Peripheral Coupled Waveguide Traveling-Wave Electroabsorption Modulator

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Abstract – **We present the design and preliminary analysis of an efficient and wide bandwidth peripheral coupled waveguide traveling-wave electroabsorption modulator (PCW-TW-EAM), which aims to decouple the optical waveguide and the microwave transmission line. The optical waveguide mode of this device is designed to closely match to a single mode fiber mode for the ease of coupling. The waveguide has presently shown an optical propagation loss of ~2dB/mm at the modulation wavelength which is essential for wide bandwidth and high modulation efficiency to be achieved in the same design. Simulations indicate that equivalent V_π less than 1V over a very large bandwidth can be obtained.**

I. INTRODUCTION

Electroabsorption modulators have been employed more and more often in both analog and digital optical fiber communication applications, and extended to higher operating frequencies. For digital applications, 3.7ps pulse generation at 30GHz by dual-drive electroabsorption modulators has been reported [1]. Furthermore, a 60GHz millimeter-wave band point-to-point fiber-wireless network has been demonstrated [2]. The advantages of TW-EAM include small size, easy integration with other optoelectronic devices, high speed (i.e. large bandwidth) and high modulation efficiency with small drive voltage. TW-EAM utilizes the synchronized modulation of the traveling optical wave in the waveguide by a RF traveling wave in the microwave transmission line. It has been expected to accomplish three objectives. (1) It overcomes the transit time limitation of the P-I-N modulators at high modulation frequencies. (2) It overcomes the RC electrical bandwidth limitation of the lumped element EAM driven by a RF source because the impedance of properly terminated microwave transmission line is a constant. (3) It allows long interaction length to achieve high modulation efficiency. Using low impedance matching, TW-EAM with a 40GHz bandwidth has been reported for a 150μm long device [3]. A bandwidth of 43GHz has been measured for TW-EAM with integrated termination resistor [4]. However, the insertion loss of the modulators has been high, and the optical saturation power of the modulators is expected to be in the order of 10dBm.

It was pointed out in existing analysis, [1]-[7], that the frequency response of a TW-EAM is commonly limited by three factors:

1) Impedance mismatch: Normally the microwave transmission line impedance of the existing TW-EAM is much smaller than 50Ω (~20-30Ω). The impedance mismatch with the driving circuit and the termination load will cause reflections at both source and termination ends. The optical wave will be modulated by not only the forward microwave but the reflected backward microwave as well.

A solution is to increase the EAM transmission line impedance by increasing the inductance per unit length, L, or reducing the capacitance per unit length, C [2].

2) Mismatch between the microwave phase velocity and the optical group velocity limits the effective interaction length: For a typical TW-EAM the velocity of the microwave phase (phase velocity index of 6-10) is normally smaller than that of the optical group (group velocity index of ~3.5). We can increase the microwave phase velocity by reducing the inductance and the capacitance per unit length [2], [5].

3) Microwave attenuation limits also the effective interaction length: The microwave attenuation increases at high frequency. This causes the modulation efficiency to drop at high frequency.

Changing the inductance leads to the opposite effect in impedance matching and velocity matching. A reduction of capacitance per unit length can increase the microwave impedance and phase velocity, which will improve both the impedance matching and velocity matching. This is the commonly adopted approach [1]-[3].

However, existing TW-EAM designs use a material structure in which the intrinsic region is shared by the optical waveguide and the microwave transmission line. Such a structure has conflicts in design requirement. (1) As the intrinsic layer thickness is reduced to increase the electric field for the EA effect of a given applied voltage, it increases the capacitance per unit length of the microwave transmission line, (2) As the size of the optical waveguide mode is increased to obtain high coupling efficiency to fibers, it requires a wider intrinsic region W that increases the microwave capacitance per unit length.

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For efficient coupling even to a lensed fiber, W of the order of 2 μm is required. It is difficult to package a lensed fiber coupled to a modulator, it will be more desirable to couple to a cleaved single mode fiber that requires even much larger optical mode size. The 1-2 μm waveguide width results also in a large residual optical propagation loss in the optical waveguide, which can be as high as 10-20dB/mm. (3) The absorption coefficient of the EA layer at the dc bias voltage, α_{bias} times its optical confinement factor Γ, and the residual propagation loss determine the optimum length L of the traveling wave interaction, this large amount of optical propagation loss limits the device length to around 200μm, which limits the modulation efficiency (for analog applications) or affects the extinction ratio (for digital applications). (4) Existing TW-EAM typically has an optical saturation power of 10 to 20mW. For the same electric field screening effect produced by the photo-generated carriers in the EA region, the saturation power of the modulator is increased inversely proportional to Γ.

