第7卷　第3期
2014年6月

中国光学
Chinese Optics

Vol. 7　No. 3
Jun. 2014

文章编号　2095-1531(2014)03-0499-10

Simple qualitative explanations for light guidance in index-guiding fibres, holey fibres, photonic band-gap fibres and nanowires

LOVE John
(*Physics Education Centre*, *College of Mathematical & Physical Sciences*,
Australian National University, *Canberra* 0200, *Australia*)
* *Corresponding author*, *E-mail*: *John. Love@ anu. edu. au*

Abstract: This is a tutorial-style paper in which simple explanations are presented to provide qualitative insight into the different physical processes that account for the guidance of light in the broadening spectrum of fibre types. These types include solid-material index-guiding fibres, holey fibres, photonic band-gap fibres and nano-wires.

Key words: light guidance; index-guiding fibres; holey fibres; photonic band-gap fibres; nanowires

光导在折射率引导光纤、多孔光纤、光子带隙光纤和纳米线中的简要定性解释

LOVE John
(澳大利亚国立大学 数学与物理科学学院 物理教育中心,堪培拉 30419, 澳大利亚)

摘要:本文是一篇教学论文,旨在通过对具体实例中不同物理过程的分析来定性解释光导拓宽固体材料折射率引导光纤光谱、多孔光纤光谱、光子带隙光纤光谱和纳米线光谱的原理。

关　键　词:光导;折射率引导光纤;多孔光纤;光子带隙光纤;纳米线
中图分类号:TN252; TN253　　**文献标识码**:A　　doi:10.3788/CO.20140703.0499

收稿日期:2013-10-11;**修订日期**:2014-02-13

1 Introduction

The increasing use of glass in optical fibres of various types has become an increasingly significant part of our technological development since the late twentieth century. Glass fibres themselves have probably been known since the accidental discovery of glass several thousand years and the inevitable drawing of a piece of hot softened glass into a thin thread; probably something that most of us have performed at some time in our lives in a school or university laboratory.

1.1 Glass fibre dresses

However, the first fabricated glass fibres were not used for optical communications. In fact they were produced commercially for weaving into very expensive, full-length, flashy dresses not too dissimilar to the more modern one depicted in Fig. 1. Such dresses were worn only by the ladies of the wealthiest Victorian families in London towards the end of the nineteenth century. Apart from fabrication, the sheer cost of making these dresses with what would have been then extremely fragile fibres made them affordable only to the upper classes and would have cost the order of one million yuan even in those days[1]. Interestingly, clothing that incorporates fibres has become popular again, at much more realistic prices and using less fragile and cheaper polymer-based optical fibres.

Fig. 1 Fibre-based illuminated dress

The glass fibres used in these dresses were crudely made single-material fibres but the high light absorption and poor uniformity of the glass employed would have rendered them virtually useless for propagating light over any significant distance. Besides, there were no suitable sources of intense light generation available that could be used for exciting the relatively minute size end-faces of the fibres, nor were there any sufficiently sensitive devices for detecting the low-level light output at the far end of any very long length of fibre.

Historically the first recorded laboratory demonstration of the ability of a transparent material to guide and contain light over a short distance occurred in 1841 at the University of Geneva in Switzerland. This experiment was performed under the auspices of Professor Colladon but he did not use glass as the guiding medium. Instead Professor Colladon showed that a jet of clear water propagating in air could act as a light waveguide. He focussed a light source (carbon arc) into a container of water such that the beam excited light in the jet of water emerging from the opposite side of the container, as shown by the upper sketch in Fig. 2[1]. Interestingly, the same experiment was repeated thirteen years later by John Tyndall at the Royal Institution in London and has generally been recognised incorrectly since as the first demonstration of light guidance.

