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GENERATION OF FRACTIONAL OPTICAL VORTICES

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We have made a theoretical modeling of the evolution of a monochromatic Gaussian beam diffracted by the angle formed by three sides of the phase wedge different types. We have found that the edges of the phase wedge generate macroscopic chains of identical optical vortices that disappear at the far field zone. At the same time, the π -phase plate can reproduce a very complex wave field whose structure depends on the scale of observation. At large scales there appear two π -cuts resembling broken edge dislocations with perpendicular directions. At small (some microns) scales two short vortex chains consisting of alternating-sign optical vortices are nucleated near the corner of the wedge. The analysis shows that the sizes of the chains decrease quickly when approaching the wedge surface. This enables us to assume that the π -phase plate can create so-called optical quarks in the evanescent waves of the edge field.
On the basis of theoretical considerations experiment was conducted in which were obtained fractions optical vortices at the edge of the phase wedge.
Keywords: phase wedge, optical vortex, optical quark.

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1. INTRODUCTION

It is well known [1] that the diffraction process reproduces geometry of the edges of obstacle that scatters incident monochromatic beam. For example, a straight edge of a slab-sided phase plate begets a set of rectilinear diffracted maxima and minima parallel to the edge. However, even a very small disturbance of slab-sidedness leads inevitably to breaking the former symmetry down. There appears a new, hidden symmetry of the diffracted field, structural sells of which are optical vortices. Indeed, a slab-sided phase plane turns into a phase wedge, while the rectilinear diffracted maxima and minima are transformed into chains of optical vortices along the wedge brink [2–4]. The nature of such threaded vortex structure is rather simple. The brink of the wedge tears the wave front out, whereas the slope of the wedge medium entails smooth phase changing. If we go around some axis perpendicular to the wedge base, though passing through the wedge brink along a closed contour, we will find that the phase incursion can reach the value 2π at a definite contour radius. This is a necessary condition for nucleating an optical vortex with an integer topological charge at the corresponding site of the wave front in the propagating beam. Since the extension of the wave front is much larger than the wavelength of the incident light, a whole chain of identical optical vortices will spring up at the wave zone of the diffracted beam.

Generally speaking, the phase wedge can be treated as an involute of a spiral phase plate [2] for generating optical vortices. However, such an involute presupposes a presence of all four edges of the wedge. It is these edges that bring additional perturbations into the symmetry of the diffracted beams in the shape of hidden chains of the optical vortices. As a rule, such additional vortex chains can stretch over comparatively short lengths (several wavelengths), being got lost in the general diffraction pattern.

However, sometimes they come to the foreground, breaking the basic diffraction pattern down. This takes place, e.g., when the optical vortices with fractional topological charges are generated. Some fragments of this phenomenon have been considered by Berry [5] on the example of a spiral wave plate with a fractional topological charge. The fact is that the spiral phase plate with the phase step being equal to a multiple of 2π is intended for shaping integer-order optical vortices [6]. It would have been logical to assume that the spiral phase plate could generate the fractional-order optical vortices. As far back as in 1995 Soskin has shown [7] that computer-generated optical vortices can bear fractional topological charges, though remaining structurally unstable, while Berry [6] has described destruction of the fractional-order vortices into chains of integer order optical vortices in the Gaussian beam evolving in the free space. Recently it has been shown that the phase singularities can nevertheless exist at sufficiently large distances in so-called error function beams [8].

The aim of the present study is to trace the evolution of the vortex chains in the beam diffracted by the edges of the optical wedge, including the angles of slab-sided phase plates, which originate from nucleation of the fractional-order optical vortices.

1. GAUSSIAN BEAM DIFFRACTED BY THE PHASE WEDGE

Let us consider a monochromatic Gaussian beam passing through a transparent dielectric phase wedge (with the refractive index n_w) lodged in a vacuum as shown in Fig. 1, a and b. The phase wedge is characterised by the two angles α and β and the basic height h. The axis of the Gaussian beam is directed along the verge of the wedge.

