Transmission and Distribution of Optical Field in Prism Coupler

C Q Huang 1, J Liu 2, P Tian 3, Z M Wan 2, Z M Luo 2 and M Chen 1

1 College of Physics & Electronics Information, Hunan Institute of Science and Technology, Yueyang 414006, China
2 College of Information & Communication Engineering, Hunan Institute of Science and Technology, Yueyang 414006, China
3 College of Optoelectronic Science and Engineering, Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan, 430074, China

E-mail: namecqh@yahoo.com.cn

Abstract. Transmission and distribution characteristics of optical field in prism coupler are studies, and the phase matching function of prism coupler is deduced based on coupled wave theory. It is shown that the stable light field distribution and mode pattern are determined by its own geometric and dielectric parameters, but have nothing to do with the categories of incident light sources. It is also found that the coupling effect would generate between waveguides through evanescent field. Our numerical simulation is based on the finite difference time domain method with perfectly matched layer absorbing boundary condition. The simulation program is compiled in MATLAB. The simulation results are analyzed carefully.

1. Introduction

The necessary condition for realizing the integrated optical circuit is that optical energy can be coupled from one waveguide to the other [1]. At present, although there are several devices for realizing the coupling, most of them are either low efficient, or difficult to fabricate. For example, end-fire coupler has been shown to have a very low efficiency because of not having a finely-adjustable experimental setup. Grating coupler is a very promising optical device with high extraction efficiency of the light, but it is not well-suited for optical integrated circuits due to difficulty in mode matching, sensitivity to wavelengths, complexity of design and fabrication [2-4]. For these reasons, prism coupler is proposed for coupling power into or out of a planar optical circuit by us.

This letter is devoted to the study of energy transmission and distribution of guided modes in prism coupler. Because of the considerable mathematical complexity of the coupler construction, numerical simulation based on the finite difference time domain (FDTD) [5] technique with perfectly matched layer absorbing boundary condition [6,7] is employed. By using this technique, the optical propagation problems can be formulated systematically in terms of the well-known Maxwell’s equations without using special mathematic knowledge. To the authors’ knowledge, it is for the first time that the FDTD technique has been systematically performed to clarify the transmission and distribution of optical field in prism coupler.

2. Physical model and theoretical method

A schematic diagram of grating couplers which we discuss is shown in Figure 1. This can be seen that the prism coupler of our consideration is composed of four coupled media: a prism, an air gap, a thin-film, and a substrate. The prism is placed above the thin-film guide and is separated from it by the air gap of low refractive index. The refractive indices of air, prism, thin-film, and substrate are expressed by \( n_a = 1 \), \( n_p \), \( n_f \) , and \( n_s \), respectively. The thickness of thin-film is \( h_f \), the distance between the
prism and thin-film (air gap) is $h_a$, the width of incident beam is $2W$. The vacuum wavelength of incident beam is $\lambda_0$, it refracts to bottom of the prime, and its direction of propagation is along the $z$ axis. The bottom incident angle is $\alpha$, and the critical angle is $\alpha_c$.

Assumed that the optical wave refracted to bottom of the prime is given by the following [8]

$$A_0 \exp(jk_p(x\cos\alpha - z\sin\alpha))$$

Where $A_0$ is the amplitude, $k_p(=k_p n_p/\lambda_0)$ is wave vector.

![Figure 1. Basic structure of prism coupler](image)

The reflected light can be expressed as

$$rA_0 \exp(jk_p(-x\cos\alpha - z\sin\alpha))$$

Thus the total field in the prime can be expressed as

$$A_0 \exp(-jk_p z\sin\alpha)[\exp(jk_p x\cos\alpha) + r \exp(-jk_p x\cos\alpha)]$$

While total internal reflection occurs, the relation $r=1$ is satisfied, a stronger standing wave field is localized in $x$ direction of prime

$$2A_0 \cos(k_p x\cos\alpha)\exp(-jk_p z\sin\alpha)$$

It can be deduced that, the optical field of refractive wave is

$$A_0t \exp(jk_p x\cos\alpha' - z\sin\alpha') = A_0t \exp(jk_{\alpha'} x\cos\alpha')\exp(-jk_{\alpha'} z\sin\alpha')$$

(1)

