ACCURATE OPTICAL FIBER REFRACTIVE INDEX RECONSTRUCTION FROM NEAR FIELD

A. C. Boucouvalas and C. A. Thraskias
Department of Telecommunications Science and Technology, Faculty of Science and Technology, University of Peloponnese, Tripoli, 22100, Greece,
e-mail: {acb, tst06059}@uop.gr

ABSTRACT
A new and efficient algorithm is proposed for calculating directly and accurately the refractive index profile of cylindrical waveguides from knowledge of the mode near field. This inverse problem is solved using transmission line techniques. From Maxwell’s equations, we derive an equivalent transmission-line circuit for a cylindrical dielectric waveguide. Based on an analytical method, that computes the error in the reconstructed refractive index due to inaccuracy in the propagation constant $\beta$. The proposed analytical method computes the refractive index error directly without the need for curve fitting or numerical differentiation. Subsequently we work out the exact value of the propagation constant $\beta$. The calculation of the propagation constant $\beta$ is vital for the refractive index reconstruction and we show that it implies error minimization in the refractive index synthesis from near field. We demonstrate this algorithm with example reconstructions for step, triangular and parabolic optical fiber refractive index profiles. Furthermore we present example reconstructions for step optical fiber refractive index profiles using higher order modes near electric field. This technique is exact, fast and rapidly convergent.

1 INTRODUCTION

The main characteristics of optical waveguides, such as bandwidth, spot size, single-mode propagation conditions, and interwaveguide coupling coefficients are all related to their refractive index profiles. So the characterization of optical fiber refractive index profiles has the fundamental importance for the determination of waveguide optical properties. Refractive index profile measurement, however, is generally very difficult due to small optical fiber dimensions and low refractive index differences between core and cladding. A number of techniques, [1], have been proposed for determining the refractive index distribution of optical fibres from the propagation mode near field, and the most well known rely on the seminal theoretical work by Morishita,[2]. Reference [2] relies on an inverse solution of the scalar wave equation for the refractive index profile. In [1], the measurement of the near field intensity is improved using a scanning optical microscopy technique rather than conventional optics. Improvements from [2], have been recently reported in [3], which is a robust method to noise and errors, and non-iterative, but reported for planar waveguides.

Using transmission line techniques we have shown that they can be applied in optical fibres and can determine exactly the mode propagation constants [4], and cutoff wavelengths of waveguide modes [5]. In general from knowledge of the refractive index, complete waveguide characterization can be achieved using this powerful technique [6].

In this paper we extend the transmission line theory and present a novel method for the exact reconstruction of the waveguide refractive index profile using the fundamental or other higher order modes near electric field data. Although in most cases instrumentation uses the fundamental mode for reconstruction, in some cases this may not be easy and especially if a good higher order mode is present at a convenient wavelength rather than an operation wavelength, it may be suitable to use higher order modes. The following section describes the basic theory our technique is based upon.

2 FORWARD SOLUTION

We divide an optical waveguide into a large number of homogeneous cylindrical layers of thickness $\delta r$, permittivity $\varepsilon$, permeability $\mu$ and conductivity $\sigma$ in Fig.1.

![Homogeneous cylindrical layer](image)
The E and H components of Maxwell’s equations for any such layer can be written as:

\[
\begin{align*}
\beta r E_0 - IE_z &= \omega \mu r H_r, \\
IH_z - \beta r H_0 &= (\omega - j\sigma)rE_r, \\
\frac{\partial (\omega \mu r H_r)}{\partial r} &= -j\omega (IH_r + \beta r H_z) \\
\frac{\partial ((\omega - j\sigma)rE_r)}{\partial r} &= -(\sigma + j\omega)(IE_0 + \beta rE_z) \\
\frac{\partial (IH_r + \beta r H_z)}{\partial r} &= -\frac{\gamma^2}{\omega \mu} + (\omega - j\sigma)rE_r + \beta E_z - \frac{1}{r} E_0 \\
\frac{\partial (IE_0 + \beta rE_z)}{\partial r} &= -\frac{\gamma^2}{\sigma + j\omega} (\omega - j\sigma)rE_r + \beta E_z - \frac{1}{r} E_0 \\
\end{align*}
\]

where \( \gamma^2 = \beta^2 + \left(\frac{1}{r}\right)^2 - \omega^2 \mu \varepsilon + j\omega \mu \sigma \)