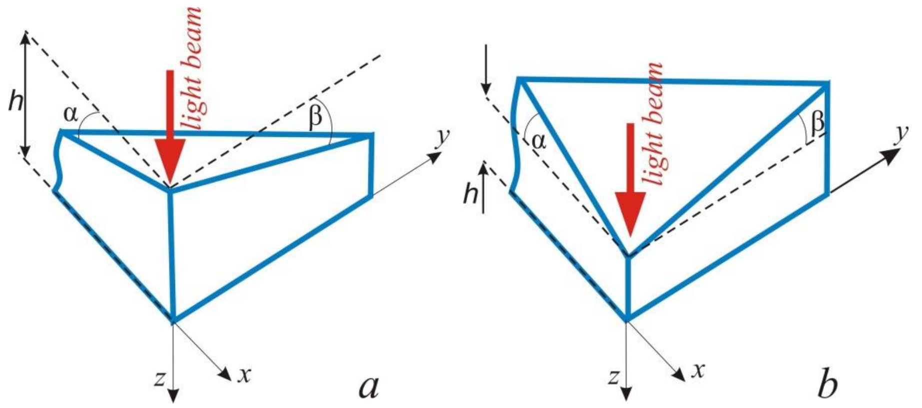

Fig. 1. Different types of phase wedges: (a) $\alpha, \beta > 0$, (b) $\alpha, \beta < 0$.

We deal in fact with five principal waves: two waves are reflected by the wedge along the x and y directions, one of them passes through the free space, and the remaining two are boundary waves diffracted by the two wedge brinks. Typical diffraction patterns for different wedges (see Fig. 1, a, b) are shown in Fig. 2. Far from the verge of the wedge (at $x = y = 0$), the diffraction pattern is shaped by only three waves: a free propagating wave, a reflected one, and a boundary wave diffracted by the wedge brink (at either $x = 0$ or $y = 0$). We observe here two sets of identical optical vortices along the brinks of the wedge. The principal condition for shaping a vortex is that the pass-by along a circle of radius 0 r around the vortex axis must get the phase incursion equal to 2π. In fact, the boundary wave forms a set of parallel lines of equal phases and amplitudes. The two other waves also form a set of such lines which are inclined at some angle with respect to the first ones. The vortex is nucleated when the amplitudes of these two wave combinations are the same and the phase difference is equal to π. However, the mutual tilt of the equiphase lines results in perturbing the vortex form, the vortex becoming the elliptical one. In order to flatten the vortex shape, the radius 0 r of the pass-by and the beam waist radius 0 w are to be equal to each other.

The structure of the beam field near the verge (at $x = y = 0$) is defined by the phase $\Delta\Phi$ and the signs of the angles α and β (see the framed patterns in Fig. 2).

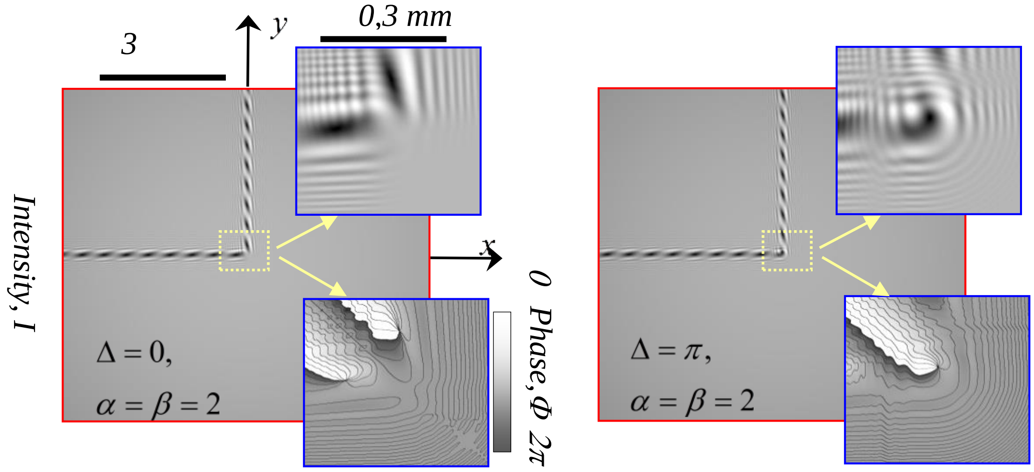

Fig. 2. Distributions of intensity I and phase Φ after diffraction of the Gaussian beam by the phase wedge with the equal angles $\alpha = \beta$ between the verges ($z = 0.1$ mm and $w_0 = 1$ mm).

