GUIDED-TO-RADIATION MODE CONVERSION IN HETERO-STRUCTURE PLANAR WAVEGUIDES AND ITS APPLICATION TO A LIGHT MODULATOR

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ABSTRACT

By making an investigation of the coupling strength of guided mode to radiation mode due to electrooptic effect in hetero-structure waveguides, it is suggested that a high-efficiency light intensiey modulator can be built of a simplified structure and with ease of fabrication.

Introduction

Among various types of thin-film light modulators utilizing electrooptic effect, the modulator which makes use of guided-to-radiation mode coupling[1,2] has the advantage of simplified structure, direct intensity modulation and relaxed dimonsional tolerance in fabrication. The modulation efficiency, however, is relatively low in the case of metal diffused $LiNbO_3$ and $LiTaO_3$.[1] This is because of the insufficient field overlapping of guided and radiation modes which has a direct effect on the strength of the coupling.

In this paper, we will show that the field overlapping could be considerably improved by use of hetero-structure waveguides in which the refractive indices of film and substrate can be chosen comparatively freely to satisfy an approximately optimum condition. Since the light extinction ratio is proportional to the squared field overlap, the modulation efficiency will be dramatically improved.

Mode Coupling

We consider a case of a positive anisotropic crystal taken as a substrate in which the TE guided mode couples to TM radiation mode, as shown in Fig.1.

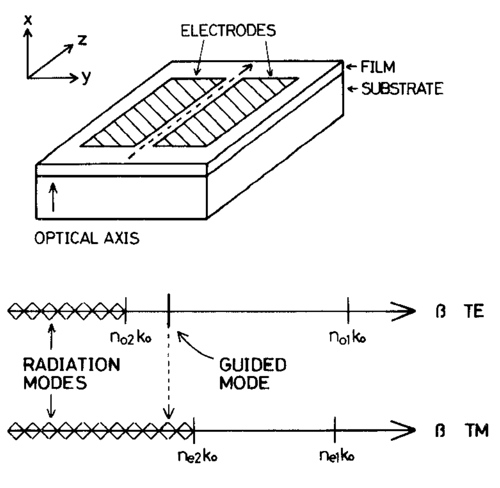

Fig.1 Configuration of a light intensity modulator and the ranges of TE guided and TM radiation modes. Owing to the positive anisotropy of the substrate, a TE guided mode degenerates to a TM radiation mode.

In the case of a negative anisotropic crystal, the roles of TE and TM modes are interchanged. The substrate and/or the film are assumed to have the electrooptic coefficient r_{51} with the optical axes directed normal to the surface. By placing a film of proper refractive indices and thickness on the positive anisotropic substrate, the fundamental TE guided mode can be made degenerate to the TM radiation mode. Since the radiation mode has a continuous spectrum of propagation constant, the degeneracy is automatic within a certain range of film thickness so that the severe control of film thickness is not required as compared with the case of guided-to-guided mode coupling. If a modulation electric field is applied at a right angle to the light propagation in the surface plane, the guided mode couples to the radiation mode through the off-diagonal elements of dielectric tensor caused by the electrooptic effect, the power of the TE guided mode leaking out into the substrate.

Marcuse derived the approximate solution for the power attenuation constant 2α of the TE guided mode, which corresponds to the modulation efficiency, as[1]

$$2\alpha = 2\pi \frac{n_{o2}^2}{n_{e2}^2} |K_{em}|^2 \frac{\beta}{\rho} \tag{1}$$

$$\text{with} \quad K_{em} = \frac{j\omega\varepsilon_0}{4P} \int_{-\infty}^{0} n_o^2 n_e^2 r_{51} E_y^{TE} E_x^{TM} E_m \, dx$$

where E_m is the modulation field, ρ is the transverse decay constant of the TM radiation mode in the substrate and β is the propagation constant of the TE guided mode. Though eq.(1) bears a convenient form for physical interpretation of guided to radiation mode coupling, noticeable error appears as the coupling strength increases. Consequently, we have developed a more accurate method for numerical calculation, which quantizes the TM radiation modes into multiple TM guided modes taking the thickness of substrate into account.

Numerical Caluculations and Discussion

As is obvious from eq.(1), the modulation efficiency directly depends on the overlap integral of the two electric fields of the TE guided and TM radiation modes, as well as on the magnitude of the electrooptic constant. The field distributions of both modes are determined by the refractive indices of the film (n_{o1}, n_{e1}) and the substrate (n_{o2}, n_{e2}), and the thickness of the film. The modulation efficiency, therefore, may be improved by employing hetero-structure waveguides which have proper refractive indices for obtaining large field overlap.

