Design of InGaAsP-InP Tapered Ridge Mode Transformer Using an Underlying ARROW Coupling Waveguide

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Abstract

We propose a tapered ridge mode transformer, which uses an underlying antiresonant reflecting optical waveguide (ARROW) to obtain an expanded fiber-matched output mode. The thick layer defining the large ARROW mode consists of InP, which is easy to grow. From simulation results a maximum butt-coupling efficiency improvement of 5.6 dB (2.5 dB coupling loss) is estimated to a standard single mode fiber for an optimum taper length of 315 μm. Far field divergence angles of 7.7º × 22.7º and a mode transformation loss of 0.11 dB are calculated. The presented device requires only a single planar epitaxial growth and two conventional etching steps.

Introduction

The packaging of optoelectronic integrated semiconductor circuits amounts up to about 80% of the cost of the final module imposing one of the largest barriers to future mass production needs. Highly-efficient chip-to-fiber coupling with large alignment tolerances is a critical requirement to obtain low-cost optoelectronic devices. The problem arises because of the mode mismatch between the semiconductor waveguide and the optical fiber. The former has typically a 1-2 μm elliptical modal spot, which is neither well-sized nor shaped to match the standard 8-9 μm circular modal spot of conventional single-mode optical fibers. Directly butt-coupled devices present 7-10 dB insertion loss and submicron alignment tolerances. Nonintegrated solutions improve this coupling but not the alignment requirements. To achieve both low coupling loss and large alignment tolerances it is necessary to transform the mode on-chip to better match the fiber.

Recently, various integrated mode transformers have been proposed [1]. Most of these approaches involve complex growth and/or processing steps, requiring extensive process development. However, there is an attractive group of devices that uses a single standard planar epitaxial growth step and conventional processing techniques [2]-[4]. These devices need a large and close to cut-off rib waveguide that, in InP technology, involves the growth of low Ga and As fraction quaternary materials, which is difficult to achieve. This problem was solved in [2], by introducing a diluted structure. In the present work, we propose a device based on the lateral tapering of a rib waveguide to adiabatically convert the rib mode to the fundamental mode of an underlying fiber-matched ARROW waveguide. The quasiguided ARROW-modes exhibit very attractive features for a fiber coupling function [5, 6]: large mode sizes, low losses for the fundamental mode, high discrimination for the rest of the modes, and ease of fabrication owing to its high tolerances and to the fact that the thick core consists of InP. The wavelength and polarization dependence of such waveguides are negligible.

Waveguide design

The device is shown schematically in Fig. 1. We chose waveguide optical parameters corresponding to InP-InGaAsP waveguides at a wavelength of 1.55 μm. The taper

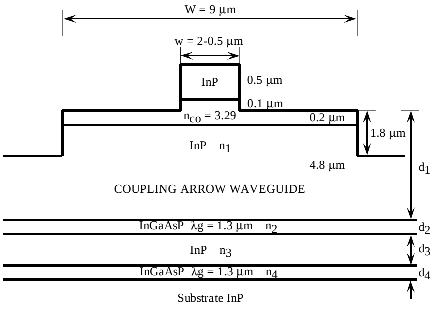
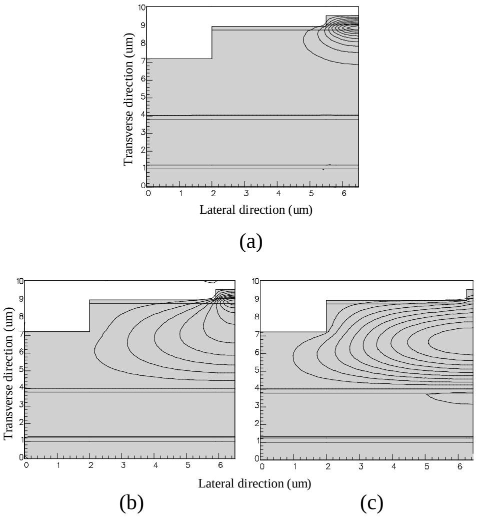


Fig. 1. Schematic drawing of the adiabatic mode expander showing the tapered upper rib and the underlying fiber-matched ARROW waveguide.



