Efficient green-light generation from waveguide crystal

M. Achtenhagen, W.D. Bragg, J. O'Daniel and P. Young

Data are presented of efficient single-pass green-light second-harmonic generation from a periodically-poled $LiNbO_3$ waveguide crystal. Over 220 mW maximum green light output power with an optical-to-optical conversion efficiency of over 70% is measured. Green-induced infrared absorption is indicated to be the major absorption loss in this waveguide. A simple analytic expression is derived and used to estimate the crystal waveguide absorption coefficient, which was found to be 7×10^{-3} cm^{-1}.

Introduction: Green-light emission is of great interest for many applications, including sensing, fluorescent measurement and projection displays. Recently, micro-projection displays based on red, green and blue (RGB) lasers have attracted much attention owing to their superior image quality. Additionally, they can be incorporated into handheld or mobile devices owing to their compact size and high wallplug efficiency. Blue and red lasers are already meeting the requirements of high-power, high modulation capability, high wallplug efficiency, and small footprint. However, efficient high-power green lasers have yet to be demonstrated. Second-harmonic generation (SHG) of light from an infrared laser diode in a waveguide crystal is a promising alternative approach to green-light generation with minimal sacrifice in terms of wallplug efficiency and footprint. A configuration consisting of a high-power distributed Bragg reflector (DBR) laser in combination with a lithium niobate ($LiNbO_3$) waveguide crystal has been successfully demonstrated, reaching green power levels of 184 mW with a conversion efficiency of 67% [1, 2]. In this Letter, a similar experimental setup for IR to visible green light conversion via a waveguide crystal is used to explore practical operating limits in terms of maximum green power and conversion efficiency. Data for record-high green-light power generation and optical-to-optical conversion efficiency above 70% are presented. Finally, a simple equation is introduced to estimate the green-induced IR absorption coefficient in waveguide crystals.

Experimental setup: A high-power single-frequency DBR laser diode is used as the seed laser for a Yb-doped fibre amplifier to generate stable narrow-linewidth power around 1064 nm [3]. The DBR laser diode is mounted in a standard 14-pin butterfly package with output coupling through a polarisation maintaining fibre. Maximum output power from these butterfly-packaged devices is typically limited to slightly greater than 200 mW under continuous wave (CW) conditions. To achieve higher output power for these crystal characterisation experiments, a Yb-doped fibre amplifier is directly coupled to the seed laser, as schematically shown in Fig. 1. The current and the temperature of the laser diode are maintained by Newport Model 560B and Model 3040 controllers, respectively.

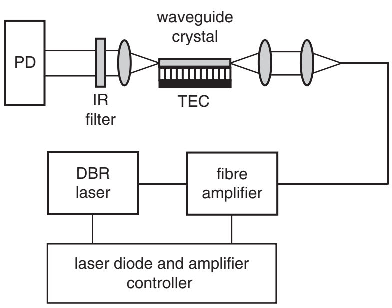

Fig. 1 *Experimental setup to demonstrate high-efficiency of waveguide crystal*

The fibre output of the amplifier is collimated and focused into the waveguide of a periodically-poled $LiNbO_3$ crystal by an aspheric lens pair (both with focal lengths of approximately 8 mm.) The cross-section of the waveguide is approximately 8×8 μm and the length is 22 mm. The 8 μm-thick $LiNbO_3$ crystal is fused to a 500 μm-thick $LiTaO_3$ wafer and the facets are angled-polished in order to suppress optical feedback. The crystal temperature is maintained by a Keithley Model 2510-AT thermoelectric cooler (TEC) controller with an accuracy of ± 0.005°C. The waveguide crystal and the TEC are mounted on an alignment stage with three micro-positioners to accurately control the optical coupling. Typical waveguide-coupling efficiencies between 60 and 70% are routinely achieved with this setup.

The waveguide crystal output is collimated and the remaining IR power is blocked by an IR absorptive filter. The second-harmonic power is directly measured with an ILX Model OMM-6810B optical multimeter and a Silicon OMH-6722B power head.

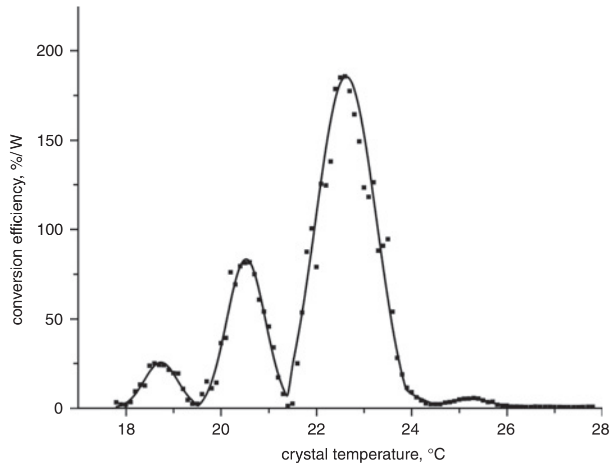

Fig. 2 *Measured data points and fitted wavelength tuning curve (solid line) against crystal temperature*

Results: Fig. 2 shows a measured temperature tuning curve typical for the sampled waveguide crystals. The maximum conversion efficiency varied between 200 and 400%/W depending on the specific waveguide selected. The curve-fitted data of Fig. 2 show an asymmetric deviation from the theoretical sinc^2 shape and is attributed to the non-optimised waveguide dimensions [4]. The 0.6°C full-width at half maximum conversion efficiency temperature span corresponds directly to the waveguide length of 22 mm [5].

