Computer Optics Vol. 2, No. 1, pp. 95–99, 1990
Printed in Great Britain

0955-355X/90 $10.00 + 0.00

USE OF SYNTHESIZED HOLOGRAMS FOR SELECTIVE MODE EXCITATION IN GRADIENT INDEX FIBRES. ANALYSIS OF SENSITIVITY TO RADIAL DISPLACEMENT OF LAUNCH BEAMS

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Abstract—Synthesized holograms were used for selective excitation of the lower order modes in multimode graded index fibres. The coefficients of mode excitation were measured as functions of the radial displacement of the launch beam.

Interest in selective excitation of modes in optical fibres was aroused in the mid-70s when there were investigations of differential mode delays, differential modal attenuation, and mode coupling in optical fibres [1–5]. Keck [1], Olshansky and Oaks [2], and Jeunhomme and Lamouler [3] excited modes with an off-axis laser that launched a small-diameter beam skew of parallel to the fibre axis. However, these methods excited at best separate mode groups each with close mode propagation constants, the mode selectivity having been rather poor except for lower order modes.

Stewart [4] used a prism coupler for selective launching of modes close to cutoff both into step index and graded index fibres. A series of selectively excited modes was obtained by Midwinter [3] in a few-mode step index fibre with the aid of a prism-cone coupler. Unfortunately, prism launch methods are difficult to use and there are complexities in coupling them with commercial multimode fibres of 50–60 μm core diameter.

A more obvious and theoretically simple method of selective mode launching at the fibre end is to surround it with an electromagnetic field which completely matches the field of the mode or mode superposition to be supported. The first attempt at using such a technique was made by Kapany *et al.* [6]. The parameter V defining the number of modes supported by a fibre was equal to nine for the few-mode step-index fibre used by these workers. Selective excitation was achieved with Fraunhofer diffraction pattern at an annular aperture. For a suitable size of annular aperture and focal length of Fourier lens, this pattern is a good approximation to the distribution of complex amplitude across the core for the axially symmetric modes of the lowest order. The modes HE_{11} (LP_{01}) and HE_{12} (LP_{02}) were selectively excited by this method. For higher order modes including those with nonzero azimuthal indices, however, it was suggested that computer-synthesized holograms should be used, forming the distribution of complex amplitude required to match the fields of the modes to be excited.

The approach of Kapany and co-workers [6] has been extended by a number of authors [7–9], who employed a set of complex spatial filters formed by binary amplitude masks with controlled air pressure in the apertures to effect the required phase retardations. The fields generated were equivalent to the Gauss–Laguerre modes ψ_{pl} with radial index $l = 0$. This allowed the selective excitation of modes with azimuthal indices $p = 2$, 4 and 12, and of a superposition of the modes with $p = 2$ and $p = 12$. The 10-m long fibre used in these experiments was an essentially multimode type of $V = 70$.

Notwithstanding the impressive achievements of these experiments [7–9] spatial filters of this type fail to solve all the problems associated with the selective launching of modes into multimode fibres, above all on account of the filters' complexity. Although the history of selective mode excitation in optical fibres is more than a decade long, the topic has not become less acute. Indeed it has acquired new aspects due to the application of selective launching in fibre-optical transducers [10]; and to attempts at improving the capacity of optical fibre communication links by mode multiplexing, in the hope of using individual modes supported by a fibre as separate communication channels [8].

The present paper seems to be the first successful attempt to use synthesized holograms for

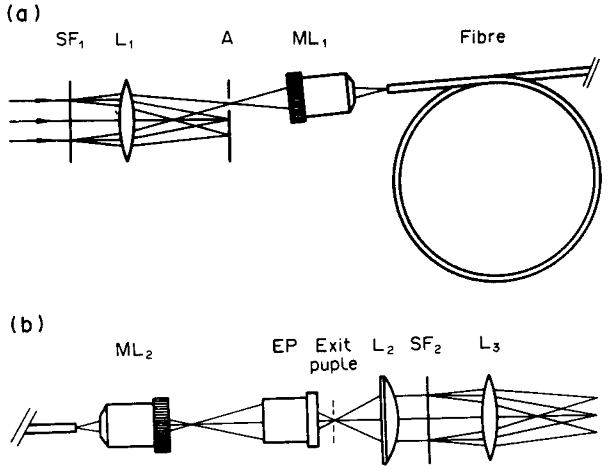

Fig. 1. (a) Optical system for selective mode launching. (b) Optical system for quantitative mode analysis.

