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## Near field diffraction grating for atoms

V.I. Balykin, D.A. Lapshin, M.V. Subbotin, V.S. Letokhov<sup>1</sup>*Institute of Spectroscopy, Russian Academy of Sciences, Troitsk 142092, Moscow Region, Russian Federation*

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### Abstract

We propose to use the periodic light potential of an evanescent light wave produced on the surface of a dielectric prism and modulated through the absorption in parallel metal strips applied onto the dielectric surface as a diffraction grating and a coherent beam splitter for a precooled atomic beam. We have measured the spatial intensity distribution of the near field over the surface of such a microstructure using a photon scanning tunnelling microscope. The microstructure with a period of 10  $\mu\text{m}$  was formed by nickel grooves 40 nm thick and 3  $\mu\text{m}$  wide fabricated on the quartz surface. The possibility of coherent splitting of a precooled atomic beam into components of approximately the same intensity with an angular splitting of a few milliradians is shown using the semiclassical approach. © 1998 Elsevier Science B.V.

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### 1. Introduction

The transfer of a momentum to an atom by a quasisonant laser light is being widely used nowadays in atomic optics experiments. Numerous de Broglie wave optics elements, such as atomic mirrors, lenses, waveguides, and interferometers [1–6] have been developed on the basis of various laser field configurations. The interest in such interferometers is due to their enormous sensitivity combined with a number of other advantages over electron and neutron interferometers. The development of an atomic interferometer would help to perform many fundamental experiments associated with quantum physics, measurement theory, field theory, and so on. The key element of an atomic interferometer is a coherent beam splitter of an atomic beam which creates two beams forming the interferometer arms. Various types of beam splitters have been demonstrated experimentally. These include devices using a running wave [7], the optical Stern-Gerlach effect [8], stimulated Raman transitions [9], a modulated atomic mirror [10], and magneto-optical atomic interaction [11]. The diffraction of a thermal atomic beam propagating through

a standing light wave at normal angle to the wave vector was demonstrated in Ref. [12]. But the angular resolution of the diffraction orders in these experiments was as small as  $10^{-5}$  rad because the momentum transferred by light to the atoms was small in comparison with the thermal motion momentum. The authors of Ref. [13] attempted to improve this parameter by replacing the sinusoidal grating with a triangular optical potential similar to the conception of a blazed grating. Another, most promising way to increase the diffraction angles of a thermal atomic beam is to use a scheme whereby atoms are incident at a grazing angle on an evanescent standing light wave and undergo reflection and diffraction by the periodic light potential [14]. The diffraction angles attained in that case are large (comparable with the grazing angle of incidence of the atomic beam) and depend solely on the de Broglie wavelength of the incident atoms and the groove period. Evanescent wave frequency and, consequently, the evanescent standing wave period is determined by the resonant frequency of the atom transition used.

However, the detailed theoretical analysis of this scheme carried out by a number of authors [14–16] has shown that any substantial filling of the nonzero diffraction orders in the case of thermal beams requires high power of the laser producing the evanescent light wave. The process of atom

<sup>1</sup> Corresponding author. E-mail: letokhov@lls.isan.troitsk.ru.

diffraction by a standing evanescent wave in momentum representation is explained by the Raman-like process when the atom redistributes an even number of photons between the propagating and counterpropagating parts of the standing wave. This process is out of resonance due to the double Doppler shift which suppresses the coupling between these two channels and hence diminishes the population of nonzero diffraction orders [15,17]. In other words, the periodic potential of the standing evanescent light wave is averaged over the classical atomic trajectory which in the case of grazing incidence intersects many potential minima and maxima [16]. To eliminate the adverse influence of the Doppler effect, the authors of Ref. [17] used a bichromatic evanescent wave: the nodes of the light potential formed by it moved over the surface of the dielectric in the same direction as the atoms and with a velocity close to that of the latter. Another way to solve this problem is to increase the period of the light potential, which would make it possible to increase appreciably the filling of the diffraction orders.

