Curvature analysis of periodically segmented waveguides using a modified BPM

Masanori Inoue 1, Jun-ichi Sakai *

Faculty of Science and Engineering, Ritsumeikan University, Noji-higashi, Kusatsu-city, Shiga 525-8577, Japan

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Abstract

Periodically segmented waveguides (PSWs) are analyzed using a finite-difference beam propagation method (BPM) combined with a coordinate rotation technique. For the analysis of curved PSW, a new technique is proposed to apply the BPM to a waveguide with large propagation angle such as 40° or more, and the curvature effect is taken into consideration in the analysis. The method is applied to treating two kinds of two-dimensional (2-D) PSW, namely straight and bent waveguides with a fixed curvature. For designing 2-D straight PSW, the propagation dependence on the segment period, duty-cycle, etc. is investigated numerically.

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1. Introduction

Optical waveguides are used in many technology fields, especially in optical integrated circuits or optical communications. Optical waveguides have core whose refractive index is higher than cladding’s one. Refractive index change has been demonstrated by Ti indiffusion [1] or ion exchange [2] in LiNbO3. It is desirable that core region is flexibly fabricated in intentional shapes, such as a waveguide bent freely with respect to the direction of the light. This can be done by the lithography technique or the optical beam scanning, as shown next. A permanent refractive-index increase is induced in several glasses by the femtosecond laser radiation [3]. This technique is also applied to making an optical waveguide [4], a Y coupler [5] and a directional coupler [6]. In these applications, a waveguide is formed by the collection of sequential pulses. It is ideally regarded as a periodically segmented waveguide (PSW) where index profile is periodically modulated along the direction of propagation.

Quasi-modes of the PSW has been analyzed, and the power loss arising from segment intervals and the mode size have been calculated numerically [7]. For practical use of the optical beam scanning technique, it is better to radiate as few pulses as possible.
In this paper, an attention is paid to the power confined in the PSW. Two kinds of PSW have been analyzed; the straight waveguide and curved waveguide with a fixed curvature. For these waveguides, power confinement rate inside core is calculated as a function of the segment period and duty-cycle. Two-dimensional finite-difference beam propagation method (FD-BPM) [8] is used here because it gives an unconditionally stable solution. In addition, the curvature of PSW is also taken into consideration in an analysis of PSW since it is indispensable to the design of flexible optical waveguides. The analysis for curved PSW is achieved by a wide-angle beam propagation method newly proposed here.

2. Analysis method for curved waveguides using BPM

The BPM is a powerful tool for analyzing a waveguide whose refractive index changes along the direction of propagation. The fast Fourier transform BPM (FFT-BPM) has been widely used to design optical waveguides [9] before the FD-BPM was developed. The FD-BPM is utilized among various BPM techniques because it has high calculation efficiency and high accuracy compared to other methods. In this paper, the PSW is analyzed by a FD-BPM using Padé approximation operator [10] to treat the propagation with wide angle. This paper makes use of the transparent boundary condition [11] as well as the wide-angle analysis.

The BPM is a method which performs computation sequentially along the z-axis of rectangular coordinates. The FD-BPM has been adopted for an abrupt bent waveguides [12] or bent dielectric waveguides [13]. A combination of the BPM with conformal mapping has treated radiation loss in S-shaped curves [14]. However, they cannot be applied to a PSW even if the wide-angle BPM is used.

The PSW structure can be changed freely by the arrangement of segments. The Padé approximation operator can be used to analyze the PSW with a certain curvature. However, Padé approximant-based wide-angle FD-BPM secures a high accuracy only for a waveguide with a propagation angle less than 20–30°. Therefore, a new technique is proposed here that can deal with a waveguide with more and more wide propagation angle, and it is employed to analyze the curved PSW in this paper. The new analysis method for the curved waveguide will be described after briefly explaining the FD-BPM.

