

# Generation of vortex beams by controllable phase elements

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A feasibility of generating laser beams with screw (or vortex) dislocations of the wave front with the aid of controllable phase optical elements having a continuous surface profile: bimorph adaptive mirror and electrically controllable liquid-crystal modulator, has been studied experimentally.

## Introduction

As a beam scatters at a rough surface, after the propagation to a significant distance in the turbulent atmosphere, its optical field acquires the speckle structure. Such fields are characterized by the presence of isolated points with zero intensity and undetermined phase in the cross plane. The integration of the phase gradient over a closed contour encompassing such a branch point yields nonzero circulation.

The main property of a screw dislocation is that passing around the axis of an optical vortex along any closed contour, not encompassing another optical vortex, leads to a phase change of  $2m\pi$ . The integer parameter  $m$  is referred to as a topological charge of a vortex. The combination of the circular and translational motion of the electromagnetic wave energy leads to formation of a helical equal-phase surface, the so-called screw (or vortex) dislocation of a wave front. In this case, the wave front has a smooth surface everywhere except for the helicoid axis.<sup>1-4</sup> A typical example of an optical vortex is the toroidal Laguerre–Gauss ( $LG_0^{-1}$ ) mode of a laser cavity.

The presence of vortex dislocations in the wave front of radiation markedly decreases the efficiency of adaptive control systems. Traditional methods of wavefront correction appear to be inefficient for these problems, because development of correctors capable of reconstructing screw dislocations is a complicated scientific and technological problem.

At the same time, laser beams with vortex dislocations can be used for solution of practically important problems. They can be applied for development of optical traps, optical manipulators, optical forceps, and in communication systems.<sup>5,6</sup> That is why the development of methods both for formation and for compensation of vortex dislocations of wave front of laser beams is an important problem. However, traditional phase correctors, such as, for example, flexible bimorph mirrors<sup>7,8</sup> and liquid-crystal (LC) modulators,<sup>9</sup> have a continuous surface, and, therefore, formation of a discontinuous phase profile with their aid is an object of specialized study, presented by us.

## 1. Flexible bimorph adaptive mirror and liquid crystal light modulator as elements for formation of vortex beams

Different methods for formation of vortex beams are known now. For example, in Refs. 10 and 11, it is proposed to use amplitude holographic elements. However, the efficiency of holographic elements decreases considerably, if the parameters of the incident laser radiation fluctuate. In addition, the dynamic change of the radiation wave front is sometimes necessary. For such problems, it is convenient to use controllable phase optical elements, in particular, a flexible bimorph mirror.<sup>7,8</sup> The bimorph mirror consists of a thick glass or metal substrate and one or several piezoceramic disks with electrodes. The disks are glued to the substrate. Under the action of the inverse transversal piezoelectric effect, the piezoceramic plate expands or contracts and there appears a bending moment deforming the mirror.

It is difficult to reconstruct the discontinuous screw wave front of a vortex beam by a model bimorph corrector having a continuous surface profile. Therefore, to imitate a discontinuous surface by such a corrector with the highest accuracy, we have specially designed and fabricated a flexible mirror with an electrode network (Fig. 1). The profile of the mirror surface needed for formation of an optical vortex (Fig. 1c) has, according to the calculation, deformation amplitude of  $0.633\ \mu\text{m}$  and is achieved at voltages of  $+300\ \text{V}$  and  $-300\ \text{V}$  applied, respectively, to even and odd electrodes of the mirror.

The flexible mirror has a continuous surface, but a rather sharp local slope of the surface is seen at the place, where a break should be observed. In this paper, we solved the problem of experimental check of the capability of generating optical vortices by the fabricated mirror.

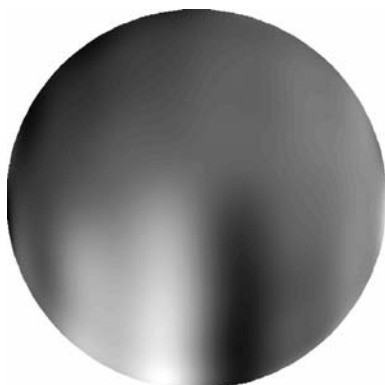
The application of bimorph mirrors is efficient for controlling high-power laser radiation. To control low-power radiation, it is convenient to use a LC modulator. A liquid-crystal controllable light modulator is now one of the widely used optical elements for control and correction of laser radiation,<sup>9</sup> because it is simple in control and consumes low energy.



