ured data agree well with the theory for these values. For large Ge-layer thicknesses $\Delta > 0.2\mu m$, the measured threshold current agrees with curves representing smaller facet reflectivities. This behaviour is mainly caused by an increase of the facet roughness as discussed earlier and an increase of the Ge absorption which amounts to ~10% for $\Delta = 0.25\mu m$.

RIN measurements reveal a similar periodicity with changing phase brought about by an increasing Ge-layer thickness. The periodicity in RIN follows inphase with the threshold current characteristics.The RIN minimum occurs at a facet phase that also yields the lowest threshold current.

Conclusion: In summary, we have introduced a method for systematically changing the phase between the internal grating and the facets. We have demonstrated that the threshold current reveals an estimation of the overlap between the optical mode and the lossy region in a CC DFB laser diode. This simple method has the advantage of allowing the controlled modification of the laser operating conditions and thus the study of the influence of a saturable absorber on the laser dynamics.

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Frequency doubling a CW diode laser to generate 489 nm blue light in optical superlattice $LiNbO_3$

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Indexing terms: Semiconductor superlattices, Lithium niobate, Optical harmonic generation, Semiconductor junction lasers

The generation of 489nm blue light by direct frequency doubling a CW 978nm InGaAs diode laser radiation was demonstrated in optical superlattice $LiNbO_3$ crystals at room temperature. When the incident power was 150, 1.35mW and 1.0mW blue lights were achieved in the samples with and without an enhancement cavity, respectively.

Introduction: Compact solid state sources of coherent blue or green radiation are of considerable technological interest in certain applications, such as optical data storage, laser printing and spectroscopy. Diode-laser-based second-harmonic-generation (SHG) devices are now attracting more and more attention in the area. The primary concern for such devices is that of reliability and high conversion efficiency.

SHG through quasi-phase-matching (QPM) is a good technique to construct such blue-light sources because it can be phase-matched at an arbitrary temperature and over the crystals' entire transparency range of wavelength [1]. Using this method, several frequency doubling devices both in the form of waveguide and bulk were achieved in $LiNbO_3$ [2 – 4] and $LiTaO_3$ [5, 6] optical superlattice crystals (i.e. crystals with periodic domain structures).

In our previous works, we developed an effective method to grow bulk optical superlattice $LiNbO_3$ crystals via the conventional Czochralski process [7, 8]. $LiNbO_3$ optical superlattice crystals with modulation period number >200 and modulation period from 2 to >15μm have been successfully grown by the method [9]. Picosecond 430nm blue light generation in a $LiNbO_3$ optical superlattice sample with its modulation period of 3.4μm has been reported, the conversion efficiency being 4.2% [9]. Using third-order QPM, 405nm blue light was achieved by directly frequency doubling a CW 810nm GaAlAs diode laser. The output power was ~0.35mW with incident power of 250mW [10].

In this Letter, we report the 489nm radiation output by frequency doubling the output of a 978nm InGaAs laser diode in two $LiNbO_3$ optical superlattice samples through first-order QPM. To increase the conversion efficiency, an SHG enhancement cavity is employed by directly coating the well designed multilayer media films on one sample's faces.

Formation of samples: The $LiNbO_3$ crystals doped with 0.4wt% yttrium were grown along the *a*-axis. Because of the asymmetric temperature field [7], a periodic temperature fluctuation was induced on the solid–liquid interface (SLI). The fluctuation would cause the periodic yttrium concentration distribution along the growing direction that corresponded to a periodic space-charge-field (SCF) distribution. When the crystals were cooled down through the Curie temperature, the paraelectric to ferroelectric phase transition took place and the periodic domain structures were written in the crystal by the periodic SCF. If we choose proper rolling and pulling speed, the modulation period can be adjusted equal to $2L_c$, where L_c is the coherence length for the proper fundamental wavelength. In our experiments below, for the fundamental wavelength (output wavelength of the diode laser) of 978nm, the coherence length is 2.63μm, and thus the measured crystals should have the modulation of near 5.26μm to satisfy the QPM condition.

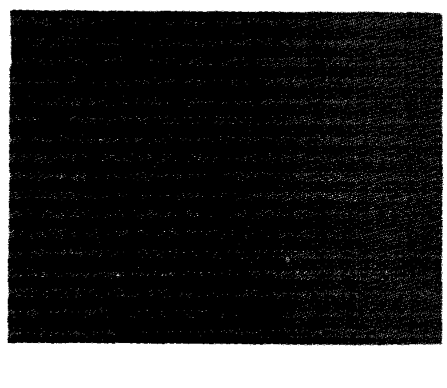

Fig. 1 *Optical microscope photograph showing periodic domain structures of etched b-face in $LiNbO_3$ optical superlattice sample*

Samples for the experiments were cut out parallel to the domain walls from the as-grown crystals, which have dimensions of 4 × 4 × 1.5mm³ (sample A) and 4 × 4 × 1.4mm³ (sample B), respectively. Fig. 1 shows the periodic domain structures of one sample's b-face after etching with 1HF:3HNO_3 for 10min at 100°C. It can be found that the continuity of the periodic domain structures is very good. The modulation periods of these two samples were finely measured on the etched faces with an optical microscope. We find that the average period of these two samples are both ~5.26μm; the period fluctuations are <4 and 5%, respectively.

