with the use of a 25 μm taper an angle of about 4° is possible. The losses for both cases are nearly identical.

The losses consist of taper losses, radiation losses and crosstalk in the other waveguides. Crosstalk contributes to the intersection loss primarily at low angles. The interaction losses for angles lower than 4° with a taper are much lower than those without one, because the better directional pattern reduces crosstalk. With the exception of the 25 μm taper and TE-polarised light the losses for angles greater than 4° are nearly identical for all versions. This means that the taper losses are compensated for through the better directional pattern. The large taper losses (about 1·4 dB) of the 25 μm taper (TE) can not however be compensated for. As Fig. 3 shows, the losses of the intersection with the 15 μm taper are even slightly less than the losses of the intersection without the taper. This means that it is thus possible to design an optimal taper with the lowest intersection losses.

In conclusion we have found that a taper reduces crosstalk and intersection angle. By finding an optimal taper, losses can also be minimised. If there are no space problems on an integrated optic chip, a high intersection angle is desirable because crosstalk and losses are then minimised.

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BLUE LIGHT GENERATION BY FREQUENCY DOUBLING IN PERIODICALLY POLED LITHIUM NIOBATE CHANNEL WAVEGUIDE

Indexing terms: Optics, Integrated optics, Optical waveguides, Nonlinear optics

Blue light at 410 nm was generated by continuous-wave frequency-doubling in a periodically poled lithium niobate channel waveguide at room temperature. Quasi-phasematching allowed generation of the blue light using the d_{33} nonlinear coefficient.

Introduction: Efficient generation of coherent visible radiation in solid-state devices is of considerable technological importance. Frequency doubling of infra-red diode laser radiation in waveguides is an attractive approach, but compensation for the dispersion of the refractive indices is necessary. Quasi-phasematching achieved by periodic-poling in a nonlinear medium is an alternative to phasematching methods based on birefringence, modal dispersion or the Cerenkov effect.

Second harmonic generation (SHG) of green light has been demonstrated using quasiphasematching in periodically poled bulk lithium niobate ($LiNbO_3$),[1] and more recently in periodically poled $LiNbO_3$ waveguides.[2,3] In addition, SHG of blue light has been demonstrated in a bulk interaction in periodically poled $LiNbO_3$,[4] and in a slab waveguide in periodically poled $LiNbO_3$.[5] We report the fabrication and operation of a channel waveguide doubler in periodically poled $LiNbO_3$ for the generation of blue light.

Device fabrication: The fabrication of the current device is similar to a previously published process for making periodically poled waveguide doublers for the generation of green radiation.[2] Lift-off lithography was used to pattern four Ti gratings on the $+c$ face of a 1 mm-thick $LiNbO_3$ substrate. The periods of the four gratings were 6·5, 7·0, 7·5 and 7·75 μm. Each grating was about 1 mm long, and comprised Ti lines 2 μm wide and 5 nm thick. The grating periods were chosen so the resulting domains would be three coherence lengths long for frequency doubling of wavelengths in the 800–900 nm range. The gratings were arranged so that the channel waveguides would traverse all four gratings.

The heat treatment consisted of a 2 h ramp up from room temperature to 1100°C and a 10 minute soak at 1100°C, after which the oven was turned off. The oven had an initial cooling rate of 8 K per minute. The substrate was placed in a closed aluminium boat filled with congruent $LiNbO_3$ powder during the heat treatment to prevent outdiffusion of lithium oxide.

After the heat treatment, annealed proton-exchange channel waveguides were fabricated in the substrate.[6] Lift-off lithography was used to define 3 μm-wide channels in a 200 nm-thick layer of aluminium. Following a 20 min soak in pure benzoic acid at 200°C, the Al mask was removed in a solution of sodium hydroxide. The sample was then annealed for 3 h at 350°C in flowing oxygen. After end-polishing the length of the sample was about 1 cm.

Experiment: The sample was characterised using a CW Styryl-9 dye laser as a source. Input and output coupling was accomplished in an end-fire geometry using microscope objectives. The infra-red insertion loss was 4·4 dB. With 14·7 mW of 820 nm radiation measured at the output of a waveguide, we observed 940 nW of the 410 nm second harmonic. Both the fundamental and harmonic signals were in the fundamental mode, and had the proper polarisation for operating using the nonlinear coefficient d_{33}. Presuming a 14% Fresnel reflection at the exit face of the waveguide gives an internal normalised conversion efficiency of 37%/W cm^2. This is an increase over the 2%/W cm^2 efficiency obtained with a slab waveguide doubler for the generation of blue radiation.[5] Fig. 1 displays the quadratic dependence of the second harmonic power upon the fundamental power. At the power levels used in this experiment, we did not observe photorefractive damage in the waveguide.

Fig. 2 displays the measured wavelength tuning curve for the sample as well as a sinc^2 curve fitted to the data. The observed full width at half maximum (FWHM) is about 0·5 nm.