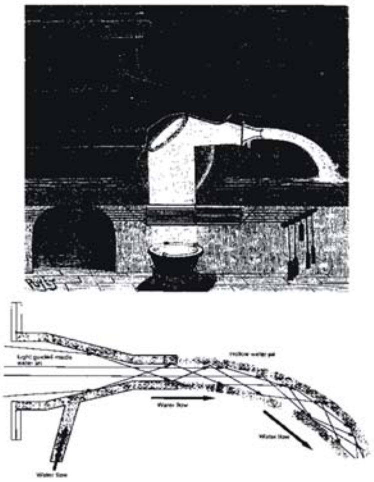


Fig. 2 (upper) Experimental set-up for the experiment and (lower) segmented straight- line ray paths in the water[1]

The water jet emerging from the side of the container curved downwards under gravity following a parabolic path and some of the light followed the path as segmented straight-line paths shown by the lower sketch in Fig. 2. Light rays propagate along straight lines inside the water jet that has a uniform refractive index of 1.333. At the surface of the jet, the index decreases abruptly to that of air with an index of 1. Snell's Laws tell us that any ray impinging on the water-air interface at an angle greater than the critical angle relative to the normal to the interface is totally reflected back into the water and then reflected again the next time it hits the interface. For water and air, the value of the critical angle is given in radians by the inverse sine of the ratio 1/1.333, equivalent to 48.6 degrees.

For such a large critical angle value, a significant fraction of all the light entering the jet from the source would be reflected at this interface, while the remainder is partially refracted out of the water at every reflection along its path and eventually totally lost into the air. It is the refracted light emerging from the side of the jet that enables us to see the path of the light in the jet. If there were no refracted light, the presence of the light propagating in the jet could not be verified by observation from the side of the beam.

At the time, this pioneering demonstration of light guidance was of little use for any practical application of light guidance for communications purposes and remained a physical curiosity for many years. However it did see artistic applications such as the illumination of water fountains at Victorian expositions. This was a precursor to the illuminated plastic fibre light sprays that were commonly found in family homes in the 1970's and still appear in various guises today, such as Christmas tree decorations.

1.2 Endoscopy

There was little progress with the development and application of fibre light guiding of any sort until the 1930's when a German scientist, Herbert Lamm, used a small bundle of identical thin single-material glass fibres in a laboratory demonstration to transmit a complete image of a simple object (he used the English letter "vee") over a very short distance. This can be gauged from Fig. 3[2]. Lamm's experiment was fairly crude but it clearly demonstrated the principal involved.

Physically, the left hand end-face of each thin fibre in the short bundle held between the two retort stands in the upper drawing in Fig. 3 can be thought of as a guide for a single pixel. Each pixel accepts part of the incident image generated by the cylindrical light source and adjacent object just to the left of it, and then guides the pixel unperturbed to the far right hand end of that fibre. Provided the fibres are of equal length and are coherently bunched together, i. e. each fibre keeps the same relative position in the bundle cross-section, and the output emerging from the fibres at the right hand end of the bundle should reproduce the input image incident at the beginning of the fibre. This basic result is clear from the two drawings in the lower part of Fig. 3.

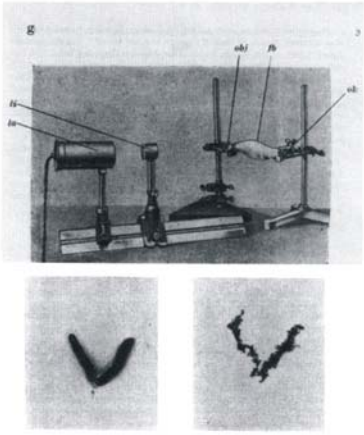


Fig. 3　Set-up of Lamm's apparatus (top), with object (lower left) & image (lower right)

This simple demonstration marked the beginning of modern endoscopy that uses essentially the same set-up with thousands of extremely thin fibres in the bundle to transmit very high-resolution pictures over several metres.

1.3 Communications fibres

Interest in using glass optical fibres for longer distance telecommunications increased rapidly fol-


Fig. 4 Professor Charles Kao

lowing the invention of the laser in the 1960′s. The laser is used here as a high-intensity, coherent light source that can be pulsed very rapidly (internally or externally) to produce a high-density steam of digital light pulses, ideal for long-distance optical communications. This proposal was further enhanced in the mid 1960′s by the pioneering optical fibre research of the Chinese scientist and 2009 Nobel Prize winner in physics, Professor Charles Kao (see Fig. 4). At that time Kao was conducting his research at Standard Telephones Limited (STL) just outside of London. Kao had proposed the simple idea of using very pure, low-loss, silica glass for the fabrication of long-distance communications fibres coupled to lasers.

