Scattering Loss of Antiresonant Reflecting Optical Waveguides

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Abstract—Scattering loss of two-dimensional ARROW-type waveguides, i.e., antiresonant reflecting optical waveguide (ARROW) and ARROW-B, is analyzed by the first-order perturbation theory. Calculated results are compared with those of conventional three-layer waveguides. Optimum design for the reduction of scattering loss of these ARROW-type waveguides is discussed.

It was found that the scattering loss of ARROW-type waveguides is no larger than that of a conventional waveguide having a relative refractive-index difference Δ of 2.5%, despite each interface of ARROW-type waveguides has a large Δ , normally larger than 20%. The optimum design for the reduction of essential radiation loss of ARROW is also optimum for the reduction of scattering loss. As for ARROW-B, both scattering loss and radiation loss are small enough, even though some high-index material like polycrystalline glasses and semiconductors are adopted for the core.

I. INTRODUCTION

SINGLE-MODE optical waveguides on a semiconductor substrate are advantageous to integrated photonics owing to the possibility of integrating various optical and electrical devices monolithically [1]–[6]. Antiresonant reflecting optical waveguide (ARROW) [7]–[9] is a new type single-mode planar waveguide on a semiconductor substrate. Its low-loss propagation and some applications for integrated photonics have been reported [10]–[14]. Also, we have proposed and demonstrated ARROW-B [15] which has a similar structure to ARROW and less polarization dependence than ARROW. These ARROW-type waveguides are promising for integrated photonics because of many features, e.g., (1) low radiation loss, (2) ease of fabrication owing to thin cladding and lack of necessity to control refractive indexes precisely, (3) large light confinement inside the core, and so on.

Since these ARROW's have peculiar leaky waveguide structures, as shown in Fig. 1, the radiation loss from the core to the high-index semiconductor substrate is essentially inevitable. The optimum design for reducing the radiation loss has been discussed in detail in our previous

Fig. 1. Structure illustration of ARROW-type waveguides. (a) ARROW, (b) ARROW-B.

reports [8], [9]. However, the scattering loss caused by the imperfection of the waveguide has never been analyzed, although it is another important problem in such multilayer waveguides whose interfaces have large relative refractive-index difference Δ . In this paper, we analyze the scattering loss of ARROW and ARROW-B by the first-order perturbation theory. We also calculate the scattering loss of conventional symmetric three layer waveguides with various Δ and compare with the results of ARROW's. The optimum design for the reduction of scattering loss is discussed from the results.

In this paper, we restrict the discussion to the TE polarization because ARROW has a strong polarization dependence of radiation loss, i.e., only TE mode can propagate with low radiation loss [7], [9].

II. EXPRESSION OF SCATTERING LOSS

The analysis of scattering loss in a conventional waveguide, based on the first-order perturbation theory, has been reported by Suematsu and Furuya [16]. A similar formalism is applicable to ARROW-type waveguides. In this section, we first summarize the general expression of scattering loss. The expression includes the field distribution of all types of orthogonal normal modes and fundamental mode of ARROW's. We next give definite expressions for these modes. To simplify the analysis and to reduce the computation time, we adopted the quasi-guided-mode approximation for the expression of the fundamental mode of ARROW, which is a kind of leaky mode.

A. General Formalism

In the following discussion, we assume multilayer slab waveguides having step-index profiles like ARROW and

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ARROW-B. First, we express the waveguide imperfection as an irregularity distribution of refractive index

$$n^2(x, z) = n_0^2(x) + \delta n^2(x, z) \quad (1)$$

where n_0^2 and δn^2 are an ideal index distribution and a perturbation due to the microscopic imperfection, respectively. The coordinate system of waveguide is chosen as shown in Fig. 1. Generally, y component of the electric field distribution at each point of the waveguide $\mathcal{E}_y(x, z)$ is expressed by the sum of guided modes, semiradiation modes and radiation modes

$$\mathcal{E}_y(x, z) = \sum_{\nu=0}^N c_\nu(z) E_\nu + \sum \int g(z; \beta) E(\beta) d\beta \quad (2)$$

where N and ν are the total number and the label of guided modes, respectively, β is a propagation constant of radiation mode, E_ν and $E(\beta)$ are electric field distributions of ν th-order guided mode and radiation mode labeled by β , respectively, and $c_\nu(z)$ and $g(z; \beta)$ are expansion coefficients. Σ in the second term signifies the summation of degenerate modes. In (2), the components of semiradiation modes are included into those of radiation modes. When the interfaces of waveguide are perfectly smooth, $c_\nu(z)$ and $g(z; \beta)$ in (2) are the same as those of initial field distribution and are kept constant along the propagation axis z . However, they change against z when there is an irregularity expressed by (1).