selective excitation of modes in optical fibres. We employed a 1-m long gradient index multimode fibre ($V = 61$) with a refractive index profile close to parabolic. The refractive index at the axis $n_1 = 1.458$, the absolute difference of refractive indices $\Delta n = 0.0145$, and the core radius $a = 30\ \mu$m.

A diagram of the experimental setup for selective launching and analysis of modes is shown in Fig. 1. The spatial filters SF_1 for selective excitation and the spatial filters SF_2 are focused image holograms synthesized by the superposition of a plane carrier with spatial frequency $\beta_0 = 10$ lines/mm. They contain 256 × 256 samples spaced at 25 μm. The holograms were synthesized with the axially symmetric modes ($p = 0$) of Gauss–Laguerre, ψ_{pl}, with radial indices $l = 0$–3, 5, 7, 8, 10 and 16–18. Each of these holograms has an amplitude transmittance $\psi = \psi^*_{pl}(x, y)\cos(2\pi\beta_0 x)$. When this hologram is illuminated with a collimated beam at $\lambda = 0.6328\ \mu$m, it recovers in the first diffraction order a light beam with amplitude distribution $\psi_{pl}(x, y)$ across the beam. To select this beam from the total diffraction pattern and match its size with the dimensions of the excited mode, we used an optical system consisting of a lens L_1, a point aperture A, and a microlens ML_1 (see Fig. 1a).

The waist of the illuminating beam was formed by the microlens ML_1 and adjusted by varying the spacing between ML_1 and the preceding waist at the aperture A. This size was monitored and measured by a microscope with an eyepiece micrometer. The criterion indicating that the dimensions were matched was that the diameter of the dark ring (first minimum) in the waist of the beam producing mode ψ_{01} should be equal to the calculated value—approximately 7.9 μm in our experiment.

In order to achieve selective mode launching we placed the waist of the beam, formed by the hologram and the optical system, at the butt end of the fibre, and we eliminated decentring and rotation of the beam with respect to the fibre end by adjustment.

In Fig. 2(a) are photographs of the beams forming the modes ψ_{00}, ψ_{01} and ψ_{02}. Figure 2(b) gives the photographs of the field near the fibre output indicating that selective excitation of the said modes was taking place. We failed to selectively launch modes with radial index $l > 2$.

The high degree of selectivity for the modes ψ_{00}–ψ_{02} was also borne out by measuring the coefficients of excitation of these modes and of the adjacent axially symmetric modes. The measurements were carried out by quantitative mode analysis, a method that was reported by us in several publications (see, e.g. Ref. 11). The method allows any mode to be selected out of the full set of supported modes and the power of this mode to be measured. This purpose was served by the part of the experimental system shown in Fig. 1(b). It consisted of a projection system (microlens ML_2, eyepiece EP, and lens L_2), a spatial filter SF_2, a Fourier lens L_3, and a linear video-signal transducer coupled with an oscilloscope.

