UCRL-CONF-203140

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For submission to Nonlinear Optics: Materials, Fundament
and Applications, Waikoloa, HI, August 2-6, 2004

Studies of nondegenerate, quasi-phase-matched optical parametric amplification

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Abstract: We have performed extensive numerical studies of quasi-phase-matched optical parametric amplification with the aim to improve its nondegenerate spectral bandwidth. Our multi-section fan-out design calculations indicate a 35-fold increase in spectral bandwidth.

OCIS Codes: (190.4410) Nonlinear optics, parametric processes; (190.4970) Parametric oscillators and amplifiers

Quasi phase matching (QPM) is an established and preferred technology for compact, low-threshold, frequency-agile sources such as optical parametric oscillators. When used near degeneracy, QPM exhibits intrinsically broad spectral bandwidth, which has been previously explored to develop broadband optical parametric amplifiers (OPAs) and optical parametric chirped-pulse amplifiers (OPCPAs) [1,2] with high beam quality, high beam divergence tolerance, and high stability. When used far from degeneracy, however, simple QPM that utilizes constant, uniform periodically inverted direction of one of the crystal principal axes, is severely limited in its spectral bandwidth. It is thus necessary to consider more complex periodically poled (PP) designs to develop nondegenerate broadband OPAs. Such nondegenerate designs would benefit from potential favorable energy splitting ratio between the signal and the idler, allowing higher theoretical conversion efficiency than degenerate designs. Additionally, phase matching central wavelength and bandwidth could be designed to allow OPA and/or frequency conversion at an arbitrary center wavelength, allowing generation of tunable femtosecond pulses. Finally, nondegenerate QPM devices would exhibit high beam quality and low required pump power as a result of high nonlinearity and collinear geometry when compared to nondegenerate OPA in bulk crystals. In this work we have numerically modeled and optimized several PP-methods, with a goal to develop a general scheme for broadband OPA at an arbitrary central wavelength.

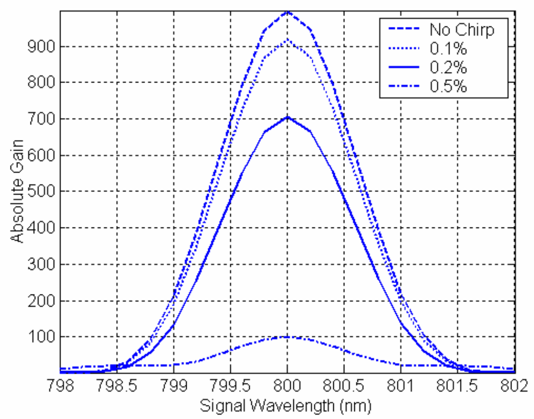

Fig. 1. Comparison of OPA with various degrees of linear chirp in 1-cm periodically-poled potassium-titanyl-phosphate (PPKTP) with signal and pump wavelengths of 800 nm and 532 nm and initial intensities of 1 W/cm^2 and 100 MW/cm, respectively. Chirp is centered at the calculated QPM period for the center wavelength.

A numerical model has been developed for the OPA process by direct solution of traveling-wave coupled-wave equations for an arbitrary structure. Electric field is calculated in each crystal domain for all spectral components of a broadband signal pulse. The crystal structure and length is optimized to maximize the spectral bandwidth both in the small-signal and the high-pump-depletion regime. Simulations were performed at signal and pump wavelengths of 800 nm and 532 nm, respectively, in potassium-titanyl-phosphate ($KTiOPO_4$) and stoichiometric lithium-tantalate ($LiTaO_3$). [3] Our selection of specific nonlinear crystals is based on minimization of effects such as green-induced infrared absorption (GRIIRA) and photorefractive damage.

We have first considered a linearly chirped PP, with its period centered for perfect QPM at the signal center wavelength. The results in Fig. 1 show a drop in gain and conversion efficiency with no significant increase in spectral bandwidth. Our analysis shows that this is the result of the fact that the incremental increase in the domain size does not produce an appreciable effective phase-matched distance at the wavelengths far from the central wavelength. Furthermore, this change also significantly reduces the effective phase-matched length for the central wavelength, thus decreasing overall gain. As a result, we show that the effect of linearly chirped PP is similar in effect to reduction of the nonlinear coefficient of the crystal.

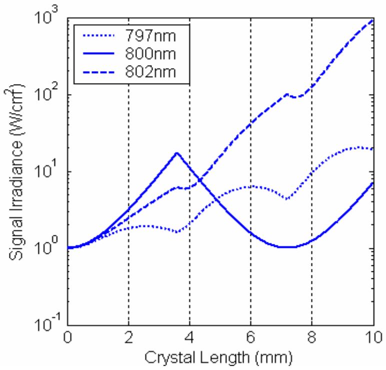

Fig. 2. Effect of phase discontinuity on OPA at central and peripheral wavelengths. Calculation corresponds to intensity distribution in a 1-cm PPKTP crystal with signal and pump wavelengths of 800 nm and 532 nm and initial intensities of 1 W/cm^2 and 200 MW/cm^2, respectively.