We restrict our analysis to the case \( \sigma = 0, \mu = \mu_0, \varepsilon = n^2 \varepsilon_0 \), where \( n \) is the refractive index of the layer at distance \( r \) from the axis.

We define the following variable voltages and currents:

\[
\begin{align*}
V_s &= \frac{V_o}{\sqrt{n}} + V_i \sqrt{n} \quad \text{(sum)} \\
V_d &= \frac{V_o}{\sqrt{n}} - V_i \sqrt{n} \quad \text{(difference)} \\
I_s &= I_o \sqrt{n} + \frac{I_i}{\sqrt{n}} \quad \text{(sum)} \\
I_d &= I_o \sqrt{n} - \frac{I_i}{\sqrt{n}} \quad \text{(difference)}
\end{align*}
\]

where

\[
\begin{align*}
V_o &= \frac{IH_0 + \beta r H_z}{jF} \quad \text{(magnetic voltage)} \\
I_o &= \frac{\omega \mu r H_r}{jF} \quad \text{(magnetic current)} \\
V_i &= \frac{IE_0 + \beta r E_z}{F} \quad \text{(electric voltage)} \\
I_i &= \omega \varepsilon_0 n^3 r E_r \quad \text{(electric current)}
\end{align*}
\]

After algebraic derivatives, (1) and (2) can be transformed into:

\[
\begin{align*}
\frac{\partial V_s}{\partial r} &= -\frac{\gamma_s^2}{jF} I_s \\
\frac{\partial I_s}{\partial r} &= -j\omega \varepsilon_0 n F V_s \\
\frac{\partial V_d}{\partial r} &= -\frac{\gamma_d^2}{F} I_d \\
\frac{\partial I_d}{\partial r} &= -j\omega \varepsilon_0 n F V_d
\end{align*}
\]

where \( \gamma_s^2 = \beta^2 + \left(\frac{1}{r}\right)^2 - n^2 \varepsilon \varepsilon_0^2 + \frac{2nk_0\beta l}{(\beta r)^2 + i^2} \) (for HE modes).

Equations (4) and (5) represent two independent transmission lines with voltages \( V_s, V_d \) and currents \( I_s, I_d \). The corresponding characteristic impedances are:

\[
\begin{align*}
Z_s &= \frac{\gamma_s}{j\omega \varepsilon_0 n F} \\
Z_d &= \frac{\gamma_d}{j\omega \varepsilon_0 n F}
\end{align*}
\]

The above equations are recognized as the well known transmission line equations with the solution represented by the following electric circuit Fig. 2.

**Figure 2:** Equivalent circuit for an optical fibre cylindrical thin layer

\[
\begin{align*}
Z_B &= Z_s \tanh(\gamma_s \delta r) \\
Z_P &= \frac{Z_s}{\sinh(\gamma_d \delta r)}
\end{align*}
\]
where $\delta r$ is the length of the transmission line.

The resonance frequency of the cascade of those electric circuits for a fixed wavelength represents the mode propagation constants $\beta$ of the relevant waveguide with certain refractive index profile.

