Gaussian Beam Coupling to Multi-Layer ARROW

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Abstract

A multi-layer Anti-Resonant Reflecting Optical Waveguide (ARROW) is used in order to enhance the evanescent field in low-index media. End fire coupling of a Gaussian beam into the multi-layer ARROW is analyzed. The effect of the coupling parameters such as the ARROW core thickness, spot size of the Gaussian beam, and lateral position of the Gaussian beam is studied. The Method of Lines (MoL) is used in the analysis of this problem in order to account for the reflected, transmitted, as well as the radiated field due to the presence of material discontinuity at the input end of the ARROW waveguide. The MoL is implemented using higher order approximation 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 a special type of optical waveguide in which guidance of the optical field is achieved partially by total internal reflection (TIR) and partially by the high reflectivity from a narrow high index layer (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 reflectivity due to the ARROW layer is less than unity and thus the modes of the ARROW waveguide are leaky (lossy) and are characterized by a complex effective index. In general the TM polarized modes of the ARROW waveguide are much more lossy than TE polarized modes [1, 3, 4, 5, 6]. The ARROW waveguide has a number of advantages compared to conventional optical waveguides such as the relatively wider core for single mode operation [7, 8]and polarization discrimination [2, 3, 9].

An ARROW waveguide can be used to enhance the evanescent field in the low-index superstrate above the core region. The evanescent field enhancement is done in order to provide increased access to the guided optical field. Sensing methods that rely on detecting the evanescent field should benefit from this enhancement due the expected increase in the sensitivity of those methods. 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, 10]. 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.

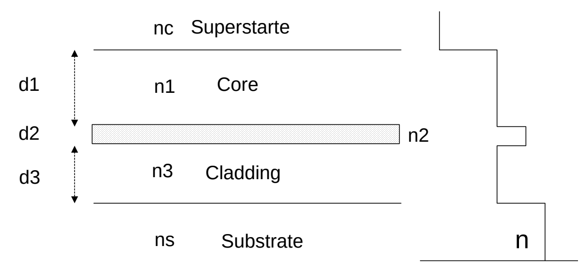

Figure 1: Refractive Index Profile in an ARROW Waveguide

In this work, we focus on the problem of Gaussian beam coupling to the multi-layer ARROW waveguide mentioned above using end-fire coupling [11]. The parameters of interest include the Gaussian beam spot size, lateral position of the Gaussian beam center with respect to the ARROW core, and the width of the ARROW waveguide core. The Method of Lines (MoL) is used for this purpose. The reflected, the transmitted, as well as the radiative field at the input end can be accounted for using the MoL. 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, 12, 13]. 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 [14]. 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.

2 Endfire/Butt Coupling Technique

There are two major methods for coupled optical power from a laser diode into an integrated optics waveguide. The first method relies on coupling light into the waveguide from the superstrate side and includes the prism and grating coupling techniques [15, 16]. The other method couples light from the edge of the waveguide which include butt or endfire coupling [17, 18]. This is usually accomplished by either directly shining the laser beam into the edge of the waveguide core or by focusing the laser beam using a lens into the waveguide edge. In this work, we will study the coupling of a focused Gaussian beam into the edge of the multi-layer ARROW waveguide using endfire coupling.

In the case of endfire coupling, maximum coupling efficiency is obtained when the focused beam pattern matches the field profile of the guided optical mode to be excited. There are two main sources of loss associated with endfire coupling. The first and most important source of power loss is due to mismatch between the focused beam pattern and that of the waveguide mode, as mentioned above. The resulting mismatch can cause large loss of the optical power through radiation. The second source of power loss is associated with wave reflection due to the material discontinuity at the input side of the waveguide. This is called Fresnel loss. This later source of loss can be dramatically reduced using anti-reflection coating or an index matching fluid. Other sources of loss may also arise; this includes for instance loss due to the quality of waveguide end preparation. In the present work, we assume that the waveguide edge is perfectly flat.

3 The multi-Layer ARROW Wavegude

Figure 2 shows the general multi-layer ARROW waveguide structure [2, 3]. The low-index superstrate in this case (water, $n = 1.333$) is immediately on top of the waveguide core, which is made of silica glass ($n = 1.46$) of thickness t_C . The alternating high/low index pairs of layers below the core are used to insure low leakage loss from the waveguide core [2]. Each pair of layers consists of a high index layer (($n_H = 2.3$)) on top of a low-index silica layer. The high/low layers have a thickness of t_H and t_s respectively. The thickness of these layers are chosen to be quarter wavelength in the vertical direction. The number of high/low pairs of layers is taken to be N=5 in this work, which is sufficient for the TE_0 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. As the superstrate used is water, we assumed glass in region(0).