2.1. Outline of calculation procedure

Calculation proposed here proceeds in the following steps; curved waveguide is separated into a few fan-shaded sections as shown in Fig. 1. Each section is calculated part by part using a previous BPM. In short, the present method is a method where the propagation angle is decreased by rotating the analysis region in proportional to bending of waveguide such that the BPM can be applied to a waveguide with small propagation angle.

Suppose that the z-axis corresponds to the longitudinal direction of optical dielectric waveguide, and that its structure is uniform along the y-direction. The lateral component of field \( E_y \) is set to be \( E_y = \phi(x, z) \exp(-j\beta z) \) under the slowly varying envelope approximation (SVEA). Here, \( \beta \)
is the $z$-component of wave number. The 2-D scalar Helmholtz equation can be written by

$$\frac{\partial \phi}{\partial z} + \frac{j}{2\beta} \frac{\partial^2 \phi}{\partial z^2} = -j\frac{P}{2\beta} \phi,$$

(1)

where $P$ is an operator defined by

$$P = \frac{\partial^2}{\partial x^2} + \frac{k_0^2}{n^2(x, z) - n_{eff}^2}.$$  

(2)

Here, $n(x, z)$ is the refractive index profile, $n_{eff} = \beta/n_0$ is the reference refractive index and $k_0$ is the free space wave number.

When a structure of the waveguide changes slowly along the $z$-direction, Eq. (1) can be solved by using Padé rational expansion [10]. In this paper, in order to calculate field in a limited area, we make use of Padé (2,2) order by which a sufficiently high accuracy is acquired.

2.2. Calculation of field for curved waveguides

2.2.1. Size of calculation region

Two types of coordinate systems are defined here. One is coordinates which are fixed in the waveguide to be analyzed, and it is represented by $\zeta-\zeta$ coordinates (see Fig. 1). The other is coordinates $x-z$ rearranged every step of the BPM analysis, where the $x$-axis is the transverse direction of the analysis region and the $z$-axis is orthogonal to the $x$-axis.

It is assumed that incident field $\phi_0$ is given on $X_{L0}X_{R0}$ in Fig. 1, and that the segment center $X_{C0}$ is situated on this line. $X_{L0}$ and $X_{R0}$ are edges of the analysis region. Positions of the edges are set to be far from the segment center $X_{C0}$ such that their fields sufficiently decay. In the present calculation, both $X_{L0}X_{C0}$ and $X_{C0}X_{R0}$ were set to be $20a$ with the core half width $a$. We need determine the size of calculation region before fields are calculated along a direction perpendicular to the $X_{L0}X_{R0}$ using the BPM.

We evaluate a next field $\phi_1$ obtained after plane is rotated from the line $X_{L0}X_{R0}$ by an angle $\theta_1$ around the curvature center $O$. Arc $X_{C0}X_{C1}$ and its extension line is on the core center. The rotation angle $\theta$ was set to be $10^\circ$ in Padé (2,2) order approximation, since its application limit is about 20–30°.

Size of calculation region for BPM is determined such that most of the field $\phi_1$ is included within the region $l_x \times l_z$, as shown by the broken line of Fig. 1. Here, $l_x$ indicates the length along the rearranged x-direction of calculation window, for example, $l_x = X_{L0}X_{R0}$ in Fig. 1. Length $l_z$ along the rearranged z-direction depends on whether the curvature center is situated in the left-hand side against the core center or in the right-hand side. Once the calculation region size is determined, we can calculate fields with the help of the BPM with pertinent wide-angle order.

2.2.2. How to obtain an incident field for next step

Fields obtained directly by the BPM are those only for the lattice points of calculation window. On the other hand, field $\phi_1$ must be evaluated on the line $X_{L1}X_{R1}$ in Fig. 1. Accordingly, field $\phi(X)$ for an arbitrary point $X$ must be calculated from fields at three lattice points, $A$, $B$ and $C$, being the nearest to the $X$ (see Fig. 2). Their fields, $\phi(A)$, $\phi(B)$ and $\phi(C)$, can be obtained by the BPM.

