fold reduction in the peak conversion efficiency, and < 3dB of ripple in the central passband. Note that by shortening the length of a uniformly quasi-phasematched interaction this bandwidth enhancement would require a conversion efficiency reduction of 225.

Experiments and results: When using quasi-phasematching, the phase reversals necessary for bandwidth enhancement can be obtained by alternating the polarity of the QPM grating at certain positions along the interaction length. To demonstrate an enhanced acceptance bandwidth we fabricated a QPM-SHG waveguide in $LiNbO_3$. A 100Å thick titanium film was patterned into a grating with a 4.0μm period and 1.0μm wide lines on the $+z$ face of $LiNbO_3$. The grating length was 3.9mm, and in addition to the variably spaced phase reversed grating described above, uniform gratings with lengths of 1.95 and 3.9mm were formed on the same substrate. Ferroelectric domain inversion was performed by placing the sample on top of congruent $LiNbO_3$ powder in a closed crucible and annealing with a 2 h ramp to 1050°C for a 4min soak, after which the furnace was turned off and cooled at ~8°C/min. After domain inversion, annealed proton exchanged channel waveguides were formed by wet etching 5 μm wide channels in a 1000Å thick SiO_2 mask layer, proton exchanging in pure benzoic acid for 100 min at 160°C, and annealing in air for 6h at 333°C. The waveguides were singlemode at λ_ω, and were phasematched with the second harmonic (SH) in the TM_{00} mode at ~922nm. Tuning curves from uniform QPM gratings exhibited bandwidths that scaled inversely with grating length and peak conversion efficiencies that scaled quadratically with grating length.

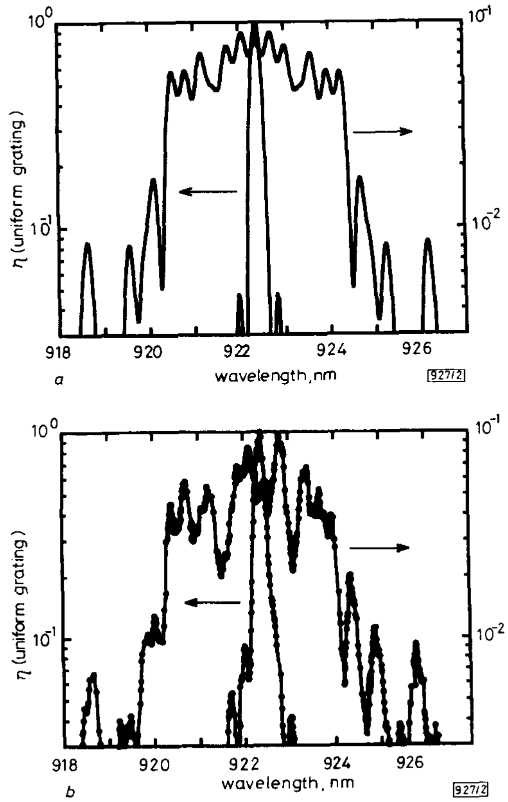

Fig. 2 *Theoretical and experimental SHG tuning curves from waveguides with uniform and variably-spaced phase-reversed QPM gratings*

a Theoretical
b Experimental

Shown in Fig. 2*a* and *b* are the theoretical and experimental wavelength tuning curves from waveguides with a uniform QPM grating and the variably spaced phase reversed QPM grating described above. The theoretical tuning curves shown in Fig. 2*a* are calculated using the bulk $LiNbO_3$ refractive index dispersion [3], evaluated at the measured 922.4nm phasematching wavelength. The measured peak conversion efficiency from the uniform grating was used to normalise both experimental tuning curves shown in Fig. 2*b*. There are no free parameters used in the comparison between experimental and theoretical tuning curves. The central passband bandwidth for the phase reversed grating exceeds that of the uniform grating by a factor of 15, whereas the peak conversion efficiency is reduced by only a factor of 10. The experimental bandwidth enhancement and conversion efficiency tradeoff are in excellent agreement with theoretical predictions, however the observed ripple within the passband is somewhat larger than expected. We attribute the small differences between theory and experiment within the central passband to either axial variations in the phase velocity mismatch or the magnitude of the effective nonlinear coefficient; the latter could be caused by variations in the depth of the Ti-diffused domain grating.

