

High-efficiency frequency doubling of continuous-wave laser light

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We report on the observation of high-efficiency frequency doubling of 1550 nm continuous-wave laser light in a nonlinear cavity containing a periodically poled potassium titanyl phosphate crystal (PPKTP). The fundamental field had a power of 1.10 W and was converted into 1.05 W at 775 nm, yielding a total external conversion efficiency of $95 \pm 1\%$. The latter value is based on the measured depletion of the fundamental field being consistent with the absolute values derived from numerical simulations. According to our model, the conversion efficiency achieved was limited by the nonperfect mode matching into the nonlinear cavity and by the nonperfect impedance matching for the maximum input power available. Our result shows that cavity-assisted frequency conversion based on PPKTP is well suited for low-decoherence frequency conversion of quantum states of light. © 2011 Optical Society of America

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In quantum information science, low-decoherence interfaces are required in order to map quantum information from one system to another. Light at near-infrared frequencies, i.e., around 1550 nm, is well suited to distribute information over standard telecommunication fiber networks with low optical loss [1,2]. For quantum storage devices atomic transitions at around 800 nm are actively researched, in the pulsed as well as in the continuous-wave regime [3–5]. In order to link these frequency regimes, light at telecommunication wavelengths might be upconverted, e.g., by second harmonic generation (SHG) [6–8]. In past years a lot of progress in high-efficiency frequency upconversion has been achieved. In [9], a pump depletion of 99% was reported for 50 ns pulses. In [10], a single-photon conversion efficiency of 96% was observed. Here, however, the efficiency of the quantum state transfer was lower than this value due to a 25% background (dark) count rate. For second-harmonic generation of *continuous-wave* (cw) light [11,12], the highest external conversion efficiency reported so far is 90% [13]. This value also reflects the efficiency of the quantum state transfer since loss due to imperfect matching between input mode and cavity mode of the frequency converter was included and background and dark noise of the detection scheme was negligible.

In this Letter, we experimentally investigate the efficiency of cavity-assisted SHG of cw light at 1550 nm in PPKTP. This material is a promising candidate for reaching high quantum state transfer efficiencies, since the optical absorption of the material is low enough to observe up to 12.7 dB of quantum noise squeezing [14]. We are particularly interested in maximizing the *external* conversion efficiency, as given by the power ratio of the 775 nm cavity output beam and the 1550 nm input beam, i.e., our conversion efficiency value is not artificially increased by inferring to a situation with perfect mode matching into the cavity. In the case of intracavity

frequency doubling inside a laser resonator, a value of nearly 100% was recently observed [15]. To the best of our knowledge, we report the highest external cw second harmonic conversion efficiency observed so far. Our result is in full agreement with absolute values derived from a numerical model of the nonlinear cavity.

Theoretically, frequency conversion of up to 100% efficiency is possible in (lossless) nonlinear optical materials. In practice, a limitation occurs due to finite values of the nonlinearity of the material or of the optical pump power available, but in particular due to optical loss. A lack of pump power or nonlinearity can partially be compensated by using an optical resonator, but materials with low optical absorption eventually are essential for reaching high conversion efficiencies. Absorption directly reduces the conversion efficiency, but also limits the maximum value of the cavity finesse and the resonant field enhancement possible. Absorption also leads to heating, thermal lensing, and a deformation of the cavity mode limiting the conversion efficiency [16].

In the experimental setup (Fig. 1) we started with cw light from a 1550 nm fiber laser. After transmission through a three mirror ring resonator for spatial mode cleaning up to 1.1 W of the fundamental field was mode-matched into a standing-wave cavity containing a PPKTP crystal. A phase modulation was applied to the light field via an electro-optical modulator and used for active length stabilization of the cavity. Before the 1550 nm laser entered the frequency doubling unit, an antireflective coated substrate reflected part of the beam onto a photodiode *PD_input-monitor* in order to monitor power drifts. To separate the fundamental and harmonic fields, a dichroic beam splitter with $R_{1550} > 99.98\%$ and $R_{775} = 0.7\%$ was also placed directly in front of the PPKTP cavity. The PPKTP crystal [17] was plano-convex and had a dimension of $1 \times 2 \times 9.3 \text{ mm}^3$ with a quasi-phase-matching temperature of about 45°C . The curved surface had a radius of 12 mm and was dielectrically

