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High efficiency second harmonic generation with a low power diode laser

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Abstract. We demonstrate generation of 8 mW (10 mW corrected for the output mirror reflection) of the cw coherent blue light around 430 nm by frequency doubling of only 20 mW from a diode laser. With IR power of 90 mW we reach the doubling efficiency of 60%. The overall conversion efficiency from the electrical power into the blue light is 10%. By the way of careful analysis of the Blue Light Induced IR Absorption (BLIIRA) in the potassium niobate based external doubling cavity we obtain good agreement with the theoretical conversion efficiency.

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Diode lasers are attractive tunable laser sources due to their compactness and low cost. Narrow linewidths suitable for pumping external cavities and for spectroscopic applications [1, 2] can be achieved by stabilizing them with optical feedback. Furthermore, by pumping a diode laser with a well filtered current, it is possible to get light with amplitude fluctuations at or even below the shot-noise limit [3]. Compact visible lasers are interesting in several aspects, for example, in optical communications and storage and in atomic physics for laser cooling and spectroscopy. Therefore it is of interest to have a highly efficient converter from the infrared region into the visible and ultraviolet regions of the spectrum. Efficient external cavity doubling of diode lasers has been demonstrated in [4]. This method is advantageous because the second harmonic beam is automatically created with the same narrow linewidth as the fundamental source and can be directly used for, e.g. trapping and cooling [5] or to pump another frequency doubler to get into the ultraviolet region [6]. Although recent research has succeeded in developing blue-green diode lasers [7] they still lack long behind the red and infrared diode lasers with regard to spectral purity, efficiency and reliable operation at non-cryogenic temperatures. Our interest in efficient SHG is also driven by its ability to provide sub-shot-noise light in the blue as well as in the IR domains [8–11].

Although a substantial amount of work has been done on the blue light generation by frequency doubling of diode lasers (mostly in $KNbO_3$ – potassium niobate) [4–6] little attention has been paid to the analysis of the achieved doubling efficiency. In general, it is easier to reach high doubling efficiency at higher power levels due to the nonlinear character of the process. Efficient cavity enhanced doubling of low power diode lasers requires full understanding of the intracavity loss mechanisms which is the main purpose of the present publication. $KNbO_3$ possesses the highest among the commercially available crystals nonlinearity (up to $2\%\,W^{-1}cm^{-1}$), however, it does not deliver the external cavity doubling efficiency expected from its nonlinearity and passive losses. One of the main reasons for that is the process of BLIIRA [12–14]. We devote special attention to this additional nonlinear loss mechanism which enables us to understand the upper limit for the IR/blue conversion efficiency.

In the present paper we report the record efficiency (about 50%) for low power cw doubling with 10 mW (8 mW usable) of the blue generated from just 20 mW IR laser output. We also report 60% conversion for 90 mW input to the cavity. We demonstrate that the measured conversion efficiency is in good agreement with the values calculated from the measured intracavity losses, with BLIIRA included.

The experimental setup is shown in Fig. 1. A temperature stabilized SDL-5421-G1 150 mW GaAlAs index guided diode laser is driven by a low noise current controller, which is a homemade modified version of the one described in [15]. The diverging diffraction limited beam is collimated with a $f = 8$ mm lens. By external optical stabilization of the laser with a grating and a high-reflecting mirror in the Littman configuration [16] it is forced to operate on a single frequency around 860 nm. The holographic grating has 1800 lines/mm and gives about 6% of the power in the first order which is reflected at the mirror and gives overall 0.36% back to the laser (neglecting coupling losses). 86% is coupled out through the zero-th order of the grating. At the output after the grating we have up to 130 mW of infrared light, but the laser could only be operated single frequency up to a power of 110 mW at a driving current of 155 mA.

The elliptically shaped output beam is circularized by an anamorphic prism pair and modematched to a ring cavity. We have demonstrated that in this way the diode laser beam can be converted into a nearly perfect Gaussian beam. Indeed, we

