Broadband and Triple-Wavelength Continuous Wave Orange Laser by Single-Pass Sum-Frequency Generation in Step-Chirped MgO:PPLN

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Abstract: We have demonstrated sum-frequency generation of a compact continuous-wave orange laser in a step-chirped magnesium oxide doped periodically poled lithium niobate in single-pass mode. A 974 nm laser diode was mixed with a C-band amplified spontaneous emission laser source to yield a triple-wavelength operation at 594.9, 596.9, and 598.6 nm with a maximum output power of 9.3 mW and broad bandwidth of ~4.4 nm. The triple-wavelength output power stability was ~2.5% in 30 min. This technique provides a path to generate broadband laser sources at shorter wavelengths which are potentially useful for biomedical and spectroscopic applications.

Keywords: lithium-niobate; sum frequency generation; quasi-phase matching; lasers

1. Introduction

Continuous-wave (CW) lasers in the visible wavelength have drawn increased interest over the past decades for applications in fundamental research, industry, and light displays. For example, orange lasers with wavelengths close to 600 nm assume a critical part in a plethora of present-day applications, for example, photodynamic treatment [1], flow cytometry [2], spectroscopy [3], astronomy [4], optogenetics and neuroscience [5], and laser projection shows [6].

Until now, there are no traditional diode lasers emitting in the near 600 nm because of an absence of appropriate direct band gap materials [7]. Despite noteworthy progress towards achieving the shortest wavelength in the orange range at 599 nm using direct emission by GaInP material, the approach is restricted in wavelength adjustability [8]. Therefore, the development of smaller and more efficient solid-state lasers with the utilization of a nonlinear effect is an attractive path for overcoming this restriction. Likewise, sum frequency generation (SFG), in particular, is a potential approach to generating orange light with periodically inverted structures [9]. The quasi-phase-matching (QPM) method utilizing periodically poled lithium niobate (PPLN) is very appealing for actualizing broadband SFG due to its several advantages [10]. Meanwhile, various CW light sources near the 600 nm wavelength region have already been illustrated using several approaches, for instance, use of resonant cavities in SFG [11,12], frequency doubling in Raman-shifted 1064 nm lasers [13], tunable output in Cr: Forsterite material [14], avalanche upconversion in Pr, Yb:BaY2F8 [15], and in quantum-well InGaP/InAlGaP semiconductor lasers [16]. Unfortunately, the input wavelength acceptance bandwidth in single-period structures is very restricted and also constrained in tunability. Nevertheless, non-uniform structures have been created, which are commonly more appropriate for
wide-band wavelength converters since they give numerous spatial vectors contrasted to single-period structures. Until now, the different ways of dealing with executing QPM range from single-period structures to Fibonacci optical superlattice [17], non-uniform [18], linearly chirped [19], apodized and un-apodized [20,21], and multi-sectioned [22]. A widely-tunable source within the 770 nm wavelength region has additionally been implemented based on chirped periodically poled lithium niobate with a phase matching bandwidth as extensive as 50 nm [23]. This advancement has prompted the use of a single crystal for the generation of several wavelengths in the visible range that are very reasonable for entertainment applications. For instance, a tunable orange laser in the range of 601 nm to 604 nm in quasi-periodically poled lithium tantalate (LT) superlattice has been implemented [24]. Additionally, more than 1 W optical parametric oscillator (OPO) tunable from 605 to 616 nm based on MgO:PPLN was implemented recently [25]. OPOs, emitting in the visible wavelength range, have also been utilized for high resolution Doppler-free spectroscopy, albeit, such OPOs are excessively bulky [26]. It would be more attractive to extend the QPM capabilities of the non-uniform poled structures, with fixed grating parameters, and, thus, further broaden the fundamental wavelength acceptance bandwidth. One of the more promising simple approaches to add reconfigurable abilities to step-chirped structures is by utilization of varying temperature distribution along the length of the crystal. The inhomogeneity of temperature distribution as a result of the thermal differences set at MgO:PPLN crystal facets, actsuates a wave vector mismatch in each step (with a different uniform period) resulting from non-uniform distribution of refractive index along the crystal length, i.e., different wavelength regions can be reconfigured. The temperature gradient method can viably chirp each grating section in a reconfigurable way and in this manner, introduces continuously adjustable abilities to the grating in contrast to fixed chirped grating in PPLN. This method offers an advantage over multi-grating QPM structures for some applications where lateral translation of the crystal is undesirable.

