Upconversion blue laser by intracavity frequency self-doubling of periodically poled lithium tantalate parametric oscillator


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We report a design for upconversion 435 nm blue lasers based on simultaneously fulfilling the nonlinear processes of optical parametric oscillation (OPO) and second-harmonic generation (SHG) in a 7.9 μm periodically poled lithium tantalate (PPLT). The uncoated 15-mm-long PPLT device exhibits a low threshold of 150 mW and a differential slope efficiency of 22.6%, rendering 56 mW blue generation when pumped by a pulsed 532 nm green laser with an average power rating of 400 mW. These observations were attributed to a quasi-phase-matching (QPM) structural design with a 75% domain duty cycle to ensure the concurrence of frequency doubling with the first-order QPM-OPO PPLT device via the second-order QPM-SHG process.

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Electric poling of ferroelectric crystals can initiate inverted domains at designated lattice sites by high field action, which is utilized to overcome the crystal’s coercive field [1]. For such an engineered ferroelectric crystal, there exists a set of structurally related reciprocal lattice vectors that compensate for the phase-mismatch effect accumulated by the interacting waves propagating through the crystal. A subtle effect of domain poling is that it flips the sign of the nonlinear susceptibility tensor χ(2) as the domain changes polarity. This phenomenon, when combined with a nonvanishing Fourier component χ(2), constitutes a quasi-phase-matching (QPM) mechanism that can facilitate efficient energy transfer in nonlinear optics [2,3]. Parametric frequency downconversion of IR generation [4] and second-harmonic generation (SHG) [5] are examples of nonlinear optical processes that have benefited from the QPM processes.

Moreover, by invoking 1D or 2D domain structure design, one can incorporate into the ferroelectric nonlinear photonic crystal a set of desirable χ(2) components to activate the cascaded harmonic generation processes [6,7]. Recent demonstrations of the third- and fourth-harmonic generation in a 1D quasi-periodically [8] and 2D periodically [9] poled nonlinear photonic crystal highlight such achievements. It further inspires interest to explore the feasibility of concurrent difference- or sum-frequency generation (SFG) with optical parametric generation or optical parametric oscillation (OPO) in QPM devices [10,11]. Aside from providing temporal controllability for synthesizing optical short pulses [12], frequency upconversion using the cascaded QPM-OPO and -SFG (or -SHG) processes can expand the laser spectral range into the short-wavelength regime [13,14]. In these applications, parasitic higher-order QPM processes can be incidentally excited in a nonlinear photonic crystal with large periodicity [15]. The latter, however, is known to constitute an undesirable loss mechanism and can lead to the increase of lasing threshold and reduce the nonlinear conversion efficiency.

Here we report a design for 435 nm blue lasers that invokes a self-frequency doubling process on the intracavity OPO signal wave of 870 nm in a single-period periodically poled lithium tantalate (PPLT) device. The governing mechanism is to simultaneously enable the nonlinear processes of first-order QPM-OPO and second-order QPM-SHG. With a 532 nm green laser used as the pump source, this proposal is realized in an engineered PPLT device with a periodicity of Λ=7.9 μm and a domain duty cycle of 75%. The undesirable energy loss path due to the third-order QPM-SFG process, between the green pump and the OPO idler at 1370 nm, can be eliminated by a temperature detuning effect. These considerations allow a cavity design of PPLT upconversion blue lasers to operate at a low threshold value of 150 mW and a differential slope efficiency above 20% when pumped by a Q-switched green laser with a 20 ns pulse width and a 4 KHz repetition rate.

To illustrate the design principle of the proposed upconversion blue lasers, we calculated in Fig. 1 the spectral and temperature tuning curves of a 7.9 μm period PPLT for (i) the signal wave in the first-order QPM-OPO process and (ii) the fundamental wave in the second-order QPM-SHG process. In the calculations, we considered the Sellmeier equation of refractive index for lithium tantalate [16] and a periodically poled domain structure of 75% duty cycle to maximize the second-order QPM-SHG process. A
phase-matching condition, in which a concurrence of an OPO signal wave at 870 nm and its frequency doubling at 435 nm exist, can be found at 150°C. In comparison, our calculations indicate that ultraviolet generation, via the third-order QPM-SFG process between the 532 nm pump beam and the OPO idler at 1370 nm, would occur at a much lower phase-matching temperature at around 20°C. The latter, which would otherwise act as an optical loss path to the SHG process, can thus be avoided by operating the device at a QPM temperature of 150°C.

