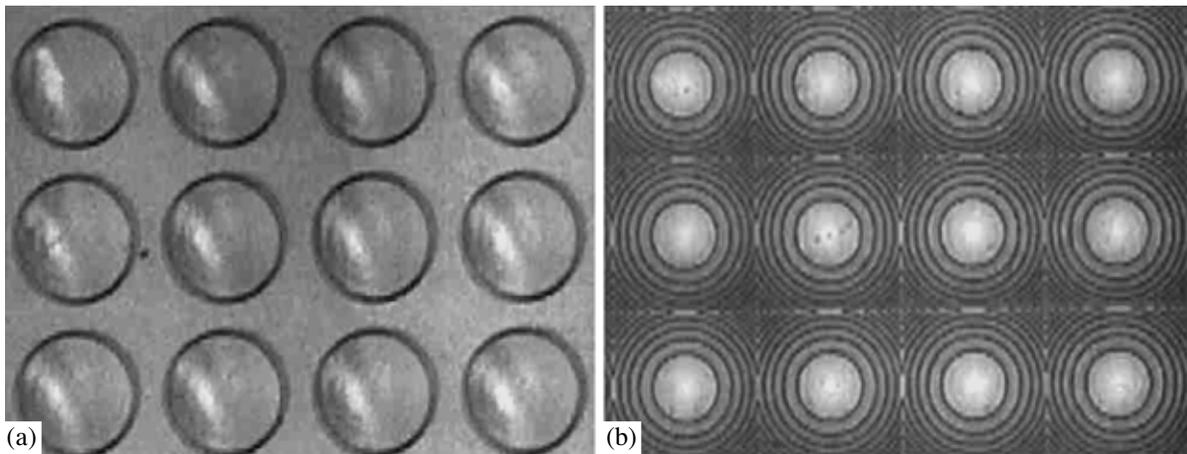

Fig. 3. (a) Refractive and (b) diffractive array of spherical microlenses.

and should make it possible to cool the atoms to the ground state of the dipole potential via sideband cooling in all dimensions. For the parameters given in [17] the size of the atomic wavefunction reaches values that are significantly smaller than 100 nm, even approaching 10 nm in many cases, thus making microlens arrays well suited for the generation of strongly confined and well localized atom samples.

The lateral distances between the individual traps (typically 100 μm) make it easy to selectively detect and address the atom samples in each dipole trap. While the natural way of addressing an individual trap consists in sending the addressing laser beams through the corresponding microlens, there are also more sophisticated methods possible, e.g., with a two-photon Raman-excitation technique as depicted in Fig. 4. This technique has been applied frequently to create superposition states in alkali atoms [28] and can be used to implement single qubit rotations for quantum information processing. It relies on the simultaneous interaction of the atoms with two mutually coherent laser fields. For a sufficiently large detuning from the single photon resonance, only the atoms in the trap that is addressed by both laser beams are affected by them.