The peripheral coupled waveguide TW-EAM (PCW-TW-EAM) concept has been conceived at UCSD [8]. In this scheme, the microwave transmission line, including the EA region, is placed only peripheral to the optical waveguide mode, in its evanescent field. Therefore the design of the microwave transmission line will affect as little as possible the optical mode. The microwave waveguide can then be designed to be very narrow and with small intrinsic thickness to yield the desirable impedance, phase velocity and microwave attenuation. The optical waveguide will have large mode size to match to the single mode fiber mode, small residual attenuation, and low Γ to obtain high optical saturation power.

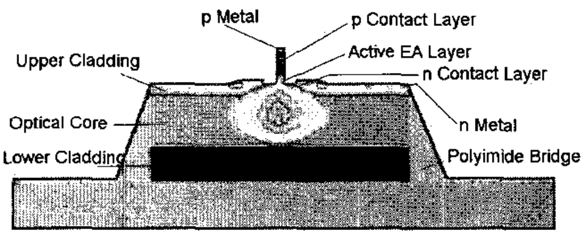


Fig. 1. Schematic Cross Section of a PCW-TW-EAM

A first generation design of PCW-TW-EAM is illustrated in Fig.1. The optical waveguide structure includes an upper cladding layer, optical core layer and lower cladding layer. By etching down a very thin upper cladding layer, we can form a ridged waveguide with a relatively wide mesa (~10μm) that has an optical waveguide mode matched to that of a single mode fiber. The active EA structure is situated at the peripheral region of this optical mode. A very narrow top mesa is formed on top of this EA layer so that the center electrode of the microwave transmission line is on top of this narrow mesa. The electric field profile across the active absorption layer leads to electroabsorption.

A consequence of this peripheral coupled EA waveguide design is the reduction of the confinement factor in the active EA layer. This allows the high optical power input to the modulators without saturation. This high saturation power allows us to improve the link gain. Furthermore, the insertion loss of the PCW-TW-EAM can be reduced significantly by having large coupling from/to fiber and low propagation loss. Our simulation and experimental results show that this structure can reduce the optical propagation loss to at least 1-2dB/mm, and the coupling from/to fiber can be as high as 95%. All these contribute to improvement of the link gain. With this, we can still ensure low equivalent V_π by having the waveguide length in the order of a millimeter to have enough optical/microwave interaction length.

II. PCW-TW-EAM ANALYSIS

For TW-EAM, it is very important to optimize the RF link gain, which is defined as:

$$G_{RF} = (P_{opt} \cdot \eta_{ins} \cdot \frac{\partial T}{\partial V} \cdot \eta_{det})^2 \cdot R_{in} \cdot R_{out} \quad \ldots(1)$$

In (1), η_{det} is the detector responsivity. R_{in} and R_{out} are input and output impedances. Three main factors that can be improved at the modulator are optical saturation power, optical insertion loss η_{ins}, and slope efficiency $\partial T/\partial V$. From the analysis PCW-TW-EAM can provide better performance than conventional EAM in all three factors.

Saturation is mainly caused by the screening effect at high optical power levels, and photo generated holes in the active EA layer cannot escape quickly. An approach to increase the saturation power is to reduce the optical intensity at the EA layer so as to reduce photo generated current density. In the PCW design the confinement factor in the EA layer can be as small as ~2%, whereas it is 20-30% for a conventional TW-EAM.

The insertion loss of an EAM is attributed to the coupling loss at the two facets and the waveguide propagation loss α_0. Conventional waveguide design typically has a 10-20 dB/mm propagation loss. In the PCW design, we improve the insertion loss by improving both the coupling and the propagation loss. The wide waveguide width in the PCW is advantageous for low scattering loss, especially when the mode is largely in the low doped region that is buried below the narrow mesa. In additional, the placement of the EA layer at the peripheral region of the waveguide implies very small attenuation by the p-doped material.

The wide optical waveguide in the PCW design also enhances the butt coupling efficiency to lensed single mode fiber mode. This is confirmed using R-soft BeamProp simulation code.

