REFERENCES

[1] T. Kato, T. Sasaki, K. Komatsu, and I. Mito, "DFB-LD/modulator integrated light source by bandgap energy controlled selective MOVPE," *Electron. Lett.*, vol. 28, pp. 153–154, 1992.

[2] M. Aoki, H. Sano, M. Suzuki, M. Takahashi, K. Uomi, and A. Taki, "Novel MQW electroabsorbtion modulator/DFB-laser integrated device grown by selective area MOCVD," in *Proc. OFC'92*, paper FB6.

[3] M. Takahashi, M. Suzuki, M. Aoki, and T. Kawano, "In-plane quantum energy control of InGaAs/InGaAsP MQW structure by MOCVD selective area growth," in *Proc. Fourth Internat. Conf. InP and Related Compounds '92*, paper WB3.

[4] Y. D. Galeuchet and P. Roentgen, "Selective area MOVPE of GaInAs/InP heterostructures on masked and nonplanar (100) and (111) substrates," *J. Crystal Growth*, vol. 107, pp. 147–150, 1991.

[5] M. Murata, T. Morita, K. Koike, T. Katsuyama, and K. Ono, "Planar embedded growth of GaInAs by OMVPE," in *Proc. Int. Symp. GaAs Related Comp'89*, ser. 106, pp. 87–92.

[6] M. Murata, T. Katsuyama, and H. Hayashi, "Selective growth of high quality GaInAs by low pressure OMVPE," in *Proc. Int. Symp. GaAs related Comp'90*, ser. 112, pp. 181–186.

[7] D. Coronell and K. Jensen, "Analysis of MOCVD of GaAs on patterned substrates," *J. Crystal Growth*, vol. 114, pp. 581–592, 1991.

[8] O. Kayser, B. Opitz, R. Westphalen, U. Niggebrugge, and K. Schneider, "Selective embedded growth of GaInAs by low pressure MOVPE," *J. Crystal Growth*, vol. 107, pp. 141–146, 1991.

[9] J. Finders, J. Geurts, A. Kohl, M. Weyers, B. Opitz, O. Kayser, and P. Balk, "Composition of selectively grown InGaAs structures from locally resolved Raman spectroscopy," *J. Crystal Growth*, vol. 107, pp. 151–155, 1991.

A Low-Loss Beam Splitter with an Optimized Waveguide Structure

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***Abstract*—Novel beam splitters with optimized waveguide structures are designed and fabricated using reactive ion etching. At 1.15 μm the excess loss of the beam splitter is measured to be 1.2 dB for TE and 1.8 dB for TM polarizations, respectively, which are the lowest among the reported values.**

INTEGRATED beam splitters and turning mirrors in III-V compound semiconductors are important components for the realization of compact integrated optical circuits due to their ability to split the beam or change its direction in a very short distance. After the first demonstration of waveguides with total internally reflecting mirrors [1], [2], a self-aligned etching scheme was introduced to reduce the loss due to the displacement and the rotation of the etched mirror surface from its ideal position [3], [4]. Subsequently, turning mirrors have been employed to realize several kinds of photonic devices, such as laser diodes with turning mirrors in their cavity [4], 2 × 2 matrix switches [5], beam splitters integrated with laser diodes [6], amplifier arrays [7], and ring lasers [8]. The reported losses of turning mirrors are typically less than 1 dB per mirror.

For the realization of beam splitters, either a partially grooved geometry [9] or a splitting mirror at the center of a tapered waveguide have been employed [6]. In the partially grooved beam splitter geometry, the calculated excess radiation loss is always larger than 3 dB. The reported experimental results also showed too high excess radiation loss eliminating this structure from practical use [9]. In the tapered waveguide structure with a splitting mirror [6], the incoming optical field has its peak at the tip of the splitting mirror. But most fabricated beam splitters do not have ideal sharp tips but rather have unintentionally formed round tips resulting in high scattering loss. This loss can be significantly reduced if one reduces the optical field intensity at the tip of the splitting mirror. This can be achieved by using a triple-moded waveguide of appropriate length in front of the splitting mirror. Modal interference in this waveguide section could result in a desired mode shape in front of the splitting mirror reducing the undesired scattering loss significantly. In this letter, design, fabrication, and characterization of such novel beam splitters with optimized waveguide structures are described.

