Novel Designs and Modeling of Electro-Absorption Modulators

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Abstract: This paper describes the modeling and design of a novel Electro-Absorption Modulator (EAM) based on a Multi-Mode Interference (MMI) waveguide that utilizes the combination of optical absorption and mode interference effects to improve the extinction ratio of the EAM. In addition, modeling and design of an Evanescent Coupler based EAM with improved performance based on a similar dual extinction principle is presented. Feasibility of fabrication of such devices is discussed.

1. INTRODUCTION

Electro-Absorption Modulators (EAM) are among the most important components of high-speed Wavelength Division Multiplexing (WDM) optical communications devices and systems. EAM are widely used as stand alone devices [1, 2], as part of Electro-Absorption Modulated Lasers (EML) [3-5], and as part of multi-component Planar Lightwave Circuits (PLC) [6, 7]. Since the first proposed EAM based on optical absorption of light in a bulk structure more than two decades ago [8], advances have been made in modulator performances such as extinction ratio, polarization insensitivity, and bandwidth. Multiple Quantum Well (MQW) structures in the active region have become the structures of choice for EAM due to their improved extinction and reduced polarization sensitivity through applied strain [9, 10]. While lumped electrode devices have demonstrated performance at rates of 10 Gb/s and higher [10, 11], the more recent traveling wave electrode devices have been shown to work at rates of 43 Gb/s and above [12-14].

Compared to the other popular class of modulators, Mach Zehnder based Lithium Niobate modulators, EAM offer a number of advantages such as low voltage drive, small size, high bandwidth, and potential for monolithic integration with other optoelectronic devices. For good performance of the modulator, a high extinction ratio is necessary. The vast majority of all designed and fabricated EAM employ a straight section of single-mode waveguide where optical absorption takes place under a bias voltage. In this work, we present a new approach for EAM design, based on the use of 1x1 Multimode Interference structures (MMI). We demonstrate improvements in the extinction ratio of the EAM through a combination of electro-absorption and optical interference effects in the MMI structure. The increase in extinction ratio is not accompanied by an increase in insertion loss or chirp, nor does it lead to higher drive voltage or lower bandwidth. The MMI based EAM devices can be easily fabricated using current InP-based fabrication technologies and, in fact, allow for less stringent tolerance requirements than currently used for traditional EAM devices. We also present new modeling of Evanescent Coupler based EAM design. This design was previously suggested by Wood [9]. Modeling results for InP-based EAM devices are presented, and the feasibility of manufacturing such devices is discussed.

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2. DESCRIPTION OF THE PROPOSED EAM DESIGNS

The proposed designs are based on the ridge waveguide structure commonly used for single-mode waveguide InGaAs on InP EAM. The waveguide grown on an InP semi-insulating substrate consists of an n-doped under cladding, a bulk insulating core layer or an insulating core layer containing a Multiple Quantum Well structure (MQW modulator), and a p-doped upper cladding. The indices of refraction we choose for these layers are 3.17 for the cladding and 3.42 for the core [15]. Typical dimensions for a single-mode waveguide in this material system are width 2μm, and height 4μm. Fig. (**1**) illustrates the geometry and refractive index map of the single-mode waveguide.

Various single-mode optical waveguides can be directly coupled to the modulator if they have similar mode size and shape. For coupling light from standard single mode fibers, typically mode converters are used. Lens tip fibers have also been used to improve mode matching and therefore reduce the coupling loss at the fiber-modulator interfaces.

We consider the case of coupling directly from single-mode waveguide which has a mode size and shape similar to that of the modulator waveguide. Optical absorption is introduced in the waveguide by applying a dc bias voltage between an electrode deposited on top of the waveguide, and the semi-insulating substrate. Typically the electrode has a rectangular shape extending over the entire width and length of the waveguide, the latter being several hundreds of micrometers. The narrow and long shape of the electrode is not optimized however for maximum electrical modulation bandwidth. More recently, improvements in the electrical bandwidth have been demonstrated with a Traveling Wave (TW) configuration for the electrode [12]. We consider a lumped electrode design, and show how special designs of the waveguide and the electrode result in improvements in

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the extinction ratio of the modulator. The proposed designs can be used in conjunction with a TW configuration to benefit the modulation bandwidth of the EAM.

