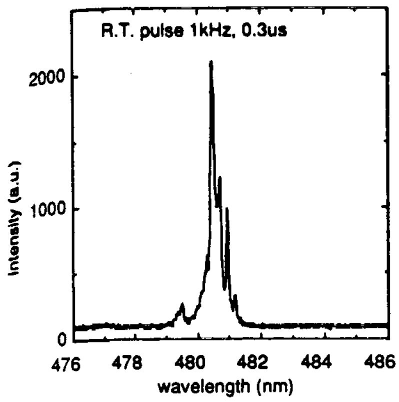
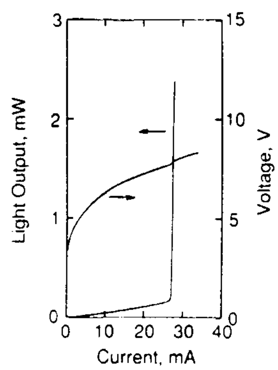


CWK1 Fig. 2. Emission spectrum for 480.5 nm-laser diode just above threshold current at room temperature.



CWK1 Fig. 3. L-I and V-I characteristics for a 507.5 nm-laser diode.

threshold current density was 460 A/cm^2 and the operation voltage was 7.9 V with 70/95% reflectivity facet. Figure 3 shows L-I and V-I characteristics for a 507.5 nm-laser diode. The stripe width of the electrode was 10 μm and the cavity length was 590 μm. The lifetime of this LD was about one minute at room temperature when it was operated in a cw mode at the output of 1 mW. The maximum output of this device was 30 mW/facet.

1. M. A. Haase, *et al.*, Appl. Phys. Lett. 59, 1272–1274 (1991).
2. N. Nakayama, *et al.*, Elect. Lett. **29**, 1488–1489 (1993).
3. H. Okuyama, *et al.*, Jpn. J. Appl. Phys. **30**, L1620–1623 (1991).
4. R. M. Park, *et al.*, Appl. Phys. Lett. 57, 2127–2129 (1990).
5. K. Ohkawa, *et al.*, Jpn. J. Appl. Phys. 30, L152–155 (1991).

CWK2 (Invited) **1530**

Porous silicon

L. Canham, *DRA/RSRE, St. Andrews Rd., Great Malvern, Worcester U.K. WR743PS*

Summary not available.

CWK3 (Invited) **1600**

Organic multiple quantum well: fabrication and optical properties

S. R. Forrest, *Princeton University Advanced Technical Center for Photonic and Optoelectronic Materials, Princeton, NJ 08544*

Summary not available.

CWL 1700

Forum

Frequency Doubling

R. Wallenstein, *Univesitaet Fachbereich Physik, Germany, Presider*

CWL1 **1700**

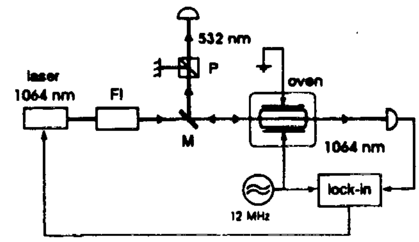
82% efficient monolithic frequency doubler

R. Paschotta, P. Kürz, K. Fiedler, R. Henking,* S. Schiller, J. Mlynek, *University of Konstanz, 78434 Konstanz, Germany*

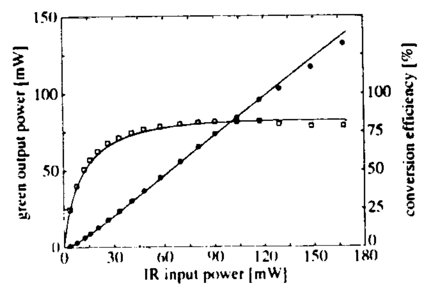
In the last few years there has been increasing interest in frequency doublers used as powerful light sources at wavelengths that are not directly accessible by suitable lasers. One important goal is to reach high conversion efficiencies; about 50% or more was achieved in several experiments,[1–4] most of them using $LiNbO_3$ (often doped with MgO) because of its high nonlinear coefficient and the uncritical type-I phase-matching for 1064/532 nm.

