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# TE-TM mode splitter with heterogeneously coupled Ti-diffused and Ni-diffused waveguides on Z-cut lithium niobate

Ruey-Ching Twu, Chia-Chih Huang and Way-Seen Wang

A coupling type mode splitter with an extraordinary polarisation and a random polarisation waveguide made by Ni and Ti indiffusion, respectively, on a Z-cut $LiNbO_3$ substrate is described for the first time. With optimised process parameters, a very small TM mode profile mismatch is obtained due to the similar characteristics of the Ti- and Ni-diffused waveguides. The measured extinction ratios of the TE and TM modes at 1.55µm wavelength are > 22dB.

*Introduction:* Integrated TE/TM mode splitters are essential components for use in optical communication and sensor systems. Most splitters either have a directional coupler or a Y-branch structure based on the interference or the sorting effect of optical modes [1 – 5], respectively. In the former, the spatial separation of the TE and TM modes is due to the difference in coupling lengths between the two polarisations. To obtain a high-output extinction ratio, the interaction length must be precisely controlled to an odd number of coupling lengths for one polarisation and an even number of coupling lengths for the other polarisation. Moreover, a long interaction length is desirable when the coupling length difference is small. Therefore, to relax the fabrication tolerance and reduce the interaction length, asymmetric, rather than symmetric, couplers with a large propagation constant difference ($\Delta\beta > 0$) for one polarisation and a near-zero propagation constant difference ($\Delta\beta \simeq 0$) for the other polarisation have been proposed [1, 2]. The specified polarisation ($\Delta\beta \simeq 0$) can be transferred to the cross-waveguide and the other polarisation ($\Delta\beta > 0$) is still kept within the through waveguide. Based on coupled-mode theory, its maximum coupling ratio is dependent on the ratio of $\kappa/\Delta\beta$ and interaction length, where $\kappa$ is the coupling coefficient [1].

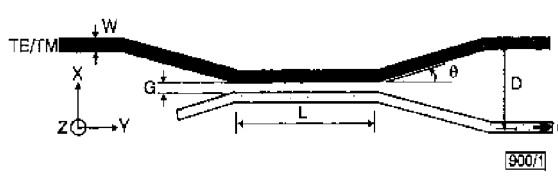


**Fig. 1** *Schematic diagram of heterogeneous directional coupler*

(i) TI waveguide (TE/TM)
(ii) NI waveguide (TM)

In this Letter, a coupling-type mode splitter consisting of an extraordinary and a random polarisation waveguide made by Ni indiffusion (NI) and Ti indiffusion (TI), respectively, on a Z-cut $LiNbO_3$ substrate is demonstrated for the first time. In the past, extraordinary polarisation waveguides formed by NI techniques have been reported and applied to the fabrication of Y-branch mode splitters and Mach-Zehnder modulators on $LiNbO_3$ substrates at 0.6328 or 1.32µm wavelengths [4 – 6]. With some specific process parameters, the waveguide supports only the extraordinary waves due to the large change in the extraordinary index ($\Delta n_e > 0$) and near-zero change in the ordinary index ($\Delta n_o \simeq 0$). Compared with the similar splitter in [1], our proposed splitter using the NI waveguide to replace the proton exchanged (PE) waveguide has two advantages. First, to attain the maximum coupling ratio for the extraordinary wave, $\kappa$ must be greater than $\Delta\beta$, which leads to a relatively narrow waveguide spacing. Unlike PE waveguides where $\Delta n_o < 0$, the ordinary wave in the TI waveguide is unaffected by the adjacent NI waveguide ($\Delta n_o \simeq 0$) when the waveguide gap is reduced. Secondly, on Y-cut substrate, well-confined PE waveguides cannot be easily realised especially for operation in the near-IR wavelength region due to surface damage [8], whereas a single extraordinary-polarisation waveguide on a Y-cut substrate can easily be realised using the NI technique. Moreover, if the interaction length is not an odd number of coupling lengths, then a reverse electrode can be used to adjust only the extraordinary wave coupling, where the $r_{33}$ coefficient is utilised, which is larger than the $r_{13}$ coefficient used for ordinary wave in the design in [3]. Thus, a lower switching voltage is achieved.