Let us assume the initial field distribution as that of the fundamental mode of waveguide E_0 . By solving the first-order perturbed wave equation, the averaged scattering loss of the waveguide is given by [16]

$$\begin{aligned} \alpha L(\text{Neper}) = & \sum_{\nu=1}^N \{ \overline{\langle |c_\nu^{(+)}(L)|^2 \rangle} + \overline{\langle |c_\nu^{(-)}(0)|^2 \rangle} \} \\ & + \sum \int \overline{\langle |g^{(+)}(L; \beta)|^2 \rangle} \\ & + \overline{\langle |g^{(-)}(0; \beta)|^2 \rangle} d\beta \end{aligned} \quad (3)$$

where L is a waveguide length, notation $\overline{\langle \rangle}$ denotes an ensemble averaged value, and (+) and (−) denote forward and backward propagating waves, respectively. Now, we specify the correlation of perturbation between i th and j th interfaces of the waveguide as

$$\begin{aligned} \overline{\langle \delta n^2(x_i, z) \delta n^2(x_j, z') \rangle} = & A^2 \Delta n_i^2 \Delta n_j^2 \exp(-|x_i - x_j|/B_x) \\ & \cdot \exp(-|z - z'|/B_z) \end{aligned} \quad (4)$$

where A is an averaged amplitude of perturbation, $\Delta n_i^2 \equiv (n_{i+1}^2 - n_i^2)$, and B_x and B_z are correlation lengths [16] in the x and z directions, respectively. We consider only the case that the signs of perturbation in the x direction among the interfaces are the same, since it is more likely to happen than the opposite case when we fabricate planar waveguides by stacking thin films onto a substrate. (This type of correlation is called “(+) type” in [16].) Then, the expansion coefficient for the radiation mode $g^{(\pm)}$ is

given by

$$\begin{aligned} \overline{\langle |g^{(\pm)}(\beta)|^2 \rangle} = & \frac{A^2 L k_0^4}{8(\omega \mu_0 P)^2} \cdot \frac{B_z}{\{B_z(\beta \mp \beta_0)\}^2 + 1} \\ & \cdot \sum_{i=0}^{l-1} \sum_{j=0}^{l-1} \Delta n_i^2 \Delta n_j^2 E(x_i, \beta) E(x_j, \beta) \\ & \cdot E_0(x_i) E_0(x_j) \exp(-|x_i - x_j|/B_x) \end{aligned} \quad (5)$$

where l is the total number of layers in the waveguide. The expansion coefficient for the guided mode c_ν is given by the almost similar equation to (5). What we should do in the actual calculation of scattering loss is to obtain the field distribution of various modes, E_ν , $E(\beta)$, and E_0 in order to give the expansion coefficients c_ν and $g(\beta)$.

B. Expression of Modes in ARROW's

In the classification of orthogonal normal modes, there exist only two types of modes in ARROW-type waveguides, i.e., semiradiation mode and radiation mode. This is because the waveguide structure is asymmetric and fabricated on a semiconductor substrate having the highest refractive index in the waveguide layers. The electric field of semiradiation mode and radiation mode are generally expressed as

$$E(x, z; \beta) = \sum N(\beta) f(x; \beta) e^{-j\beta z} \quad (6)$$

where $f(x; \beta)$ is a function of field distribution in the x direction, satisfying the boundary conditions. In the upper cladding layer (air is assumed in typical ARROW's), $f(x; \beta)$ is an exponentially decaying function for semiradiation modes and a set of orthogonal sinusoidal functions for radiation modes. It should be noticed that there are two field functions which are determined arbitrarily as they mutually satisfy the orthogonal relation [20] and degenerate with respect to the propagation constant β of a radiation mode. Σ signifies the summation of these degenerate modes. $N(\beta)$ is a normalization factor derived from the normalization condition of time-averaged Poynting power, and is given by

$$N^2(\beta) = \frac{4\omega \mu_0 P}{\pi \kappa_s C_s^2} \quad (7)$$

for semiradiation modes [11] and

$$N^2(\beta) = \frac{4\omega \mu_0 P}{\pi(\kappa_0 C_0^2 + \kappa_s C_s^2)} \quad (8)$$

for radiation modes. P is the mode power per unit interval of β , C_s and C_0 are relative field amplitudes in the substrate and the upper cladding layer, respectively, and κ_s and κ_0 are phase constants in the x direction in the substrate and the upper cladding layer, respectively, which are generally defined by $\kappa_i^2 \equiv (k_0 n_i)^2 - \beta^2$.