However, whilst this combination of source and guidance would produce a dense stream of guided light pulses propagating with low loss over long distances, there remained a final basic obstacle. The simplest type of optical fibre comprises a narrow circular cross-section of flexible pure silica glass surrounded by air with light propagating over the entire cross-section, as depicted in Fig. 5. This fibre guides light because its core index is much larger than the index of the surrounding air and total internal reflection occurs at the interface between the two to keep the light in the fibre. Over any significant distance the fibre must necessarily be supported either continuously (with a coating) or discretely. Wherever support occurs, as shown in Fig. 5, light will necessarily leak out of the fibre into the support material. One way to avoid leakage is to introduce a central layer of glass the core that has a slightly higher refractive index than the surrounding glass the cladding as shown by the double-material fibre in Fig. 6. This way propagating light is confined within and close to the core and does not reach the cladding-air interface.

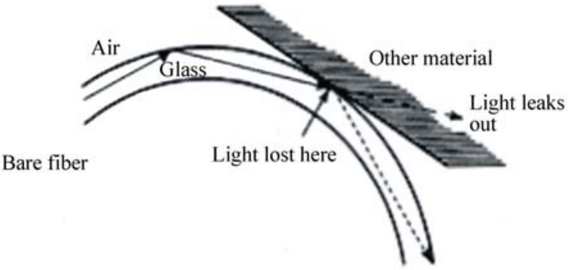


Fig. 5 Single-material fibre

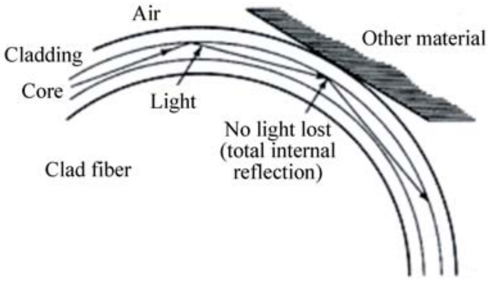


Fig. 6 Double-material, core & cladding fibre

1.4 Single-Mode and Multimode Fibres

We need to distinguish between two basic types of glass fibres, or more generally, solid material fibres. This delineation relates to the radius of the core, wavelength of the light and the core and cladding refractive indices. For small core sizes, typically around 5 microns radius, these fibres are categorized as single-mode fibres for reasons that will become clear in Section 3. For large core radii, typically around 50 microns or larger, these fibres are categorized as multimode fibres again for reasons that will become clearer in Section 3. Historically, multimode fibres were the first type of fibre to be produced commercially in the 1970′s, mainly because of the ease of fabrication, while single-mode fibres that now dominate communications networks appeared in commercial quantity several years later.

1.5 Step- and graded-index fibre profiles

Optical fibres generally have a cladding with a uniform refractive index glass, typically pure silica glass, but the core may have either a uniform refractive index, in the case of a step-profile fibre, or an index that varies across the core in the case of a graded-index profile fibre. An example of a graded index fibre is the parabolic profile for which the core index has a maximum on the fibre core axis core and decreases with a parabolic slope towards the cladding. In both the cases the core index needs to be larger than the cladding index to ensure light guidance along the fibre.

Understanding light propagation in multimode fibres is more straightforward than that in single-mode fibres because the relatively large core dimension compared to the wavelength of the light source employed, typically 0.5 – 1.5 μm, allows the adoption of ray tracing techniques to determine the light path that are independent of the source wavelength. This is explained in Section 2. On the other hand, propagation along single-mode fibres is much more sensitive to the source wavelength and core size, and therefore requires a full electromagnetic analysis to accurately determine their propagation properties. This is outlined in Section 3.

