Bent Asymmetric Y-Branch Integrated Optical Broadband WavelengthMulti/Demultiplexer

T. H. Hoekstra, H. J. van Weerden, P. V. Lambeck and Th. J. A. Popma

Abstract—**A new integrated optic wavelength multi/demultiplexer based on a bent asymmetric Y-branch is proposed and investigated. The broadband multi/demultiplexer is demonstrated to combine/split 660 nm pump light and 1535 nm signal light with coupling efficiencies of about 85% and 95% respectively, which is useful for erbium doped integrated optic lasers. The bent Y-branch multi/demultiplexer is simple to fabricate and rather insensitive to processing variations.**

I. INTRODUCTION

BROADBAND integrated optic wavelength multiplexers are of interest for combining pump and signal wavelengths in rare earth doped integrated optical amplifiers and lasers. For example, an integrated optic erbium doped ring laser resonator requires high coupling efficiencies of both signal and pump beam for maintaining the round trip gain in the ring and obtaining a high pump efficiency respectively. Conventional directional couplers [1], nonsymmetric Mach-Zehnder interferometers [2] have been demonstrated to show the necessary multiplexing behaviour to inject a pump beam in a ring laser configuration. Furthermore, composite asymmetric Y-branches operating as multi/demultiplexers have been reported [3]–[5], but these devices require a two mask fabrication process. In this letter a novel integrated optic bent asymmetric Y-branch is proposed for efficiently combining 660 nm pump light [6] with 1535 nm signal light, where bending of the input arms provides the necessary waveguide dispersion for wavelength multiplexing behaviour. The bent Y-branch multi/demultiplexer, as shown in Fig. 1, is attractive because of the broadband spectral behaviour, the easy device fabrication using a single mask level, the simple tailoring of the device properties by adjusting the bending radii, which is rather insensitive to fabrication variations, and its nice compatibility with a ring resonator. The wavelength multi/demultiplexing behaviour of bent Y-branches, fabricated using Y_2O_3 channel waveguides, is experimentally demonstrated.

II. DEVICE OPERATION

The operation principle of the bent Y-branch is considered by examining the demultiplexing behaviour, which is more apparent than the reciprocal multiplexer operation. In a conventional straight adiabatic asymmetric Y-branch operated as a mode splitter, a fundamental mode launched in the input branch is converted to a mode located in the output branch with the highest effective refractive index [7]. However, the difference between the effective refractive indices of the two output branches shows the same sign as function of wavelength, whereas a sign change is necessary for wavelength dependent routing. Therefore the desired multiplexing behaviour requires intersection of the effective refractive index wavelength dispersion of the two output arms [8], where the crossing may result from using different materials in asymmetrical output branches [3]–[5]. In Fig. 2 it is shown that this crossing also can be obtained by bending the output branches, affording application of one material only. At the longer wavelengths the effective index is less modified by bending, whereas the bending induced change of the effective refractive index is more apparent if the modal field is less spread, as in the case of short wavelengths in a wider branch.

A convenient treatment of straight Y-branch waveguides is the step approximation, where coupled mode theory (CMT) based on the local normal modes of two parallel waveguides, defined at each point along the propagation axis, is applied [7]. Accordingly, the effective refractive indices of the bent branches followed from the local normal modes of two well separated concentric waveguides. The concentric waveguides are transformed into straight parallel ones using conformal mapping [9], of which the local normal modes are calculated using the transfer matrix technique. Only the fundamental TE modes are considered whereas these modes result in optimal gain in the ring laser. Fig. 2 shows the difference of the effective refractive index dispersion for various bend radii of the two bent output channels of a Y-branch, with a similar layout as the multiplexer of Fig. 1. The difference in bending radii of the two branches is small enough to provide adiabatic coupling, so multi/demultiplexing behaviour is expected.

To investigate the quantitative properties of the bent Y-branch two dimensional finite-difference beam propagation method (FD-BPM) of the effective index structure has been applied. As a consistency check first the modal fields of isolated bent waveguides have been studied with both FD-BPM and conformal mapping with subsequent transfer matrix calculations, showing the same results for both approaches. Fig. 3 shows the spectral performance of the bent Y-branch multiplexer of Fig. 1, as calculated by FD-BPM simulations for several wavelengths, taking into account the materials refractive index dispersion. The performance is indicated by the coupling efficiency of the pump and signal TE_{00} modes from the input branches to the corresponding TE_{00} modes in