Where $k_{\alpha'} = \frac{2\pi}{\lambda_0}n_{\alpha'}$, $\sin\alpha' = \frac{n_p}{n_{\alpha'}} \sin\alpha$

Obviously,

$$\cos\alpha' = \frac{n_p}{n_{\alpha'}} \sqrt{\frac{n_{\alpha'}^2 - \sin^2\alpha}{n_p^2 - \sin^2\alpha}}$$

While $n_{\alpha'} > n_p$, $\cos\alpha'$ is a imaginary number , which is given by the equation $\cos\alpha' = j(n_p/n_{\alpha'})\sqrt{\sin^2\alpha - n_{\alpha'}^2/n_p^2}$. The distribution of refractive wave in air gap is then expressed as

$$A_0t \exp\left[-k_{\alpha'} \frac{n_p}{n_{\alpha'}} \sqrt{\sin^2\alpha - \frac{n_{\alpha'}^2}{n_p^2} x}\right] \exp\left(-j k_{\alpha'} \frac{n_p}{n_{\alpha'}} z\sin\alpha'\right)$$

(2)
It demonstrates that, the optical field is exponentially decayed in $x$ direction (called as elapsed wave), however the optical field in $z$ direction is traveling wave field. Simultaneously, the wave field is coupled into air gap and thin-film.

According to the coupled wave theory, the phase matching condition must be satisfied in this coupler. That is to say, the change of optical-wave phase of prime in $z$ direction must be equal to that of guided-mode in wave

$$2\pi n_p \sin \alpha / \lambda_0 = \beta_m$$

(3)

Where $\beta_m$ is the propagation constant of preplanned guided-mode which is planned to couple. With different $\beta_m$ of different order $(m)$, the bottom incident angle $\alpha$ is different.

The condition for the optimal couple is

$$K L = \pi / 2$$

(4)

Where $K$ is coupling coefficient, $L$ is length of interaction which represent the intercept at the bottom of prime.

From Figure 1, it can be seen that

$$L = 2W / \cos \alpha$$

(5)

Thus

$$K = \pi \cos \beta / (4W)$$

(6)

From the aforementioned discussions, we can see that, in order to match the phase and obtain the high coupling efficiency, proper incident angle $\alpha$ and light-beam width $W$ must be chosen, the edge of the incident angle is just intersected with corner angle of prime, and the spacing interval between the prime and the film is not suitable too big. Generally, chosen $h_y = (1/4 - 1/8)\lambda_0$.

Our research is based on FDTD technique with perfectly matched layer absorbing boundary condition. For a detailed description, see for example [6-8]. In what follows, only essential steps are outlined.

There are six vector field components in the system of Maxwell equations ($E_x$, $E_y$, $E_z$, $H_x$, $H_y$, $H_z$). From Figure 1, it can see that our chosen structure has nothing to do with variable $y$. For the sake of simplicity, Only $TE_0$ mode is considered in this paper. In these cases, it is easily proved that there is only three field components ($E_y$, $H_x$, $H_z$), and $H_x$ and $H_z$ can be expressed by $E_y$. Thus the field distribution of electric-field intensity $E_y$ can be regarded as the total field distribution. To simplify solution procedure, we start with scalar wave equation for $E_y$

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2} + \mu \varepsilon \frac{\partial^2 E_y}{\partial t^2} = 0$$

(7)

Where $\mu$ is magnetic permeability, $\varepsilon$ is electrical permittivity.

According to central difference formula, at the conditions of satisfying the stabilization and avoiding the numerical dispersion, the Equation 7 becomes

$$p(i)[E_y^{N+1}(i+1,k)+E_y^{N+1}(i-1,k)+E_y^N(i,k-1)+E_y^N(i,k+1)-4E_y^N(i,k)]$$

$$+E_y^{N+1}(i,k)-4E_y^N(i,k) = 0$$

(8)

Where $p(i) = 0.25 \left( n_{\text{min}} / n(i,k) \right)^2$, $n_{\text{min}}$ is the minimum refractive index of waveguide mediums, and $n(i,k)$ is the refractive index of the researched mesh.

