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CHARACTERIZATION OF SINGLE-MODE OPTICAL FIBERS FROM FAR FIELD INTENSITY PATTERN

MOUSTAFA H . ALY

Department of Engineering Mathematics and Physics
Faculty of Engineering
University of Alexandria
Member of the Optical Society of America

Abstract

This paper proposes a theoretical method for characterizing single-mode optical fibers from the measurement of its far field intensity pattern. Two types of fibers are considered , namely : step index and graded index optical fibers. Three points , in the far field pattern , are studied , where the intensity falls to 10% , 25% and 50% of its maximum value. The main fiber parameters which can be obtained through this method are the core refractive index , the normalized frequency and the core diameter.

Introduction

Single-mode optical fibers and single-mode planar waveguides form the basis of a variety of devices in the field of integrated optics. The advantage of the propagation of a single mode within an optical fiber is that the signal dispersion caused by the delay differences between different modes in a multimode fiber may be avoided. An accurate knowledge of the core refractive index "n_c" , the normalized frequency "V" and the core radius "a" is essential to design and optimize the performance of optical waveguide devices. R.Sinha et al. [1] have used the far field radiation pattern of the fundamental mode to characterize the single-mode asymmetric slab waveguide.

In the present work , the method used by Sinha is modified to suit the optical fiber which is a symmetric (cylindrical) waveguide. Our results are justified by comparing them with that obtained by Sinha , in the limit that the waveguide is a symmetric one. Both are found in the same order of magnitude.

Theory

I- Step Index Fibers

For a step index optical fiber of radius "a", the refractive index profile is defined as :

$$n(r) = n_c \qquad r < a \quad , \qquad (1\text{-a})$$

$$= n_{clad} \qquad r \geq a \quad , \qquad (1\text{-b})$$

where n_c and n_{clad} are , respectively , the core and cladding refractive indices.

The electric field distribution of the dominant mode which corresponds to this profile is of the form [2] :

$$E(r) = G\, J_o(U\rho) \qquad \rho < 1 \quad \text{(core)} \quad , \qquad (2\text{-a})$$

$$= G\, J_o(U)\,\frac{K_o(W\rho)}{K_o(W)} \qquad \rho > 1 \quad \text{(clad)} \quad , \qquad (2\text{-b})$$

where G is the amplitude coefficient , ρ is the normalized radial position (=r/a) , J_o and K_o are , respectively , the zero order Bessel and modified Bessel functions. The quantities U and W are the eigen values in the core and cladding , respectively , defined as [2] :

$$U = a\,(n^2_c\,k^2 - \beta^2)^{1/2} \quad , \qquad (3)$$

and

$$W = a\,(\beta^2 - n^2_{clad}\,k^2)^{1/2} \quad , \qquad (4)$$

where k is the free space propagation constant ($=2\pi/\lambda$ with λ the free space wavelength) and β is the longitudinal propagation constant which lies in the range [3] :

$$n_{clad}\,k \;<\; \beta \;<\; n_c\,k \quad . \qquad (5)$$

It is well known , for the step index fiber to do its function , i.e. to maintain the laser ray within its core , that [4] :

$$n_{clad} = n_c\,(1 - \Delta) \quad , \qquad (6)$$

where Δ ($<< 1$) is the relative refractive index difference between the fiber core and its cladding. The sum of the squares of U and W defines the normalized frequency as [5] :

$$V = (U^2 + W^2)^{1/2} = k\,a\,(n^2_c - n^2_{clad})^{1/2}$$

$$\simeq k\,a\,n_c\,(2\,\Delta)^{1/2} \quad . \qquad (7)$$

For a step index fiber , single-mode propagation is possible over the range [2] :

$$0 \;\leq\; V \;<\; 2.405 \quad . \qquad (8)$$

It is apparent that the normalized frequency "V" for the fiber may be adjusted to within the range given by eq.(8) by reducing the core diameter and possibly the relative refractive index difference following eq.(7).