Summarising, use of a variable spaced phase reversed quasi-phasematched grating allows a nearly linear tradeoff between conversion efficiency and bandwidth in any nonlinear optical interaction. This was demonstrated in an $LiNbO_3$ waveguide second harmonic generation device.

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Novel TE-TM mode splitter on lithium niobate using nickel indiffusion and proton exchange techniques

P.-K. Wei and W.-S. Wang

Indexing terms: Integrated optics, Lithium niobate, Optical waveguide components

A new TE-TM mode splitter with an asymmetric Y-junction structure operated by directly focusing randomly polarised light on to a titanium indiffused waveguide which is then directed to in ordinary-polarised nickel indiffusion waveguide and an extraordinary-polarised proton exchange waveguide in lithium niobate is demonstrated. The measured extinction ratio is greater than 20dB for both TE and TM modes.

Introduction: TE-TM mode splitters are important integrated optical devices when orthogonal polarisation states of the propagating light signals are particularly emphasised. To date, various guided-wave TE-TM mode splitters have been proposed [1–4]. For example, using optical interference, [1, 2] the TE and TM modes of a directional coupler can be split by the difference in phase velocities of a fundamental and a first-order mode. Also, with an asymmetrical Y-junction structure, [3, 4] the incident TE and TM waveguide modes can be split and separately guided by two output arms due to different preferences of polarisations. In practical applications, those which use the Y-like structure have a larger fabrication tolerance [3]. To improve the performance of TE and TM mode splitting, Goto and Yip [3] first used an asymmetric Y-junction with its waveguide branches made of different fabrication techniques, namely the proton exchange and titanium indiffusion techniques. As the fabricated device is based on the adiabatic mode conversion of the extraordinary-polarised modes, careful design of the waveguide pattern for a specific index distribution is then required to obtain maximum extinction ratio.

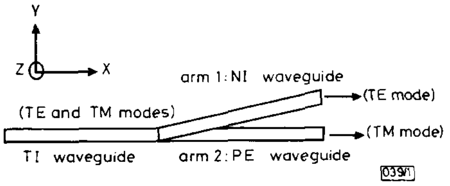

Fig. 1 1×2 *Y-branch TE-TM mode splitter on Z-cut $LiNbO_3$ substrate*

In this Letter, we demonstrate a similar 1×2 asymmetric TE-TM mode splitter in $LiNbOB_3$ except that one of its waveguide branches made by titanium indiffusion [5] (TI) is now replaced by nickel indiffusion [6] (NI) as shown in Fig. 1. It is well known that the TI process increases both the ordinary and extraordinary indices n_o and n_e of $LiNbO_3$, hence randomly polarised waves can be guided by the TI waveguide. However, the PE process only increases n_e, and therefore only extraordinary-polarised waves can be supported in the PE waveguide. It was reported in [6], however, that when nickel diffuses into $LiNbO_3$ under certain diffusion conditions, the waveguides can be polarised for the propagation of ordinary-polarised waves only. As the ordinary- and the extraordinary-polarised waveguides can be fabricated by NI and PE techniques, respectively, the TE and TM modes originally guided by the same TI waveguide can be split and directed to NI and PE waveguides according to the orientation of the $LiNbO_3$ substrate. Thus, an ideal TE-TM mode splitter with a high extinction ratio and capable of operating within a wide range of wavelengths, either singlemoded or multimoded, can be realised.

