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Design of 2 μm Wavelength Polarization Mode Controllers

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***Abstract*—A single-slot waveguide for transverse electric (*TE*) to transverse magnetic (*TM*) mode conversion operating at wavelengths around 2 μm is proposed based on an InGaSb/AlGaAsSb quantum well structure. The polarization mode convertor has a deep-etched ridge waveguide and a single shallow-etched slot, and can be fabricated in a single stage of dry-etching. The dependence of polarization conversion efficiency on slot width, slot position, slot depth and waveguide length was investigated, and a design that was insensitive to fabrication tolerances was identified. A *TE-TM* mode conversion efficiency of more than 97% can be obtained in a 2141-μm-long waveguide.**

Keywords—polarization convertor, slot waveguide, InGaSb/AlGaAsSb

I. Introduction

Controlling and manipulating the state of polarization of light has become increasingly desirable for many applications including metrology, polarimetry and polarization mode division multiplexing. Integrated optic devices offering continuous polarization control require waveguide sections that convert transverse electric (*TE*) to transverse magnetic (*TM*) modes and vice-versa. A wide range of such waveguide-based devices for controlling polarization has been established, based on the principle of waveguide mode-beating [1] and mode evolution. However most of these designs are focused on the GaAs-AlGaAs [2], InP-InGaAsP [3], or silicon on insulator material systems [4]. To the best of our knowledge, no polarization modulators have been reported around the wavelength of 2 μm. In this paper, we investigate a passive waveguide polarization mode converter (PMC) design, which converts a *TE* mode to a *TM* mode at wavelengths around 2 μm.

In order to change the polarization state of light, several types of passive waveguide polarization converters have been proposed. These make use of asymmetry in the waveguide and include periodically loaded waveguides [5], slanted sidewall waveguides [6], waveguides with asymmetric trenches, and so on. In this paper, a *TE-TM* mode polarization converter is proposed with a single slot shallow-etched in a ridge waveguide fabricated in a strained InGaSb/AlGaAsSb quantum well (QW) structure. Here we report the dependence of the polarization conversion efficiency (PCE) on the slot width, slot depth and slot position from simulations using the Finite-Element Method (FEM) [7], with the fabrication tolerances of the slot position and slot width being investigated in detail. A *TE-TM* PCE of more than 97% was realized at operating wavelengths around 2 μm.

The paper is organized as follows. Section Ⅱ presents an outline of the operation principle of the single-slot polarization converter at a wavelength of 2 μm. Section Ⅲ provides detailed simulation results of the device and presents a tolerance analysis of the geometrical design.

II. Design and Optimization

The GaSb-based InGaSb/AlGaAsSb quantum well structure considered in this work is similar to that we previously designed as a high-power laser. The core region is a sandwich-like structure comprising a strained InGaSb QW (9 nm) with $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$ layers on either side. This waveguide core is in turn sandwiched by $Al_{0.5}Ga_{0.5}As_{0.04}S4b_{0.96}$ cladding layers, which have a lower refractive index to provide optical confinement. The InGaSb QW is compressive strained which results in *TE* polarized laser operation because of the quantum mechanical selection rules. Here we study a waveguide device to convert this to the *TM* polarization.

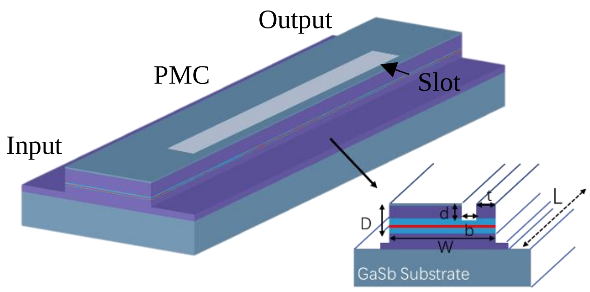

Fig. 1 Schematic representation of the InGaSb/AlGaAsSb mode convertor.

