In-situ study of multi-wavelength NIR OPOs and yellow-orange lasers from monolithic nonlinear photonic crystal

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Abstract: We reported the use of monolithic quasi-phase-matched nonlinear photonic crystal(QPM-NPC) to enable simultaneous dual-optical parametric oscillations(OPOs) followed by serial up-conversion processes to generate tri-wavelength yellow-orange lasers. We further resolve the spatial distribution of the OPO wavelengths and the up-conversion components inside cavity. Despite the non-resonant dual-signals were spatially separated due to path-enabled QPM conditions, the resonant counterpart of the dual-idlers, however, maintained spatially overlapped and so did on the generated yellow-orange waves. These results suggest that the parallel QPM-NPC design can generate multi-oscillations of OPOs simultaneously, and it can also assist in the generation of spatially overlapped multi-wavelength visible lasers.

Key Word—*Optical Parametric Oscillator, Intracavity up converter, multi-wavelength yellow-orange*

1. Introduction

Multi-wavelength yellow-orange lasers are desirable to biomedical image applications such as stimulated emission depletion (STED) microscopy [1] and colocalization analysis [2]. Prabhu et al. [3] recently reported four broad peaks emission, spanning from 552 nm to 708 nm, by manipulating Sm^{3+} concentration in the BaO-ZnO-LiF-B_2O_3 glass. However, the emission wavelength from the formal technique is highly relied on the transition energy levels of the rare-earth metal ions. In comparison, the QPM technique can be a more flexible approach for wavelength generation if the phase-matching structure can be properly design [4].

In this paper, we report on the design and in-situ observation of spatial mode distribution for multi-near infrared (NIR) oscillations and yellow-orange frequency-up conversion lasers from the textile-like periodically poled lithium tantalate. Our QPM-structure design of such NPC was schematically shown in Fig. 1. The device design was comprised of two parts, i.e., first of the OPOs segments followed by the serial sections of up-conversion processes for second-harmonic generation (SHG) and sum frequency generation (SFG). In this case the OPO part had two different QPM structures arranged in parallel. Since these two optical paths can offer sufficient gain when surpass the loss, one can expect to achieve simultaneous oscillation of dual OPOs. In the up-conversion part, it consisted of a step-chirp QPM design to satisfy the phase-matching conditions for SHG of the two independent idlers and their SFG.

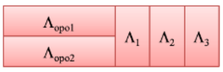

Fig. 1 Illustration of multi-wavelength visible laser design

2. Experimental setup and results

Details of the QPM structures, as shown in Fig. 1, were as follows. In the OPOs section, we had Λ_{opo1} of 7.66 μm and Λ_{opo2} of 7.68 μm, each of them had a length of 2 cm. In the up-conversion part, the length of each cascaded QPM periodicity was 0.3 cm, and their periodicities were 9.915 μm, 10.188 μm and 10.468 μm. The pumping source, shown in Fig. 2, was a Q-switched Nd:YVO_4 laser with repetition rate of 500Hz, pulse width of 7ns, and wavelength of 1064nm. A half wave plate (HWP) was used to rotate the polarization of the 1064nm laser, and a KTP crystal was used for frequency doubling of the 1064nm fundamental wave. The 532 nm laser was then focused into the NLO cavity by a lens with focal length of 40 cm. The input coupler (I.C.) and output coupler (O.C.) both had radius of curvature of 5 cm. The transmittance of I.C. was 94%(@532 nm), 85%(@ signal), 4%(@ idler) and 73% (@ yellow-orange). The transmittance of O.C. was 80%(@532 nm), 80%(@ signal), 30%(@ idler) and 60% (@ yellow-orange). And finally, the residual green pump was filtered out before we made in-situ observation of the OPO and up-conversion processes. A power meter (Ophir 12A-SH-V1) and optical spectrum analyzer (Agilent 86140B) were used for optical characterization of the aforementioned QPM laser, respectively. We added in Fig. 2, a home-built imaging system to observe the mode distribution of multi-wavelength laser either inside or outside the NLO cavity. In Fig. 3(a) to (b), we illustrate the measured optical power of the dual-signal waves, the dual-idler waves, and the tri-yellow-orange lasers with respect to the green pump beam. We denote a slope efficiency of 33%, 25% and 5.52%, respectively, can be achieved for the aforementioned OPO signals, idlers, and the up-conversion processes. Spectra shown in Fig. 3 (c) to (d) correspond to those of the dual-signal waves, the dual-idler waves, and the tri-yellow-orange waves. They confirm a compact design of using a QPM-NPC in a NLO cavity to enable simultaneous oscillation of two sets of NIR OPOs followed by collinear frequency-up conversion in the yellow-orange range.