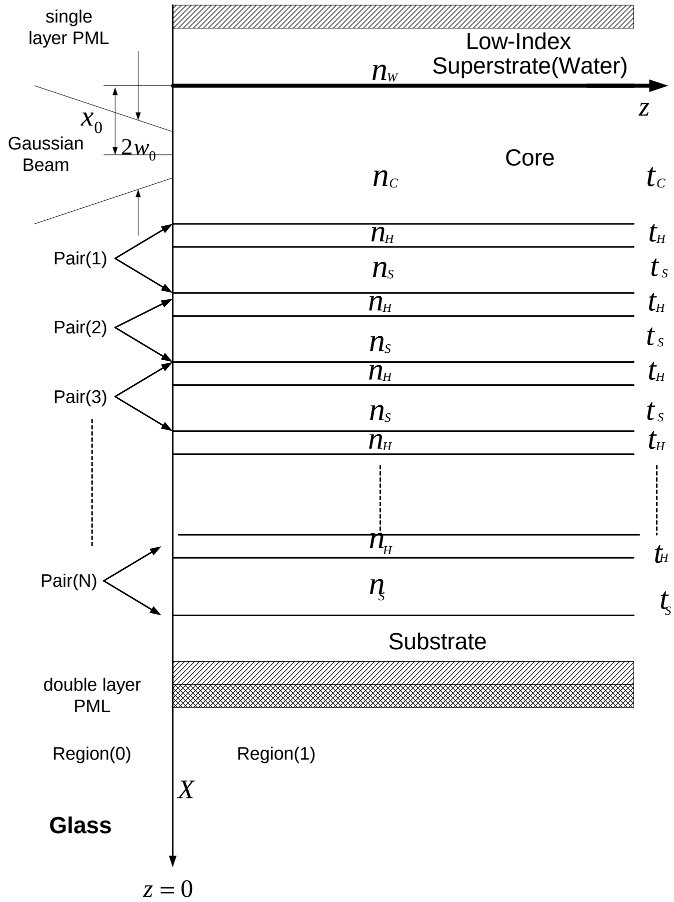

Figure 2: Coupling of Guassian beam into a Multi-layer ARROW

Consider a focused Gaussian beam having a spot size of w_0, incident normally on the edge of the multi-layer ARROW waveguide, as shown in figure 2. The waveguide edge is positioned at $Z = 0$, while the Gaussian beam center is positioned at $x = x_0$. The incident Gaussian beam profile at the waveguide edge is given by the following expression:

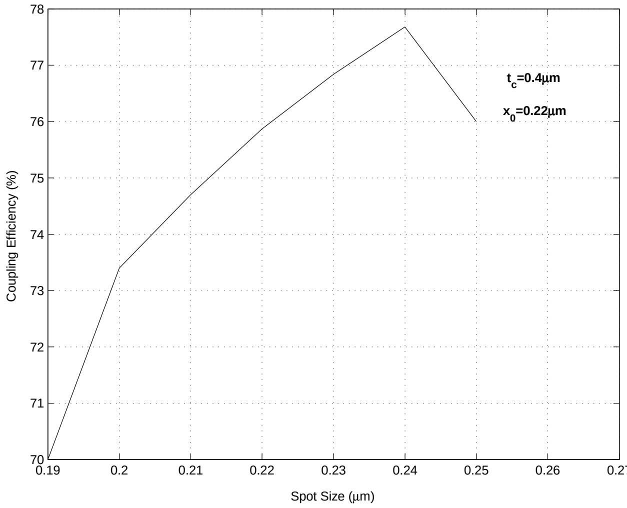

Figure 3: Coupling Efficiency Versus Spot Size (w_0)