The technique can further be extended in order to be used for plotting the electric or magnetic field components of the waveguides as follows:

From the above equations, we can derive the Electric current $I$ and Electric field $E_r$. We know that:

$$
V_{HE} = \frac{V_s}{\sqrt{n(r)}} + \frac{V_E}{\sqrt{n(r)}} \tag{8}
$$

$$
V = \frac{V_s}{\sqrt{n(r)}} - \frac{V_E}{\sqrt{n(r)}} \tag{9}
$$

$$
I_{HE} = I_M \sqrt{n(r)} + \frac{1}{n(r)} \frac{I_E}{\sqrt{n(r)}} \tag{10}
$$

$$
I_{EH} = I_M \sqrt{n(r)} - \frac{1}{n(r)} \frac{I_E}{\sqrt{n(r)}} \tag{11}
$$

We wish to determine the E/M field of the HE mode in terms of $I_{HE}$ and $V_{HE}$ variables, we can set $I_{EH} = V_{EH} = 0$ when the HE modes are of interest. This implies that

$$
I_M \sqrt{n(r)} = \frac{I_E}{n(r)} \tag{12}
$$

$$
\frac{V_M}{\sqrt{n(r)}} = V_E \frac{1}{\sqrt{n(r)}} \tag{13}
$$

Substituting into (8) and (9), the following equations can be derived:

$$
V_{HE} = 2V_s \sqrt{n(r)}, \quad I_{HE} = 2I_M \sqrt{n(r)} \tag{14}
$$

$$
V_{HE} = 2 \frac{V_M}{\sqrt{n(r)}}, \quad I_{HE} = 2 \frac{I_E}{\sqrt{n(r)}} \tag{15}
$$

Note that $I_{HE}$, $V_{HE}$ are also referred to as $I_s$, $V_s$ respectively. Hence:

$$
V_E = \frac{V_s}{2\sqrt{n(r)}}, \quad I_M = \frac{I_E}{2\sqrt{n(r)}} \tag{16}
$$

$$
V_M = \frac{V_s}{2}, \quad I_E = \frac{I_E}{2} \tag{17}
$$

$$
I_E = \omega \epsilon_0 n^2(r) r E_r \tag{18}
$$

Hence:

$$
E_r = \frac{I_E}{\omega \epsilon_0 n^2(r)} \frac{Z_0 I_E}{k_r n^2(r) r} \tag{19}
$$

and:

$$
F_\tau = \frac{Z_0 I_E}{n^2(\tau) F} \tag{20}
$$

where $\tau = r k_s$, $\delta \tau = \delta r k_s$, $\beta = \frac{\beta}{k_s}$.

Therefore if we already know the refractive index as a function of radius, we can use the (13) to plot the Electric fields, $E_r$ and subsequent Magnetic fields precisely.

### 3 INVERSE PROBLEM

The equivalent circuit for a cylindrical thin dielectric layer, Fig. 1, of constant refractive index $n$ and thickness $\delta r$ at distance $\tau$ from the core is represented as an electric circuit in Fig. 3. For determining the refractive index profile from knowledge of $E_r$, we assume the following boundary condition: At $r = \infty$, we assume $n = n_2$ (silica refractive index). At $r = \infty$, $Z_{prev} = 0$ and $n(\infty) = n_2$ are assumed.
We know that $\bar{\beta}$ is the effective refractive index and for typical waveguides lies between $n_1$ and $n_2$. Furthermore, as we know $\lambda_n$, $\bar{\beta}$, $\delta$ and $n(\infty) = n_1$, $1(\bar{\beta} + \delta)$ and $V(\bar{\beta} + \delta)$ can be calculated for any radius. Hence we work out $n(\bar{\beta})$ as follows:

$$I_{m}(\bar{\beta}) = \frac{\Delta l}{\sqrt{n(\bar{\beta})}}$$

$$E_{m}(\bar{\beta}) = \frac{1}{2n(\bar{\beta})}$$

and finally

$$E_{m}(\bar{\beta}) = \frac{1}{2n(\bar{\beta})}Z_0$$

$$n(\bar{\beta}) = \left(\frac{1}{2n(\bar{\beta})}\right)^{1/2}$$

$$2E_{m}(\bar{\beta})$$

Since we know $E_{m}(\bar{\beta})$ and $I_{m}(\bar{\beta})$, hence we can calculate $n(\bar{\beta})$ for every $\bar{\beta}$ recursively.