These factors open the possibility to prepare and modify quantum states in a controlled way ("quantum
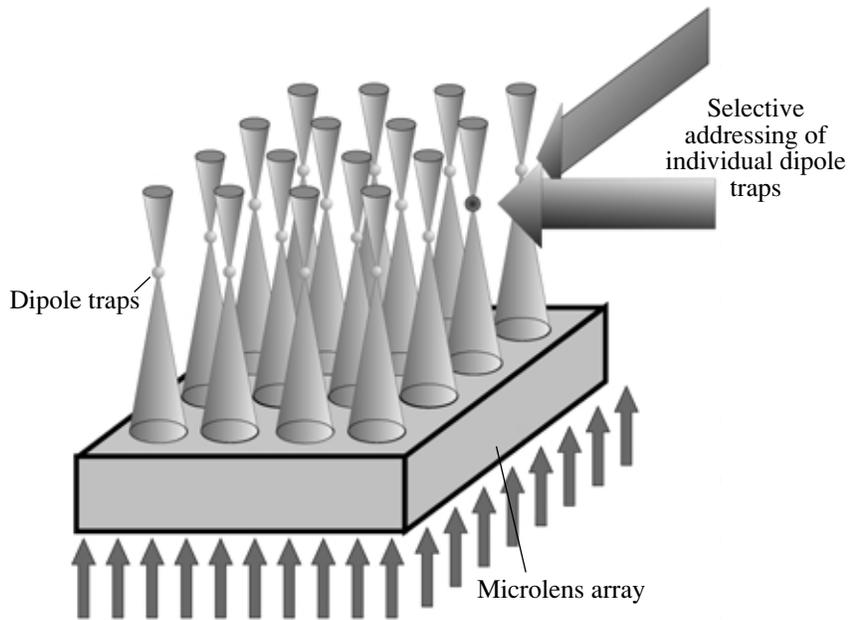
Fig. 4. Two-dimensional array of dipole traps created by focusing a red-detuned laser beam with an array of microlenses. Due to their large separation (typically 100 μm) individual traps can be addressed selectively, e.g., by two-photon Raman-excitation, as depicted.
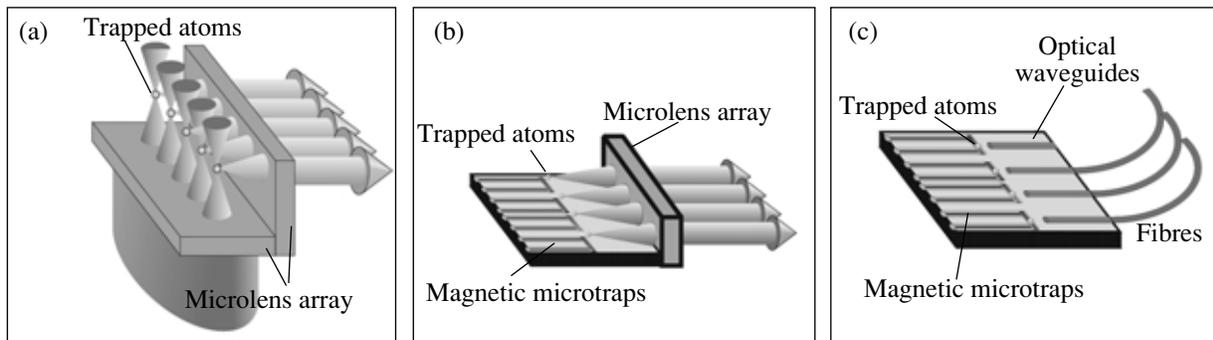

Fig. 5. Spatially resolved readout of the internal and external states of atoms (e.g., the state of a qubit) using microlens arrays: (a) Integration of two spherical microlens arrays creates a combined system of dipole traps and efficient detection optics. (b) Integration of a microlens array (for readout) with microfabricated magnetic or electrostatic trapping structures. (c) Optical waveguides and fibres can also be integrated on the substrate.

engineering") in each trap, which is a necessary ingredient for quantum computing. As a first and easily achievable implementation, single qubits associated with long-lived internal states can be prepared and rotated in each individual trap of a two-dimensional dipole trap array (Fig. 4), stored and later read out again. Thus, this device can serve as a quantum state register.

The manipulation of atoms with microlens arrays is extremely flexible: It is easily possible to temporarily modify the distances between individual traps if smaller or adjustable distances between traps are required. This can be accomplished either by using two independent microlens arrays which are laterally shifted with respect to each other or by illuminating a microlens array with two beams (possibly of different wavelength) under slightly different angles, thereby generating two distinct sets of dipole trap arrays. Their mutual distance can be controlled by changing the angle between the two beams. With a fast beam deflector, this can be done in real-time during the experiment.

Due to this flexibility, setups based on microlens arrays are also well suited for the implementation of two-qubit gates. Considering, for example, quantum phase gates based on dipole-dipole interactions between atoms [6] all requirements are fulfilled in the configuration depicted in Fig. 4. Atoms localized in neighboring traps can be first initialized and then be brought close to each other with a definable separation in the single-micron range and for a predefined dura-
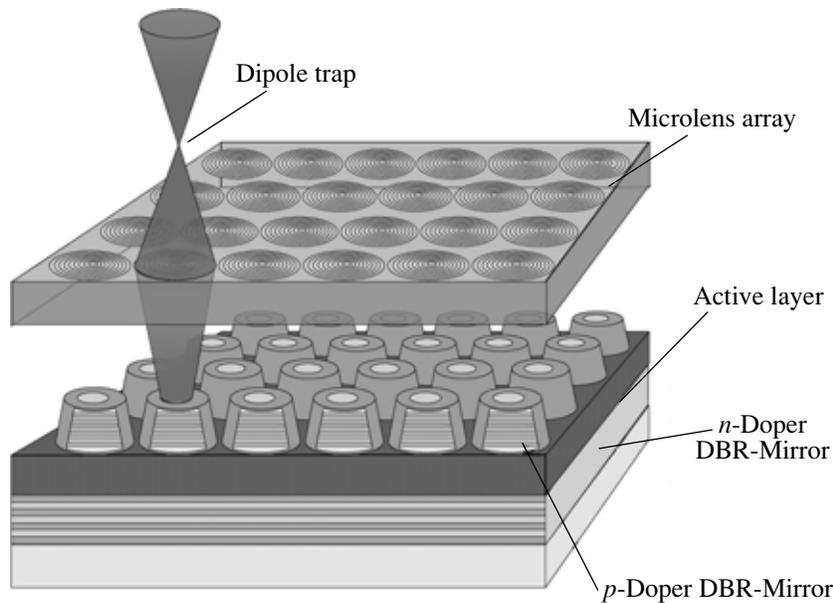
Fig. 6. Integration of microoptical components and laser sources. An array of vertical cavity surface emitting lasers (VCSELs) illuminates a microlens array with matched lens separation. Each trap of the resulting two-dimensional array of dipole traps can be individually switched on and off because the individual VCSELs are selectively addressable.

