Optical Analysis of Mushroom-type Traveling Wave Electroabsorption Modulators Using Full-vectorial Finite Difference Method

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***Abstract*-Larger width of P-cladding layer in p-i-n waveguide of traveling wave electroabsorption modulator (TWEAM) results in lower resistance and microwave propagation loss which provides an enhanced high speed electro-optical response. In this paper, a full-vectorial finite-difference-based optical mode solver is presented to analyze mushroom-type TWEAM. The important parameters in the high-frequency TWEAM design such as optical effective index and transverse mode confinement factor are calculated. The modulation response of mushroom-type TWEAM is calculated by considering interaction between microwave and optical fields in waveguide and compared with conventional ridge-type TWEAM. The calculated 3dB bandwidths for ridge-type and mushroom-type TWEAM are about 139 GHz and 166 GHz for 200 µm and 114 GHz and 126 GHz for 300 µm waveguide length, respectively.**

Keywords: Full-vectorial Finite difference method, Traveling wave modulator, Electroabsorption, Mushroom-type TWEAM.

I. INTRODUCTION

The limitation of TWEAM in p-i-n layers is generally restricted by the high microwave propagation loss because of the metal skin effect, highly-loaded capacitance and the high resistance in p-layer [1]. It was found that increasing the width of p-cladding layer with the same i-layer for reduction of the p-i-n waveguide resistance can improve the microwave propagation loss and thus the high-speed electro-optical response [2].

The optical waveguide defines the intrinsic cross-sectional geometry of the TWEAM. The optical wave is guided by the index guiding layers formed by the active layer (absorption region) together with upper and lower cladding layers. The optical effective index defines the optical velocity, which is an important parameter in the high-frequency TWEAM design. Transverse mode confinement factor is also very important since only the confined fraction of the optical mode within the active region can be modulated.

In this paper, a full-vectorial finite-difference-based optical mode solver is used to analyze mushroom-type traveling wave electroabsorption modulator. The discontinuities of the normal components of the electric field across abrupt dielectric interfaces which are known as the limitations of scalar and semivectorial approximation methods are considered. The modulation response of mushroom-type TWEAM is calculated by considering interaction between microwave and optical fields in waveguide and compared with conventional ridge-type TWEAM.

II. THEORY AND ANALYSIS

A. *Full-vector Wave Equation*

The full-vector wave equation can be written in terms of the two transverse filed components e_x and e_y and the differential operators are defined as:

$$\begin{bmatrix} P_{xx} & P_{xy} \\ P_{yx} & P_{yy} \end{bmatrix} \begin{bmatrix} e_x \\ e_y \end{bmatrix} = \beta^2 \begin{bmatrix} e_x \\ e_y \end{bmatrix} \tag{1}$$

$$P_{xx}e_x = \frac{\partial}{\partial x}\left[\frac{1}{n^2}\frac{\partial\left(n^2 e_x\right)}{\partial x}\right] + \frac{\partial^2 e_x}{\partial y^2} + n^2k^2 e_x \,,\; P_{yy}e_y = \frac{\partial^2 e_y}{\partial x^2} + \frac{\partial}{\partial y}\left[\frac{1}{n^2}\frac{\partial\left(n^2 e_y\right)}{\partial y}\right] + n^2k^2 e_y$$

$$P_{xy}e_y = \frac{\partial}{\partial x}\left[\frac{1}{n^2}\frac{\partial\left(n^2 e_y\right)}{\partial y}\right] - \frac{\partial^2 e_y}{\partial x\partial y} \,,\; P_{yx}e_x = \frac{\partial}{\partial y}\left[\frac{1}{n^2}\frac{\partial\left(n^2 e_x\right)}{\partial x}\right] - \frac{\partial^2 e_x}{\partial y\partial x}$$

The non-zero diagonal terms p_{xy} and p_{yx} reveal that the two field components e_x and e_y are coupled, that is, the eigenvalue equation cannot be divided into two independent eigenvalue equations to be solved separately for e_x and e_y. Because of this coupling, the eigen modes of an optical waveguide are usually not purely TE or TM in nature.

B. *OPTICAL WAVEGUIDE STRUCTURE AND FREQUENCY RESPONSE OF TWEAM*

TWEAMs are devices to modulate light waves corresponding to traveling electric fields along the electrode consisting of a transmission line. Because the absorption coefficient of TWEAMs is dependent on the electric voltage, the modulation of optical wave occurs by the absorption change due to modulated electric signals. Fig. 1 shows the principle of operation of TWEAM transmission line [3, 4].