a



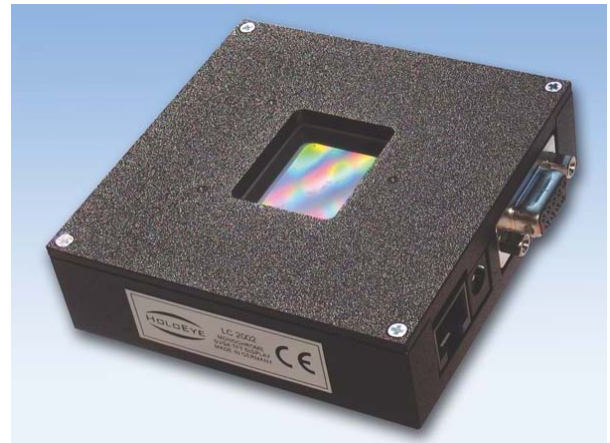
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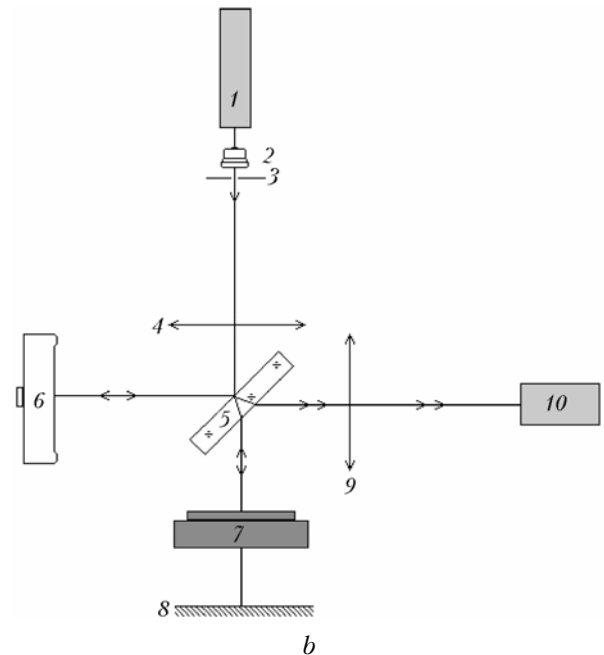
c

**Fig. 1.** Electrode configuration of the bimorph mirror (a), its photo (b), and profile of the mirror surface (shown in the gray scale) needed for formation of an optical vortex in the far field (c).

The used Holoeye-SLM-LC-2002 liquid-crystal electrically controllable modulator (Fig. 2a) is a phase optical element capable of changing the wave front of the passing through it laser radiation.



a



b

**Fig. 2.** Photo of a Holoeye-SLM-LC-2002 modulator (a) and block diagram of the experimental setup for generation and detection of a screw dislocation of wave front (b).

The SLM-LC-2002 modulator is a uniaxial nematic liquid crystal placed between transparent electrodes, one of which is continuous, while another consists of cells. The operating principle of the modulator is the following. Optical radiation propagates along the principal optical axis of the liquid crystal. As voltage is applied across the electrodes, molecular axes of the liquid crystal change the orientation and the refractive index for the laser radiation passing through the medium changes due to anisotropy of permittivity. Thus, applying different voltage across different electrodes

of the LC modulator, we can control phase delays of different parts of the laser beam passing through the LC modulator. The LC modulator is controlled with the aid of the specialized control program (included in the delivery kit). In this program, a black-and-white VGA or SVGA video signal is converted into the electric signal with the aid of the specialized converter included in the delivery kit. The electric signal is applied to control modulator electrodes. The black point corresponds to the minimal phase delay, while the white point corresponds to the maximal one. The used modulator has specifications and technical characteristics summarized below.

LC matrix	SONY LCX016AL-6
Panel size	26.6 × 20.0 mm (1.3")
Pixels	832 × 624
Pixel pitch	32 μm
Image frame rate	60 Hz
Max phase delay	2π at 532 nm
Fill factor	85%
External dimensions	82 × 82 × 23 mm
Addressing	256 pixel values (8 bit)
Control signal formats	VGA, SVGA

