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# The Propagation of Light in Optical Fibers*

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## ABSTRACT

The technology of using glass fibers to carry signals impressed on light beams has grown exponentially over the past decade owing to the many advantages of this transmission medium. These include small size, low weight, high bandwidth and immunity to electromagnetic interference. Applications already realized range from telephone and television subscriber loops to data acquisition for nuclear weapons tests.

We have developed a very complete theoretical model of light propagation in optical fibers, which treats the total transmitted beam rather than individual modes of the system. The model allows us to study important aspects of light propagation in realistic fibers: spatial and angular confinement of the transmitted light, power losses due to absorbing jackets and splices, and bandwidth restrictions that result because the individual modes propagate energy with differing group velocities. In addition, we can retrieve a complete modal description of the light, i.e., find all the mode shapes and their corresponding wavenumbers.

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This model allows us to treat fibers with arbitrary refractive index profiles, with finite core and cladding regions, and with lossy components. It also serves as a check on more approximate theoretical methods. Excellent agreement with experimental results gives us confidence in the applicability of the model to real situations.

It is common knowledge today that telephone signals are being carried by light over hair-thin glass fibers. The growth of this technology, only a decade old, has been explosive. The Bell System is installing a 980-km fiber-optic trunk line along the nation's busiest communication route (between Boston and Washington, D.C.). Fibers are also being used to bring cable television to remote areas of Canada; to bring television, computer, and other information services to homes in Japan; and to provide airborne, shipborne, and battlefield communication links for the military. The largest planned system is an approximately 10,000-km network that will serve as the nervous system of the vast MX missile complex. At Lawrence Livermore National Laboratory, optical fibers are being used to carry data from Shiva laser fusion experiments and from nuclear experiments at the Nevada Test Site.

The idea of using light for communication is not new. A century ago, Alexander Graham Bell invented the photophone, a device that used modulated light beams to convey voice signals. Unfortunately, it and other similar devices were far from practical. With the invention of the laser in 1960, interest in light-wave communication was renewed.

The maximum potential information-carrying capacity (bandwidth) of a transmission channel is a function of the frequency of the signal, and since the frequency of light waves is 1,000 to 10,000 times that of microwaves, the potential capacity is very great. In the past, the difficulty has been the absence of an adequate medium for the light to travel in. The atmosphere is unsatisfactory because, even under the best of weather conditions, light beams spread and distort and are absorbed in it. It was only with the development of extremely pure (transparent) glass fibers (in 1970) that optical communication over long distances became a practical possibility.

Fibers have been improved greatly in 10 years. Early ones had an attenuation of about 20 dB/km; today's have transmission losses as low as a fraction of 1 dB/km. The lower the attenuation, the longer a fiber link can be and still transmit a detectable signal. Low attenuation is necessary to minimize the need for costly signal regenerators (repeaters).

Another limit on link length is dispersion, i.e., the tendency of short optical pulses to spread (in time) in proportion to the distance traveled. The information capacity of the link is reached when the pulses begin to overlap and can no longer be distinguished.

Optical fibers consist of a circular core region surrounded by an outer cladding (Fig. 1). Most of the transmitted light is carried by the core; however, some penetrates the cladding, which acts as a buffer between the core and outside environment. In the earliest fibers (called step fibers), the core's refractive index was constant and slightly larger than that of the cladding. It was later realized that maximum bandwidth (information capacity) would be achieved by grading the refractive index from a maximum at the center to the cladding value at the core--cladding interface. This can be thought of as providing a situation in which light rays that travel nearly straight down the fiber have a short path length and a high refractive index (low velocity), while those that bounce back and forth across the core have a longer path length and a lower average refractive index (higher velocity). Thus, all rays tend to arrive at the output end at nearly the same time. Fibers built on this principle are called graded-index fibers. A typical graded-index fiber might have a core diameter of 60 μm, a cladding diameter of 120 μm, and a maximum refractive-index difference between core and cladding of about 1 . Another useful parameter of the fiber is its numerical aperture, which is a

measure of the maximum angle a light ray can make with the axis and still remain trapped in the core. The numerical aperture is typically about 7°.