We know that the calculation of the exact propagation constant $\bar{\beta}$ is necessary for solving the inverse problem of refractive index reconstruction. In [7], we have shown empirically that the error in the propagation constant is minimum at the exact value. Here we present an analysis which confirms this result and we demonstrate reconstruction of the index profiles using this method. In the following we provide exact analytical formulas for the calculation of the radial refractive index gradient with respect to radius and as a function of the required propagation constant $\bar{\beta}$.

The derivative (17) can be calculated. We first work out $\bar{\beta}$ for every $\bar{\beta}$ recursively.

$$n(\bar{\beta}) = \left(\frac{1}{2n(\bar{\beta})}\right)^{1/2}$$

$$2E_{m}(\bar{\beta})$$

Notice that for equations (18) and (19) $\frac{\partial Z_B}{\partial \bar{\beta}}$ and $\frac{\partial Z_B}{\partial \bar{\beta}}$ are required and are given by:

$$\frac{\partial Z_B}{\partial \bar{\beta}} = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

$$\frac{\partial Z_B}{\partial \bar{\beta}} = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

For a certain $\bar{\beta}$, we change $\bar{\beta}$ within $k_n, n_2 \leq \bar{\beta} \leq k_n$ and recalculate the refractive index profile until the error in the radial refractive index, $\bar{\beta}$ at certain $\bar{\beta}$ is minimum. When the error is minimum we have the exact $\bar{\beta}$, and the reconstructed refractive index is also exact. The analytical computation of the refractive index error can be achieved with use of derivative (17). From (7) we know that the equivalent T-circuit impedances are functions of propagation constant $\bar{\beta}$.

The following derivative can be extended as follows:

$$\frac{\partial \bar{\beta}}{\partial \bar{\beta}} = \frac{n}{\frac{\partial \bar{\beta}}{\partial \bar{\beta}} |_{\bar{\beta}=\bar{\beta}_0}}$$

where

$$Z_B = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

And finally

$$Z_B = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

For a certain $\bar{\beta}$, we change $\bar{\beta}$ within $k_n, n_2 \leq \bar{\beta} \leq k_n$ and recalculate the refractive index profile until the error in the radial refractive index, $\bar{\beta}$ at certain $\bar{\beta}$ is minimum. When the error is minimum we have the exact $\bar{\beta}$, and the reconstructed refractive index is also exact. The analytical computation of the refractive index error can be achieved with use of derivative (17). From (7) we know that the equivalent T-circuit impedances are functions of propagation constant $\bar{\beta}$.

The following derivative can be extended as follows:

$$\frac{\partial \bar{\beta}}{\partial \bar{\beta}} = \frac{n}{\frac{\partial \bar{\beta}}{\partial \bar{\beta}} |_{\bar{\beta}=\bar{\beta}_0}}$$

where

$$Z_B = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

And finally

$$Z_B = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

For a certain $\bar{\beta}$, we change $\bar{\beta}$ within $k_n, n_2 \leq \bar{\beta} \leq k_n$ and recalculate the refractive index profile until the error in the radial refractive index, $\bar{\beta}$ at certain $\bar{\beta}$ is minimum. When the error is minimum we have the exact $\bar{\beta}$, and the reconstructed refractive index is also exact. The analytical computation of the refractive index error can be achieved with use of derivative (17). From (7) we know that the equivalent T-circuit impedances are functions of propagation constant $\bar{\beta}$.

The following derivative can be extended as follows:

$$\frac{\partial \bar{\beta}}{\partial \bar{\beta}} = \frac{n}{\frac{\partial \bar{\beta}}{\partial \bar{\beta}} |_{\bar{\beta}=\bar{\beta}_0}}$$

where

$$Z_B = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

And finally

$$Z_B = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

For a certain $\bar{\beta}$, we change $\bar{\beta}$ within $k_n, n_2 \leq \bar{\beta} \leq k_n$ and recalculate the refractive index profile until the error in the radial refractive index, $\bar{\beta}$ at certain $\bar{\beta}$ is minimum. When the error is minimum we have the exact $\bar{\beta}$, and the reconstructed refractive index is also exact. The analytical computation of the refractive index error can be achieved with use of derivative (17). From (7) we know that the equivalent T-circuit impedances are functions of propagation constant $\bar{\beta}$.

