A STUDY OF THE PRISM-GRATING COUPLER

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I. Introduction

The principal advantage of the prism coupler is that any guide mode can be excited by properly selected incident angle of laser[1-4]. Thus, the prism coupler has become a very useful device for investigating the properties of various thin film waveguides. The refractive index of the prism selected must be higher than the index of waveguide thin film material. In studying thin film waveguide of high refractive index, however, it is difficult to find a prism material having refractive index higher than that of thin film. In order to solve this problem, we use photolightgraphy, holography, ion milling and mechanical methods to fabricate fixed grating on the surface of the prism. Usually, we call this device the prism-grating couplers. Just like conventional prism couplers, the light wave is coupled by means of the evanescent field of the gap between the prism and thin film. But there is some difference between the prism coupler and the prism-grating coupler. When the prism-grating couplers are used, even if the refractive index of the thin film is higher than that of the prism, various orders of guided modes can still be excited in the thin film. Hence, the prism-grating couplers as well as conventional prism couplers are available in the laboratory and the production line.

II. The Phase-matching Condition

As we know, the amplitudes of the grating vector $\boldsymbol{K}$, the propagation vector of the free space $\boldsymbol{k}$ and the propagation vector of the prism beam $\boldsymbol{K}_p$ are $K = \nu(2\pi/\Lambda)$, $k = 2\pi/\lambda$ and $K_p = n_p\boldsymbol{k}$, respectively, where Λ is the periodicity of grating, ν is diffraction order ($\nu = 0, \pm1, \pm2, \cdots$), λ is the free space wavelength of the laser beam, n_p is the refractive index of prism. The diffracted wave in prism has a propagation vector given by $(\boldsymbol{K} + \boldsymbol{K}_p)$. If z component of the propagation vector of the diffracted wave and the propagation constant of m order guided mode of thin film is phase-matched, i. e. $\beta_m = (\boldsymbol{K} + \boldsymbol{K}_p)_z$, then the evanescent field of the diffracted wave will be coupled into m order guided mode of film. Thus, the phase-matching condition can be expressed as

$$\beta_m = \nu\frac{2\pi}{\Lambda} + kn_p\sin\theta_p. \tag{1}$$

The first term of Eq. (1) is the amplitude of ν order grating vector, and the second is z component of the propagation vector of the prism beam. The vector relation of the phase-matching condition satisfied by the two terms is shown in Fig. 1.

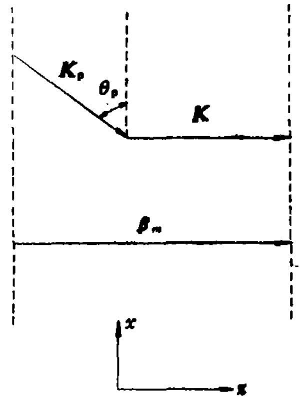

Fig. 1. The vector relation of the phase-matching condition. If the phase-matching con dition is satisfied by the sum of the amplitude of the grating vector K and z component of the propagation vector of the prism beam, then the evanensent field of the diffracted wave will be coupled to m order guided mode of thin film.

In fact, the prism coupler[1-4] and the grating coupler[5-9] are two special examples of the prism-grating coupler. In the case of the prism coupler the first term of Eq. (1) is zero, and Eq. (1) can be changed into the following form:

$$\beta_m = kn_p \sin\theta_p. \tag{2}$$

In the case of the grating coupler (see Fig. 2) n_p and θ_p of the second term of Eq. (1) are substituted by the refractive index of the air n_a and incident angle of the laser beam θ_a. Then Eq. (1) can be changed into the following form:

$$\beta_m = \nu\frac{2\pi}{\Lambda} + kn_a \sin\theta_a. \tag{3}$$

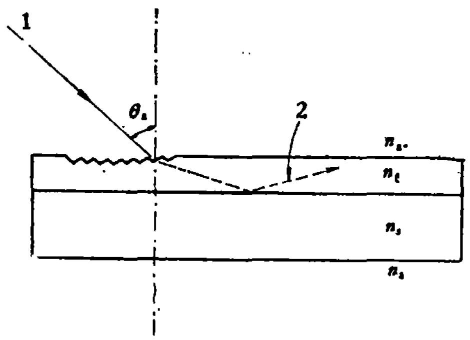

Fig. 2. The grating coupler.
1—Incident beam; 2—waveguide beam.

Obviously, Eq. (1) is a general expression satisfying the phase-matching condition of light wave coupling.