Figure 1 shows a schematic of the proposed polarization convertor, which consists of an input section, a PMC section in the middle, and an output section. The input section has a symmetric waveguide and is used to input a *TE*-polarized beam. As the beam propagates into the asymmetric waveguide

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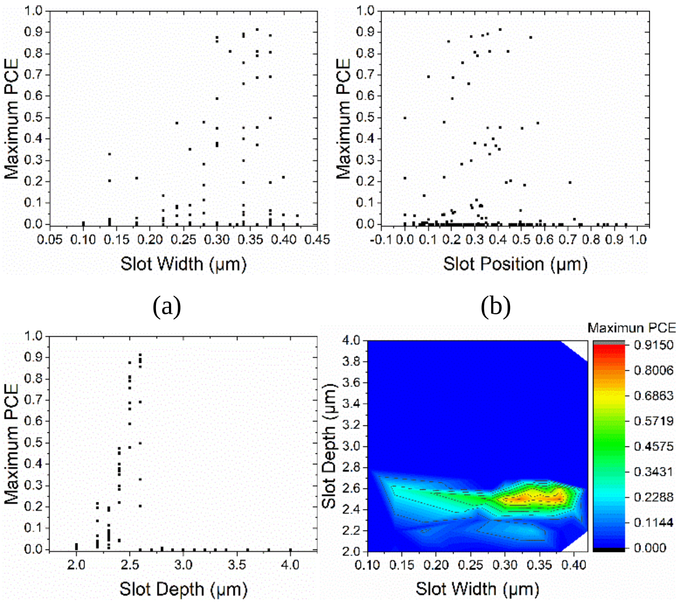
of the PMC, two eigenmodes are excited, which have different propagation constants β_1 and β_2. The relative phase difference between the two modes will lead to the overall polarization evolving periodically. When length of the PMC is a half beat-length, L_π (or at odd multiples of the half beat-length), the light is converted into the orthogonal polarization state, and the maximum *TE-TM* polarization conversion is achieved.

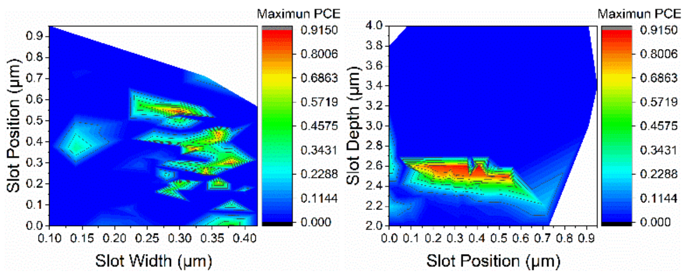
$$L_\pi = \frac{\pi}{\beta_1 - \beta_2} \tag{1}$$

To obtain a pure *TM*-polarized beam, it is necessary that the two excited modes have an approximately equal magnitude, which is realized, in this paper, by introducing a simple single slot into the waveguide to give it an asymmetric profile. As shown schematically in Fig 1, the PMC section has a deep-etched waveguide (etched to the middle of the lower cladding layer) and a shallow-etched trench within the waveguide. By adjusting the waveguide width (*W*), slot length (*L*), slot width (*b*), slot position (*t*) and slot depth (*d*), we could identify the conditions giving the maximum *TE-TM* PCE.

We used an EME solver (Eigenmode Expansion Solver, one of the tools in the Lumerical FDTD Solutions package) combined with a self-written script based on the Finite-Element Method to automatically optimize the PMC structure. At first, we set *W* to 2.1 μm, a width at which only fundamental *TE* and *TM* modes can propagate. We then set ranges for the slot length, slot width, slot position and slot depth (*L*, *b*, *t*, *d*) and let the program randomly chose a set of values within these ranges to define a waveguide structure. The EME solver then received the structure information and simulated the polarization conversion process. Each run included 200 different structures. After every 50 loops, the program would automatically optimize the value span, which allowed the PMC structure with the maximum PCE to be found efficiently.

III. Result and Analysis





(e) (f)

Fig. 2 Simulated maximum PCE as a function of (a) slot width *b*, (b) slot position *t*, (c) slot depth *d*, and combinations of (d) slot width *b* and slot depth *d*, (e) slot width *b* and slot position *t*, and (f) slot position *t* and slot depth *d* from a 200-loop calculation.