A simple way to obtain unknown field at $X$ is to assume that the field $\phi(X)$ is on a plane which is formed by $\phi(A)$, $\phi(B)$ and $\phi(C)$. In order to obtain the unknown field $\phi(X)$ at $X$, we put a triangular

![Fig. 2. Calculation of field at an arbitrary point $X$ from those at three points. Three points, $A$, $B$ and $C$, are lattice points and are closest to an arbitrary point $X$ where field is to be evaluated. Each height in the vertexes corresponds to the real or imaginary part of each complex amplitude, from which real or imaginary part of complex amplitude $\phi(X)$ in point $X$ can be calculated.](image-url)
prism on the $x$–$z$-plane in Fig. 2. The base of the prism is formed by three vertexes $A$, $B$ and $C$. Each height of the prism corresponds to the real or imaginary part of complex amplitude at points, $A$, $B$ and $C$. If unknown field $\phi(X)$ is approximated by $\phi(A)$, $\phi(B)$ and $\phi(C)$ formed on a triangular plane, the field $\phi(X)$ can be expressed by

$$\phi(X) = (1 - s - t)\phi(A) + s\phi(B) + t\phi(C).$$  \quad (3)

Here, both $s$ and $t$ are the real numbers and they satisfy

$$AX = sAB + tAC.$$  \quad (4)

Parameters $s$ and $t$ can be determined immediately by solving Eq. (4). Then unknown field $\phi(X)$ at an arbitrary point $X$ can be evaluated by substituting the $s$ and $t$ values into Eq. (3).

The field $\phi_1$ on $X_{L1}X_{R1}$ is used as an incident field to obtain field for the next divided region (see Fig. 1). Thus, the line $X_{L1}X_{R1}$ becomes a new $x$-axis and an axis orthogonal to the new $x$-axis becomes the new $z$-axis in the rearranged coordinates.

Repeating the above procedures enables us to calculate fields for a curved waveguide with an arbitrary shape. Fields for various kind of bent waveguides can be analyzed by changing the curvature radius, its center location or the rotation angle every calculation loop. This method can easily be applied to the 3-D analyzing region.

3. Straight periodically segmented waveguides

A 2-D PSWs shown in Fig. 3 is considered here. We set that the $z$-axis is longitudinal direction of the waveguide and that the structure is uniform along the $y$-direction. Important parameters to design PSWs are the period $\Lambda$, duty-cycle $\eta$, entire length of PSWs $L$ and normalized frequency $V$. The duty-cycle $\eta$ is defined by the ratio of the segment length along the $z$-axis to the period of PSWs. The normalized frequency $V$ of the optical waveguide is defined by $V = \frac{2\pi an_{core}}{\lambda\sqrt{2\Delta/\lambda}}$ [15]. Here, $a$ is the core half width, $n_{core}$ is the core refractive index, $\Delta$ is the relative index difference between core and cladding and $\lambda$ is the wavelength.

Refractive index increase due to the photo-induced process amounts to a value of 0.035 in silica glasses [3], although its value depends on the radiation exposure. It is possible to get a relative index difference value as large as about 2.3%.

Fig. 4 shows the wave propagation for the incidence of TE fundamental mode in a PSW where $\Lambda = 20$ $\mu$m, $\eta = 0.5$, $V = \pi/2$ and $\Delta = 0.88\%$. It is observed from the figure that the field undulates in terms of the period of PSWs along the propagation direction unlike the usual waveguide without segment intervals. After optical intensity at the core center decreases in the no-core region, it recovers...
its value in the next core region. Optical waves escape from the core-cladding interface of no-core region. We must design the period and duty-cycle appropriately to avoid the power loss caused by the intervals between segments.