We next considered aperiodic PP-designs, where periodic discontinuities are used in the usual PP-pattern with a goal to introduce a systematic phase shift for spectral components that accumulate large spectral phase. The strategy of this correction is to produce higher order QPM at constant spacing from the center frequency, resulting in a frequency “comb”. The results are shown in Fig. 2. A considerable increase in gain occurs for spectral components corresponding to corrected phase shift; however, gain at the central wavelength is considerably reduced due to accumulated phase mismatch. This method has been previously considered for amplifying signal sidebands in optical communication; however, spectrally uniform gain is necessary for high-fidelity amplification of ultrashort pulses or for generation of broadband light. A potential application of this method is compensation of gain narrowing by producing a double-hump spectrum prior to injection into a gain-narrowing laser medium.

Finally, we studied transversely structured PP, [4] which utilizes transversely varying PP-periods in combination with spectrally dispersed beams. In this way, spectral content of the signal or pump can be spatially separated and mapped to different spatial positions. Spatial nonuniformities in crystal properties such as PP-period can then be introduced, allowing nonlinear conversion of different spectral components at different positions. A practical example of implementation of this design is shown in Fig. 3(a). A zero-dispersion pulse stretcher setup can be used to produce collimated dispersed beams, which can be subsequently amplified in a nonlinear crystal. Cylindrical lens in combination with a diffraction grating and a roof mirror can be used for both forward and backward propagation; in a reverse pass the beam does not pass through the thin QPM crystal.

Our calculations that utilize a 300 mm^{-1} diffraction grating and a f=300 mm cylindrical lens show that a linear transverse increase in PP domain size produces spectral broadening of a factor of ~15, limited by the departure of the actual transverse distribution of wave vector mismatch from linearity. We have determined that the origin of this departure of wave vector mismatch from nonlinearity is due almost entirely to material dispersion, with a very small (<1%) contribution of the angular dispersion of the diffraction grating.

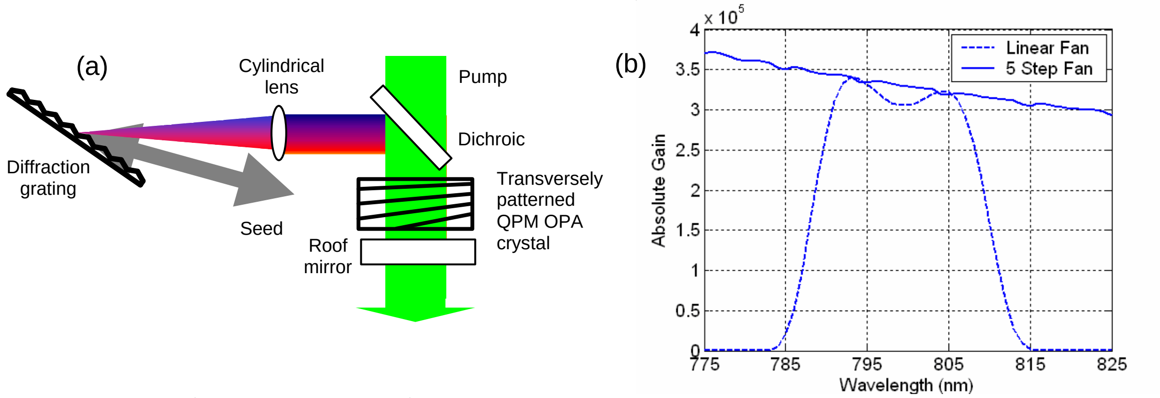

Fig. 3.(a) Principle of an experimental setup for transversely-patterned QPM. Broadband signal is spectrally dispersed and collimated before injection into a QPM crystal in a zero-dispersion stretcher-like device. Pump beam is coupled into the crystal through a dichroic beam combiner; (b) small signal gain for a 15 mm long stoichiometric lithium tantalate (SLT) crytal with a linear fan-out design and a 5-step fan-out design approximating the wavevector mismatch distribution. Calculations were performed for signal and pump wavelengths of 800 nm and 532 nm and initial intensities of 100 W/cm^2 and 100 MW/cm^2, respectively.

If the actual, dispersion-dominated, wavevector mismatch distribution is approximated \\ a series of small linear sections, much broader spectral bandwidths are possible. Specifically, we have approximated the calculated wave vector mismatch curve that includes angular and material dispersion with a series of 5 linear sections, in an effort to mimic the device that is manufacturable. Our results show that such a device produces a ~35-fold spectral broadening in the same setup – Fig. 3(b)). Approximating the wave vector mismatch with a large number of linear sections is a straightforward way for increasing the spectral bandwidth. While the alignment of spectral components on the exact transverse section of the QPM crystal is required to produce significant gain at that position, this is not a limitation in practice. Due to finite beam size, small but finite bandwidth is present at any position, which eliminates the need for stringent tolerances in crystal manufacturing and alignment.

In conclusion, we have systematically investigated several modifications of simple QPM in order to increase its spectral acceptance in nondegenerate OPA. Our most encouraging results are obtained using a transversely patterned QPM design. A design based on such structure is manufacturable and will be beneficial as a possibility to achieve universally tunable broadband parametric devices. Applications of such devices include broadband frequency converters and optical parametric amplifiers and chirped-pulse amplifiers which can be extended into single-cycle, full-octave regime.

This work was performed under the auspices of the U. S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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