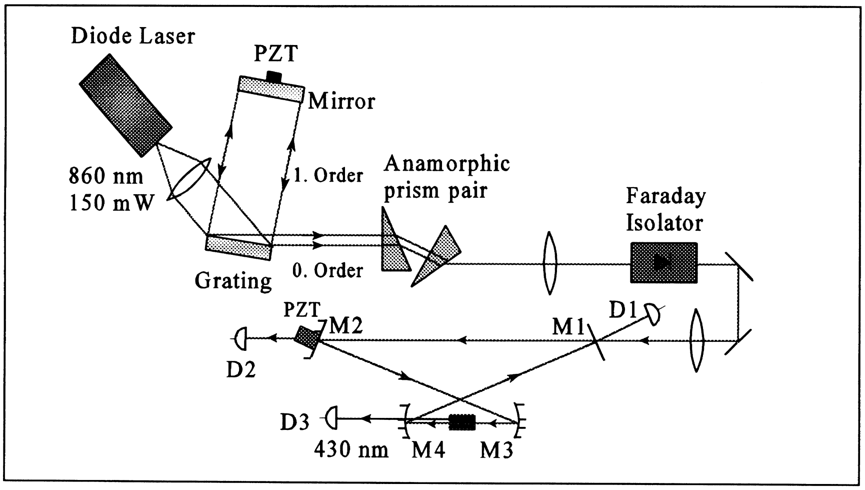

Fig. 1. Schematics of the experimental setup. M1 is the input coupler with transmission $T = 4.00 \pm 0.02\%$ at 860 nm. M2, M3, M4 are highreflectors at 860 nm. M4 has 81% transmission at 430 nm

have been able to get as much as 95% modematching of the diode laser beam into the TEM_{00} mode of the cavity.

The ring cavity consists of two plane mirrors and two curved mirrors with radius of curvature of 5 cm each. Three of the mirrors are high reflectors at 860 nm with a transmission about 150 ppm each, but transmit 81% at 430 nm. The input coupler is chosen to have a transmission $T = 4\%$, which is close to the optimal impedance matched value for our maximal available input of 90 mW given the intra-cavity losses and non-linearity of the crystal we happen to have. The distance between the curved mirrors is 6.1 cm and the total cavity length is 69 cm. The 10 mm a-cut and antireflection coated $KNbO_3$ crystal is placed in the focus between the two curved mirrors and the cavity is constructed to give a waist of 16 ¯m, which is chosen to get the optimal focusing for the given wavelength and crystal length [17].

The $KNbO_3$ crystal can be temperature tuned with a Peltier element to a precision better than 1 mK. In this way non-critical 90° phasematching is achieved near room-temperature. The cavity is locked to the frequency of the laser via FM locking technique [18]. The diode laser current is modulated at 20 MHz and the signal reflected off the cavity is mixed with the 20 MHz reference input to produce an error signal, which can be fed back to the piezo mounted mirror. In this way the cavity is held on resonance and stable cw blue output is produced.

Because of the extreme sensitivity of the diode lasers to optical feedback, we found it necessary to have 80 dB of optical isolation between the doubling cavity and the laser by using two Faraday isolators in series. This introduces a loss of 15% and leaves up to 90 mW of infrared to pump the cavity. The major feedback contribution is from the light scattered in the crystal, which is amplified by build up in the cavity. It has been shown before that control of this feedback can be used for an optical lock-in of the cavity [19].

At the output of the cavity we have observed up to 39 mW of the second harmonic blue light at 430 nm for 85 mW of modematched infrared input. The overall conversion from electrical power into the diode laser to blue light output from the cavity is 10%. The escape efficiency of the blue from the cavity is only 79% due to about 2.5% reflection at the crystal surface and 19% reflection at the output mirror. This could be improved much by a more narrow coating of the output mirror. When correcting for this escape efficiency of blue, we have 49 mW of blue inside the cavity at the crystal output which corresponds to a conversion efficiency of the infrared to the blue of 58%.

The scattering and absorption loss of the blue light is measured by illuminating the doubling crystal with the blue light from another cavity. The loss is 12%, but this is measured for a constant blue power propagating through the crystal. Inside the cavity the blue light builds up quadratically with the propagated distance in the crystal (in the plane wave approx-

