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Self-imaging by ring-core fibers

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Abstract

A tubular dielectric waveguide of typically 100 λ diameter and single-moded wall-thickness can produce single or multiple images of one endface on the opposite one. Applications, as single-mode N × N directional couplers are possible.

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Summary

In certain multimode optical waveguides, a reconstruction of an arbitrary input light-distribution may occur in cross-sectional planes further down the guide, resulting from constructive interferences of all excited waveguide modes. This 'self-imaging' effect is known to exist in parabolic-graded-index media, and in planar and rectangular step-index waveguides.[1]

We present theoretical and experimental results on a new type of self-imaging waveguide: The radially single-moded ring-core fiber (Fig.1). The high-index 'core' region of this fiber is a thin-walled dielectric tube, with lower-index inner and outer cladding regions. We show, that a monochromatic light-distribution coupled into one end-face of such a tubular core will be reconstructed in other cross-sectional planes of the guide by phase coincidences of the excited waveguide modes. These reconstructions are Fourier- and Fresnel-images of the (input) object light-distribution. Thus, ring-shaped linear objects can be imaged by the fiber. Fresnel double-imaging may permit applications as single-

mode fiber-optic 3 dB-directional couplers, and higher-order imaging the construction of $N \times N$ couplers.

Image formation in a ring-core guide can be explained conveniently by a simplified, scalar theory and the assumption, that the diameter $2R$ of the ring-core is much larger than the wavelength λ, so that the guide may be treated as a wrapped-up single-mode slab waveguide. An arbitrary light-distribution $A(r,\Theta)$ in the object plane can be represented as a superposition of all waveguide modes, i.e.

$$A(r,\Theta) = \sum_m a_m F_m (r,\Theta) \qquad (1)$$

with complex amplitude coefficients a_m (time factor $\exp(-i\omega t)$ omitted). After propagation through a distance z the light-distribution becomes

$$B(r,\Theta) = e^{i\beta_o z} \sum_m a_m F_m (r,\Theta) e^{i\phi_m} \qquad (2)$$

Here, $\phi_m = (\beta_m - \beta_o)z$ denotes the phase difference between the m-th and the fundamental mode (m=0). In good approximation we have

$$\phi_m \approx -\pi m^2 z/L_1 = -\pi m^2 h \qquad (3)$$

where $L_1 = N(2\pi R)^2/\lambda$ and N is the effective index of the equivalent planar guide.

At a distance $z=L$, $(h=1)$ we get $B(r,\Theta) = A(r,\Theta+\pi)$ which is a single inverted self-image. The simplest multiple image is at $h = 1/2$ where we find

$$B(r,\Theta) = \frac{1-i}{2} A(r,\Theta) + \frac{1+i}{2} A(r,\Theta+\pi) \tag{4}$$

This is a double image. Higher-order images are formed in an analogous way.

In order to demonstrate these self-imaging properties, we have prepared a ring-core fiber by depositing high-index core glass ($\Delta n = 0.4\%$) on the inner wall of a silica tube, fitting a silica rod into it, and pulling this combination into fibers of various core diameters. Suitable lengths were cleaved, and TEM_{oo} light of a tuneable dye laser was focussed as a diffraction-limited spot onto a point $(\Theta=0)$ of the end-face of the core. Fig. 2 shows the observed images for h=1; 1/2; 1/3; 1/4.

For the spatial resolution we got about 4 µm and 2 µm in the azimuthal and radial coordinate, respectively. The latter is limited by the radial field distribution which depends on both, the index-difference and the core's wall-thickness. These spot sizes fit well with typical single-mode core diameters. We therefore anticipate directional couplers by jointing single-mode fibers to the ring-core fiber.

Reference: [1] R. Ulrich, Optics Communications 13, 259 (1975).

Figure captions

Fig. 1: Schematic view of ring-core fiber, with laser beam focussed onto input plane at $\Theta=0$, and single inverted self-image ($h=1$; $\Theta=\pi$) in output plane.