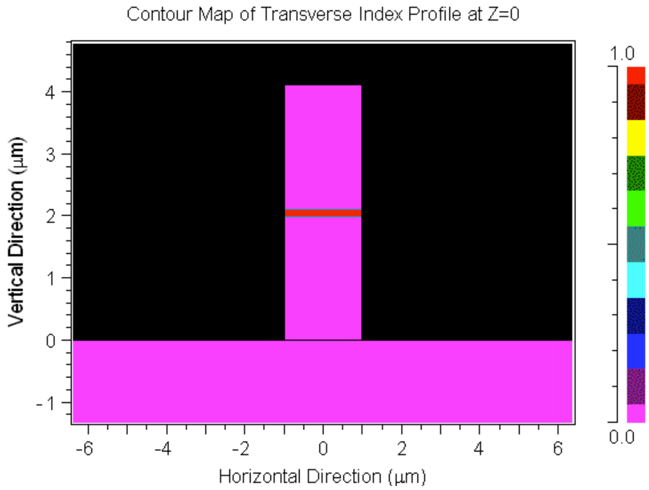

Fig. (1). Geometry and refractive index map for single-mode ridge waveguide based on InGaAs on InP material system.

2.1. Multi-Mode Interference Based EAM

The proposed MMI based EAM modulator can be built in two versions. The first design represents a 1x1 MMI coupler that consists of a single-mode straight input waveguide, a wide straight multi-mode section, and a single-mode straight output waveguide. Fig. (**2**) depicts conceptually such a design. The waveguide type is a ridge waveguide, as shown in Fig. (**1**). The insulating higher refractive index waveguide core can be either a bulk absorption layer, or contain an MQW structure, which allows for higher extinction ratio and reduced polarization sensitivity [9, 10]. An electrode is placed on top of the waveguide to allow for application of an electric field between electrode and the electrically conductive substrate.

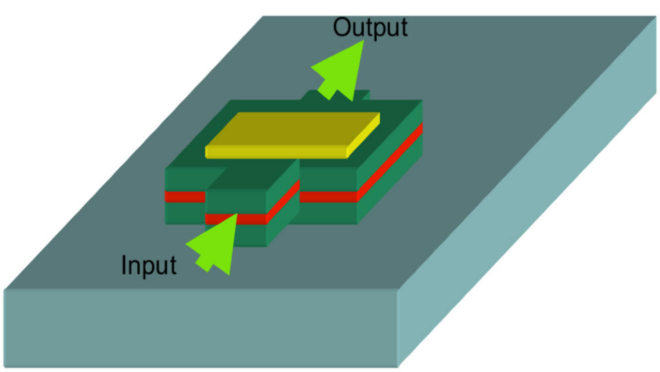

Fig. (2). MMI based EAM with single-mode sections at input and output of the multi-mode section.

This device can be fabricated using the photolithographic InP-based ternary (InGaAs) or Quaternary (InGaAsP or InGaAlP) technique of choice currently used for making conventional straight single-mode waveguide based EAM. Both the width and the length of the wide multi-mode section are not critical as long as the mode interference pattern at the point where the light enters the output waveguide produces a single maximum which ensures efficient coupling of light. This means that there can be multiple different designs of the wide section, i.e. it can be a 2-mode structure, 3-mode structure, 5-mode structure, etc. In fact having a wider structure and therefore wider electrode with lower aspect ratio (length/width) can be very beneficial for more efficient RF impedance matching. The principle of operation of such a device is similar to the conventional EAM. When there is no voltage applied, the device will act like a conventional 1x1 MMI coupler and, if designed properly, will transfer with minimal loss light from the input waveguide to the output waveguide. When reverse bias is applied, the absorption curve of the p-n junction *vs* wavelength shifts and the device absorbs light. However, due to the changes in absorption characteristics, i.e. in the imaginary index of refraction, the real part of the index of refraction also changes, by 3-5% or even more [9]. Because of this change the interference of the modes in the MMI region is also changed, and therefore the efficiency of the coupling into the output waveguide is further reduced.

Furthermore, in addition to these two phenomena working together to increase the extinction ratio or, alternatively, reduce the driving RF voltage necessary to achieve a certain extinction ratio, we propose one additional mechanism to increase the extinction even more. Any asymmetry of the electrode shape or its placement on top of the wide section of the device will have an additional effect in distorting the field symmetry and therefore further distorting the interference of the light modes entering the output waveguide. This will have an additional extinction effect. In less measure, the small imperfections due to fabrication tolerances will also become beneficial to device performance characteristics. It is also worth noting that unlike many other single-mode photonic devices, MMI couplers generally tend to be easy to fabricate because they are relatively insensitive to fabrication tolerances. Small fluctuations/fabrication tolerances in waveguide index of refraction or size of the MMI structure tend to affect the MMI performance in a very limited way.