D.Gloge [6] has developed an approximate analytic expression for the propagation constant β , with $\Delta << 1$, as :

$$\beta = n_c\,k\,(b\,\Delta + 1) \quad , \qquad (9)$$

where b is the normalized propagation constant defined as :

$$b = 1 - U^2/\,V^2 \quad . \qquad (10)$$

Based on Ref.[6] , we have fitted the relation between the normalized propagation constant "b" and the normalized frequency "V" , for the dominant mode , in the form :

$$b = -7.3\text{x}10^{-5} - 0.328\,V + 0.4958\,V^2 - 0.1302\,V^3 - 0.007\,V^4 + 0.01\,V^5 - 0.0023\,V^6 + 0.00026\,V^7 - 1.685\text{x}10^{-5}\,V^8 + 5.826\text{x}10^{-7}\,V^9 - 8.4229\text{x}10^{-9}\,V^{10} \quad , \qquad (11)$$

The normalized far field intensity distribution for the waveguide is defined as [7] :

$$I\,(\alpha) = I_N\,/\,I_D \quad , \qquad (12)$$

where α is the normalized radiation angle defined as [8] :

$$\alpha = a\,k\,\sin\theta \quad , \qquad (13)$$

with θ the measured angle at a specific intensity , a the core radius and k the free space propagation constant.

In case of an optical fiber , which is a symmetric (cylindrical) waveguide , one has modified the quantities I_N and I_D [7] as:

i- for $\alpha \neq U$

$$I_N = [\frac{2\,U}{W^2 + \alpha^2} \cdot \frac{W \cos U - \alpha \sin \alpha}{W \sin U + U \cos U} + (\frac{\sin (U + \alpha)}{U + \alpha} + \frac{\sin (U - \alpha)}{U - \alpha}) (\frac{(U + W) \sin U + (U - W) \cos U}{W \sin U + U \cos U})]^2 \qquad (14)$$

ii- for $\alpha = U$

$$I_N = [\frac{2\,U}{W^2 + U^2} \cdot \frac{W \cos U - U \sin U}{W \sin U + U \cos U} + (1 + \frac{\sin 2\,U}{2\,U}) (\frac{(U + W) \sin U + (U - W) \cos U}{W \sin U + U \cos U})]^2 \qquad (15)$$

and

$$I_D = [\frac{2\,U}{W\,(W \sin U + U \cos U)} + \frac{\sin U}{U} (2 + \frac{U \sin U + W \cos U}{W \sin U + U \cos U})]^2 . \qquad (16)$$

II- Graded Index Fibers

Graded index optical fibers do not have a constant refractive index in the core , but a decreasing core index "n_c" with radial distance from a maximum value n_1 at the axis to a constant value "n_{clad}" beyond the core radius "a" in the cladding. This index variation may be represented as :

$$n_c = n_1 (1 - 2 \Delta r^2/a^2)^{1/2} \qquad r < a \quad , \qquad (17\text{-a})$$

$$n_{clad} = n_1 (1 - 2 \Delta)^{1/2} \qquad r \geq a \quad , \qquad (17\text{-b})$$

where Δ is the relative refractive index difference.

The normalized frequency "V" , in this case , covers the range [9] :

$$0 \leq V < 3.402 \qquad . \qquad (18)$$

Equations (10-16) describing the quantities b , I (α) , α . I_N and I_D hold also in case of graded index fibers.

Characterization Procedure

As mentioned before , we are concerned with single mode optical fibers. Hence the values of the normalized frequency "V" are chosen according to eq.(8) for the step index fibers and eq.(18) for graded index ones. For each value of V , the normalized propagation constant "b" , eq.(11) , is calculated. The eigen values U and W are then obtained from eq.(10) and eq.(7) , respectively. Using these values , eq.(12) is solved for α at certain values of I(α). For example , one can get α_{10} by solving eq.(12) with $I(\alpha) = 0.1$. This procedure is repeated for different values of the relative refractive index difference Δ. The obtained results are displayed in Figs. 1 and 2 for the step index fibers , and in Figs. 3 and 4 for the graded index ones.

The second step requires the measurements of the far field intensity at three points , i.e. θ_{10} , θ_{25} and θ_{50} which are the angles where the intensity becomes 10% , 25% and 50% of its maximum value , respectively. From the measured values of these angles , the ratios α_{25}/α_{50} (=sin θ_{25}/sin θ_{50}) and α_{10}/α_{50} (=sin θ_{10}/sin θ_{50}) are formed.

The computed values of α_{25}/α_{50} and α_{10}/α_{50} represent a point on the graph of Fig. 1 for the step index fibers (or of Fig. 3 for the graded index fibers). If this point lies on one of the curves , the value of Δ of this curve gives the value of Δ for the measured fiber. However , if the point lies between two consecutive curves , then the value of Δ is determined by the method of extrapolation.