If the two side of Eq. (1) are divided by $k = 2\pi/\lambda$, and the relation between α and θ_p given by [3] is taken into account, then the corresponding effective refractive index of m order guided mode can be written as:

$$\tilde{N}_m = \gamma \frac{\lambda}{\Lambda} + \sin\alpha\cos\varepsilon + (n_p^2 - \sin^2\alpha)^{\frac{1}{2}}\sin\varepsilon, \tag{4}$$

where ε is the angle of the prism (see Fig. 3). From Eq. (4), one can see that $\tilde{N}_m$ can be varied by changing the incident angle α. If we only want to excite one specified waveguide mode, then by properly selecting α we can make Eq. (4) equal to intrinsic effective refractive index of specified waveguide mode.

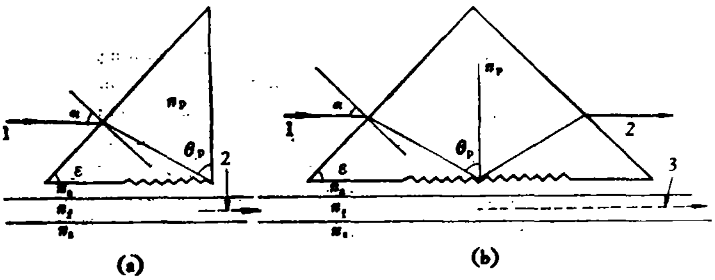

Fig. 3. The prim-grating coupler.
(a) Right angle prism-grating coupler.
1—Incident beam; 2—waveguide beam.
(b) The symmetrical prism-grating coupler.
1—Incident beam; 2—refractive beam; 3—waveguide beam.

III. Incident Angle of the Laser Beam

To couple the light wave in the prism-grating coupler, the incident angle of the laser beam is required to accord with the following cases.

When incident wave of the laser beam is total-reflected by interface of the prism base-air and reflected partly by that of the prism-grating, incident angle of the laser beam θ_p will satisfy the following relation:

$$\theta_p^c = \sin^{-1}\left(\frac{1}{n_p}\right) \leqslant \theta_p < \sin^{-1}(n_r/n_p), \tag{5}$$

where θ_p^c is the critical angle, n_r is the refractive index of the grating material. If Eq. (1) of the phase-matching condition is satisfied by the incident angle of the laser beam, then the laser beam will be coupled by means of the evanescent field of the gap and the grating structure.

When incident wave of the laser beam is total-reflected by both the interface of the prism-air and that of the prism-grating, the incident angle of the laser beam θ_p should satisfy the following relation:

$$\sin^{-1}\left(\frac{n_r}{n_p}\right) < \theta_p < 90^\circ. \tag{6}$$

If Eq. (1) of the phase-matching condition is satisfied by the incident angle of the laser beam, then the laser beam will realize the couple of the light wave by means of the evanescent field.

IV. The Selection of the Grating Periodicity

When we use the prism-grating coupler, we must consider not only $n_p, \theta_p, \varepsilon$, but also the grating parameter, i. e. the grating periodicity Λ and the diffracted order ν. If the design of device is not suitable and all the parameters are not carefully selected, even on the surface of prism fabricated with high-quality grating, efficient excitation of light wave is not realizable.

For simplicity, we only consider the case of the first order diffracted wave. To achieve the coupling condition, incident angle of the laser beam θ_p must be adjusted within the critical angle θ_p^c of total-reflection and 90°. If the two sides of Eq. (1) are divided by k, we can derive the form of θ_p

$$\theta_p = \sin^{-1}\left(\frac{\tilde{N}_m - \dfrac{\lambda}{\Lambda}}{n_p}\right). \tag{7}$$

For the given refractive index of the prism n_p and the effective refractive index $\tilde{N}_m$, to satisfy the inequality $\theta_p \geqslant \theta_p^c$, we should select suitable grating periodicity Λ, so as to make $(\tilde{N}_m - \lambda/\Lambda)$ value of Eq. (7) satisfy the inequality

$$n_p > \left(\tilde{N}_m - \frac{\lambda}{\Lambda}\right) \geqslant 1. \tag{8}$$

Any selection of grating periodity in designing prism-grating coupler has to be in accord with Eq. (8).

In order to design and select the grating periodicity, it is necessary to calculate the variation of $\tilde{N}_m$ and θ_p with the grating periodicity in advance. Let n_p=1.80009, ε=45°, for each considered grating periodicity in the region of total-relation angle, we compute the corresponding value $\tilde{N}$. When the grating periodicity is chosen to be 1.67 μm (600/mm), 0.83 μm (1200/mm) and 0.42μm (2400/mm), the values of $\tilde{N}$ are 1.38—2.18, 1.76—2.56 and 2.5—3.32, respectively. Obviously, to study the waveguide material of lower refractive index, we must select long-periodicity grating, while to study the high refractive index waveguide material, we must select short periodicity grating.

