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ANALYSIS OF DIRECTIONAL COUPLER WITH SYMMETRICAL ADJACENT PARALLEL WAVEGUIDES USING BEAM PROPAGATION METHOD

MR. PRASENJEET DAMODAR PATIL[1], DR. GAJANAN G. SARATE[2], MRS. JYOTI MADANRAO WAYKULE[1]

1. Assistant Professor, Dept. of E&TC, S.G.I, Atigre – 416118.
2. Lecturer in Electronics, Dept. of Electronics, Government Polytechnic, Amravati-444602

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Abstract- In this paper, the existence of mode coupling in parallel waveguides is experimentally verified. Beam propagation method with paraxial approximation along with coupled mode theory is used for numerical modelling of wave propagation through slab waveguides. Simulation results shows that the maximum amount of optical power coupled depends on waveguides separation which validates with the theoretical results. The wavelength response of directional coupler is also investigated.

Keywords:- Symmetrical adjacent parallel waveguides, Beam propagation method, coupled mode theory, directional coupler.

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INTRODUCTION

A directional couplers is bi-directional passive component that can be used for combining optical power, wavelength filtering and polarization selection [1][2].

It consist of two identical waveguides placed in close proximity with each other.
Various numerical methods like FDTD, MOL, BPM, rigorous wave analysis are developed for the analysis of such waveguides.
The beam propagation method is one of the commonly used numerical method used to determine the field's propagation inside the waveguide [3][4]. It decomposes the wave into superposition of plane waves, each travelling in different direction. These individual plane waves are propagated through a finite predetermined distance through the waveguide until the point where the field needs to be determined has arrived. At this point, all the individual plane waves are numerically added in order to get back the spatial mode.
Coupled mode theory or mode coupling explains the exchange of fields between waveguides by evanescent coupling [5].

I. SOLUTION OF WAVE PROPAGATION THROUGH SLAB WAVEGUIDE

II. The dielectric slab waveguide is a simplest structure consisting of a central waveguide with higher refractive index than the surrounding material know as substrate. Because of its simple geometry, it forms the basis of analysis of guided and radiation modes in complex dielectric slab waveguides.

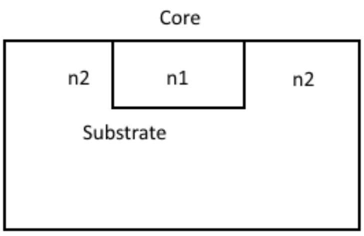

Figure. 1 Dielectric slab waveguide

The time harmonic two dimensional scalar wave equation for TE polarized wave propagating in non-magnetic dielectric slab waveguide having three homogenous layers shown in fig. 1 is given by

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial z^2} + k_0^2 n^2 E_y = 0 \qquad (1)$$

In equation 1, it has been assumed that ∂/∂*y*=0, which is valid for infinite and uniform structures in the y-direction. To obtain modal solution of wave propagation in the *z* direction, the field is assumed to vary as $e^{j\beta z}$ in the *z* direction (β is the longitudinal propagation constant). In this case equation 1 reduces to the well-known Helmholtz equation:

$$\frac{d^2E_y}{dx^2}+(k_0^2n^2-\beta^2)E_y=0 \tag{2}$$

Using equation 2 and imposing the boundary conditions at the substrate-core interface, the modal solutions (guided modes) of the structure as well as the corresponding propagation constants can be obtained.

II.1Guided modes in symmetrical waveguides

A symmetrical waveguide is consisting of identical medium on either sides of the waveguide, which supports a finite number of guided modes and an infinite number of radiation modes. In order to achieve guidance, the refractive index of the core(n_1) of a symmetric slab waveguide has to be higher than the refractive index of the substrate (n_2).

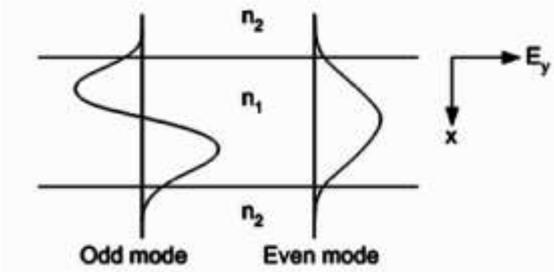

Figure 2. Electric Field Distribution in a Symmetric Slab Waveguide

The guided modes of a symmetric slab waveguide are either even or odd in their transverse field distributions, as shown in figure 2. The number of guided modes that can be supported by a symmetric slab waveguide depends on the thickness *2d*, the wavelength λ and the refractive index of core (n_1) and substrate (n_2).