The following derivative can be extended as follows:

$$\frac{\partial \bar{\beta}}{\partial \bar{\beta}} = \frac{n}{\frac{\partial \bar{\beta}}{\partial \bar{\beta}} |_{\bar{\beta}=\bar{\beta}_0}}$$

where

$$Z_B = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

And finally

$$Z_B = \frac{Z_0}{n} \left[ Z_0 \left( \frac{1}{Z_B + Z_{n-1}} + \frac{1}{Z_p} \right) \right]$$

For a certain $\bar{\beta}$, we change $\bar{\beta}$ within $k_n, n_2 \leq \bar{\beta} \leq k_n$ and recalculate the refractive index profile until the error in the radial refractive index, $\bar{\beta}$ at certain $\bar{\beta}$ is minimum. When the error is minimum we have the exact $\bar{\beta}$, and the reconstructed refractive index is also exact. The analytical computation of the refractive index error can be achieved with use of derivative (17). From (7) we know that the equivalent T-circuit impedances are functions of propagation constant $\bar{\beta}$.
\[
\frac{\partial^2 \gamma}{\partial r^2} = -\frac{2l^2}{r^3} + \frac{4nk_b \beta^3 r l}{((\beta r)^2 + l^2)^2}
\]

\[
\frac{\partial^2 \gamma}{\partial n^2} = -2k_b^2 n - \frac{2k_b \beta l}{(\beta r)^2 + l^2}
\]

4 NUMERICAL RESULTS AND DISCUSSION

Fig. 4 shows the reconstructed refractive index profile of a step index optical fibre of refractive index \( n_1 = 1.51508 \) and \( n_2 = 1.508 \) and \( V = 2.3 \) using the fundamental mode near electric field data. In the fig. 4 we assume we have full knowledge of the exact propagation constant \( \beta \). Fig. 5 shows the reconstructed refractive index profile of the same step index optical fibre for an incorrect propagation constant \( \beta \neq \beta_{\text{exact}} \). We observe that the reconstructed refractive index is sensitive to the propagation constant \( \beta \). Hence, if we want to minimize the error in the refractive index reconstruction we require to work out the exact value of the propagation constant.

Figure 4: The reconstructed refractive index using (16) with \( \beta = \beta_{\text{exact}} \). The normalized value of the exact propagation constant used is \( b = 0.5032 \).

![Figure 5: The reconstructed refractive index using (16) with \( \beta \neq \beta_{\text{exact}} \). The normalized propagation constant used is \( b = 0.5112 \).](image)

![Figure 6 (a): The derivative \( dn/dr \) versus the normalized radius \( r \) using the fundamental mode near field data with \( \beta \neq \beta_{\text{exact}} \). The normalized propagation constant used is \( b \).](image)

Figure 6 (a): The derivative \( dn/dr \) versus the normalized radius \( r \) using the fundamental mode near field data with \( \beta \neq \beta_{\text{exact}} \). The normalized propagation constant used is \( b \).
constant used is \( b = 0.2889 \). (b): The ripple of the derivative \( \frac{dn}{dr} \) versus the normalised propagation constant \( b \) for three different step index optical fibres with the same \( V = 2.3 \) and different \( \Delta \) using the fundamental mode near field data.

Fig.6(a) shows the derivative \( \frac{dn}{dr} \) versus the normalised radius \( r \) with \( \beta \neq \beta_{\text{exact}} \). Since in this example we study a step index optical fiber, the derivative \( \frac{dn}{dr} \) should be zero in the core of the fiber. The oscillations of the derivative in the core prove the existence of error in the refractive index reconstruction which we expect to be near zero when the exact \( \beta \) is used.

