A NOVEL ANALYSIS FOR THREE-LAYER OPTICAL WAVEGUIDE USING EFFECTIVE-INDEX METHOD WITH PERTURBATION CORRECTION

Weiwei HU, Keizo INAGAKI and Yoshihiko MIZUGUCHI
ATR Adaptive Communications Research Laboratories
2-2, Hikaridai, Seika-cho, Soraku-gun, Kyoto, 619-0288, Japan
E-mail: wwhu@acr.atr.co.jp

1. Introduction

Phase shifters play a key role in array antennas, especially phased array antennas. Recently, a wavelength controlled variable phase shifter for an independently steerable multibeam antenna was proposed, where optical beam forming networks (BFN) are used aiming at broadband BFN, and reducing size and complexity of microwave BFN [1]. One important point of this optical BFN is that the microwave phases of array antennas are changed by the optical wavelength. The phase shifter requires an optical waveguide with high birefringence $B = n_{TE} - n_{TM}$ and high $dB/d\lambda$ (n_{TE} and n_{TM} are the fundamental mode indices for TE and TM modes, we called $dB/d\lambda$ birefringence dispersion) [2]. In order to obtain such an optical waveguide, we have proposed a novel waveguide having higher values of B and $dB/d\lambda$ taking not only material of the waveguide but also structure into account, as shown in Fig. 1 [3].

Analysis of optical waveguides fall into two categories: numerical methods such as BPM or FEM, and analytic or semi-analytic methods. To analyze the propagation of waveguide in Fig.1, numerical methods are used first. However, to obtain accurate results, a fine mesh and a long calculation are needed. In some cases, the calculation length is moderated by a very small waveguide size. Analytic methods are preferable in terms of ease and computer resources. However, few waveguides determined from Maxwell's equations can be solved exactly [4]. Among the many approximate methods, the effective-index method (EIM) is probably more popular one for the study of rectangular-core waveguides. Since only the solutions for the slab waveguides are required, the EIM method is more efficient than methods that solve the rectangular structure directly. Recently, an improved method with built-in perturbation correction has been proposed which give accurate results to the close-to-cutoff region [5]. However, the method is used to analyse rectangular waveguide.

In this paper, we extend the classical EIM method to three-layer optical waveguide. The new theoretical method is presented first. Then, by using this method, computed results of three-layer waveguide for the use of the phase shifter are demonstrated.

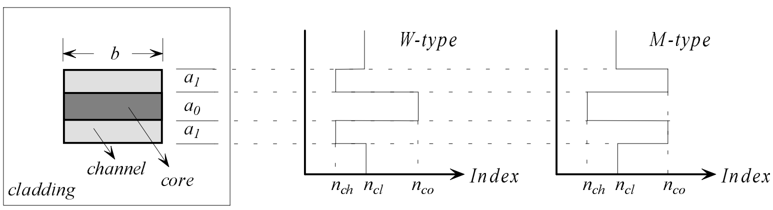
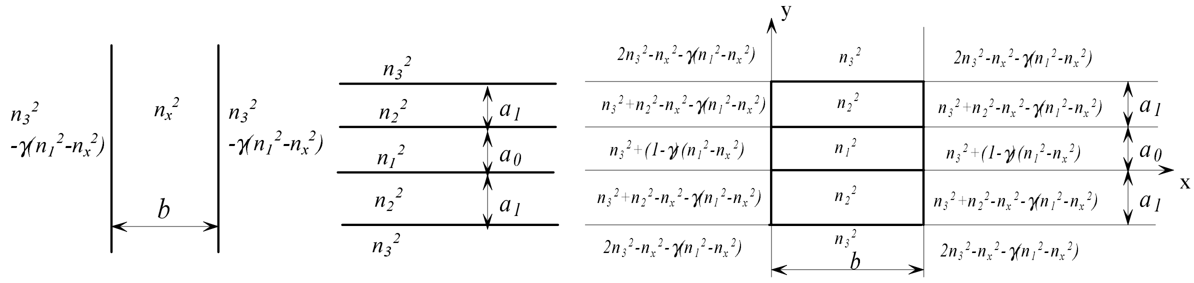


Fig. 1: Profile of a three-dimensional three-layer optical waveguide, where a_0 and a_1 are the thickness of the layers and b is the width of the layers. n_{co}, n_{ch} and n_{cl} ($n_{co} > n_{cl} > n_{ch}$) are the refractive indices of the core, the channel and the cladding, respectively.