The highest conversion efficiency of 85%, however, was reported for KTP despite its lower nonlinear coefficient;[4] this material does not display a variety of deleterious effects, which are present in $LiNbO_3$, especially at higher power levels, e.g., thermal and photorefractive effects. KTP, however, causes some disadvantages; the required noncritical type-II phase-matching is not possible at the common wavelength of 1064 nm and requires two fundamental wave resonances to behold; the lower nonlinearity allows for high conversion efficiencies only at higher powers.

In this paper we show that high-quality $MgO:LiNbO_3$, combined with a low-loss monolithic resonator concept with optimized standing-wave geometry and special dielectric mirror coatings (optimized for impedance matching around 100-mW input power), can be used to achieve comparable high efficiency at considerably lower power levels, avoiding the technical difficulties mentioned above, since noncritical type-I phase-matching is possible at 1064 nm. Figure 1 shows the experimental setup, Fig. 2 the output power as a function of the input power and the power efficiency calculated from the same data. The solid lines refer to a fit of the effective nonlinearity. The simplicity and inherent stability of the device allows for very stable operation with a simple feedback loop locking the laser frequency to the fundamental wave length (see Fig. 1); we have measured variations of the output power (at 100-mW input power) of less than 1% within 30 minutes.



CWL1 Fig. 1. Experimental setup. The laser beam is mode-matched to the frequency doubler mounted in the oven, protected against backreflected light by the Faraday isolator (FI). The laser frequency is locked to the fundamental wave resonance with the lock-in feedback system. The polarizer P eliminates residual pump light.



CWL1 Fig. 2. Circles: measured second-harmonic output power as a function of the IR input power; the solid curve is a fit for the nonlinearity. Rectangles: conversion efficiency, calculated from the same data.

**Permanent address: Lazerzentrum Hannover, 30419 Hannover, Germany*

1. W. J. Kozlovsky, W. Lenth, E. E. Latta, A. Moser, G. L. Bona, Appl. Phys. Lett. **56**, 2291 (1990).
2. D. C. Gerstenberger, G. E. Tye, R. W. Wallace, Opt. Lett. **16**, 992 (1991).
3. D. H. Jundt, M. M. Fejer, R. L. Byer, R. G. Norwood, P. F. Bordui, Opt. Lett. **16**, 1856 (1991).
4. Z. Y. Ou, S. F. Pereira, E. S. Polzik, H. J. Kimble, Opt. Lett. **17**, 640 (1992).

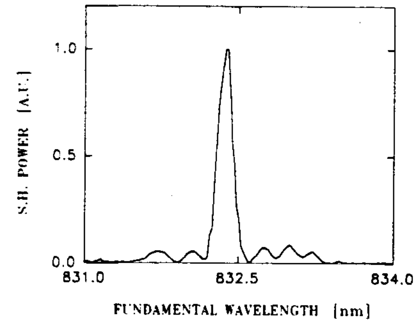
CWL2 **1715**

Periodically poled lithium niobate for bulk optical frequency doubling

J. Webjörn, V. Pruneri, P. St. J. Russell, J. R. M. Barr, D. C. Hanna, *Optoelectronics Research Centre, University of Southampton, Hants SO9 5NH, U.K.*

Quasi-phase-matching (QPM) has attracted much interest for second-harmonic generation (SHG).[1,2] In this paper we present SHG experiments in periodically poled lithium niobate, fabricated through field poling via liquid electrodes. The experimental phase-matching bandwidth of a 3.3-mm bulk crystal was equal to the theoretically expected value, indicating that the domain inversion was uniform throughout the volume of the crystal.

