Frequency filtering in diffused optical planar waveguides

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The propagation characteristic of a four layered planar optical waveguide grown on a silicon substrate has been analytically investigated using the perturbation technique. The results obtained show that the attenuation curve with wavelength gives a distinct narrow dip, suggesting for the development of frequency filtering devices. Moreover, this attenuation characteristic can be varied by changing the guiding layer and buffer layer thickness or their refractive index. As a result, the present study deals with frequency filtering effect more analytically and physically.

1 Introduction

Diffusion techniques have provided as alternative to thin-films technology for fabrication of planar optical waveguides in CdS, ZnSe, LiNbO₃ and LiTaO₃ etc. It is seen that silicon clad planar optical waveguides are also often useful for many applications in the development of integrated optical devices like phase modulator, selective mode filter, polarizers and mode discriminators[5-8]. Various types of four layer structures have been studied with a view to reducing attenuation in planar optical waveguides[7,8]. Different types of multilayered planar waveguides grown on silicon substrates have been extensively studied towards propagation, attenuation or mode discrimination characteristics[5,9,10]. Since the substrate of these structures are semiconductors having a complex permittivity, the waveguide modes are not strictly bound modes, but instead leaky modes[12]. The modes are thus characterized by a complex propagation constant, with the imaginary part corresponding to attenuation due to energy radiation away from the guiding layer. Further, it is also known that permittivity of silicon is particularly sensitive to the wavelength passing through the structure. For this reason, silicon-clad planar diffused optical waveguides have been studied theoretically using numerical techniques to obtain frequency filtering property of four layered structures. However, in our earlier paper[13], we have studied theoretically wavelength filtering effects in silicon substrate waveguides using a more physical approach-perturbation technique. In the paper, we have considered a substrate having constant refractive index. However, in real application we use doped substrate having some refractive index profile. Since silicon-clad planar diffused waveguides are useful for low loss optical devices[14,15], we are considering in the present investigation the substrate having an exponentially decaying profile with a finite diffusion depth. We have developed the characteristic equation for the mentioned structure and hence an approach to yield the analytical expression for the imaginary part of the propagation constant using the perturbation technique.

2 Theory

This paper attempts to study the frequency filtering characteristics of four-layered optical waveguides. The transverse section of the optical waveguide considered as depicted in Fig. 1, consists of the following regions:

Region I, which is air (refractive index n₁); Region II, a waveguiding region, composed of silicon-oxynitride (refractive index n₂); The refractive index n₃ is assumed

![Fig. 1 — Cross-sectional view of the planar waveguide](image-url)
to be a constant (Step Index); Region III, a buffer layer of silicon nitride (refractive index \( n_3 \)); Region IV, the silicon substrate, which is diffused with an exponential profile of finite diffusion depth. The refractive index \( n_k \) is a complex quantity and depends on the wavelength is presented in Table 1.

The electric fields in the four regions are given by:

\[
\psi_1(x) = A \exp(-q_1x), \quad x > t_{\text{wg}} \quad \ldots (1)
\]

\[
\psi_2(x) = B \sin(q_2x) + C \cos(q_2x), \quad t_{\text{wg}} \geq x \geq 0 \quad \ldots (2)
\]

\[
\psi_3(x) = D \exp(q_3x) + E \exp(-q_3x), \quad 0 \geq x \geq -t_{\text{buf}} \quad \ldots (3)
\]

\[
\psi_4(x) = F J_a \left[ \exp(x/2d), \quad x < -t_{\text{buf}} \right] \quad \ldots (4)
\]

where,

\[
\tau = 2k_0d(n_4^2 - n_3^2)^{1/2}
\]

\[
\alpha = 2d \left( \beta^2 - k_0^2 n_3^2 \right)^{1/2}
\]

\[d = \text{diffusion depth of the substrate} \]

\[q_1 = k_0(n_3^2 - n_3^2)^{1/2} \]

\[q_2 = k_0(n_2^2 - n_3^2)^{1/2} \]

\[q_3 = k_0(n_1^2 - n_3^2)^{1/2} \]

where \( \beta \) is the propagation constant and \( n_e \) is the effective refractive index of the mode.

The characteristic equation can be derived by applying continuities of the electric fields and their derivatives at the boundaries. The following expression is obtained:

\[
(J_0 + J_0q_3) \times \left\{ (\tan(q_3t_{\text{wg}})(q_2^2q_1q_3 - q_2(q_1 + q_3)) + \exp(-2q_3t_{\text{buf}})(J_0 - J_0q_3) \times \left\{ (\tan(q_3t_{\text{wg}})(q_2^2q_1q_3 - q_2(q_1 + q_3)) + q_2(q_1 - q_3) \right) = 0 \right. \quad \ldots (5)
\]

where

\[
J_0 = J_0 \left[ \exp(-t_{\text{buf}}/2d) \right]
\]

It is easily seen that Eq (5) can be reduced to that for the standard three layer waveguide by making the buffer layer thickness very large, i.e. \( t_{\text{buf}} \rightarrow \infty \). In cases where the field confinement is good, the change in the propagation constant \( \beta \) of the guide by the inclusion of additional layers can be calculated using perturbation approximation as suggested by Stuitt and Streifer. Since the waveguide is grown on a silicon substrate having a complex refractive index \( n_k \), we find that \( \delta \beta \) is a complex quantity. The real part of \( \delta \beta \) modifies the propagation characteristics of the structure, however the imaginary part gives information about the attenuation parameter with which the field attenuates along the direction of propagation. Therefore, as the imaginary part varies, the field and the corresponding power varies. Since here in the present study we are interested in power response with various input wavelengths we shall be solving for the imaginary part of \( \delta \beta \), which we may write as:

\[
\text{Imag}(\delta \beta) = \frac{\exp(-2q_3t_{\text{buf}})(J_0 - J_0')}{\beta \times W \times (J_0 + J_0')}
\]

\[
\left[ (q_2^2 + q_3^2)(q_2 + q_3) + (q_2q_3)(2q_2 - q_3) \right] \quad \ldots (6)
\]

where \( W \) is the effective thickness of the waveguiding region given by:

\[
w = t_{\text{wg}} + 1/(\rho_1q_1) + 1/q_1
\]

and \( \rho_1 = n_2^2/n_1^2 \)