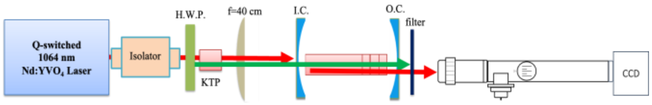

Fig. 2 Experimental setup of in-situ observation of multi-wavelength IR and yellow-orange laser

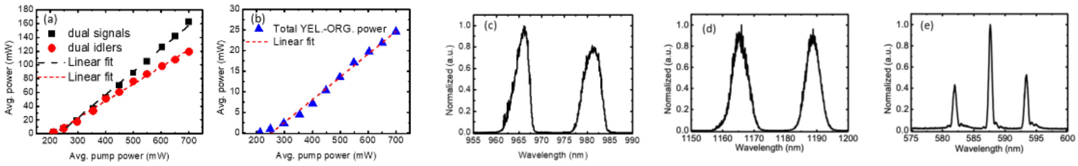

Fig. 3 Measured power of (a) dual-signals and dual-idlers (b) tri-yellow-orange laser. Spectrum of (c) dual-signals (d) dual-idlers (e) tri-yellow-orange laser

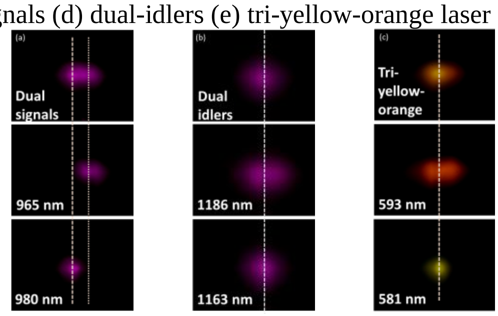

Fig. 4 In-situ spatial mode observation near the concave side of the O.C. (a) dual-signals, (b) dual-idlers and (c) tri-yellow-orange laser

Further shown in Fig. 4 are the spatial distributions of cavity modes measured from the O.C. side of QPM-NPC laser cavity of Fig.2. First, in the transverse plane of Fig. 4(a), one can clearly resolve the mode separation between of two signal waves corresponding to 965 and 980 nm wavelength. A classical reasoning of such mode distribution was that the NLO cavity didn't provide feedback on the modes of two signal waves, and thus they left the cavity after they were generated. In contrast, the transversal modes of the two idlers, at wavelength of 1186 and 1163 nm, were shown to be spatially overlapped in Fig. 4(b). Since the two idler waves were designed to confine and oscillate inside the NLO cavity, they correspond to the eigen modes of the NLO cavity when reaching the steady state condition. This would explain their modes of spatial overlapping along the beam propagation direction, either within or outside the NLO cavity. Such reasoning supports the observation of spatial overlapping in the mode distribution of the yellow-orange lasers in Fig. 4(c). Here we denote a one to one correspondence between the spatial modes of the idler waves in Fig. 4(b) and the tri-yellow-orange waves in Fig. 4(c). Despite we didn't have color filter for the SFG wave at 587 nm, the mode distribution of SHG waves at 581nm and 593nm follows the path of their idler counterparts at 1163nm and 1186nm, respectively.

3. Conclusion

Multi-wavelength NIR OPOs followed by visible SHG/SFG were demonstrated from a monolithic QPM-NPC made of textile-like PPLT. We measured a slope efficiency of 33%, 25% and 5.52%, corresponding to the dual-OPO signals, idlers, and cascaded SHG/SFG processes. Such parallel-path enabled OPOs design is shown to eliminate the gain competition process in the conventional approach of serial NLO, this technique would have great potential for multi-wavelength OPOs application. From the in-situ observation of the NLO laser mode distribution, we found that the resonant modes, i.e., the OPO-idler waves, would oscillate and spatially overlap as reaching the steady state, but the non-resonant counterpart of the OPO-signals would not. This suggests that even with more than dual-OPOs design, the transversal mode distribution of the resonant OPO-waves would remain spatially overlapped and behave as the cavity eigen modes.

References

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