Figure 2 shows the variation of the maximum *TE-TM PCE* as a function of slot width (*b*), slot position (*t*) and slot depth (*d*) respectively. The ‘maximum PCE’ requires the slot length (*L*) to be the corresponding half-beat length. Each data point in these figures represents one calculation run, which brings the total to 200 calculation runs.

It is apparent that data points which represent high PCEs center around particular value spans for these three slot variables. For example, PMC structures with slot width from 2.3 μm to 2.7 μm have high PCEs according to Fig. 2(c). This feature can be seen more clearly using two-dimensional contour images, as shown in Fig. 2(d, e, f). Analyzing the data, a *TE-TM* PCE of more than 91% can be obtained with the set of values (*L*=988 μm, *b*=0.36 μm, *t*=0.281 μm, *d*=2.6 μm).

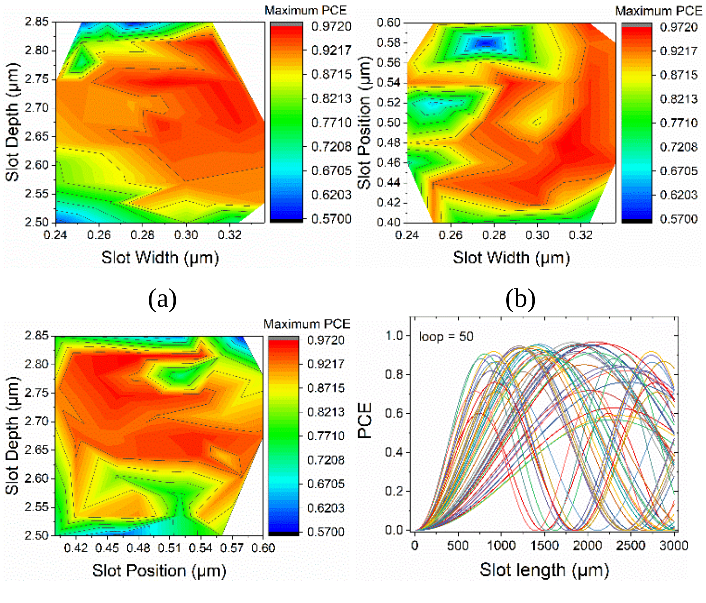
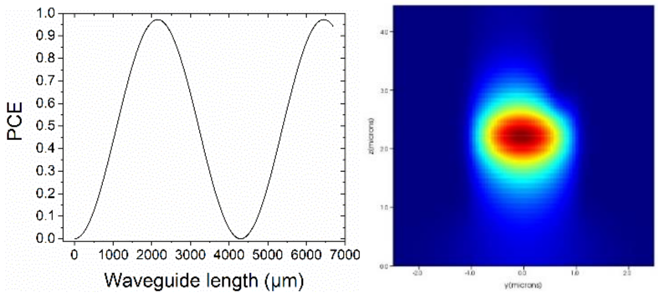


Fig. 3 (a b c) Maximum conversion efficiency as a function of slot width *b*, slot position *t* and slot depth *d* respectively from a 50-loop calculation. (d) Conversion efficiency as a function of PMC section length *L*.

To further optimize the PCE, we narrowed the value span for these three slot variables based on the results in Fig. 2. With the narrower value span, we ran the simulation with 50 loops and obtained the two-dimensional contour image results shown in Fig. 3(a, b, c).

Figure 3 is more centered on the areas of maximum PCE than Fig 2, as expected. The dependence of PCE on the slot length is illustrated in Fig. 3(d). We can see a periodic change in the PCE as the slot length is increased. The waveguide length associated with the first peak of each of these curves corresponds to the half-beat length, L_π, for each simulated PMC structure.