Concerning with ARROW, the first cladding layer supports some modes which can be approximated by guided modes in a conventional symmetric three layer wave-

Fig. 2. Schematic field distribution of fundamental mode, first cladding mode, and radiation mode in ARROW.

guide, since the field of these modes is confined in the vicinity of the first cladding layer, as shown in Fig. 2. In our previous paper, we called this type of mode the first cladding mode [11]. The field of the first cladding mode is generally expressed as

$$E_{(v)}(x, z) = N_{(v)} f_{(v)}(x) e^{-j\beta_{(v)} z} \quad (9)$$

where we added the notation () to the subscript of physical quantities, e.g., $f_{(0)}$, $\beta_{(0)}$, etc., to notify this mode the first cladding mode. The normalization factor $N_{(v)}$ is given by

$$N_{(v)}^2 = \frac{4\omega\mu_0 P}{\beta_{(v)}(d_1 + 2/\gamma_c)} \quad (10)$$

The field of the first cladding mode is a rapidly decaying function in the core and the second cladding layer of ARROW. γ_c is a decay constant defined by $\gamma_c^2 \equiv \beta_{(v)}^2 - (k_0 n_c)^2$.

C. Expression of Fundamental Mode in ARROW's

In ARROW and ARROW-B, the fundamental mode is a kind of leaky mode which propagates with extremely low radiation loss. There also exist some higher order leaky modes. However, they are sufficiently filtered out by the radiation loss discrimination. Also, first cladding modes of ARROW are hardly guided practically due to their large scattering loss, as shown in the following. Thus, we can use ARROW-type waveguides as virtual single-mode waveguides.

The definition and physical features of the fundamental mode of ARROW have been discussed in detail in our previous paper [11]. Almost the same discussion can be available for ARROW-B. In the strict electromagnetic theory, the behavior of a leaky mode in ARROW's is expressed as an overlap integral of a group of continuous semiradiation mode labeled by a certain range of propagation constant β [11]. The propagation characteristics of such a leaky mode is described clearly by the normalization factor $N(\beta)$. Fig. 3 shows an example of $N^2(\beta)$ of the fundamental mode of typical ARROW calculated by

Fig. 3. Calculated result of squared normalization factor $N^2(\beta)$ of fundamental mode in ARROW.

(7). $N^2(\beta)$ exhibits a sharp peak in the extremely narrow range of β . Since the coefficient of radiation loss is given by the half width of half maximum (HWHM) of peak in N^2 [18], [19], this implies that the radiation loss of the fundamental mode is low enough to regard this mode as a quasi-guided mode [18]. In order to simplify the numerical calculation described in the next section, we introduce the following quasi-guided-mode approximation for the expression of fundamental mode:

$$\begin{aligned} E_0^*(x, z) E_0(x', z') \\ \approx f_0(x) f_0(x') \exp[-j\beta_0(z - z')] \int_{\beta_0 - \delta}^{\beta_0 + \delta} N^2(\beta) d\beta \end{aligned} \quad (11)$$

where δ must be chosen to be much larger than HWHM of N^2 maximum. We put the sinusoidal function $e^{-j\beta_0(z - z')}$ out of the integral of conventional quasi-guided-mode approximation. This is possible in the calculation of scattering loss because the expansion coefficient varies slowly enough against β as to be seen from (5).

III. CALCULATED RESULTS OF SCATTERING LOSS

In this section, the calculated results of scattering loss of ARROW, ARROW-B, and conventional symmetric three-layer waveguide are presented and compared with each other. The scattering loss of the conventional waveguide was calculated by the method presented by Sue-matsu and Furuya [16]. The correlation of perturbation between the boundaries was also limited to (+) type, as explained in Section II-A. In the actual calculation process, we first obtained the propagation constants of guided and quasi-guided modes in each waveguide by the mode analysis method [9] using the interference matrix. Next, we calculated $c_{(v)}$ and $g(\beta)$ using the calculated results of propagation constants and then obtained the scattering loss. Every result of scattering loss was given in the form normalized by the wavelength λ and the amplitude of perturbation A as

