Propagation Characteristics of Single Mode Optical Fibers with Arbitrary Index Profiles: A Simple Numerical Approach

ENAKSHI KHULAR SHARMA, ANURAG SHARMA, AND I. C. GOYAL

Abstract—We present here a rapidly converging numerical procedure for the direct evaluation of the propagation constant and its first and second derivatives in single mode optical fibers with arbitrary refractive index profiles. To illustrate the procedure we have also used it to evaluate the propagation constant and its derivatives in single mode optical fibers with power law profiles in the presence of a Gaussian axial index dip, and hence, studied the effect of a dip on the dispersion characteristics of the fibers.

Introduction

It is now well known that the scalar wave equation can be used to determine the propagation characteristics of graded index optical fibers in most regions of practical interest. It may, however, be mentioned that analytical expressions for the propagation constants and their derivatives with respect to frequency are available only for an infinitely extended parabolic profile [1]. For a step profile or a cladded parabolic profile one has transcendental equations determining the propagation constant; the derivatives, however, can be expressed as analytical expressions in terms of the propagation constant. For all other profiles one has to numerically solve the wave equation to calculate the propagation constant as a function of frequency and then calculate the first and second derivatives required to evaluate the group velocities and dispersion coefficient. Such a numerical calculation of the derivatives requires the calculation of the propagation constant to a considerable accuracy. We may point out that the various approximate and semianalytical techniques usually give sufficient accuracy in the calculation of the propagation constant, but are, in general, not sufficiently accurate to obtain its first and second derivatives [2].

In this paper we present a direct numerical procedure to calculate the propagation constant and its first and second derivatives accurately in single mode optical fibers with any arbitrary index profile; the numerical method is similar to that used in [3] for the calculation of the cutoff frequency for single mode operation. As an illustration of the procedure, we have also used it to evaluate the propagation constant and its derivatives in single mode optical fibers in the presence of an axial dip, and hence, studied the effect of the dip on the dispersion characteristics of the fiber.

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Procedure

For an optical fiber with refractive index profile given by

$$n^2(R) = n_1^2 - (n_1^2 - n_2^2)\delta f(R) \qquad R < 1$$
$$= n_2^2 \qquad R > 1 \tag{1}$$

(where $R = r/a$, a being the core radius of the fiber, $f(R)$ defines the profile shape, and δ defines the "index jump" at the core cladding interface) the scalar wave equation for the fundamental mode can be written as

$$\frac{d^2\psi}{dR^2} + \frac{1}{R}\frac{d\psi}{dR} + v^2\,\{1 - b - \delta f(R)\}\,\psi = 0 \qquad R < 1 \tag{2}$$

where v and b are normalized parameters defined as

$$v = k_o a(n_1^2 - n_2^2)^{1/2} \tag{3}$$

and

$$b = 1 - u^2/v^2; \qquad u = k_o a(n_1^2 - \beta^2/k_o^2)^{1/2} \tag{4}$$

β being the propagation constant and k_o the free space wave number. The boundary conditions on $\psi(R)$ at $R = 0$ and $R = 1$ are given by [4]

$$\left(\frac{d\psi}{dR}\right)_{R=0} = 0 \quad \text{and} \quad \left(\frac{1}{\psi}\frac{d\psi}{dR}\right)_{R=1} = -\frac{wK_1(w)}{K_o(w)} \tag{5}$$

where

$$w^2 = v^2 - u^2.$$

Following the Ricatti transformation as in [3], we can reduce (2) to the following first order differential equation

$$\frac{dG}{dR} = v^2\delta f(R) - v^2(1 - b) - G/R - G^2 \tag{6}$$

where

$$G(R) = \frac{1}{\psi}\frac{d\psi}{dR} \tag{7}$$

and the boundary conditions transform to

$$G(R = 0) = 0 \tag{8a}$$

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and

$$G(R = 1) = -\frac{wK_1(w)}{K_o(w)}. \tag{8b}$$

Further, by differentiating (6) and (8), we can write the following differential equations to be solved along with the associated boundary conditions to obtain the derivatives of the propagation constant, i.e., b' and b'' (the prime denotes differentiation with respect to v).