The use of optical fibers has grown rapidly because of their technical and economic advantages. They are lightweight, small, capable of high data rates, and immune to electromagnetic interference. At present, optical-fiber cables cost about the same as the highest bandwidth coaxial (copper) cables, but the price of copper is increasing much faster than that of glass. One motivation behind early telecommunication applications was the lack of space in cities and buildings for more bulky coaxial cables. Optical fibers are appealing for military applications because of their low weight and imperviousness to electromagnetic interference. At Lawrence Livermore National Laboratory, fiber links are used to transmit test and diagnostic data in electro magnetically noisy environments.

## THE PROPAGATING-BEAM METHOD

In any waveguide structure, the propagated light can be resolved into a number of normal modes. Each mode propagates independently of the others without changing shape. However, each mode changes its phase at a unique rate, i.e., has a unique propagation constant (wavenumber) so that the total field (a coherent sum of the modes) is constantly changing shape. If one knows the mode shapes and the corresponding propagation constants, the field at a given position along the fiber can be extrapolated to any distance merely by advancing the phase of each modal term in the sum by the appropriate amount. There are two types of modes: trapped (or guided) modes, whose power is confined principally to the core, and radiation modes that carry power away from the core. In real fibers, the latter are always lost by being absorbed

in the cladding or surrounding jacket and are of little importance in a discussion of propagation over long distances. In what follows, mode will mean guided mode only. The propagation constant dividing guided from radiation modes is called cutoff, and occurs at 0 $cm^{-1}$ in our units.

On our spectral plots, guided modes have negative wavenumbers. Tightly bound modes, whose power is carried almost exclusively in the core, appear with large negative wavenumbers. Loosely bound modes, which extend significantly into the cladding, have wavenumbers closer to zero.

The vast majority of theoretical determinations of modal wavenumber have been based on geometric optics, principally the Wentzel-Kramer-Brillouin (WKB) approximation, which neglects the wave nature of light. Actually, the light propagation is governed by a wave equation analogous to the Schroedinger equation of quantum mechanics. In this analogy, the WKB method is equivalent to the Bohr-Sommerfeld old quantum theory: it is exact for a small class of potentials (refractive index profiles), but only approximate for most.

Over the past few years, we have developed a very accurate and complete wave optics description[1] of light propagation in fibers based on a numerical solution of the wave equation. This propagating-beam method differs from past approaches in that it considers the propagated beam (made up of many modes) rather than the individual modes themselves. The individual modes and modal wavenumbers, however, are recovered, a posteriori, by Fourier transforming the field.

We can examine the basic idea of the method by analogy to a mechanical system. Suppose one wanted to find the normal modes of a mechanical system, e.g., point masses connected by springs. The standard technique is to calculate the so-called dynamic matrix, which connects the force on each mass

with all the displacements in the system. One then has to diagonalize this matrix. The eigenvalues of the matrix yield the normal frequencies, and the eigenvectors of the matrix are the normal modes. If there are many particles, diagonalizing the matrix may be difficult. Instead, suppose we solve the equations of motion starting from some arbitrary initial condition. This leads to the vector displacement as a function of time; this displacement is a coherent sum of modal terms. The key is that each modal term in the sum has harmonic time dependence, i.e., has a definite frequency. Thus, if we Fourier transform the displacement with respect to time, the corresponding spectrum will have distinct spectral lines at the normal frequencies. In the spectral domain, the various modal contributions are separated and the positions of the spectral lines give the normal frequencies. Actually, it is advantageous to form a correlation function between the initial displacement and that at later times. The transform of this function again determines the modal frequencies, with the added advantage that the height of each peak is proportional to the power carried by that mode.

This is essentially the method by which we find the modes of the fiber. Time in the mechanical system is replaced by propagation distance (z), mode frequency by mode wavenumber, and Newton's equations of motion by the wave equation. We solve the wave equation for the field as a function of z and form the field correlation function between the initial and propagated fields. The transform of this function is a power spectrum consisting of spectral lines whose positions determine the modal propagation constants and whose heights determine the power in each mode. For a circularly symmetric refractive index profile, the modes can be classified with two indices. The first is an angular index $\nu$, which measures the phase change (in units of $2\pi$)

encountered in traversing a circle around the origin. The second is a radial index $\mu$ that counts the number of zeroes in the modal intensity along a radius.