Three calculation patterns will be shown in the following:

1. Variation of period \( \lambda = 10 \) to \( 100 \) \( \mu m \),
   \( \eta = 0.5 \), \( L = 1000 \) \( \mu m \),

2. Variation of duty-cycle \( \eta = 0.1 \) to \( 1.0 \),
   \( \lambda = 10 \) \( \mu m \), \( L = 1000 \) \( \mu m \) and

3. Variation of entire length of PSWs \( L = 50 \) to \( 1000 \) \( \mu m \), \( \lambda = 10 \) \( \mu m \), \( \eta = 0.5 \).

Although the straight PSW has been treated as a function of parameters similar to the above using an equivalent continuous waveguide \( [7] \), the present paper stresses the normalized frequency dependence of the power confinement. In each pattern, an incident field is set to be the eigenmode field of TE fundamental mode for each \( V \). After output field is calculated using the BPM, the confinement power in segment is evaluated. Core refractive index \( n_{core} = 1.46 \), core half width \( a = 2.0 \) \( \mu m \) and wavelength \( \lambda = 1.55 \) \( \mu m \) are fixed throughout numerical calculations. Normalized frequency \( V \) is varied from 0.758 to 1.692 by changing the cladding index \( n_{clad} \) from 1.445 to 1.457 (\( \Delta = 0.205\% \) to \( 1.022\% \)). In addition, propagation constant and reference index needed in the BPM calculation are utilized for values corresponding to its mode.

In calculating numerical examples, the transverse and longitudinal step sizes are set to be \( \Delta x = 0.5 \) \( \mu m \) and \( \Delta z = 0.5 \) \( \mu m \), respectively, throughout this paper. Transverse analyzing area is \( -100 \) \( \mu m \) \( \leq x \leq 100 \) \( \mu m \).

Reflection arising from the boundary of segments or substrate can give rise to an error. Intensity reflectivity is represented by

\[
R = \left( \frac{n_{core} - n_{clad}}{n_{core} + n_{clad}} \right)^2 = \left( \frac{\Delta}{2 - \Delta} \right)^2
\]

under a weak guidance approximation. For \( \Delta = 0.2 \) (\( 1.0\% \)), \( R \) value becomes \( 1.0 \times 10^{-4}\% \) (\( 2.5 \times 10^{-3}\% \)). Therefore, the error due to reflections is negligible for such \( \Delta \) values.

Figs. 5–7 show the power confinement, respectively, as a function of the period, duty-cycle and entire length of PSWs. The ordinate in each figure shows the transmitted power through the core of the PSW divided by that in the usual slab waveguide (no segments, namely \( \eta = 1.0 \) in PSWs). The single-mode operation region is represented by \( V \leq \pi/2 \).

![Fig. 5. Power confinement in straight PSW as a function of the period \( \lambda = 1000 \) \( \mu m \) and \( \eta = 0.5 \). Core half width \( a = 2.0 \) \( \mu m \), core index \( n_{core} = 1.46 \) and wavelength \( \lambda = 1.55 \) \( \mu m \) are fixed from Figs. 5–7. Normalized frequency is varied by changing the relative index difference \( \Delta \).](image)

![Fig. 6. Power confinement of straight PSW as a function of the duty-cycle \( \eta = 1.0 \) in PSWs. The larger the duty-cycle is, the more strongly PSW confines power into segments.](image)
3.1. Variation of period

It should be noted in Fig. 5 that the entire length and duty-cycle are fixed, respectively, at \( L = 1000 \mu m \) and \( \eta = 0.5 \). Accordingly, the sum of segment intervals is equal to 500 \( \mu m \) in spite of PSWs period. The number of segments becomes small as the period becomes large. These facts should be taken into account when Fig. 5 is considered.