2 Propagation along index-guiding fibres using ray tracing

When a light source, such as an LED illuminates the end-face at the beginning of a multimode fibre, the LED output is assumed to excite all possible ray directions within the fibre core. Furthermore an LED is an incoherent source that ensures that all ray directions can be assumed to be equally excited, i. e. every ray carries the same amount of power at the beginning of the fibre. The evolution of the light distribution along the fibre then depends only on the ray path. If the path is that of a bound ray, then the power carried by those rays remains constant along the fibre in the core but if it is that of a refracting ray, then power is lost by refraction at every reflection from the cladding until eventually there is essentially no power left in that ray.

2.1 Step-index profile fibres

In applying Snell's Laws of reflection formally to rays propagating along a periodic zig-zag path in the core of a fibre, one would expect that a simple angular delineation between bound rays and refracting rays would emerge. If the wavelength of light were zero, this conclusion would be correct, but because of the small, but finite wavelength of all practical light sources coupled with the curved interface of the fibre between the core and the cladding, a blurring of the strict delineation of Snell's Laws needs to be taken into account.

Consider a ray in the fibre core incident from the left at the point P on the core-cladding interface at angle θ_z relative to the fibre dashed axis or, equivalently angle α relative to the normal PN at P in Fig. 7 where $\theta_z = \pi/2 - \alpha$. Snell's Laws correctly predict that the ray will be partially reflected and partially refracted if α lies within the range

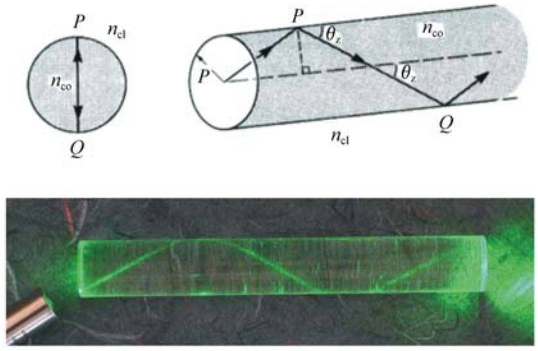


Fig. 7 (Top) The predicted zig-zag path of a straight-line bound ray in the core of the fibre & (bottom) the same path excited by a laser beam in a cylindrical plastic rod

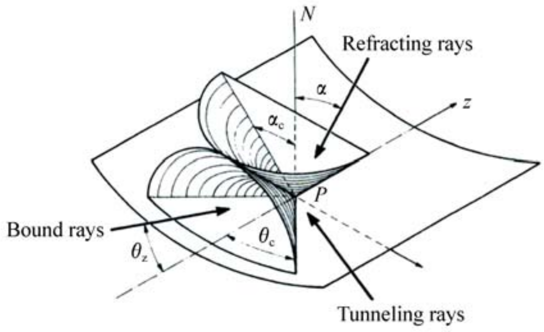


Fig. 8 Delineation between rays incident on a curved interface

of directions contained within the vertical half-cone with semi-vertical angle α_c, where $\alpha_c = \sin^{-1}(n_{cl}/n_{co})$ is the critical angle. However the remaining ray directions do not all define bound ray directions that are reflected from the interface. Bound ray directions belong to the horizontal half-cone with semi-vertical angle θ_c, where $\theta_c = \cos^{-1}(n_{cl}/n_{co})$ is the complementary critical angle, i. e. $\theta_c = \pi/2 - \alpha_c$. The range of directions lying between the two half-cones in Fig. 8 define rays that are neither 7 bound rays nor refracting rays and belong to a third class known as tunnelling rays[3].

Tunnelling rays are a type of leaky ray and lose power at every partial reflection from the core-cladding interface. However, unlike refracting rays where the refracted power follows a straight-line path away from the interface into the cladding, a tunnelling ray is evanescent at the interface and reappears as a straight-line ray a finite distance into the cladding.

Furthermore the direction of the emergent ray is rotated relative to the axis of the fibre. Depending on the tunnelling ray's incident orientation in Fig. 6, its leakage rate increases from zero on the surface of the lower half-cone of angles for bound rays to a finite value on the surface of the refracting rays half-cone.

