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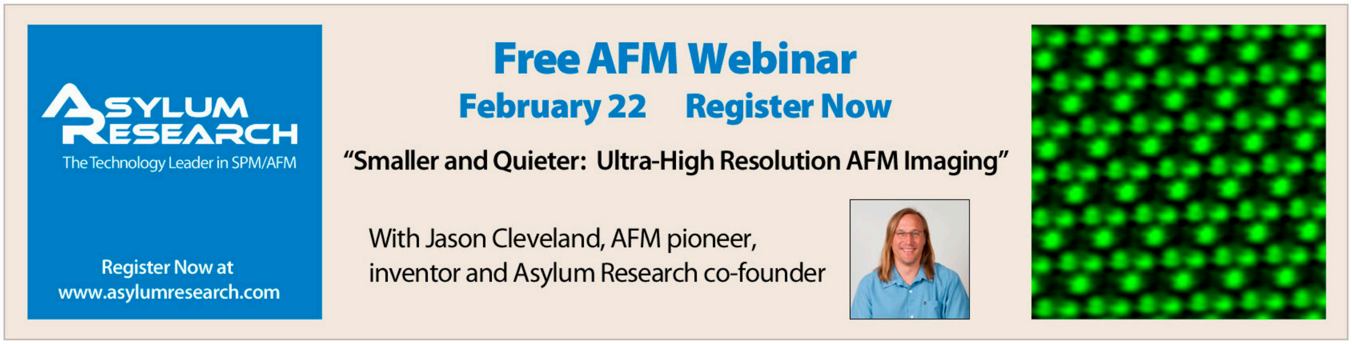

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Efficient continuous wave blue light generation in optical superlattice $LiNbO_3$ by direct frequency doubling a 978 nm InGaAs diode laser

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First-order quasiphase matched blue light generation in a $LiNbO_3$ optical superlattice was performed by direct frequency doubling of a continuous wave 978-nm diode laser. 1.27 mW output power of blue light was obtained with an incidence power of 500 mW. The frequency conversion efficiency is 0.25%. © *1996 American Institute of Physics.* [S0003-6951(96)01138-2]

Quasiphase matching (QPM)[1] techniques allow the light to be polarized such that the material's nonlinearity is maximized, and also permit use of material for which birefringent phase matching is not possible, e.g., the second-harmonic generation (SHG) of blue light in $LiNbO_3$ crystals using d_{33}, the maximum nonlinear coefficient. Periodic reversals in the sign of the nonlinear coefficient to compensate for dispersion is the main technique to achieve QPM and has recently been demonstrated in bulk [2] as well as in waveguide devices.[3,4] Alternating ferroelectric domains have been achieved in $LiNbO_3$, $LiTaO_3$, and KTP by modulating the dopant concentration during growth,[5] indiffusing dopants[6] applying electric fields,[7] or by techniques using electron beams[8] or SiO_2 masks.[9]

In $LiNbO_3$, QPM allows use of input radiation polarized along the *z* axis, for which the largest nonlinear coefficient $d_{\mathrm{eff}}=2d_{33}/\pi=20.9$ pm/v can be used.[10] SHG of blue light can be achieved in $LiNbO_3$ crystal through QPM. Thus, it makes the material attractive for frequency doubling of diode lasers to construct an all solid-state blue laser. The Czochralski method for growing crystals is one of the most important techniques to obtain $LiNbO_3$ (Ref. 10) or $LiTaO_3$ (Ref. 11) crystals with periodic ferroelectric domain structures (i.e., optical superlattice). Feng *et al.*[5,10,12] produced Czochralski-grown $LiNbO_3$ crystals doped with 0.5–1 wt % yttrium with domain thickness of 3.4 μm to frequency double the 1.064 μm Nd:YAG laser line. The observed conversion efficiency increased quadratically with the crystal length as expected for perfect domain periodicity up to crystal length of about 1.36 mm, corresponding to 400 domains. For longer crystals the increase was linear, revealing domain–boundary position errors on the order of the coherence length. These position errors are probably caused by variations in growth speed due to thermal fluctuations during the Czochralski growth. In practice, the creation of the required, finely spaced domain with sufficiently accurate periodicity is a challenging task. One of the authors of this paper has grown $LiNbO_3$ crystals with its modulating period ranging from 2.0 to over 15.0 μm.[13] The continuity and the periodicity of the domain structures are good for SHG experiments. Picosecond radiation at 430 and 490 nm (Ref. 14) light was generated in a 0.78 mm long and a 1.56 mm long samples with frequency doubling efficiency of 4.2% and 24.0%, respectively. Picosecond light as 385 nm was generated in a 0.98 mm long sample with conversion efficiency of 1.6% through third-order QPM.[15] For direct frequency doubling of a 810 nm GaAlAs diode laser, 0.35 mW of blue light was obtained for an incidence power of 250 mW.[16]

In this letter, we report harmonic generation of 490 nm in $LiNbO_3$ optical superlattice crystals by direct frequency doubling of a continuous wave (cw), 980 nm InGaAs diode laser. 1.27 mW blue light was obtained with an incidence power of 500 mW.