In this work, we demonstrate the generation of CW orange light using single-pass SFG phase-matching in a step-chirped magnesium oxide doped periodically poled lithium niobate (MgO:PPLN) crystal. The technologically important orange light is specifically generated using a 974 nm laser diode (LD) mixed with a C-band amplified spontaneous emission (ASE) laser source (1525–1565 nm). Multiple wavelengths in the range of 593–599 nm were obtained by applying a temperature gradient to the 21-mm crystal, which could find many potential applications in biomedicine and spectroscopy. To control the local heating of distinctive areas, two temperature-controlled thermoelectric ovens were utilized, therefore, controlling the fundamental wavelength acceptance bandwidth which adds a unique advantage of continuous reconfigurability and adjustable abilities to the step-chirped QPM structure. Therefore, this technique has the potential to expand the existing capabilities of step-chirped structures and is expected to additionally broaden the wavelength coverage of solid-state lasers in the visible spectrum. Up to 9.3 mW CW triple-wavelength output power was realized corresponding to ~20.3%/W normalized conversion efficiency.

2. Experimental Set Up

The schematic of the laser setup is shown in Figure 1.

Here, the MgO:PPLN crystal is a step-chirped structure with poling periods increasing from 10.1 to 10.3 µm in steps of 0.1 µm, and the length is 21 mm with three equivalent segments and intended to fulfill the phase-matching condition of the SFG process. We used the standard electric poling technique to fabricate the step-chirped QPM device on a 1 mm-thick z-cut MgO:LN crystal as reported in Reference [27]. After poling, the crystal was cleaned and wet etched in hydrofluoric acid (HF) to reveal the domain structure, and the end faces were optically polished. However, no anti-reflection coating was performed. It is important to note the difficulty in achieving the same QPM grating as the initially designed QPM mask because of fabrication errors which are expected to significantly affect the efficiency profile and bandwidth. By setting up a temperature gradient along the MgO:PPLN crystal, a chirp is induced in each section, henceforth, extending the input wavelength acceptance range. The
pump \((P_1)\), was a laser diode (LD) at 974 nm \((\lambda_1)\) of 0.20 nm spectral width, while the signal \((P_2)\) was a C-band (1525–1565 nm) amplified spontaneous emission (ASE) source \((\lambda_2)\). Using a 50:50 wavelength division multiplexer (WDM) coupler, we combined the output of C-band ASE and collimated with a C-lens before focusing at the center of nonlinear MgO:PPLN crystal with a 125 mm focal length plano-convex lens. The QPM period of the SFG grating, which combines \(\lambda_1\) and \(\lambda_2\) to yield \(\lambda_3\) in the 600 nm spectral region, was calculated using the Sellmeier expression for MgO-doped lithium niobate crystal at 25 °C [28].

![Figure 1. Schematic of the experimental setup. The beams are focused into single-pass MgO:PPLN to produce orange light by sum frequency generation (SFG). LD, laser diode, ASE: amplified spontaneous emission, WDM: wave division multiplexer; C-lens: collimator lens. Inset: close view of crystal gratings with different sections.](image)