2. SLAB-SIDED PHASE PLATE

An ordinary slab-sided phase plate is a habitual optical element used, as a rule, in optical interferometers or similar devices for introducing desirable phase differences. However, in our case the slab-sided phase plane manifests unusual properties.

A typical pattern for the Gaussian beam diffracted by the verge $x = y = 0$ of the π -phase plate is shown in Fig. 3. It seems at the first glance that the black lines along the brinks $x = 0$ and $y = 0$ of the plate are two broken edge dislocations with orthogonal directions and the origin located at the point $x = y = 0$. However, the beam field at a small scale (see the framed pictures in Fig. 3) turns out to be of a complicated singular structure. There are two short vortex chains near the beam axis. The distance between two neighbouring vortices shortens quickly as the coordinates along the x and y axes increase. The vortex chains vanish far from the beam axis and the equiphase lines smooth gradually out. *This means that the π -phase plate can never introduce the exact π -phase shift into the beam (i.e., an edge dislocation), even in a purely theoretical case*. The latter represents a result of the edge effect.

When the beam is propagating, the singular structure does not change, as shown in Fig. 4.

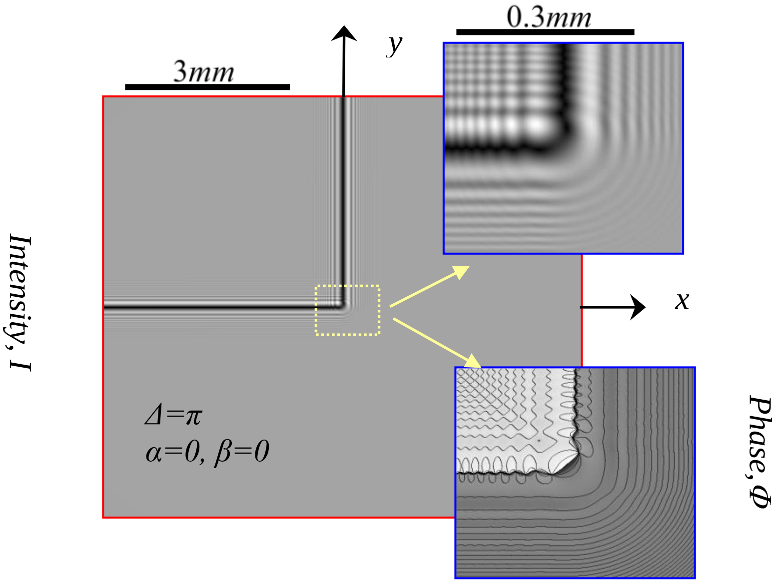

Fig. 3. Distributions of intensity I and phase Φ after diffraction of the Gaussian beam by the π -phase plate $\alpha = \beta = 0$ and $\Delta\Phi = \pi$).