The second version of the MMI based EAM consists of only the wide multi-mode section of the structure. The input and output waveguides or fibers can be later aligned (actively or passively) and bonded to the MMI EAM structure. Active alignment tends to be expensive and therefore is generally not desired. Such a device, however, may be used as a component placed on the hybrid integration substrate. In this case having a wide multi-mode structure can be beneficial, because misalignment of the input waveguide with respect to the MMI structure can be compensated by the intentional misalignment of the output waveguide with respect to the MMI structure.

2.2. Evanescent Coupler Based EAM

This design was suggested by Wood [9], but has always been considered unrealistic due to the tight fabrication tolerances. Light inside InP-based waveguides, unlike single-mode fibers, is tightly confined due to the very large refractive index difference between the waveguide core and cladding. In horizontal direction InP waveguides usually don't have any cladding layer, i.e. air becomes the cladding, and the index of refraction difference becomes very large. Therefore for the short, 200μm – 500μm typical, length of many InP devices, an evanescent directional coupler based on two parallel identical waveguides with a narrow gap between them requires a gap on the order of 0.1-0.2 μm. This very small gap has been difficult to realize using older technology. However with continuous improvements in the InP fabrication technology, fabrication of evanescent directional couplers using III-V technologies is possible today and, we believe, will become relatively inexpensive in the very near future. Therefore we present the design of Evanescent Coupler (EC) based EAM.

Conceptually, the advantage of using the EC EAM is almost identical to the MMI EAM. This device will also combine the absorption of the light with the reduced mode interference based coupling into the output arm of the EC EAM. Fig. (**3**) presents the conceptual design of the EC EAM.

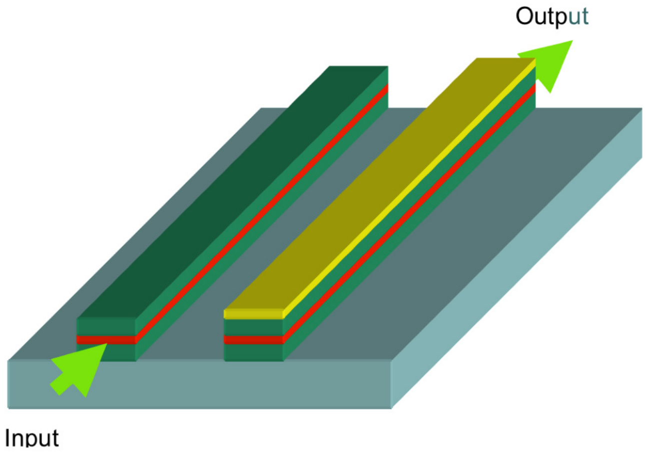

Fig. (3). EC based EAM. A thin film electrode is placed on top of the output waveguide.

The structure of the input and output waveguides of the EC EAM is identical to the structure of the conventional straight single-mode InP-based EAM. The electrode is placed on top of the output waveguide. When no voltage is applied to the electrode, the device acts like a conventional evanescent coupler and, if designed properly, transfers with minimal loss light from the input waveguide to the output waveguide. When reverse bias voltage is applied, the output arm of the coupler absorbs light. Additionally, much like in the previously described MMI EAM, the mode interference results in incomplete transfer of light to the opposite arm. Evanescent directional couplers tend to be very sensitive to any changes in the fabrication parameters/tolerances, including geometry and index of refraction. They are also extremely sensitive to any asymmetries, i.e. if the waveguides are not identical the coupling efficiency sharply declines. When voltage is applied to the output waveguide the real part of the effective refractive index changes and therefore the waveguides become different which decreases the coupling efficiency, i.e. increases the extinction ratio, or alternatively, decreases the driving RF voltage necessary to achieve a certain extinction ratio.

