

- 3 KURIMOTO, K., ODAKE, Y., and ODANAKA, S.: 'Drain leakage current characteristics due to band-to-band tunneling in LDD MOS devices'. IEDM Tech. Dig., 1989, p. 621
- 4 WANN, H.J., KO, P.K., and HU, C.: 'Gate induced band-to-band tunneling leakage current in LDD MOSFETs'. IEDM Tech. Dig., 1992, p. 147
- 5 Special issues of *IEEE Trans. Electron. Devices*, vols. 34, 36, 1987, 1989
- 6 KIRSCHMAN, R.K.: 'Cold electronics: An overview', *Cryogenics*, 1985, 25, pp. 115-121
- 7 GHIBAUDO, G., BALESTRA, F., and EMRANI, A.: 'A survey of the MOS device physics for low temperature electronics', *Microelectron. Eng.*, 1992, 19, pp. 833-840
- 8 BREWS, J.R.: 'The submicron MOSFET in high speed semiconductor devices' in SZE, S.N.: 'High speed semiconductor devices' (Wiley, New York, 1990), p. 139

Increased acceptance bandwidth for quasi-phaseshifted second harmonic generation in LiNbO₃ waveguides

M.L. Bortz, M. Fujimura and M.M. Fejer

Indexing terms: Lithium niobate, Optical waveguides, Optical harmonic generation

The authors demonstrate waveguide second harmonic generation using a variable-spaced phase-reversed quasi-phaseshifted grating that has an acceptance bandwidth 15 times greater than a uniformly quasi-phaseshifted interaction of the same length.

Introduction: Quasi-phaseshifted second harmonic generation (QPM-SHG) in periodically poled LiNbO₃, LiTaO₃, and KTP waveguides is an attractive technique for the generation of short wavelength radiation from infra-red laser diodes. Conversion efficiencies approaching 15-20% and blue output powers exceeding 20mW have been demonstrated in all three material systems. Factors other than conversion efficiency now limit the utility of waveguide frequency conversion. One practical problem is the narrow wavelength and temperature acceptance bandwidths of waveguide QPM-SHG devices. For example, for a fundamental wavelength λ_0 of 850nm, the SHG wavelength acceptance-length products ($\Delta\lambda L$) are 0.6, 0.7, and 0.8 Åcm in bulk LiNbO₃, LiTaO₃, and KTP, respectively. Useful conversion efficiencies require interaction lengths of ~1cm, resulting in very narrow bandwidths that exceed the fabrication tolerances on laser diode wavelengths. Similarly, SHG temperature acceptance-length products ($\Delta T L$) of ~1-2°Ccm necessitate waveguide temperature control. In this work we demonstrate a technique for increasing the wavelength and temperature acceptance bandwidth of a QPM frequency conversion device while maintaining a high conversion efficiency. We experimentally demonstrate a QPM-SHG waveguide device with a factor of 15 enhancement in the acceptance bandwidth over a typical device with the same length but with only a factor of 10 reduction in the peak conversion efficiency, in excellent agreement with theoretical calculations.

Theory: Acceptance bandwidths may be increased by reducing interaction length. In a uniformly phaseshifted nonlinear optical interaction the bandwidth scales inversely with length while the conversion efficiency scales quadratically with length. Given the normalised conversion efficiencies for QPM-SHG in waveguides, reducing the length results in an unacceptable tradeoff between conversion efficiency and acceptance bandwidth. For example, assuming a normalised conversion efficiency of 1000%/Wcm² and $\Delta\lambda L = 0.6$ cm, a 1mm long uniformly quasi-phaseshifted frequency doubler would have a conversion efficiency of 10%/W and a bandwidth of 6Å. The conversion efficiency reduction to 10%/W is unacceptable given the 100-200mW output powers of available single longitudinal and transverse mode laser diode pump sources. Another technique is necessary for increasing acceptance bandwidth.

Modification of the tuning curve shape and acceptance band-

width can be accomplished by introducing axial variations in either the effective indices of the waveguide modes or the QPM grating; however the former is generally unacceptable because phase velocity variations are difficult to control and may lead to optical scattering loss. The acceptance bandwidth may be increased by perturbing the QPM grating such that spectral components are spread from the central lobe into the wings. The integrated area under the tuning curve and the gain-bandwidth product are nearly conserved when perturbations to a uniform QPM grating do not reduce the magnitude of the effective nonlinear coefficient, making it possible to achieve a linear tradeoff between conversion efficiency and bandwidth using a nonuniform QPM grating. Tuning curve modifications may be obtained without changing the local periodicity of the QPM grating but by reversing the phase of the QPM grating on a length scale large compared to the QPM period [1]. In this latter technique, a device of length L can be divided into N equal or variable length segments, and in each segment the polarity of the nonlinear coupling may be varied by reversing the phase of the grating. The tuning curve is then approximately given by the Fourier transform of the autocorrelation function of the bipolar phase reversal sequence. Whereas the acceptance bandwidth obtained using a uniform QPM grating is determined by the overall device length L , the bandwidth obtained using a phase reversed QPM grating is determined by the individual segment length L/N . [1] contains a derivation of these results. Different phase reversal sequences will result in tradeoffs between conversion efficiency, bandwidth, and ripple within the passband.