2.2 Graded-index profile fibres

Ray tracing can be applied to multimode fibres with a graded-index core profile. All the basic properties of bound, refracting and tunnelling rays are similar to those for the step-index profile fibres in Section 2.1. The major difference is that the ray paths are no longer segmented straight lines and are replaced by successive curved paths. These paths are determined from a generalisation of Snell's Laws into a differential form that requires analytical or numerical solution of the eikonal equation [3, Ch.2].

3 Propagation along index-guiding fibres using electromagnetic modes

We saw in Section 2 how light propagation in multimode fibres can be analysed in terms of ray tracing. This technique provides an accurate general analysis of light propagation along the fibre because the core size of the fibre is very large compared to wavelength of the light source. Conversely in a single-mode fibre ray tracing is no longer an accurate technique as the light wavelength is not sufficiently large compared to the core dimension and electromagnetic theory is needed.

An electromagnetic analysis of the fields of a straight, longitudinally invariant optical fibre starts with either the current-free Maxwell equations for large core-cladding index differences or the scalar wave (or Helmholtz equation) for small core-cladding index differences (known as weakly guiding fibres), both leading to a boundary value problem. Matching either the vector or scalar fields, respectively, across the core-cladding interface leads to an eigenvalue equation for the propagation constant of each possible bound mode [3, Ch. 11].

The solutions of these governing field equations lead to a discrete set of electromagnetic fields that propagate along the fibre. Each field travels with a constant velocity and represents a bound mode of the fibre [3, Ch. 11]. Of prime importance is the condition under which only a single mode, known as the fundamental mode, propagates, since this is the basis of nearly all of the world's long-distance optical fibre networks.

For a nominally step-profile fibre with constant core and cladding index values, the single-mode condition can be expressed in terms of the fibre parameter V by

$$V = \frac{2\pi\rho n_{co}}{\lambda}(2\Delta)^{1/2} < 2.405 , \tag{1}$$

for core diameter 2ρ, (maximum) core index n_{co}, source wavelength λ and relative index difference $\Delta = (n_{co}^2 - n_{cl}^2)/2\, n_{co}^2$, where n_{cl} is the cladding index. For multimode fibres, this condition can be expressed as $V >> 1$.

The solution of the governing equations for the fields of modes can only be undertaken analytically for a small number of special fibre profiles [3, Chs. 12/15], but there is a range of software products available from a number of sources that generate accurate vector or scalar numerical solutions for almost any core index profile regardless of profile shape.

4 Holey fibres

Holey fibres, also known as micro-structured fibres or photonics crystal fibres, were introduced and developed on the optical fibre scene over the last 15 years. They have attracted significant interest for their many special light-guiding properties[4], but are unlikely to see wholesale application in long-distance communications mainly because of fabrication and associated application costs. As their name suggests, a holey fibre relies on light guidance using an array of air holes that run the length of a single material fibre fabricated from glass or polymer, as shown by the photograph in Fig. 9.

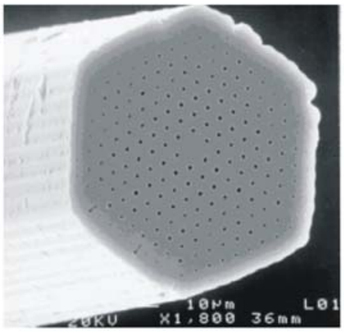


Fig. 9 Cross-section of an unclad holey fibre showing the array of air holes in a single material

As can be seen in Fig. 9, the centre or so-called core of the fibre is solid and omits the centre hole that would otherwise complete a symmetric holey distribution pattern. The precise arrangement of holes, the separation and size of the air holes is determined from a numerical analysis for the type of fibre required and the operating wavelength.

Traditional solid-material fibres have a core with some or all of its refractive index distribution higher than that of the uniform surrounding cladding in order to provide guidance for bound modes or rays as discussed in Sections 2 and 3.

