Short Communication

Transmission technique for planar film index-profile measurements

A simple technique that provides the index-profile of multimode optical fibres, the so-called near field technique, has been proposed by Gloge and Marcatili [1]. A modification of that technique that does not require the source to be Lambertian was proposed independently by Arnaud and Derosier [2] and Sumner [3]. According to that 'transmission' technique, the light from a coherent source is focused on the optical fibre core, and the total transmitted optical power is measured. One can show that the transmitted power collected is proportional to the difference between the refractive index at the point where the light beam is focused and the cladding index, except for small corrections due to slightly leaky rays [4] and wave-optics effects [2].

In integrated optics, the wave-guiding films usually carry few modes in their depth, and the transmission (or near-field) techniques are not applicable because these techniques rest on the WKB approximation which assumes that a large number of modes is transmitted. Very recently, a new technique was reported by Chartier *et al.* [5], which allows the fabrication of thick films that can carry hundreds of modes. It is an intriguing question whether the transmission technique can be applied to such films. We report, to our knowledge for the first time, that the transmission technique is indeed quite suited to the measurement of the index profiles of thick planar films. However, for thick planar films, the transmitted power is proportional to the *square root* of the difference between the film index and the substrate index (Fig. 1a).

The theory of operation differs somewhat from the theory presented, for example in [2] for circularly symmetric fibres, because, in planar films, not all of the rays are collected, as Fig. 1b shows. Rays that go beyond the detector boundary are absorbed rather than reflected.

The theory that follows is based on ray optics. Let **k** denote the local wave vector with length $k(x) = (\omega/c)n(x)$, where ω/c is the free-space wavenumber. Let a particular ray excited by the source focused at some location x of the film be defined by a vector **k** with rectangular components k_x, k_y, k_z (Fig. 1a) we have

$$k^2(x) = k_x^2 + k_y^2 + k_z^2. \tag{1}$$

The condition that a ray is not absorbed by the substrate is

$$k_y^2 + k_z^2 > k_s^2 \tag{2}$$

where $k_s = (\omega/c)n_s$, n_s being the substrate index. If Equation 2 is fulfilled, rays are necessarily reflected at the air–glass interface. Because the detector subtends an angle $2\alpha \ll 1$, only those rays that fullfil the condition $|k_y/k_z| < \tan\alpha$ are collected. Approximately, $k_z \simeq k_s$, which means that $|k_y|$ is bounded by a constant that we shall call k_{ym}. From Equations 1 and 2 we have

$$|k_x| < [k^2(x) - k_s^2]^{1/2}. \tag{3}$$

On the other hand: $|k_y| < k_{ym}$. If the source excites rays isotropically, at least within the small acceptance angle of the film, the collected power is proportional to the rectangular area defined above in the k_x, k_y-plane. Thus, the measured intensity is proportional to:

$$I(x) = [k^2(x) - k_s^2]^{1/2} \propto [n(x) - n_s]^{1/2} \tag{4}$$

because the relative index change $\Delta = 1 - n_s/n(0)$ is small, typically 1%.

The ultimate resolution is limited, as in the case of fibres, by wave optics effects to roughly $\lambda_0/n_s\sqrt{(2\Delta)} \simeq 2\,\mu\text{m}$ in the visible [2]. In the present case there is no need for slightly leaky ray corrections.

Fig. 2 gives the details of the experimental set-up. In order to get a small spot size the source must be spatially coherent in the x-direction, but not necessarily in the y-direction. Thus a thin tungsten wire sufficiently far away from the focusing microscope objective is a suitable source. In fact, we used a tungsten ribbon imaged on a $100\,\mu\text{m}$ wide slit (F_1 in Fig. 2), 210 mm from the microscope objective. The proper focusing on the polished input face of the film is achieved as usual by reverse illumination. The aperture A shown in Fig. 1 is in fact carried to the object plane F_2 in Fig. 2. The detector should have good uniformity over a broad area. In our set-up, we found it practical to use diffusing screens and small area

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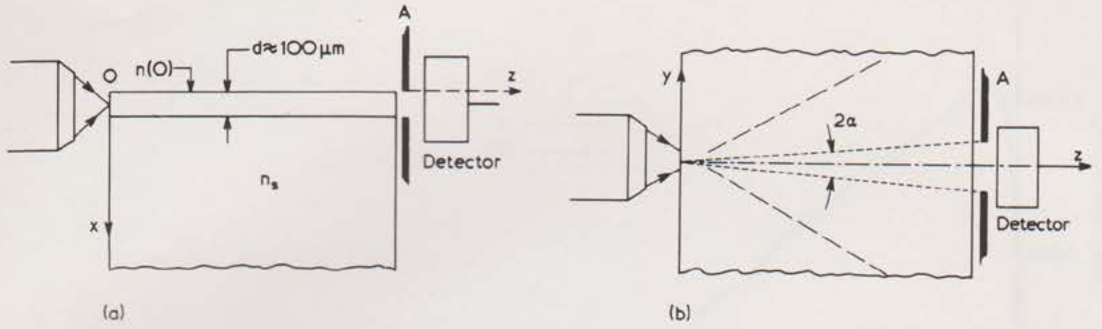

Figure 1 Schematic of the measurement system. The film thickness is $d \simeq 100\,\mu\text{m}$. (a) sideview, (b) topview; only part of the transmitted power is collected. The rough sides shown by a wavy line are made as perfectly absorbing as possible.

detectors. Let us emphasize that if the condition of detector uniformity is not fulfilled, large spurious oscillations are found in the $I(x)$ response. In our set-up, the $I(x)$ profile was automatically recorded.