tion, in order to inscribe the required phase shift. Especially well suited is this configuration also for quantum gates based on the dipole-dipole interaction of low-lying Rydberg states in constant electric fields, as proposed in [7].

5. INTEGRATION

The huge potential for integration of microoptical components can be used for quantum information purposes. Due to their large numerical aperture, microoptical components can also be used for efficient spatially resolved read-out of quantum information (Fig. 5). In most cases the state of a qubit is recorded by exciting the atom state-selectively with resonant light and collecting the fluorescence light. Microoptical components can be used for the collection optics. Furthermore, the optical detection of quantum states with microoptical components is not restricted to optical trapping structures (Fig. 5a): Since the same techniques are applied for the fabrication of microoptical components and microstructured wires on surfaces, microoptical components can be easily combined with the magnetic and electric structures of [9–16] (Fig. 5b). In addition, microfabricated atom-optical components can be integrated with optical fibres and waveguides so that quantum information after being read-out by detection of the scattered light can be further processed by optical means (Fig. 5c).

Another canonical extension is given by the integration of microoptical components with optoelectronic devices such as semiconductor laser sources and photodiode detectors. In this case, the communication with

the outside world can take place fully electronically, with the required laser light created *in situ* and the optical signals converted back to electrical signals on the same integrated structure. Figure 6 illustrates a simple but powerful configuration based on this approach. The depicted setup utilizes vertical cavity surface emitting lasers (VCSELs) [19, 29, 30] which are directly mounted onto a two-dimensional microlens array. VCSELs emit circular symmetrical non-astigmatic beams while their structure is optimized for the lithographic fabrication of densely packed 2D arrays. Since VCSELs generally emit a single longitudinal mode at a wavelength which can be tuned by changing the current, the light coming from a two-dimensional array of VCSELs can be directly focused by the microlens array to create a two-dimensional array of stable dipole traps (Fig. 6). With VCSELs it becomes now possible to selectively switch on and off individual traps or to selectively change their potential depth resulting in further flexibility in the atom manipulation.

6. CONCLUSION

In this paper we have discussed the new research direction of using microfabricated optical elements for quantum information processing with neutral atoms. This application hugely benefits from the many inherent advantages of microoptical components. Specifically, this approach addresses two of the most important requirements for the technological implementation of quantum information processing: parallelization and scalability. In addition, the possibility to selectively address individual qubits is essential for most schemes

proposed for quantum computing with neutral atoms. Thus, all steps required for quantum information processing with neutral atoms, i.e., the preparation, manipulation and storage of qubits, entanglement and gate operations as well as the efficient read-out of quantum information, can be performed using microfabricated optical elements.

ACKNOWLEDGMENTS

REFERENCES

1. Steane, A.M., 1998, *Rep. Prog. Phys.*, **61**, 117; Gruska, J., 1999, *Quantum Computing* (London: McGraw-Hill); 2000, *The Physics of Quantum Information*, Bouwmeester, D., Ekert, A., and Zeilinger, A., Eds. (Berlin: Springer).

2. 2000, Special Issue of *Fortschr. Phys.*, **48**, issues 9–11.

3. Monroe, C., Meekhof, D.M., King, B.E., Jeffers, S.R., Itano, W.M., Wineland, D.J., and Gould, P., 1995, *Phys. Rev. Lett.*, **74**, 4011.

4. Hagley, E., Maître, X., Nogues, G., Wunderlich, C., Brune, M., Raimond, J.M., and Haroche, S., 1997, *Phys. Rev. Lett.*, **79**, 1.