We measured the maximum input powers to be \(P_1 = 229\) mW and \(P_2 = 200\) mW. The output power and bandwidth were evaluated using a laser power meter (PM100D, Thorlabs, Newton, NJ, USA) and a fiber spectrometer (BIM-6001, Brolight, Hangzhou, China), whereas the \(M^2\) factor was measured using knife-edge method with Beamgage (Ophir-Spiricon, Inc., Jerusalem, Israel) laser beam analyzer. At the output, the rest of the pump and signal wavelengths including other harmonics from the MgO:PPLN were filtered. Our device was set to attain a temperature gradient by specifically attaching the hot and cold temperature-controlled thermoelectric ovens (model TCS-100, CTL photonics, Fuzhou, China) with a precision of ±0.1 °C near the input and output faces of the crystal, respectively, subsequently forcing the heat flow through it. We set the thermal contacts at both ends of the MgO:PPLN crystal to be around 5 mm and measured the actual temperature of the MgO:PPLN crystal using a thermal camera (FLIR-E64501, FLIR Systems, Tallin, Estonia). \(\Delta T = T_1 - T_2\) represents the temperature difference between the two ends of the crystal, where \(T_1\) and \(T_2\) are the temperatures at the input and output faces of the MgO:PPLN crystal, respectively. Once different points along the crystal length attain distinctive temperatures (temperature gradient), perfect phase matching of various incoming wavelengths of the ASE can be achieved at those points by constantly changing the temperature limits as desired.

### 3. Results and Discussion

We first measured the sum frequency output spectrum at room temperature \((T_1 = T_2 = 25\) °C, \(\Delta T = 0\) °C) before setting up a temperature difference at the end faces of the MgO:PPLN. A fiber spectrometer with a resolution of ~0.8 nm was used to measure the orange light spectrum. A simultaneous triple-wavelength output at 594.9, 596.9, and 598.6 nm was observed as shown in Figure 2a. The relative intensities of the triple-wavelength operation could be varied to achieve dual-wavelength output by introducing a longitudinal temperature change to the MgO:PPLN crystal. Accordingly, a dual-wavelength operation was achieved at 594.9 and 598.6 nm (Figure 2b) by setting the temperature difference to \(\Delta T = 7.1\) °C \((T_1 \sim 41.2\) °C, \(T_2 \sim 34.1\) °C). This could be attributed to the longitudinal temperature change induced on the crystal that causes a variation of phase matching along the crystal, which either enhances or lowers the phase mismatching. Each incoming wavelength of the fundamental is quasi-phase-matched in a different crystal segment. The bandwidth of orange light would as well be broadened by increasing the temperature gradient of the MgO:PPLN crystal,
which has an effect of inducing a chirp within the crystal and allows to achieve several phase matching conditions, hence extending the SFG process to other wavelengths and widens the fundamental wavelength acceptance range of the MgO:PPLN crystal. Accordingly, the fundamental wavelengths that simultaneously meet the condition of energy (1/\(\lambda_3 = 1/\lambda_1 + 1/\lambda_2\)) and momentum conservation (\(\Delta k\)) will be upconverted in the PPLN, resulting in broad wavelength up-conversion. This effect is depicted in Figure 2c, which shows the broadened orange light output when the temperature difference was set at \(\Delta T = 22.1^\circ\text{C} (T_1 \approx 73.0^\circ\text{C}, T_2 \approx 50.9^\circ\text{C})\) with an effective bandwidth of \(~4.4\) nm. However, when the bandwidth is increased, the conversion efficiency is decreased as a penalty.

The calculated temperature profile along the MgO:PPLN crystal is shown in Figure 3 where we have used \(\Delta T = 22.1^\circ\text{C}\) since it relates to the widest bandwidth of the measured sum frequency up-conversion. It can be observed that shorter thermal contacts yield a linear temperature distribution contrasted with longer thermal contacts. Nevertheless, due to the limitations of our set up, we employed \(~5\) mm thermal contacts in our experiment. We note that it would be attractive to achieve a ‘flat-top’ spectra of the up-converted wavelengths by precisely adjusting the temperature distribution along the crystal length using several smaller temperature controllers, which may result in bandwidth broadening and also by using shorter thermal contacts.