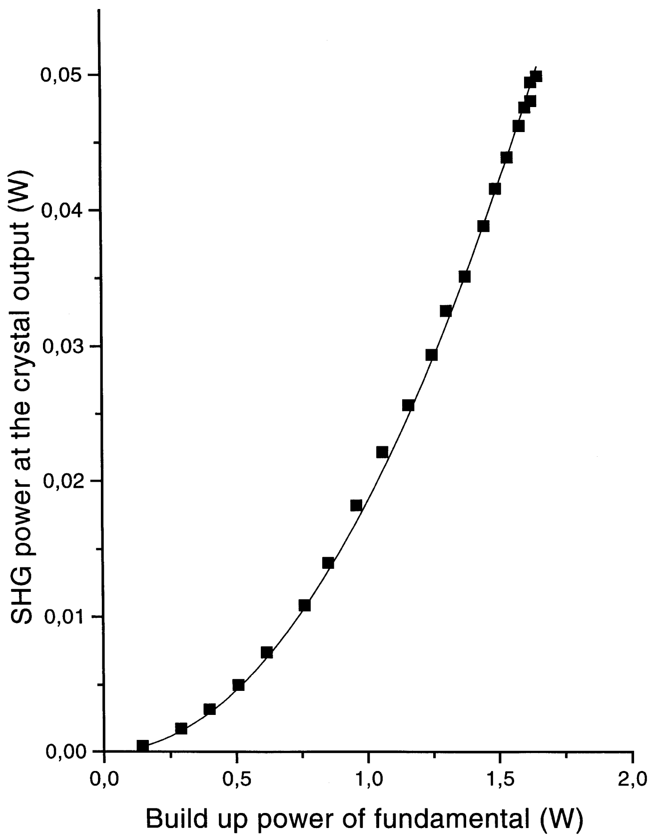

Fig. 2. The SHG power at the crystal output as a function of the fundamental power in the cavity. The fit gives the value: $E_{NL} = 0.0184 \pm 0.008\ W^{-1}$

imation), which means the loss only is $1/3$ of the constant power measurement, i.e. 4%.

The generated blue power at the crystal output depends quadratically on the IR build-up power inside the cavity according to the formula: $P_{2\omega} = E_{NL} P_{ins}^2$. The non-linearity E_{NL} depends on the focusing and the length and non-linear coefficient of the crystal. By measuring the transmission $T_1 = 137 \pm 0.6$ ppm of one of the high-reflectors the build-up power can be calculated with a properly calibrated photodetector.

In Fig. 2 we have plotted $P_{2\omega}$ as a function of P_{ins}. The quadratic fit gives $E_{NL} = 0.0184 \pm 0.0008\,\mathrm{W}^{-1}$. This is in agreement with the value measured in a single pass after removing the input-coupler. Minimizing the internal losses in the cavity is very important since the conversion efficiency depends strongly on them. Scanning the cavity with the piezo-mounted mirror gives the possibility of measuring the passive internal losses of the cavity when detuned away from phasematching. This is done by observing the resonance dip in the reflection off the cavity, and the losses are found to be $L_{pass.} = 0.74 \pm 0.03\%$ (excluding the input coupler transmission). The major contribution comes from losses in the crystal, since the overall losses on the mirrors are about 0.05%. The signal transmitted through the cavity can also be monitored, and the transmitted power is given by:

$$P_{tr.} = \frac{4\alpha T T_1 P_{inc.}}{\left(T + L_{pass.} + L_{BLIIRA} + P_{ins.} E_{NL}\right)^2} \tag{1}$$

where α is the modematching efficiency, T is the transmission of the input coupler and T_1 is the IR transmission of the output coupler highreflector. L_{BLIIRA} is an additional blue light induced absorption loss for the infrared fundamental, which arises when blue light is generated in the crystal. This inherent property of $KNbO_3$ is known to be the major limitation for the achieve able conversion efficiency [12, 13], and also for the amount of squeezing obtained in $KNbO_3$ based OPO's [14]. Away from phasematching the latter term in the denominator of (1) is zero. This is used to measure the BLIIRA loss by monitoring the transmitted power at phasematching and away from phasematching. This relative measurement is independent of α and P_{inc}. Figure 3 shows how BLIIRA for the crystal we have used depends on the level of the blue light generated. At highest powers BLIIRA reaches the value of 1.3% which unfortunately is twice as much as the value for the best samples reported in [12] for the same wavelength and amount of blue power. In figure 4 the measured conversion efficiency is plotted (the squares). It is seen, that it grows very rapidly but levels off at around 60%. The passive losses and BLIIRA are measured independently of the conversion measurement, so to check the consistency we have used (1) and the equation relating $P_{2\omega}$ to $P_{ins.}$ to calculate the conversion. The result of the calculation is also plotted in Fig. 4 (the triangles) and shows good agreement with the experimental results. The solid curve in the figure is the calculated conversion efficiency (corrected for 4% absorption/scattering of the

