SELF-IMAGING DEVICES FOR MULTIMODE OPTICS (*)

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ABSTRACT — Planar optical waveguides, suitable for light-propagation can be used for self-imaging. The formation of one–dimensional self-images is demonstrated experimentally in solid waveguide slabs of homogenous refractive index. The position of the self-images along the guide are shown to be dependent on the optical path of the signal wave. Reflective means can shorten the device size, and provide focussing so that a two-dimensional imaging device could be fabricated. The integration of a dispersive element such as a grating is proposed to permit the design of angularly dispersive devices for multiplexing of several optical signals at different wavelengths. Possible applications in multimode optics include branching couplers and frequency multiplexers for multimode transmission systems.

1 — INTRODUCTION

The self-imaging propriety for optical waveguides was first suggested by Bryngdahl [1]. The formation of single and multiple self-images in thick dielectric homogenous slab has been described, and demonstrated experimentally by Ulrich [2] employing liquid waveguides. The use of a liquid held between two optical flats facilitates variations of the slab thickness in order to adjust to the imaging condition. The liquid is contained by capillary forces which also provide an easy mechanism to the implementation of a guide whose width is tapered. A magnified or demagnified image is then produced according to the direction of propagation of the radiation along the tapered waveguide [3].

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Practical applications in optical communications suggest the research for self-imaging devices on a sheet of homogenous transparent material in the form of solid planar dielectric waveguides.

The inherent mechanical simplicity of such a component would permit easy fabrication in quantity and therefore potential low cost.

To study the method application, we used glass slides, 60 μm to 230 μm thick to simulate the waveguiding structure, which proved to exhibit self-imaging performance.

Whilst a glass slide component has mechanical simplicity, the device design must embody means of adjustment so that tolerance demands in the direct realization of the device are practically tractable. Further, the overall device size should be kept small enough so that it can be incorporated as an integrated part of an optical fibre cable system if necessary. We have then considered the introduction of reflective means to provide miniaturization features. This is possible as reflective optics can be used to form a non-dispersive system of the propagable mode spectrum [4]. Reflective optics also provides a focussing mechanism so that a convenient device design can be achieved to offer simultaneously two-dimensional imaging. Furthermore, it also presents favourable performance with respect to aberrations [5] when compared with a refractive element.

A dispersive element such as a grating can be, in principle, properly integrated in the system so that different wavelength components of the optical signal are diffracted or reflected from the grating at slightly different angles. These angularly dispersed beams offer the possibility of separating several signals supported by different wavelengths, i.e. exhibiting means for multiplexing and demultiplexing [6].

2 — SELF-IMAGING PLANAR WAVEGUIDE

The planar optical waveguide with uniform refractive index can produce images of one-dimensional objects in which the information is arranged along a line normal to the direction of propagation along the guide [7].

However, we consider here a thick planar guide and a one-dimensional object in which the information is arranged in the direction of propagation along the waveguide — a narrow slit P, Fig. 1, at one end of the guide, illuminated from the left. It is an inherent property of highly multimode, parallel or weakly tapered guides (adiabatic adaptation of all modes), that to any interior object point P there exists a number of real self-images S_1, S_2... S_j further down the guide. At intermediate positions multiple self-images of P are formed e.g. M_1, M_2... M_j [3]. The self-images result from the interference of a number of modes which propagate at different velocities, and whose phases all coincide in the self-image.

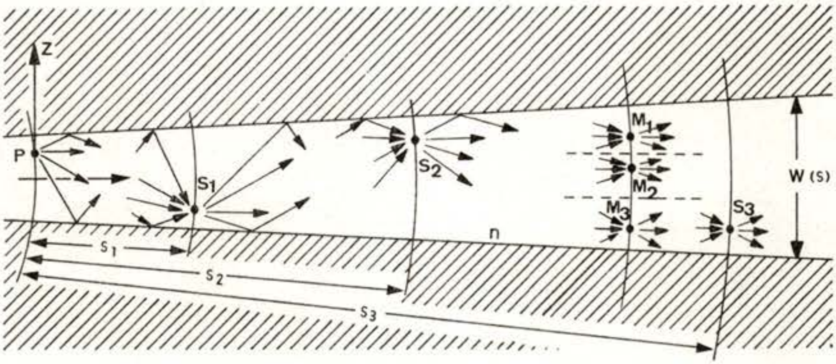

Fig. 1 — Cross-section of a planar optical guide.