Figure 4 depicts the characteristics of the CW orange light outputs as a function of the product of the fundamental powers \(P_1\) and \(P_2\). Without applying a temperature gradient, the
maximum triple-wavelength orange light output power of 9.3 mW was obtained. On this point, we steadily increased $P_1$ to 229 mW (maximum) while $P_2$ was fixed at a maximum of 200 mW. For $\Delta T = 0 \, ^\circ C$, an overall nonlinear conversion efficiency of $\sim 20.3\%/W$ was calculated using the relation $\eta_{SFG} = P_{SFG}/(P_1P_2)$, where $P_{SFG}$ is the sum frequency power. This is, however, lower than the theoretical value of $\sim 33.4\%/W$ calculated approximately from $P_{SFG} = 32\pi^2 d_{eff}^2 P_1P_2/(\Delta V P_0n_{SFG}c(n_1\lambda_2 + n_2\lambda_1))$ [29], where $c$ is the speed of light in vacuum, $\varepsilon_0$ is the permittivity in vacuum, and $d_{eff} = 2d_{33}/\pi$ is the effective nonlinear coefficient of MgO:PPLN $n_{SFG}$, $n_1$, and $n_2$ are refractive indices at $\lambda_{SFG}$, $\lambda_1$, and $\lambda_2$, respectively. We noted a reduced SFG power measured to be $\sim 22\%$ of its maximum (at $\Delta T = 0 \, ^\circ C$) when the SFG bandwidth is maximum (at $\Delta T = 22.1 \, ^\circ C$). The reduction in conversion efficiency is attributable to fabrication errors of the crystal structure. However, the efficiency of the up-converted output can be increased by using different approaches, for instance, use of high power fundamental lasers, focusing the two incident beams at the same point in the crystal, and/or by anti-reflection (AR) coating the crystal facets to minimize Fresnel reflection losses.

![Figure 4](image_url)

**Figure 4.** Measured SFG output power (green circles) as a function of the product of input fundamental power at $\Delta T = 0 \, ^\circ C$. The solid red curve is a quadratic fit to the SFG data using $P_{SFG} = \eta_{SFG}P_1P_2$, where $\eta_{SFG} = 20.3\%/W$ is the SFG normalized conversion efficiency determined from power measurements. The error bars include the uncertainty in the output power measurements.

The spatial profile of the orange light beam was measured with the knife-edge method using Beamgage (Ophir-Spiricon, Inc., Jerusalem, Israel) laser beam analyzer at a distance of $\sim 20$ cm from the output face of the crystal. The horizontal and vertical M$^2$ factors were measured to be $\sim 1.9$ and $\sim 2.1$ respectively. The degradation of the beam quality could be attributed to the use of a non-achromatic lens which leads to different focus positions inside the MgO:PPLN crystal.

Figure 5 shows the time dependence of the orange light output power at triple-wavelength operation over a period of 30 mins measured using the StarLab 2.11 software from Ophir, Incl., Jerusalem, Israel, indicating $<2.5\%$ fluctuation about 9.3 mW. This fluctuation can be attributed to the stability of both input lasers, fluctuation in temperature of the MgO:PPLN crystal, air currents and mechanical vibrations of the laboratory environment (Ophir-Spiricon Inc.).
In this work, we have demonstrated the generation of a compact continuous-wave (CW) orange light using a step-chirped magnesium oxide doped periodically poled lithium niobate crystal. Multiple wavelengths within 593 nm to 599 nm spectral range have been specifically produced using a 974 nm laser diode mixed with a C-band amplified spontaneous emission laser source. With a maximum incident power of 429 mW, up to 9.3 mW was achieved for triple-wavelength operation at room temperature. The output power stability for 30 mins was better than 2.5%. We believe the CW orange light output power can be further increased by using high fundamental power and will be potentially useful for biomedical and spectroscopic applications.

4. Conclusions

A compact tunable CW light source was realized using a step-chirped MgO:PPLN crystal which is particularly useful for biomedical and spectroscopic applications.

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References


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