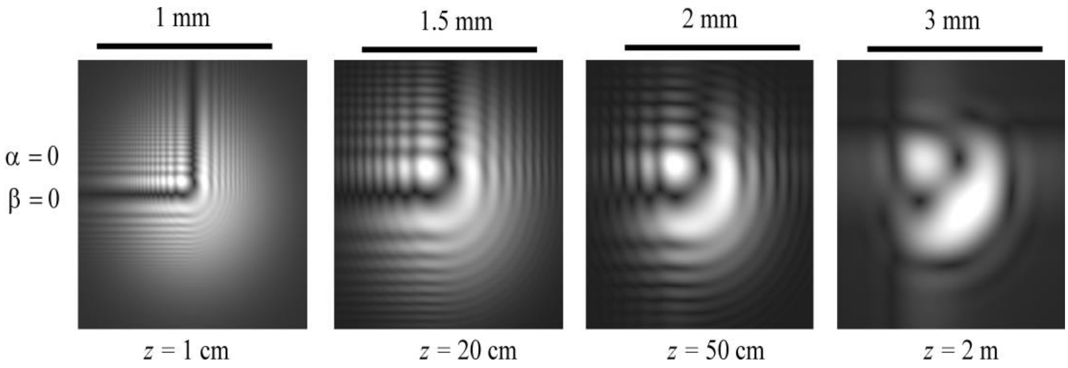

Fig. 4. Evolution of singular structure along the Gaussian beam diffracted by the π -phase plate (w_0 = 0.5 mm).

The observable variations of the field structure for the evolving beam are due to changing transverse field scale, whereas the solid angle of the beam divergence remains constant. In contrast to the phase wedge, near the axis of the π -phase plate we observe a structurally stable topological dipole consisting of two oppositely charged optical vortices.

3. EXPERIMENTAL VERIFICATION OF THE THEORETICAL MODEL

The theoretical results [9] described above are in need of experimental verification.

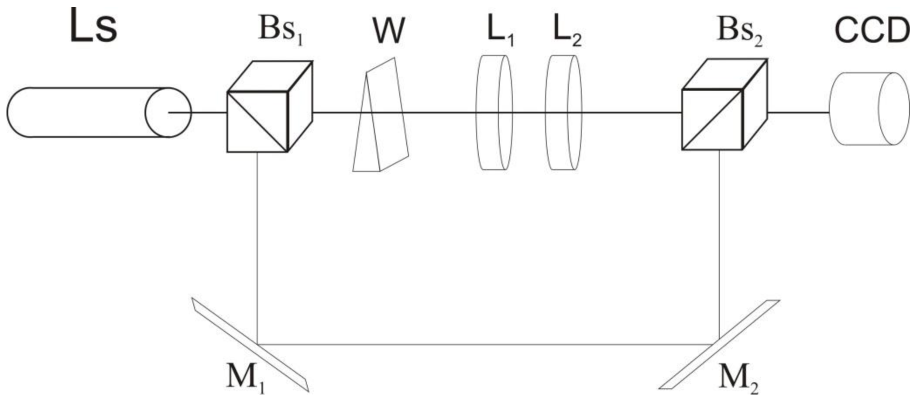

Fig. 5. The sketch of the experimental setup: (He-Ne) laser, (Bs) (beam splitting), (W) wedge, (L) lens, (M) mirror, (CCD) CCD camera.

The parallel Gaussian beam is incident on the angular edge of a dielectric wedge, which is diffracted. After passing through the dielectric wedge beam passes through the lens, whereby it is aligned. Further the MachZander interferometer distributing vortices in the field.

In Fig. 6. located behavior vortices generated on the dielectric wedge. In Fig. 7. is the interference pattern corresponding to Fig. 6.

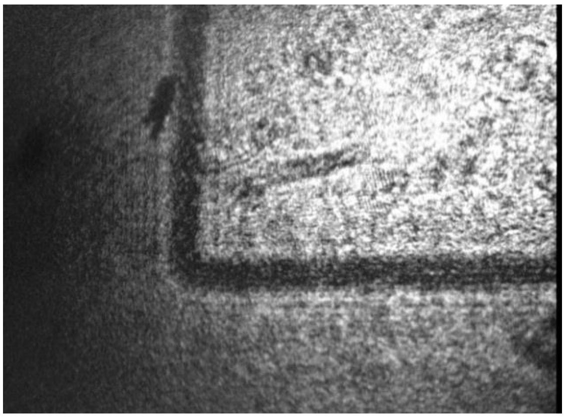

Fig. 6. Behavior vortices generated on the dielectric wedge.