II.2Directional coupler with adjacent symmetrical waveguides

A directional coupler or diffusion coupler can be realized by keeping two symmetrical waveguides in close proximity to each other. The port through which wave is propagated can be called as primary wave guide & the adjacent waveguide as auxiliary waveguide. When the wave is propagated from one of the waveguide, field power is coupled in the auxiliary waveguide by evanescent field coupling. The amount of field power coupled depends on the symmetry, mode and distance between two waveguides. Very weak power coupling has been reported by Charles K. Kao [6], for multimode waveguide. In this paper, single mode and symmetrical waveguide is considered.

Two modes exists in the combined coupled structure of single mode waveguides, known as even transvers mode and odd transverse mode as shown in fig 3. The effective n_{eff} refractive index of the even mode is slightly greater than odd mode.

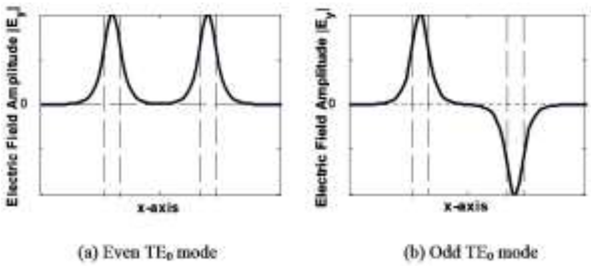

Figure 3. The overlap of the transverse fields and refractive indices of two adjacent, parallel symmetric slab waveguides

The interchange of power between two waveguides becomes very significant, when they are kept very close to each other & they remain parallel up to certain length. The field power is exchanged periodically between two waveguides over the entire length as shown in the fig. 4

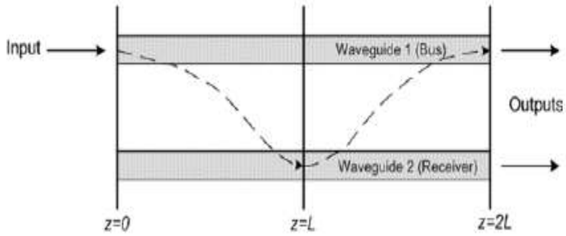

Fig.4 Field coupling between slab waveguides

The input is applied to waveguide 1, at *z = 0.* Assuming that complete coupling in waveguide 2 occurs at *z = L.* At *z = 2L*, therefore, the light will have been completely coupled back to waveguide 1, and process is continuous through the length. For 100 % power transfer the two waveguides must be symmetrical and must be in close proximity with each other.

III. ANALYSIS OF DIRECTIONAL COUPLER USING BEAM PROPAGATION METHOD

The BPM algorithm has been implemented in MATLAB for the analysis of symmetrical adjacent dielectric parallel waveguides in close proximity over the substrate and surrounded by air. TE_0 mode is used at input of one waveguide

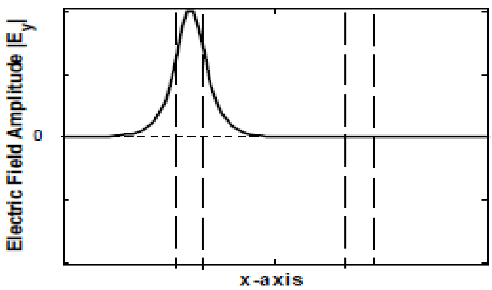

Figure 5. Electric Field Amplitude at the Input (port 1)

IV. EXPERIMENTAL SETUP, OBSERVATIONS AND RESULTS

Each waveguide core is assumed to be 0.2µm wide and the distance between the two waveguides is set at 0.5 *µm*. Each waveguide core has a refractive index of 3.2. The surroundings material is assumed to be air, with a refractive index of 1. The fundamental TE mode of an isolated single waveguide at the wavelength of 1550 *nm* is used to excite the waveguide from port1.