Using a 12 μm wide peripheral coupled waveguide, the optical insertion loss of PCW shown in Fig. 2 is simulated with AR coated facet as a function of waveguide length and the results are depicted in Fig.2. Lensed fibers with 3μm spot size is used to couple to the PCW, with closed to 95% coupling efficiency per facet.

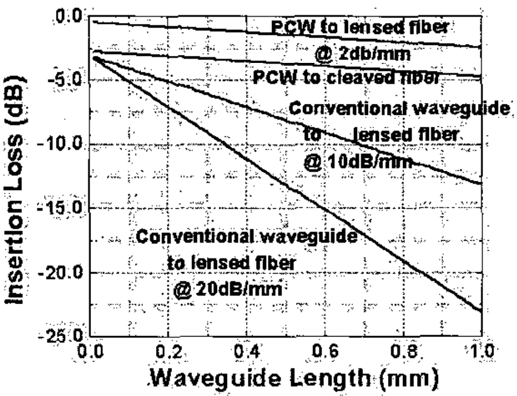


Fig. 2. Optical insertion loss vs. Waveguide length

Direct coupling the PCW to single mode fiber can simplify the package design and ensure the coupling stability. From simulation the coupling coefficient of the above PCW to a cleaved single mode fiber is 73%, in agreement with mode measurement in III.

For EAM, the slope efficiency is defined as

$$\frac{\partial T_{norm}}{\partial V} = -\frac{\Gamma L}{d_i} e^{-\Gamma L\alpha_{bias}} e^{-\Gamma L\Delta\alpha_{eff}} \cdot \left.\frac{\partial\Delta\alpha}{\partial F}\right|_{bias} \cong -\frac{\Gamma L}{d_i} e^{-\Gamma L\alpha_{bias}} \cdot \left.\frac{\partial\Delta\alpha}{\partial F}\right|_{bias} \quad ...(2)$$

where Γ is the confinement factor in the EA layer, L is the length of modulation region, d_i is the EA layer thickness, α_{bias} is the absorption coefficient at the bias point, and $\Delta\alpha_{eff}$ is change in absorption due to the RF modulation, it is highly dependent on the nature and quality of the materials used for electroabsorption [9].

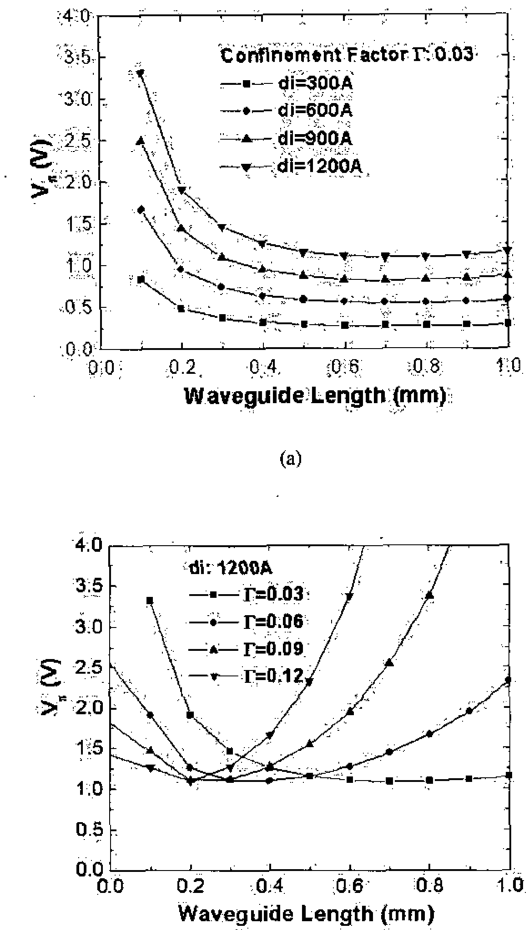
Slope efficiency is typically represented in term of "Equivalent V_π" which is π/2 times the inverse of slope efficiency. We simulated the case of InAsP/InGaP strained multiple quantum well in the EA region, and used the material data from [9], namely,

$$\alpha_{bias} = 463.0cm^{-1}, \left.\frac{\partial\alpha}{\partial F}\right|_{bias} = 217.6*10^{-4}V^{-1},$$

to calculate the equivalent V_π as a function of d_i (Table 1):