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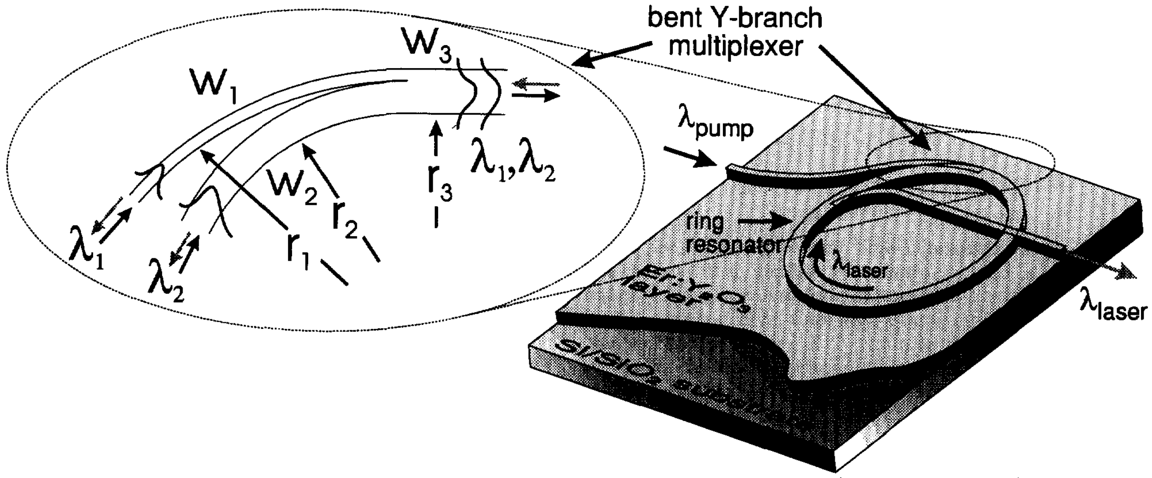

Fig. 1. Bent Y-branch wavelength multiplexer used as input coupler in an integrated optic ring laser. The output coupler in the ring laser example is of a conventional asymmetric Y-branch type. (black arrow: multiplexer operation, grey arrow: demultiplexer operation).

parameters:	*wavelength*	*channel width*	*channel radius*
branch1 (pump)	$\lambda = 660$ nm	$w_1 = 2\ \mu$m	$r_1 = 5500\ \mu$m
branch2 (signal)	$\lambda_2 = 1535$ nm	$w_2 = 8\ \mu$m	$r_2 = 5000\ \mu$m
branch3 (common)	$\lambda_1 \& \lambda_2$	$w_3 = 10\ \mu$m	$r_3 = \infty$

Refractive indices and waveguide dimensions: see experimental section.

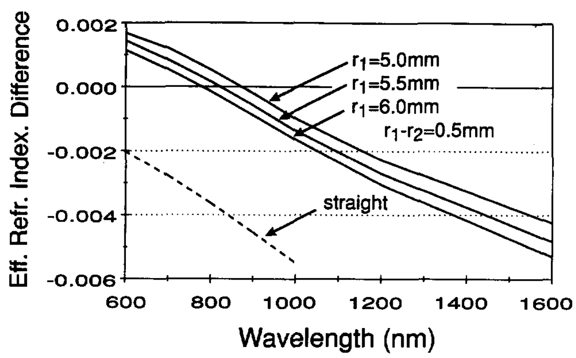

Fig. 2. Effective refractive index difference ($N_{\mathrm{eff,branch1}} - N_{\mathrm{eff,branch2}}$) of bent Y-branch as function of wavelength for various bend radii (solid) and for straight branches (dashed).

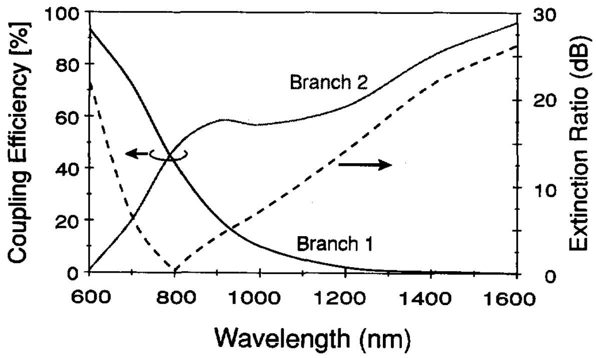

Fig. 3. Solid: Calculated coupling efficiency of branch1 and branch2 to output branch of bent Y-branch multiplexer as function of wavelength. Dashed: Calculated extinction ratio of output branches of bent Y-branch demultiplexer as function of wavelength.