It is found in Fig. 5 that the power rapidly attenuates for period \( \lambda \) larger than about 40 \( \mu m \) in case of large \( V \). For \( V = 0.758 \), the power hardly decays even in \( \lambda = 100 \mu m \). These behavior can be explained as follows: in general, power confinement into the core becomes strong as normalized frequency \( V \) increases. This means that the light propagating through the core is inclined to be diffracted for large \( V \). Accordingly, the larger the \( V \) is, the more fields are sensitive to the period \( \lambda \) and segment interval of PSWs because the sum of segment intervals is kept identical as mentioned above. It is desirable to keep period \( \lambda \) less than about 40 \( \mu m \).

3.2. Variation of duty-cycle

In Fig. 6, the entire length and period of PSWs are fixed at \( L = 1000 \mu m \) and \( \lambda = 10 \mu m \). Therefore, total number of segments is always kept constant for every duty-cycle. Instead of this, the sum of intervals between segments changes for every duty-cycles. For example, the sum is 900 \( \mu m \) for \( \eta = 0.1 \) and is 100 \( \mu m \) for \( \eta = 0.9 \). These points should be kept in mind when seeing Fig. 6.

It can be seen from Fig. 6 that the power confinement is roughly proportional to the duty-cycle \( \eta \). Fluctuation from the proportionality is large in the middle duty-cycle values as normalized frequency becomes large. The proportionality means that PSWs with large duty-cycle are desirable as the natural conclusion. We can evaluate the permissible duty-cycle from this figure if total loss is prescribed.

Although the power confinement was not so weak for normalized frequency \( V = 0.758 \) in Fig. 5, large power loss is observed for small duty-cycle in the identical normalized frequency. It indicates that the power attenuation is remarkably observed for small normalized frequency \( V \) if total interval of segments is sufficiently long.

The ordinate value always becomes unity at \( \eta = 1 \) because it corresponds to the three-layered slab waveguide without segment intervals.

3.3. Variation of entire length of PSWs

Both period \( \lambda = 10 \mu m \) and duty-cycle \( \eta = 0.5 \) are fixed in Fig. 7. After the power confinement once decreases, it slightly increases and again is reduced with increasing the entire length of PSWs. For example, for \( V = 1.072 \) power confinement at \( z = 800 \mu m \) is larger than that at \( z = 300 \mu m \). Undulation in power can be seen with a period of several hundreds micrometer or more at \( \lambda = 1.55 \mu m \). In particular, the degradation in confinement is marked for large \( V \) where power confinement is relatively good in the usual waveguide without interval. Note that plotted-values show those in the end of the segments but that all the behavior for \( z = 0 \) to 1000 \( \mu m \) is not shown.

The above tendency in Fig. 7 can be explained as follows; Property for \( V \) can be convinced by the field spread, as already described. Reason for the undulation is somewhat complicated. The ordinate in Fig. 7 indicates the ratio of core fractional intensity of PSW to that of usual waveguide. Optical
waves transmitted through the core are diffracted in no-segment region and the diffracted waves are again coupled to the core region. On the other hand, optical waves in the cladding region continue to be diffracted with propagation. Coupling efficiency between segment and no-segment regions is determined by matching between the diffracted field and the eigenmode field. This efficiency means that for the overall field in the cross-section. There may be a case where the efficiency decreases with propagation, however core fractional intensity increases with propagation.

4. Curved periodically segmented waveguides

The period and duty-cycle for the curved PSWs must be redefined in a manner different from the straight one since their values depend on measured positions. Lengths such as period and duty-cycle in the curved PSWs are measured along the segment center, as shown in Fig. 8. The period \( A \) is defined by the length of arc \( AC \) (\( = \) arc \( BD = \) arc \( CE \)), and the duty-cycle \( \eta \) is defined by the ratio of the arc \( BC \) length to the arc \( AC \) length.