The mode sizes of the fundamental and second harmonic were measured by imaging the near-field output mode patterns onto a CCD video camera. The $1/e^2$ intensity contours of the images were used to define the mode sizes. The full-width in-plane dimensions for the fundamental and second harmonic were approximately 3·7 and 2·1 μm, respectively, and the out-of-plane dimensions were 3·1 and 1·5 μm.

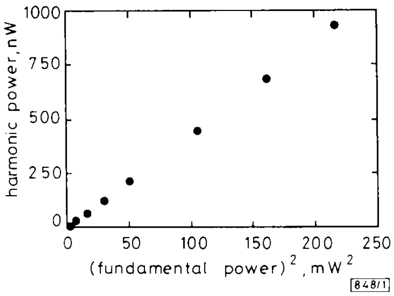

Fig. 1 *Plot of measured harmonic power against square of fundamental power, showing quadratic relationship between them*

To determine which of the four gratings provided efficient second harmonic generation, the top surface of the sample was coated with a thin layer of Coumarin 6 dye. The dye was dissolved in methanol, mixed with a plastic cement and then diluted with acetone. When applied to the waveguide surface, the solvents in the liquid evaporated, leaving a gelatinous suspension of the dye. The location of the green fluorescence caused by the evanescent field of the guided blue light identified the 6·5 μm period grating as the one quasiphasematched to the 820 nm fundamental.

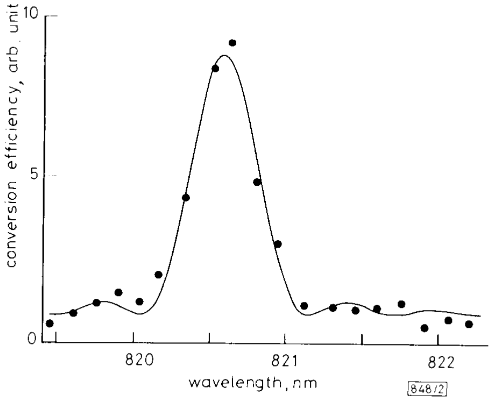

Fig. 2 *Experimental wavelength tuning curve for second harmonic generation with fitted sinc^2 curve*

FWHM is about 0·5 nm

Discussion: The normalised conversion efficiency η_{nor} is related to the conventional conversion efficiency η by

$$\eta = \frac{P_{2\omega}}{P_\omega} = \eta_{nor} P_\omega L^2 \tag{1}$$

where P_ω and $P_{2\omega}$ are the powers of the fundamental and harmonic, respectively, and L is the length over which quasiphasematching occurs. The normalised conversion efficiency η_{nor} accounts for the effective nonlinear coefficient of the material, the overlap of the fundamental and harmonic waveguide modes, and quasiphasematching.[7]

The normalised conversion efficiency η_{nor} within the waveguide is 350%/W cm^2, calculated by approximating the modal fields to be elliptical Gaussians with the measured $1/e^2$ diameters and neglecting the depth dependence of the domains. The difference between the theoretical and experimental values of η_{nor} is probably due to the reduced overlap of the actual asymmetric modal fields and the somewhat triangularly-shaped ferroelectric domains. Careful measurements of the modes and the domain shapes are underway to refine the overlap calculation.

From refractive index data for $LiNbO_3$, we can calculate the expected FWHM wavelength acceptance bandwidth for doubling using d_{33} to be about 0·4 nm mm. The observed FWHM of 0·5 nm for a 1 mm doubling length is in reasonable agreement with this value.

Future work on the devices involves increasing the length of the periodically poled region from 1 mm to 1 cm. This should increase the conversion efficiency by two orders of magnitude. With this improvement the observed normalised conversion efficiency of 37%/W cm^2 implies that 1 mW of blue light could be achieved with about 50 mW of fundamental power. Thus mW levels of blue light could be obtained by frequency doubling of diode lasers.

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565 Mbit/s AMI FSK COHERENT SYSTEM USING COMMERCIAL DFB LASERS

Indexing terms: Optical communications, Semiconductor lasers, FSK

Alternate mark invert (AMI) encoding is shown to overcome the low-frequency nonlinear FM response of DFB lasers. Results from an experimental heterodyne system are presented where the local oscillator (LO) and the signal carrier are at nearly the same frequency. This has the same sensitivity in theory as an ideal single-filter FSK detection system and offers the advantage of a compact optical spectrum when used in FDM systems.

Introduction: DFB lasers are now commercially available with linewidths less than 100 MHz. Such linewidths are acceptable for high bit rate, single or dual-filter FSK systems with modulation applied via the laser bias current. The combination of thermal and carrier density effects tends to produce a distortion of the FM response at low frequencies; NRZ formated data is particularly susceptible to this effect. Owing to the inversion in phase of the low-frequency thermal effect, a linear electrical network prior to the laser cannot give complete compensation; however a number of modulation formats have been proposed to overcome this problem.[1,2] This letter describes a simple modulation encoding technique which causes no inherent penalty with single-filter detection, has a compact optical spectrum and has advantages if used in an in-phase and quadrature (I&Q) or phase diversity system.