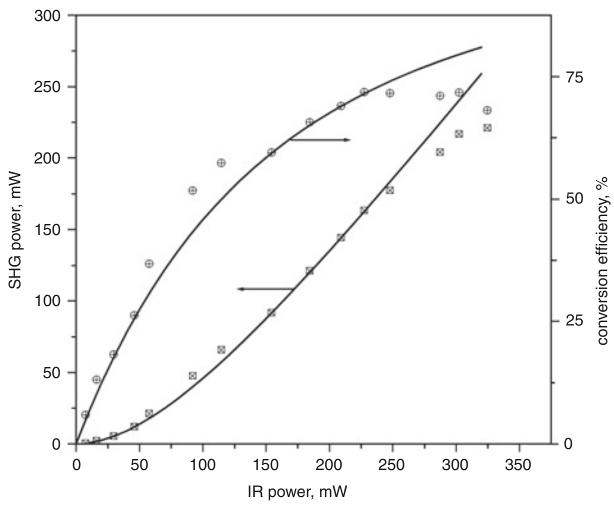

Fig. 3 *Measured second-harmonic power and conversion efficiency against IR power in waveguide*

Fitted curves (solid lines) obtained from analytic expression [5]

Waveguide second-harmonic output power and conversion efficiency data are given in Fig. 3. The results show that, for low IR waveguide pump power ($P_\omega < 100$ mW), the second-harmonic power increases following a square-law dependency and the optical-to-optical conversion efficiency increases linearly. With increasing IR power, the conversion efficiency begins to saturate owing to pump depletion and converges toward a maximum value approaching 75%. The green SHG output power peaks at around 220 mW and the maximum conversion efficiency is above 70%. As a consequence, the overall wallplug efficiency between a direct-coupled laser diode and a waveguide crystal can exceed 25% in this configuration (assuming a typical DBR laser wallplug efficiency greater than 50% and waveguide coupling efficiency of approximately 70%). To the best of our knowledge, this is the highest value of green-light power generated by single-pass frequency doubling of a DBR laser diode in a ridge waveguide configuration.

For IR pump power above 250 mW the conversion efficiency of the waveguide deteriorates and the second-harmonic power becomes saturated. Along with increasing IR power, a constant increase in the TEC current required for waveguide temperature stabilisation is observed. Part of the IR and green power is absorbed by the waveguide crystal and converted into heat. Previous work indicates that the dominant absorption loss originates from green-induced infrared absorption [6]. Attendant to the waveguide heating, an associated wavelength change is observed according to the following equation $\Delta\lambda = cR_{th}\Delta P_{diss}$, where ΔP_{diss} is the dissipated power, R_{th} is the thermal resistance of the waveguide crystal and c is the relative wavelength shift with temperature calculated to be 1.683 nm/K [7] for this material system. The thermal resistance was numerically calculated with a commercially-available two-dimensional finite-difference time-domain (FDTD) simulation tool and found to be 47.4 K/W. Relating the dissipated power to the absorption loss yields the following approximate relationship $\Delta\lambda \simeq \eta cR_{th}(1 - e^{-\alpha L})P_{\omega}$, where η is the coupling efficiency, L is the waveguide crystal length and α is the absorption loss, which contributes to direct heating of the waveguide. The above equations then serve to derive an approximate estimate of the green-induced IR absorption losses:

$$\alpha \simeq \frac{m}{\eta cR_{th}L} \qquad (1)$$

where m is a proportionality factor between the wavelength shift and the waveguide IR pump power.

Fig. 4 shows the results of a separate experiment, where the coupling efficiency between the laser and the waveguide was intentionally varied and the slope m calculated from the measured wavelength change. An average value for the absorption loss of 7×10^{-3} cm^{-1} is found. This value corresponds closely to previously reported values [6] and shows that the increase in IR absorption loss is approximately five times higher with the presence of green light in the waveguide.

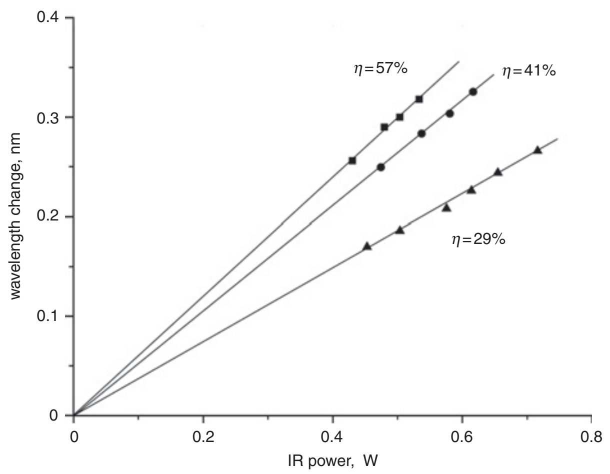

Fig. 4 *Measured heat induced wavelength change against IR power for three different coupling efficiencies and three corresponding linear fits*

Conclusions: A high-efficiency method for SHG of green light from infrared pumping of waveguide crystals using a DBR laser diode has been demonstrated. By using direct-coupling between the DBR laser diode and waveguide crystal, the setup can be integrated into a very compact module. Owing to the high wallplug efficiency, this module would be well-suited for portable applications. In this work, the maximum green power output was 220 mW, and the optical-to-optical conversion efficiency exceeded 70%. Practical upper power and conversion efficiency limits for SHG of green light in crystal waveguides are determined and attributed to green-induced absorption losses in the waveguides. By using the measured results and a simple derived equation, the green-induced infrared absorption coefficient in a $LiNbO_3$ waveguide is determined.

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