The error in the cladding is forced to zero using the knowledge of the cladding silica refractive index.

Fig.6(b) shows that there is a minimum ripple (error) in the reconstructed index at a specific \( \beta \) value. We observe that the ripple oscillations increase with incorrect \( \beta \). At the minimum ripple point we have the exact \( \beta \), and Table 1 shows the calculated error for \( b \), the derived normalised \( \beta \), \((0<b<1)\).

### Table 1

<table>
<thead>
<tr>
<th>Three different optical fibres</th>
<th>( \beta_{\text{exact}} )</th>
<th>( \beta_{\min} )</th>
<th>( \frac{\beta_{\min} - \beta_{\text{exact}}}{\beta_{\text{exact}}} \times 100 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta = 0.000662 ), ( V = 2.3 )</td>
<td>0.5032</td>
<td>0.5033</td>
<td>0.01987</td>
</tr>
<tr>
<td>( \Delta = 0.0013 ), ( V = 2.3 )</td>
<td>0.5032</td>
<td>0.5039</td>
<td>0.14</td>
</tr>
<tr>
<td>( \Delta = 0.0026 ), ( V = 2.3 )</td>
<td>0.5032</td>
<td>0.5041</td>
<td>0.18</td>
</tr>
</tbody>
</table>

In order to derive the exact value of the propagation constant \( \beta \) we start to calculate the derivative \( \frac{dn}{dr} \) versus the radius \( r \) with \( \beta = n_2 \) and repeat the process with a \( \beta \) change within \( n_2 \leq \beta \leq n_1 \) until the ripple is minimum, Fig.5(b). At this minimum ripple point we have the exact \( \beta \), and the reconstructed refractive index is also exact. The measurement of the oscillation can be achieved with the standard deviation. In the Fig.6(b) the three curves correspond to three different step index optical fibers with the same \( V = k_\text{n0} \left( n_1^2 - n_2^2 \right)^{1/2} \) and different \( \Delta = \left( n_1 - n_2 \right) / n_0 \). So the three optical fibers have the same normalised propagation constant and, hence, the three curves have the same minimum.

Fig.7(a), shows an example refractive index reconstruction for a triangular refractive index optical fiber. Fig.7(b), shows the index oscillation, the derivative \( \frac{dn}{dr} \) versus \( \beta \) for the triangular refractive index optical fiber. Fig.8(a), shows an example refractive index reconstruction for a parabolic refractive index optical fiber. Fig.8(b), shows the oscillation of the derivative \( \frac{dn}{dr} \) versus \( \beta \) for the parabolic refractive index optical fiber. Finally, table 2, shows the accuracy of our method for the triangular and parabolic refractive index optical fibres.
Fig. 9(a) shows the reconstructed refractive index profile of a step index optical fibre of refractive index $n_1 = 1.51508$ and $n_2 = 1.508$ and $V = 5$ using the HE$_{12}$ mode near field data. We demonstrate that the method reconstructs the refractive index profile successfully for this and other higher mode fields. Fig. 9(b) shows the ripple of the derivative $dn/dr$ versus the normalised propagation constant $b$ using the HE$_{12}$ mode.

![Graph](image1.png)

Figure 8 (a): A parabolic refractive index reconstruction from the fundamental mode near field. (b): The ripple of the derivative $dn/dr$ versus the normalised propagation constant $\beta$ for the parabolic refractive index optical fiber.