$$\frac{\lambda^3 \alpha}{A^2} \quad (12)$$

TABLE I
PARAMETERS OF WAVEGUIDES USED IN NUMERICAL CALCULATION
OF SCATTERING LOSS

Conventional waveguide	Cladding layer: $n_2 = 1.46$
ARROW	Upper cladding: n_0 Core: $n_c, d_c/\lambda = 6.3$ First cladding: $n_1 = 2.3$ (TiO ₂), d_1 Second cladding: $n_2 = n_c, d_2/\lambda = 3.15$ Substrate: $n_s = 3.85$
ARROW-B	Upper cladding: n_0 Core: $n_c, d_c/\lambda = 6.3$ First cladding: $n_1 = 1.46$ (SiO ₂), d_1 Second cladding: $n_2 = n_c, d_2/\lambda = 3.15$ Substrate: $n_s = 3.85$

where the loss coefficient α is measured in the unit of decibels per meter. The fixed parameters used in the numerical calculation are summarized in Table I. Symbols of refractive indexes and thicknesses in Table I are designated in Fig. 1. We assumed the typical values of refractive indexes and thicknesses for the ARROW-type waveguides, which have been reported so far [8], [9], [15]. We also assumed that the interference cladding layers of ARROW satisfy the first-order antiresonant conditions given by [9]

$$d_1 \approx \frac{\lambda}{4n_1} \left[1 - \left(\frac{n_c}{n_1} \right)^2 + \left(\frac{\lambda}{2n_1 d_{ce}} \right)^2 \right]^{-1/2} \quad (13)$$

$$d_2 \approx \frac{d_{ce}}{2} \quad (14)$$

where d_{ce} is an equivalent thickness of core involving the light power penetration from the core to the claddings, which is given approximately by

$$d_{ce} \approx d_c + \frac{\lambda}{2\pi\sqrt{n_c^2 - n_0^2}} \quad (15)$$

for ARROW, and

$$d_{ce} \approx d_c + \frac{\lambda}{2\pi\sqrt{n_c^2 - n_0^2}} + \frac{\lambda}{2\pi\sqrt{n_c^2 - n_1^2} \tanh \{ (2\pi/\lambda) d_1 \sqrt{n_c^2 - n_1^2} \}} \quad (16)$$

for ARROW-B [21]. Under the condition given by (13), there exists only one first cladding mode in ARROW. As for ARROW-B, we also assume the condition of (14).

A. Scattering-Loss Characteristics

First, we present the scattering-loss characteristics of conventional waveguides in order to compare with calculated results of ARROW-type waveguides. Fig. 4 shows the scattering loss of conventional waveguides against the normalized correlation length in the propagation direction B_z/λ , when the normalized thickness of core d_1/λ satisfies

Fig. 4. Scattering loss of conventional symmetric three-layer waveguide against various values of relative refractive-index difference Δ .

Fig. 5. Scattering loss of conventional symmetric three-layer waveguide versus normalized thickness of core d_1/λ .

the cut-off condition of the first higher order guided mode. The loss strongly depends on the relative refractive-index difference Δ between the core and the cladding. In general, the scattering loss of conventional waveguide is proportional to $\Delta^{2.5}$. The loss takes its maximum value at $B_z/\lambda = 1 \sim 100$. Fig. 5 shows the scattering-loss characteristic against d_1/λ . Except in the vicinity of $d_1/\lambda \approx 0$, the loss does not change so much in the broad range of d_1/λ . Thus, Δ is a key parameter in the comparison of scattering loss of ARROW's and conventional waveguide.

Fig. 6 shows the comparison of scattering-loss characteristics of ARROW, ARROW-B, and the conventional waveguides versus B_z/λ . The normalized thickness of core of the conventional waveguide d_1/λ satisfies the cut-off condition of the first higher order guided mode. It can be seen in Fig. 6 that the scattering loss of ARROW is nearly equal to that of the conventional waveguide having Δ of 2.5% in the range of $B_z/\lambda < 1$ and is smaller than that in the range of $B_z/\lambda \geq 1$, despite that Δ of each boundary in ARROW assumed here is as large as 29%. Comparing with the curve of conventional waveguide having $\Delta = 29\%$, the scattering loss of ARROW is extremely small. This seems to owe the large light confinement inside the core and large size of core of ARROW's [11]. Since the light power of fundamental mode is local-

Fig. 6. Comparison of scattering loss between ARROW, ARROW-B, and conventional waveguide.