Once "Δ" is determined , and knowing the cladding refractive index "n_{clad}" , the core refractive index "n_c" and the core radius "a" can be obtained as follows :

I- Step Index Fibers

The core refractive index is obtained directly from eq.(6). From Fig. 2 , using the value of α_{25}/α_{50} one can get the value of the normalized frequency "V". The values obtained for Δ and V are used in eq.(7) to get the core radius "a", where k , the free space propagation constant , is known from the source wavelength "λ".
The obtained results are compared with that obtained by Sinha [1] , in the limit that the waveguide is a symmetric one , showing a fair agreement.

II- Graded Index Fibers

The values of Δ and n_{clad} are used in eq.(17-b) to get the maximum value of the core refractive index n_1 , which is used in eq.(17-a) to get the index profile in the fiber core. The core radius is obtained exactly as in the case of the step index fiber but with using Fig.4 instead of Fig.2 , and replacing n_c , eq.(7) , by n_1. From Fig.4 it is very important to notice that the normalized frequency "V" has two different values if the quantity α_{25}/α_{50} is less than 1.52. Hence , it is advised to work in a range over this value , otherwise , V , and consequently the core radius "a" , will have two values , which is an impracticable case.
The curves shown in Fig. 1-4 are drawn for a specific value for the cladding refractive index n_{clad} . Changing this specific value , one can obtain similar groups of curves.

Conclusion

We have presented a simple method to theoretically characterize single mode , step and graded index optical fibers when their far field intensity patterns are measured. The core refractive index and radius can be predicted if the cladding refractive index is known. It is clearly seen that the obtained curves are very close to each other , this is because the variation of the relative refractive index difference "Δ" is very small. For this reason , the techniques used in measuring the far field intensity pattern must be of a very high degree of accuracy in order to minimize the error in predicting the values of "Δ" and "a". For single-mode graded index fibers , one must avoide the use of values less than 1.52 for the quantity α_{25}/α_{50} in order to get only one value for the core raduis. For the single-mode step index fibers , this restriction does not hold.
Through this work , we have also obtained an important relation for the normalized propagation constant "b" for single-mode fibers , represented by eq.(11).

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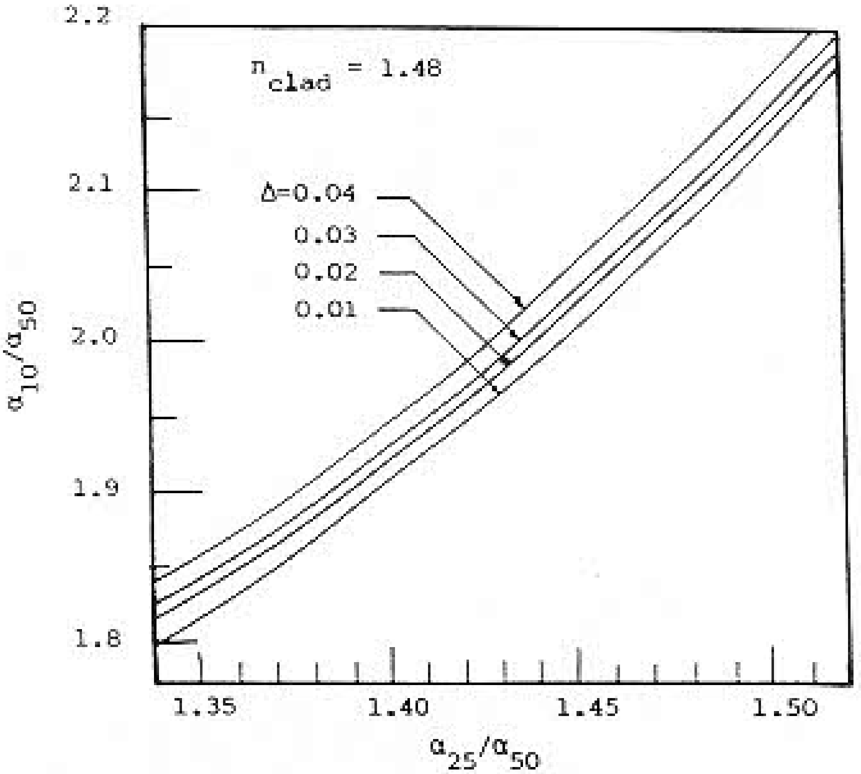

Fig.1 Variation of α_{10}/α_{50} versus α_{25}/α_{50} for step index fibers.

