High-power, single-frequency, continuous-wave second-harmonic-generation of ytterbium fiber laser in PPKTP and MgO:sPPLT

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Abstract: Characteristics of high-power, narrow-linewidth, continuous-wave (cw) green radiation obtained by simple single-pass second-harmonic-generation (SHG) of a cw ytterbium fiber laser at 1064 nm in the nonlinear crystals of PPKTP and MgO:sPPLT are studied and compared. Temperature tuning and SHG power scaling up to nearly 10 W for input fundamental power levels up to 30 W are performed. Various contributions to thermal effects in both crystals, limiting the SHG conversion efficiency, are studied. Optimal focusing conditions and thermal management schemes are investigated to maximize SHG performance in MgO:sPPLT. Stable green output power and high spatial beam quality with M^2<1.33 and M^2<1.34 is achieved in MgO:sPPLT and PPKTP, respectively.

OCIS codes: (190.2620) Harmonic generation and mixing; (190.4400) Nonlinear optics, materials; (140.3510) Lasers, fiber; (140.7300) Visible lasers.

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1. Introduction

Compact, high-power, green lasers are of interest for a variety of scientific and technological applications such as material processing [1], human surgery [2], and laser display technology [3]. In continuous-wave (cw), single-frequency operation, they hold promise as pumps for singly-resonant optical parametric oscillators (SROs) [4] and Ti:sapphire lasers. The combination of a cw infrared fiber laser and a simple single-pass second-harmonic-generation (SHG) scheme based on periodically poled nonlinear crystals is a potentially attractive approach for high-power cw green generation, not only because of its compact and practical architecture, but also due to the narrow linewidth and high spatial beam quality that are inherently transferable from the fiber pump laser to the green output. With the rapid advances in fiber laser technology, access to high cw fundamental powers of tens of watts is also no longer a limitation, making the choice of nonlinear material the most critical factor in the attainment of high optical powers and practical single-pass SHG efficiencies. In this regard, the most important material properties include high optical nonlinearity, long interaction length, noncritical phase-matching capability, and high optical damage threshold to withstand the large cw optical intensities. These requirements can be met by the new generation of quasi-phase-matched (QPM) nonlinear crystals. Although the well-established nonlinear material, periodically poled $LiNbO_3$ (PPLN), with high effective nonlinearity (d_{eff}~16 pm/V), can in principle enable SHG into the visible spectral range, in practice stable and room-temperature operation is problematic due to the photorefractive effect, with increasing difficulty at higher power levels. Doping PPLN with MgO (MgO:PPLN) not only reduces the photorefractive effect, but also increases the laser damage threshold. However, SHG into the green using MgO:PPLN is still limited by green-induced infrared absorption (GRIIRA) effects [5]. Periodically poled $KTiOPO_4$ (PPKTP), with relatively high effective nonlinearity (d_{eff}~10 pm/V) and high damage threshold [6], is another interesting nonlinear material for SHG into the green. With its low susceptibility to photorefractive damage, PPKTP can permit the generation of several watts of frequency-doubled green light at room temperature. However, the high sensitivity of PPKTP to defect-induced absorption, the so-called gray tracking, and other optically-induced thermal effects resulting from absorption of the fundamental and generated second harmonic green light, have been the major limiting factors in improving output power and beam quality. Despite these thermal effects, PPKTP has so far been effectively used for cw green light generation in various configurations. Earlier reports include single-pass SHG of a Yb:YAG thin-disk solid-state laser in PPKTP, providing 1.2 W of cw single-frequency green radiation for 13.6 W of fundamental power at a conversion efficiency of 8.8% [7]. Only recently, we reported a fiber-laser-based SHG device providing 6.2 W of cw single-frequency green output at a single-pass conversion efficiency of 20.8% [8]. At the same time, the emergence of other QPM nonlinear materials such as MgO-doped periodically poled stoichiometric $LiTaO_3$ (MgO:sPPLT) with improved optical and thermal properties [9], along with increased resistance to photorefractive damage and GRIIRA, has provided an attractive new alternative to further overcome the limitations due to thermal effects to permit cw green radiation at elevated power levels. Earlier reports include external single-pass SHG of a 91.5-W Nd:YAG laser in MgO:sPPLT, providing a maximum single-mode green power of 16.1 W at 532 nm at a conversion efficiency of 17.6% [10]. Most recently, we also reported the generation of 9.6 W of green radiation at 532 nm using single-pass SHG of a ytterbium fiber laser in MgO:sPPLT at 32.7% conversion efficiency [11]. Saturation of SHG efficiency and power has been observed in both PPKTP and MgO:sPPLT at high input fundamental powers due to thermal phase-mismatch effects [8,10], indicating that achieving high output power and at the same time retaining single-frequency operation along with good spatial beam quality are important challenges to overcome. Although it is pointed out that light-induced absorption at the fundamental [12] and second harmonic [10] wavelengths cause crystal heating, the true origin of thermal effects is still not completely clear. Hence, a comprehensive study of high-power SHG in both PPKTP and MgO:sPPLT is of considerable importance.

In the present work, we perform a detailed study and compare the characteristics of PPKTP and MgO:sPPLT crystals for high-power cw SHG in external single-pass configuration using a 30-W cw, single-frequency ytterbium fiber laser at 1064 nm. Temperature tuning properties of the two crystals are compared at different fundamental power levels up to a maximum available 30 W. Measurements at low input power of ~1 W are used to estimate the temperature acceptance bandwidth and effective nonlinearity of the crystals. Power scaling of SHG has been performed to characterize the crystals for maximum attainable green output, and power stability measurements are compared to gain insight into thermal effects that set in at high input fundamental powers. Optimal focusing conditions and thermal management schemes have been investigated to maximize output power and SHG conversion efficiency. Single-frequency performance and frequency stability characteristics of the generated green radiation are studied, and spatial beam quality measurements of the output are presented.

2. Experimental setup

The schematic of experimental setup for single-pass SHG experiments is shown in Fig. 1. The fundamental pump source is a cw ytterbium fiber laser (IPG Photonics, YLR-30-1064-LP-SF) delivering linearly polarized single-frequency radiation at 1064 nm with a maximum output power of 30 W with a power stability of <1% over one hour and a nominal linewidth of 89 kHz. Using a confocal scanning Fabry-Perot interferometer (free-spectral-range ~ 1 GHz, finesse ~ 400), we confirm single-frequency operation of the laser, with a measured linewidth of 12.5 MHz, limited by the resolution of the interferometer. The frequency stability of the fiber laser is measured to be <120 MHz over one hour and <50 MHz over 30 minutes [4], while the power stability is measured to be <1% over 65 minutes. An isolator at the output end of the fiber protects the laser from any back-reflections. Using a 25 cm focal length lens and a scanning beam profiler, we measured the laser to have a beam quality factor M^2<1.01. In order to maintain stable output characteristics, the pump laser is operated at maximum power and the input power to the SHG crystal is adjusted by using a combination of half-wave plate and polarizing beam-splitter cube. A second half-wave plate is used to obtain the correct polarization for phase-matched SHG in the nonlinear crystal. The fundamental beam is focused into the SHG crystal using a single lens, with the resulting beam waist positioned at the center of the crystal. The nonlinear crystals used in the experiments are bulk PPKTP [13]