2. Proposed Method

Following the technique in Ref. [5], the effective-index method shown in Fig. 2 (a) and (b) is equivalent to solving the profile shown in Fig. 2(c), which differs from the original profile shown in Fig. 1. Figure 2 (a) shows that $\gamma = 0$ gives the conventional effective-index method, and $\gamma = 1$ gives the Marcatili method [6], [7]. We can solve the propagation questions after determining the γ value. The next section contains results for the dependence on the normalized frequency V, calculated with an accurate γ, with $0 < \gamma < 1$.



(a) (b) (c)

Fig. 2: (a) Slab waveguide that approximates the three-layer structure in Fig. 1. (b) Slab waveguide from which the effective index n_x in (a) is determined. (c) Exact structure for (a) and (b).

According to the standard perturbation analysis [4], we can write $\beta'^2 = \beta^2 + \Delta\beta^2$ where β' *is* the calculated propagation constant, β is the exact value, and $\Delta\beta$ is the difference. We treat the profile shown in Fig. 2 (c) as a perturbation of the original profile. The propagation constant difference is given by

$$\Delta\beta^2 = (1-\gamma)(n_1^2 - n_x^2)k^2 P_{cl}^a P_1^b + [(n_2^2 - n_x^2) - \gamma(n_1^2 - n_x^2)]k^2 P_{cl}^a P_2^b + [(n_3^2 - n_x^2) - \gamma(n_1^2 - n_x^2)]k^2 P_{cl}^a P_3^b \quad (1)$$

Where, $P_1^b + P_2^b + P_3^b = 1$,

$$P_{cl}^a = \frac{\int_{-\infty}^{0} \psi_a^2 dx + \int_{b}^{+\infty} \psi_a^2 dx}{\int_{-\infty}^{+\infty} \psi_a^2 dx},$$

$$P_1^b = \frac{\int_{0}^{a_0} \psi_b^2 dy}{\int_{-\infty}^{+\infty} \psi_b^2 dy}, \quad P_2^b = \frac{\int_{-a_1}^{0} \psi_b^2 dy + \int_{a_0}^{a_0+a_1} \psi_b^2 dy}{\int_{-\infty}^{+\infty} \psi_b^2 dy}, \quad P_3^b = \frac{\int_{-\infty}^{-a_1} \psi_b^2 dy + \int_{a_0+a_1}^{+\infty} \psi_b^2 dy}{\int_{-\infty}^{+\infty} \psi_b^2 dy}.$$

k is the free-space wavenumber, ψ_a and ψ_b are the mode fields in the slab waveguides shown in Fig. 2 (a) and (b), respectively. The optimal value of γ is found by setting the $\Delta\beta^2$ to zero. It gives:

$$\gamma = \frac{n_1^2 P_1^b + n_2^2 P_2^b + n_3^2 P_3^b - n_x^2}{n_1^2 - n_x^2} \quad (2)$$

3. Validity Check of the Proposed Method

Figure 3 shows our calculated results of the fundamental TE-mode and TM-mode. The normalized propagation constant is $b = (n_{eff} - n_3)/(n_1 - n_3)$, and the normalized frequency is $V = ka_0\sqrt{n_1^2 - n_3^2}$. The size of the W-type three-layer optical waveguide structure in Fig.1 are a_0 = 0.5 μm, a_1 = 0.2 μm, and b = 1 μm. The refractive indices are those of GaAs-AlGaAs with $n_1 = n_{co}$ = 3.4, $n_2 = n_{ch}$ = 3.25, and $n_3 = n_{cl}$ = 3.3 [8]. The circular points and the solid triangular points are the numerical results of mode solvers of ADI method in BPM-CAD [9] and mode solvers in FEM [10], which meshed enough and agreed with each other, and are used as comparisons for our data. The dashed line γ = 0 is for the conventional effective-index method, and the dashed line γ = 1 is for the

Marcatili method. The solid line is our novel result. The accurate results for the frequency are found between these two approximations $0 < \gamma < 1$. The figure shows that our method is much more accurate than other approximations.