Fig. 7. Comparison of scattering loss between fundamental mode and first cladding mode of ARROW.

ized around the center of the ARROW core and the field at the interfaces upper and under the core is very small, as shown in Fig. 2, the light is hardly affected by the imperfection of the waveguide boundaries. On the other hand, the first cladding mode suffers large scattering loss. We can see in Fig. 7 that the scattering loss of this mode is larger than that of the fundamental mode by the figure of three. As mentioned in Section II-B, the first cladding mode can be approximated by a guided mode in a conventional three-layer waveguide. Therefore, the large Δ between the first cladding layer and surrounding layers enormously enhances the scattering loss in proportion to $\Delta^{2.5}$. This is the reason why the first cladding mode was not observed in the experiment [9]. Similarly, the scattering loss of ARROW-B is of the same order of that of conventional waveguide having Δ of 1% despite that each boundary in ARROW-B has a Δ larger than 5%. Thus, the scattering loss of ARROW-type waveguides is sufficiently lower than the value which is intuitively predicted from the large Δ .

Next, let us investigate the details on the scattering loss of ARROW-type waveguides. As seen from (3), the scattering loss is expressed by the sum of expansion coefficients of various types of modes. Fig. 8 shows the difference of the scattering-loss characteristics against the types of converted modes. In Fig. 8(a), the solid curve shows the total scattering loss of ARROW, and dashed curve and dash-dotted curve show the scattering loss for the cases in which the light power of fundamental mode is converted to semiradiation modes and radiation modes, respectively, by the imperfection of the waveguide. It can be seen that the relatively large amount of light power is converted to the first cladding mode. On the other hand, the scattering loss in ARROW-B is smaller than that of ARROW by the amount of the conversion loss to the first cladding mode, because there is no first cladding mode in ARROW-B. We can see from this result that the reduction of this conversion loss is one of the significant point in the design of ARROW. This will be discussed in detail in the next section. Fig. 9 shows the scattering loss versus the normalized correlation length in the x direction B_x/λ .

Fig. 8. Difference of scattering-loss characteristics in ARROW-type waveguides against types of converted modes. (a) ARROW. (b) ARROW-B.

The total loss of both ARROW and ARROW-B hardly changes even though B_x/λ changes in a broad range from 0.01 to 100. B_x/λ dependence of scattering loss of ARROW-type waveguides is much smaller than that of conventional waveguide, as shown in Fig. 5.

B. Optimum Design for Reduction of Scattering Loss

As seen from (5), the scattering loss occurs at the boundaries at which there exist appreciable field amplitudes of the fundamental mode. In ARROW, the fundamental mode has its nonzero amplitudes at two bounda-

Fig. 9. Scattering loss of ARROW and ARROW-B versus normalized correlation length in x direction B_x/λ .

ries, between the core and the upper cladding and between the first cladding and the second cladding, as shown in Fig. 2. Thus, the origin of scattering loss is roughly divided into the surface scattering of the interface between the core and the upper cladding and the conversion loss to the first cladding mode. On the other hand, the surface scattering may be dominant in ARROW-B because ARROW-B has no first cladding modes.

Fig. 10 shows the dependence of scattering loss on the refractive index of core n_c and upper cladding n_0 . The dependence on n_c is very small in ARROW in the range $n_c = 1.46 \sim 1.54$. The loss decreases monotonically as n_0 approaches to the refractive index of core n_c . When we adopt a glass having $n_c = 1.54$ for the core, the loss of ARROW can be reduced to nearly 1/2 by stacking some glass of $n_0 = 1.53$. On the other hand, the loss reduction by increasing n_0 is more effective for ARROW-B, i.e., loss is reduced to 1/3 by stacking a film of $n_0 = 1.53$.

These reduction of surface scattering is naturally expected in the conventional waveguide. According to the $\Delta^{2.5}$ law, the scattering loss of conventional three-layer waveguide is reduced to 1/165 by stacking a film of $n_0 = 1.53$ onto the core of $n_c = 1.54$. Therefore, the effect of increasing n_0 on the reduction of surface scattering of ARROW-type waveguides is much smaller than that in the conventional waveguide. In other words, the scattering loss does not increase rapidly against the increase of refractive index of core n_c . The increase of n_c results in the increase of essential radiation loss in ARROW and the reduction of it in ARROW-B [9], [15]. Therefore, it is important to know the scattering-loss characteristics of ARROW-B against n_c in order to reduce the total loss of ARROW-B. As shown in Fig. 11, the scattering loss of ARROW-B does not increase so much when we adopt some high-index material for the core of ARROW-B. Even though the material of $n_c > 2.0$ (Δ between the core and the air is larger than 37.5%), the scattering loss is the same value as that of conventional waveguide having Δ of 5%. Thus, it is possible by using ARROW-B to construct a low scattering loss and low radiation loss single-mode waveguide with large core of several microns. This enables us to use some high-index materials as the core

Fig. 10. Scattering loss of ARROW and ARROW-B against various values of refractive indexes of core n_c and upper cladding layer n_0 . The interference cladding layers satisfy antiresonant condition for each n_c and n_0 .