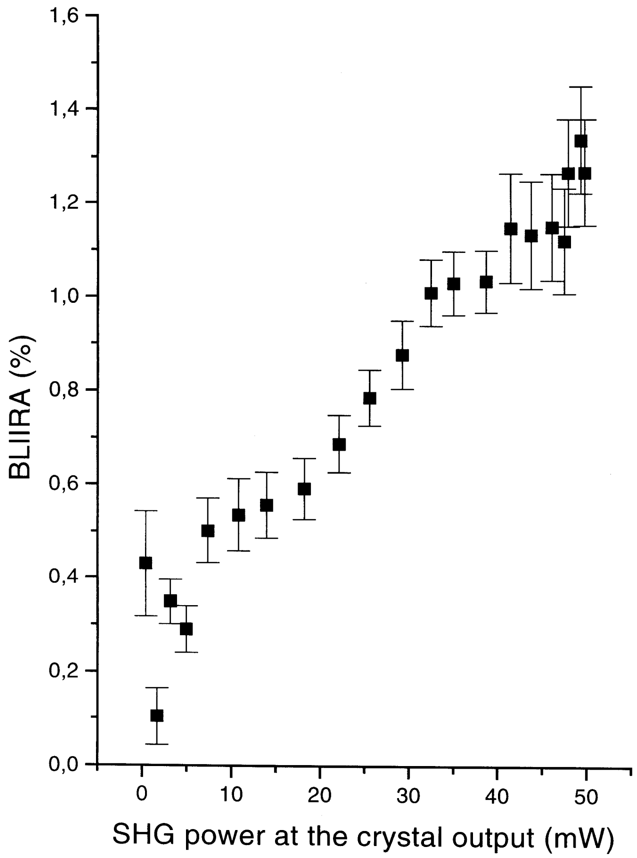

Fig. 3. Blue Light Induced IR Absorption (BLIIRA) measured as a function of the blue SH power at the crystal output

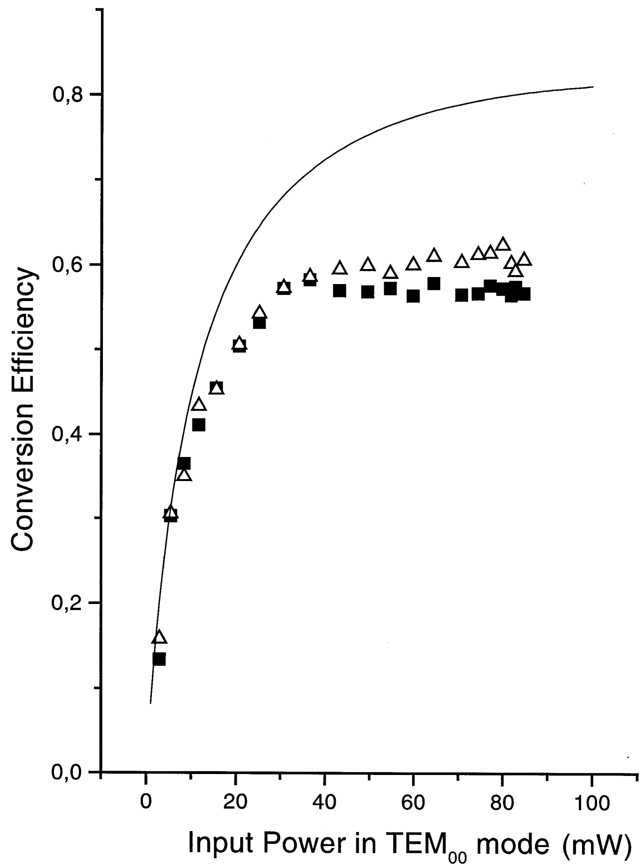

Fig. 4. The measured conversion efficiency as a function of the input fundamental power (the squares). The triangles are calculated conversion efficiencies with BLIIRA taken into account. The solid curve is calculated in the absence of BLIIRA

blue in the crystal) in the absence of BLIIRA. It is seen to follow the experimental points well at low powers where BLIIRA is negligible and at higher powers it shows that BLIIRA is really the limiting factor for getting higher conversion. In general there are large variations in BLIIRA from sample to sample probably due to different impurity concentrations, but the mechanism of BLIIRA is not yet fully understood [12]. It should be mentioned, that it's possible to reduce BLIIRA significantly by going to longer wavelengths [13] and hence higher phasematching temperatures.

In conclusion, we have demonstrated that 10 mW of coherent frequency tunable blue light can be generated by using only 20 mW of the diode laser output. Such an efficiency should be achievable within the whole phasematching range of an a-cut $KNbO_3$ between 420 and 460 nm. At higher powers we measure conversion efficiencies of up to 60% and explain the levelling off efficiency by the effect of BLIIRA. Future work will concern studies of the quantum noise of the second harmonic and the IR in such a system with special emphasis on the role of amplitude and phase noise of the diode laser on the second order cavity enhanced nonlinear processes.

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