In this paper, we propose a new method of forming the evanescent electric field potential for the diffraction of neutral atoms.

The paper is designed as follows. Section 2 gives a description of the new diffraction grating scheme. In Section 3, we present the results of direct photon scanning tunnelling microscope (PSTM) measurements of the intensity of the evanescent wave over the surface of the grating described in Section 2. Next, in Section 4, we show the possibility of using the spatially modulated evanescent wave grating described as a coherent atomic beam splitter by presenting the results of our analysis of the process of diffraction of de Broglie atomic waves by the periodic potential measured.

## 2. Main idea

Most generally our proposal is based on the possibility to form an evanescent light field by means of a periodic surface microstructure. One of the possible ways to implement this approach is illustrated in Fig. 1. The periodic microstructure is formed by parallel metal strips on the surfaces of a quartz prism in the same way as in the case of an ordinary optical reflective diffraction grating. The laser beam propagates inside the prism at an angle equal to that of total internal reflection. The evanescent wave is formed on the surface of the grating on the side of the incident atomic beam. The intensity of the evanescent wave depends exponentially on the distance to the surface [1]. Over the metal grooves of the grating a strong reduction of the evanescent wave intensity as a result of light absorption by the metal must be observed. Thus, at the surface of the prism an intensity-modulated light field is formed with a period equal to that of the surface microstructure.

## 3. Experimental study of modulated evanescent wave

Mie scattering of the evanescent light wave by the elements of the microstructure located on the dielectric–vacuum interface may give rise to propagating photons [18]. The short-range atom–evanescent wave interaction potential may be spoiled by these propagating photons which may induce the diffuse scattering of atoms. In other words, these photons add a long-range component to the short-range interaction potential, which may make the latter unsuitable as a phase transparency for atomic de Broglie waves. This circumstance has impelled us to measure the evanescent wave intensity directly using an apertureless photon scanning tunnelling microscope. We have used an apertureless nonmetallized probe, for it causes less distortion of the field under study. All our measurements were fulfilled using a tip with curvature radius of 0.1  $\mu\text{m}$ , as estimated using the replica method [19].

To test the validity of using the microscope to study the evanescent wave, we have investigated the spatial intensity distribution of a standing evanescent wave. The experiment is schematically illustrated in Fig. 2a. A He-Ne laser beam undergoes total internal reflection at the quartz–air interface, leaves the prism, and comes back, being reflected from a plane metal mirror. Thus, two evanescent waves propagate in the forward and backward directions over the quartz surface of wavelength  $\lambda$ , which form a partial standing wave with the period

$$d = \frac{\lambda}{2n \sin(\theta)}, \quad (1a)$$

where  $n$  is the refractive index of quartz and  $\theta$  is the angle of incidence of light. At  $n = 1.5$  and  $\theta = 45^\circ$  the distance between the nodes of the standing wave with  $\lambda = 633$  nm amounts to some 300 nm. When the apex of the probe is immersed into the evanescent wave, the non-propagating near-field is transformed into propagating modes by scat-

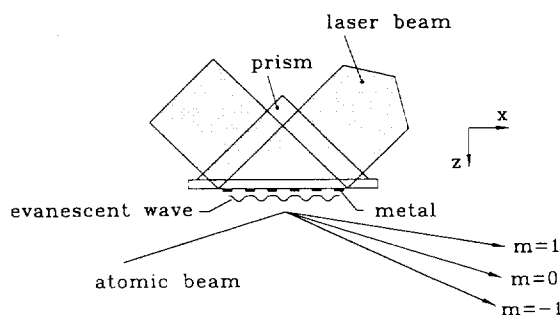


Fig. 1. Near-field grating for atoms. A periodic microstructure in the form of metal strips (reflection grating) is fabricated on the surface of a dielectric. In the case of total internal reflection of the laser field, a periodic evanescent light wave is formed on the dielectric surface due to strong absorption of light in the metal grooves.

tering on the apex of the tip, as described by Vigoureux et al. [20]. The propagating photons are detected by the photomultiplier tube at the other end of the fiber. The tip of the fiber is fixed to the piezotube, thus the distance tip–sample may be regulated in the micrometer range. The sample is scanned relative to the tip using a piezoscanner. The scanning range of our microscope is of  $15 \times 15 \mu\text{m}$ . More detailed information on the design of our custom-made microscope can be found elsewhere [19].