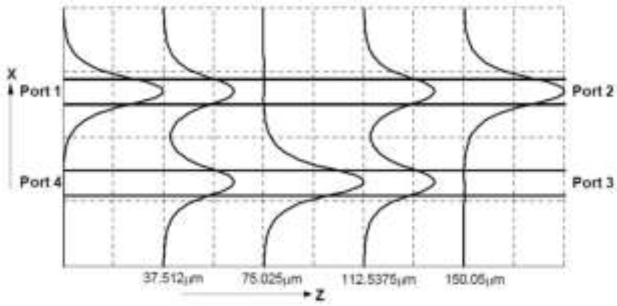

Fig. 6 TE_0 mode propagation through Directional Coupler

From the simulation results it can be seen that the field traveling through the bus is coupled to the receiver completely after a distance 75.025 *µm*, and again coupled back to the bus after the same distance.

IV. Effects of waveguide separation

For complete power transfer, the two waveguides have to be kept parallel for a certain distance. This length is known as the coupling length. The coupling length of a directional coupler can be theoretically calculated by:

$$L_c = \frac{\pi}{\Delta\beta} \quad (3)$$

where $\Delta\beta$ is the difference of the propagation constant of the even and odd modes of the structure. Figure 7 shows a plot of coupling length vs separation distance between two slabs of the directional couple. The separation is varied from 0.1*µm* to 1*µm*. As seen in figure.7, the coupling length increases with waveguide separation. The coupling length is found by calculating the phase constant of the TE_0 and the TE_1 modes of the coupled structure (namely β_0 and β_1) from which we can obtain $\Delta\beta$ by using $\Delta\beta = (\beta_0 - \beta_1)$. The coupling length calculated numerically and theoretically are both shown in figure 6. The theoretical and the numerical results have exact match.

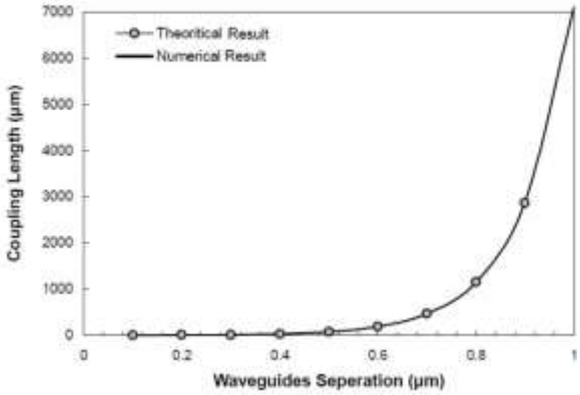

Fig .7: Effect of coupling length at different waveguide separations

V. Wavelength Response of the directional coupler

Wavelength has an effect on a directional coupler with fixed waveguide separations. Figure 8 shows the trasmissivities at port 2 and port 3 of the directional coupler for a range of wavelength from 1 μm to 1.7 μm. The separation between the waveguides is 0.5 μm and the length of the directional coupler is assumed to be 75 μm. Transmissivity at the bus port 2 drops to zero and the transmissivity at the receiver port 3 reach unity at λ = 1.55 μm. This implies a complete coupling between the waveguides at this wavelength. The coupling also occurs at higher wavelengths. The wavelength response of this directional coupler is very broad. So it becomes unsuitable for narrow band operations.

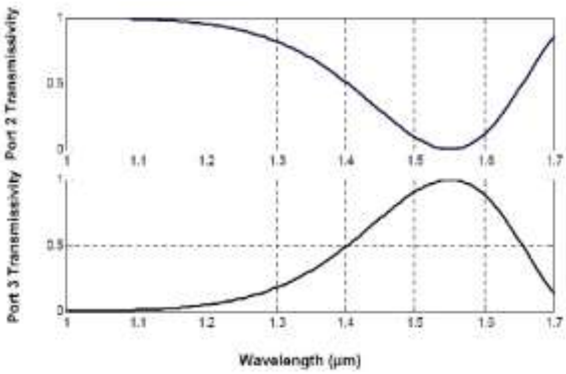

Figure 8: Trasmissivities at port 2 and port 3 of a directional coupler at different wavelengths

VI. CONCLUSION

This paper demonstrate that symmetric parallel slab waveguides over substrate can be used as directional coupler. 100% coupling can be achieved by selecting proper separation between the waveguides.

It also shows that beam propagation method along with coupled mode theory can be effectively used for analysis of waveguides.

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