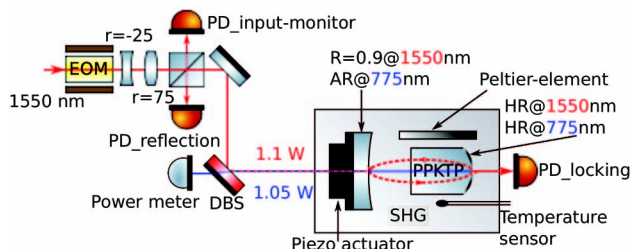


Fig. 1. Schematic of experimental setup. SHG, second harmonic generation with nonlinear PPKTP crystal; DBS, dichroic beam splitter to separate 775 nm and 1550 nm light; PD_input-monitor, photodetector monitoring power fluctuations of the 1550 nm pump field; PD-reflection, photodetector for relative measurement of the conversion efficiency; PD_locking, photodetector for the cavity length stabilization; EOM, electro-optic modulator producing sidebands of 138 MHz for the cavity length stabilization.

coated yielding a reflectivity of about 99.95% at the wavelengths of 1550 nm and 775 nm. The crystal's plane surface was antireflection coated ($R < 0.05\%$). We measured the absorption of the PPKTP to be $\alpha_{1550} < 0.01 \frac{\%}{\text{cm}}$ and $\alpha_{775} = (0.028 \pm 0.005) \frac{\%}{\text{cm}}$ for the fundamental and harmonic wavelengths, respectively, using the method described in [18]. The PPKTP cavity was completed by an external cavity mirror with 25 mm radius of curvature and with reflectivities $R_{1550} = 90.0 \pm 1.5\%$ and $R_{775} < 0.2\%$. The mirror had a distance from the plane crystal surface of about 24 mm, resulting in a cavity waist size of $w_0 = 37.6 \mu\text{m}$ and was attached to a piezoelectric transducer to scan and stabilize the resonator length. The measured mode matching of the TEM₀₀ mode into the SHG cavity was better than 98%, a value that sets an upper limit for our conversion efficiency.

For low absorption and scattering losses, a pump depletion measurement is a feasible technique to determine the conversion efficiency [9]. In our setup, this was done by detecting the 1550 nm light in reflection of the cavity using photodiode PD_reflection. For a cavity operated off-resonance the fundamental input field did not enter the cavity and, hence, gave a 0% conversion efficiency reference on our photodiode PD_reflection. When the nonlinear cavity length was set on resonance, the fundamental field entered the SHG and some fraction of it was converted to its harmonic, which appeared as loss on the detected signal. A reference for maximum conversion (100%) was measured by blocking all light in front of the photodiode. Figure 2 shows the result of our depletion measurement for a fundamental input power of about 1.1 W. Apart from the two reference levels, the graph shows the depletion for a swept cavity length and for a cavity length controlled on maximum conversion. Note that for an increasing conversion the high overcoupling of the cavity got slightly reduced. We could quantify this effect by our simulation and also by a measurement of the less pronounced reduction of the faint light transmitted through the cavity. In order to take into account this effect, we reduced our conversion efficiency value by 0.2 percentage points; however, this small correction was within the error bars of our final value of $(95 \pm 1)\%$. The error bar was given by measurement statistics as well as the nonperfect antireflection coating of the

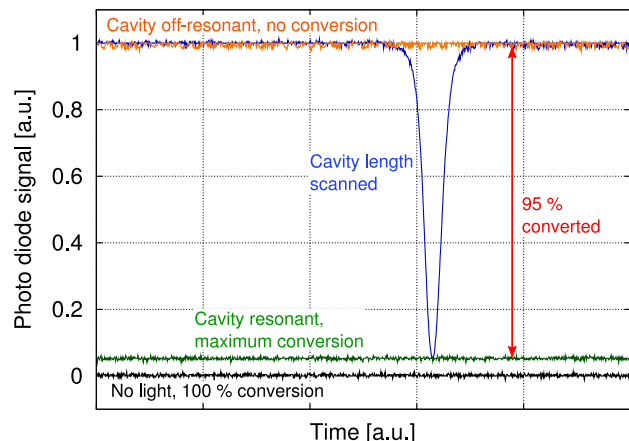


Fig. 2. Depletion measurement for a fundamental input power of 1.1 W. Bottom trace (black), no light on PD_reflection refers to 100% conversion. Top trace (orange), SHG cavity off-resonant refers to 0% conversion. Trace at about 0.05 (green), SHG cavity is stabilized on maximum conversion. Peaked curve (blue), scan of the cavity length over an Airy peak of the TEM₀₀ mode. The maximum conversion efficiency is 95%.