Fig. 2b presents the evanescent wave intensity distribution obtained with the aid of the photon scanning tunnel microscope. When taking measurements, a constant distance of 50 nm was kept between the probe and the quartz surface. As one would expect, the signal profile is of sinusoidal shape, its period corresponding to Eq. (1a). The local irregularities in the image are due to the external mechanical perturbations that occurred in the course of scanning. The increase of the period of the structure from the left to the right results from the nonlinearity of the piezoelectric scanning device.

To illustrate the evanescent character of the near field we have carried out also the measurement of the dependence of the intensity of the optical signal on the distance tip–surface. In Fig. 2c the result of the measurement when scanning the tip in the direction normal to the surface is shown. The characteristic decay length of the evanescent wave for the quartz–vacuum interface is defined by

$$A(\theta) = \frac{\lambda}{2\pi\sqrt{n^2 \sin^2(\theta) - 1}}. \quad (1b)$$

Using the experimental parameters defined above, we estimate  $A$  to be 300 nm. The intensity of the evanescent wave represented in the Fig. 2c is proportional to the square of the field amplitude. So the measured decay length should be equal to  $A/2 = 150$  nm. That is in a good agreement with observed value. The exponential character of the curve in Fig. 2c together with the image in Fig. 2b demonstrate the microscope ability to measure the intensity of the evanescent wave in each direction.

The measurement of the evanescent wave intensity over the microfabricated metal–dielectric structure is illustrated in Fig. 3a. The He-Ne laser beam is incident at an angle greater than the critical value upon the grating through the prism which is conjugated to the grating substrate by a thin layer of oil to minimize light scattering. The diffraction grating under study was fabricated by the method of photolithography. It consists of Ni strips on a quartz substrate. The strips 40 nm thick and 3  $\mu\text{m}$  wide form a grating with a period of 10  $\mu\text{m}$ .

The intensity distribution of the evanescent field over the grating is presented in Fig. 3b. The wave vector of the evanescent wave (s polarization) is perpendicular to the plane of incidence and is parallel to the surface. The probe substrate distance was kept at 40 nm. As one can see, the profile of the diffracted field is periodic in the  $X$ -direction,