The small signal frequency response for TWEAM can be obtained as follows [2]

$$\left|P_{ac}\right|^2 = \left|\sum_{i=1}^{n}\left(V_i e^{j\frac{\omega}{c_0}n_{o\_eff}(i-1)\Delta l}\,\Delta l\right)\right|^2 \tag{2}$$

where V_i is the modulating voltage in i section. The calculation of the small signal modulation response requires the knowledge

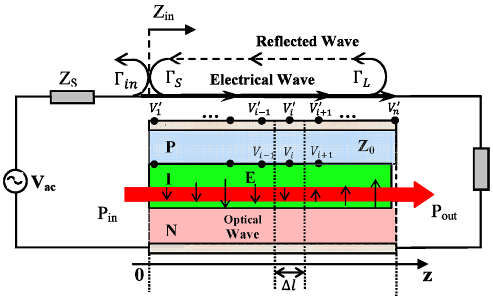

Fig. 1 Principle of operation of TWEAM transmission line.

of the optical index n_{o_eff} and the circuit model elements for calculation of V_i. The circuit elements can easily be extracted from the TWEAM transmission line microwave properties Z_0 (characteristic impedance) and γ (propagation constant), which are obtained via full-wave simulations of the given geometry.

III. RESULTS AND DISCUSSIONS

The waveguide simulation considers 2-dimentional structures. The active region with thickness h_i is composed of MQW. Fig.2 shows the waveguides cross-section and the calculated TE field contour of mushroom-type waveguides for e_x and e_y. The e_x transverse field component is much larger than the e_y component and the mode is treated as approximately TE in nature.

The variation of microwave loss vs. P-layer width is illustrated in Fig. 3. In this analysis, the microwave frequency is assumed to be 80 GHz. As shown in the figure, increasing P-layer width leads to decrease microwave loss. As the P-layer width is increased the junction capacitance increases because of the higher parasitic capacitance.

Fig. 4 shows the calculated frequency response for mushroom-type and ridge-type TWEAM with different lengths and Z_L=25 Ω. In this case, all the waveguide parameters are the same. The overall waveguide loss and velocity mismatch increase as the device length increases. The microwave loss and velocity mismatch reflect the decrease in optical modulation, as shown in the plot. The 3dB bandwidths for ridge-type and mushroom-type TWEAM are about 139 GHz and 166 GHz for 200 μm and 114 GHz and 126 GHz for 300 μm waveguide length, respectively.

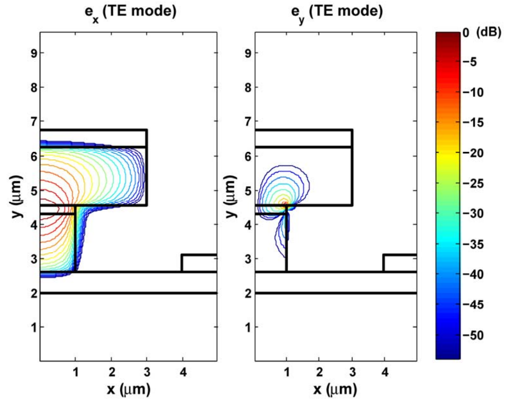

Fig. 2 Transverse electric field components e_x and e_y for the fundamental TE mode of mushroom-type TWEAM.

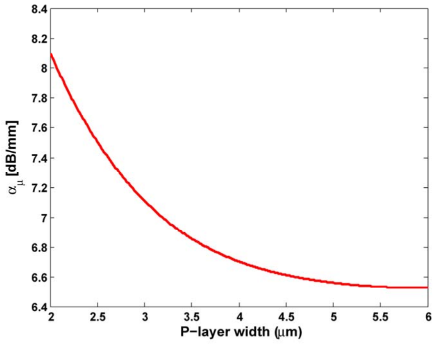

Fig. 3 Microwave loss vs. P-layer width.

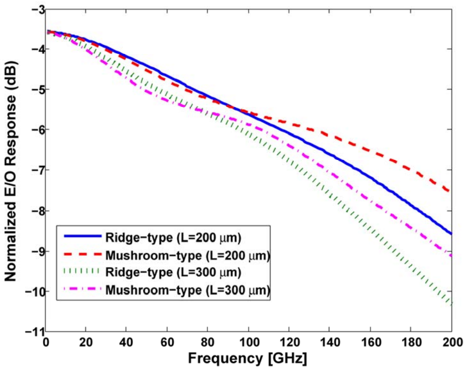

Fig. 4 Frequency response for ridge-type and mushroom-type TWEAM with different waveguide lengths.

IV. CONCLUSION

We have presented a full-vectorial finite-difference-based optical mode solver to analyze mushroom-type traveling wave electroabsorption modulator. The important parameters in the high-frequency TWEAM design such as optical effective index and transverse mode confinement factor were calculated. Then, the modulation response of mushroom-type TWEAM was calculated by considering interaction between microwave and optical fields and compared with conventional ridge-type TWEAM. Numerical values showed higher bandwidth for the mushroom-type TWEAM compared with the ridge-type of the same active region.

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