3. MODELING AND RESULTS

Modeling was performed using the commercially available R-Soft BeamPROP package. The multi-layer waveguide structure used for modeling the conventional single-mode waveguide EAM, and the MMI and EC based EAM devices introduced in this paper, is a single mode ridge waveguide of width 2 µm, height 4 µm, and refractive indices 3.17 for the cladding, and 3.42 for the core layer. The core layer contains the MQW region, made of ternary or quaternary materials such as InGaAs, InAlAs, InGaAsP or InGaAlAs, with a typical thickness of 0.1 µm for InP applications. The width of the single-mode waveguide has been chosen to be 2 µm in order to maintain the single mode regime of light propagation. Such width is common in commercially available stand alone and integrated EAMs. For the multi-mode section of the MMI based EAM, the width of the multi-mode waveguide is 10µm, as illustrated in Fig. (**4**). The model used to study light propagation in all the structures is the 3D, Semi-Vectorial model, with simulations for both the TE and the TM polarizations.

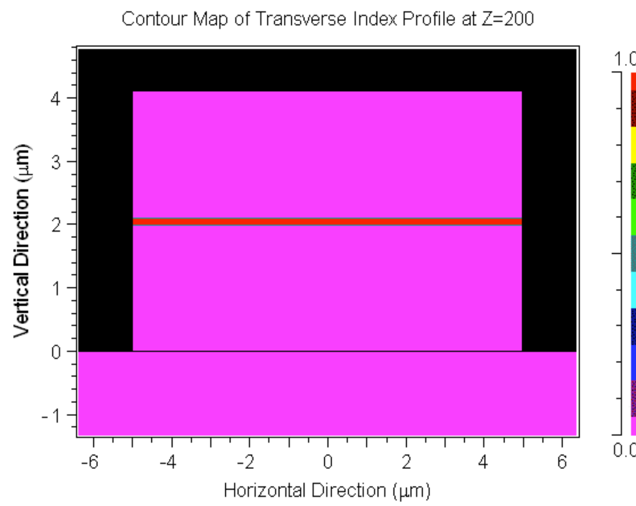

Fig. (4). MMI section of the EAM: width w = 10µm, height h = 4µm, substrate, under clad and upper clad index n_s = 3.17 (InP), core index n_c = 3.42. MQW region thickness 0.1 µm.

3.1. Modeling of MMI Based EAM

Fig. (**5**) presents the simulation results for the transparency, or low loss, state of the first version of MMI EAM in TE polarization, where no voltage is applied to the electrode.

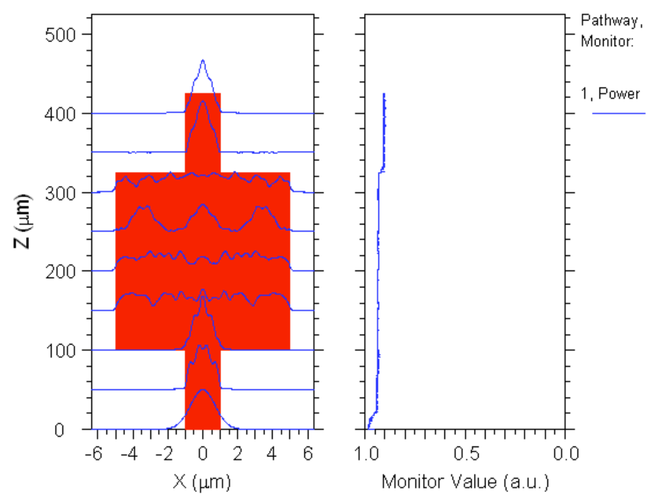

Fig. (5). Light propagation in MMI EAM when no voltage is applied to the electrode. Length of the multimode section is 245 µm, total device length is 445 µm.

As seen in Fig. (**5**), there is a small insertion loss at transparency, about 0.9dB, which is attributed to mode mismatch coupling loss at the entrance and exit of the device, and mode mismatch loss when light enters the single-mode output waveguide from the wide multi-mode section. Such behavior is very typical in all MMI devices and can be further minimized by optimal design.

An important parameter for a stand-alone modulator is the Polarization Dependent Loss (PDL) in the transparency state. For the proposed MMI based EAM the PDL at transparency, obtained after running the TM polarization simulation, is 0.1 dB, appropriate for good performance of the device.

When voltage is applied to the electrode, the absorption coefficient of the modulator increases, and light is absorbed predominantly by the MQW region of the waveguide core. This mechanism by which conventional single-mode waveguide EAM perform allows for extinction ratios of 3dB and higher depending on the voltage applied. As described by the Kramers-Koenig relations, in addition to the absorption coefficient change, the real part of the refractive index also changes when voltage is applied to the electrode. The proposed MMI EAM and EC EAM devices take advantage of this change in the real index of refraction to increase the extinction of the modulator without any other performance adverse effects or increase in cost.