The object P forms single self-images S_j and multiple self-images like M_j.

The positions of the self-images along the guide are characterized by an imaging parameter [3]:

$$h = s\ \lambda / 4\, n\ W_a(0)\ W_a(s) \qquad (1)$$

where s is the radial separation of object P and image, λ is the vacuum wavelength, and n is the refractive index of the guide material. W_a is the active thickness of the guide, equal to the local physical thickness corrected by the Goos-Hänchen penetration. On a surface characterized by $h = p/q$, where p and q are small integers with no common factor, q separated sub-images are formed. The self-image has a magnification factor equal to $W_a(s)/W_a(0)$. In a uniform guide (W = const), the single self-images have unit magnification and lie equidistant at:

$$S_h = 4\ h\ n\ W_a{}^2 / \lambda \qquad (2)$$

It should be noticed that the device is reciprocal, and can function with both coherent and incoherent illumination provided the source is sufficiently monochromatic or means for wavelength separation are taken into account.

To study some applications of the self-imaging property to multimode optics, we used a glass slab as the waveguide (Deckglas, D236, Deutsche Spezialglas AG).

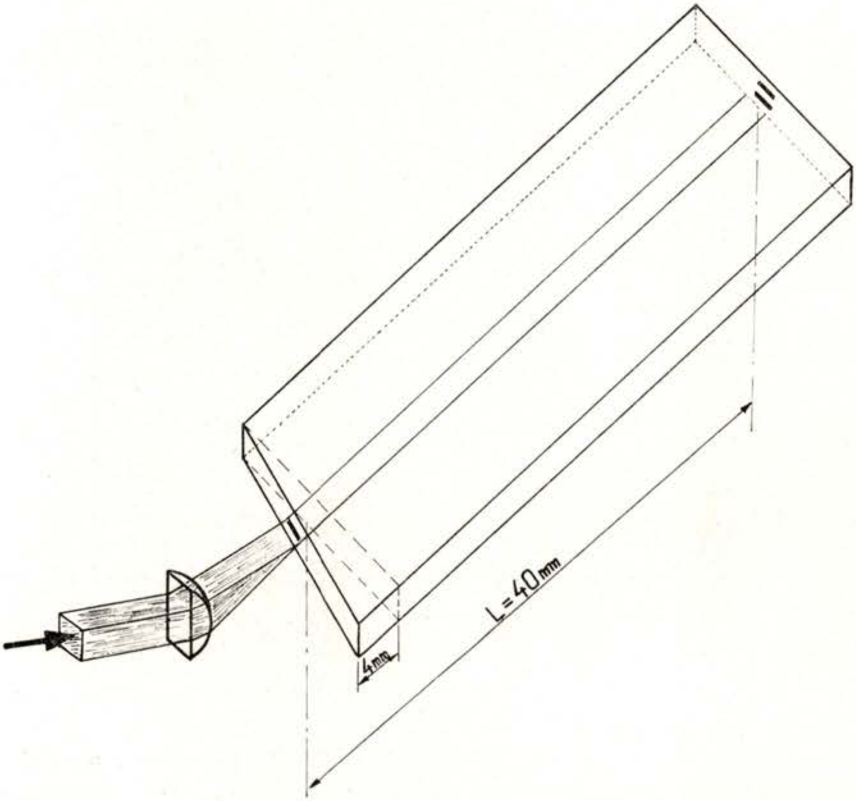

Fig. 2 — Waveguide geometry for self-imaging.

While there are several possible methods of fabrication which could be investigated we have chosen a polishing technique in view of simplicity. A stack of plates is formed by waxing together about ten glass sheets cut to size. It is obviously essential that all the plate edges are of good optical finish and this is checked by inspection.

In a typical experiment we used a sheet of glass, $n = 1.5217$ at $\lambda = 0.6328$ μm with a thickness of 185 ± 5 μm. To verify the self-imaging condition we carried out experiments using a tunable dye laser source ($0.56 \div 0.62$ μm). The waveguide endfaces were made oblique, Fig. 2, to provide an easy way for adjustement of the waveguide length. It has been possible to observe the formation of multiple self-images, Fig. 3 with a resolution better than 5 μm.