Liquid electrodes are well known for



CWL2 Fig. 1. Second-harmonic power as function of fundamental wavelength. A cw Ti:sapphire laser was frequency-doubled into blue by third-order quasi-phase-matching.

their benefits in electric field poling of ferroelectrics.[3] We have developed the method further to induce periodic inversion, exploiting the fact that ordinary positive photoresist inhibits domain inversion. We used liquid electrodes in the form of filter paper soaked in a solution of LiCl in water placed on both sides of a sample with a periodic photoresist pattern on one side. These were then clamped between electrodes connected to ground and a high-voltage pulse generator. In our initial trials, we found that it made little difference whether the photoresist pattern was applied to z^- or z^+, and indeed in later fabrication of periodic structures, we patterned z^-.

The best optical results to date were obtained in a 0.2-m thick sample with a domain period of 9 μm. It was used both for third-order SHG of cw blue light (416 nm) and for first-order SHG of pulsed yellow light (582.5 nm). After cutting and polishing, the crystal length was 3.3 mm. In the fabrication of this sample, we applied ten 4.5 kV pulses with a duration of 4 ms each. The current through the electrodes during each pulse was approximately 1 mA.

A cw tunable Ti:sapphire laser with a 0.04-nm bandwidth was used for third-order phase-matching. The spot size inside the crystal was w_0 = 18 μm, which gives a ratio of sample length to confocal length L/b = 0.63. The output SH power had a square dependence on the input power all the way up to an output of 20 μW for an input of 300 mW, which indicates that photorefractive damage does not occur.

Fig. 1 shows the third-order phase-matching peak. It has the bandwidth predicted by theory, just below 0.2 nm, demonstrating that the full length of the crystal was involved in the interaction. The conversion efficiency of 0.07%/Wcm was about ten times smaller than the theoretical value for a perfectly periodic crystal. We attribute this to random offsets of the domain-walls from their ideal positions. Visual inspection of the etched crystal surfaces confirms this.

The first-order experiments were carried out with a pulsed tunable optical parametric oscillator as pump source.[4] Nearly transform limited 1.6-ps pulses with 105-MHz repetition rate and 35-mW average power gave 1.4-mW average second-harmonic power at a wavelength of 582.5 nm. Power spectra were measured for both the fundamental and the second harmonic. The 0.4-nm bandwidth of the second harmonic agreed with the group velocity mismatch in the crystal.

In conclusion, the combination of pulsed electric fields, liquid electrodes, and a photoresist mask permits reproducible periodic poling of bulk lithium niobate. The periodically poled crystals exhibited no photorefractive damage when used for frequency doubling into the yellow and blue.

1. D. H. Jundt, G. A. Magel, M. M. Fejer, R. L. Byer, "Periodically poled $LiNbO_3$ for high-efficiency second-harmonic generation," Appl. Phys. Lett. **59**, 2657–2659 (1991).
2. W. K. Burns, W. McElhanon, L. Goldberg, "Second-harmonic generation in field-poled, quasi-phase-matched, bulk $LiNbO_3$," in *Compact Blue-Green Lasers*, Vol. 1, 1994 OSA Tech. Dig. Ser. (Optical Society of America, Washington, DC, 1994) pp. 38–40.
3. I. Camlibel, "Spontaneous polarization measurements in several ferroelectric oxides using a pulsed-field method," J. Appl. Phys. **40** 1690–1693 (1969).
4. M. J. McCarthy, S D. Butterworth, D. C. Hanna, "High-power widely tunable picosecond pulses from an all-solid-state synchronously-pumped optical parametric oscillator," Opt. Comm **102**, 297–303 (1993).