For b'

$$\frac{dG'}{dR} = -2GG' - \frac{G'}{R} - 2v[1 - b - \delta f(R)] + v^2 b' \tag{9}$$

with the boundary conditions

$$G'(R = 0) = 0 \tag{10a}$$

and

$$G'(R = 1) = vb\left[1 - \frac{K_1^2(w)}{K_o^2(w)}\right] + \frac{v^2 b'}{2}\left[1 - \frac{K_1^2(w)}{K_o^2(w)}\right]. \tag{10b}$$

For b''

$$\frac{dG''}{dR} = -2G'^2 - 2GG'' - \frac{G''}{R} - 2[1 - b - \delta f(R)] + 4vb' + v^2 b'' \tag{11}$$

with the boundary conditions

$$G''(R = 0) = 0 \tag{12a}$$

and

$$G''(R = 1) = \frac{w^2}{2b}(2b + vb')^2 \frac{K_1(w)}{wK_o(w)}\left\{1 - \frac{K_1^2(w)}{K_o^2(w)} + \frac{K_1(w)}{wK_o(w)}\right\} + \left\{1 + \frac{K_1^2(w)}{K_o^2(w)}\right\}\left\{b + 2vb' + \frac{v^2 b''}{2}\right\}. \tag{12b}$$

The procedure to obtain the propagation constant and its derivatives accurately now requires the solution of the three boundary value problems in sequence. A close look at (6) shows that the last term on the RHS is indeterminate at $R = 0$ and hence, one has to take the limiting form of the equation at $R = 0$. Similar terms also occur in (9) and (10) and it can be easily shown [3] that the limiting forms are

$$\left(\frac{dG}{dR}\right)_{R=0} = [v^2\delta f(0) - v^2(1 - b)]/2 \tag{13}$$

$$\left(\frac{dG'}{dR}\right)_{R=0} = \frac{v^2 b'}{2} - v[(1 - b) - \delta f(0)] \tag{14}$$

and

$$\left(\frac{dG''}{dR}\right)_{R=0} = \frac{v^2 b''}{2} + 2vb' - [(1 - b) - \delta f(0)]. \tag{15}$$

Numerical Examples and Discussion

To illustrate the use of the procedure and test its convergence, we carried out numerical calculations for single mode fibers with various refractive index profiles. The steps in the calculation[1] of the propagation constants and its derivatives are summarized below.

1) The transcendental equation (8b) is solved to obtain b; the LHS is obtained by a numerical solution of the first order differential equation (6) with boundary condition (8a) at $R = 0$ and step size $h = 1/N$ (i.e., N is the number of divisions into which the domain $R = 0$ to $R = 1$ is divided).

2) With b known, (6) is solved with step size $h = 1/4N$ and the numerical values of $G(R)$ are stored at each step at $4N$ discrete points ($R = 1/4N, 2/4N, \cdots, 1$) for subsequent calculations in steps 3), 4), and 5).

3) The transcendental equation (10b) is solved for b'; the LHS is now obtained by solving (9) with boundary condition (10a), step size $h = 1/N$ and values of $G(R)$ stored at step 2).

4) Again with the known value of b', (9) is solved and numerical values of $G'(R)$ stored at $2N$ discrete points $R = 1/2N, 2/2N, \cdots, 1$ for use in step 5). (Step size $h = 1/2N$.)

5) Equation (12b) is solved to obtain b''; the LHS is now obtained by solving (11) with boundary condition (12a), stored values of $G(R)$ and $G'(R)$ from steps 2) and 4) and step size $h = 1/N$.

Further, we also used the propagation constants so calculated to evaluate the dispersion characteristics of single mode fibers in terms of the dispersion coefficient s, defined as [6]

$$s = -\frac{\lambda}{cn_e}\left\{(1 - b)\nu_2 + b\nu_1 + 2\dot{b}\phi + \frac{1}{2}\ddot{b}\theta - \frac{1}{n_e^2}\left(n_2\dot{n}_2 + b\phi + \frac{1}{2}\dot{b}\theta\right)^2\right\} \tag{16}$$