In order to improve the field overlap in the substrate where the field of the TE guided mode varies exponentially and that of the TM radiation mode varies sinusoidally, it is desirable that the anisotropy of the substrate should be small so that the transverse field variation of the radiation mode is small enough in this region. As a good example of such materials, we take $LiTaO_3$ as a substrate, which has small anisotropy of n_o=2.176, n_e=2.181 and an electrooptic constant of $r_{51}=20\times10^{-12}$m/V at 0.6328μm. As a function of the

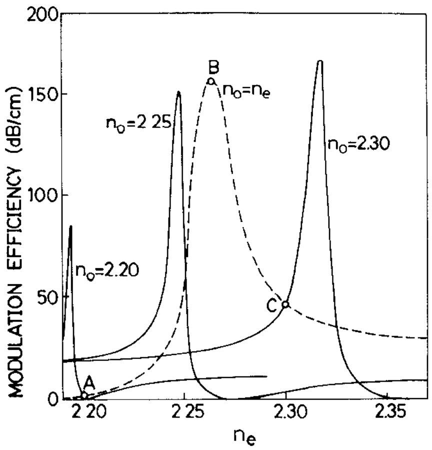

Fig.2 Modulation efficiency as a function of the extraordinary refractive index of the film as a parameter of ordinary refractive indices of 2.20, 2.25 and 2.30. At any point, the thickness of the film is determined to give the maximum modulation efficiency. The dotted line represents the case of isotropic film.

refractive indices (n_o and n_e) of the film, the maximum value of modulation efficiency for TE_0 guided mode is plotted in Fig.2 which is attained by choosing the proper thickness of the film. The dotted line in the figure represents the case of isotropic film. In this calculation we have assumed that the film has no electrooptic effect and the modulation voltage is 238.5V with the electrode spacing of 50.6μm, which corresponds to the case of D/λ=100 of Marcuse[1]. As the modulation efficiency increases, the assumption that the power of TE_0 guided mode decays exponentially fails to hold, i.e., it shows an oscilatory behavior as well as exponontial decay with propagation. In such cases, we have defined the modulation efficiency by approximating the first part of monotonous decrease to an exponential function. From this figure, we can see that the optimum film on $LiTaO_3$ substrate is of slightly negative anisotropy if n_o<2.265, of slightly positive anisotropy if n_o>2.265, or isotropic with $n_o = n_e$ =2.265.

In order to interpret these results, let us examine the field distributions of the relevant TE and TM modes. Fig.3(a), (b) and (c) show the field distributions at points A, B and C of Fig.2. In the case of isotropic-film waveguide, the transverse field of TM radiation mode in the film region 'lags in phase' in the negative x direction with respect to TE guided mode by

$$\theta = \arctan\left(\frac{\kappa}{\Delta}\right) - \arctan\left(\frac{1}{n^2}\cdot\frac{\kappa}{\Delta}\right) \qquad (2)$$

where κ is the transverse propagation constant of the TE and TM modes in the film, Δ is the transverse decay constant of the TE and TM modes in the air and n is the refractive index of the film. At point A, as the phase difference between the peak of the TE_0 guided mode field and the film-substrate boundary is greater than θ, the peak of the TM radiation mode exists also in the film, which is the cause of cancellation of positive and negative field overlap in the substrate. As the refractive index n_{o1} of the film increases, the TE_0 guided mode approaches relatively to cutoff state because its propagation constant should remain between $n_{o2}k_o$ and $n_{e2}k_o$. In other words, the degree of the power confinement in the film region becomes less and the peaks of both modes move toward the substrate. At point B, the peak of the TM radiation mode is located just below the film-substrate boundary, which results in the maximum of the overlap integral of TE and TM modes. At point C, the peak sinks into the substrate and hence the degree of field overlapping becoms less.

For an isotropic film, we have Nb_2O_5 which satisfies the desirable condition obtained above. Reactively sputtered film of this material were reported to have refractive index ranging from 2.21 to 2.27.[3] By the proper arrangement of the condition of film fabrication, we can obtain an isotropic film of refractive index 2.265 on $LiTaO_3$ substrate. Fig.4 shows the modulation efficiency as a function of the film thickness of the Nb_2O_5-$LiTaO_3$ structure. The power variations of TE_0 guided mode are plotted in Fig.5 as functions of propagation distance at several values of film thickness. The curves A, B and C correspond to points A, B and C in Fig.4, at which the film thickness are 0.24μm, 0.245μm and 0.2464μm, respectively.

At the film thickness of 0.24μm(A), the power decays exponentially. As the film becomes thicker, the coupling becomes strong and the oscillatory power variation appears as shown by curve B. At the film thickness of 0.2464μm(C) where the propagation constant of TE_0 guided mode is located near $n_{e2}k_o$, the modulation efficiency is determined to be around 150dB/cm, which