To take Ta_2O_5 waveguide thin film reported in [10] as an example, when He—Ne laser with wavelength 6328Å and the prism-grating couplers are used, we can calculate how long it is necessary for the grating periodicity to excite (see Table 1). The effective indexes of four modes of Ta_2O_5 waveguide thin film are $\tilde{N}_0$ = 2.185568, $\tilde{N}_1$ = 2.096807, $\tilde{N}_2$ = 1.944711, $\tilde{N}_3$ = 1.721096, respectively.

From Table 1 it can be seen that the four angles are all smaller than the criti-

Table 1[a)]

θ_p	$\sin^{-1}\left(\frac{\bar{N}_m - \lambda/\Lambda}{n_p}\right)$				
Λ	1μm (1000/mm)	0.833μm (1200/mm)	0.625μm (1600/mm)	0.556μm (1800/mm)	0.417μm (2400/mm)
M / m	4	3	2	1	0
0	59.61°	52.40°	40.67°	35.55°	21.74°
1	1	54.42°	47.99°	32.15°	18.73°
2	2	46°79°	41.19°	26.59°	13.69°
3	3	37.20°	32.30°	18.87°	6.46°

a) Since the selected grating periodicities are different for the same prism material (n_p=1.80009) So Ta_2O_5 thin film guided mode will vary with respect to the case of excitation. Let M represent the number of the waveguide mode excited in the table, $\theta_p^c = 33.75°$

cal angle θ_p^c at $\Lambda = 0.417\mu m$ (2400/mm), hence, no mode can be excited. Only when $\Lambda = 1\mu m$ (1000/mm), can all modes be excited. When the selected grating periodicities are $\Lambda = 0.556\mu m$, $0.625\mu m$ and $0.833\mu m$, only one, two or three modes can be excited, respectively. Obviously, in order to excite all guided modes in the case of given n_p, ε, λ and ν, we must select the correct grating periodicity Λ. Otherwise, the prism-grating coupler cannot be used as an efficient coupler as shown in Table 1.

V. Discussion

The prism coupler has a number of advantages[3], but it also has some limitations, that is to say, it is limited to certain optical materials. The optical glass prism can only apply to the lower refractive index waveguide material, because the refractive index of the applicable optical glass can by no means be greater than 2. In studying various waveguide material, according to the requiremnt of the phase-matching condition, namely, Eq. (4) and the inequality (8), we can fabricate the grating of various periodicities on the surface of the glass prism with different refraction indexes. Since the prism made of optical glass is cheap, manufacture technology is well-developed, and the cost is low, the prism-grating coupler made of optical glass is available in study of various refractive index waveguide samples. So it is of significance for us to make use of this coupler as a substitute for TiO_2 prism which is short in our country. We can solve the practical difficult in measuring work in the same manner, in addition, another prism material-gallium arsenide crystal is available, as it has some advantages: (i) techniques for growing high optical quality gallium arsenide crystals are relatively well developed, (ii) for IR wavelength gallium arsenide is an optical transparent, hard, and durable material and can be well polished, (iii) its diffraction efficiency of laser beam by grating is proportional to $(n_p^2 - n_s^2)^2$, and GaAs crystal has high refractive index ($n_p = 3.43$ at $1.06\mu m$). Hence, it is possible to obtain the relatively high diffraction efficiencies for gallium arsenide coupler.

There are some other crystals having index of refraction higher than that of gallium arsenide GaAs crystal. For example, the index of monocrystaline silicon at the wavelength of 1.06 micrometer is about 3.5, but it is useless, for it is opaque to light with wavelength less than about 1.15 micrometers.

If we study a waveguide sample by means of different types of the couplers, the grating periodicity required in the prism-grating couplers is much longer than that of grating coupler. For example, if we observe GaAs waveguide with GaAs prism-grating couplers, a grating periodicity of 2.28μm is required, the excitation of guided mode is realizable at $\theta_p = 60°$, while with the grating coupler, the grating periodicity should be 0.41 μm. So according to the phase-matching condition —Eq. (1), when designing and fabricating the prism-grating coupler, the value of the prism-refractive index could be lowered. A proper combination of the merits of the two sides is conducive to investigating the waveguide materials of both mean and high refractive index.

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