Experiments and results: The novel TE-TM mode splitter on a Z-cut, X-propagating $LiNbO_3$ substrate is illustrated as shown in Fig. 1. The input waveguide is made by the TI process. Arm 1 of the Y-branch, bent from the TI waveguide at an angle θ of 0.5°, is made by the NI process, and arm 2 of the Y-branch, disconnected from the TI waveguide, is made by the PE process. Note that $\theta \le 1°$ is chosen to reduce the bending loss. As the diffusion of nickel is faster than that of titanium [6], the TI waveguide has to be made first. The TI waveguide was formed by diffusing a titanium strip of width 4μm and thickness 200Å into $LiNbO_3$ at 1050°C for 6h. The diffusion process is performed in an alumina crucible with a small amount of lithium oxide powder to eliminate the unwanted outdiffusion guiding layer. The second step is to fabricate the ordinary-polarised NI waveguide. This waveguide was made by diffusing a nickel strip of width 4μm and thickness 300Å at 950°C for 5h. Note that randomly polarised NI waveguides can also be made under certain diffusion conditions [6]. From our experiments, the critical time t_c for the above ordinary-polarised NI waveguide to be fabricated is ~3h. When t_c < 3h, the waveguide becomes able to support both ordinary- and extraordinary-polarised waves. As the diffusion temperature for the NI waveguide is 100°C lower than that for the TI waveguide, the TI waveguide was assumed hardly changed during the NI process. The last step is the fabrication of the PE waveguide. A tantalum film of thickness 400Å deposited on the lithium niobate by electron gun evaporation was used as the mask for proton exchange. After opening a waveguide pattern of width 4μm on the mask, the substrate was immersed in the benzoic acid at 235°C for 2h. To reduce the propagation loss, the PE waveguide was then annealed at 300°C for 6h. Measurement of the TE-TM mode splitter was carried out by an He-Ne laser of wavelength 0.6328μm. The incident light is focused directly to the waveguide end facet by a ×40 lens to excite both TE and TM modes. The output power distribution is enlarged by a ×40 lens and passed through a polariser to investigate their polarisation states. Fig. 2*a*–*c* show the power distributions measured by a linear detector array with polarisation angles of 45, 0, and 90° relative to the *y*-axis, respectively. Note that only the TE mode is supported by the NI waveguide, and similarly, only the TM mode is found in the PE waveguide. The measured extinction ratios were 24dB for the TE mode and 23dB for the TM mode. Another TE-TM mode splitter was also made using the same fabrication processes as those for the TI, NI, and PE waveguides, except that the strip widths of these waveguides were 5, 6, and 4μm, respectively. Fig. 3*a*–*c* show the similar results to those of Fig. 2*a*–*c*. As can be seen from these Figures, the NI waveguide supports a multimode wave. The measured extinction ratios were 22dB for the TE mode and 21dB for the TM mode. The previous TE-TM power splitter operated under multimode conditions has a low extinction ratio [4]. However, in this Letter, splitters that operate under multimode conditions can be easily realised with high extinction ratios. Thus, the new TE-TM mode splitters, using three different fabrication processes, indeed have a larger fabrication tolerance and are capable of splitting multiple TE and TM modes.

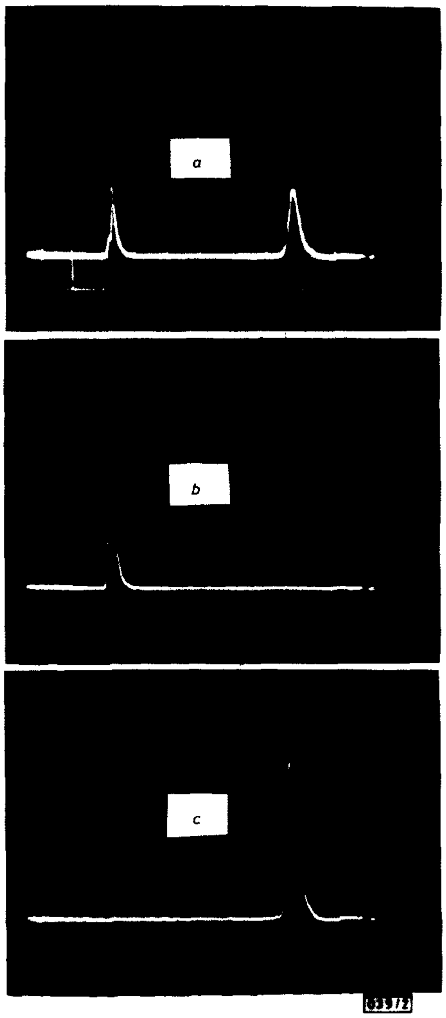

Fig. 2 *Near field distributions at output end*

a Both TE and TM modes
b TM mode
c TE mode

Conclusion: A 1×2 TE-TM mode splitter based on an asymmetric Y-junction is successively fabricated by a combination of TI, NI, and PE processes in $LiNbO_3$. Owing to the inherent single polarisation properties of individual waveguide branches, the extinction ratios of the TE and TM modes are greater than 20dB, which makes the performance of the device excellent. Obviously, the combination of ordinary- and extraordinary-polarised waveguides in $LiNbO_3$ such as those made by NI and PE, is not the only

