GaAs/GaAlAs Asymmetric Mach–Zehnder Demultiplexer with Reduced Polarization Dependence

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Abstract—**A GaAs/AlGaAs asymmetric Mach–Zehnder wavelength demultiplexer with reduced polarization dependence is demonstrated. Extinction ratios of 24.1 dB for TE and 22.5 dB for TM polarized light have been measured on a device with an anti-reflection coating on its input and output facets. The "active" length of the device is ~6.5 mm and total loss of 1.1 dB has been obtained in a 16 mm long chip.**

Introduction

IN A recent communication [1], we reported the first demonstration of a two-channel GaAs/GaAlAs asymmetric Mach–Zehnder wavelength demultiplexer. The device, fabricated using a double-heterostructure epilayer configuration, exhibited channel spacing of 19 nm in the 1500 nm wavelength range and extinction ratios of 18.0 and 7.8 dB for TE and TM polarized light, respectively. Although suitable for wavelength demultiplexing in fiber systems requiring only single-polarization operation, this device is not useful for applications which require polarization-independent behavior. In fact, all asymmetric Mach–Zehnder demultiplexers reported to date, including integrated-optic devices on other substrates and fiber-based devices [2]–[6], have exhibited a strong polarization dependence which precludes their use in many systems applications. With a view to implementing an integrated-optic Mach–Zehnder interferometer useful for systems where nonpolarization preserving fibers are employed, we report in this letter an improved device with higher extinction ratios and reduced polarization dependence. We also discuss the effects of mechanical strain and anti-reflection coatings on the device performance.

Operating Principle

A schematic diagram of our device is shown in Fig. 1. A 3 dB, three-guide coupler separates the input light into the two arms of the interferometer. Because of the pathlength difference ΔL between the two arms, a sinusoidal wavelength response of the approximate form $\sin^2(\pi\lambda/\Delta\lambda)$ and $\cos^2(\pi\lambda/\Delta\lambda)$ are obtained at the outputs of the two-guide coupler. The channel spacing, defined as the peak-to-trough distance, is given by $\Delta\lambda \approx \lambda^2/(2N\Delta L)$ where N is the guided mode effective index.

In practice, two phenomena cause polarization dependence in such devices. First, the polarization dependence of the coupling length of the two-guide coupler prevents optimization of the extinction ratio for both polarizations in a single device. This effect accounts for the poor TM extinction exhibited by our previously reported device [1]. Second, residual waveguide birefringence results in a phase shift of the sinusoidal demultiplexer response with polarization; for example, in the previous device the peak transmission wavelengths for TE and TM polarization differed by 4 nm. In this work, we demonstrate that the polarization dependence of the coupler beat length can be significantly reduced by appropriate epilayer design. In particular, single-heterostructure rib waveguides, which expose light in the guiding layer directly to the laterally confining rib boundary, are superior to double heterostructures, in which lateral confinement is determined by the polarization-dependent field penetration into an upper cladding into which a rib is etched. Calculations indicate that, for the device of Fig. 1, the coupling length for TM is ≈ 15 percent larger than for TE polarization using the single heterostructure described below, whereas the coupling lengths vary by 50 percent with polarization for the double-heterostructure of [1].

Fabrication

The device was fabricated on a single heterostructure comprising a 1.45 μm thick layer of GaAs on a 6.0 μm thick $Ga_{0.85}Al_{0.15}As$ buffer layer. The epitaxial layers were grown by OMCVD on an n^+ GaAs substrate at Spire Corp.[1] The single-mode rib waveguides, 3 μm wide and 0.29 μm high, were fabricated using standard photolithographic techniques followed by chemical etch and removal of the resist mask. Several devices with different two-guide coupler length L_c as well as calibration guides were fabricated on the same chip. Prior to testing, the wafer was lapped down to a thickness of 150 μm and subsequently cleaved to produce the input and output facets. The device mask and interferometer layout were identical to that used in our previous investigation of double-heterostructure Mach–Zehnder ($\Delta L = 17$ μm) [1], and the etch depth was chosen to provide lateral optical confinement in the waveguides equal to that used in the double-heterostructure devices (effective index difference $\approx 1.1 \times 10^{-2}$).