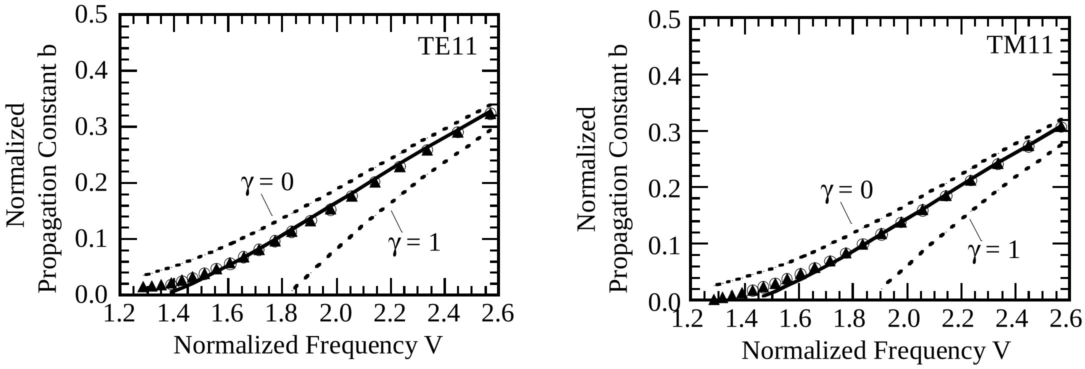


Fig. 3: Theoretically and numerically calculated results for (a) the TE_{11}-mode, (b) the TM_{11}-mode. The middle solid line is the result of using eq. (2). The circular points and the solid triangular points are the numerical mode solves of the ADI and FEM methods.

For a comparison, Figure 4 shows the effective index error $\Delta n_{eff} / n_1$ in the close-to-cutoff region (V < 2): the slab layered waveguide, $\gamma = 1$ (the Marcatili method), $\gamma = 0$ (the conventional effective-index method), and our results. The refractive-index differences are $\Delta n_2 = (n_1 - n_2)/n_1 = 0.044$ and $\Delta n_3 = (n_1 - n_3)/n_1 = 0.029$. The aspect ratio $K = b/ a_0$ ranges from 2 to 10. Our results show that the error in the improved method is much smaller than that in other methods and all of the error values are less than 0.00015, even in the close-to-cutoff propagation region. The results get closer to the slab waveguide results, when the aspect ratio $K = b/a_0$ increases.

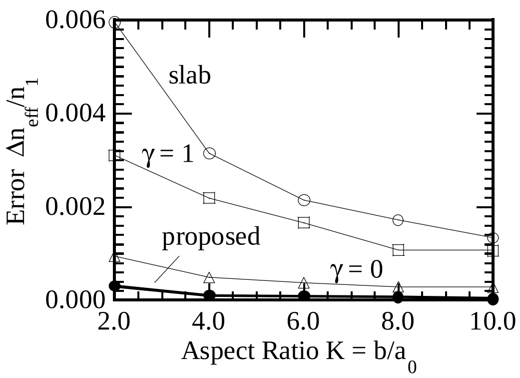


Fig. 4: Error comparison of EIM methods in close-to-cutoff region while $K = b/a_0$ changed.

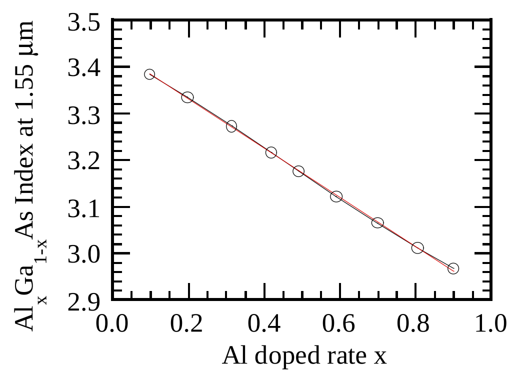


Fig. 5: The refractive indices of GaAs-AlGaAs at $1.55\mu m$ [8].

4. *B* and *dB/dλ* of Three-Layer GaAs-AlGaAs Optical Waveguides

We calculated the birefringence $B = n_{TE} - n_{TM}$ and birefringence dispersion $dB/d\lambda$ of the three-layer optical waveguide with M-type and W-type structures, and compared with the results for rectangular structures. The refractive indices are those of GaAs-AlGaAs at $1.55\mu m$, shown in Fig. 5 [8]. Figure 6 shows the birefringence vs. normalized wavelength. The dashed lines belong to the multi-mode region and the solid lines belong to the single-mode region. From the curve we can see that the birefringence *B* has a peak in or near the second-mode region, and the peak birefringence dispersion $dB/d\lambda$ is in the middle of single-mode region. The peak $dB/d\lambda$ and its V value can be controlled by the waveguide structure, refractive index, and wavelength. Among the structures, the W-type three-layer waveguide produces the highest *B* and $dB/d\lambda$. To move the peak $dB/d\lambda$ to the wavelength of 1.55 μm region, we need to change the parameter of the optical waveguide.

Figure7 shows an example of high $dB/d\lambda$ three-layer GaAs-AlGaAs optical waveguide structure around 1.55μm. The data are $B = 0.033$, $dB/d\lambda = -0.049\ 1/\mu m$, $B\text{-}\lambda dB/d\lambda = 0.11$. By using these data, ±11 *nm* wavelength tuning can result in ±90° array antenna beam steering in the case of $\Delta L = 1$ *mm* [1].