*Experiments and results:* A schematic diagram of the proposed splitter is shown in Fig. 1. A set of heterogeneous couplers with different interaction lengths ($L$ = 1, 2, 3, ..., and 9mm) was fabricated on Z-cut $LiNbO_3$ substrate. The gap width $G$ between the TI and NI waveguides was 6µm. The width $W$ and bending angle $\theta$ of two waveguides were 8µm and 0.5°, respectively. The centre-to-centre distance $D$ between two output waveguides was 32µm.

As the diffusion of nickel is faster than that of titanium [7], the TI waveguide has to be made first by diffusing a titanium strip of thickness 400Å at 1050°C for 8h. To avoid the formation of an unwanted outdiffusion guiding layer, the sample was sealed with platinum foil and placed in a covered alumina crucible which was then put in a high temperature oven. The second step involves fabricating the extraordinary-polarisation NI waveguide by diffusing a nickel strip of thickness 350Å at 850°C for 2h. In our measurement, the characteristics of the TI waveguide were hardly changed during the NI process. After the previous two diffusion steps, the substrate end faces were cut and polished to allow end butt coupling. A distributed feedback laser with wavelength $\lambda$ = 1.55µm was used for the measurement. Incident linearly polarised light controlled by the polariser was coupled into the front end face of the TI waveguide using a ×40 lens and the output beams were imaged onto a CCD camera or an InGaAs photodetector also using a ×40 lens.

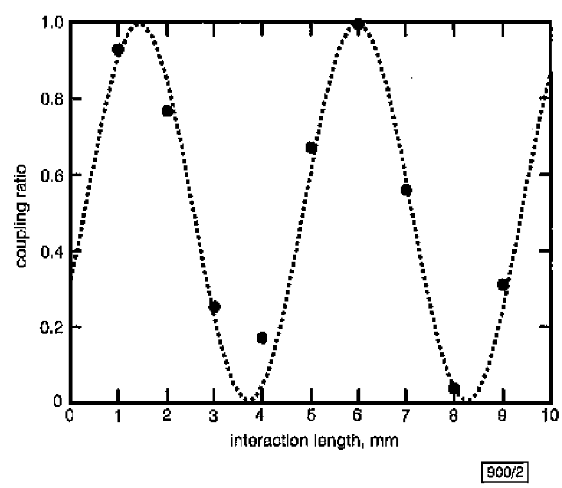


**Fig. 2** *Measured coupling ratio against interaction length for TM mode*

·········· fitted
● measured

Using the optimised process parameters for the fabrication of the TI and NI waveguides, similar TM mode (the extraordinary wave) profiles were obtained. The values of $W_x$ were 9.1 and 9.2µm for the TI and NI waveguides, respectively, and the values of $W_y$ were 6.4 and 6.5µm for the TI and NI waveguides, respectively, where $W_x$ and $W_y$ are the mode sizes (full width at half maximum power intensity) in the directions parallel and perpendicular to the crystal surface.

Fig. 2 shows the coupling ratio against interaction length and the maximum coupling ratio was 0.993 for the TM mode. From the fitted curve, the values of $\kappa$ and $\Delta\beta$ are about 0.68 and 0.058rad/mm, respectively. The corresponding coupling length and the effective index difference $\Delta N$ ($=\Delta\beta \times \lambda/2\pi$) are 2.3mm and $2.8 \times 10^{-5}$, respectively. The shortest interaction length is ~1.4mm for an almost complete spatial separation of TE (the ordinary wave) and TM modes. Fig. 3 shows the output intensity profiles of the near field at $L$ = 6mm with incident light polarised at angles 90° (TE wave), 0° (TM wave), and 45° (both TE and TM waves) relative to the z-axis. The extinction ratios of the TE and TM modes are defined as $R_{TE} = 10\log(P_{TI}^{TE}/P_{NI}^{TE})$ and $R_{TM} = 10\log(P_{TI}^{TM}/P_{NI}^{TM})$, where $P_{TI}^{TE}$ is the fractional TE output power in the TI waveguide (and similar definitions for $P_{TI}^{TM}$, $P_{NI}^{TE}$, and $P_{NI}^{TM}$). The measured TM and TE mode extinction ratios were ~22dB and > 35dB, respectively.