Table 1. Minimum V_π vs. Active EA layer thickness d_i

di (A)	1200	900	600	300
$V_{\pi min}$ (V)	1.09	0.82	0.55	0.27



(a)

(b)

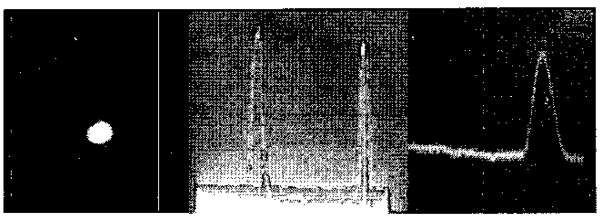
Fig. 3. V_π vs. Waveguide length at (a) different d_i's (b) different Γ's

Fig. 3a depicts the equivalent V_π as a function of waveguide length for different d_i for a PCW with a Γ of 0.03. Small V_π value is achievable for waveguide length less than 0.5 mm. As shown in Fig. 3b, a benefit of PCW is that at small Γ it is more tolerant to waveguide length for minimum V_π.

From the above discussion we see that PCW TWEAM can have high saturation power, low insertion loss, and low V_π properties, provided that we use small confinement factor in EA layer and small EA layer thickness d_i. The result is a high frequency EAM with high RF link gain. In contrast, in conventional EAM waveguide the center of the optical mode is close to the active EA layer with large confinement factor for efficiency. But it is not optimal for high power operation.

III. EXPERIMENT TO DEMONSTRATE THE LOW PCW LOSS

Experimental verification is done to confirm that this PCW-TW-EAM has a waveguide mode similar to a fiber mode as well as low propagation loss. The sample tested has InGaAsP (Eg~0.80eV) / InGaAsP (Eg~0.99eV) MQW EA layer. The thickness of this layer is about 0.1μm which can give a V_π as low as 0.91V for a modulator length of 700μm. The optical core layer is 1.2μm thick InGaAsP (Eg~1.12eV).



(a) (b) (c)

Fig 4a, waveguide mode shape recorded by vidicon; b, intensity profile along horizontal (left) and vertical (left) directions; c, horizontal intensity profile along the mode center.

The mode measurement for this structure shows single mode profile with 1/e mode size of 11μm by 7μm (Fig. 4). We found close agreement between simulated results and measurement results, in terms of mode structure, shape and size.

As mentioned, PCW-TW-EAM requires a long waveguide to ensure sufficient electrical-optical interactive volume for high RF link gain so propagation loss becomes a concern. Waveguide cut-back method is used to evaluate the loss per unit length of PCW [10]. Many optical waveguides are measured to reduce the statistical variations due to differences in cleaving.

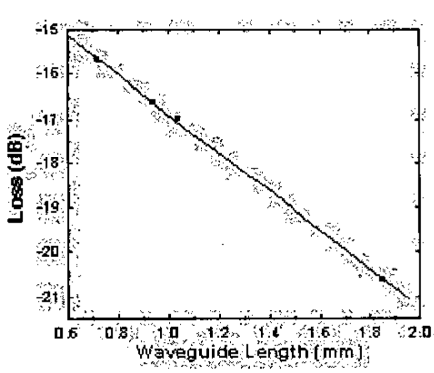


Fig. 5. Insertion loss measurement of waveguide at λ=1.52 μm

Fig. 5 shows the propagation loss at 1520nm, which is the exciton resonance wavelength of the quantum wells. The loss is 4.39dB/mm. At the operation wavelength of 1566 nm the loss is measured at 2.48dB/mm.

The initial PCW-TW-EA waveguide modulators made show an insertion loss of 15dB for a 910μm long device without AR coating using lensed fiber coupling, and 19dB using cleaved fiber coupling. For these devices, a 20mW optical saturation power, corresponding to 1-dB RF compression point, is measured.

IV. CONCLUSION

The RF performance advantages of a peripheral coupled waveguide TW-EAM concept are described. High RF link gain is expected by using small EA layer thickness and wide optical waveguide ridge width. Experiment validation of the low propagation loss in the waveguide structure is obtained.

Acknowledgment: This work is supported by DARPA, AFRL, and NSF-ANIR program. The authors acknowledge Profs. W.X. Chen and L.S. Yu at University of California, San Diego for their help in measurement.

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