$LiNbO_3$ optical superlattice crystals were grown along the *a* axis by the Czochralski method, as reported in previous papers.[5,10,12] Samples were cut parallel to the periodic domain wall that is not exactly in the $b-c$ plane. Two samples (A and B), which have dimensions of $4\times4\times2.2$ mm^3 (here 2.2 mm is the crystal's length in the direction of propagation, which is nearly along the *a* axis) and $4\times4\times2.0$ mm^3 (2.0 mm is also the propagation length), respectively, have been chosen for our experiments. No antireflection coating was used on the two sample's light transmitting surfaces. The observed average modulation periods of the two samples, which were observed by an optical microscope on crystal's acid-etched *b* face, are 5.22 and 5.20 μm, respectively. In the two samples, the thickness of the positive domain laminae is nearly equal to the *t* of the negative (i.e., the average duty cycle of the domain grating is about 1/2). The average period fluctuations in the two samples are below 5%.

For characterizing the periodicity of the two samples, the relationship between SHG efficiency and fundamental wavelength in the two samples have been measured by using a tunable optical parametric oscillator (OPO) as fundamental source. Using first-order QPM, sample A has maximal SHG efficiency at fundamental wavelength of 975.8 nm when the fundamental light is at the normal incidence, and has an acceptance bandwidth of about 4.5 nm. Sample B has its maximal SHG efficiency at fundamental wavelength of 976 nm and has an acceptance bandwidth of about 4.0 nm. The large bandwidth of the two samples is primarily caused by the modulation period fluctuations along the growing direction

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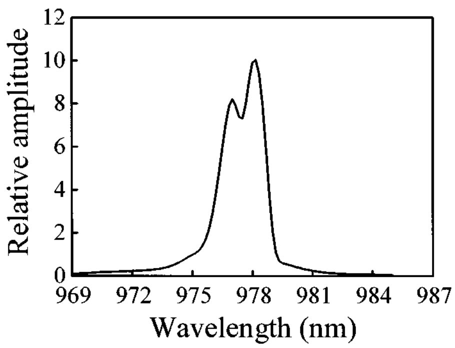

FIG. 1. The emission spectrum of the InGaAs diode laser.

(*a* axis). For frequency doubling the 978 nm light of our diode laser, the best QPM condition could be achieved by rotating the samples around their *c* axis (i.e., fundamental light is not at normal incidence).

The diode laser that we used was a SDL-6363-P1. The laser's output is continuous wave, multilongitudinal mode, and multitransverse mode. The diode laser has an emitting dimension of 100×1 μm^2 with beam divergence of $\theta_{+}36°$, $\theta_{\|}=16°$, respectively. In its parallel far-field energy distribution, two peaks exist (i.e., the output of the laser shows two bright horizontal bars). The diode laser's emission spectrum is shown in Fig. 1. Two maxims at 977 and 978 nm are evident. The emission linewidth of the laser is about 3.0 nm, and fully falls within the acceptance bandwidth of the two samples. Figure 2 shows the experimental setup. The output of the diode laser is collected to be nearly a parallel beam by a lens with a focal length $f=1$ cm, and is focused into the crystal by another lens with a focal length $f=5$ cm. Three filers, which have high reflectivity at 978 nm ($R>99.6\%$), were used to block the transmitted infrared light. The generated blue light is focused by a lens into a detector. The full convergence angle of the beam onto the sample is about 20°. The spot of generated blue light is circular. The divergence angle of the generated blue light beam is about 8° and is much smaller than the beam divergence (about 20°) of the transmitted infrared light.

The *c* axis of the crystal sample was parallel to the diode laser's polarization direction. The best QPM condition was achieved when the incidence angle of fundamental light is about 7°. Figure 3 shows the experimental results in samples A and B. We measured the relationship between the blue output power and the fundamental power (measured at the diode laser), in intervals of 50 mW, from 0 to 500 mW. The harmonic output increases nonlinearly with increasing fundamental power. When the incident fundamental power is 500 mW, the measured harmonic power generated in sample A and sample B reaches 1.27 and 1.0 mW, respectively, corresponding to a conversion efficiency of 0.25% and 0.20%, respectively. It is difficult to compare our observed efficiencies with the expected theoretical efficiency due to the difficulties in quantitative estimation of light beam quality. Our best obtained efficiency of 0.25% corresponds to about 2.27%/W cm and is lower than the expected theoretical efficiency of 8% W cm.[17] The expected efficiency is estimated for the case of a continuous wave, optimally focused, diffraction-limited, single-longitudinal-mode EM_{00} beam. Better power at the blue harmonic can be expected by improving the quality of the fundamental radiation beam of the diode laser through beam circularization and/or astigmatism correction.

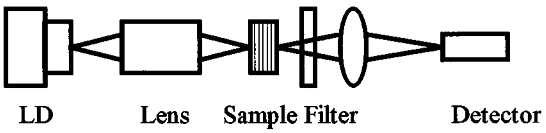

FIG. 2. The experimental setup of the direct frequency doubling scheme.

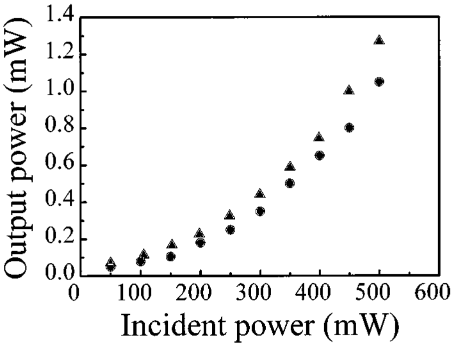

FIG. 3. The blue output power vs the fundamental power obtained both from sample A (symbol: ▲) and sample B (symbol: ●).

In conclusion, first-order, QPM, blue light generation in a $\mathrm{LiNbO_3}$ optical superlattice crystal by direct frequency doubling of a cw 978 nm InGaAs diode laser has been demonstrated. Second harmonic power 1.27 mW has been obtained at 489 nm.

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