where

$$\nu_i = n_i\ddot{n}_i + \dot{n}_i^2 \tag{17}$$

$$\phi = n_1\dot{n}_1 - n_2\dot{n}_2 \tag{18}$$

$$\theta = n_1^2 - n_2^2 \tag{19}$$

and the dot denotes differentiation with respect to λ; $\dot{b}$ and $\ddot{b}$ can be related to b' and b'' as

$$\dot{b} = b'v\left(\frac{\phi}{\theta} - \frac{1}{\lambda}\right) \tag{20}$$

$$\ddot{b} = b'v\left(\frac{\nu_1 - \nu_2}{\theta} - \frac{\phi^2}{\theta^2} - \frac{2\phi}{\lambda\theta} + \frac{2}{\lambda^2}\right) + b''v^2\left(\frac{\phi}{\theta} - \frac{1}{\lambda}\right)^2. \tag{21}$$

It may be noted that (9)-(12) are so normalized that the solutions depend only on normalized frequency v and normalized profile shape $f(R)$. Hence, once b, b', and b'' are known as functions of v for any profile, s as a function of λ can be calculated directly using the algebraic expression (16) without any further computation. All the calculations carried out correspond to silica fibers with GeO_2 doping in the core; the refractive index n_1 corresponding to a 13.8 percent GeO_2 doping and the cladding index n_2 corresponding to silica. The

[1] We used the fourth order Runge-Kutta procedure for the numerical solution of the differential equation [5]. The number of points, step size, storage, etc., are hence in reference to this procedure.

TABLE I
CONVERGENCE OF THE NUMERICAL RESULTS FOR A FEW TYPICAL REFRACTIVE INDEX PROFILES

Profile	Parameters	N	$\frac{U^2}{V^2} = 1-b$	b'	-b"	s(ps/km-nm)
$f(R) = R^\alpha$	$\alpha = 2$, $\lambda = 1.75\ \mu m$, $a = 2.5\ \mu m$, $v = 2.2371$	2	0.792691	0.228573	0.040334	2.3377
		3	0.793175	0.229558	0.042248	2.5371
		4	0.793366	0.229705	0.042293	2.5233
		5	0.793420	0.229735	0.042279	2.5164
		6	0.793439	0.229744	0.042271	2.5135
		8	0.793451	0.229749	0.042263	2.5114
		10	0.793454	0.229750	0.042261	2.5108
		12	0.793454	0.229750	0.042261	2.5108
	$\alpha = \infty$, $\lambda = 1.4\ \mu m$, $a = 2.5\ \mu m$, $v = 2.7743$	2	0.362587	0.168126	0.103860	1.1616
		3	0.384163	0.187228	0.126158	2.1317
		4	0.387402	0.189882	0.129282	2.6016
		5	0.388110	0.190491	0.130020	2.7170
		6	0.388319	0.190682	0.130257	2.7551
		8	0.388428	0.190790	0.130394	2.7777
		10	0.388452	0.190815	0.130427	2.7832
		12	0.388459	0.190824	0.130438	2.7850
$f(R) = R^\alpha + p(e^{-R^2/d^2} - e^{-1/d^2})$	$\alpha = 2$, $p = d = 0.4$, $\lambda = 1.6\ \mu m$, $a = 2.5\ \mu m$, $v = 2.4373$	2	0.826535	0.164472	0.036558	0.3278
		3	0.827699	0.165937	0.037956	0.2669
		4	0.828562	0.166325	0.037638	0.4146
		5	0.828872	0.166436	0.037479	0.4730
		6	0.828996	0.166477	0.037408	0.4975
		8	0.829082	0.166503	0.037357	0.5144
		10	0.829105	0.166510	0.037341	0.5193
		12	0.829113	0.166513	0.037336	0.5210
	$\alpha = \infty$, $p = d = 0.4$, $\lambda = 1.35\ \mu m$, $a = 2.5\ \mu m$, $v = 2.8749$	2	0.433647	0.144542	0.087801	3.9108
		3	0.451618	0.158319	0.102940	1.5008
		4	0.455619	0.160700	0.105473	1.1101
		5	0.456671	0.161287	0.106102	1.0117
		6	0.457026	0.161481	0.106310	0.9791
		8	0.457234	0.161595	0.106432	0.9599
		10	0.457287	0.161624	0.106462	0.9553
		12	0.457306	0.161633	0.106472	0.9537

Sellmeier coefficients for the calculation of n_1, n_2, and their derivatives were taken from [7].