Examples of power spectra are shown in Fig. 2, corresponding to the graded-index power-law (exponent $\alpha = 1.85$) fiber discusssd in the section on dispersion below. For each of these spectra, the angular mode index $\nu$ (corresponding to the angular momentum quantum number) is held fixed; the peaks correspond to different values of the radial mode index $\mu$. The modal wavenumbers may be found quite accurately by fitting the numerically computed spectrum to a modal sum of the proper form. Once one knows the modal wavenumbers, the wavefunctions are recovered by Fourier transforming the transmitted field with respect to z at these wavenumbers, thus projecting out the individual modal contributions.[2]

If one wishes to determine the dispersive properties of the fiber, a second correlation function involving the frequency derivative of the transmitted field is required. Analyzing the second correlation function in a way similar to that used for the first gives us the individual group velocities.

The method has been extensively checked for accuracy by comparison with analytic solutions where they exist. One such case is that of a refractive index that varies as the square of distance from the optic axis and has infinite extent. In the quantum mechanical analogy, this is a harmonic oscillator. The modal propagation constants, group velocities, and wavefunctions were calculated and all showed excellent agreement with analytic results. In Fig. 3 are shown two comparisons of computed and analytic wavefunctions. Note the excellent agreement, even at high values of the radial and angular mode indices $\mu$ and $\nu$. Such results give confidence in

applying the method to realistic situations for which no analytic solutions are available, and for which other theoretical approaches are difficult to apply or of unknown accuracy.

The remainder of this article briefly describes applications of the method to some problems of practical interest: dispersion, fibers with lossy components, and the effect of splices.

## DISPERSION IN REALISTIC FIBERS

An outstanding feature of optical fibers is their high bandwidth, i.e., ability to transmit information at high rates. For fibers that support many guided modes, the major limitation on this rate is the "intermodal dispersion" due to modes traveling along the fiber with different velocities. Thus, even if all modes start out together at the input end of the fiber, they arrive at different times at the output end. The amount of pulse spreading (in time) is proportional to the length of the fiber, and depends on the fiber's intrinsic properties as well as on the specific illumination used.

We were particularly interested in studying the effects of realistic fiber index profiles. Theory indicates that power-law profiles with the exponent $\alpha$ in the range of 2 constitute a favorable class, and most graded-index fibers are, in fact, manufactured at such a square law index. Unfortunately, the method by which most fibers are manufactured leads to a deficit of the index-increasing dopant at the center so that the resultant index is approximately a power law with a dip in the center. We completely characterized dispersion in a typical refractive index profile with and without the central dip.[3] The two profiles are shown in Fig. 4. To avoid exciting nearly degenerate modes (i.e., different modes of nearly equal

wavenumber, which would be difficult to distinguish in the spectrum), it was necessary to use initial fields with definite angular symmetry properties.

In this way, with several runs, we found 85 distinct modes in the $\alpha = 1.85$ profile, and 84 for the fiber with dip (one of the previously trapped modes is no longer so). Modal wavenumbers and group delays (the inverse of the group velocity) of the two fibers were calculated. The results are shown in Fig. 5. The main effect of the dip is to break the degeneracy that previously existed for deeply bound modes. That is, single dots in the upper graph, which are actually superpositions of many states with nearly the same wavenumber and group delay, have now been split. The perturbation is greatest for the small-$\nu$ modes. These modes have the highest power at the center and, therefore, sample the dip to the greatest extent.

Assuming equal power in each guided mode, the impulse response and frequency response of each fiber was calculated. Both fibers had 3-dB bandwidths of about 0.5 GHz-km. The dip has little effect on bandwidth in this case because the underlying profile is far from optimal. That is, at the wavelength at which the calculations were carried out (1 μm), the $\alpha = 1.85$ index profile does not yield the highest possible bandwidth for a power law profile. This would occur for $\alpha$ closer to 2, and, in this case, the dip would be a more serious defect.[4] On the other hand, the rms temporal pulsewidth increases considerably for the fiber with a dip, pointing out the inadequacy of the pulsewidth as an indicator of bandwidth. The effect is due to a few modes arriving considerably before the main pulse, but containing only a small fraction of the total power. Thus, one cannot use rms and bandwidth measures of dispersion interchangeably.