The samples tested are 20 mm in length (z-axis), 15 mm in width (y-axis) and 1 mm in thickness (x-axis). There are two higher index films obtained by diffusion of lithium, one on each side of the glass microscope slide [5]. Input and output faces are polished. The other faces are coated with a mixture of cedar oil (70%) and smoke black (30%) to absorb the spurious rays. When the film is illuminated on one side, one can check that a proper absorption of the spurious rays has been achieved by looking at the power carried by the opposite film. Note that the two films are 800 µm apart, and cannot be coupled to each other directly, but only by spurious rays.

The input microscope objective being scanned mechanically, the transmitted power is recorded and processed according to Equation 4. The resulting index profile $n(x) - n_s$ is shown in Fig. 3 as a function of depth below the air–glass interface. The total lithium diffusion length is 100 µm on that sample. The fact that the method affords a good resolution is demonstrated by the high slope at the air–glass interface. We believe that the resolution could be improved by a better polishing of the input face. The vertical scale is obtained by measuring the divergence angle of the output optical beam. We found $n(0) - n_s =$ 0.011. The profile obtained as described above agrees extremely well with the profile obtained by measuring the so-called M-lines [5]. The measured value of Δ also agrees with the M-line result [5].

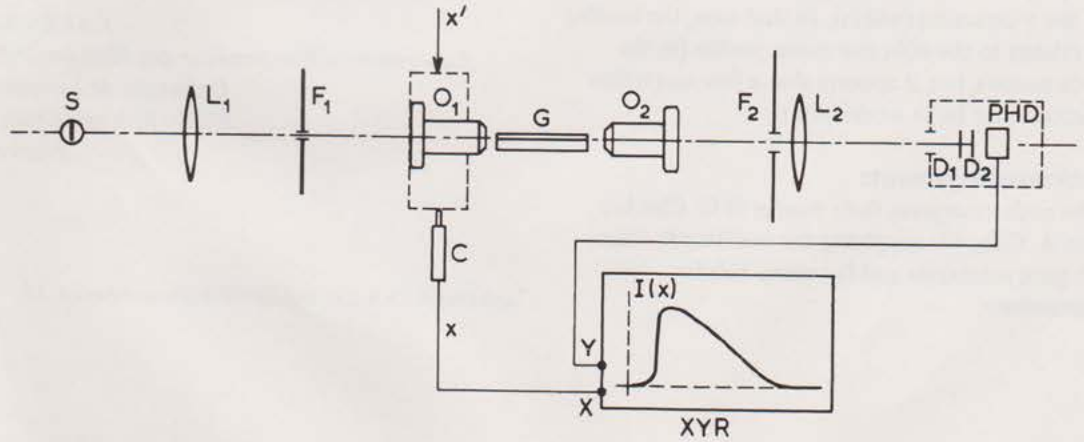

Figure 2 Details of the planar films measuring system. S, tungsten lamp; G, planar guide; L_1, achromatic condensor; O_2, output objective (× 20, ON = 0.35); F_1, slit (0.1 mm wide); F_2, slit (3 mm wide); O_1, input objective (× 40, ON = 0.65) translatable in the x-direction; L_2, field lens, D_1, D_2, diffusing screens; C displacement gauge; PHD, photodiode; XYR, X–Y recorder.

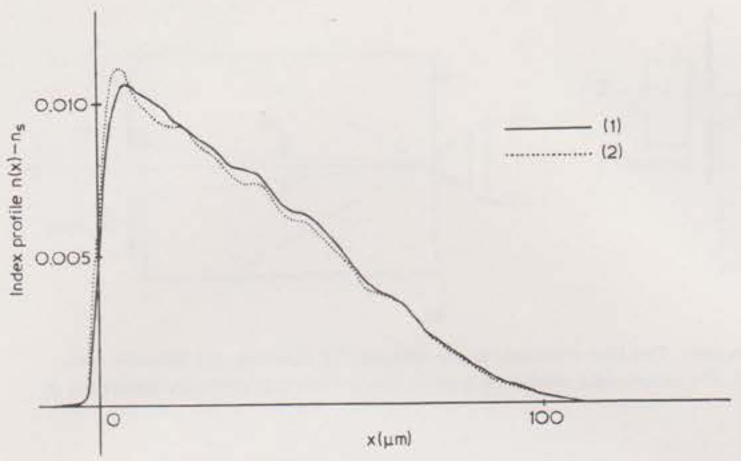

Figure 3 Index profile measured with the transmission technique on a lithium-diffused film on glass. Excitation from both ends (1 and 2).

The transmission technique reported in this communication was shown to be very useful in measuring the index profile of thick (multimode) films and to be very accurate. It requires only conventional optical sources (which can be frequency filtered for better definition of the central wavelength) and conventional detectors. This technique can be used for buried waveguides for which the M-line technique is not applicable because of poor coupling. It can be used also for films that are single-moded in the x-direction (depth) but limited transversely and multimode in the y-direction (width). In that case, the reading is related to the *effective* index profile (in the y-direction), but it appears that a few correction factors need to be worked out.

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