To show how each mechanism contributes to the extinction of the modulator we ran simulations with each mechanism being active separately. Results are shown in Fig. (**6a**,**b**). Fig. (**6a**) presents the absorption of light in the wide section of the MMI structure due to the first mechanism only, while Fig. (**6b**) presents the reduction in light transmission due to mode mismatch created by the change in the real part of the refractive index, as well as to using an asymmetric shape of the electrode on top of the wide section. The latter represents a novel design we are proposing to further optimize the extinction of the modulator, one illustration of this design being shown in Fig. (**7**).

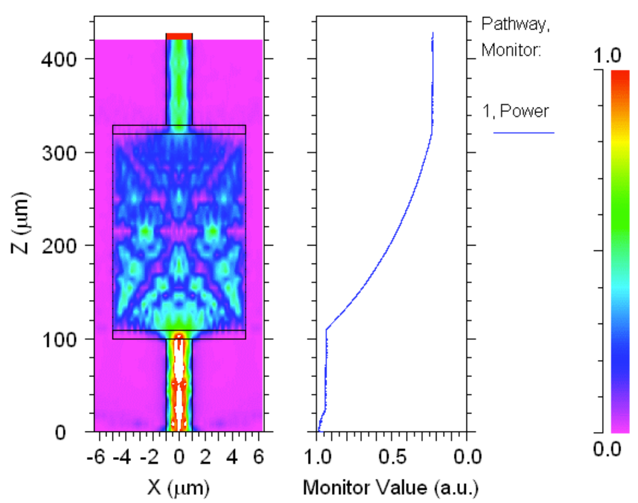

Fig. (6a). Effect of absorption only on light transmission through device.

When acting separately, each mechanism is achieving an extinction ratio of about 4-5 dB. In practice however, the extinction in this device will be provided by both of these mechanisms combined. Fig. (**7**) shows the simulation of MMI EAM device with both effects combined, which achieves a much better extinction, about 14 dB. It is worth noting that the increase in the extinction ratio is achieved without any drawback.

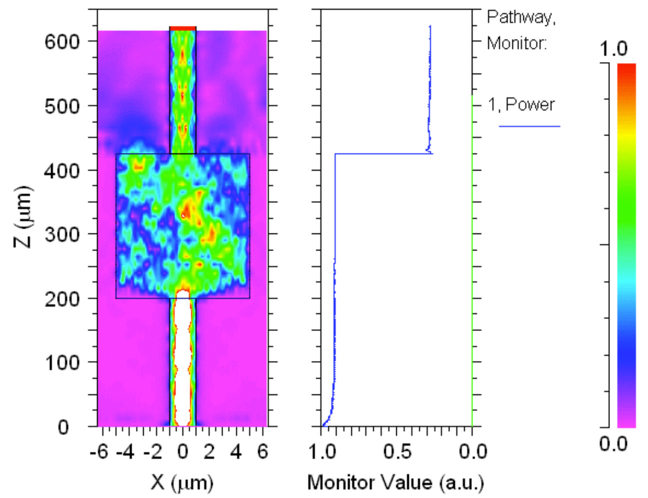

Fig. (6b). Effect of mode interference only on light transmission through device.

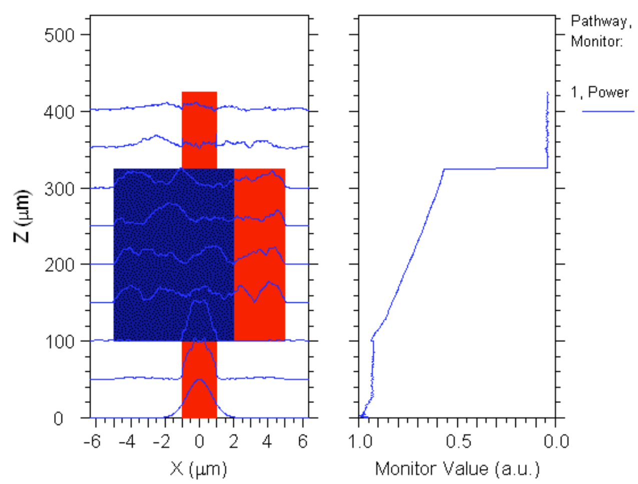

Fig. (7). Light transmission through device with asymmetric electrode when both absorption and mode interference are taken into account.