DESIGN, FABRICATION, AND CHARACTERIZATION OF BEAM SPLITTERS WITH OPTIMIZED WAVEGUIDE STRUCTURES

The geometry and the basic principle of operation of the new beam splitter based on optimized waveguide structure are shown in Fig. 1. It is basically an improved version of the tapered waveguide geometry with a splitting mirror. The single mode input waveguide excites the two even modes of the triple moded waveguide in front of the

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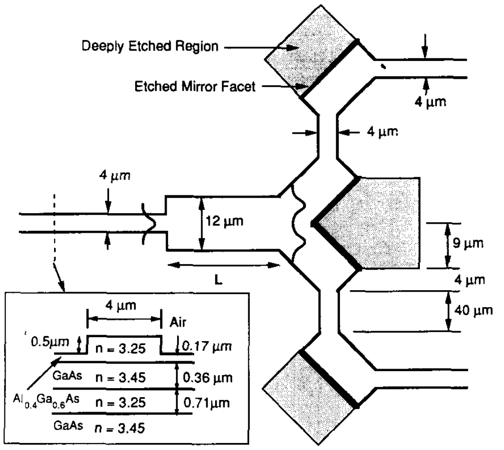

Fig. 1. The geometry and basic principle of operation of the beam splitter with optimized waveguide geometry. L varied from 100 to 400 μm. Inset shows cross sectional profile of the 4 μm wide single mode rib waveguides. Epitaxial layers are undoped.

splitting mirror. If these modes are excited with equal amplitude and if the length of the triple moded waveguide is chosen such that these modes go 180° out of phase at the beginning of the splitting mirror, the field amplitude will be very small at the tip of the mirror. Hence, the roundness of the tip will not contribute a significant loss. A similar idea was proposed for an optimized waveguide Y-junction design [10]. Another advantage of this approach is the following. With this design the incoming field distributed is divided into two lobes, hence into two halves at the beginning of the splitting mirror. When these halves are reflected from the two sides of the splitting mirror, the reflections will overlap very well with the fundamental modes of the single mode output waveguides. If the incoming beam is not split into two lobes and is directly incident on the splitting mirror, as in the conventional design, overlap of the reflections with the eigenmodes of the output waveguides will be very poor. This will result in a significant radiation loss which will be in the vicinity of 3 dB. On the other hand, one pays a price for these improvements in the form of increased length and wavelength sensitivity. The length can still be made much shorter than a Y junction splitter and the wavelength sensitivity is not a problem for most applications. Therefore this design can be suitable for the majority of the practical applications.

The lateral dimensions of the pattern on the mask as well as the cross sectional profile are shown in Fig. 1. The epitaxial layers are grown on semi-insulating GaAs using molecular beam epitaxy. In the fabrication first a 500 Å PMMA layer is spin coated onto the wafer and a 700 Å-thick Si layer is electron beam evaporated on top of it. Then regular liftoff technique is used to generate a 1000 Å thick Ni pattern, which is the etch mask for the waveguide geometry. Then photoresist is spin coated and openings in the mirror areas are formed using standard photolithography. Next Cl_2 based RIE is carried out to form the mirror etch to a depth of 4 μm. For the mirror etch the mask that defines the mirror interface is the Ni layer patterned by lift off. The thick photoresist layer protects the sample from being etched everywhere except in the mirror openings. After the mirror etch O_2 based RIE is done to remove photoresist. Then Cl_2 (to etch Si), O_2 (to etch PMMA), and Cl_2 (to etch the semiconductor) based RIE are sequentially used to etch waveguides. This way the waveguide geometry and the mirror plane are defined by the same Ni mask, hence the process is self aligned. The waveguides are etched 0.5 μm deep and during waveguide etching, He-Ne laser interferometry is used to monitor the etching depth *in situ*. After the formation of the mirror and the waveguide, the etching mask is removed by soaking the sample in acetone. For this waveguide design, the proper length of the 12 μm-wide waveguide is about 250 μm based on an effective index analysis.

