ANALYSIS OF MULTI-LAYER ARROW

Alisher Abdullah and Mohammed Abdul Majid

Department of Electrical Engineering
King Fahd University of Petroleum and Minerals
Dhahran-31261, Saudi Arábia

ABSTRACT

A multi-layer Anti-Resonant Reflecting Optical Waveguide (ARROW) is used in order to enhance the evanescent field in low-index media. Polarization properties and the spectral response showing the variation of the real and imaginary parts of the modal effective index as a function of wavelength for various values of core thickness is studied. The fraction of the modal power in the superstrate region is calculated for various values of wavelength. Also the sensitivity of the multi-layer structure (i.e., the variation of the modal loss and phase difference of the fundamental as a function of superstrate bulk loss and superstrate refractive index) is calculated. The Method of Lines (MoL) is used in the analysis of the problem with higher order and a Perfectly Matched Layer (PML) based on transformation of space into the complex domain is used in order to absorb the radiative field.

1. INTRODUCTION

Anti-Resonant Reflecting Optical Waveguide (ARROW) is intensively studied recently as a special type of optical waveguide in which guidance of the optical field is partially by total internal reflection (TIR) and partially by the high reflectivity from a narrow high index (see figure 1) [1]-[3]. The core/superstrate interface provides guidance by the conventional TIR and the narrow high index ARROW layer on the bottom side of the core provides the high reflectivity. The TM polarized modes of the ARROW waveguide are much more lossy than TE polarized modes [1, 3, 4, 5, 6]. The ARROW waveguide a number of advantages compared to conventional optical such as the relatively wider core for single operation [7, 8] and polarization discrimination [2, 3, 9].

ARROWs can be used to enhance the evanescent field (to provide increased access to the guided optical field) the low-index superstrate to sense the surface refractive [10], optical absorption [11] or fluorescence [12] associated with the sensing reaction. A possible method for enhancing the evanescent field can be achieved by reducing the ARROW waveguide core width. However, it is well-known that the leakage loss of the ARROW waveguide increases substantially when the core width is reduced [1, 3, 13]. In order to overcome this problem, a multi-layer ARROW waveguide is used for this purpose (see figure 2) [2, 3] in order to reduce the core width, while maintaining low-loss operation.

Optical wavelength filter is a key element in the future of wavelength-division multiplexing photonic networks. Singlemode waveguiding, low fabrication costs, highly efficient connection to optical fibers, low loss are some of the desirable features for these wavelength selective de-layer vices. ARROW waveguides can be used for wavelength...
filtering. The structure itself is wavelength selective as the anti-resonance condition is satisfied only in a certain wavelength range. So for wavelengths above or below the design wavelength, the modes will have higher loss. However, the ARROW has low-loss over a wide wavelength range. The multi-layer ARROW has low-loss (single mode polarizer) which prompted us to study its spectral response. In [14, 15, 16], the authors describe various ARROW-based optical wavelength filters. These filters are based on a directional coupler arrangement using two adjacent ARROW waveguides. Due to different core thickness, the two waveguides have different propagation constant for the fundamental ARROW mode and are phase-matched only at a central wavelength.

In the MoL implementation, we use a higher order approximation for the second derivative operator that appears in the wave equation in order to achieve reduced matrix size and thus enhance the MoL efficiency [4, 17, 18]. In addition, a Perfectly-Matched Layer (PML) is used to terminate both sides of the computational window. This particular PML is based on the transformation of real space into the complex domain [19]. The PML is necessary in order to correctly account for both the leakage loss from the multi-layer ARROW waveguide as well as the radiative field due to wave scattering at the input end of the multi-layer ARROW waveguide.

Figure 1. Refractive Index Profile in an ARROW Waveguide

2. THE MULTI-LAYER ARROW WAVEGUIDE

Figure 2 shows the general multi-layer ARROW waveguide structure [2, 3]. The low-index superstrate in this case (air, \( n = 1 \)) is immediately on top of the waveguide core, which is made of silica glass \( (n = 1.46) \) of thickness \( t_c \). The layer below core is an ARROW layer [1] which is used here to cause wave reflection in the vertical direction towards the core layer. The alternating low/high index pairs of layers below the ARROW layer are used to insure low leakage loss from the waveguide core [2]. Each pair of layers consists of a low-index silica layer on top of high index layer \( (n_H = 2.3) \). The low/high layers have a thickness of \( t_s \) and \( t_H \) respectively. The thicknesses of these layers are chosen to be quarter wavelength in the vertical direction. The number of low/high pairs of layers is taken to be \( N = 10 \) in this work, which is sufficient for the \( TE_0 \) (see Figure 3) mode of the waveguide to have sufficiently small leakage loss, even when the core width is small. The bottom most layer is the substrate, which is assumed to be made of silicon.
2.1. TE pass polarizer