Using Eqs.(5) and (6), the values of the attenuation parameter can be calculated computationally for different values of the wavelength. The parameters chosen were \( n_1 = 1.00, n_2 = 1.75, n_3 = 1.46 \) and \( n_4 \) from the Table 1. Also, the effects of alterations in the values of waveguide thickness, buffer layer thickness, and diffusion depth on the attenuation parameter were studied for different wavelengths.

### 3 Results and Discussions

Eq(6) is the analytical expression for the estimation of attenuation property of the four layered planar optical waveguide. Thus attenuation parameter of the lowest order guided (TM) mode has been numerically computed for various input wavelengths ranging from 0.35 to 1.15 \( \mu \text{m} \). Fig. 2 depicts the attenuation parameter with exposed wavelength for three different values of buffer layer thickness, keeping the guiding layer thickness constant.
It is evident from the curve that the attenuation in the structure is very sensitive to the wavelength in some specific regions. The attenuation parameter given by the imaginary part of $\delta\beta$ dips to a minimum nearly at 0.67 $\mu$m corresponding to a buffer layer of thickness 75 nm. Since the power varies as the square of the modal field, the propagated power sharply increases at 0.67 $\mu$m. Therefore the dip in the attenuation curve gives scope for selecting the structure as a suitable frequency filter at that particular wavelength. It is interesting to note that if we increase the buffer layer from 75 to 160 nm, the dip of the curve shifts towards lower value of the wavelength and also gives a less sharper dip. It is clear that as we change the thickness of the buffer layer or the guiding layer, the boundary for a given mode gets changed and hence the field distribution or the power distribution for the corresponding mode will also change. Further, the refractive index of the substrate is sensitive to the input wavelength and so the relative separation of substrate with the guiding region would give rise to a variation of $\delta\beta$ value. Thus any geometrical or compositional variation in the various regions of the structure may lead to redistribution of modal field in the structure giving a different coupling with the substrate. This gives a different $\delta\beta$ value providing an estimation of the attenuation parameter for the given particular mode.

In Figs 3(a) and 3(b) the variation of the attenuation parameter with wavelength are presented for different waveguide thicknesses keeping the buffer layer thickness as a constant value i.e., 75 to 100 nm respectively. Therefore as we increase the buffer layer thickness, from 75 and 100 nm, the dip in the attenuation parameter shifts towards a lower wavelength, which is obvious.

It is observed from the figure that as we increase the guiding layer thickness, the value of the attenuation parameter as well as dip wavelength point varies significantly. It is also clearly emphasized that the effect of guiding layer thickness on the curve is more pronounced, which makes choosing the guiding layer very important. This qualitative and quantitative difference in the curves may be attributed to the coupling strength of the guided mode with the lossy substrate. Finally, we have studied the effect of diffusion depth on the attenuation response. This is made for two different diffusion depths and the results are shown in Figs 4(a) and 4(b). Fig 4(a) shows the effect of diffusion depth on the attenuation parameter for the buffer layer thickness of 75 nm. We may infer from the figure that multiple minima occur with a prominent dip at 0.67 $\mu$m. This may be attributed to the proximity of the substrate with the guiding layer. However, if we increase the buffer layer thickness to 160 nm (Fig 4.b), the dip becomes broadened due to the poor control of the substrate over the mode coupling. It is inferred that the response is not

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![Graph](image-url)
Fig. 3(a) — Variation of attenuation parameter with wavelength for a diffusion depth of 0.3 μm, buffer thickness 75 nm and for different waveguide thicknesses (--- 75 nm; -- 93 nm; - 110 nm).

Fig. 3(b) — Variation of attenuation parameter with wavelength for a diffusion depth of 0.3 μm, buffer thickness 100 nm and for different waveguide thicknesses (--- 75 nm; -- 93 nm; - 110 nm).
sensitive to the diffusion depth after a certain critical thickness. It is obvious because the near surface of the semiconductor is more important in affecting the mode field of the structure.

The study can be extended for TE modes also to aid the mode discrimination property of the device.

4 Conclusions

The characteristic equation for the modal field propagation for a four-layered planar optical waveguide grown on an exponentially diffused silicon substrate has been developed and solved for the lower order TM modes. Using the first order perturbation technique the imaginary part of \( \delta \beta \) is estimated for some given waveguide parameters.

It has been observed in numerical analysis of the structure that attenuation parameter (imaginary part of \( \delta \beta \)) is very much sensitive to some specific wavelength regions. This region depends on the waveguide parameters chosen for design. Moreover, this characteristic
depends on guiding layer and buffer layer thickness and the refractive indices of the different regions. It is also inferred that minimum dip attenuation wavelength can be systematically controlled with the substrate position relative to the waveguide. This sensitive nature of the attenuation may be useful for frequency filtering. Using the present analysis, it is possible to design a wavelength filter for 0.67 μm with the available data. Similar studies were also performed using a numerical analysis such as the finite element method by Kumagami and Koshiba for designing a wavelength filter having a similar structure. Since the present paper deals with the analytical approach using perturbation technique, it provides systematic information regarding the effect of geometrical and compositional variations on the filtering effect.

References