To further study the performance of the modulator in terms of insertion loss, extinction ratio and PDL, we ran simulations where we varied the width of the electrode shown in blue in Fig. (**7**), and also the value of the real refractive index of the core. The electrode width was varied between 6 and 10 μm, and the real refractive index was varied between 3.30 and 3.54, corresponding to a 5% maximum relative index difference from the 3.42 value of the core refractive index in the absence of applied voltage, as suggested by Wood [9].

Fig. (**8a**) shows the extinction ratio of the MMI EAM in average polarization *vs* the real refractive index of the MQW layer for different widths of the asymmetric electrode, and Fig. (**8b**) shows the extinction ratio *vs* the PDL in the extinc-

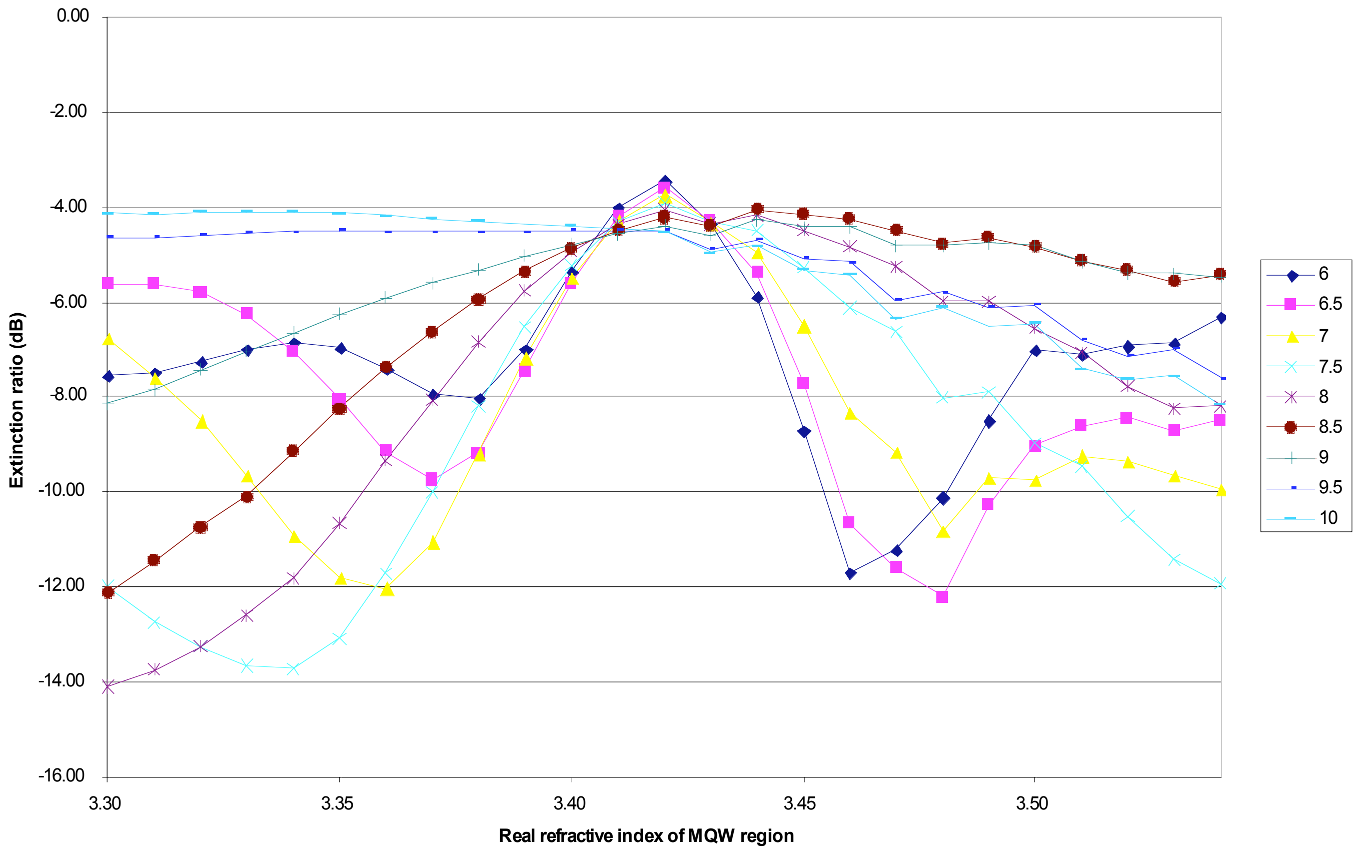

Fig. (8a). Extinction ratio *vs* MQW region real refractive index for various widths of the asymmetric electrode. With no voltage applied to the electrode the core index is $n_c = 3.42$.