Such calculations give a very complete picture of the propagation and dispersion properties of realistic index profiles.

LOSSY CLADDINGS AND JACKETS

The theory of optical fibers has been concerned mainly with propagation in ideal lossless waveguides. Although real fibers are composed of core materials with extremely small absorption coefficients, they may have claddings with substantially higher losses. In addition, the fiber is usually surrounded by a plastic jacket of still higher absorption. While spatially homogeneous losses may be accounted for a posteriori, this is not true of spatially inhomogeneous losses. The reason is that each mode, according to its own power distribution, samples the absorptive components to a different extent. Thus, each mode has its own loss coefficient. In particular, modes that penetrate deeply into the cladding may be so lossy that they are effectively removed whenever propagation over significant distances is considered. This is important since such modes, near cutoff (zero wavenumber in Fig. 5), have significantly reduced group delay times. Their elimination then can affect both the mode distribution and the fiber bandwidth.

An advantage of the propagating-beam method is that is is just as easy to treat the case of differential mode attenuation at it is to treat the lossless case. All that is required is a generalization of the method of fitting the power spectrum to find the mode wavenumbers. The generalization is to allow the mode wavenumber to be a complex number. The real part of the eigenvalue gives the rate at which the phase advances, as before. The imaginary part of the eigenvalue is just the amplitude attentuation coefficient. Actually, there is an independent way of calculating attenuation. Since the

propagating-beam method allows us to find the mode functions (with the absorbers present), one can calculate the mode power-weighted average of the absorption coefficient. In our calculation, we have used both methods.

We studied the effects of both absorbing claddings and highly absorbing jackets.[5] In the former case, it was found that the mode attenuation scaled nearly linearly with the strength of the cladding absorption coefficient. This indicates that the mode eigenfunctions are only slightly affected by the presence of the lossy cladding. Thus, one could find a reasonably accurate estimate of the modal losses by using perturbation theory, i.e., by taking the power-weighted losses, with the eigenfunctions corresponding to the lossless case.

The situation is quite different in the case of strongly absorbing jackets. The reason is that the absorption is so strong that it tends to exclude the eigenfunction from the jacket region. This exclusion, similar to the self-shielding effect in nuclear physics, becomes stronger as the jacket absorption coefficient becomes higher. This means that, as the jacket absorber becomes stronger, the attentuation of affected modes actually decreases. The application of perturbation theory, in this case, leads to a severe overestimate of the modal attenuation, but the attenuation is high in any case for modes very near cutoff.

An example of this exclusion effect is shown in Fig. 6, in which, for a mode near cutoff, the logarithm of the modal intensity is plotted vs distance from the center of a slab waveguide. (A slab waveguide is one in which the refractive index varies in only one direction across the slab.) The two arrows indicate the core cladding interface and the cladding-jacket interface, respectively. The four curves correspond to four values of the jacket

absorptivity, varying from 0 to 300 $cm^{-1}$. Note that in the core and most of the cladding, the wavefunction is hardly affected by the jacket. Also note the exponential decay of the wavefunction in the cladding. When the jacket absorber is turned on, the decay rate in the jacket, where all the absorption takes place, is greatly increased. The effect is very much less on more tightly bound modes. Indeed, since jackets are so highly lossy and so far away from the core, the effect on a given mode is either to attenuate it strongly or scarcely affect it at all. The loss of modes near cutoff due to an absorbing jacket probably explains why many real fibers exhibit a higher bandwidth than that predicted by theoretical models that do not account for differential losses.

These results show the ability of the propagating beam method to compute guided mode-attenuation coefficients. They indicate that theoretical analyses of modes near cutoff may not be meaningful unless the details of the fiber's finite core, finite cladding, and packaging are taken into account.

## EFFECT OF SPLICES

Another practical factor to consider in optical-fiber performance is the effect of splices. A fiber system will contain splices between either identical or different fibers. These splices are important for two reasons. First, today's fibers have such low intrinsic losses that a significant part of the total system losses may be due to connections. Secondly, there is generally some redistribution of power between the modes at a connection, and this can affect the bandwidth of the link.