The difference scheme of the lower boundary can be expressed as

$$E_y^{N+1}(1,k) = \frac{1}{2} [E_y^{N+1}(2,k) + 7E_y^{N+1}(1,k) + E_y^N(k,k)]$$

(9)

$$+ \frac{1}{12} (E_y^{N+1}(1,k+1) + E_y^N(2,k+1) - E_y^{N+1}(2,k) - E_y^N(1,k))$$

Other difference schemes of the otherwise boundaries can be deduced in the same way. The procedure for calculating is compiled in MATLAB.
3. Numerical results

In the course of the numerical calculation, the geometric and dielectric parameters we have chosen are as follows: $h_a = 0.5 \, \mu m$, $h_f = 1 \, \mu m$, $h_s = 0.5 \, \mu m$, $n_p = 2.192$, $n_f = 1.563$, $n_s = 1.55$, $\alpha = 45^\circ$, and the data of space step $\Delta x$ and time step $\Delta t$ are 0.0416 $\mu m$ and 0.1074 ns, respectively. The incident wave is vertical to the sloped edge of prime with $\lambda_0 = 1.3 \, \mu m$, and the edge of the incident beam is just overlapped each other in the right-angle of prime. Three kinds of optical sources are used as stimulants. They are Guass optical source, spherical optical source, and plane optical source.

![Figure 2. Field distribution stimulated by plane wave](image)

![Figure 3. Field distribution stimulated by Guass wave](image)

![Figure 4. Field distribution stimulated by spherical wave](image)

![Figure 5. The stable mode of TE0 for different incident waves](image)

The transmissions and distributions of optical field profiles of $TE_0$ stimulated by different optical sources are shown in Figures 2, 3, 4, respectively. From these figures, it can be seen that the energy of incident light beam could be coupled from prime to waveguide film, and the guided-wave could be stimulated in the film. This fact can be explained that, while the incident light enters the prime, the high refractive index causes it to suffer total internal reflections, leading to the form of standing wave field. At the same time, part of the energy of standing wave field penetrates down into the air gap. Through the coupling effect of evanescent fields, the transition energy could transfer from the air gap.
to film, and could excite any modes existed in the film. It is clear that, at the beginning of prime coupler, there are not formed the stable modes. But with the increasing of propagation distance, the stable light field distributions are gradually formed. The stable mode pattern of $TE_0$ is illustrated in Figure 5, it is the same with analytic solutions.

From the aforementioned discussions, we know that a stable light field mode is determined by the geometric and dielectric parameters rather than the driving sources. Based on the profiles of transmissions and distributions, the transmission processes of energy in the prime coupler can be seen clearly, the accurate coupling length through evanescent field can be obtained, the coupling efficiency can be forecasted, and thus highly-efficient waveguide couplers which are of practical use in integrated optical circuits and optoelectronic devices can be designed conveniently.

4. Conclusion

This letter is devoted to the study of energy transmission and distribution of guided modes in prism coupler based on the FDTD technique with perfectly matched layer absorbing boundary condition, and the phase matching function of prism coupler is deduced based on coupled wave theory. It is found that a stable field distribution and mode pattern are determined by dielectric and geometric parameters of devices, but have nothing to do with the categories of incident light. According to the field distributions, the characteristic coupling length, detuning, resonance amplitudes of the fields can be also found. It is shown that the coupling is strongest if the components of wave vectors parallel to the air gap are equal to the propagation constant, of one of the film modes, and optical energy can be transferred from the prism to the film effectively. In these ways, the coupling efficiency of prism coupler can be predicted.

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References

[1] Chaganti K, Salakhutdinov I, Avrutsky I and Auner G W 2006 Opt. Express 14 4064-4072
[2] Liu X M, Zhu P F, Cao Z Q, Shen Q S and Chen J L 2006 JOSA B 23 353-357
[3] Fick J and Vitrant G 1995 Optics Letters 20 1462-1464
[4] Apiratikul P, Rossi A M and Murphy T E 2009 Opt. Express 17 3396-3406
[5] Yee K S 1966 IEEE Trans. Antennas Propagat 14 302-307
[6] Engquist B and Majda A 1975 Mathematics of Computation 31 629-651
[7] Taflove A and Hagness S C 2000 Computational Electrodynamics: The Finite- Difference Time-Domain Method (Boston. London: Artech House)
[8] Ming H, Zhang G P and Xie J P 1998 Photoelectronic Technique(Hefei: China University of Science and Technology Press) pp 66-70