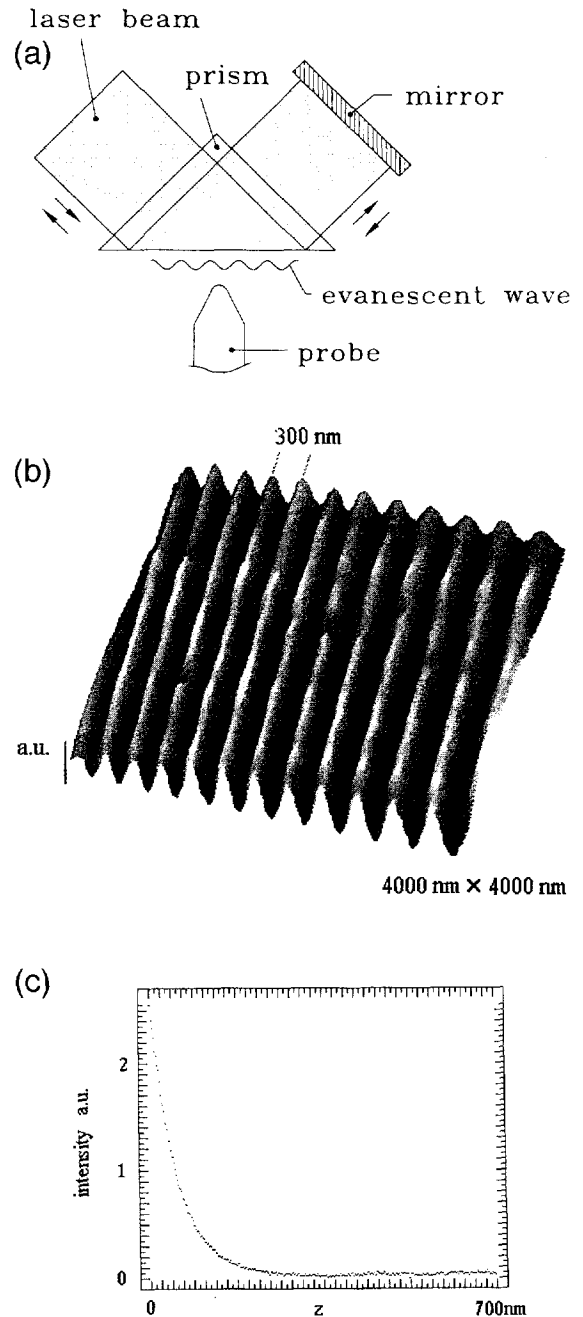


Fig. 2. (a) Experimental arrangement for studying the intensity of the evanescent standing light wave over the quartz surface. The incident and reflected beams generate two counter-propagating waves on the prism surface, which interfere to form the standing evanescent wave. (b) Intensity distribution of the evanescent standing wave measured with a photon scanning tunnel microscope (PSTM). (c) Evanescent wave intensity in the direction normal to the surface of the prism as measured by PSTM.

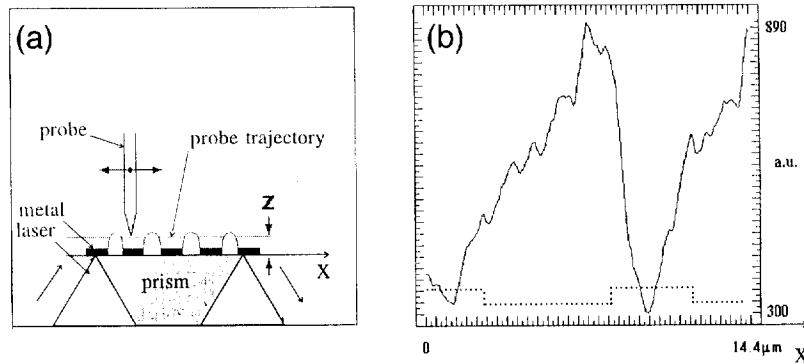


Fig. 3. (a) Experimental arrangement for studying the intensity of the modulated evanescent wave over the metal grating. (b) PSTM intensity profile of the evanescent field over the surface of the diffraction grating. The dotted line shows an approximate topographic profile of the surface microstructure. Scanning height is around 40 nm above the microstructure substrate.

with a period of  $d = 10 \mu\text{m}$ . The profile shape is asymmetric as a result of transformation of the spatial frequency spectrum of the evanescent wave field. This effect was discussed in detail in Ref. [21]. The ratio between the intensity variation and the maximum intensity value amounts to around 40%.

The small spatial oscillations of the signal observed are associated with the presence of propagating modes in the diffracted light field. To minimize distortions, we used an apertureless probe. This means that the probe tip was not coated, i.e., there was no submicrometer-size aperture at the probe apex. In that case, light quanta could also find their way into the probe via the lateral surface of the tip cone to be detected by the photomultiplier. Hence the photomultiplier signal is proportional to the sum of the near- and far-field intensities. The interference pattern may be formed if the period of the grating is greater than the light wavelength. These interference patterns are represented by the ripples in Fig. 3b. Since ripples do not reflect the true near-field profile, these oscillations were not taken into account in further calculations.