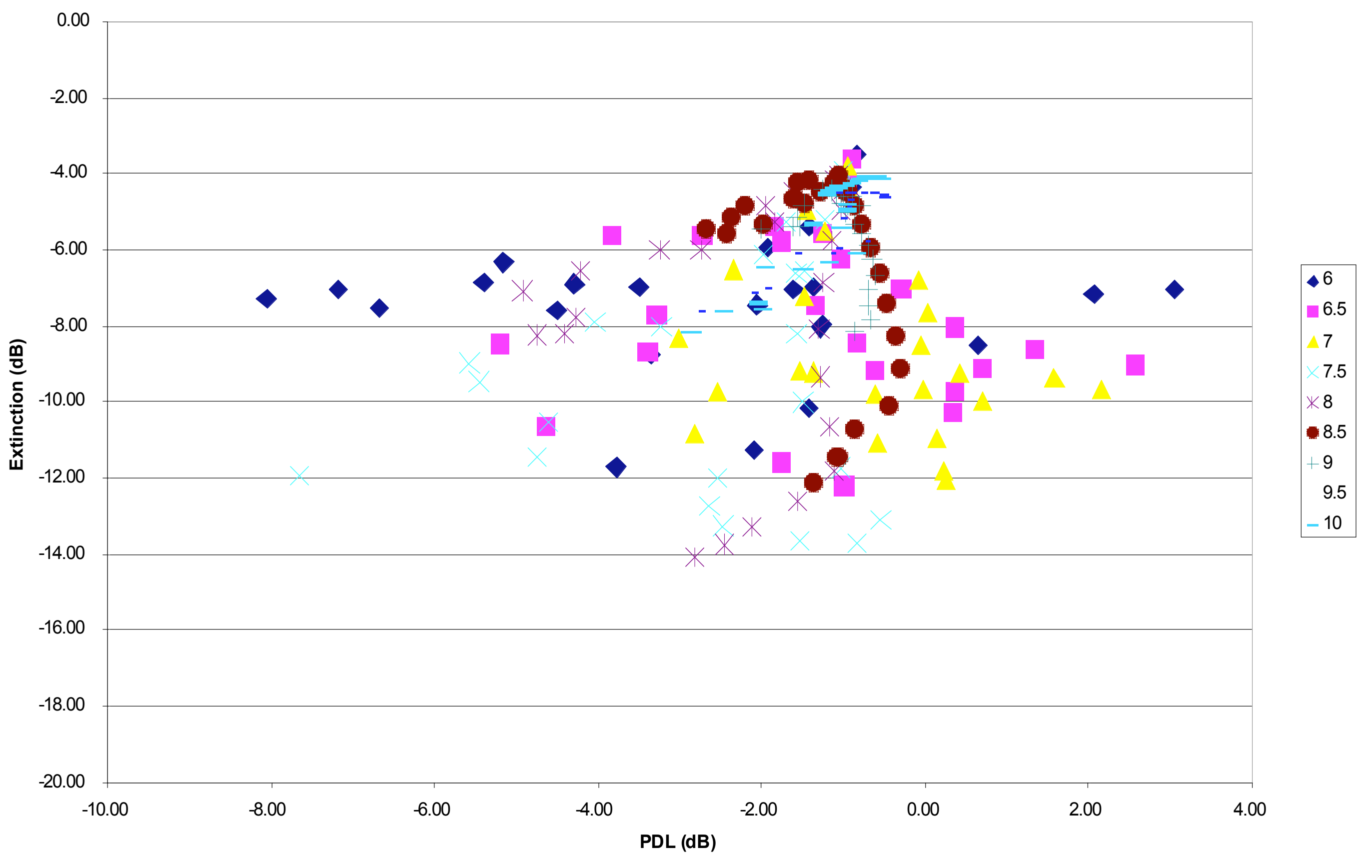

Fig. (8b). Extinction ratio *vs* PDL for various widths of the asymmetric electrode.

tion state of the device. The two figures can be used to choose an optimum design of the electrode resulting in the highest extinction ratio accompanied by low PDL in the extinction state for the modulator. For example, 14 dB extinction with a low PDL of 0.8 dB can be obtained with a heater of width 7.5 µm, requiring only a 2.3% relative change of the real refractive index with applied voltage.