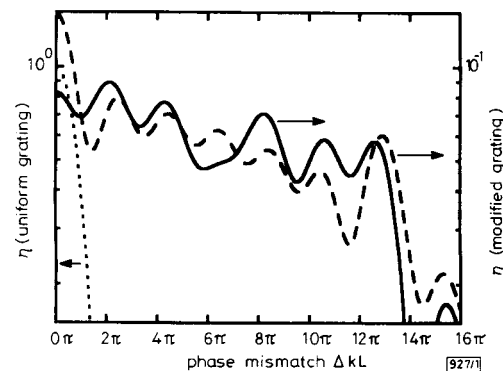


Fig. 1 Theoretical tuning curves assuming a uniform QPM grating and QPM gratings with equally spaced and variably spaced phase reversals

..... uniform QPM grating
 - - - - - equally spaced phase reversal
 ——— variably spaced phase reversal

Previous theoretical work applied to optical frequency conversion [1] and experimental work on travelling wave electro-optic modulators [2] suggested that pseudorandom bit sequences with low sidelobes in their autocorrelation functions, such as Barker codes, should yield broadband, flat phase mismatch responses. Such response functions were experimentally demonstrated in modulators with phase reversed electrode patterns [2]. Shown in Fig. 1 as the dotted and dashed curves are the theoretical tuning curves for phasematching with a uniform QPM grating and with a grating modified by equally spaced phase reversals with the sign of the phase reversals determined by a 13 bit Barker code [2, Note 1]. The latter tuning curve has a greatly enhanced bandwidth over that from a uniform QPM grating, but the ripple exceeds 7 dB within the central passband. To reduce the passband ripple we let the phase reversal positions vary and numerically evaluate the normalised variance of the tuning curve over the passband. Shown in Fig. 1 as the solid curve is the theoretical tuning curve for phasematching with a variably spaced phase reversed QPM grating [2, Note 2] with a 15 fold enhancement in the 3dB bandwidth, an 11

Note 1: The 13 bit Barker code is defined by the following bit sequence: (+, -, -, +, -, -, +, -, -, +, +, +, +)

Note 2: The phase reversals were located, in units of grating length L , at positions 0.06359, 0.14308, 0.22564, 0.32103, 0.38462, 0.45436, 0.53846, 0.62769, 0.69231, 0.76923, 0.84615, 0.92308.

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-phasesmatched interaction this bandwidth enhancement would require a conversion efficiency reduction of 225.

Experiments and results: When using quasi-phasesmatching, 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 LiNbO₃. 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 LiNbO₃. 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 LiNbO₃ 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 SiO₂ 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 λ₀, and were phase-matched with the second harmonic (SH) in the TM₀₀ 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.

described above. The theoretical tuning curves shown in Fig. 2a are calculated using the bulk LiNbO₃ 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. 2b. 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 trade-off 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-phasesmatched grating allows a nearly linear tradeoff between conversion efficiency and bandwidth in any nonlinear optical interaction. This was demonstrated in an LiNbO₃ waveguide second harmonic generation device.

© IEE 1993

28 October 1993

Electronics Letters Online No: 19940025

M. L. Bortz, M. Fujimura and M. M. Fejer (E. L. Ginzton Laboratory Stanford University, Stanford, California 94305, USA)

References

- 1 NAZARATHY, M., and DOLFI, D.W.: 'Spread-spectrum nonlinear optical interactions: Quasi-phasesmatching with pseudorandom polarity reversals', *Opt. Lett.*, 1987, 12, p. 823
- 2 NAZARATHY, M., DOLFI, D.W., and JUNGERMAN, R.L.: 'Velocity mismatch compensation in traveling wave modulators using pseudorandom switched electrode patterns', *J. Opt. Soc. Am. A*, 1987, 4, p. 1071
- 3 EDWARDS, G.J. and LAWRENCE, M.: 'A temperature dependent dispersion equation for congruently grown lithium niobate', *Opt. Quantum Electron.*, 1984, 16, p. 373

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

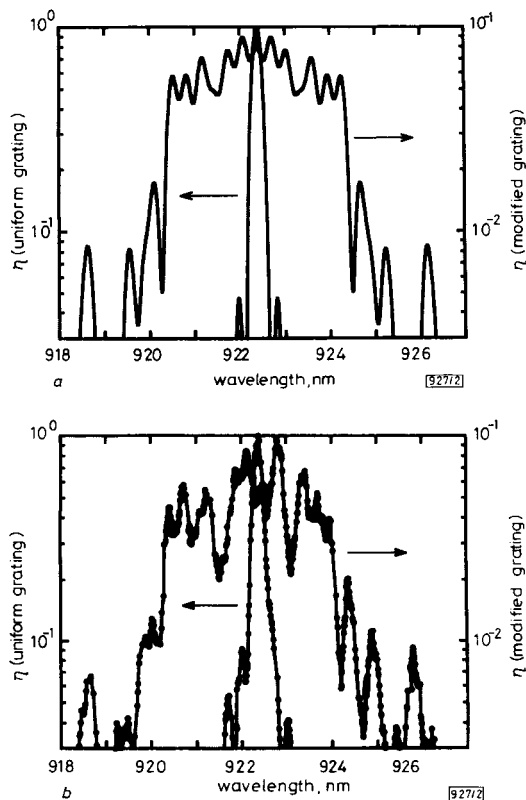


Fig. 2 Theoretical and experimental SHG tuning curves from waveguides with uniform and variably-spaced phase-reversed QPM gratings

a Theoretical
b Experimental

Shown in Fig. 2a 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