(b) (c)

Fig. 2. The fundamental TE mode for (a) w = 2 µm, (b) w = 1.4 µm and (c) w = 0.5 µm.

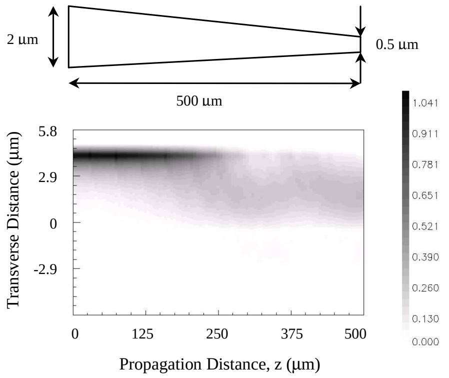


Fig. 3. Lateral view on the TE field distribution in the 500 µm long linearly tapered device.

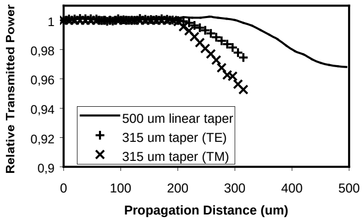


Fig. 4. Relative transmitted power as a function of distance for the 500 µm long linear taper, and for the TE and TM polarizations of the 315 µm long optimized taper.

comprises a narrow rib waveguide, which is placed on top of a larger mesa that is optimized for coupling to a single mode fiber. The vertical confinement in the latter guide is provided by an ARROW-structure for which the optimum thickness of its three cladding layers (d2, d3, d4) is given by the following approximate antiresonance conditions [6]:

$$d_{2(4)} = \frac{\lambda}{4n_{2(4)}}\left(1-\left(\frac{n_1}{n_{2(4)}}\right)^2+\left(\frac{\lambda}{2n_{2(4)}d_{ce}}\right)^2\right)^{-1/2}(2M+1) \tag{1}$$

$$d_3 = \frac{d_{ce}}{2}(2N+1) \qquad (M, N = 0, 1, 2, ...) \tag{2}$$

where λ is the vacuum wavelength, n_1, n_2, n_4 the refractive index of the ARROW InP core, the first cladding layer and the third, respectively. d_{ce} is the equivalent core thickness, which involves the Goos-Hänchen shift at the top of the ARROW core and is defined as

$$d_{ce} = d_1 + \zeta\frac{\lambda}{2\pi\sqrt{n_{co}{}^2 - n_0{}^2}}, \tag{3}$$

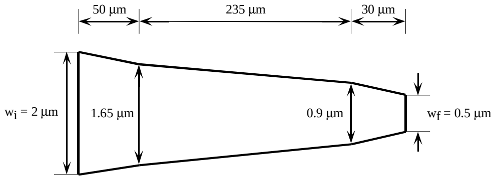


Fig. 5. The optimum taper shape found consists of three linear sections over a length of 315 µm.

$$\zeta = \begin{cases} 1, & \text{for TE modes;} \\ \left(n_0/n_{co}\right)^2, & \text{for TM modes.} \end{cases} \tag{4}$$

In the above expressions n_{co} denotes the refractive index of the core layer that remains over the ARROW core and n_0 the refractive index of a homogeneous cover (air in this case). For the numerical computation we chose a quaternary compound $In_{1-x}Ga_xAs_yP_{1-y}$ with λ_g = 1.3 µm for the high refractive index ARROW layers. The calculated values of the cladding layer thickness for TE polarization are: $d_{2(4)}$ = 0.32 and d_3 = 2.54 µm.