We have investigated the losses and mode redistribution due to joints in which there are spatial and/or angular misalignments and those due to gaps

between the two fibers joined. The calculations refer to joints between identical fibers, and were carried out for a parabolic graded-index fiber excited with a spatially incoherent source that overfilled the numerical aperture of the fiber. That is, the initial incoherent source field contains light rays at larger angles with the axis that the fiber will propagate. This excess power is eventually radiated away from the core. The field was propagated until the radiation modes were eliminated by an absorbing jacket. The splice was made at this point. A spatial offset is modeled by translating the optical field with respect to the refractive index. An angular misalignment, or tilt, is modeled by tilting the phase front on the field so that it is initially propagating at an angle to the optic axis. Of course, a gap can be treated directly by propagating through a short section with constant refractive index.

It turns out that gaps are not very serious, i.e., the resultant losses are small for reasonable values. On the other hand, losses due to spatial and angular misalignments can be significant. We found that a series of calculations treating offsets up to half the core radius or tilts up to half the numerical aperture (or both) led to losses in fair agreement with a simple geometric optics argument. This geometric optics formula can then be used to easily estimate losses expected from given conditions.

By forming the field correlation functions both before and after the splice, the change in mode distribution can be determined. For example, in Fig. 7, we show modal power spectra before and after the splice. The figure refers again to the parabolic graded index, this time being excited with a coherent, narrow Gaussian beam. Before the splice, only a few low-order modes are excited. Indeed since the initial field is axially symmetric, only the

circularly symmetric or meridional modes are excited. With a splice displacement s equal to 15.7% of the core radius a, we see both a shift to higher modes and the excitation of modes between the original modes. These latter modes were originally forbidden by symmetry. With a still larger offset, the mode distribution is shifted farther and spread out still more. The change in mode distribution is much more dramatic in this case than in the case of incoherent illumination, where all modes are initially excited. For incoherent illumination, the splice tends to shift the center of the distribution to the left because higher-order modes tend to be lost. Changes in mode distribution as extreme as these shown in Fig. 7 significantly affect the bandwidth of the link.

Such calculations help to determine practical tolerances needed for minimal power loss at connectors. They also aid in understanding the changes in mode distribution that take place.

## SUMMARY

We have developed a very complete theoretical description of light propagation in optical fibers. Called the propagating-beam method, this technique allows the determination of all bound modes as well as of corresponding wavenumbers and group delays. The model takes into account the wave nature of light, realistic fiber-index profiles, and arbitrary illumination. Because it is just as easy to treat the case of differential mode attenuation as it is to treat the lossless case, practical problems such as the effect of absorbing jackets and splices have been addressed. With the propagating-beam method, we have found that:

- Both the finiteness of the core and deviations from a power-law profile are significant in determining the fiber's propagation properties and information-carrying capacity.
- The rms pulsewidth can be a poor indicator of fiber bandwidth.
- Modes very near cutoff tend to be strongly attenuated by an absorbing jacket.
- Small gaps between fibers do not contribute significantly to splice losses.
- Spatial and angular misalignments of splices lead to significant losses.

This article has described the development and application of the propagating beam method. There is now a vast research literature of fiber optics. In reference 6 are given several sources of broad introductions to all aspects of fiber use and entry into this literature.

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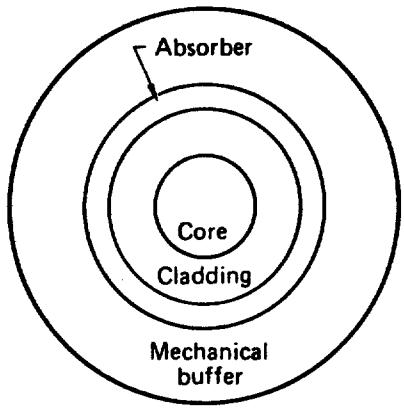



**Fig. 1** *An optical fiber consists of an inner core, which carries most of the transmitted light, and an outer cladding, which acts as an electromagnetic buffer. Most fibers are coated with a strong absorber to prevent light from passing from one fiber to another in cables. There may also be a further jacket to provide mechanical strength. Typical core and cladding diameters are 60 and 120 μm, respectively.*

