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Optimization of Radiation Modes in Asymmetric Planar Slab Optical Waveguides

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In this paper, we try to optimize the substrate-radiation/substrate-cladding (cover) radiation modes in terms of their performance parameters. It is well known that the guided modes can only be normalized. However the radiation modes can also be normalized by using the Delta/Dirac function. We try to optimize the waveguide design parameters for the known cases to achieve performance as good as guided modes. The formal electromagnetic theory is applied to study the radiation modes. The normalization condition on radiation mode has been taken care in to analysis. The results are found satisfactory. It has been concluded that we can modify the performance of radiation modes according to our requirements. The performance is compared with guided mode. The paper discusses guidelines to optimize the radiation modes for various constraints.

Keywords: Leaky, Radiation, Optimized, Guided, Asymmetric

Introduction

Radiation modes are useful to study the power leakage loss and to design passive WDM fiber optic network components. Lots of power can flow through the substrate and cover region. These radiation modes are useful to design fiber optic coupler and WDM optical network components. These are also useful to predict the power loss in various passive WDM optical network components. It is inevitable to find out the optimum waveguide design parameters for the purpose to achieve the better device performance [1-2]. We need to optimize these modes to avoid the leakage of power in optical communication systems.

By choosing appropriate waveguide design parameters, it is possible to match the radiation modes at the interfaces perfectly [3-9]. In fact the radiation modes can be completely removed at the interfaces, which may not be possible even with guided modes.

Optimization of Substrate Radiation Modes

We implicitly assumed the rectangular coordinate system to have refractive index variation in x-direction. The wave is propagating in the z-direction and the medium is infinite in the y-direction (no refractive index variation). We consider, n_c, n_s and n_f as the refractive index of cover, substrate and film regions respectively. Since the phase constant β for the substrate radiation mode is in the range of (free space wave-number k_0),

$$k_0 n_c < \beta < k_0 n_s \tag{1}$$

the x-direction transverse wave-vector κ in the substrate satisfies [1-2],

$$0 \le \kappa \le k_0 \sqrt{n_s^2 - n_c^2} \tag{2}$$

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Here subscripts s, c, f and r are used to mention the substrate, cover, film and radiation mode respectively. After applying the continuity condition for the tangential electromagnetic field components at the interfaces, the lateral electromagnetic fields are obtained as follows:
Here the lateral electromagnetic field distribution function $\Phi_r(\chi, \rho_s)$ would be [1- 2],

$$\phi_r(x,\rho_s) = \frac{1}{\sqrt{D_r}}\begin{cases} e^{-\alpha_c x}, & 0 \le x \\ \cos(\sigma_f x) + B_{rf}\sin(\sigma_f x), & -t \le x \le 0 \\ A_{rs}\cos\{\kappa(x+t)\} + B_{rs}\sin\{\kappa(x+t)\}, & y \le -t \end{cases} \quad (3)$$

where

$$s_f = \sqrt{k_0^2\left(n_f^2 - n_s^2\right) + k^2}$$

$$a_c = \sqrt{k_0^2\left(n_s^2 - n_c^2\right) - k^2}$$

If the normalization factor D is

$$D_r = \frac{\pi}{2}\left(A_{rs}^2 + B_{rs}^2\right) \quad (4)$$

the distribution function satisfies the orthonormality condition,

$$\int_{-\infty}^{+\infty} \phi_r(x,\rho_s)\phi_r(x,\rho_s')dx = \delta(\rho_s - \rho_s') \quad (5)$$

where $\delta(\rho_s - \rho_s')$ is the Dirac delta function. The The Figs. 1 and 2 show the various calculations done on the substrate radiation modes. From the Fig. 1, it is apparent that the film-cover region is perfectly matched while the film substrate region is not.