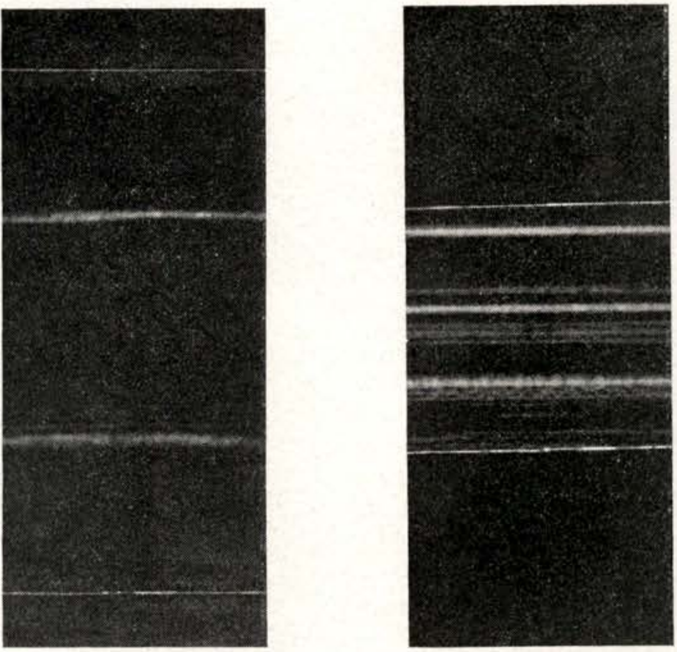
(a) *(b)*

Fig. 3 — Multiple self-images in glasse sheet planar waveguide.
(a) $h = 1/2$, $W_a = 185 \pm 5$ μm *(b)* $h = 1/3$, $W_a = 185 \pm 5$ μm

3 — MINIATURIZATION BY REFLECTIVE MEANS

Practical applications in multimode systems require that the overall device size should be kept small enough to be incorporated as an integral part of the system. Furthermore, the thickness of the plate must be at least twice the core diameter of the optical fibre. The optical path of the beam becomes then rather lengthy. A compromise can be found by folding over the optical path by recourse to multiple reflections as reflective optics can be made non-dispersive of the propagating mode spectrum.

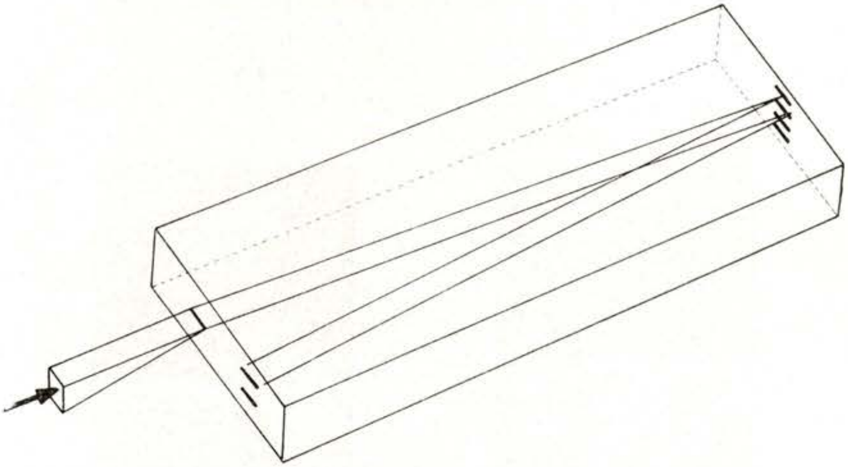

Fig. 4 — Reflective means to the miniaturization of self-imaging devices

We conducted experiments that show the formation of self-images following multiple reflections, Fig. 4.

In addition, it is expected to be possible to use total internal reflection for the sake of simplicity of design, Fig. 5.

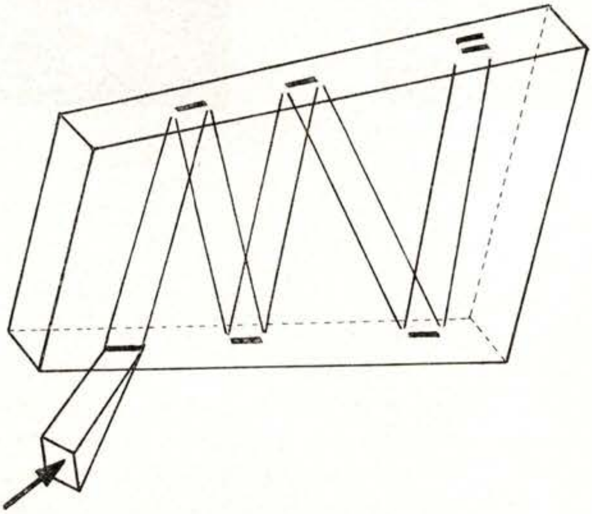

Fig. 5 — Miniaturization by recourse to the total internal reflection for self-imaging devices