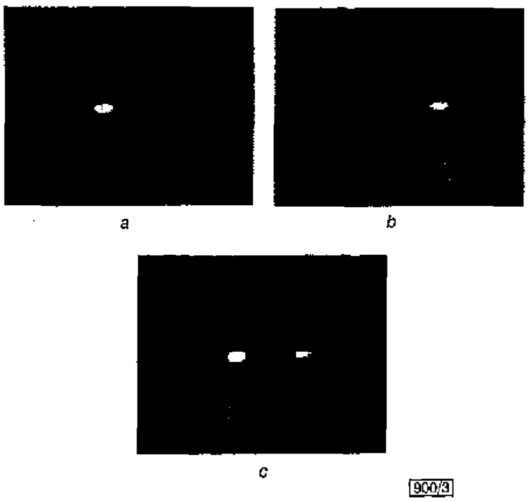


**Fig. 3** *Output near field intensity profiles using different incident waves*

*a* TE wave only
*b* TM wave only
*c* Both TE and TM waves

*Conclusion:* A heterogeneously coupled Ti- and Ni-diffused waveguide fabricated on Z-cut $LiNbO_3$ has been used to realise an efficient polarisation splitter. The output extinction ratios of the TM and TE modes at 1.5μm wavelength are > 22dB at $L$ = 6mm. The shortest interaction length is 1.4mm for almost complete separation at $G$ = 6μm, which is acceptable for optical integration. Details of the practical application will be of great interest in the near future.

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## 0.7W in singlemode fibre from 1.48μm semiconductor unstable-cavity laser with low-confinement asymmetric epilayer structure

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Applied to 1.48μm high-power unstable-cavity lasers, the concept of low modal gain is demonstrated to efficiently repel filamentation effects, enabling more than 700mW to be coupled in a singlemode fibre from a single semiconductor laser diode.

With the current development of dense wavelength division multiplexing (DWDM) networks, Raman amplifiers and EDFAs with saturation power > 25dBm are required, which means that very high pump power from a single device is desirable. From this point of view, unstable-cavity lasers emitting > 1W near-diffraction-limited power can be considered ideal sources when efficiently coupled into singlemode fibres. Recently, with this type of semiconductor laser, a diffraction-limited power of 1.8W was obtained [1]; however, the singlemode fibre coupled power was limited to ~500mW [2]. The main limitation seems to be the degradation of the mode. At shorter wavelengths the dependence of the beam quality of tapered amplifiers on the modal optical gain was demonstrated [3]: a low modal gain enables the optical index variation due to spatial-hole burning (SHB) to be reduced. However, the parameter used to decrease the confinement value was the thickness of the two confinement layers, which may change some beam properties such as optical mode size and singlemode behaviour, and therefore degrade the coupling capability of the beam. Recently, a more versatile asymmetric design was applied to broad-area lasers at 970nm [4], which led to record high output power before catastrophic optical damage. We have successfully improved the design of our 1.48μm laser structures by adapting the latter low-confinement concept to a longer wavelength, enabling us to obtain significantly better modal characteristics and therefore higher singlemode fibre coupled power than previously reported [5].

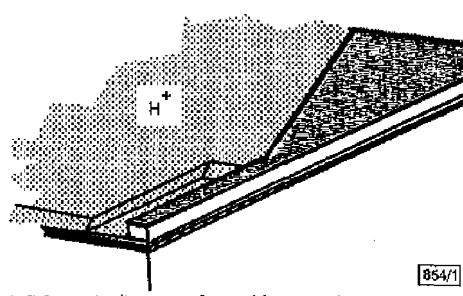


**Fig. 1** *Schematic diagram of unstable-cavity laser*

As shown in Fig. 1, the device consists of a 3μm wide singlemode ridge waveguide followed by a flared amplifying section