As shown in Figure 3, that as N, the number of pairs used is increased the power (leakage) loss of the $TE_0$ mode is reduced and become very small (below 0.1 dB/cm), when N=10 for all values of $t_c$ in the range of graph. The $TM$ mode are highly lossy, infact it passes $TE_0$ mode with low leakage loss as compared to higher modes. We conclude that our proposed structure works as single mode polarizer.
2.2. Spectral response and sensitivity

Figure 4 shows the variation of power loss of the fundamental $TE_0$ mode with respect to wavelength for different core thickness. It is shown that, when $t_c = 0.2 \, \mu m$, the power loss is less than 0.1 dB/cm for the wavelength range of 0.25 $\mu m$ to 0.55 $\mu m$. Also, the power loss is less than 0.1 dB/cm for the wavelength range 0.15 $\mu m$ to 0.46 $\mu m$, when $t_c = 0.6 \, \mu m$. This shows that the anti-resonance condition is well satisfied only in this range of wavelength. The wavelength above or below this range, the anti-resonance condition is not well satisfied. We can conclude that this multi-layer ARROW waveguide structure has low-loss over a wide range of wavelength. We choose to fix the wavelength as 0.45 $\mu m$, for all analysis in this paper.

Figure 4. Variation of power loss of the fundamental $TE_0$ mode with respect to wavelength for different core thickness

Figure 5 shows the variation of the fraction of modal power in the air superstrate of the fundamental $TE_0$ mode with respect to wavelength for different core thickness. It is shown in figure 5 that, when $t_c = 0.2 \, \mu m$, the fraction of power in the air superstrate starts increasing substantially at $\lambda = 0.25 \, \mu m$, but for $t_c = 0.6 \, \mu m$, it requires a large value of wavelength ($\lambda = 0.85 \, \mu m$) for the fraction of power in the superstrate to start increasing substantially to higher values. For $t_c = 0.6 \, \mu m$, the field will be mostly confined to the core region rather than to the superstrate region. As the wavelength increases, the field starts to shift from the core towards the superstrate (Increased access of field in superstrate and high sensitivity).

Figure 6 shows the acquired phase difference in degrees per millimeter as a function of superstrate refractive index for $t_c = 0.11 \, \mu m$ and $t_c = 0.6 \, \mu m$. It is evident from the figure that the acquired phase difference for $t_c = 0.11 \, \mu m$ is approximately 100 times higher than that corresponding to $t_c = 0.6 \, \mu m$. This means, when $t_c = 0.11 \, \mu m$, an increase of 0.0003 in the refractive index of the superstrate, results in a phase difference slightly larger than 180 degrees per millimeter. This very high sensitivity may be required for some applications. However, one can always control the phase sensitivity by adjusting the value of $t_c$. 

Figure 6. Variation of phase difference in degrees per millimeter as a function of superstrate refractive index
Figure 7 shows the variation of Modal loss as a function of bulk loss. We define sensitivity as:

\[ \chi = \frac{\text{Modal Loss}}{\text{Superstrate Bulk Loss}} \]  

We see that, when \( t_c = 0.11 \, \mu m \), the sensitivity is much higher than that compared to \( t_c = 0.6 \, \mu m \). It is seen that as the core layer thickness \( t_c \) is decreased, the sensitivity due to the change in the real part and imaginary parts of the superstrate refractive index increases substantially. This high sensitivity can be used to detect small changes in the optical properties of the low-index superstrate.

Figure 5. Variation of the fraction of modal power in the air superstrate of the fundamental \( TE_0 \) mode with respect to wavelength for different core thickness.
Figure 6. Acquired Phase Difference of the Fundamental $TE$-like mode as Function of Superstrate Refractive Index

Figure 7. Variation of Modal loss of the Fundamental $TE$ as a Function of Superstrate Bulk Loss
3. CONCLUSIONS

It is seen in the analysis of the multi-layer ARROW waveguide structure that as the core thickness becomes small, the evanescent field is enhanced in the superstrate region due to the high reflectivity from the stack of ARROW layers below the core.

The sensitivity (i.e., the variation of the modal loss and phase difference of the fundamental TE as a function of superstrate bulk loss and superstrate refractive index) of the multi-layer ARROW structure increases when the core thickness is decreased. This very high sensitivity is useful for many applications and is used to detect very small changes in refractive index and material absorption.

The spectral response of the multi-layer ARROW waveguide is studied. We have seen that the structure is wavelength selective as the anti-resonance condition is satisfied only in a certain wavelength range. So for wavelengths above or below the design wavelength, the modes will have higher loss.

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