Table I shows the convergence of the numerical results with N (i.e., the number of divisions used in the numerical solution) for a few typical refractive index profiles, including profiles with a Gaussian[2] refractive index dip at the axis. In the presence of the dip the index profile can be written as

$$n^2(R) = n_0^2(R) - (n_1^2 - n_2^2)p(e^{-R^2/d^2} - e^{-1/d^2}) \quad R < 1$$
$$= n_2^2 \quad R > 1 \quad (22)$$

where $n_0^2(R)$ is the refractive index profile in the absence of the dip and p and d define the fractional dip depth and fractional dip width, respectively. The profile is shown in Fig. 1.

As can be seen from the table, extremely good accuracy is obtained in the calculated values of the propagation constant b and its derivatives b' and b'' with $N \lesssim 8$ or step size $h \gtrsim 0.125$. In fact, the calculation of the dispersion coefficient shows that even when the propagation constants are calculated with $N = 4$ the error is only ~0.2 ps/km · nm.

Further, we also carried out calculations to study the effect of the dip on the dispersion characteristics of the fibers. Fig. 2(a) and (b) show the variation of s with λ for power-law profile fibers of radii 2.5 μm and 2.0 μm, respectively, in the presence and absence of the dip. As can be seen, the dip does not always cause the shift of the zero dispersion wavelength

[2]In [8] it has been shown that the observed dip profiles can be well matched to a Gaussian profile.

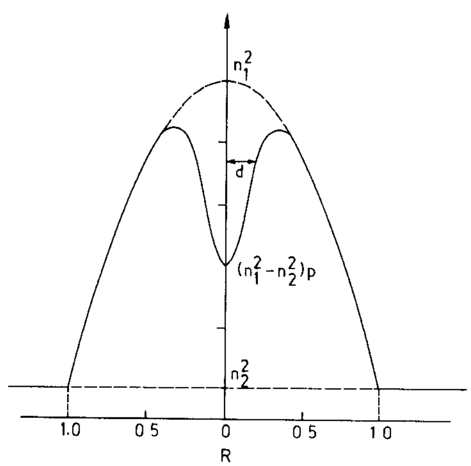
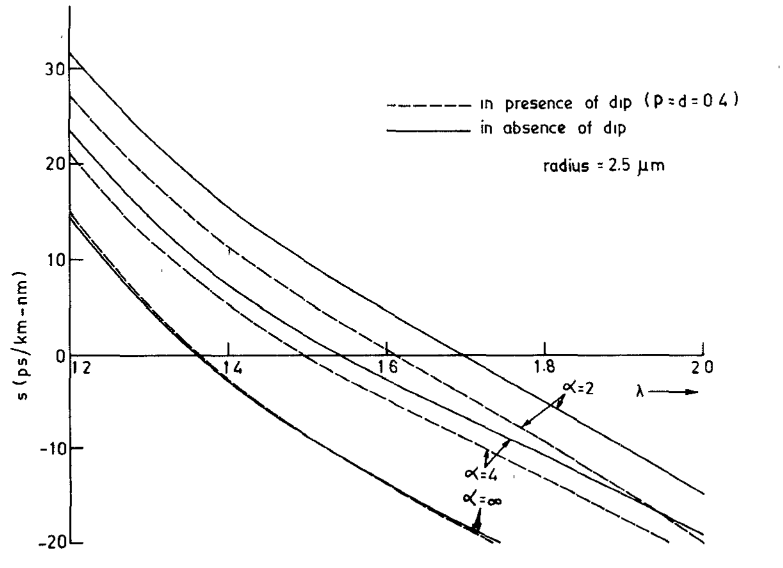
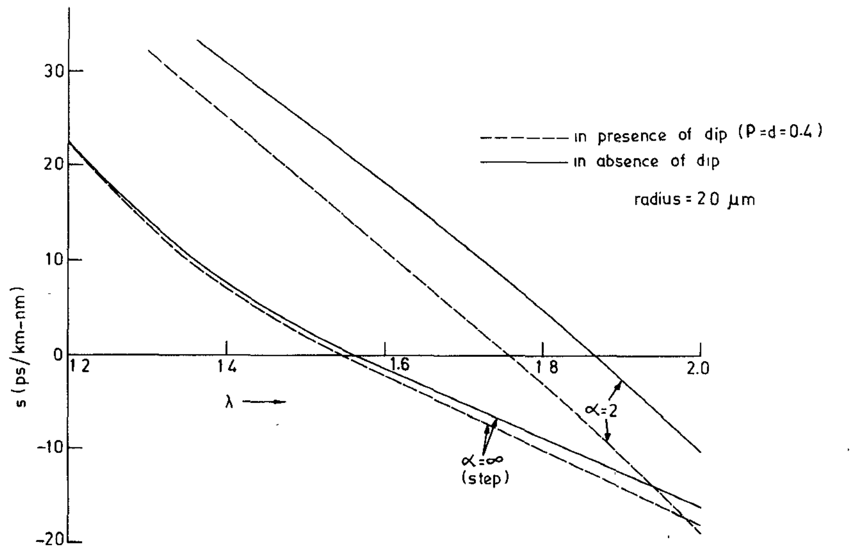