In another possible configuration of the atom diffraction experiment the plane of incidence of light is parallel to the grooves of the surface grating while the atoms move as previously described. As discussed in Ref. [18] the intensity profile of the near field in this case has symmetric appearance. But the analyses of the atom diffraction problem show (see Section 4) that the form of a single period of a near field light potential plays a minor role on the diffraction pattern in the case of grazing incident angles in contrast to the blazed grating in classical optics. Therefore we constrict our consideration of the configuration of Fig. 1.

Thus, on the surface of the prism a light field decaying exponentially with the increasing distance from the surface was observed, the characteristic decay length of the field amounting to 300 nm (at an angle of incidence of  $45^\circ$ ) and intensity varying periodically in a direction normal to the

ruling of the grating. We propose to use such a two-dimensional light field intensity distribution varying periodically in one direction as a diffraction grating for atomic de Broglie waves.

#### 4. Diffraction of atoms by the modulated evanescent wave

Let us use the results presented in Ref. [16] to study the diffraction pattern arising in the case of a beam of sodium atoms incident on the diffraction grid described above. In contrast with the standing evanescent wave, the period of the grating formed by a modulated evanescent field is independent of the wavelength of the laser used to produce the evanescent wave, hence independent of the chemical element used for diffraction. In our case, the period  $d$  of the grating is  $10 \mu\text{m}$ , which is approximately 30 times that in the case of a grating formed by a standing evanescent wave. The Doppler frequency shift preventing effective filling of the nonzero diffraction orders is reduced accordingly. The angular distribution of diffraction maxima can easily be obtained proceeding from the assumption that the atom experiences no spontaneous decays during the time it interacts with the light grating, i.e., the mechanical energy of the atom remains unchanged. The deflection angle  $\alpha_n$  of the  $n$ th diffraction order (in a plane normal to the surface of the prism) can easily be found from the equality of the kinetic energies of the atoms in the zeroth and  $n$ th diffraction orders (without regard for a small recoil effect):

$$\alpha_n \approx \sqrt{\alpha_i^2 - \frac{n\hbar \Delta_D}{E_k}}, \quad n \text{ integer}, \quad (2)$$

where  $\alpha_i$  is the angle between the incident beam and the grating plane,  $E_k$  is the kinetic energy of atoms having mass  $M$  and moving with velocity  $v$ , and  $\Delta_D = (2\pi/d)v \cos(\alpha_i)$  is the Doppler shift. When using a beam

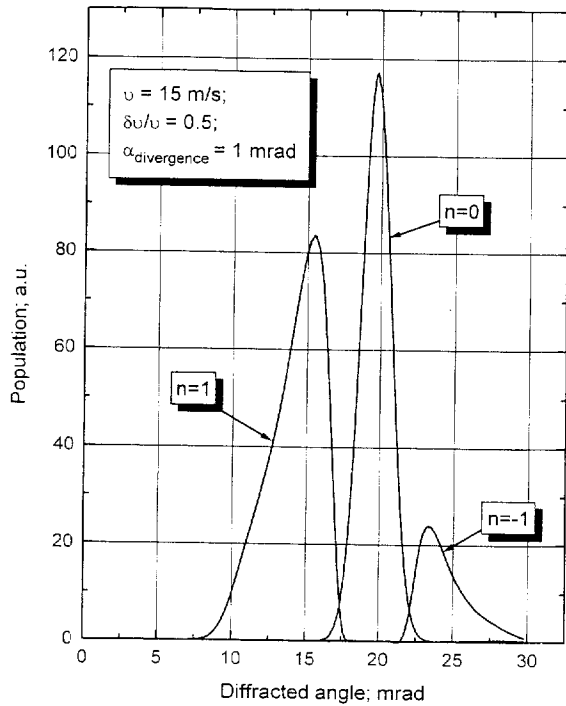


Fig. 4. Angular intensity distribution pattern of the atomic flux diffracted by the modulated evanescent wave. For an evanescent wave laser power of 1 W and spot area of  $10^{-3}$  cm<sup>2</sup>, the ratio between the populations of the diffraction orders  $n = 1, 0,$  and  $-1$  is 3:3:1. The divergence of the incident beam ( $\alpha_{div} = 1$  mrad) governs the final angular width of the zeroth maximum and, together with the nonmonochromaticity of the beam ( $\Delta v/v = 0.5$ ), the width and shape of the nonzero maxima.