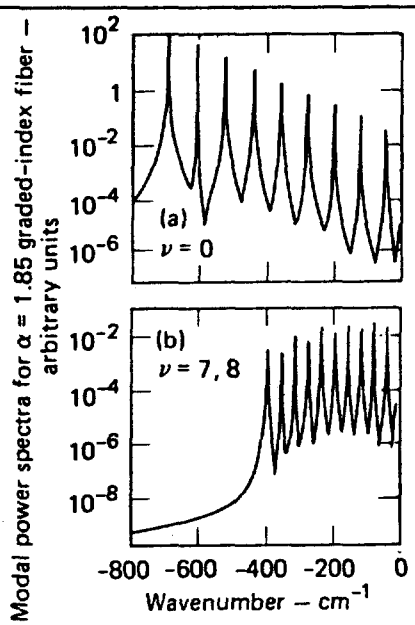



**Fig. 2** *In the propagating-beam method, the wave equation is solved for the propagated field. A correlation function is formed between the propagated and initial fields. The Fourier transform, with respect to propagation distance z, of the correlation function is a power spectrum consisting of distinct "lines" whose position identifies the corresponding modal wavenumber. The spectra shown here are taken from the power-law index profile discussed in the section on dispersion. In order to avoid exciting modes that are nearly degenerate, we pick an initial field of fixed angular symmetry. In this way, with a number of runs, the entire modal spectrum is mapped out. The mode index ν refers to angular symmetry; in the quantum mechanical analogy it is the angular momentum quantum number. Trapped modes have negative wavenumbers.*

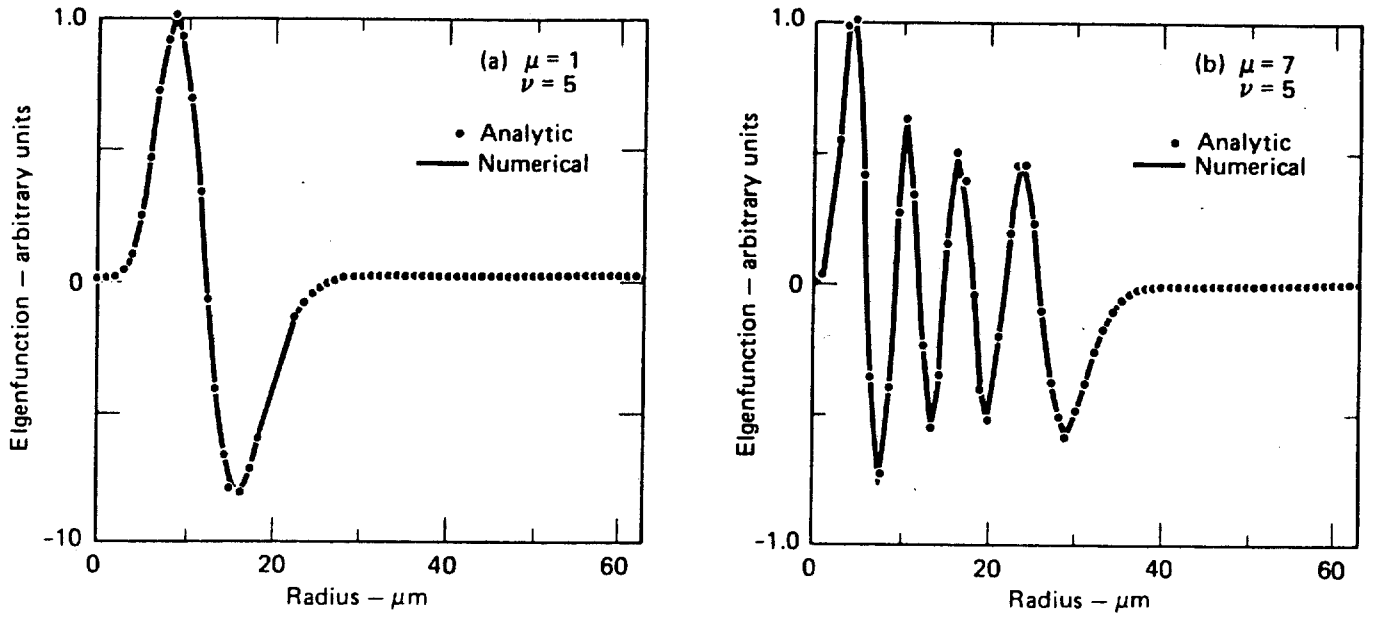



**Fig. 3** *Once the modal wavenumbers have been determined from the power spectrum, the mode wavefunctions are found by Fourier transforming the propagated field at these wavenumbers. The figure shows two wavefunctions corresponding to a square-law refractive-index profile of infinite extent. This index was chosen because analytic results are available. The dots give the analytic function at the points sampled in the calculation; the straight lines join the numerically determined values. The agreement for wavefunctions, wavenumbers, and group velocities is excellent and gives us confidence in the method.*