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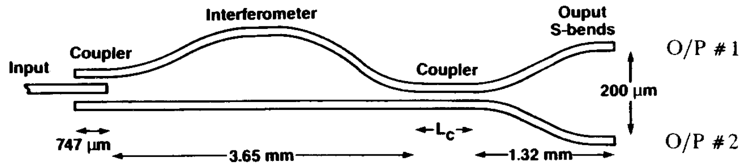

Fig. 1. Schematic diagram of Mach–Zehnder interferometric filter.

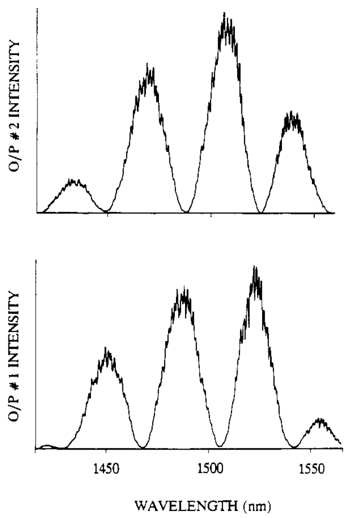

Fig. 2. Sample response curves obtained from the two outputs of a filter with L_c = 792 μm, TE polarization. Changes in peak transmission are due to the wavelength dependence of the laser gain curve.

TABLE I
MEASURED EXTINCTION RATIOS (dB) OF BOTH OUTPUTS FOR TE AND TM POLARIZATION AS A FUNCTION OF COUPLER BEAT LENGTH L_c. SAMPLE MOUNTED WITH APPLIED VACUUM. NO AR COATING.

	TE		TM	
L_c (μm)	#1	#2	#1	#2
528	10.5	16.8	8.7	13.8
660	16.0	21.2	12.7	17.5
792	19.6	20.3	20.5	17.5
924	18.5	18.2	21.5	19.8
1056	7.7	10.9	11.5	10.7

RESULTS

Linearly polarized light from a 1.43–1.58 μm tunable color center laser was endfired into the devices using a polarization preserving fiber (York HB1500/2). The laser linewidth was ~0.1 nm. The output of the device was imaged, through a polarizer, onto an apertured Ge photodetector using a ×16 strain-free microscope objective lens. Fig. 2 shows sample response curves obtained from the two outputs of a device. The observed change in transmission peaks is due to the gain curve of the tunable laser. Table I shows the results obtained from a set of devices comprising five different values of L_c; data were obtained without AR coatings and with the chip held in place by a vacuum chuck (described below). Small changes in the input coupling, obtained by repositioning the input fiber, resulted in extinction variations ≤0.5 dB, which is approximately our experimental uncertainty. The results show that, with appropriate choice of L_c, an extinction >18 dB can be obtained on both device outputs for both polarizations. The new design, therefore, significantly reduces polarization dependence of the coupler beat length and device extinction.

Possible causes for the finite extinction ratio in our devices are an incorrect two-guide coupler length L_c, interferometer imbalance (differential attenuation in one arm or imbalanced intensity division in the three-guide coupler), and the existence of stray light at the outputs. The effect of incorrect L_c on the on/off ratio was studied by varying L_c in 132 μm steps (Table I), corresponding to ≈8 percent of the coupler beat length; >23 dB extinction should have been observed for one of the devices in the absence of imbalance and stray light. Therefore, the largest extinction (20.5 dB for single-polarization, uncoated devices) observed was not limited by an incorrect L_c. For fixed polarization, differing extinction at each output is expected when a combination of imbalance and incorrect L_c exists. Table I shows such behavior, and analysis of these data suggests an interferometer imbalance of <1.5 dB, which in turn would limit the extinction to 21 dB for devices with no stray light or error in L_c. The observed imbalance in the single-heterostructure device is much larger than that previously observed [1] in double-heterostructure interferometers using the same Mach–Zehnder mask and the same lateral effective index difference. We tentatively attribute this difference to changes in the strain within the epilayers and suggest that residual strain causes polarization conversion within the waveguides which, in combination with reflections from uncoated device facets, degrades the interferometer performance.