## 2. Results of experiments on generation of vortex beams

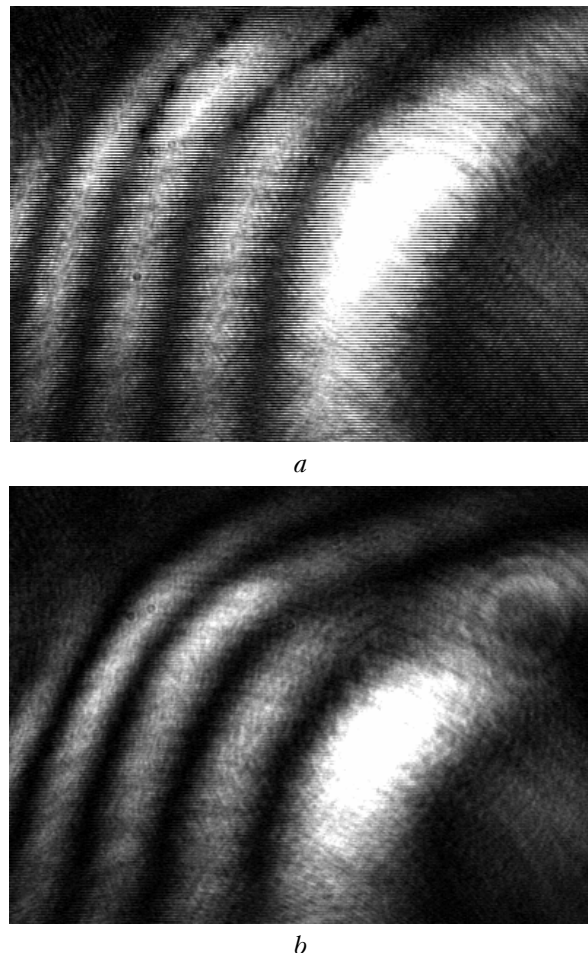
Let us consider experimental results on generation of laser beams with a screw wavefront dislocation with the aid of the electrically controlled LC modulator and the bimorph adaptive mirror.

The wave front of a vortex beam was recorded with a Michelson interferometer. The block diagram of the experimental setup is shown in Fig. 2*b*. The laser beam of an LGN-303 He–Ne laser 1 after the passage through a 20x micro-objective 2, a diaphragm (10 μm) 3, and a collimating lens 4 is incident onto the beam-splitting plate 5 of the Michelson interferometer. The flexible bimorph corrector 6 is used as one of the interferometer mirrors. The LC modulator 7 is inserted in another arm of the interferometer. The lens 4 can be set or dismantled from the setup to observe an interference pattern in collimated or divergent beams, respectively. The maximal phase delay of the LC modulator set for double passage is roughly equal to the wavelength of the used He–Ne laser ( $\lambda = 638$  nm). The output radiation from the interferometer is focused by a lens 9 with a focal length of 300 mm to the CCD array of a camera 10. The lens 9 is used to match the aperture of the beam from the interferometer with the size of the entrance window of the CCD camera 10. In addition, the lens 9 allows the beam intensity distribution in the far field to be observed in the focal plane.

The experiment with the flexible bimorph mirror was carried out in collimated beams (lens 4 installed in Fig. 2*b*). As was already mentioned, the flexible