the output branch. For the same bent Y-branch operated as a demultiplexer the calculated extinction ratio as a function of wavelength is also shown in Fig. 3. The spectral response of the multiplexer is shown in Fig. 3. to be broadband, which is advantageous for the pump injection application. Note that for the pump mode at $\lambda = 660$ nm and the laser mode at $\lambda = 1535$ nm the coupling efficiencies are calculated to be 84% and 93% respectively. The coupling efficiency of the TE_{00} mode in the wider input branch shows a small decline at 1100 nm due to the coupling to higher order modes. From Fig. 3. it can be seen that the multiplexer behaves like a power combiner at about 800 nm, which compares well to the intersection point shown in Fig. 2, again indicating the correspondence between the results of conformal mapping and FD-BPM. For TM_{00} modes the intersection point is shifted down by approximately 60 nm in the present design, but the multi/demultiplexing behaviour is maintained.

III. EXPERIMENTAL

Bent Y-branch multi/demultiplexers, as shown in Fig. 1, are fabricated using Y_2O_3 waveguides, which is an excellent host material for erbium-doping to achieve laser action [10]. Channel waveguides are made by etching a ridge with a height of 90 nm in a planar Y_2O_3 waveguide of 0.75 μm thickness deposited on oxidised silicon wafers. The refractive indices of Y_2O_3 /SiO_2 measured to be 1.902/1.444 at 1522 nm and 1.918/1.456 at 660 nm. The measured output mode profiles of the realised bent Y-branch with radii $r_1 = 5.5$ mm and $r_2 = 5.0$ mm, operated in multiplexer configuration, correspond to the fundamental TE mode for 632 nm and 1480 nm wavelength launched in the narrow and wide input branch respectively. This qualitatively indicates the occurrence of the predicted mode coupling. The demultiplexing behaviour

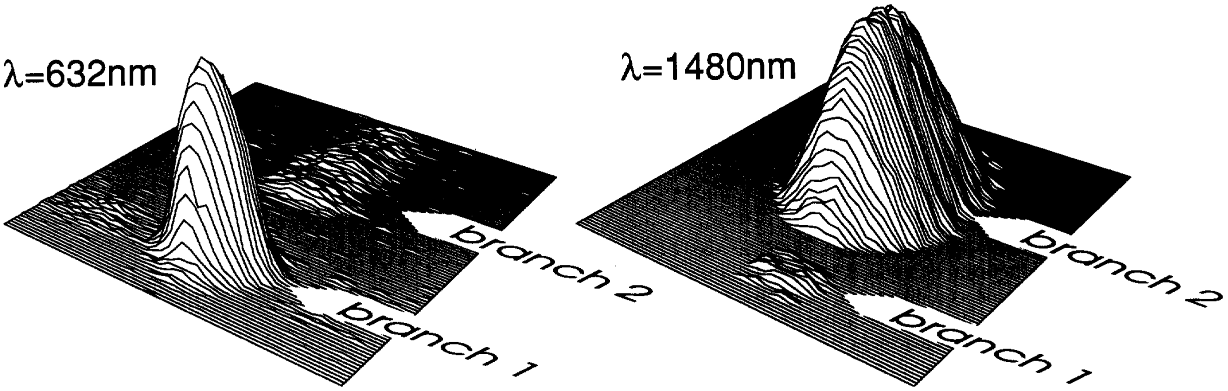

Fig. 4. Measured near field of output branches at end facet of bent Y-branch demultiplexer for 632 nm (left) and 1480 nm (right) input wavelength.

is studied by launching 632 nm and 1480 nm TE_{00} modes in the common input branch and measuring the near fields of the two output branches for both wavelengths, as shown in Fig. 4. From these measurements the extinction ratios are found to be 9.2 dB and 20 dB for 632 nm and 1480 nm respectively, corresponding well to the calculated extinction's of 11 dB and 23 dB respectively. These results indicate the feasibility of such a bent Y-branch multi/demultiplexer and the reliability of the modelling. This provides a sound base for further optimising the bent Y-branch multi/demultiplexer and extending the modelling, which work is in progress.

IV. CONCLUSION

A new integrated optic bent asymmetric Y-branch broadband wavelength multi/demultiplexer is presented. A bent Y-branch multiplexer to combine 660 nm pump light with 1535 nm signal light is investigated. Coupling efficiencies are calculated to be 83% and 93% for pump and signal TE_{00} modes respectively. The multi/demultiplexing operation of bent Y-branches realised with Y_2O_3 waveguides is demonstrated. Measured and calculated extinction ratio's of the bent Y-branch demultiplexer are in good agreement.

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