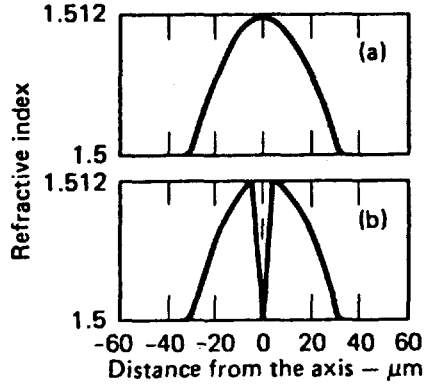
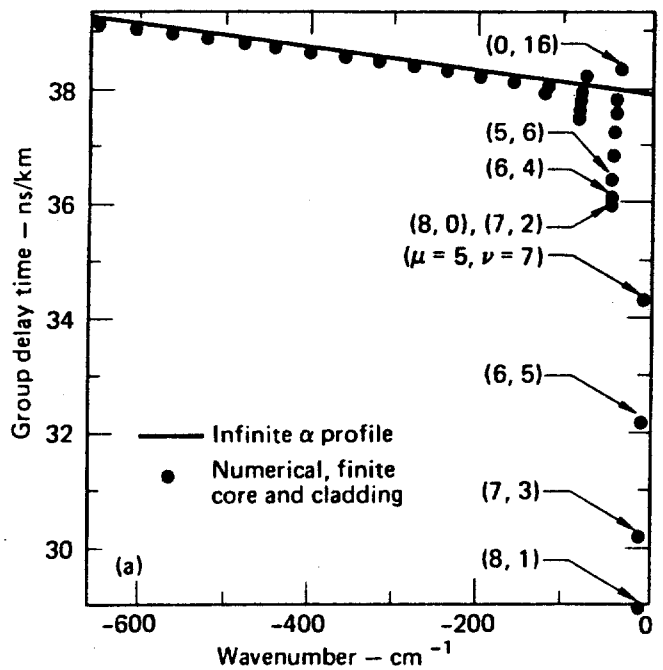



**Fig. 4** *Theory indicates that high bandwidth can be obtained for refractive index profiles that vary as a power of distance from the axis, with the exponent near 2. Because of the method of manufacture, however, real fibers generally suffer from a deficit of the index-raising dopant on axis, leading to a dip in the index profile. We compared the propagation and dispersion properties of two profiles, identical except for the presence of a narrow dip in the second one. The basic shape of the index profile is a power law with an exponent of 1.85.*