![Graph](image2.png)

**Table 2**

<table>
<thead>
<tr>
<th></th>
<th>$\bar{\beta}$ exact</th>
<th>$\bar{\beta}$ min</th>
<th>$\frac{\bar{\beta} - \beta}{\bar{\beta}} \times 100$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangular refractive index</td>
<td>1.510877</td>
<td>1.510872</td>
<td>0.00033093</td>
</tr>
<tr>
<td>Parabolic refractive index</td>
<td>1.512256</td>
<td>1.512251</td>
<td>0.00033063</td>
</tr>
</tbody>
</table>

Figure 9 (a): The reconstructed refractive index using the HE$_{12}$ mode. (b): The ripple of the derivative $dn/dr$ versus the normalised propagation constant $b$ for three different step index optical fibres with the same $V = 5$ and different $\Delta$ using the HE$_{12}$ mode.
Three different optical fibres | $b_{\text{exact}}$ | $b_{\text{min}}$ | $\frac{b_{\text{exact}} - b_{\text{min}}}{b_{\text{exact}}} \%$
---|---|---|---
$\Delta = 0.0047$, $V = 5$ | 0.2149 | 0.2151 | 0.093
$\Delta = 0.0013$, $V = 5$ | 0.2149 | 0.2152 | 0.14
$\Delta = 0.000662$, $V = 5$ | 0.2149 | 0.2148 | 0.046

Fig. 10 shows the ripple of the derivative $d\beta/dr$ versus the normalised propagation constant $b$ using the HE$_{21}$ mode. Table 4 shows the calculated error.

The accuracy of our method in the calculation of the propagation constant using the HE$_{21}$ mode.

Three different optical fibres | $b_{\text{exact}}$ | $b_{\text{min}}$ | $\frac{b_{\text{exact}} - b_{\text{min}}}{b_{\text{exact}}} \%$
---|---|---|---
$\Delta = 0.0047$, $V = 5$ | 0.6018 | 0.6021 | 0.0498
$\Delta = 0.0013$, $V = 5$ | 0.6018 | 0.6019 | 0.0166
$\Delta = 0.000662$, $V = 5$ | 0.6018 | 0.6017 | 0.0166

5 CONCLUSIONS

In this paper, a new and accurate refractive index profile synthesis technique has been developed. This method is based on the Transmission-Line technique. An exact analytic method for calculating the mode $\beta$, is presented during the refractive index reconstruction from the near field. The accurate calculation of the propagation constant $\beta$ is very important for the refractive index synthesis as it results in the error minimization in the reconstructed refractive index. The method requires knowledge of the near field of the optical fibre and the reconstruction is theoretically exact. Simulation results demonstrate the potential of this new method.

6 REFERENCES

Anthony C. Boucouvalas has worked at GEC Hirst Research Centre, and became Group Leader and Divisional Chief Scientist until 1987, when he joined Hewlett Packard (HP) Laboratories as Project Manager. At HP Labs, he worked in the areas of optical communication systems, optical networks, and instrumentation, until 1994, when he joined Bournemouth University. In 1996 he became a Professor in Multimedia Communications, and in 1999 became Director of the Microelectronics and Multimedia Research Centre.

In 2006 he joined the Department of Telecommunication Sciences at the University of Peloponnese in Tripolis, Greece where he is now head of Department. His current research interests span the fields of wireless communications, optical fibre communications and components, multimedia communications, and human-computer interfaces, where he has published over 200 papers. He has contributed to the formation of IrDA as an industry standard and he is now a Member of the IrDA Architectures Council.

He is a Fellow of Fellow of the Royal Society for the encouragement of Arts, Manufacturers and Commerce, (FRSA) and a Fellow of IEE, (FIEE). In 2002 he became a Fellow of the Institute of Electrical and Electronic Engineers (FIEEE), for contributions to optical fibre components and optical wireless communications. He is a Member of the New York Academy of Sciences, and Association for Computing Machinery (ACM). He is an Editor of numerous Journals and in the Organising committee of many conferences.

Chris A. Thraskias was born in Mesolakkia, Serres, Greece, on September 23, 1983. He graduated from the Greek Air Force Academy, Athens, Greece, in 2005 and he is currently working towards the Ph.D. degree at University of Peloponnese, Tripoli, Greece. His doctoral work focuses on design of optical fibers using the inverse transmission-line technique.

Mr Thraskias is now Officer in the Hellenic Air Force and he works as avionics engineer in the military airport of Kalamata, Greece. He is head of the Computer Based Training System in the airport of Kalamata.