of sodium atoms preliminary retarded to a velocity  $v = 15$  m/s by means of the spontaneous light pressure force [22], the angle between the directions to the zeroth and the first diffraction maxima amounts to around 4 mrad (see Fig. 4).

To compute the wave function  $\psi_{\text{farfield}}(\mathbf{r}, \mathbf{p})$  of a diffracted atom at a great distance from the diffraction grating, we used the method suggested in Ref. [16], based on the extension of the atomic wave function  $\psi(\mathbf{r}_f)$  known on some surface into the surrounding space using the Huygens-Fresnel principle.

Since the light potential is a periodic function on one of the coordinates, it then follows that the atom wave function can be represented as a series of states associated with diffraction orders ([16], Appendix B):

$$\psi_{\text{farfield}}(\mathbf{r}) = \sum_{n=-\infty}^{\infty} a_n \exp\left(\frac{i}{\hbar} \mathbf{p}^{(n)} \mathbf{r}\right), \quad (3)$$

where  $a_n$  is the amplitude associated with the  $n$ th diffrac-

tion order and  $\mathbf{p}^{(n)}$  is the momentum of the atom occupying this order [16]:

$$a_n = \frac{1}{2d} \int_0^d dx_f \left[ 1 + \frac{p_{f,z}(x_f)}{p_z^{(n)}} \right] \psi(\mathbf{r}_f) \exp\left(-\frac{i}{\hbar} p^{(n)} r_f\right), \quad (4)$$

and  $\mathbf{r}_f$  belongs to a plane parallel to the grating and removed from it to a distance at which the atom-grating interaction can be disregarded (usually of the order of a few  $\lambda$ ). The wave function

$$\psi(\mathbf{r}_f) = \exp\left[\frac{i}{\hbar} S(\mathbf{r}_f | \mathbf{p}_i)\right] \quad (5)$$

was calculated by numerically integrating the equations of atomic motion in the two-dimensional periodic potential and determining the classical action along the trajectory  $S(\mathbf{r}_f | \mathbf{p}_i) = \mathbf{p}_i \mathbf{r}_i + \int_{t_i}^{t_f} L[\mathbf{r}(t), \dot{\mathbf{r}}(t)] dt$ , depending on the initial atomic momentum  $\mathbf{p}_i$  ( $L[\mathbf{r}(t), \dot{\mathbf{r}}(t)]$  is the Lagrangian of an atom; see Eq. (3) in Ref. [16]). The potential was in turn found from the experimentally measured intensity distribution of the modulated evanescent wave. The experimental curve (Fig. 3b) was in that case approximated by a periodic piecewise linear function. One can see from Eqs. (3)–(5) that in the case of grazing angles of incidence no nonzero diffraction order becomes populated because of the averaging of the periodic light potential variations along the trajectory of the atom which during the time it interacts with the evanescent wave,  $\tau = A(\theta)/\pi v \sin(\alpha_i)$  crosses  $N = v \cos(\alpha_i) \tau / d = A(\theta) / \pi d \tan(\alpha_i)$  potential periods. Obviously the noticeable diffraction splitting of the atomic beam will take place if

$$N \leq 1, \quad (6)$$

and the variations of the function  $S(\mathbf{r}_f | \mathbf{p}_i)$  in the case of normal incidence are