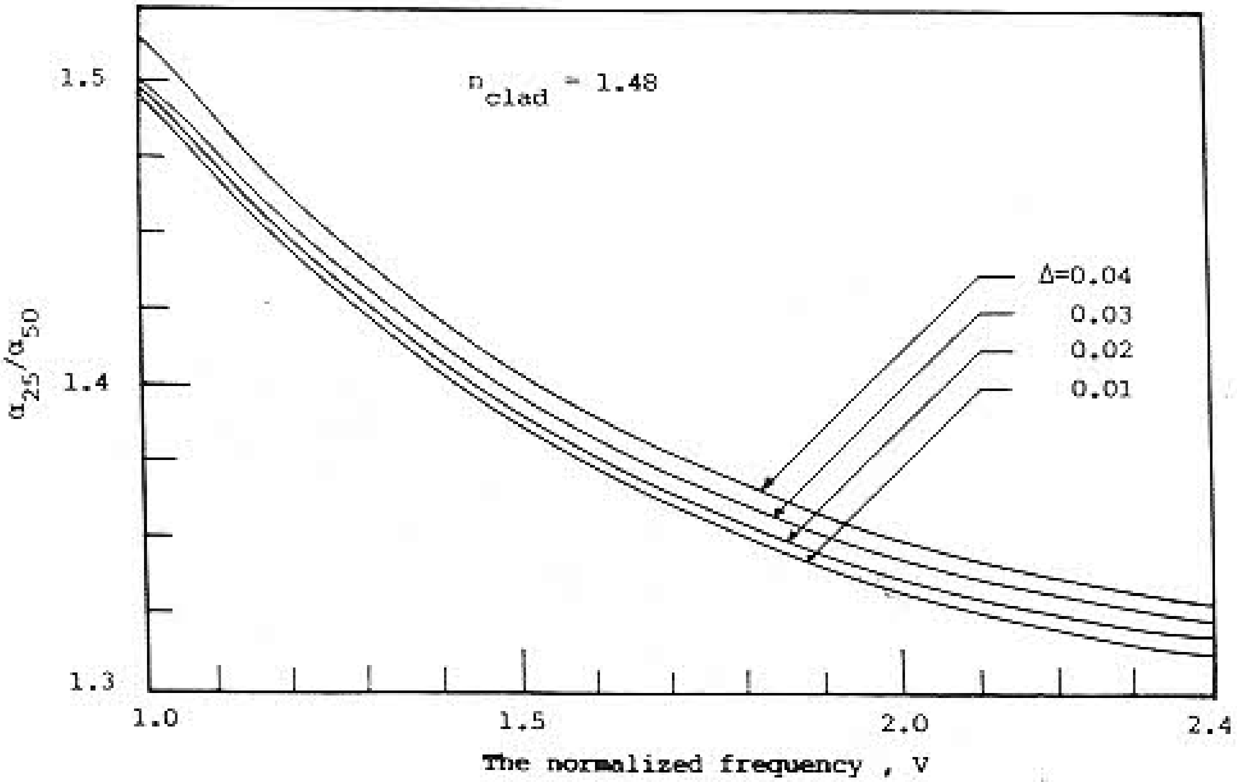

Fig.2 Variation of α_{25}/α_{50} with the normalized frequency for step index fibers.