The scanning electron microscope picture of a fabricated beam splitter as well as the detail of a splitting mirror are shown in Fig. 2. The transmission characteristics of the beam splitters are measured both for TE- and TM-polarizations. In the measurements, a 1.15 μm He–Ne laser output is end fire coupled and the output of the waveguides are measured using both an IR-vidicon camera and a Ge detector. By comparing the output power of the waveguide with a beam splitter with those from the straight waveguides, the excess radiation loss is measured. The characteristics of the beam splitters with perfect mirrors are also simulated using two-dimensional FD-BPM combined with effective index approximation [11] as well as the three-dimensional semivectorial explicit finite difference BPM [12]. The results are found to be almost the same and the optimum length is about 250 μm. The results of both experiments and calculations are shown in Fig. 3. The calculations show that the excess radiation loss of the beam splitter can be as low as 0.2 dB for an optimum length if the mirrors are perfect. This loss is due to deviations in the modal interference and mode overlap from the ideal. The minimum measured excess radiation loss is about 1.2 dB for TE mode and 1.8 dB for TM modes for $L = 250$ μm. These values are the lowest among the measured values reported. These results combined with the theoretical analysis indicate that mirror losses for these structures could be as low as 0.5 dB/mirror. As seen in Fig. 3, TM polarization has always higher loss than TE polarization. Due to Goos-Hanchen phase shift upon total internal reflection, optimum mirror position is slightly different (difference being 0.2 μm for the particular case) for TE and TM polarizations. In the mask design, mirror position was optimized with respect to TE polarization so it was off about 0.2 μm for TM polarization. But after the photolithography, lift-off, and etching, the mirror plane turned out to be about 0.3 μm off from its intended position. The direction of the error was such that it increased the displacement error for TM polarization to about 0.5 μm. This approximately results in an

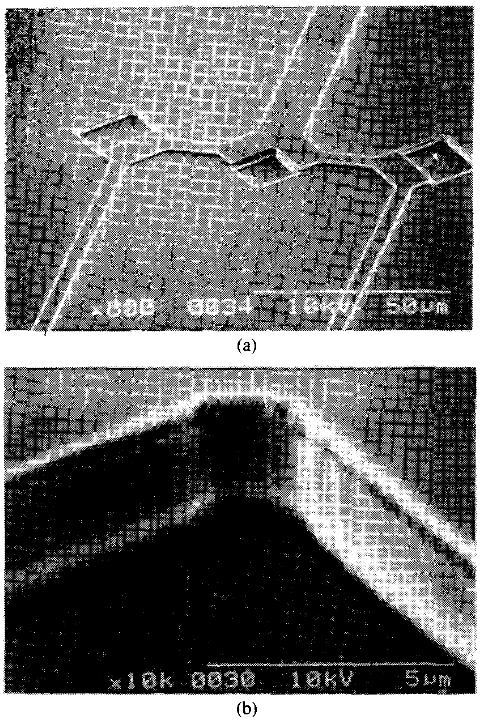

Fig. 2. (a) Scanning electron microscope picture of a fabricated beam splitter. (b) Enlarged view of the tip of the splitting mirror.

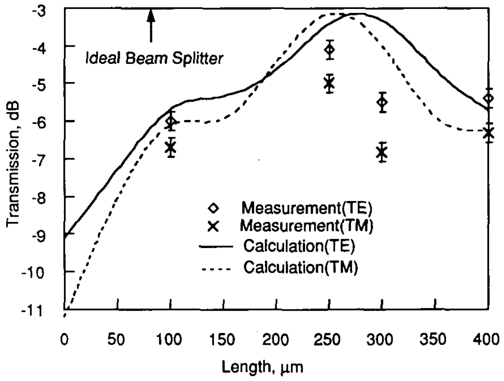

Fig. 3. The simulated and measured transmission characteristics of beam splitter with optimized waveguide structure. Points show the experimental results and continuous curves are the results of simulations assuming perfect mirrors.