We used the two methods of selective mode launching and of quantitative mode analysis, for experimental investigation of the sensitivity of launched modes to the radial shift of launching beams. More specifically, we investigated the dependence of the coefficients of excitation K_{pl} of ψ_{00}, ψ_{01} and ψ_{02} upon the radial shift δ normalized to the radius w_0 of the fundamental mode;

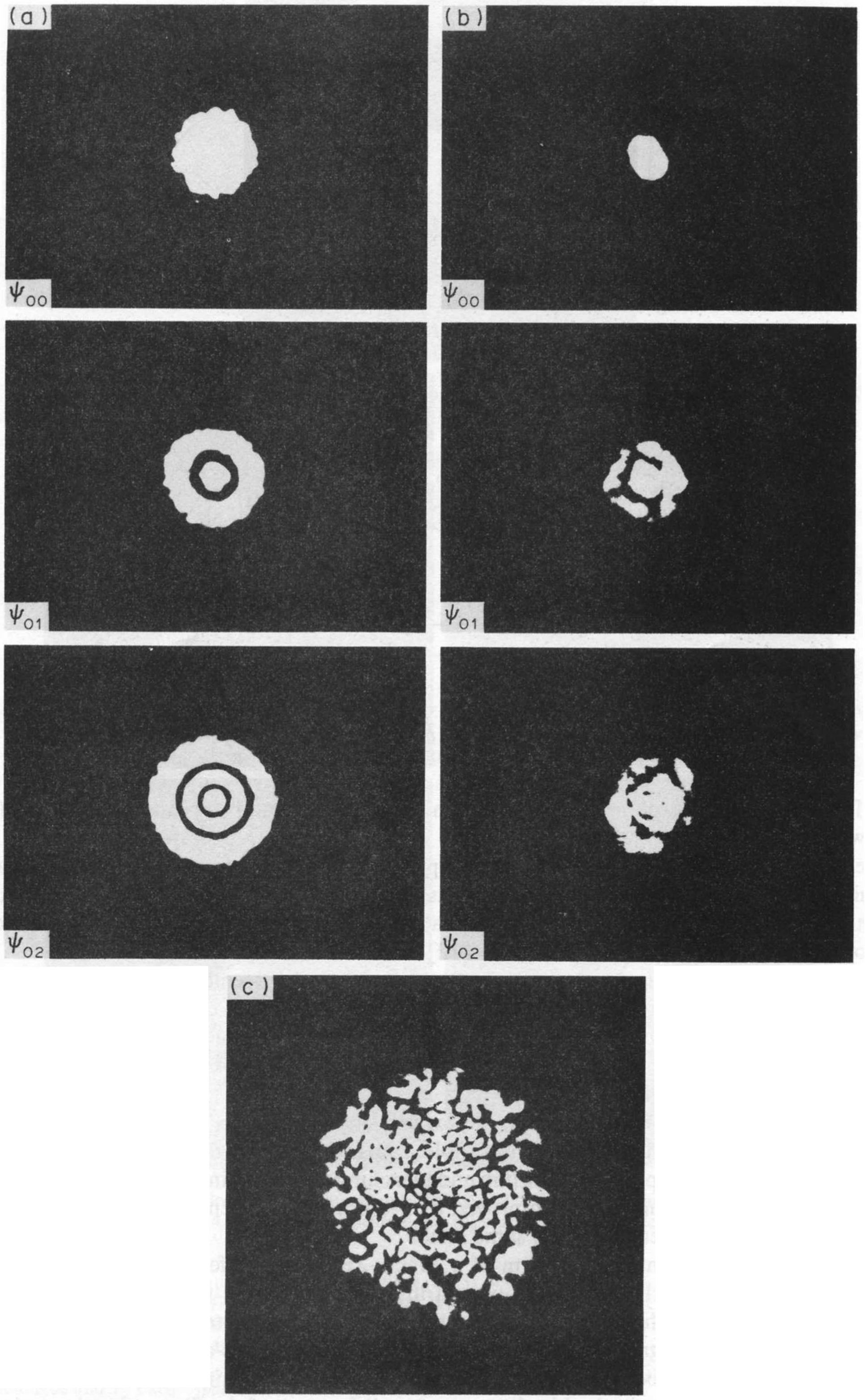

Fig. 2. Intensity distributions (a) across the mode launching beams, (b) the field near the fibre output end for the launching beams shown on the left, (c) the field near the fibre output end for all modes launched simultaneously.

