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Review

Optical waveguide theory

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This report summarizes the activites at the 4th International Workshop on Optical Waveguide Theory, held at Leuwenhorst Holland on 13–16 September 1979.

1. Introduction

Because the Optical Communication Conference is mainly concerned with applications it is most useful for research workers in the theory of optical propagation to be permitted to discuss separately the most advanced concepts and results, and subsequently share their knowledge and interest with the fibre optics community. The fourth workshop, which was held in Leuwenhorst, Holland, before the Optical Communication Conference of Amsterdam, fulfilled just that need, as did previous workshops. (For a report of the 1978 workshop see [1]).

The 4th workshop was organized by Professors Blok, Felsen and Unger. Mr Beekhuizen made the administrative arrangements. It was attended by thirty-two people coming from ten countries. There were five sessions entitled as follows: I, Realistic modelling of fibres A (Marcuse, Midwinter); II, Basic problems in optical waveguide theory (Ulrich, Snyder); III, Numerical, asymptotic and ray methods (Felsen, Blok); IV, Statistical aspects (Arnaud); V, Realistic modelling of fibres B (Marcuse, Midwinter). As you can see, realism was there from the beginning to the end!

I will present the results of the workshop, not in the order shown above, but according to potential applications, namely: multimode fibres; monomode fibres; and integrated optics. To be sure some theories and techniques are general enough to fit under many headings, but it seems appropriate to discuss asymptotic techniques, for example, under the heading 'multimode fibres with moderate V-values', because, on the one hand, the accuracy of uniform asymptotic techniques is questionable for monomode fibres, while, on the other hand, more conventional ray (or WKB) techniques appear to be sufficiently accurate for highly multimoded fibres (large V-numbers). In the following report, the names of authors actually present at the workshop are given in bold letters.

2. Multimoded fibres

Let us consider circularly symmetric multimode fibres. I will discuss first 'exact' numerical methods, since it is against such techniques that approximate analytical forms are best judged. The exact Maxwell equations can be written in the form of a radial differential equation for the E_ϕ, H_ϕ, E_z, H_z field components that are continuous at the interfaces (**Block** [2, 3], **Di Vita** [4]). A quite different formulation, called the propagating beam method was proposed by **Fleck** [5] (so far in scalar form only). It consists of evaluating the transformation of some incident beam along the guide axis (z), with the help of a parabolic wave equation. A Fourier transform with respect to z provides the propagation constants and time delays of the modes, with surprisingly good accuracy.

Ray techniques remain, however, simpler and more economical. They are applicable, except perhaps for near-to-cut-off modes and in the case of fast radial perturbations of the index profile; steps or narrow index dips, when the V-number exceeds about 20. The advantage of ray techniques, whenever applicable, is to lead to analytical formulas and to provide pleasant visual aids. This subject was reviewed by **Marcuse** [6]. The newer

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analyses (**Geckeler** [7]) take into account a possible non-linearity in the relationship between $dn/d\lambda$ and n as the dopant concentration varies (nonlinear dispersion). The theory says that, whatever the dispersion may be (linear or not), there is always an index profile that equalizes the times of flight for all paraxial rays. But this optimum profile usually varies with the carrier wavelength. A number of proposals have been made to synthesize fibres that would be good over a broad frequency range. Some experimental verifications have been reported (see [6]) but some uncertainty remains. This is perhaps because there is little agreement between the measurements available today, as far as dispersion is concerned [8]. This situation is compounded (or perhaps explained) by the stress-induced effects reported by **Scherer** [9]. **Scherer**'s calculations of the thermal history of fibres with GeO_2 doping indicate changes of index of the order of 10^{-3}, and stress induced anisotropy (n_r versus n_ϕ) of the order of 10^{-4}. These effects are small but not negligible.

Midwinter expressed the view that, on the one hand, multimode fibres may well be superseded in the near future by monomode fibres for transmission capacities exceeding 140 Mbit s^{-1}, and on the other hand, economics operate against sophisticated fabrication techniques. The following question is therefore put to us: Is it worth trying to determine an optimum doping profile, with a bandwidth of, say, 10 GHz km over a broad wavelength range, or should we be happy with what we presently have, that is, roughly 0.5 GHz km from 0.8 to 1.2 μm? It should be noted that if fibres with very high germania content (or even pure germania) in the core are made according to some recent proposals, one must be very careful about dispersion properties, if we simply want to get decent bandwidths.