4 — TWO-DIMENSIONAL IMAGING BY FOCUSSING

Self-imaging for a *planar* dielectric guide provides a mechanism for imaging the input beam into one or multiple real images in one--dimension. Correspondingly, in a *rectangular* waveguide, highly overmoded in both transverse dimensions real images can be formed when equation (2) is satisfied for both transverse dimensions [8]. A device based in this doubly self-imaging rectangular waveguide presents manufacturing tolerances that makes it unattractive. Alternatively, we sought a design using reflective means. A cylindrical mirror can realize the focussing in a transverse direction. A spherical cylinder offers a simple geometry and consequently an easy fabrication technique. However, an elliptical cylinder offers the following advantages:

- i) The aberrations can be controlled as they vary inversely with a certain power of the radius of the osculating sphere [9], which can be made large.
- ii) Total internal reflection is praticable.
- iii) Input region is largely separated from the output area.
- iv) The input aperture can be made different from the output aperture.
- v) Manufacturing tolerances are relaxed, and adjustment of imaging condition is simplified.

The advantages of using an elliptical cylinder seem thus to outweight the inconvenience of going to aspheric surfaces.

5 — BRANCHING COUPLERS

To expand communications with optical fibres further developments in branching, coupling, multiplexing and demultiplexing devices are needed. In some application areas such as the data bus and the data link, there is a strong requirement for tapping a portion of the optical signal from a main transmission line fibre (branching) or inserting another optical signal into the fibre (coupling) [10].

One configuration of a representative application of self-imaging to a branching device is schematically shown in Fig. 6, where the

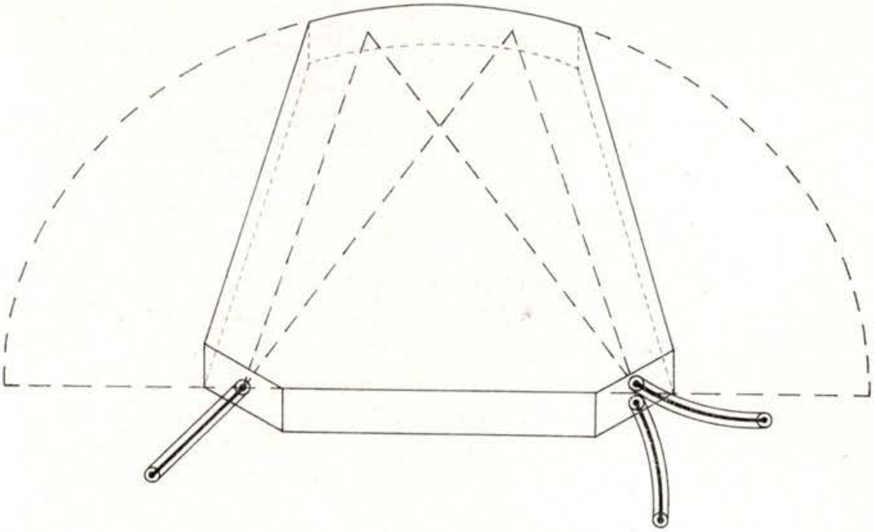

Fig. 6 — Configuration of a branching coupler.