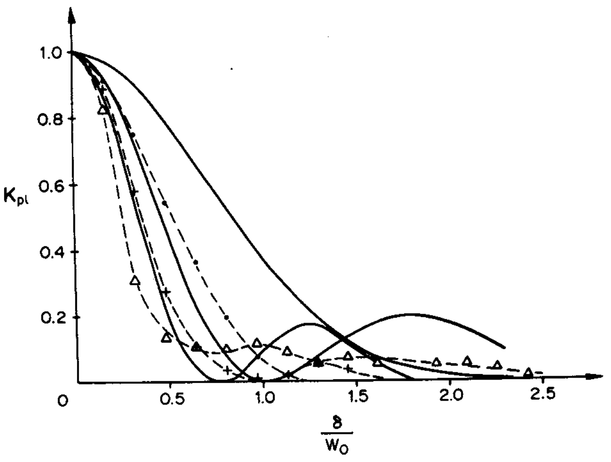

Fig. 3. Coefficients of mode excitation K_{pl} versus radial shift δ of illuminating beams divided by radius w_0 of the fundamental mode. ···· ψ_{00}; + + + + ψ_{01}; ΔΔΔ ψ_{02}.

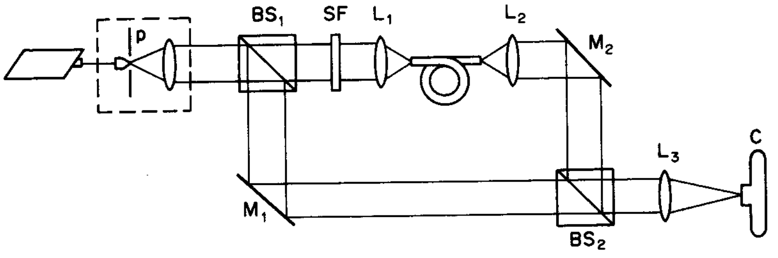

Fig. 4. Mode launching in the arrangement with a Mach–Zehnder interferometer. BS_1 and BS_2, beam-splitter cubes; SF, spatial holographic filter; M_1 and M_2, mirrors; L_1–L_3, lenses (L_1, pancratic lens focal length $f = 9 \div 27$ mm); C, photographic camera.

for the fibre used in the experiment, $w_0 = 5.6$ μm. The experimental dependencies $K_{pl} = f(\delta/w_0)$ are shown in Fig. 3.

In the experiment, the end of the fibre was displaced with respect to the illuminating beam by a precision mechanism and the shift δ was measured with a microscope. The solid-line curves represent Krivoshlykov and Sisakyan's theoretical analysis using the recurrence relations for the excitation coefficients of gradient-index fibres [12].

The curves of Fig. 3 demonstrate a satisfactory qualitative agreement of the theoretical and experimental data. With radial index $l > 2$ there are deviations between the theory and the abortive excitation of modes in practice. They seem to stem from the deviation of the refractive index profile from an exactly parabolic one. As a result the fibre modes actually are not the exact Gauss–Lagrange modes.

In parallel with the above experiments, we experimented with the selective excitation of the modes ψ_{00}–ψ_{02} using phase holograms. These holograms were prepared by copying the amplitude holograms onto Mikrat-300 photographic film and bleaching the copies in an R-10 bleacher solution. The phase recording of the holograms improved their diffraction efficiency 4–5 times and the light flux at the fibre output increased by the same factor.

When the fibre was mounted in an arm of a Mach–Zehnder interferometer (Fig. 4), we were able to record simultaneously the distribution of intensity and phase in the excited modes. The intensity distributions and the corresponding interferograms are depicted in Fig. 5.

The results of this investigation indicate that synthesized holograms are a practical proposition for selective launching of modes into optical fibres. The next advance in this direction is likely to depend on holograms synthesized with allowance for all features of the fibre refractive index.