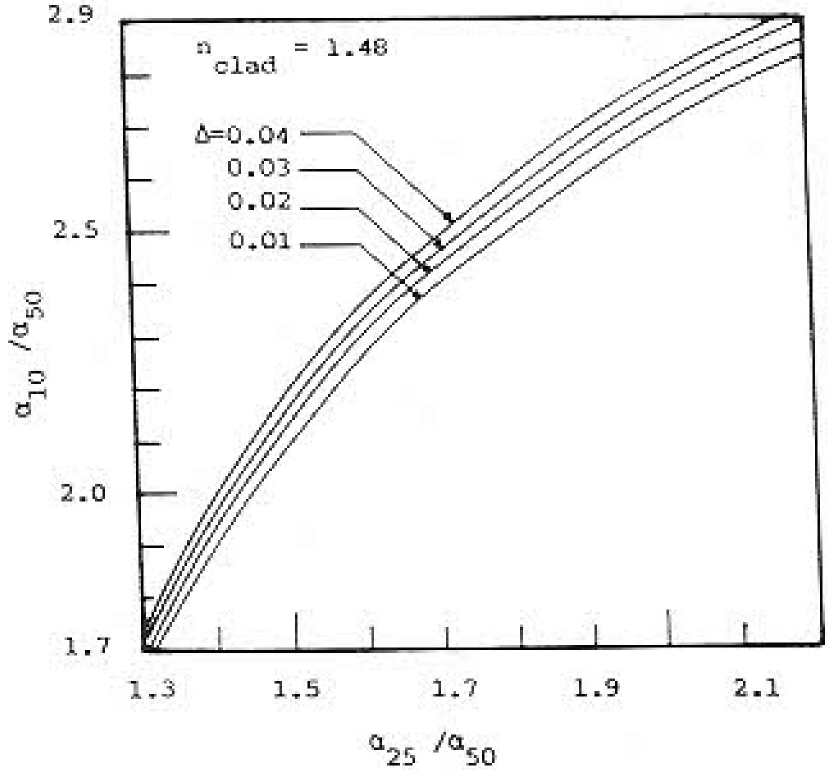

Fig.3 Variation of α_{10}/α_{50} versus α_{25}/α_{50} for graded index fibers.

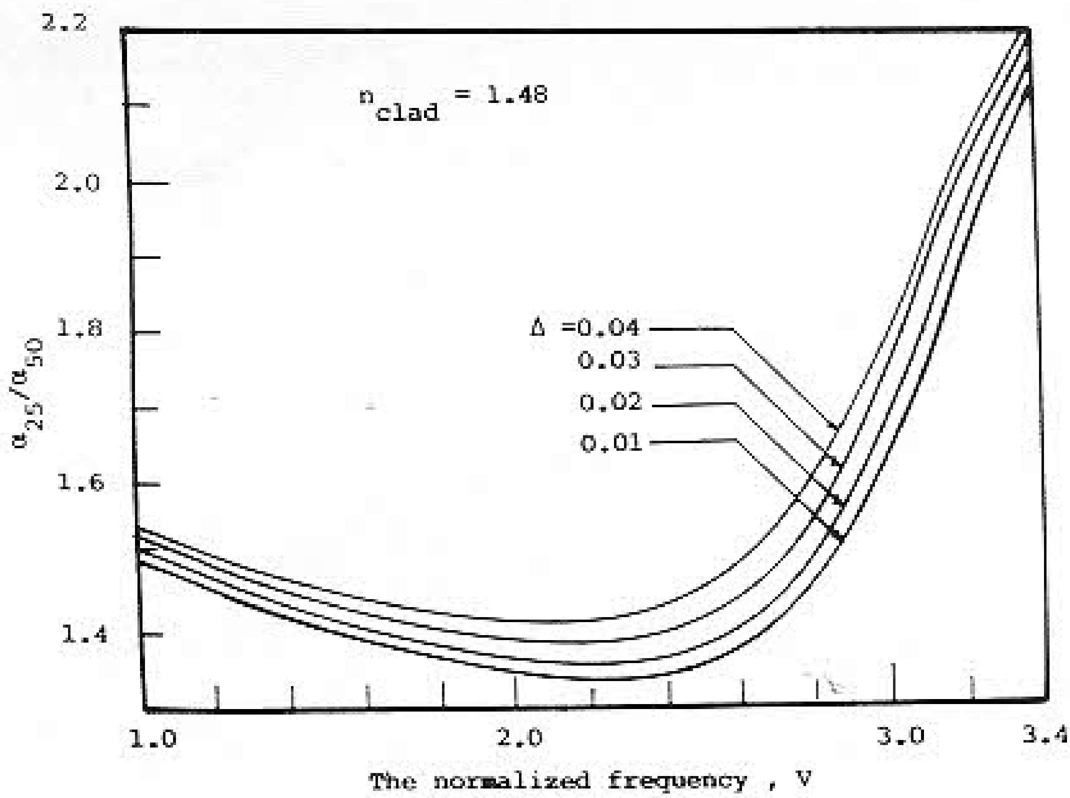

Fig.4 Variation of α_{25}/α_{50} with the normalized frequency for graded index fibers.