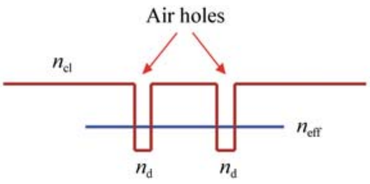


Fig. 10 Cross-section of the refractive index profile showing air holes with index $n_d = 1$ on either side of the core between them & the effective index of a mode, n_{eff}, lying below the index of the fibre material, n_{cl}

Holey fibres on the other hand cannot support bound modes or rays because light leaks away from the central core through the gaps between adjacent holes in Fig. 9 that have the same refractive index as the central core. This means that all modes of a holey fibre are necessarily leaky with an effective propagation index that has a value below the index of the cladding material as shown in Fig. 10. By increasing the air hole size and air hole density, the effective index becomes closer to the material index, thereby reducing the leakage loss. Equivalently all ray paths will leak because of the direct loss of light by propagation between the holes in the cladding.

5 Photonic band-gap fibres

The explanations presented in Sections 2 – 4 for light guidance in fibres are all based on index guiding, i. e. on the containment of light in the core due to the lower or effectively lower index of the surrounding cladding. Here an entirely different type of guiding mechanism is introduced that supports modal guidance regardless of whether the index difference between the two materials constituting the fibre core and cladding is positive or negative. This mechanism relies on the reflection properties of the classical Bragg grating.

A Bragg grating written into an optical fibre consists of a longitudinally periodic (e. g. sinusoidal) slight variation in the value of the refractive index along its core. Such a grating has the special property that a particular mode, usually the fundamental mode, can be reflected back along the fibre at a particular source wavelength whilst being transmitted at any other wavelength. In classical optics a Bragg grating can be thought of as a special mirror that reflects just one colour and transmits all other colours.

A simple photonic band-gap fibre, also known as a Bragg fibre, consists of multiple thin concentric layers alternating between slightly higher and slightly lower refractive index deposited about the central core, as shown schematically in Fig. 11. It is immaterial if the central core region has the higher or lower refractive index. All these layers constitute an axisymmetric radial Bragg grating or concentric cylindrical stack about the fibre core to provide light confinement within the fibre.

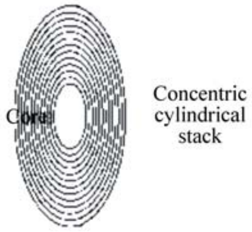


Fig. 11 Schematic cross-section of the multi-layered Bragg fibre

First consider the simpler problem of propagation of the fundamental mode along the Bragg fibre assuming that all the layers have the same refractive index. There would be no confinement in this uniform medium and classical diffraction would ensure that the modal field distribution spreads outwards symmetrically in the radial direction as it propagates. The radial velocity of this spread can be readily determined and in turn can be related to an effective transverse wavelength of the mode.

Returning to the Bragg fibre and its structure, the parameters for the stack indices, thicknesses can be determined so that the effective transverse wavelength matches the Bragg wavelength of the radial grating for a given source wavelength. In other words, the modal field remains confined close to the centre of the Bragg fibre because its radial propagating component is exactly reflected back towards the fibre centre and a standing cylindrical wave is set up in the cross-section.

6 Nanowires

Nanowires, also known as nanofibres, necessarily have a step refractive-index profile because of the nature of the fabrication process, with a core diameter that is generally less than 1 μm surrounded by air. They are single-mode fibres and hence the value of their V parameter must satisfy formula (1), where the cladding index $n_{cl} = 1$.

In a conventional solid material all-glass fibre, the relative index difference between the core and cladding materials is usually less than 10^{-2} (1%) with a core diameter of about 10 μm. For a nano-fibre with a glass core and the air cladding with $n_{cl} = 1$, the relative index is around 25% so that the single-mode condition on V for a 1 micron diameter core can be readily satisfied for standard fibre wavelengths.

Nanowires and fibres are attractive for their small cross-section and flexibility, allowing micron-size bends with low propagation loss. These properties enable the fabrication of extremely compact nano-devices, such as fibre ring resonators.