Non-circularities in the profiles would not be bad in themselves if they were carefully controlled (**Pask** [10]). At the moment, however, they appear as accidental uncontrolled departures from a nominally circular shape. All exact numerical techniques available today that can solve the problem are very time-consuming. It is easy enough to trace rays, but one does not know in general how to relate these rays to modal propagation constants of given mode numbers. For most profiles (e.g., for 'stadium' contour step-index fibres) rays exhibit stochastic motion, and fill up some volume of phase-space. Nevertheless **Scheggi** [11–13] has shown that in the special case where $n(x, y)$ is a constant along a set of confocal ellipses, one can define caustics. These caustics are in general non-confocal ellipses or hyperbolae except in the case of step-index fibres where the caustics are confocal ellipses or hyperbolas. An interesting approach to multimode non-circularly symmetric (and non-separable) index profiles is that based on adiabatic invariants (Solov'ev [14]). This approach however, was not discussed at the workshop.

An interesting issue had been raised by Petermann at the previous workshop. Petermann gave a ray optics argument that suggests that slightly leaky rays should leak out very quickly for near square-law fibres* that depart, even slightly, from circular symmetry. This conclusion is now supported and refined by the ray optics calculations of **Adams** and others [15, 17], **Jacobsen** and **Scheggi** [12]. The actual loss, however, has not been calculated.

The problem of axial non-uniformities is important since it explains the cabling loss and the near-square-root of length dependence of pulse broadening for long fibres (Personick). It was shown recently that ray equations give results identical to the power-coupled-mode equations in the continuum limit. However, as it was emphasized at the workshop (**Arnaud** [17], **Di Vita** [18]) and elsewhere (Shatrov [19]), one must use two mode numbers, radial and azimuthal, and not just one 'principal' mode number, because the modes of fibres with a power-law profile are not degenerate if $\alpha \neq 2$, and degenerate modes, if any, do not carry the same optical power. In fact, simple exact expressions were reported. For a step-index fibre with a uniform microbending spectrum, **Marcuse's** factor $R^2\mathcal{L}$ is found [17] to be precisely 0.74 dB. Note that, for axial laser excitation, the pulse width initially increases in proportion to the square of length.

When the fibre profile changes slowly with z, it is permissible to use the so-called 'adiabatic' approximation and to integrate losses and times of flight along each individual mode. A related but

*This effect is associated with the degeneracy that takes place whenever the azimuthal ray period divided by π is the ratio of two integers. For power-law index profiles, the critical values of α are 0.25, 2, 7, etc.

more difficult problem is that of different fibres jointed together. Here we must in addition take into account the mode coupling at the joints. Noticeable improvements in bandwidth with respect to naive expectations were reported by **Eve, Clarricoats** [20] and **Someda** [21]. **Midwinter**, quoting Olshansky and Keck's work, suggested that individual fibres be characterized by the surface: times of flight versus two numbers easily accessible to measurement, such as the radius of injection and the lateral angle, rather than just by the 3 dB-bandwidth, as is usually done.

Some of the fibre defects can be explained by scattering. **Yip** [22] reported improved formulae for dipole radiation into weakly guiding fibres. The modal noise and other coherent optics effects were discussed, but, in my opinion, much too briefly.

It was noted by **Di Vita** [23] that in Barnoski time-domain reflectometry, irregularities in Rayleigh scattering are virtually eliminated when one takes the ratio of the reflections (at the same z) from each fibre end.

One is sometimes tempted to reduce the V-number of a fibre in order to increase its bandwidth and yet, have a core radius that makes splicing somewhat easier than with monomode fibres. How low can the V-number be? One possible limitation to moderate or low V-number fibres is the existence of near-to-cut-off modes, because such modes usually have group delays that are very different from those of the far-from-cut-off modes. The uniform asymptotic series proposed by **Felsen** [1] and improved by **Arnold, Jacobsen,** and **Hashimoto** appear to be excellent tools to analyse such modes. **Jacobsen** has shown how the error in such series, error which is inherent to asymptotic expansions, can be reduced, and be quite small in many practical cases (for references, see for example, Ikuno [24].