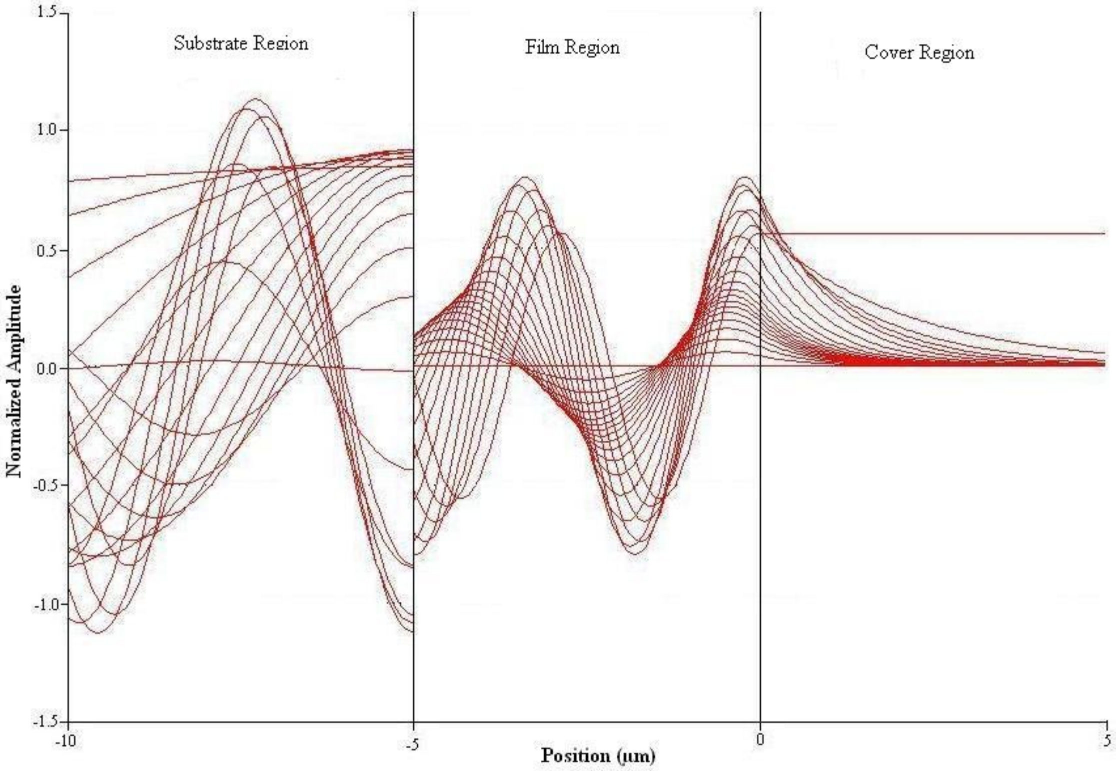

Fig. 1. Normalized substrate radiation modes for various values of the transverse wave-vector.

The film thickness $h = 5\mu m$ is considered in all calculation. The refractive indices are $n_f = 1.50$, $n_s = 1.45$, $n_c = 1.40$ and the operating wavelength is $\lambda = 1.55\mu m$ respectively. The aim is to match or avoid the substrate-film radiation modes. The computation has been carried out for the various values of transverse wave-vector for optimization purpose. Substrate radiation mode has been completely eliminate on $\kappa = 1.0712 \times 10^4\ cm^{-1}$. This is shown in Fig. 2a.

In this case there is no leakage loss and practically it can be used for designing the lossless WDM optical network components. In-fact this particular mode will suffer less leakage loss compared to the guided modes. Substrate radiation mode has been perfectly matched while on κ= 1.2242×10^{4} cm^{-1}, which is shown in Fig. 2b. Practically this may be useful to design the WDM network components for phase matching applications. In Fig. 3 shows the mode amplitude difference between the substrate-film interfaces. Hence, computational accuracy has been tested.

