Laser beams with screw dislocations in their wavefronts

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Coherent optical fields with wavefront dislocations of various orders have been produced experimentally and studied during the passage of a laser beam through a multimode waveguide and during diffraction by some holograms which have been synthesized.

Wavefront dislocations[1] or optical vortices have attracted interest as some of the new entities which exist in optical fields with a complex spatial structure or in laser cavities with a large Fresnel number.[2] When there is a screw dislocation, the wavefront is a common helical surface (right-handed or left-handed) with a singularity. When this singularity is circumvented, there is a phase shift of some multiple of 2π. The wavefront surface may have a singularity only where the modulus of the complex field amplitude E vanishes, i.e., where the real and imaginary parts are simultaneously zero. First-order dislocations (those for which the change in phase is 2π) have been observed in the speckle field of scattered coherent light.[1]

Our purpose in the present study was to produce, and learn about the properties of, regular optical fields with screw dislocations, including dislocations of higher orders.

To study the structure of the field of an isolated dislocation, we used an experimental apparatus (Fig. 1) consisting of a Mach-Zehnder interferometer with a length of braided multimode optical fibers in one arm. The beam from a helium–neon laser with a Gaussian mode is focused into one of the fibers of the braid. At the exit from this fiber we observe a pattern consisting of two or three spots of irregular shape. A diverging lens is placed in the reference arm of the interferometer in order to equalize the divergences of the interfering beams. By rotating the semitransparent exit mirror of the interferometer, we are able to observe an interference pattern in various regions of the beam emerging from the waveguide. The customary annular interference pattern is observed at the light intensity maxima. If there is instead a dislocation at the

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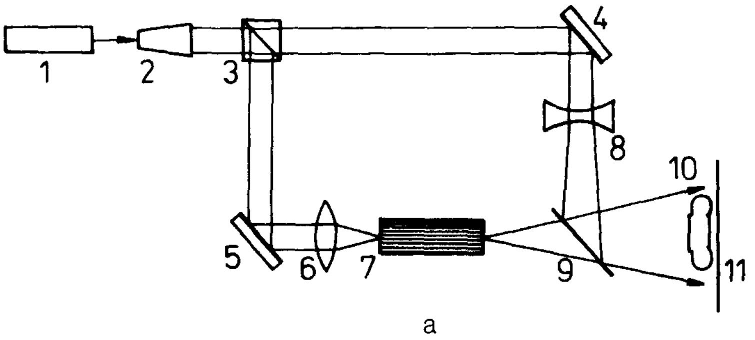

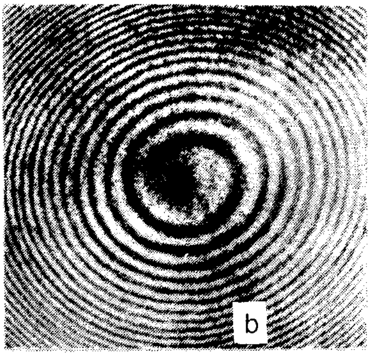

FIG. 1. a: Experimental setup. 1—He–Ne laser; 2—beam expander; 3—beam splitter; 4,5—mirrors; 6—objective; 7—braided optical fibers; 8—diverging lens; 9—half-silvered mirror; 10—camera; 11—screen for observing the interference of the beams. b: Interference pattern formed by the spherical reference wave and a wave with a screw wavefront dislocation.

center of the interference region, the pattern becomes a helix (Fig. 1b), clearly demonstrating the existence of a helical wave surface. At the center of the helix there is always an intensity zero of the beam emerging from the waveguide.

When the interfering beams are incident on a screen at a small relative angle, we observe a splitting or disappearance of an interference fringe, similar to the event described in Ref. 1 for dislocations in speckle fields.

The dislocations observed experimentally in the setup in Fig. 1a had only the plus first or minus first order (the change in phase upon a circumvention was $+2\pi$ or -2π, respectively). The numbers of right-handed and left-handed screw dislocations were the same. It is extremely unlikely that dislocations of higher orders would be observed in this setup, since such an observation would require the intersection at one point of more than two pairs of lines on which the conditions $\mathrm{Re}E = 0$ and $\mathrm{Im}E = 0$ hold. In the interference pattern of the beams this situation would correspond to a splitting of the interference fringe into four or more new fringes. In order to produce beams with dislocations of higher orders, we accordingly synthesized some amplitude

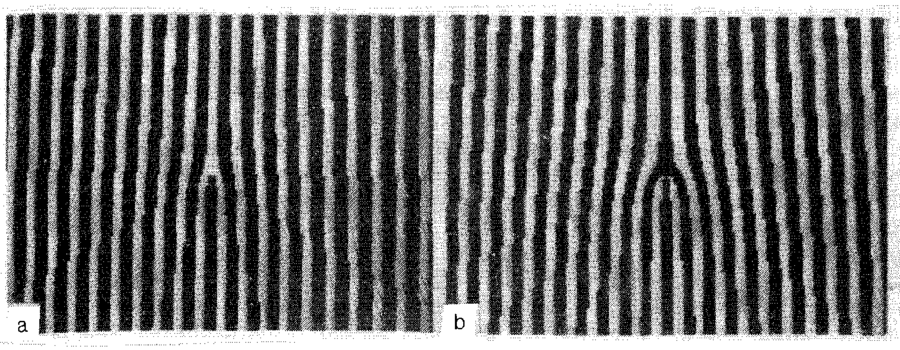

FIG. 2. a—The hologram which was synthesized in order to produce beams with a first-order dislocation; b—the same, for a second-order dislocation.

holograms to simulate the interference field of a plane wave and a wave carrying a dislocation of the desired order. After a numerical calculation was carried out, and the results displayed on a monitor, reduced copies were made on photographic film with a period of 0.1 mm and a size of 2×2.5 mm. Figure 2 shows the gratings which were synthesized.

The properties of the beams diffracted by these holograms were studied in a setup similar to that shown in Fig. 1a, in which the braided fiber and the focusing objective were replaced by this grating. A beam expander was not used in this case. An annular structure of the beams was clearly observed in the diffraction orders. With increasing order of the dislocation, the intensity dip at the center of the beam acquired progressively sharper edges. For the dislocations of higher orders, the pattern of the interference with the reference wave takes the form of seveal nested helices, in a number equal to the order of the dislocation. The helices corresponding to positive and negative diffraction orders wind in opposite directions. The transverse structure of the beams is not substantially altered as they propagate. This result means that the conclusion that there is an instability of optical fields with higher-order dislocations[1] requires refinement.

We have also observed an increase in the order of the dislocation in diffracted beams of higher orders (in precise correspondence with the order of the diffraction), but the quality of the beams produced in this manner turned out to be extremely low.

In summary, this study has demonstrated that it is possible to produce coherent light beams with a regular transverse structure which have screw wavefront dislocations. Beams with high-order dislocations have been produced for the first time with the help of some holograms which have been synthesized.

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[1]B. Ya. Zel'dovich, N. F. Pilipetskiĭ, and V. V. Shkunov, *Phase Conjugation*, Nauka, Moscow, 1986.
[2]P. Coullet, L. Gil, and F. Rocoa, Opt. Commun. **73**, 403 (1989).

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