Fig. 1. The continuous curve shows the refractive index profile of a parabolic graded index fiber in the presence of a Gaussian axial index dip given by (22). The dashed curve shows the profile in the absence of the dip.



(a)



(b)

Fig. 2. The variation of the dispersion coefficient s with wavelength λ for GeO_2 doped silica fibers with power law refractive index profiles (i.e., $f(R) = R^{\alpha}$) in the presence (dashed curves) and absence (continuous curves) of a dip; the dip parameters for the calculation are $p = d = 0.4$ and the refractive indexes n_1 and n_2 correspond to a 13.8 percent GeO_2 doping in silica and pure silica, respectively. (a) corresponds to a fiber radius 2.5 μm and (b) corresponds to a radius of 2.0 μm. Note that the shift of the zero dispersion wavelength for step fibers ($\alpha = \infty$) is in opposite directions in the two cases.

to shorter wavelengths as predicted by the earlier perturbation calculation [9], but is a sensitive function of the profile parameters. In fact, to study the validity of the perturbation calculation, we carried out calculations of the "zero dispersion wavelength shift" corresponding to the earlier pertubation calculations.[3] The results are tabulated in Table II along with the earlier results of [9]. As expected, the predictions from the perturbation calculation are correct only for small dip values; for larger dips it is necessary to carry out an exact numerical calculation.

Recently, Sammut and Pask [10] reported a numerical method which transforms the second order scalar differential equation into a first order difference equation instead of a first order differential equation. We could as well use the difference equation procedure to solve (2). In fact, to compare the convergence of the various procedures, we did transform (6) into a difference equation by replacing (dG/dR) by its central difference value to obtain[4]

$$G(R+h) = 2h\left\{v^2\delta f(R) - v^2(1-b) - G^2(R) - \frac{G(R)}{R}\right\} + G(R-h) \tag{23}$$

[3]The dip profile used in [9] does not have the term e^{-1/d^2} of (22).

[4]Recently Rose and Mitra [11] reported the transformation of the Ricatti equation (6) into a difference equation using certain approximations. The so obtained equation differs from (24) and can be shown to be identical to that obtained by Sammut and Pask [10]. Here we also show that the convergence of the difference equation procedure is faster if the difference equation (24) is used instead of the equation in [10] and [11].

TABLE II
COMPARISON OF RESULTS OBTAINED BY THE PERTURBATION CALCULATION [9] WITH PRESENT NUMERICAL RESULTS FOR THE SHIFT IN THE ZERO DISPERSION WAVELENGTH DUE TO THE AXIAL INDEX DIP IN SINGLE MODE FIBERS

Core Radius (μm)	P	$\Delta\lambda = \lambda_o$(with dip) $- \lambda_o$(without dip)					
		d = 0.1		d = 0.3		d = 0.5	
		Present	Pertn.	Present	Pertn.	Present Calcs.	Pertn.
	0.1	1.2	1.2	6.6	7.3	7.1	6.9
2.0	0.3	3.3	3.7	15.4	21.2	15.5	19.8
	0.5	5.2	6.2	18.7	34.5	16.7	31.8
	0.1	0.6	0.5	2.6	2.3	2.7	0.9
2.5	0.3	1.4	1.4	2.2	6.9	0.0	2.7
	0.5	-1.2	2.3	-4.1	11.4	-12.0	4.5