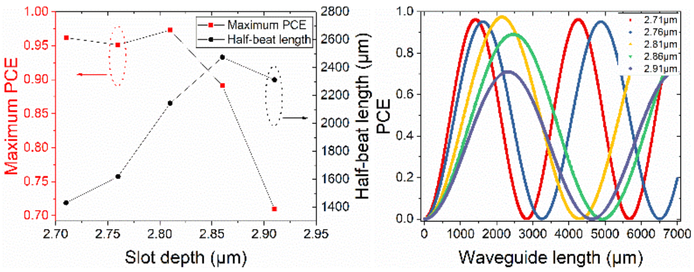
Among the 50 calculation runs, the maximum polarization conversion efficiency is more than 97% with L=2141 μm, W= 2.1 μm, b=0.33 μm, t=0.18 μm, d=2.81 μm. The periodic PCE curve and the electric field profile for this specific structure are illustrated in Fig. 4. As a waveguide with $L>2$ mm is likely to exhibit significant absorption and scattering loss, the results show that a PMC with $L\approx1$ mm can still offer a *TE-TM* PCE of >90%.



(a) (b)

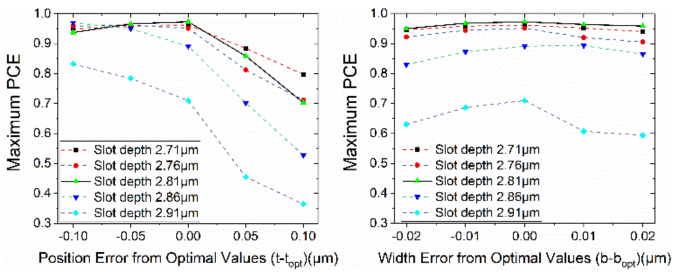
Fig.4 (a) Conversion efficiency as a function of PMC length, *L*, for the optimized slot structure. (b) Electric field profile in the optimized structure.

Figure 5(a) shows the variation of the maximum PCE as a function of slot depth, *d*, in which the other parameters are kept constant at b = 0.33 μm, t = 0.18 μm and the operating wavelength is also at 2 μm. The maximum PCE decreases dramatically when the slot is etched deeper than the optimum. The maximum PCE shows a much slower change when the slot structure has a shallower etch-depth, while the associated L_π drops sharply at the same time, making it possible to design a shorter polarization convertor structure with high conversion efficiency. Figure 5 (b) shows the sinusoidal dependence of the PCE on the length of slot section for different slot depths.



(a) (b)

Fig. 5 (a) Maximum conversion efficiency and half-beat length, L_π as a function of slot depth *d*. (b) Conversion efficiency as a function of PMC length *L*.



(a) (b)

Fig. 6 Variation of the maximum PCE with respect to (a) slot position, *t*, and (b) slot width, *b*.

The fabrication tolerances of the slot position (t) and slot width (b) were also analyzed. The dependence of the maximum conversion efficiency on fabrication errors is shown in Fig. 6. The error value changes every 10 nm for slot width (Fig. 6(a)), and every 50 nm for slot position (Fig. 6(b)). It can be observed that a deviation of ± 20 nm from the optimal slot width (b_{opt}) or −100 nm from the optimal slot position (t_{opt}) only leads to a slight decrease of the maximum conversion efficiency. The tolerance against width variation and position variation could also be improved by using a shallower slot.

IV. CONCLUSION

The design of a single-slot TE-TM mode converter at a wavelength of 2 μm based on an InGaSb/AlGaAsSb QW structure was discussed. In order to obtain pure *TM*-polarized light from a *TE*-polarized input beam, the dependence of polarization conversion efficiency on slot width, slot position, slot depth and slot length of the convertor was investigated and optimized structures identified. The fabrication tolerances on slot width, slot position and slot depth were also investigated. The structure exhibited a high conversion efficiency over a wide range of values of slot width, slot position and slot depth. We obtained a *TE-TM* mode conversion efficiency of more than 97% at a wavelength of 2 μm using a polarization convertor with a slot width of 0.33 μm, slot position at 0.18 μm, slot depth of 0.281μm, and a waveguide width of 2.1 μm and length of 2141 μm.

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