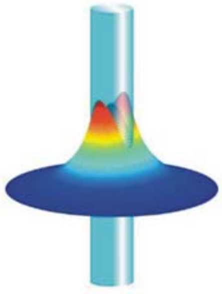


Fig. 12　Plot of the vector fundamental mode field intensity for the core & air cladding of a single-mode nanowire

Being single-mode, the guidance properties of nano-fibres cannot be investigated using ray tracing and must necessarily be analysed using a modal approach as discussed in Section 3. Unlike weakly guiding fibres with a relative small core-cladding index difference when a scalar analysis can be employed, the relatively large core-cladding index difference for the nano-wire requires a full vectorial analysis based on Maxwell´s current-free equations for accurate solutions. Such an analysis can be carried out analytically for the step profile[3] but in view of the ready availability of appropriate software programs, these days a numerical analysis would be much more straightforward.

7　Conclusions

In this paper, some simple explanations have been presented to provide simple qualitative insights into the various mechanisms that can be employed to guide light along different types of optical fibres and waveguides that are currently in use.

8　Acknowledgements

The author thanks the Editor for the invitation to write this paper and hopes it will be of some assistance to researchers and teachers working in the field of fibre optics and, in particular, to researchers entering this field. A special acknowledgement goes to the researchers from the University of Shanghai at Jardin, who between them translated the entire original English version of Optical Waveguide Theory that had been published in 1984, into the Chinese version published in 1991[3]. The material presented in Sections 3 and 4 above can be found in analytical detail in this reference.

References:

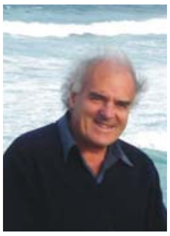
[1]　HECHT J. *City of Light*[M]. UK:Oxford University Press,1999.

[2]　LAMM H. Zeitshrift für Instrumentenkunde[J]. 1930,50:579-581.

[3]　SNYDER A W,LOVE J D. *Optical Waveguide Theory*[M]. English Edition-London: Chapman & Hall Press, 1984, 734. Chinese Edition-Beijing: Peoples' Post & Telecommunications Publishing Co,1991,924.

[4]　LARGE M,POLLADIAN L,BURTON G,*et al.*. *Microstructured Polymer Optical Fibres*[M]. Berlin:Springer Press,2008.

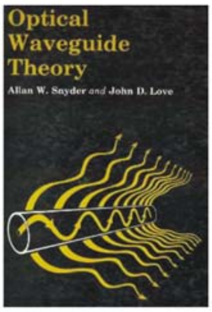
Biographies:

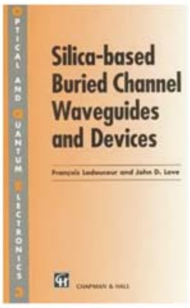


Professor John Love
MA, DPhil, DSc (Oxford)
MA, MMath (Cambridge)
Physics Education Centre College of Mathematical & Physical Sciences
The Australian National University(ANU)
Canberra, ACT, Australia 0200
E-mail:John. Love@ anu. edu. au, Phone: +61 2 6125 4691

Academic Background

My academic qualifications are in Applied Mathematics and I have worked in materials science, transport, commerce, astrophysics, plasma physics and aeronomy. I arrived at the Australian National University 40 years ago and entered the world of guided wave photonics and the early days of optical fibres. It was an exciting time as only a small band of researchers worldwide worked in the area and each development seemed a great leap forward. My first 10 years of theoretical research culminated in the publication of the now classic text "Optical Waveguide Theory" in 1984 with my colleague Allan Snyder. Remarkably this book is still in print with English, Chinese and Russian editions and has been cited more than 4 000 times. Further research into fibre and planar devices lead to the publication of "Silica-based Buried Channel Waveguides and Devices" in 1996 with my student François Ladouceur.





Current Research

Current research focuses principally on the design of passive fibre and planar light-processing devices for the excitation and detection of individual modes at the beginning and end of a few-mode fibre transmission systems. These developments include experimental fabrication and verification in collaboration with groups at the University of Sydney and Macquarie University in Sydney using holey fibre and direct writing technologies, respectively.

Teaching

Over the last 25 years I have developed and taught undergraduate and masters courses in guided wave photonics at ANU that include laboratory experiments as well as research projects and work experience with local companies. These courses cover a broad range of theory and applications and form the basis for the 1-year "Master of Photonics" degree, details of which can be accessed at: http://physics. anu. edu. au/education/master_photonics. php.