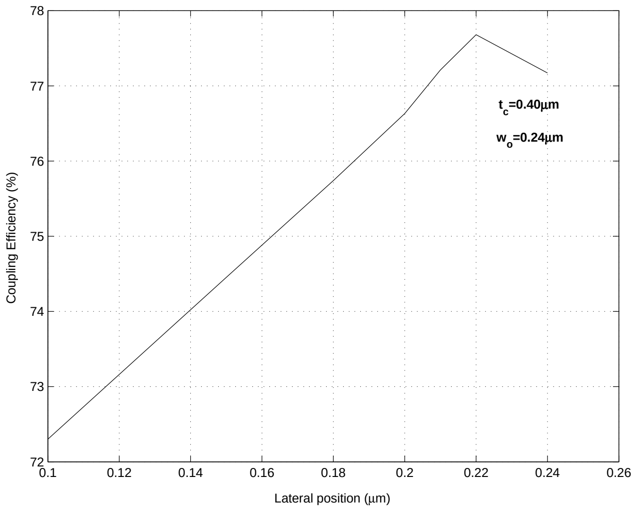

Figure 4: Coupling Efficiency Versus Lateral Position (x_0)

$$\psi = E_o \exp\left[-\frac{(x-x_o)^2}{w_o^2}\right] \qquad (1)$$

where $E_0$is the Gaussian beam amplitude at $x = x_0$. The MOL [4, 12, 13] will be used to calculate the fraction of power coupled from the Gaussian beam into the TE_0 mode of the ARROW waveguide (i.e. coupling efficiency, η). The Gaussian beam launching conditions, i.e w_0, and $x = x_0$. and will be varied in order to realize optimal launching conditions.

4 Results and Discussion

Figure 3, shows the variation of the coupling efficiency with the Gaussian beam spot size w_0 for a waveguide core thickness $t_c = 0.4\mu m$ when the beam center is positioned at $x = x_0 = 0.22\mu m$. Maximum coupling efficiency is obtained for $w_0 = 0.24\mu m$, which is roughly equal to half the core width.

Figure 4, show the variation of η with x_0 (for $t_c = 0.40\mu m$ and $w_0 = 0.24\mu m$). Maximum efficiency is seen to occur at $x_0 = 0.22\mu m$, which corresponds to a Gaussian beam position, roughly in the middle of the waveguide core.

Maximum obtainable coupling efficiency (η_m) depends on the waveguide core thickness t_c . Figure 5, shows the variation of η_m with t_c , which show monotonic increase of η_m with t_c. Very high coupling efficiency is obtained when the waveguide core is relatively large. Table 1 show the various parameters used to generate the results shown in figure 5.

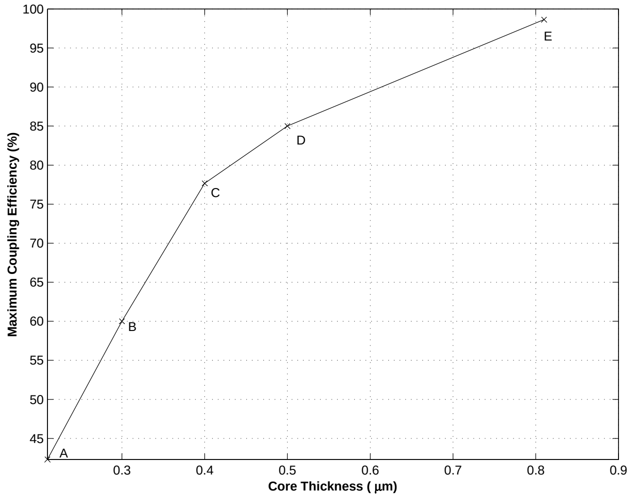

Figure 5: Maximum Coupling Efficiency Versus Core Thickness (t_c)

Label	Core Thickness (μm)	Lateral Position $x_0(\mu m)$	Spot size $w_0(\mu m)$	Coupling Efficiency (%)
A	0.21	0.06	0.095	42.31
B	0.3	0.11	0.13	60
C	0.4	0.22	0.24	77.68
D	0.5	0.23	0.19	85
E	0.81	0.3	0.34	98.64

Table 1: Maximum Coupling Efficiency Versus Core Thickness with Optimum Lateral Position and Optimum Spot Size

5 Conclusion

Gaussian beam coupling into a multi-layer ARROW waveguide using endfire excitation is studied. The results shows that maximum coupling efficiency increases with core thickness t_c. The optimum Lateral position is $x_0 = 0.22\mu m$, which is very close to the center of the core ($t_c = 0.4\mu m$). The optimum beam spot size is $w_0 = 0.24\mu m$, which is slightly larger than half the core width.

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