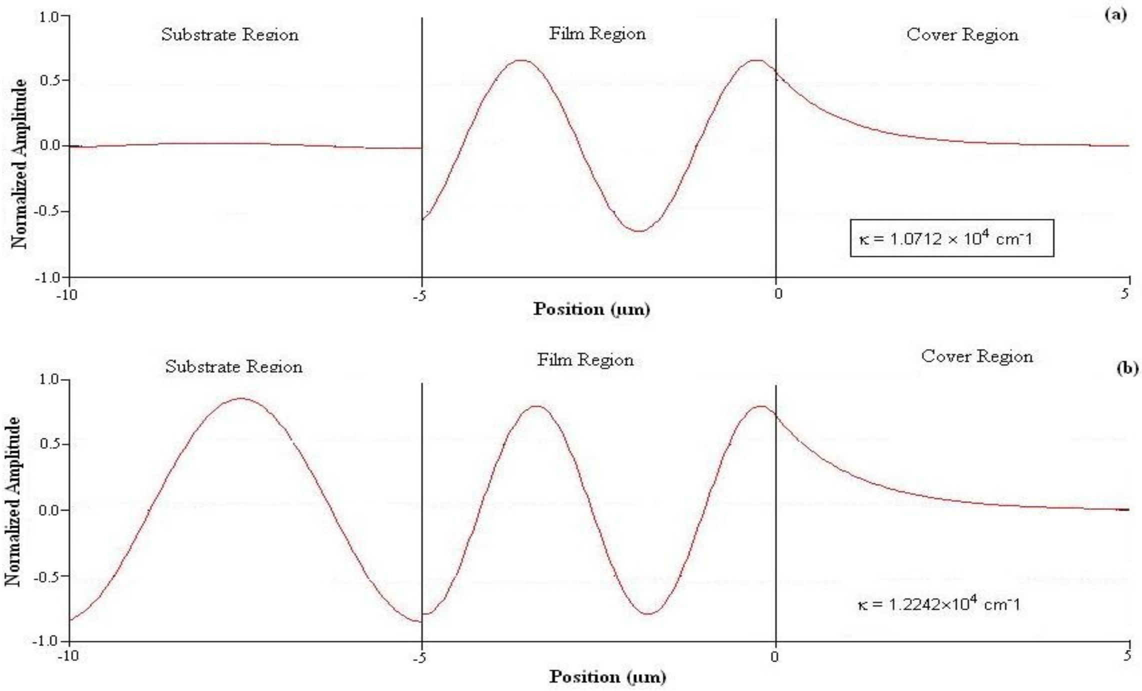

Fig. 2. (a) Substrate radiation mode has been completely eliminated. (b) The substrate Radiation-mode is almost matched with film region.

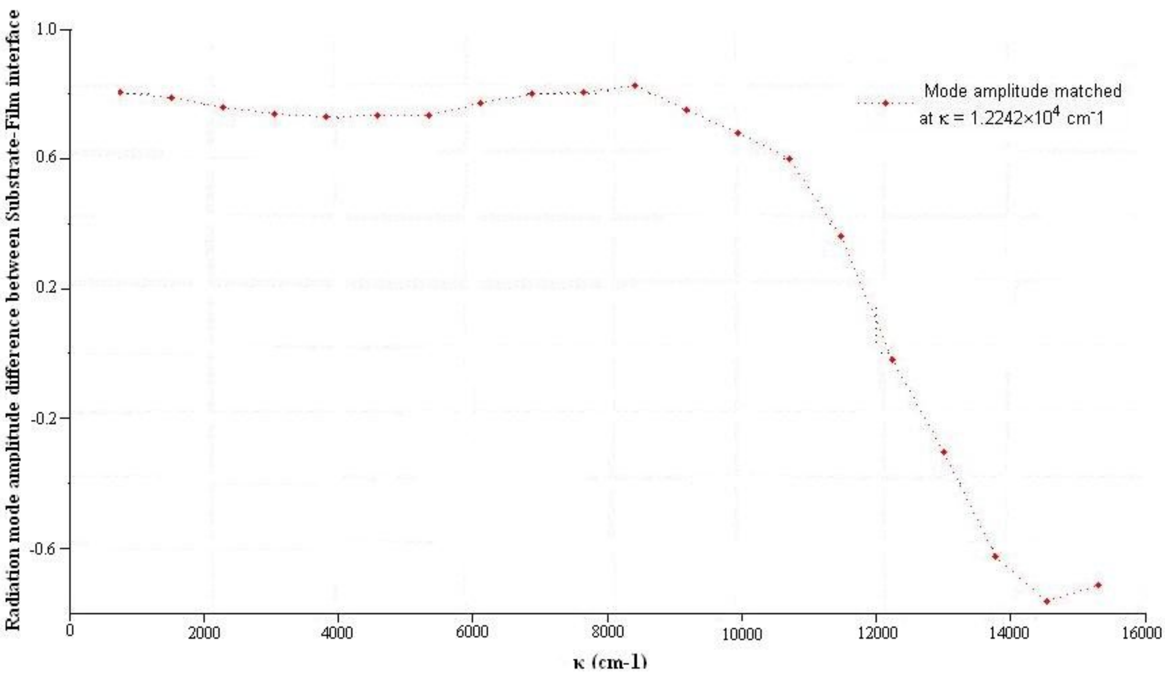

Fig. 3. Mode amplitude difference versus transverse wave-vector κ(cm-1).

The radiation mode is almost perfectly matched at κ= 1.2242 ×10^4 cm^{-1}, where the mode amplitude difference between the substrate-film regions approaches zero. These waveguide design parameters are important to achieve the optimum performance.