Waveguide parameters for the curved PSWs are the same as those used in the straight PSWs analysis; wavelength is 1.55\( \mu \)m, core half width is \( a = 2.0 \mu \)m and segment index is \( n_{\text{core}} = 1.46 \). Substrate index \( n_{\text{clad}} \) is changed from 1.445 to 1457 (relative index difference \( \Delta = 0.205\% \) to 1.022\% corresponding to the normalized frequency change \( V = 0.758 \) to 1.692). Lateral analyzing area is set to be \( 200a \) with the core half width \( a \) to cover spreading fields for curved state.

4.1. Variation of period

Evaluation of PSWs is carried out by calculating the power confinement in segments. Calculation for the curved PSWs is performed for curvature radius \( R = 1 \) mm, central angle \( \theta = 20.05^\circ \), and propagation distance \( L = 350 \mu \)m along the segment center. The field amplitude of the incident wave is adjusted such that total incident power is kept constant in spite of \( V \) value. The ordinates in Figs. 9–11 are defined by the ratio of the transmitted power inside the core to the total propagating power for each \( V \). The ordinates are not normalized by the result of slab waveguide unlike Figs. 5–7 such that we can see absolute values of the curved PSWs.

Fig. 9 shows the power confinement as a function of the period \( A \) at a fixed value \( \eta = 0.5 \). It can be found that the confinement in the light becomes worse at the vicinity of period 40 \( \mu \)m. This change point for the period is similar to that in the straight PSWs, as shown in Fig. 5. On the whole, it is
proven that light power confined inside the core increases as the normalized frequency becomes large, namely as the power confinement becomes strong. Fluctuations appear in a short period and they appear remarkably with increasing the normalized frequency $V$.

### 4.2. Variation of duty-cycle

Duty-cycle dependence of the power confinement is shown in Fig. 10. It can be seen from this figure that the power confinement improves with increasing the duty-cycle $g$. In addition, the power confinement becomes good for any duty-cycle as normalized frequency increases. For $V$ values near the single mode limit $\pi/2$, the power confinement keeps high values with decreasing the duty-cycle even at $g = 0.6$.

### 4.3. Variation of curvature radius

In this section, the period and duty-cycle are fixed at $A = 10 \, \mu m$ and $g = 0.5$. Only the curvature radius varies from 500 to 10,000 \, \mu m. The propagation distance along the optical axis is fixed at 350 \, \mu m so that central angle with respect to the curvature is changed for each curvature radius. For example, for curvature radius of 1000 \, \mu m, we need a curved PSWs having central angle of $350/1000$ rad namely the arc of 20.05°.

Relationship between the curvature radius and central angle is shown in Table 1. The number of segments becomes $350/10 = 35$ pieces for each curvature radius. If curvature radius of 500 \, \mu m is prescribed, light must propagate for central angle of 40°/rad namely the arc of 20.05°. In this case, even Padé approximation deteriorates a calculation accuracy for such wide angle propagation. Accordingly, the curved waveguide is divided into four sections using the method mentioned in Section 2.2.

Fig. 11 demonstrates the power confinement as a function of the curvature radius $R$. Period $A = 10 \, \mu m$ and duty-cycle $g = 0.5$.

![Fig. 10. Power confinement of curved PSWs as a function of the duty-cycle $g$. Curvature radius $R = 1 \, \mu m$, period $A = 10 \, \mu m$ and propagation distance 350 \, \mu m.](image)

![Fig. 11. Power confinement of curved PSWs as a function of the curvature radius $R$. Period $A = 10 \, \mu m$ and duty-cycle $g = 0.5$.](image)

<table>
<thead>
<tr>
<th>$r$ ($\mu m$)</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>5000</th>
<th>6000</th>
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<td>10.02</td>
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<td>2.86</td>
<td>2.51</td>
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<td>2.01</td>
</tr>
</tbody>
</table>

Table 1
Combination of central angle $\theta$ with curvature radius $R$ such that the total propagation distance becomes 350 \, \mu m.
Next, we estimate from the above result how much power is confined inside the core while light propagates by central angle of 90° in the following equation

\[ P_L = -10 \log_{10} \left( \frac{P_c}{P_c|_{\theta=0}} \right) \cdot \frac{90}{\theta} \text{ (dB)}. \] (6)