Fig. 11. Scattering loss of ARROW-B versus various values of refractive indexes of core n_c . The second cladding satisfies antiresonant condition and the thickness of first cladding layer d_1 is determined as the essential radiation of ARROW-B is a low value of 6.33×10^{-6} dB · λ /m for each n_0 .

material, such as optical glasses ($n_c = 1.4 \sim 1.7$), functional polycrystalline materials ($n_c = 1.8 \sim 2.5$) such as ZnO, and epitaxially grown semiconductors ($n_c > 2.5$). In addition to this, ARROW-B naturally maintains the single-mode propagation without any strict control of refractive indexes even though the size of core is so large as to minimize the coupling loss to the optical fiber. Thus, ARROW-B can be used widely, not only in the optical interconnection but also as a waveguide structure for functional devices such as polarizer, splitter, acoustooptic and electrooptic switches, modulators, and so on.

Next, let us discuss the dependence of scattering loss of ARROW on the thickness of first cladding layer d_1 in order to reduce the conversion loss to the first cladding mode. In Fig. 12, the essential radiation loss of fundamental mode [9], [11] and the scattering loss are plotted versus d_1/λ . As shown in Fig. 12(a), the radiation loss of ARROW takes its minimum value at the antiresonant condition given by (13). The scattering loss also takes minimum at this condition. This means that the minimum radiation loss condition is also optimum for the reduction of the scattering loss. This is because the light power penetration from the core to the first cladding is minimized on the antiresonant condition and thus the light is kept

Fig. 12. Dependence of radiation loss and scattering loss of ARROW on thickness of first cladding layer d_1/λ . Second cladding layer satisfies antiresonant condition. (a) ARROW, (b) ARROW-B.

away from the imperfection of the boundary between the first cladding layer and the second cladding layer. On the other hand, ARROW-B does not support the first cladding mode and thus there is no conversion loss in ARROW-B. This is the reason why the scattering loss of ARROW-B is almost constant against d_1/λ , while the radiation loss decreases monotonically against d_1 , as shown in Fig. 12(b).

IV. CONCLUSION

In this paper, we have described the numerical analysis of scattering loss of ARROW-type waveguides. First, we presented the general expression of scattering loss in planar slab waveguides. Next, we represented the expression of modes in ARROW-type waveguides, which are included in the general expression of scattering loss. To simplify the analysis, we introduced the quasi-guided-mode approximation to express the fundamental mode of ARROW-type waveguides, which is a kind of leaky mode.

From the numerical analysis of scattering loss, the following results are obtained. The scattering loss of ARROW is low enough, and is of the same order of magnitude as that of the conventional waveguide having $\Delta = 2.5\%$, despite each interface in ARROW has a large Δ ,

usually larger than 29%. On the other hand, the first cladding mode of ARROW, which is guided through the first cladding layer, suffers the scattering loss larger than that of the fundamental mode by the figure of three. Thus, it seems difficult to observe this mode practically in the experiment. Similarly, the scattering loss of ARROW-B is of the same order of magnitude as that of conventional waveguide having $\Delta = 1\%$, though the assumed ARROW-B has a Δ larger than 5%.

The surface scattering of ARROW-type waveguides can be reduced by stacking some glass onto the core. Although this characteristics is predicted from the analysis of scattering loss of conventional waveguides, the dependence on Δ between the core and the upper cladding is much smaller than that of the conventional waveguide. As for ARROW-B, both low scattering loss and low radiation loss can be achieved simultaneously even though the refractive index of core is very large. Various materials can be used for the core of ARROW-B, e.g., polycrystalline materials and semiconductors. In addition, ARROW-B maintains the single-mode propagation even though the size of core is so large as to minimize the coupling loss to the optical fiber. Thus, ARROW-B can be used widely for optical interconnection and functional devices.

The optimum design for the reduction of essential radiation loss of ARROW is also optimum for the reduction of scattering loss. On the other hand, since ARROW-B has no first cladding modes, the scattering loss of ARROW-B is almost constant against the thickness of first cladding.

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