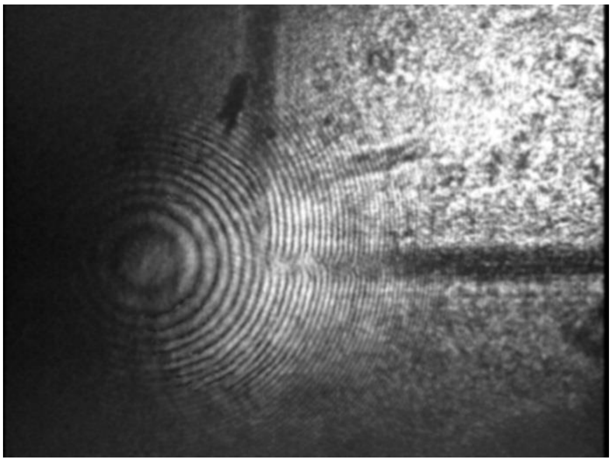

Fig. 7. The interference pattern corresponding to Fig. 6.

CONCLUSION

On the dielectric wedge can highly efficient generation of optical vortices with fractional topological charges.

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Ковальова Г. О. Генерація дрібних оптичних вихорів / Г. О. Ковальова, А. А. Марковський, Т. А. Фадеєва, О. Ф. Рибась // Вчені записки Таврійського національного університету імені В. І. Вернадського. Серія : Фізико-математичні науки. – 2013. – Т. 26 (65), № 2. – С. 13-19.

В рамках параксіального наближення в роботі розглянута еволюція монохроматичного гаусівського променя, дифрагованого на куті, сформованому трьома гранями клинів різного типу. Виявлено, що краї фазового клина генерують макроскопічний ланцюжок ідентичних оптичних вихорів, які зникають у далекій зоні. Разом з тим, π -фазова пластинка може репродукувати складну структуру хвильового поля, яка залежить від масштабу спостереження. У великих масштабах виникає два π -зрізи, які нагадують зламані крайові дислокації з перпендикулярними напрямками. При малих масштабах (кілька мікрон) два коротких ланцюжки вихорів з протилежними зарядами, які зароджуються біля клину. Як випливає з аналізу, розмір ланцюжків швидко зменшується при прямуванні до поверхні клину. Це дозволяє нам припустити, що π -фазова пластинка може створювати так звані оптичні кварки в еванесцентних хвилях на границі поля.

На підставі теоретичних передумов був проведений експеримент в результаті, якого, були отримані дробові оптичні вихори на краю фазового клина.

Ключові слова: фазовий клин, оптичний вихор, оптичний кварк.

Ковалева А. О. Генерация дробных оптических вихрей / А. О. Ковалева, А. А. Марковский, Т. А. Фадеева, А. Ф. Рыбась // Ученые записки Таврического национального университета имени В. И. Вернадского. Серия : Физико-математические науки. – 2013. – Т. 26 (65), № 2. – С. 13-19.
В рамках параксиального приближения в работе рассмотрена эволюция монохроматического Гауссового пучка, дифрагированного на углу, сформированному тремя гранями клиньев разного типа. Обнаружено, что края фазового клина генерируют макроскопическую цепочку идентичных оптических вихрей, которые исчезают в дальней зоне. Вместе с тем, π-фазовая пластинка может репродуцировать сложную структуру волнового поля, которая зависит от масштаба наблюдения. В больших масштабах возникает два π-среза, которые напоминают сломанные краевые дислокации с перпендикулярными направлениями. При малых масштабах (несколько микрон) две короткие цепочки вихрей с противоположными зарядами, которые зарождаются у клина. Как следует из анализа, размер цепочек быстро уменьшается при движении к поверхности клина. Это позволяет нам предположить, что π-фазовая пластинка может создавать так называемые оптические кварки в эванесцентных волнах на границе поля.
На основании теоретических предпосылок был проведен эксперимент в результате, которого, были получены дробные оптические вихри на краю фазового клина.
Ключевые слова: фазовый клин, оптический вихрь, оптический кварк.

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