crystal, uncertainties on the absorption, scattering losses inside the crystal, and related changes of the overcoupling. The photodetector nonlinearity was estimated to be $\sim 0.1\%$ over the dynamic range used.

The data points with small error bars (black) in Fig. 3 present depletion measurements for reduced input powers. The data perfectly fits to the result from our numerical time-domain simulation (solid red line) setting the effective nonlinearity of our crystal to a value of $d_{\text{eff}} = 7.3 \text{ pm/V}$, which is in good agreement with the slightly higher value at 1064 nm, as determined in [19]. The simulation provides absolute power values for the second harmonic output field and thus for the conversion efficiency. It numerically applies a rigorous time-domain simulation of Gaussian beams interacting with the

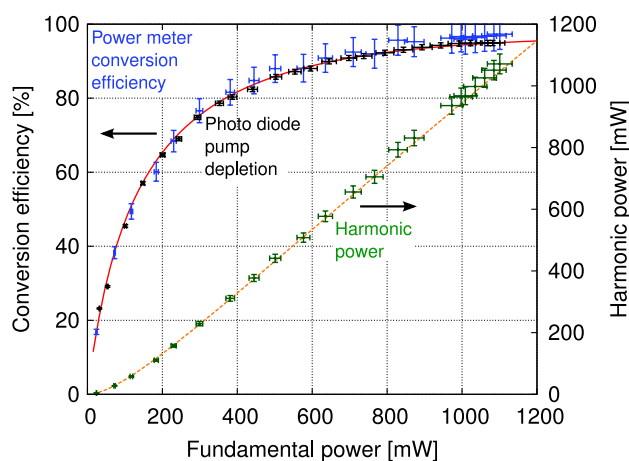


Fig. 3. Conversion efficiency and harmonic power (775 nm) versus fundamental input power (1550 nm). Data with small error bars (black): pump depletion measurements. Data with large error bars (blue and green): absolute power measurements at both wavelengths. The dotted orange line and the solid red line show the full simulation of our system based on independently determined parameters and a fitted crystal nonlinearity of 7.3 pm/V.

nonlinear medium inside an optical resonator. For this, the crystal is split into small segments of width Δz . Every segment's input and output modes (here fundamental and harmonic) are calculated analogous to a linear scattering mechanism. After each additional round trip the fields are compared with the preceding ones until a steady state is reached, which triggers the end of the simulation. For more details we refer to [20]. The input parameters of our simulation are the absolute input power at the fundamental wavelength, the cavity mirror reflectivities, and cavity waist size, as well as the crystal specifications, such as length, absorption at the fundamental and harmonic frequency, and indices of refraction.

In order to make an experimental consistency check we performed a second measurement using a commercial power meter (*Ophir Optronics*) with a thermal measuring head and an absolute error bar of 3% at both wavelengths. The data points are also shown in Fig. 3 (in blue). This data is indeed consistent, however, has considerably larger error bars and was not used to determine the conversion efficiency value reported here.

In conclusion, we observe an optical pump depletion of $(95 \pm 1)\%$ of 1.1 W cw laser light at 1550 nm through SHG in PPKTP. Based on independent measurements, we estimate absorption and other optical losses to be insignificant with respect to our error bar. Because of energy conservation, the depletion value therefore corresponds to the external conversion efficiency. The result is consistent with independent but less accurate measurements with a calibrated power meter. We also find very good agreement with a numerical time-domain simulation of our experiment. The simulation shows that our conversion efficiency is limited by the nonperfect mode matching and by the nonperfect cavity impedance matching for the maximum input power available. At a pump power of 1.3 W a maximum conversion of about 98% should be reached. From our results we expect that also nonclassical cw states of light can be frequency converted in PPKTP with similar efficiency.

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