The faces of the two samples were finely polished. To increase the blue light conversion efficiency, the two a-faces of sample B were coated with multilayer media films. Thus the input face has high reflectivity (R = 99%, where R is the reflectivity) at 489nm and high transmissivity at 978nm; the output face is highly reflective (R = 98%) for 978nm and highly transmittive for 489nm. From a simple theoretical analysis, the fundamental light will propagate double distance and the second-harmonic blue light will increase to nearly twice. As a comparison, sample A has not employed any coating. The measured transmissivity is >90% over all the visible and near-infra-red range.

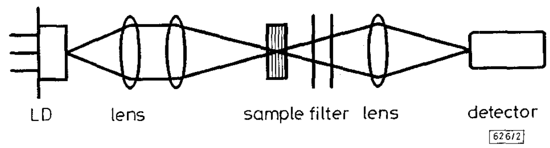

Fig. 2 *Experimental setup for frequency doubling a 978nm InGaAs diode laser*

Experiments and results: The experimental set up of frequency doubling the diode laser is shown in Fig. 2. The diode laser (SDL6362) radiation was collimated with a convex lens (f = 0.8 cm) and then focused with another lens (f = 2.0cm) to compress the light beam into an ellipse-like 1mm^2 spot normally onto the input face of the sample to be measured. The sample was put on a sample platform with its c-axis parallel to the fundamental light's polarisation direction. Two infra-red-cut filters were used to block the transmitted fundamental light completely. A 15cm focal length lens was used to focus the generated blue light into a detector. In our experiments, the fundamental power was adjusted from several milliwatts to 150mW.

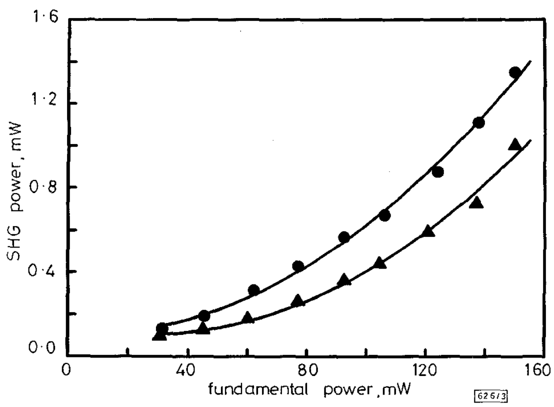

Fig. 3 *Second harmonic power at 489nm against incident fundamental power in sample A and sample B*

▲ sample A
● sample B

Fig. 3 shows the output blue light power as a function of the fundamental power with consideration of the blue light loss of the filters. Curves A and B correspond to the results of samples A and B, respectively. We can see that the SHG power becomes larger with increasing fundamental power. However, when the fundamental power is lower than 30mW, the output power of blue light is too small to be evidently distinguished from the noise, so there are no experimental data in this region. In sample B, as we expected, the blue light power was larger than that in sample A. When the fundamental power was 150mW, the output power of 489nm blue light in sample B was 1.35mW, and thus the SHG conversion efficiency was 0.9%, whereas in sample A, the blue light power was only 1.0mW, with a conversion efficiency of 0.67%.

The results show that the cavity can truly raise the frequency doubling efficiency. However, since sample B is thinner than sample A, so that the number of whole domain laminas is smaller than the latter, and the periodicity of sample B is also worse than that of sample A, therefore the output power of sample B cannot reach a higher level. Furthermore, the focusing system is not very adaptable to the output of the diode laser. So if we can improve the period stability of the $LiNbO_3$ superlattice crystals and use a more suitable optical system, for example, using an anamorphic prism pair [11] to compensate the ellipticity of the laser diode's output, the SHG conversion efficiency will greatly increase. This work is just beginning.

In the process of our experiments, no photorefractive damage in the crystal was observed. The output power of blue light is stable in the temperature variation range of ~20°C near room temperature. These two results show that the working performance of such a blue light device using the $LiNbO_3$ optical superlattice is very stable. However, we also found that the blue light output varied with the injected position across the samples, which indicates that there are defects in some regions in the periodic domain structures.

Conclusion: We report the SHG in $LiNbO_3$ optical superlattice samples fabricated by the Czochralski method. Efficient and stable blue light generation by frequency doubling a CW 978nm InGaAs laser diode was obtained at room temperature. Using an SHG enhancement cavity, 1.35mW 489nm blue light was generated from 150mW of fundamental power. The conversion efficiency was up to 0.9%. This allows us to develop a novel compact, efficient, blue laser device.

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