The effect of strain was investigated by measuring the device response with and without applied vacuum to the chuck supporting the chip. The chuck was made of a cylindrical brass mount incorporating an axial 2 mm diameter orifice to which vacuum was applied. Under vacuum, some buckling of the chip could be observed from the change of focus while observing the chip with a traveling microscope. Table II shows results obtained for a device with L_c = 720 μm, which demonstrate that the device behavior is significantly altered by the applied vacuum. Detailed interpretation of this result is difficult because the total strain comprises both intrinsic epilayer and applied vacuum contributions. Our results do indicate, however, that the device performance is strain dependent and is affected by the method of chip mounting.

The influence of facet reflectivity was investigated by depositing a 190 nm SiN_x anti-reflection coating on the device chip using plasma-enhanced chemical vapor deposition. The nitride film reduced the chip facet reflectivity ≈2 percent (as determined by Fabry–Perot loss measurements [9]) and also coated the surface of the sample. Table III shows the performance after AR coating, both with and without vacuum,

TABLE II
EFFECT OF APPLIED VACUUM ON EXTINCTION RATIOS (dB) FOR A DEVICE WITH L_c = 792 μm. NO AR COATING

	TE		TM	
Vacuum	#1	#2	#1	#2
On	19.6	20.3	20.5	17.5
Off	16.9	16.5	10.4	15.6

TABLE III
EFFECT OF APPLIED VACUUM FOR THE SAME DEVICE AS IN TABLE II BUT WITH AR COATING

	TE		TM	
Vacuum	#1	#2	#1	#2
On	21.3	24.1	21.8	22.5
Off	20.5	23.2	27.5	20.0

for the same device (L_c = 720 μm) described above. The coated device shows both improved extinction (20 dB) and much less sensitivity to the external strain (applied vacuum). Measurements on additional coated devices with different L_c values indicated, however, that the imbalance remains in the interferometer after coating.

At present, it is not clear whether the improved performance of the coated devices is simply the result of reduced facet reflectivity since additional strain introduced by the nitride may also influence the interferometer performance.

As discussed above, a truly polarization-independent device requires the peak transmission wavelengths to be polarization independent as well as the coupler beat length. The device described above exhibits a polarization-independent beat length (same extinction for TE and TM), but a polarization-dependent shift $\Delta\lambda_p \sim 2.9 \pm 0.1$ nm in the peak transmission wavelength. This value is significantly larger than that predicted from the modal birefringence calculated by the effective index method ($\Delta\lambda_p$ = 1 nm); the enhanced birefringence, corresponding to an effective index difference $\Delta N \sim 5.1 \times 10^{-3}$, is attributed to epilayer strain. We observed that $\Delta\lambda_p$ could be varied from ~ 3 to ≤ 4 nm by altering the applied strain, but conditions which minimized $\Delta\lambda_p$ generally did not minimize interferometer imbalance. Operation with $\Delta\lambda_p$ = 3 nm using unpolarized light is expected to limit the extinction ratio to ≈ 12 dB using our devices with the observed channel spacing of 18.4 nm. The birefringence present in our devices can be eliminated in future versions either by epilayer design [1] or by utilizing the polarization-dependent phase shift achievable by electrooptic tuning to balance the strain-induced birefringence.

Finally, the on-chip loss of the device was measured to be 1.1 dB using the Fabry–Perot interference method [9] to measure losses in the straight waveguides, and transmission in the AR coated devices to measure the relative loss with respect to the straight guides. The total losses can be broken down as follows: 0.9 dB propagation loss (chip length = 16 mm, α = 0.6 dB/cm) and 0.2 dB loss in bends and couplers. These low figures were achievable using our techniques developed to design waveguide bends and fabricate low-loss rib waveguides [7], [8].

CONCLUSIONS

We have demonstrated a two-channel asymmetric Mach–Zehnder demultiplexer with improved extinction ratios and reduced polarization dependence. Our results demonstrate the feasibility of devices with high extinction for both TE and TM polarization, and we describe methods which could be employed to eliminate residual waveguide birefringence and so obtain truly polarization-independent operation. These experiments also show the importance of using SiN_x coatings to achieve devices which are less susceptible to effects of external strain, which can significantly alter the performance of uncoated devices.

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