We have recently proposed the use of charged domain boundaries to constrain the nucleation and motion of 2D inverted domains in LiNbO3 [17] and LiTaO3 [18]. It utilizes the depolarization charge effect to mitigate the local distribution of the poling electric field. This method was applied to realize PPLT devices in this work. As shown in Fig. 2, the optical micrographs, taken from the etched Y and ±Z face of an electrically poled LiTaO₃ sample, illustrate reliable pattern transfers to form inverted domains at a periodicity Λ of 7.9 μm and a duty cycle of ~75%.

The energy transfer routes associated with the concurrently activated OPO and SHG processes can be observed by their optical transmittance data. The experiments were conducted by placing an uncoated 20 mm PPLT sample A inside a cavity, which consisted of concave mirrors of 50 mm radius. The mirrors were designed to transmit \( T = 91\% \) the green pump and resonate \( R = 99.9\% \) with the OPO signal wave at 870 nm. The input–output mirrors also provided reflectivity \( R = 99.2\% \) and transmittance \( T = 68\% \) to the SHG blue light. We measured the transmittance of the green pump, the OPO signal, and the SHG of sample A at the QPM temperature (150°C). Then the sample length was gradually reduced to 10 mm by applying a cut-back method [19]. The data presented in Fig. 3 were normalized to their respective peak values corresponding to a pulsed green laser pump with an average power of 400 mW. We noted that the transmitted green power approached saturated values of 108 and 200 mW at PPLT crystal lengths of 20 and 10 mm, respectively. This phenomenon resembles the optical power limiting effect earlier reported for the doubly [20] and singly [21] resonant oscillators. In a steady-state operation, it signifies a pinning process of the oscillator gain at a threshold value and suggests that excess energy from the pump beam would be transferred to the phase-matched nonlinear optical process [22].

To evaluate the efficiency of the upconversion blue lasers, the lasing characteristics of another uncoated PPLT sample B were analyzed by using the crystal length cut-back technique. From the data shown in the inset of Fig. 4(a), one can identify a peak conversion efficiency at a PPLT length of around 15 mm, where the device exhibits a lasing threshold of 150 mW and a differential slope efficiency of 22.6%. The constraining factor for the conversion efficiency

**Fig. 1.** (Color online) Calculated spectral and temperature tuning curves for the QPM-OPO and -SHG processes in a PPLT device of a 7.9 μm period.

**Fig. 2.** Scanning electron micrographs of the etched \(+Z, Y, \) and \(−Z\) face of 1D PPLT sample A of 7.9 μm period.

**Fig. 3.** (Color online) Optical transmittance data of the green pump beam, the 870 nm OPO signal, and the 435 nm blue SHG light of the PPLT sample A at a crystal cut-back length of (a) 20 and (b) 10 mm (red dashed curves, linear fit to the transmitted power of the OPO signal wave).
can be understood by resorting to a Gaussian beam numerical analysis. It takes advantage of a model analysis [23] where the single-pass gain is to balance the optical loss (Γ), with the remaining signal inside the resonator phenomenally represented by 1−Γ=(T_{x}T_{cav})/(1−Σ). Here the factors T_{x} and R_{cav} represent the transmittance of the crystal facet and the reflectance of the OPO cavity at the wavelength of OPO signal light, respectively, and Σ is the distributed scattering loss. The calculation results, as shown in Fig. 4b, display the features of the OPO-SHG lasing threshold with the PPLT crystal length. Without loss of generality, we note that with 1% of the OPO signal radiation remaining inside the resonator, i.e., Γ=0.99, a differential slope efficiency above 20% can be observed for the coupled OPO upconversion process at a PPLT length ranging from 10 to 20 mm. A peak value of 26% for the blue upconversion efficiency can be inferred at an optimum crystal length of 15 mm, which matches the experimental value of 22.6% and reaches 65% of the theoretical value [24]. For the latter calculation, an optical loss-free system, with an effective nonlinear coefficient d_{eff} of √2d_{33}/π and d_{33}/π, respectively accounting for the first-order QPM-OPO and second-order QPM-SHG processes in a PPLT device of a 75% domain duty cycle, was assumed and d_{33}=13.8 pm/V [16]. The calculation reveals the subtlety of energy backconversion from the generated blue light as the interaction length exceeds an optimum value.

In summary, we have demonstrated the design of an upconversion 435 nm blue laser by simultaneously fulfilling the QPM-OPO and -SHG processes in 7.9 μm period PPLT crystal. These observations were attributed to a proper QPM structure, designed to inhibit the (i) the energy loss path due to high-order SFG and (ii) the energy backconversion due to excess crystal length to ensure low-threshold (<150 mW) and high-efficiency (differential slope >20%) operation of the device when it is pumped by a pulsed green laser.


References

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