5. Jaksch, D., Briegel, H.J., Cirac, J.I., Gardiner, C.W., and Zoller, P., 1999, *Phys. Rev. Lett.*, **82**, 1975.

6. Brennen, G.K., Caves, C.M., Jessen, P.S., and Deutsch, I.H., 1999, *Phys. Rev. Lett.*, **82**, 1060.

7. Jaksch, D., Cirac, J.I., Zoller, P., Rolston, S.L., Côte, R., and Lukin, M.D., 2000, *Phys. Rev. Lett.*, **85**, 2208.

8. DiVincenzo, D.P., 2000, *Fortschr. Phys.*, **48**, 9.

9. Weinstein, J.D. and Libbrecht, K.G., 1995, *Phys. Rev. A*, **52**, 4004.

10. For an overview of early experimental work see: Hinds, E.A. and Hughes, I.G., 1999, *J. Phys. D: Appl. Phys.*, **32**, R119.

11. Schmiedmayer, J., 1998, *Eur. Phys. J. D*, **4**, 57; Folman, R., Krüger, P., Cassettari, D., Hessmo, B., Maier, T., and Schmiedmayer, J., 2000, *Phys. Rev. Lett.*, **84**, 4749.

12. Reichel, J., Hänsel, W., and Hänsch, T.W., 1999, *Phys. Rev. Lett.*, **83**, 3398; Hänsel, W., Reichel, J., Hommel-hoff, P., and Hänsch, T.W., 2001, *Phys. Rev. Lett.*, **86**, 608.

13. Müller, D., Anderson, D.Z., Grow, R.J., Schwindt, P.D.D., and Cornell, E.A., 1999, *Phys. Rev. Lett.*, **83**, 5194.

14. Dekker, N.H., Lee, C.S., Lorent, V., Thywissen, J.H., Smith, S.P., Drndić, M., Westervelt, R.M., and Prentiss, M., 2000, *Phys. Rev. Lett.*, **84**, 1124.

15. Engels, P., Ertmer, W., and Sengstock, K. (in preparation).

16. Key, M., Hughes, I.G., Rooijakkers, W., Sauer, B.E., and Hinds, E.A., 2000, *Phys. Rev. Lett.*, **84**, 1371.

17. Birkl, G., Buchkremer, F.B.J., Dumke, R., and Ertmer, W., 2001, *Opt. Commun.*, **191**, 67.

18. 1997, *Micro-Optics*, Herzig, H.P., Ed. (London: Taylor and Francis).

19. Sinzinger, S. and Jahns, J., 1999, *Microoptics* (Weinheim: Wiley-VCH).

20. Kuppens, S., Rauner, M., Schiffer, M., Wokurka, G., Slawinski, T., Zinner, M., Sengstock, K., and Ertmer, W., 1996, in *TOPS VII*, Burnett, K., Ed. (Washington: OSA); Schiffer, M., Rauner, M., Kuppens, S., Zinner, M., Sengstock, K., and Ertmer, W., 1998, *Appl. Phys. B*, **67**, 705; Bongs, K., Burger, S., Dettmer, S., Hellweg, D., Arlt, J., Ertmer, W., and Sengstock, K., 2001, *Phys. Rev. A*, **63**, 031602.

21. Boiron, D., Michaud, A., Fournier, J.M., Simard, L., Sprenger, M., Grynberg, G., and Salomon, C., 1998, *Phys. Rev. A*, **57**, R4106.

22. Boiron, D., Mennerat-Robilliard, C., Fournier, J.M., Guidoni, L., Salomon, C., and Grynberg, G., 1999, *Eur. Phys. J. D*, **7**, 373.

23. Ozeri, R., Khaykovich, L., and Davidson, N., 1999, *Phys. Rev. A*, **59**, R1750.

24. Klimov, V.V. and Letokhov, V.S., 1995, *Opt. Commun.*, **121**, 130.

25. Chu, S., Bjorkholm, J.E., Ashkin, A., and Cable, A., 1986, *Phys. Rev. Lett.*, **57**, 314.

26. Grimm, R., Weidemüller, M., and Ovchinnikov, Y.B., 2000, *Adv. At. Mol. Opt. Phys.*, **42**, 95.

27. Dumke, R., Müther, T., Volk, M., Buchkremer, F.B.J., Birkl, G., and Ertmer, W. (in preparation).

28. Kasevich, M. and Chu, S., 1991, *Phys. Rev. Lett.*, **67**, 181.

29. Iga, K., Koyama, F., and Kinoshita, S., 1988, *IEEE J. Quantum Electron.*, **24**, 1845.

30. Jewell, J.L., Harbison, J.P., Scherer, A., Lee, Y.H., and Florez, L.T., 1991, *IEEE J. Quantum Electron.*, **27**, 1332.