CWL3 **1730**

A multilayered semiconductor second-harmonic generator based on a new scheme of phase-matching in a cavity

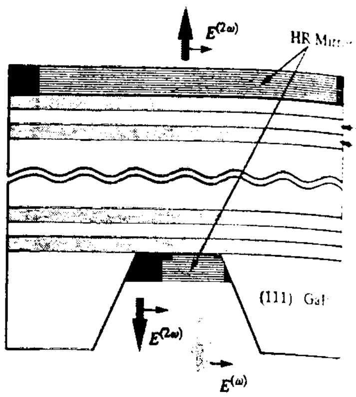
H. Takahashi, M. Ohashi,* T. Kondo,* N. Ogasawara, Y. Shiraki,** R. Ito,*
Department of Electronics Engineering, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo, 182, Japan

Our second-harmonic generation (SHG) device based on a new phase-matching scheme is illustrated in Fig. 1. Alternating layers of half-the-harmonic-wavelength ($\lambda^{2\omega}/2n^{2\omega}$) thick (111)-oriented GaP and AlP are inserted in a cavity. Because of the difference in the magnitude of second-order nonlinear optical coefficient d between GaP and AlP, the nonlinearity is modulated along the longitudinal axis of the cavity as shown by the square wave (n) in the lower part of Fig. 3.

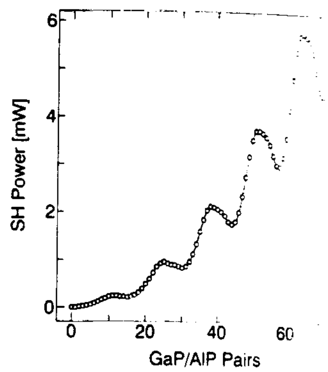
Figure 2 shows the harmonic output, calculated utilizing Green's function formalism combined with the transfer matrix technique,[1] as a function of the number of GaP/AlP pairs for a fundamental power of 100 mW (λ^{ω} = 1.064 μm) with a cross section of 10 μm^2. A harmonic output of ~6 mW is obtained from a device with 64 pairs only ~10 μm thick.

The high efficiency of the new device stems from the coexistence of two phase-matched SHG processes:

(1) The interaction between the forward and backward propagating fundamental waves in the cavity induces a nonpropagating component of the nonlinear polarization. The wavenumber



CWL3 Fig. 1. A second-harmonic generator incorporating GaP/AlP alternating layers in a cavity.



CWL3 Fig. 2. Calculated second-harmonic output as a function of device thickness. Parameters used as follows. GaP: n^{ω} = 3.11, $n^{2\omega}$ = 3.49, $\alpha^{2\omega}$ = 125 cm^{-1}, d = 45 pm/V. AlP: n^{ω} = 2.76, $n^{2\omega}$ = 2.94, d = 15 pm/V. λ^{ω} = 1.064 μm. A GaP/AlP pair is 0.1667 μm thick.

mismatch between the harmonic radiation and the nonpropagating nonlinear polarization component is $k^{2\omega}$. This is just compensated for by the modulation of d at a period of $\lambda^{2\omega}/n^{2\omega} = 2\pi/k^{2\omega}$.

(2) The forward-propagating fundamental wave consists of components with a wavenumber k^{ω} and a wavenumber $-k^{\omega} + k^{2\omega}$; the latter arises from the diffraction of the backward-propagating fundamental wave with a wavenumber $-k^{\omega}$ by the index grating with a period of $2\pi/k^{2\omega}$. The interaction between the k^{ω} and $-k^{\omega} + k^{2\omega}$ components combined with the DC component of d induces a nonlinear polarization with a wavenumber $k^{2\omega}$.

The curve (n) in the upper part of Fig. 3 shows the profile of rightward-propagating harmonic field when a fundamental wave is incident on the left end of the new GaP/AlP SHG device. The curve (c) shows the harmonic field profile in a device with the conventional quasi-phase-matching (QPM) structure composed of half-the-coherence-length ($l_c/2$) thick GaP/AlP layers. Further, the curves [illegible] and (c′) are the profiles in GaP(111)/($\bar{1}\bar{1}\bar{1}$) domain inverted structures with periods of $\lambda^{2\omega}/n^{2\omega}$ and l_c, respectively. The new device (n) proposed here [illegible] much more efficient than the conve