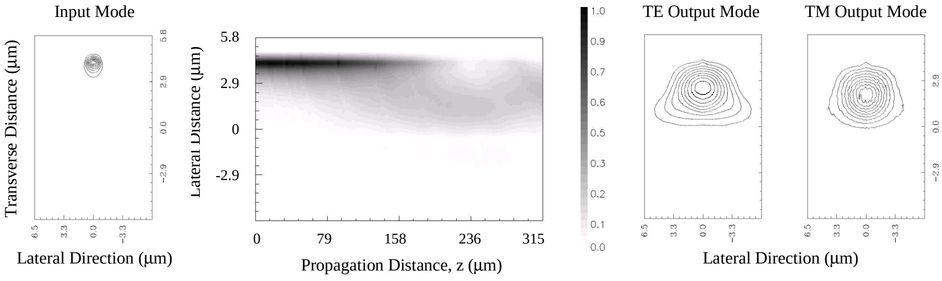
The mode conversion is achieved by narrowing the upper rib waveguide width from w_i = 2 µm to w_f = 0.5 µm. A commercial 3D eigenmode expansion algorithm (Fimmprop-3D, Photon Design) was used to observe the field profiles of the fundamental TE mode of the structure for three different values of the rib width, w (Fig. 2). For w = 2 µm (Fig. 2.a) the mode is well confined to the upper rib waveguide. As the waveguide rib is narrowed to w = 1.4 µm (Fig. 2.b), the fundamental mode is pushed down into the ARROW guide. Fig. 2.c shows that for w = 0.5 µm the fundamental mode of the structure has turned into the fundamental mode of the ARROW rib waveguide.

Taper design and simulation results

Commercial three-dimensional beam propagation method (3-D BPM) software (BPM-CAD, Optiwave Corporation) was used to analyze the propagation of the input rib mode field across the taper and to compute the radiation losses occurring due to the mode transformation. Mesh discretizations of 0.06 and 0.012 µm were used in the horizontal and vertical directions, respectively. A longitudinal step of 0.1 µm was used for propagation.

To find the critical width where the actual mode transformation takes place we first simulated (semivectorial TE-calculation) the propagation of the input rib eigenmode through the device with the upper guide linearly tapered from w_i = 2 µm to w_f = 0.5 µm over a length of 500 µm. A top view of the device and a lateral view of the light field distribution are shown in Fig. 3. It is seen that the whole power transfer between the two waveguides takes place at a ridge width range of 1.65-0.9 µm. Until w = 1.65 µm the mode is well confined in the upper rib and for w < 0.9 µm the light oscillates in the ARROW waveguide due to some excitation of higher order modes [2]. The relative transmitted power as a function of the propagation distance is shown in Fig. 4. The estimated power loss, including propagation loss from the leaky ARROW mode, is about 0.14 dB for this linear taper.

Starting from these results an optimized taper shape can be designed. This optimum taper, which ensures an adiabatic mode transformation over a short total length, was approximated by a piecewise linear device consisting of three linear sections as shown in Fig. 5. The overall length is 315 µm. The first and third sections can have larger taper angles than the central part, which requires a smoother change in its shape to obtain an adiabatic behavior.



(a) (b) (c) (d)

Fig. 6. (a) Intensity plot of the TE mode in the rib upper waveguide; (b) lateral view on the TE mode evolution in the device structure shown in Fig. 5; (c) and (d) intensity plots of the output expanded TE and TM ARROW modes.

Semivectorial calculations were used to investigate the polarization dependence of the device. Although the design of the device has been done for TE polarization we also achieved a good behavior for the TM modes. The light field distribution as a function of propagation distance is shown in Fig. 6. Input and output TE and TM near field power distributions are also presented. The loss profiles (TE and TM) for the optimized taper are shown in Fig. 4 overlaid with the loss profile for the 500 μm long linear taper. The flat response at the beginning of the taper is due to the fact that BPM calculates the transmitted power in the simulation window and, then, light needs some time to be radiated from it. Total transformation losses of 0.11 and 0.21 dB for TE and TM polarizations, respectively, were obtained. By performing a complex overlap integral with the optical mode of a standard SMF butt-coupling efficiencies of 56 % (TE) and 53 % (TM) are estimated. The improvement in the coupling introduced by the taper achieves 5.6 (TE) and 4.2 dB (TM). FWHM divergence angles of 7.7 × 22.7º and 7.6 × 24.8º were observed for TE and TM, respectively.

Conclusion

In this work, we have presented a novel mode expander based on the adiabatic transformation of a standard rib mode into a fiber-matched rib ARROW mode. The lateral tapering of the upper waveguide rib provokes the conversion. The confinement of the expanded field in the InP large core of the ARROW guide makes it easy to grow. Efficient mode transformation and significant fiber coupling improvements can be achieved.

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