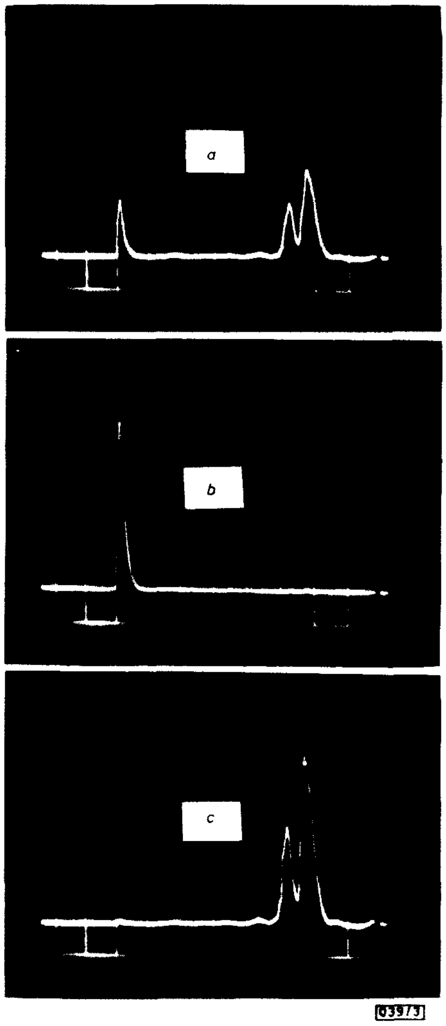

Fig. 3 *Near field distributions at output end*

a Both TE and TM modes
b TM mode
c TE mode

method. Different processes and materials will now be of great interest to determine if better performance can be outlined.

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'Inverted' gain-levered long-wavelength MQW optical transmitter with enhanced FM efficiency and suppressed AM

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Indexing terms: Frequency modulation, Semiconductor lasers

The frequency modulation characteristics of a two-electrode InGaAs/InP 'as cleaved' Fabry-Perot MQW laser reveal an FM enhancement of 1.7dB with an accompanying AM suppression of 2.3dB, relative to the uniformly pumped case, under small signal modulation at 900MHz. As a result the requirement for 'vector modulation' of multi-electrode FSK optical transmitters is relaxed.

Introduction: The frequency shift keying (FSK) modulation format in optical heterodyne communication systems require optical transmitters with high FM efficiency, flat FM response and low residual AM [1]. Two and three electrode DFB lasers are able to satisfy this condition when both of the lasers' drive currents are modulated in a 'push-pull' (or 'vector' modulated [2,3]) fashion. One problem associated with this modulation method is that the phase delay between the modulation currents has to be continually changed as the modulation frequency is changed. As a result, an FSK transmitter requiring only a single modulation current is attractive.

Recently a method of exploiting the sublinear gain/carrier density characteristic of low well number quantum well lasers to improve the laser AM modulation efficiency has been proposed [4]. Experiments performed on two electrode devices in the GaAs/AlGaAs [4] and InGaAs/InP [5] material systems have verified these predictions with measured AM enhancements of 23dB [4] and 10dB [5], respectively, with little accompanying relative intensity noise (RIM) degradation. A biasing arrangement whereby the longer section has a lower carrier density than the shorter section has been shown theoretically and experimentally [6] to result in an enhanced FM response with reduced AM for low threshold short wavelength lasers. In this Letter, we report the first observation of improved FM with suppressed AM in a long wavelength InGaAs/InP MQW semiconductor laser that exploits this mode of operation.

Experiment: The device used for this experiment is similar to the device described previously in [5]. Briefly, the split ratio of the $500\mu m$ device was 7.16:1 (allowing for a $10\mu m$ inter-electrode spacing) and the threshold current at a stabilised 25°C with contacts shorted was 25.8mA. Matching resistors of 47Ω have been inserted in series with each section and each electrode is fed through 50Ω microstrip transmission lines. An HP6625A dual current source supplies the bias currents to both sections and modulation at 900MHz is supplied to the short electrode through an HP33150A bias-tee. This frequency is chosen because it falls within the GSM system bandwidth [5] and to avoid spontaneous effects that are present at lower modulation frequencies. Light output from the laser is collimated by an AR-coated ball lens and subsequently split by a 50/50 beamsplitter. An HP71400 lightwave signal analyser measures the amplitude modulation on one half of the beamsplitter output, and the remainder of the light is passed on to the FM index measurement setup.

Because the laser is of Fabry-Perot type, a means of extracting a single mode from the spectrum is required before the FM response can be estimated. The remainder of the light is passed through a manual Fastie-Ebert monochromator having $150\mu m$