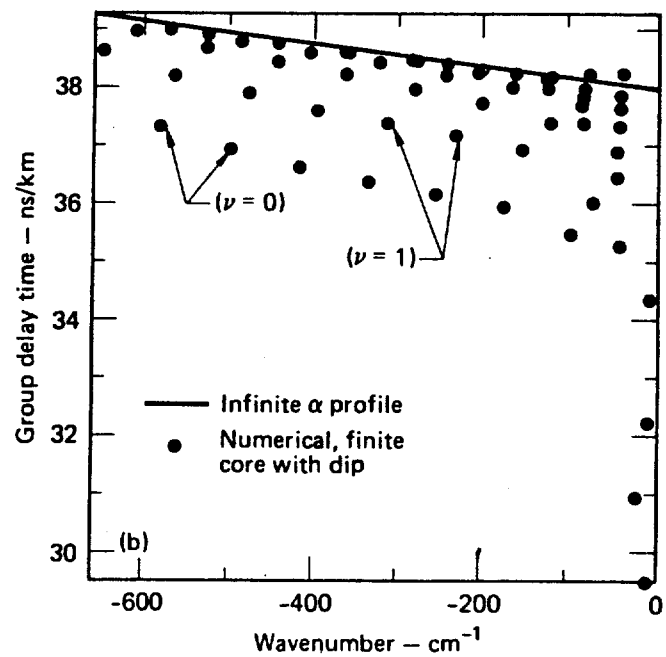




**Fig. 5** *The transmitted field in the fiber consists of a superposition of modes, each of which propagates with its own wavenumber without changing shape. Intermodal dispersion arises because each mode also has a unique group velocity. This figure displays the calculated group delay (inverse of the group velocity) characteristics for the two index profiles shown in Fig. 3. The straight line is the relationship between wavenumber and group delay expected for the $\alpha = 1.85$ profile if it were of infinite extent. In both cases, modes near zero wavenumber (i.e., modes that extend into the cladding) are significantly perturbed by the finiteness of the core. In addition, the dip in the latter case removes the degeneracy which previously held for deeply bound modes.*

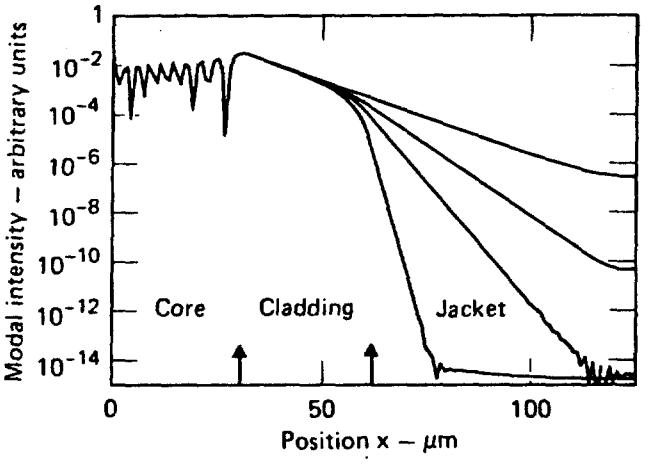



**Fig. 6** *A strongly absorbing jacket modifies the modal eigenfunctions in the jacket region. The figure shows the last bound mode of a slab waveguide whose refractive index varies as the 1.85 power of position. The arrows mark the core-cladding and cladding-jacket interfaces, respectively. Without an absorbing jacket (upper curve), the wavefunction decays exponentially throughout the cladding and jacket regions. With a jacket, the function decays faster in the jacket region. The wavefunction is progressively excluded from the jacket region as the strength of the jacket absorber is increased from 30 $cm^{-1}$ to 300 $cm^{-1}$.*

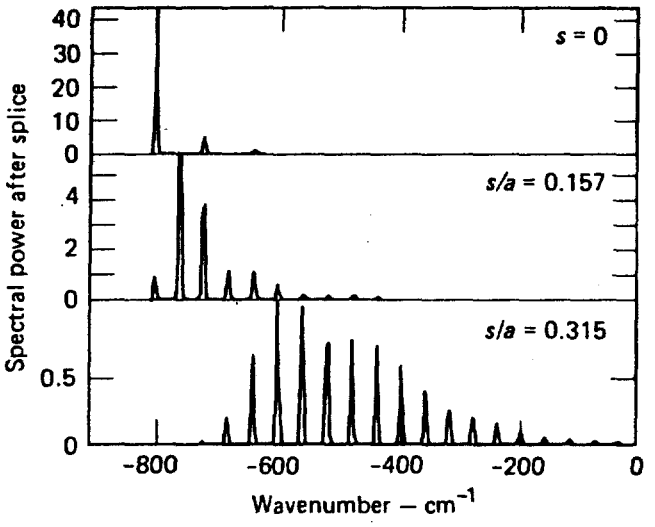



**Fig. 7** *When two identical fibers are spliced together, modal redistribution takes place unless they are perfectly aligned. The figure refers to a circularly symmetric fiber whose refractive index varies as the square of the radius. The fiber was excited with a collimated Gaussian beam so only a few low-order circularly symmetric modes were excited. The upper part of the figure shows the initial mode distribution. For splices with successively larger displacements s between centers, two effects occur. First, modes of all symmetries are excited, and, secondly, the average wavenumber of excited modes increased. This redistribution can have an important effect on loss and bandwidth.*