TABLE III
COMPARISONS OF u^2/v^2 WITH N FOR THE DIFFERENCE EQUATION AND RUNGE–KUTTA PROCEDURES

N	Difference Equation procedure		Runge-Kutta
	Using (24)	as in [10]	Procedure to Solve (6)
2	0.60608	0.58323	0.63271
3	0.62006	0.611504	0.63572
4	0.62622	0.62250	0.63655
5	0.62949	0.62766	0.63675
6	0.63154	0.63047	0.63682
8	0.63372	0.63327	0.63686
10	0.63481	0.63457	0.63687
16	0.63605	0.63598	0.63688
24	0.63650	0.63648	0.63688
32	0.63667	0.63665	0.63688
40	0.63674	0.63673	
60	0.63682	0.63682	
100	0.63686	0.63686	

or, denoting $G(R_i)$ and $f(R_i)$ by G_i and f_i, respectively, with $R_i = ih$, we can write (23) as

$$G_{i+1} = 2h\,\{v^2\delta f_i - v^2(1-b) - G_i^2 - Gi/ih\} + G_{i-1} \qquad i \geqslant 1 \tag{24}$$

with the boundary conditions at $R = 0$ giving

$$G_o = 0 \tag{25}$$

and

$$G_1 = h\left\{\frac{v^2}{2}\delta f_o - \frac{v^2}{2}(1-b)\right\}. \tag{26}$$

Table III shows the convergence of a typical set of calculations of the propagation constant b using the two difference equation procedures and the Runge-Kutta procedure. The calculations correspond to a parabolic index fiber [$f(R) = R^2$] with $v = 3.0$. As can be seen, of the two difference equation procedures, the one using (24) shows a more rapid convergence compared to the one using the difference equation of [10]. The Runge-Kutta procedure however, shows an extremely rapid convergence. For example, with $N = 4$ in the RK procedure, one obtains a better accuracy than with $N = 16$ in the difference equation procedure. Hence, even though the Runge-

Kutta procedure requires a greater number of evaluations as compared to the difference equation method for a given N, these are more than compensated by the extremely small value of N required to attain good accuracy.

Very recently, another numerical procedure to calculate b, b', and b'' has been reported by Cohen and Mammel [12]. In this procedure, b is calculated by a direct numerical integration of a second order differential equation obtained from the scalar wave equation by suitably modifying it to facilitate integration for all modes. To calculate b', the stationarity property of the Rayleigh quotient has been used, which gives b' in terms of integrals involving the profile function $f(R)$ and the field $\psi(R)$; these integrals, however, have to be evaluated numerically. Further, b'' is obtained by a numerical differentiation of the results obtained for b' as a function of v. The present procedure, instead, uses similar procedures for calculation of b, b', and b'' and hence involves less computational effort.

In summary, we have presented a numerical procedure to evaluate the propagation constant and its derivatives for a single mode fiber with an arbitrary index profile. The procedure shows a rapid convergence with step size used in the numerical solution of the differential equation by the Runge-Kutta procedure. To illustrate the procedure, we also used it to evaluate the effect of an axial dip on the dispersion characteristics of single mode fibers. Our results, in addition to describing the effect of the dip on the dispersion characteristics also enable one to determine the validity of the perturbation approach used earlier [9]; indeed, for large dips, the perturbation theory results are quite inaccurate and one should use numerical methods. Further, in an attempt to compare the convergence of the Runge-Kutta procedure with an earlier reported difference equation method [10], we have also obtained a difference equation which gives more rapid convergence than the difference equation in [10]. However, the extremely rapid convergence of the Runge-Kutta procedure still makes it more suitable than any of the difference equation procedures.

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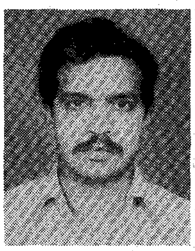

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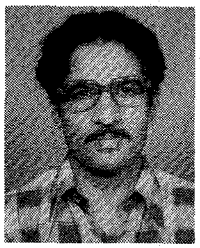

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