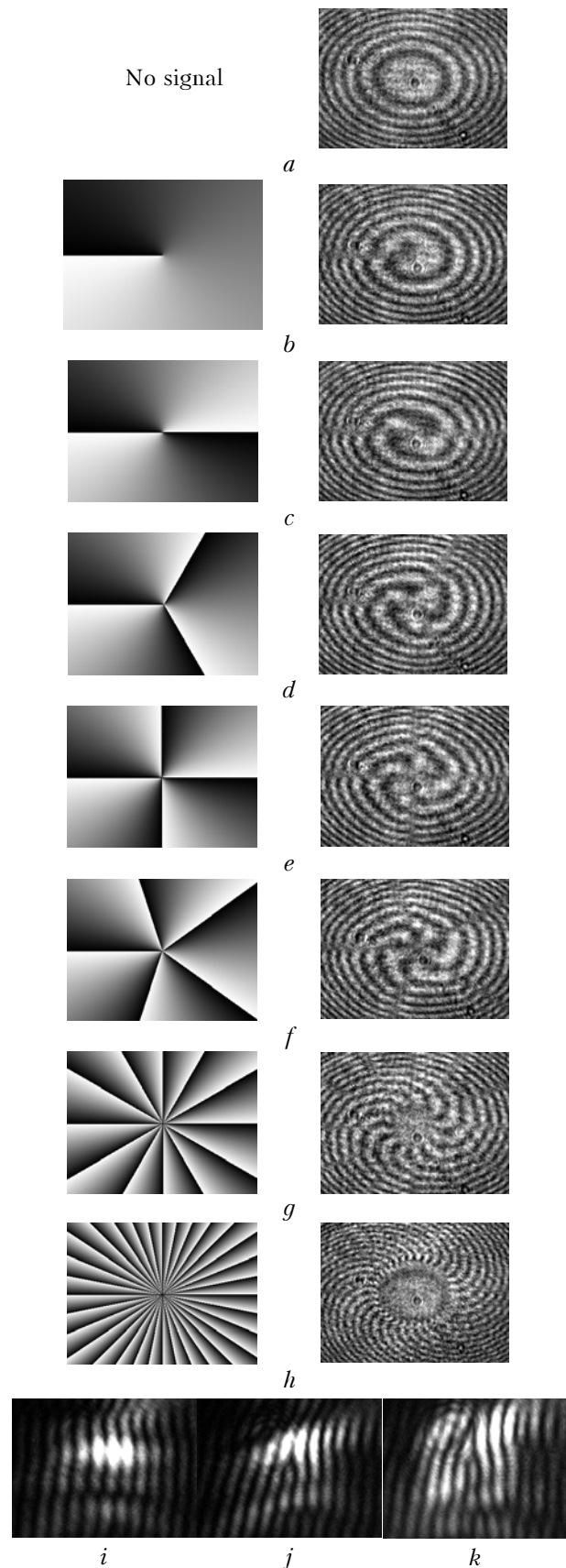
mirror nonideally reconstructs the vortex phase distribution (see Fig. 1*c*). It can be seen from Fig. 1*c* that the mirror reconstructs the break in the phase distribution more smoothly than needed for ideal formation of the vortex phase.

The experiment has shown that branching of a fringe in the interference pattern can be observed only in the focal plane of the lens 9 (see Fig. 2*b*). The voltages, which should be applied in this case, are equal to  $\pm 300$  V for even and odd control electrodes of the mirror. To observe a focal spot using a 60x objective, its magnified image was constructed on the surface of the window of the CCD camera 10 (see Fig. 2*b*). One can see from Fig. 3 that as the control voltages are applied to mirror electrodes, branching of the interference fringe is observed (Fig. 3*b*), which is indicative of the formation of a screw dislocation in the wave front.



**Fig. 3.** Interference patterns at zero voltage (*a*) and at voltage of  $\pm 300$  V applied to control electrodes of the mirror (*b*).

Screw wavefront dislocations of different orders were also formed with the use of the LC modulator. Interference patterns formed by the LC modulator were studied in divergent and collimated beams. Figures 4*a–h* show the video signals fed to the control



**Fig. 4.** Video signals and corresponding interference patterns.

unit of the LC modulator (to the left) and the corresponding interference patterns (to the right): for generation of laser beams with the screw wavefront dislocation of zero (no screw dislocation) (*a*), first (*b*), second (*c*), third (*d*), fourth (*e*), fifth (*f*), twelfth (*g*), and thirty-second (*h*) orders.

At the interference of beams having the divergent wave front, the interference pattern looks like a set of concentric rings (Fig. 4*a*). In this case, the presence of a screw dislocation leads to formation of one unwind spiral in the interference pattern for an optical vortex of the first order, two unwind spirals for an optical vortex of the second order, and so on.

If the collimating lens 4 was installed between the diaphragm 3 and the beam-splitting plate 5 (see Fig. 2*b*), interference patterns in collimated beams were observed (Fig. 4*i*), which are shown in Figs. 4*j, k*. Figure 4*i* shows the interference pattern observed in the absence of a signal at the LC modulator. As the control signal was fed (Fig. 4*b*, to the left), the interferogram (Fig. 4*j*) was formed, at which branching of the interference pattern is seen, which means the presence of a screw dislocation of the first order. Figure 4*k* shows the interference pattern formed as the signal shown in Fig. 4*c* was applied to the LC modulator. In this interferogram, branching of two fringes is seen, which corresponds to the optical vortex of the second order.

## Conclusions

A possibility of generating vortex beams with the aid of controllable phase modulators having a continuous surface profile has been demonstrated experimentally. Using the controllable nematic LC modulator with a spatial resolution of  $800 \times 600$ , we have succeeded in generation of vortex beams of the 1st, 2nd, 3rd, 4th, 5th, 12th, and 32nd orders. The possibility of generating the vortex beam of the first order with the aid of the flexible bimorph mirror is demonstrated experimentally as well.

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