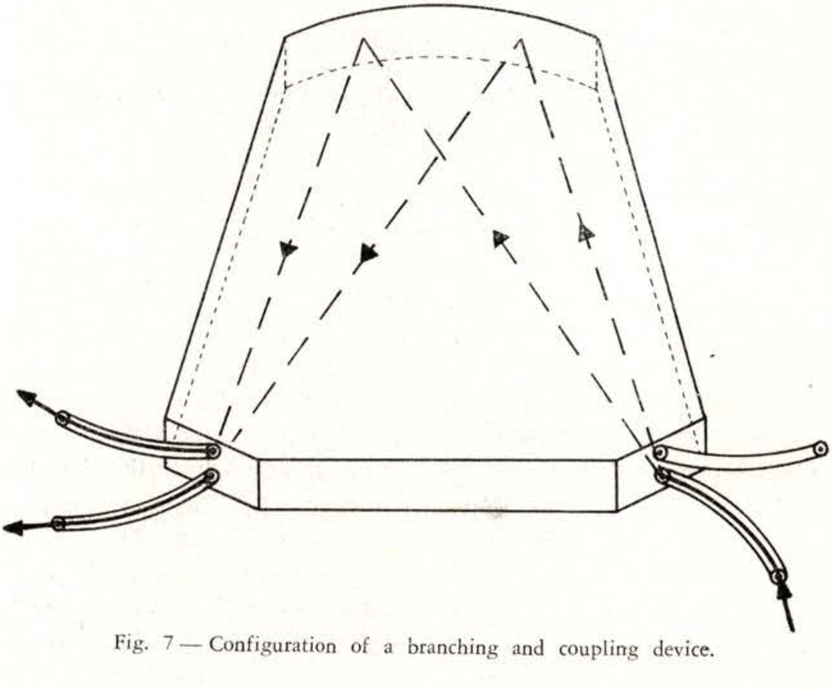

Fig. 7 — Configuration of a branching and coupling device.

signal from an optical fibre is branched into two optical fibres. Reciprocal operation of this device conducts to a 3 dB loss. However, the design can be modified to realize a bi-directional coupler as can be clearly seen from Fig. 7.

6 — OPTICAL MULTIPLEXER

One way to increase the information capacity of optical fibre transmission systems is by multiplexing signals at several different wavelengths on a single fibre [6].

The introduction into the device design of a dispersive element could be explored to make a multiplexer. The device is reciprocal, and could function either as a multiplexer or as a demultiplexer. Fig. 8 illustrates a type of multiplexer-demultiplexer design using a reflection grating.

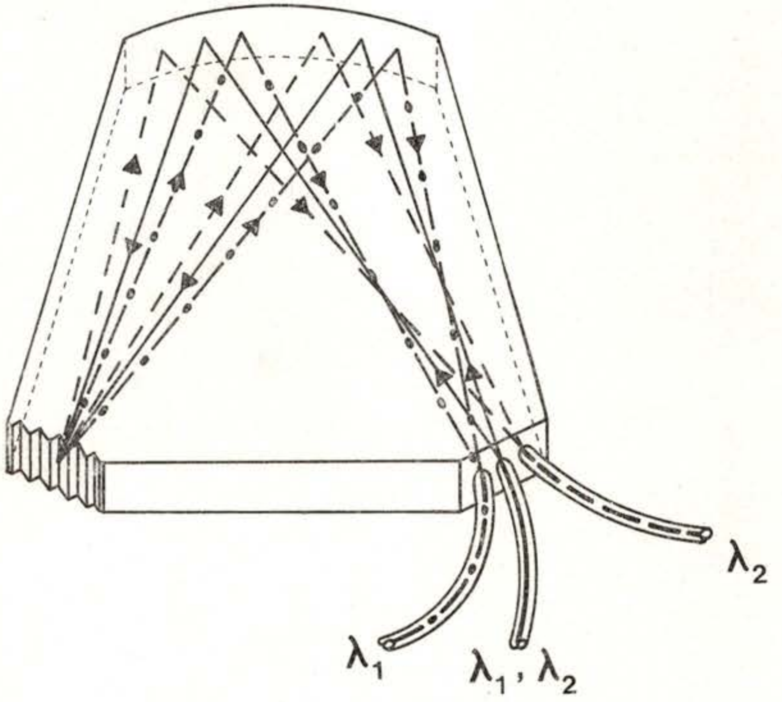

Fig. 8 — Basic design of a multiplexer using self-imaging and reflection grating.

7 — CONCLUSION

Self-imaging in solid planar waveguides has been demonstrated. Reflective means have been introduced for miniaturization.

An elliptical cylinder design has been briefly analysed to produce a two-dimensional imaging device.

A novel principle for the implementation of branching couplers and multiplexer devices for multimode fibre transmission systems has been described.

Further experimental and theoretical analysis is required to define the aberrations and imaging resolution, to assess the losses and undesirable cross-talk in the transmission, and to establish manufacturing tolerances.

Material studies should be considered to find an appropriate fabrication technology which could include the novel plastic optics area.

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