Here, \( P_c \) stands for the power confined in the core and \( P_c|_{\theta=0} \) stands for the light power inside the core at incidence, \( \theta = 0 \). Namely, \( P_L \) represents the normalized-power inside the core by comparing with that propagating through the curved PSWs by \( \theta \) with that at incidence. A value of \( 90/\theta \) is multiplied in Eq. (6) in order to normalize the 90° bending, because calculation result in Fig. 11 is obtained by a case where light propagates by angle \( \theta \) corresponding to curvature radius \( R \), as shown in Table 1.

The 90° bending waveguide can be useful for the direction converter. A combination of two 90° bend enables us to convert the light direction by 180°, namely in opposite direction or to translate it in parallel direction by slight distance \( 2R \) using an S-shaped waveguide.

Power loss calculated from Eq. (6) is shown in Fig. 12. It can be found that the power loss shows minimum near curvature radius of 1–2 mm and increases with decreasing the normalized frequency. The tendency for large curvature radius can be explained by the fact that light must pass many segments to propagate 90° bend with increasing the curvature radius. On the other hand, the increase in power loss for small curvature radius is caused by the increase due to the curvature radius.

Fig. 11 shows that the curvature has little influence on power loss above curvature radius of about 3 mm. This result will be compared to that for optical fiber next.

4.4. Consideration on bending loss

Principal part in bending loss formula can be written as

\[ \alpha_B \propto \exp \left( -\frac{4w^3 R \Delta}{3V^2} a \right) \] (7)

for both optical waveguide [16] and optical fiber [17]. Here, \( \alpha_B \) is proportional to loss per unit length, \( w \) is the lateral normalized-propagation constant in the cladding and satisfies \( w = \sqrt{V^2 - u^2} \). We see empirically that bending loss for step-index fiber disappears at curvature radius of several mm, say \( R = 4 \) mm. For \( V = 2.4 \), under the single mode operation limit, relative index difference \( \Delta = 0.2\% \) and core radius \( a = 5 \) \( \mu \text{m} \), value in the exponent of Eq. (7) is calculated to be \(-19.6\).

In the meantime, value in the exponent of Eq. (7) becomes \(-19.2\) for \( R = 4 \) mm in the three-layered slab waveguide with \( a = 2 \) \( \mu \text{m} \), \( \Delta = 0.881\% \) and \( V = \pi/2 \), the single mode operation limit. The value for the three-layered slab waveguide becomes nearly identical with that in the optical fiber.

5. Conclusions

A new calculation technique for wide-angle analysis using the beam propagation method was introduced to cover curved waveguides. This technique can utilize a usual beam propagation method with little modification. The technique can deal with not only waveguides with a fixed curvature but also waveguides with complicated bend by changing the curvature center and curvature radius every repetition step of the BPM.
Power confinement was calculated for periodically segmented waveguides (PSWs) under single-mode operation. Properties of power confinement were evaluated for curved state as well as straight one. The power confinement was investigated as a function of the period $A$, duty-cycle $\eta$, entire length $L$, curvature radius $R$ and normalized frequency $V$. In PSWs, the period $A$ should be selected as 40 $\mu$m or less than that in both straight and curved states to avoid power loss due to the interval. The power confinement is kept relatively high in straight and curved states as long as duty-cycle $\eta$ is larger than 0.6 and waveguide is operated near the single mode limit. Undulation in field with respect to the propagation direction in the PSW can be explained by the discrepancy in diffraction between core and cladding.

It turns out that dependence of the confined power on the period and duty-cycle for the curved PSW shows nearly the same tendency as that in straight PSW, although the curved PSW loses relatively larger power than the straight one. Influence of the curvature can be neglected for curvature radius above about 3 or 4 mm.

References