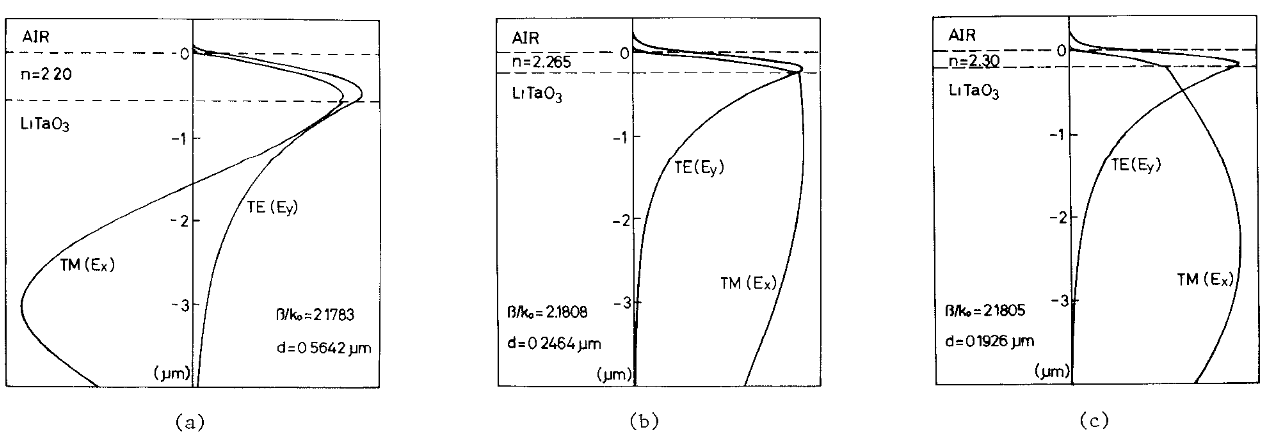

Fig.3 The field distributions of the TE guided and the TM radiation modes: (a) point A, (b) point B, (c) point C of Fig.2, respectively.

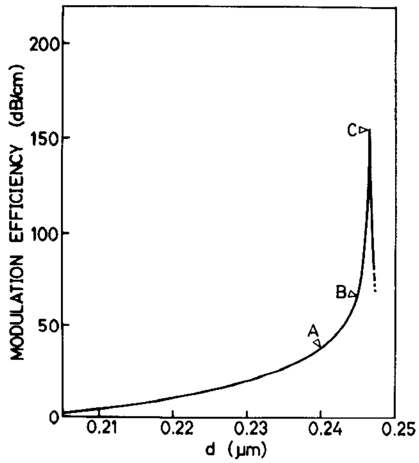

Fig.4 Modulation efficiency as a function of film thickness d in the case of Nb_2O_5-$LiTaO_3$ structure.

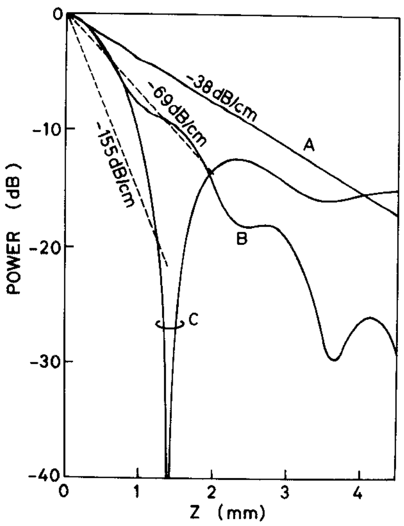

Fig.5 The power variation of the TE_0 guided mode as a function of propagation distance z in the case of Nb_2O_5-$LiTaO_3$ structure.

is the maximum value in this structure.

Such unusual behavior of TE_0 guided mode seems to be originated from the violent variation of the density of TM radiation mode and the coupling constant K_{em} in eq.(1) in the neighborhood of $n_{e2}k_o$ which is the upper limit of TM radiation mode.

As another example, we consider an anisotropic film, $Li(Nb_x,Ta_{1-x})O_3$ solid-solution crystal[4,5] which has an advantage to choose its anisotropy by selecting the x value. We can obtain the slightly negative crystal(n_o=2.1872, n_e=2.1836) by setting x=0.1. The modulation efficiency is plotted as a function of film thickness in Fig.6, taking into account the electrooptic constant of the film in this case. The maximum efficiency is near to 200dB/cm and dependence on the film thickness is greatly reduced compared with the Nb_2O_5-$LiTaO_3$ structure because the difference between the refractive indices of film and substrate becomes much smaller than that of Nb_2O_5-$LiTaO_3$ structure.

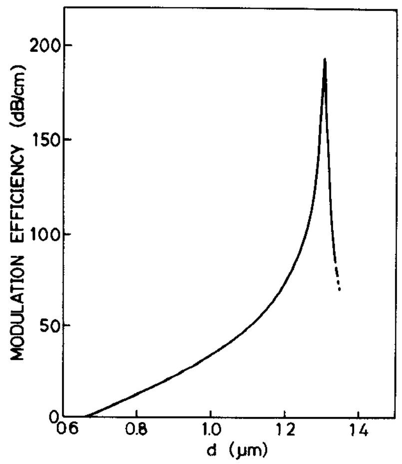

Fig.6 Modulation efficiency as a function of film thickness d in the case of $Li(Nb_{0.1},Ta_{0.9})O_3$-$LiTaO_3$ structure.

Conclusion

We have investigated the TE-guided to TM-radiation mode coupling due to electrooptic effect in a thin-film light waveguide where the film is consist of a different material from the substrate, and proposed a simplified structure of high-efficiency light modulator with ease of fabrication. The modulation efficiency of over 100 dB/cm has been found to be possible in the Nb_2O_5-$LiTaO_3$ and $Li(Nb_{0.1}Ta_{0.9})O_3$-$LiTaO_3$ heterostructure waveguides.

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