Fig. 2: Self-images of a single object point
(left: schematic, right: photographs)

(a) $h = 1$ ($L = 105.6$ mm, $2R = 65.5$ µm)

(b) $h = 1/2$ ($L = 50.4$ mm, $2R = 65.5$ µm)

(c) $h = 1/3$ ($L = 75.0$ mm, $2R = 97.0$ µm)

(d) $h = 1/4$ ($L = 57.6$ mm, $2R = 97.0$ µm)

In all cases $\Theta=0$ in the input plane

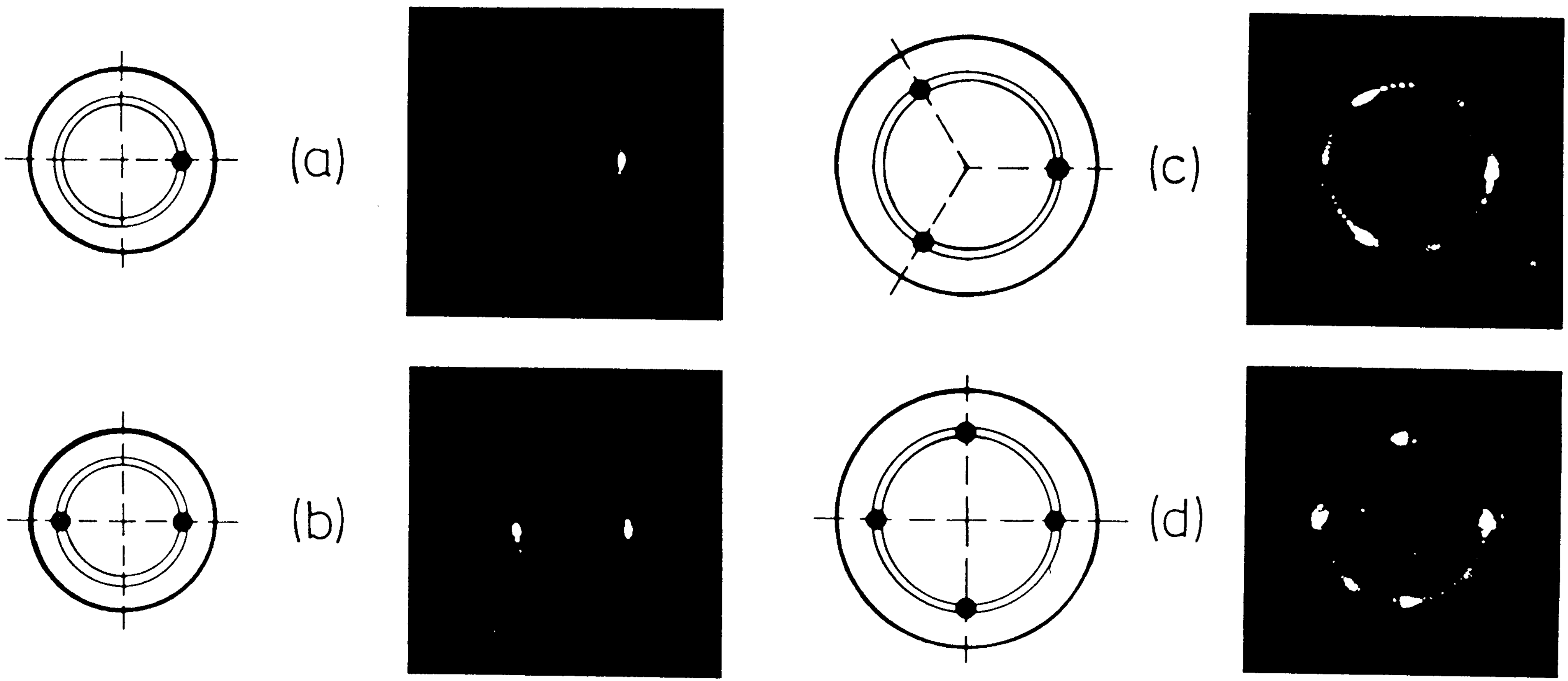

FIG. 2

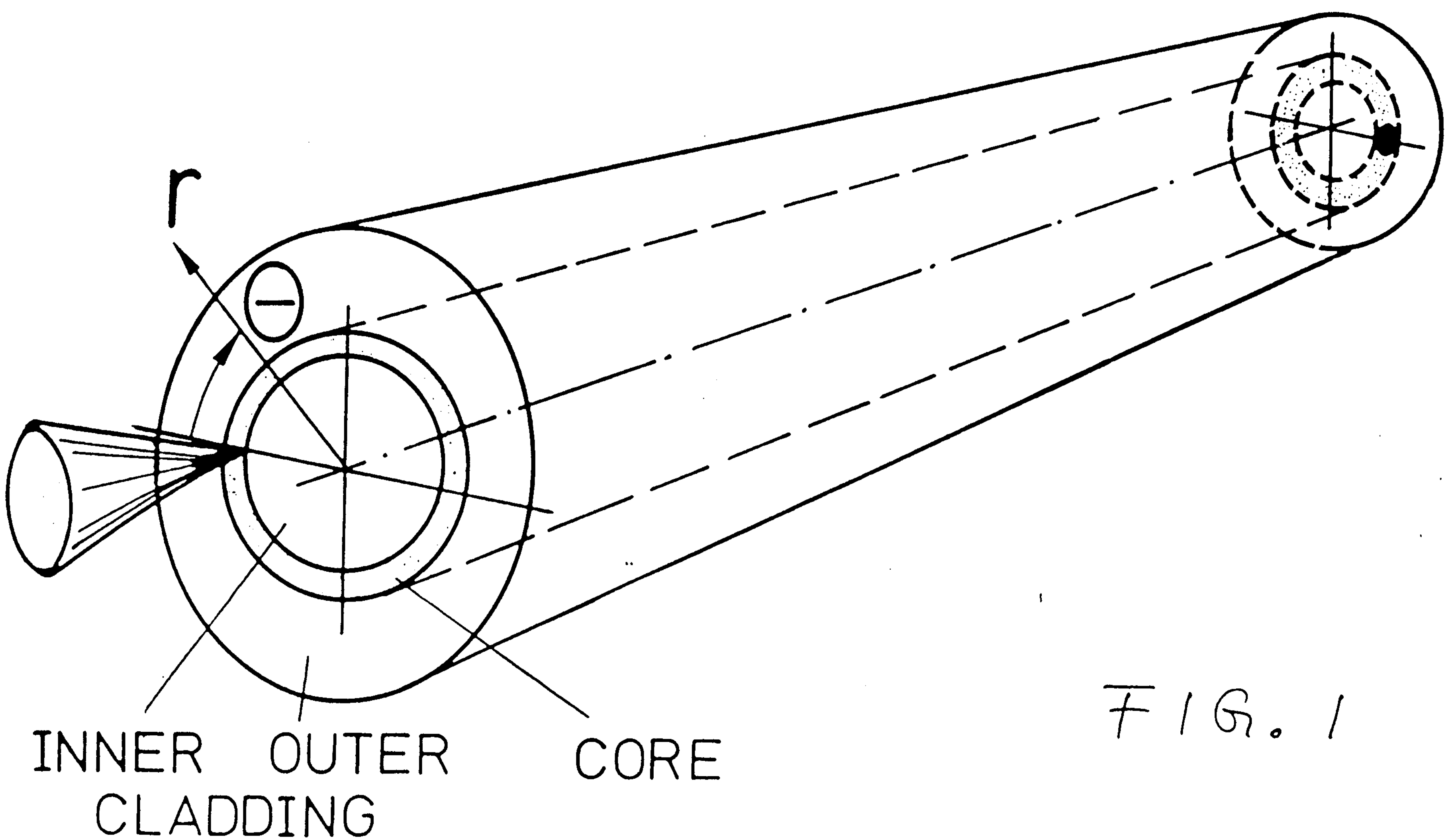

FIG. 1

Fig 8.1. Schematic of ring-core fib