0.35 dB more loss for TM polarization. Additional loss is due to a combination of several factors, such as mirror surface roughness and the tilt of the mirror plane in the vertical direction. Further improvements and optimization in photolithography and etching could reduce these factors resulting in better turning mirrors.

CONCLUSIONS

Beam splitters with optimized waveguide structures were designed and fabricated. They exhibited excess radiation losses as low as 1.2 dB for TE polarization and 1.8 dB for TM polarization which are the lowest values reported for integrated waveguide beam splitters. Trends of the measured characteristics agree well with the theoretical estimations. By optimizing the geometry and fabrication processes, the excess losses could be reduced further. In conclusion, it is demonstrated that low loss beam splitters can be realized through careful waveguide design.

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REFERENCES

[1] T. M. Benson, "Etched-wall bent-guide structure for integrated optics in the III-V semiconductors," *J. Lightwave Technol.*, vol. LT-2, pp. 31–34, 1984.

[2] P. Buchmann and H. Kaufmann, "GaAs single-mode rib waveguides with reactive ion etched totally reflecting corner mirrors," *J. Lightwave Technol.*, vol. LT-3, pp. 785–788, 1985.

[3] P. Albrecht, W. Doldissen, U. Niggerbrugge, and H. P. Schmid, "Self-aligned waveguide mirrors for optical integration on InGaAsP/InP," *ECOC Proc.*, 1987, pp. 239–242.

[4] H. Appleman, J. Levy, M. Pion, D. Krebs, C. Harding, and M. Zediker, "Self-aligned chemically assisted ion-beam etched GaAs/(Al,Ga)As turning mirrors for photonic applications," *J. Lightwave Technol.*, vol. 8, pp. 39–41, 1990.

[5] A. Ajisawa, M. Fujiwara, J. Shimizu, M. Sugimoto, M. Uchida, and Y. Ohta, "Monolithically integrated optical gate 2 × 2 matrix switch using GaAs/AlGaAs multiple quantum well structure," *Electron. Lett.*, vol. 23, pp. 1121–1122, 1987.

[6] W. J. Grande, J. E. Johnson, and C. L. Tang, "GaAs/AlGaAs photonic integrated circuits fabricated using chemically assisted ion beam etching," *Appl. Phys. Lett.*, vol. 57, pp. 2537–2539, 1990.

[7] D. Krebs, R. Herrick, K. No., W. Harting, F. Struemph, D. Driemeyer, and J. Levy, "22 W coherent GaAlAs amplifier array with 400 emitters," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 292–295, 1991.

[8] S. Oku, M. Okayasu, and M. Ikeda, "Control of unidirectional oscillation in semiconductor orbiter lasers," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 1066–1068, Dec. 1991.

[9] J. S. Osinski *et al.*, "Miniature integrated optical beam-splitter in AlGaAs/GaAs ridge waveguides," *Electron. Lett.*, vol. 23, pp. 1156–1158, 1987.

[10] C. Rolland, D. M. Adams, D. Yevick, and B. Hermansson, "Optimization of strongly guiding semiconductor rib waveguide Y-junctions," *IEEE Photon. Technol. Lett.*, vol. 2, pp. 404–406, 1990.

[11] Y. Chung and N. Dagli, "An assessment of finite difference beam propagation method," *IEEE J. Quantum Electron.*, vol. 26, pp. 1335–1339, 1990.

[12] Y. Chung, N. Dagli, and L. Thylen, "An explicit finite difference vectorial beam propagation method," *Electron Lett.*, vol. 27, pp. 2119–2120, 1991.