Optimization of Substrate Cover Radiation Modes

Since the phase constant β for the substrate-cladding radiation is in the range of [3-6],

$$0 \le \beta \le k_0 n_c \tag{6}$$

In this case the x-direction transverse phase constant κ in the substrate satisfies,

$$k_0\sqrt{n_s^2 - n_c^2} \le \kappa \le k_0 n_s \tag{7}$$

So that β is a pure imaginary number. In other words, the radiation mode may be propagated, in which case κ is given by equation (2) or may not be propagated, in which case κ is given by equation (7). The solution of wave equation for the substrate-cladding radiation mode is discussed in detail elsewhere [1]. The simulation results are the same, except the range of β which has been changed. Fig. 4, shows that neither the film-substrate nor the film-cover regions are matched. These modes are not useful for any practical purposes. Several trials have been performed to match the interfaces and to search out the optimum waveguide deign parameters. This case is even more crucial because there are two non-matching interfaces. From Fig. 4, it is apparent that the light is being guided in both the substrate and cover regions. Hence, more power will flow in cover as well as substrate regions. For any practical applications, these radiation modes are needed to be optimized.

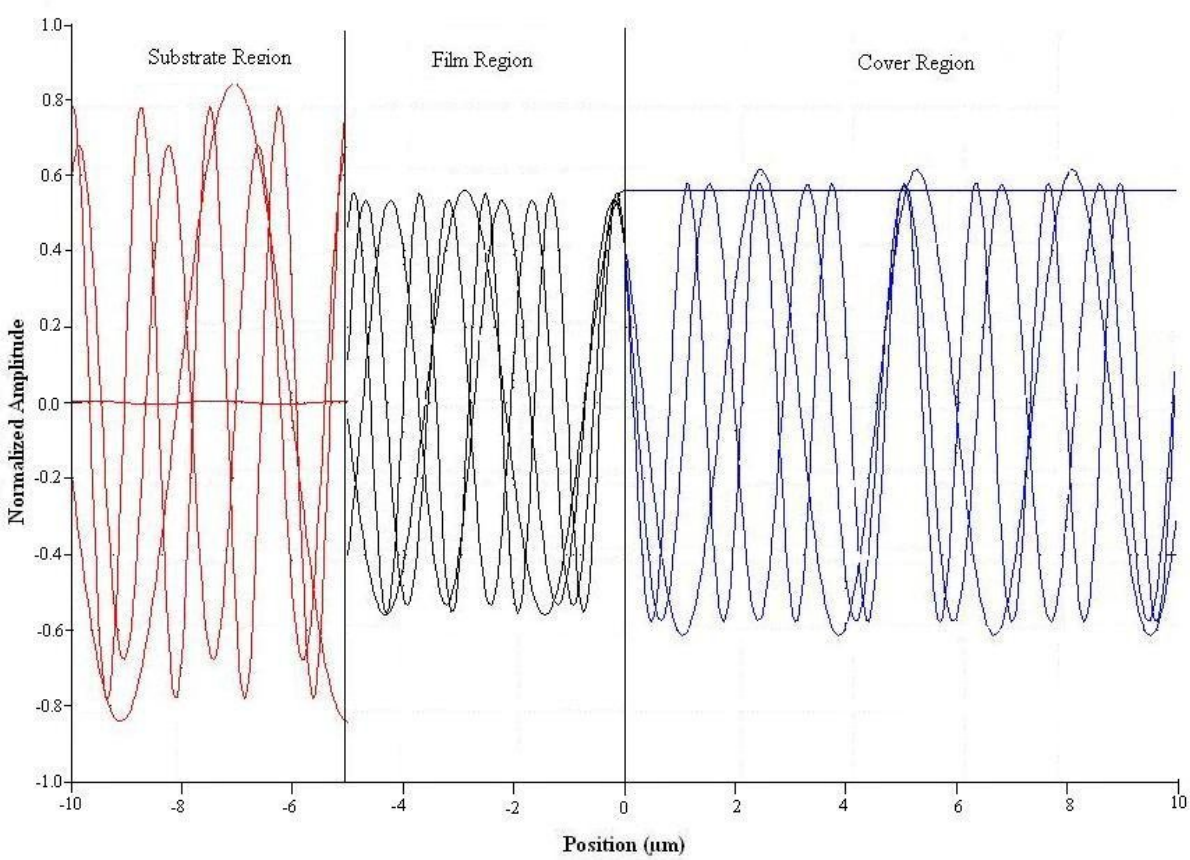

Fig. 4. Normalized substrate-cover radiation modes for various values of the transverse vector.