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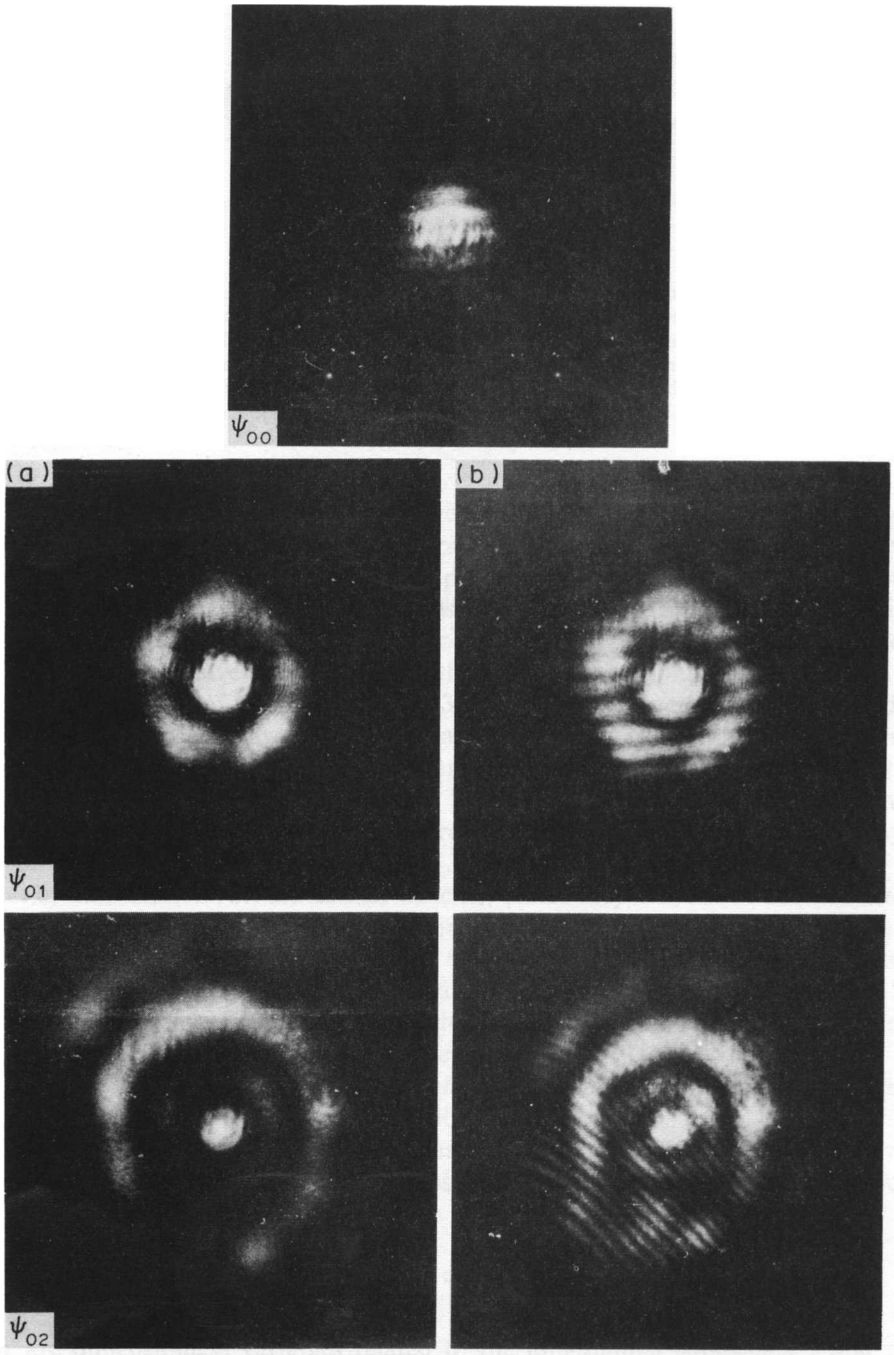

Fig. 5. Results of the selective mode launching with the aid of phase holograms in the system depicted in Fig. 4. (a) Intensity distributions, (b) corresponding interferograms.

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