For comparison, a conventional single-mode waveguide EAM with similar length of 445 µm and the same bias voltage applied obtains 5.5dB of extinction accompanied by 1.8dB of PDL. The improved extinction ratio of the MMI EAM does not increase the cost of the device, and the device is more fabrication tolerant. Another advantage of the MMI EAM is that it can allow for a higher saturation threshold *vs* the narrower single-mode waveguide, as discussed by Devaux *et al*. [10].

3.2. Modeling of EC Based EAM

The second proposed device is an Evanescent Coupler (EC) based EAM, as illustrated in Fig. (**3**).

Fig. (**9**) shows the simulation of the light propagation in the EC EAM, when only the absorption in the output waveguide is taken into account, while any changes in the coupling efficiency due to change in the real part of the refractive index of the output waveguide when voltage is applied is ignored. We intentionally examine the case when absorption only provides roughly 3dB extinction of light.

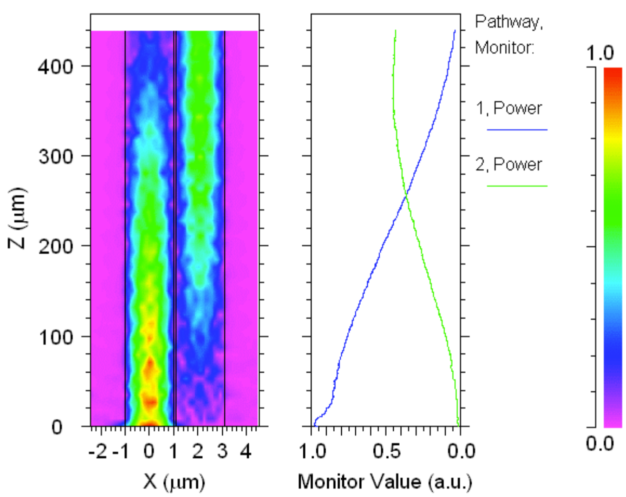

Fig. (9). Light transmission through the EC EAM when only light absorption is taken into account.

However, with only 2% relative change in the real part of refractive index taken into account, the combined extinction ratio of the device goes up to 17dB. Fig. (**10**) shows the output of both waveguides (green line represents the output of the output waveguide) *vs* the real index of refraction in the MQW region of the output waveguide.

CONCLUSIONS

We believe the proposed 1x1 MMI-based and Evanescent Coupler-based, Electro-Absorption Modulators have a potential to outperform and substitute conventional straight single-mode waveguide based Electro-Absorption Modulators. The proposed devices can be used as stand alone modulators and, more importantly, in integrated devices such as Electro-Absorption Modulated Diode Lasers (EMLs) and more complex multi-component Planar Lightwave Circuits (PLCs). Proposed MMI based EAMs can be easily fabricated today using exactly the same III-V (InP) technologies used for conventional EAMs. Fabrication of EC based EAMs is possible but challenging with current fabrication tolerances, but is expected to be feasible and relatively inexpensive in the near future.

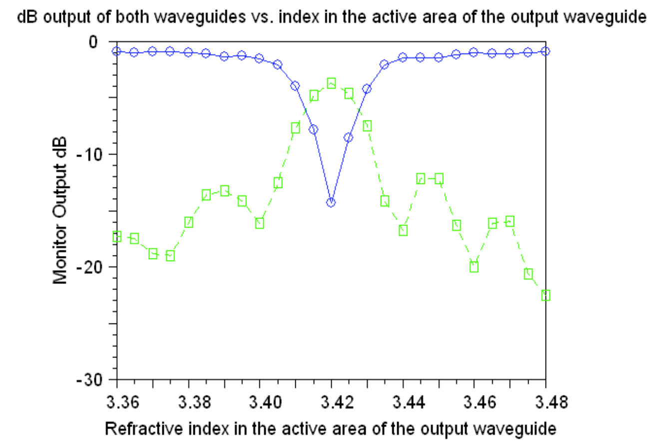

Fig. (10). Insertion loss at the modulator exit *vs* output waveguide core real refractive index. With no voltage applied to the electrode the output waveguide core index is $n_c = 3.42$.

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