Fig. 5 shows the various calculations done on the substrate-cover radiation mode. It has been found, as shown in Fig. 5a, that at κ= 2.7058 ×10^4 cm^{-1} substrate-film radiation mode is completely removed; however film-cover region is properly matched. In another observation, as shown in Fig. 5b, the substrate radiation mode is perfectly matched with both regions at κ= 6.2325 ×10^4 cm^{-1}. These design guidelines are very useful to achieve desirable performance.

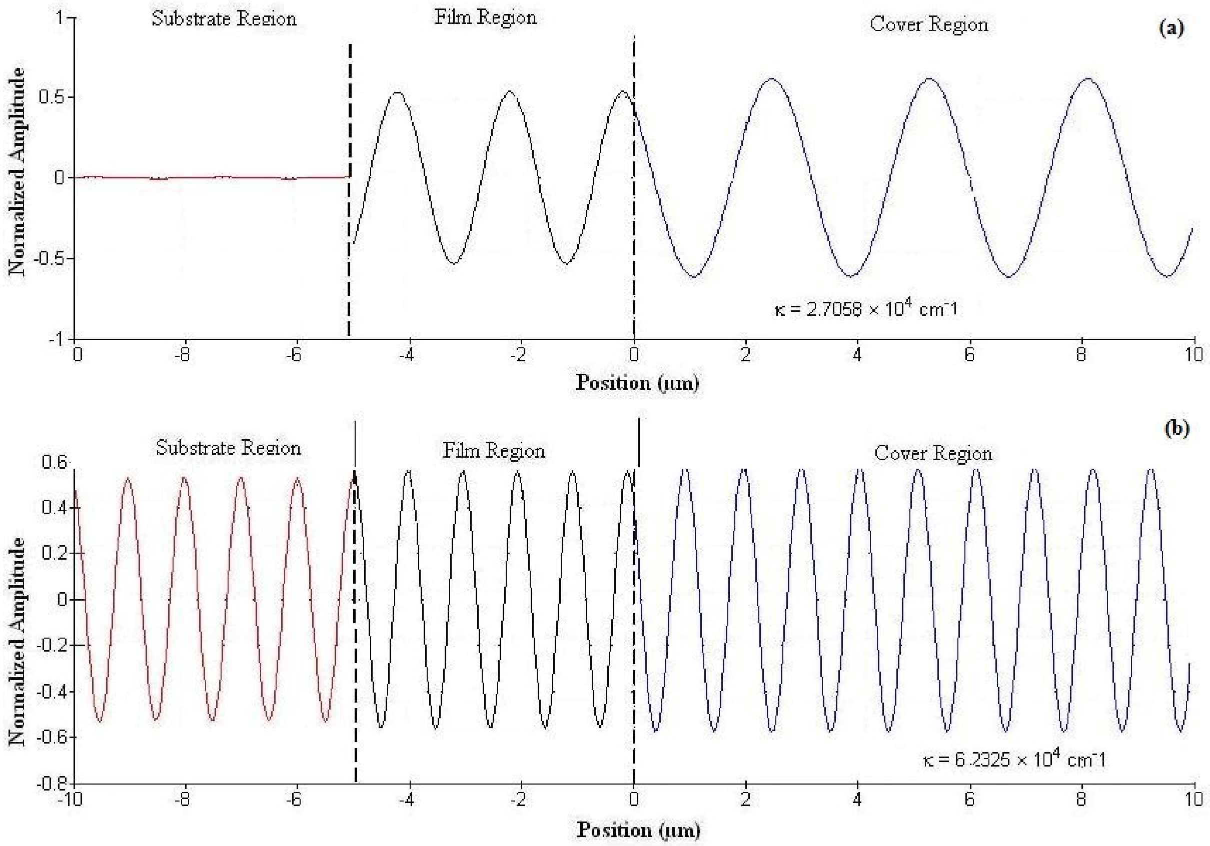

Fig. 5. (a) Substrate-film radiation mode being eliminated, however film-cover region perfectly matched. (b) Substrate radiation mode being matched with both regions.

Conclusion

Formal electromagnetic theory has been applied on asymmetric waveguide structure to find out the eigen value equation for the given cases. Mode orthogonality condition has been proved unconditionally, while it has been taken care of with every aspect during the calculation. Asymmetric waveguide structure shows non-uniform power variation in each region. The modes are not always matched for the given design parameter. In this paper radiation modes are optimized without giving much mathematical treatment. The techniques of mode optimization were found to be satisfactory. Through analysis it has been shown that either, we can eliminate the substrate radiation mode or totally match the substrate radiation mode with the film region. These design guidelines on radiation modes are very important for the purpose of designing low loss waveguide coupler, mode isolator, mode phase matching circulator and other types of WDM components.

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