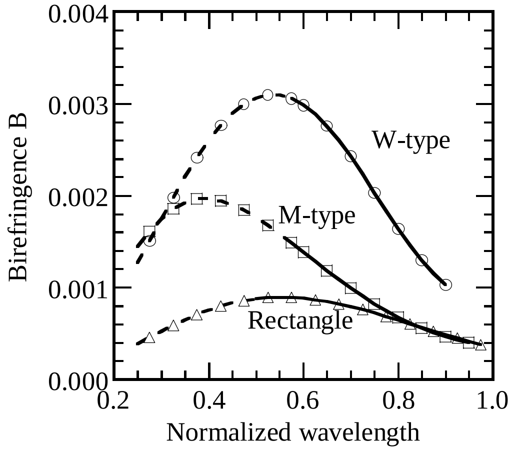


Fig. 6: Birefringence B vs. normalized wavelength λ/λ_c. The refractive indices are $n_{co} = 3.4$, $n_{ch} = 3.25$, and $n_{cl} = 3.3$.

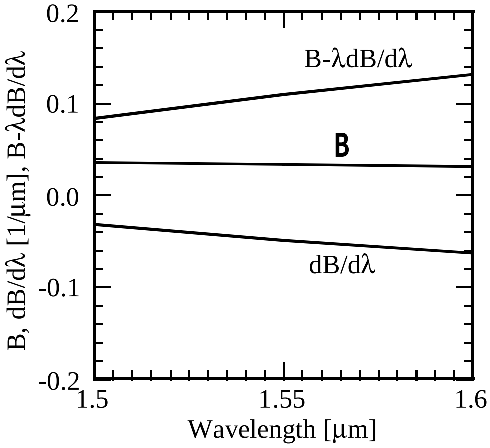


Fig. 7: An example of high $dB/d\lambda$ W-type three-layer GaAs-AlGaAs optical waveguide structure at 1.55μm with $a_0 = 0.32\ \mu m$, $a_1 = 0.24\ \mu m$, $b = 1.6\ \mu m$, $n_{co} = 3.44$, $n_{ch} = 2.91$, and $n_{cl} = 3.15$.

5. Conclusions

We theoretically analyzed the three-dimensional three-layer optical waveguide, which is useful in a broadband optical signal processing beam-forming network for a steerable multibeam array antenna, and extend the effective-index method. Numerical examples show that this improved method is simpler and more efficient than the conventional effective-index method, and the method produces more accurate results. We also obtain a high birefringence dispersion of $dB/d\lambda = 0.049\ 1/\mu m$, which is higher than 0.0038 $1/\mu m$ obtained before in a GaAs-AlGaAs optical waveguide [3]. The example optical waveguide of Fig.7 can propose a ±90° array antenna beam steering by ±11 *nm* wavelength tuning.

Acknowledgements

The authors thank Dr. B. Komiyama, president of ATR Adaptive Communications Research Laboratories, for his continuous encouragement.

References

1. K. Inagaki and Y. Mizuguchi, "Optical Signal Processing Beam Forming Network for Steerable Multibeam Antenna," APMC'98, Yokohama, Japan, 1998, pp. 611-614.
2. K. Inagaki, W. W. Hu, and Y. Mizuguchi, "Wavelength controlled variable phase shifter for independently steerable multibeam antenna," MWP'99, Melbourne, Australia, 1999, pp287-290.
3. W. W. Hu, K. Inagaki, T. Akiyama and Y. Mizuguchi, "Novel optical waveguide design for steerable multibeam antenna BFN," MOC'99, Chiba, Japan, 1999, pp22-25.
4. A. W. Snyder and J. D. Love, "Optical Waveguide Theory," Chapman & Hall, London, 1983, Chap.12, 18.
5. K. S. Chiang, K. M. Lo and K. S. Kwok, "Effective-index method with built-in perturbation correction for integrated optical waveguides," J. of Lightwave Tech., 1996, pp223-228.
6. A. Kumar, K. Thyagaraian and A. K. Ghatak, "Analysis of rectangular-core dielectric waveguides: An accurate perturbation correction," Opt. Lett. Vol. 8, 1983, pp63-65.
7. E. A. J. Marcatili, " Dielectric rectangular waveguides and directional couplers for integrated optics," Bell Syst. Tech. J., vol. 48, 1969, pp2071-2102.
8. B. L. Weiss, "Properties of aluminium gallium arsenide," ed. INSPEC, London, 1993, pp126-140.
9. Optiwave Co., "BPM-CAD waveguide optics modelling software system", Version 4.0.
10. M. Koshiba, "Computer-aided design of integrated optical waveguide devices", in "Finite element software for microwave engineering", John Wiley & Sons Inc., New York, 1996, Chapter 4.