In the preceding discussion, all polarization effects were ignored. It is now recognized that the so-called 'LP modes' are simply scalar modes to which an arbitrarily chosen linear and uniform polarization is added, and that these LP modes are not the true modes of the fibre, even in the weakly guiding approximation. **Snyder**'s [25] results exhibit the true modes of weakly guiding fibres, to the first order in $\sqrt{\Delta}$, V being held fixed. For arbitrary non-degenerate $n(x, y)$ profiles, the polarization for the two states associated with a given scalar mode are linear, uniform and mutually orthogonal.* The directions of polarization may be different for different modes of the same fibre. They are fixed only if the fibre profile exhibits a symmetry, e.g., for elliptical shapes. Because of degeneracy, the situation for circularly symmetric profiles is, in a sense, more complicated. It simplifies, however, if the fields are assumed to follow an exponential azimuthal behaviour (rather than sine and cosine) because, with that notation, the polarization is a function of radius only. In the limit of large V-numbers it is predicted in [26] that the polarization states of the true modes are almost circular. It is not clear whether **Snyder's** theory agrees with that conclusion.

3. Monomode fibres

Monomode fibres may well be the next generation of high capacity fibres, since their microbending and splicing problems do not appear to be as severe as was originally thought and since good lasers are coming up that are monomode at least in the transverse direction. For arbitrary cross-sections (some people say 'crazy shapes'), the finite element method reported by **Lagasse** [27] and others [28] seems quite appropriate. But the integral equation methods discussed by **Blok** are also applicable. **Snyder** discussed how the properties of many graded-index monomode fibres could be understood in terms of equivalent step-index fibres of appropriate radius and V-value. **White** analysed the dispersion properties of such fibres. **Stewart**'s refracted ray technique, although initially intended for multimode fibres, seems to be applicable to monomode fibres, with decent resolution.

For multimode fibres, the microbending loss is, to the first order, wavelength independent, but it strongly increases with wavelength for monomode fibres. By fitting the theoretical and experimental curves, **Suematsu** [29] found that the curvature power spectrum is close to Gaussian and used the result to predict the response of multimode fibres with the same outer diameter and

*This conclusion follows simply from the fact that (a) the transverse field is linearly polarized, and (b) one must be able to generate scalar modes with arbitrary polarization from a linear combination of the true modes, in the limit considered.

similarly cabled. It now appears (Dyott [30]) that for small core radii, polarization can be maintained in single mode fibres over long lengths by shape anisotropy, that is, by strong ellipticities in shape. Otherwise, strain-induced effects seem essential (Stolen *et al.* [31]). It is possible also to fabricate fibres with very low birefringence [32]). In any event, the field of monomode fibres appears to remain opened for refined and useful theoretical analyses [33–35].

4. Integrated optics

A new class of waveguides was introduced a few years ago, in which some modes can leak into slab modes. **Oliner** analysed the rib guide and found that only the quasi-TM mode survives, while the TE wave leaks out, with calculable losses. The application of these structures to injection lasers is well known (**Streifer**). Geodesic lenses are becoming popular, and are actually used in ultrasonic spectrum analysers. This class of lenses were reviewed by **Righini** [36, 37], while geodesic prisms (cones) were discussed by **Voges**, and thin film micro-optics by **Kersten** [38].

Last, but not least, beautiful experiments with biperiodic gratings were presented by **Ulrich**. He demonstrated that homogeneous (but anisotropic) slabs of bi-periodic gratings provide focusing, and also that incident beams get steered (directional changes) as the optical wavelength varies.* This all comes from the peculiarities of the k_x, k_y curves of biperiodic media, where **k** denotes the wave vector of a space harmonic. The feeling was expressed at the workshop that much more remains to be done on the theoretical side in integrated (planar) optics than on multimode optical fibres. A stronger effort on the analysis of integrated optics components would thus be justified if truly monomode monopolarization fibres can be fabricated economically as now seems to be the case. The general concept of radiating modes with lossy substrate may need clarification (**Vassallo** [40]).

5. Conclusions

To conclude, some theoretical puzzles have been resolved, but we still have to look with a critical mind at some of the approximations made in earlier theories. We need also consider the uncertainty existing at present in dispersion measurements and in the thermal history of the fibre before we can draw final conclusions. I would like to emphasize that a good job has been done at the 4th Workshop to evaluate and compare the merits and drawbacks of various numerical and analytical tools. The optical community should certainly guide us as to the need for more refined calculations on the basis of existing needs. But in my opinion one must keep also an eye on possible new breakthroughs in material studies; for example, the discovery of materials with extremely low loss or with odd dispersion properties, the feasibility (and desirability) of fibres with strongly non-circular geometries, and so on before discouraging seemingly academic studies.

I will give the final word to Professor **Felsen** who discussed (in verse) the ray against mode controversy. His poem ends in this way:

'The game is Science, laced with Art
There could not be a better start'.

*A similar effect had been pointed out for microwave beams in [39].

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