$$\delta S(\mathbf{r}_f | \mathbf{p}_i) \cong \pi \hbar. \quad (7)$$

Note that given the above assumptions, condition (6) contains no velocity of the incident atom and yields  $\alpha_i \geq 15$  mrad for the beam of sodium atoms at  $A = \lambda/2$  ( $\theta \approx 42^\circ$ ). The spatial Fourier transform of the potential measured by us contains harmonics with high multiple spatial frequencies, and generally speaking, their effect on the diffraction pattern may become noticeable provided that conditions similar to (6) and (7) are satisfied with the appropriate period  $d^{(m)} = d/m$  i.e., at angles of incidence of

$$\alpha_i \geq \frac{A}{\pi d/m}, \quad (8)$$

where  $m = 1, 2, \dots$  is the serial number of the spatial potential harmonic with a spatial frequency  $\omega^{(m)} = 2\pi m/d$ . At angles of incidence greater than defined by (8) for  $m = 1$ , the distribution pattern of the diffraction order

population changes greatly, the relative variations of the incidence angle  $\delta\alpha_i/\alpha_i$  being small.

The positive laser frequency detuning  $\delta$  necessary for the laser radiation power to have the required magnitude is chosen such that the total probability  $p_{\text{spont}}(\delta)$  that the atom will make a spontaneous transition during the time it interacts with the laser light of the evanescent wave is small:

$$p_{\text{spont}}(\delta) \approx \frac{MA\Gamma}{\hbar\delta} v \sin(\alpha_i), \quad (9)$$

where  $\Gamma$  is the natural linewidth. For sodium atoms,  $\Gamma = 10$  MHz, and at  $\delta = 1.5$  GHz,  $p_{\text{spont}}(\delta) \approx 0.1$ .

Fig. 4 presents the results of our calculations by the above scheme of  $|a_n|^2$  and the angular distribution of the diffracted atomic beam at the laser radiation parameters listed above for  $\alpha_i = 19.5$  mrad in the case of an atomic beam with a nonmonochromaticity of  $\Delta v/v = 0.5$  and initial divergence of  $\alpha_{\text{div}} = 1$  mrad. It is seen that the coherent splitting of a retarded atomic beam into several beams of approximately the same intensity is possible at quite realistic powers ( $\leq 1$  W) of the laser beam focused into a spot 0.5 mm across. Specifically, the ratio between the fluxes in the zeroth and the first diffraction maxima is around 1.

Note that the diffraction of atoms is different from that of light. In contrast to light, an atom has a quadratic dispersion relation in vacuum and has a zero normal velocity point as a result of the interaction with the evanescent wave potential. Under a certain initial condition this leads to a nonsinusoidal atom phase distribution on the surface of the diffraction grating. So the spatial Fourier transform of the atom wave function phase distribution contains many harmonics. This is similar to the case of a blazed diffraction grating for light when a nonsinusoidal profile of the groove gives rise to the asymmetric diffraction pattern.

The peaks corresponding to higher diffraction orders ( $n = \pm 2, \pm 3, \dots$ ) contain about 10% of the initial atomic flux. In addition, at this value of nonmonochromaticity of the incident beam they have a very broad distribution and hence the intensity of each peak is negligible as compared to those presented in Fig. 4.

## 5. Conclusions

We propose a new coherent beam splitter scheme based on the diffraction splitting of the atomic beam by means of a diffraction grating in the form of a modulated evanescent wave produced on a surface of a prism as a result of absorption in parallel metal strips applied onto it at regular intervals. The direct measurements of the light field intensity near the surface showed that there actually existed over the surface an evanescent wave with an amplitude decreasing exponentially with increasing distance from the

surface and varying periodically in a direction normal to the metal strips. An advantage of this scheme is based on the fact that the period of the diffraction grating formed by the evanescent wave is independent of the frequency of the laser light used to produce it. This makes it possible to select the period of the grating to optimize the ratio of the populations of the splitted beams. By using such a grating with a period in excess of that of the standing light wave whose frequency is quasioresonant with respect to the atomic transition frequency, one can substantially reduce the Doppler shift which prevents the observation of the thermal atomic beam diffraction by the standing evanescent wave.

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