UCRL-JC-123040
PREPRINT

CONF-960163--9

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MAR 18 1996

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This paper was prepared for submittal to the
Photonics West '96 Symposium
San Jose, California
January 27 - February 2, 1996

January 27, 1996

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OPO performance with an aberrated input pump beam

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ABSTRACT

The performance of an optical parametric oscillator (OPO) with non-ideal input pump fields is investigated numerically. The analysis consists of a beam propagation calculation based on Fourier methods including walk-off in the non-linear crystal coupled with the three-wave interaction in the crystal. The code is time dependent enabling analysis of laser pulses. The pump beam aberrations are described by Zernike polynomials. The OPO investigated is a LiNbO₃ crystal in a flat-flat resonator. The LiNbO₃ crystal is cut to produce a 1.5 μm signal and 3.6 μm idler from a 1.06 μm input pump field. The results show that the type of aberration is significant when predicting the output performance of the OPO and not simply the beam quality or M^2 angular divergence of the pump beam. While thresholds for input pump beams with $M^2=2$ only increase on the order of 10% over unaberrated beams, the divergence of the output fields can be much worse than the pump beam divergence. The output beam divergence is also a function of the input pump energy. Aberrated pump fields can also lead to angular displacements between the generated signal and idler fields.

Keywords: Optical parametric oscillator (OPO); Singly resonant oscillator (SRO); OPO modeling; Three-wave mixing

2. INTRODUCTION

Optical parametric oscillators (OPOs) have emerged as efficient devices for producing radiation in the mid-IR for applications such as the remote sensing of effluents. Their utility for these applications is determined by the efficiency and quality of the OPO output. In this paper, the performance of OPOs is investigated numerically for various aberrated input pump laser beams. The effects of pump beam phase aberrations described by Zernike polynomials are treated for a singly resonant oscillator (SRO). This paper is organized by first describing the model, including how beam quality is characterized. This is followed by a description of the SRO and the aberrations treated. The OPO output with aberrations is then presented and the paper is concluded with a brief summary.

3. MODEL DESCRIPTION

The model developed is time-dependent and includes diffraction, three-wave mixing, crystal absorption, and variable reflectivities and curvatures of the mirrors. The model solves the coupled field equations for the three waves using a spit-step operator approach in the crystal. The three-wave mixing and crystal absorption are treated with a second-order, predictor-corrector algorithm and the diffraction is treated using Fourier transform techniques. The propagation is limited to uniaxial crystals or biaxial crystal propagation in a principal crystal plane. The time dependency is treated by discretizing the pulse envelope in increments of the cavity round trip time. Each of these time slices is propagated through the cavity applying the appropriate boundary conditions at the mirrors. Fields can be injected (or extracted) at both mirrors to accommodate experimental conditions. Non-ideal input fields are treated by permitting Gaussian, super-Gaussian, and Hermite-Gaussian transverse beam shapes as well as phase aberrations described by Zernike polynomials. The input temporal pulse shape can be either Gaussian or super-Gaussian and can be specified individually for each input field.

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

3.1 Description of beam quality and TDL

In order to quantify the quality of a laser beam the angular divergence or "times diffraction limited" value (also called the M^2 value) is usually stated. The difficulty with this is defining what is meant by stating a beam is " M^2 TDL." Generally a field with a flat phase front in the near field is used as a reference to compare an aberrated field to. However, the transverse irradiance profile also affects the divergence of the beam. Therefore unless the laser beam of interest has a purely Gaussian or flat top shape there will be some ambiguity in the reference used to generate a TDL number. An ideal circular Gaussian beam has 86.5% of its energy contained in a far field angle of $\theta_g = \lambda/\pi\omega_0$, where λ is the wavelength and ω_0 is the Gaussian waist in the near field. The M^2 value of an aberrated beam with a Gaussian irradiance profile is the ratio of the angle (or bucket size) which contains 86.5% of the total energy divided by the ideal Gaussian angle, $M^2 = \theta/\theta_g$. The angle normalization used for a flat-top beam is usually the first null in the Airy pattern. For a beam with a flat phase and a flat circular irradiance profile the first zero in the far-field occurs at an angle of $\theta_f = 1.22\lambda/d$, where d is the near-field beam diameter. This angle contains 83.8% of the beam energy. If we compare the ideal Gaussian and flat top divergence angles assuming $\omega_0 = d/2$, we obtain

$$\theta_g \approx \theta_f/2 \quad (1)$$

Therefore, the Gaussian beam contains approximately the same energy as the flat-top beam (86.5% vs. 83.8%, respectively) in an angular cone half the size.

If a flat top beam is assumed for the normalizing beam profile and the beam of interest has a Gaussian or super-Gaussian near-field profile a beam quality less than 1 TDL can be obtained. This is illustrated in Figure 1 which presents the "beam quality" or M^2 value for a flat phase input beam with varying super-Gaussian exponent ($sg_{exp}=1$ for a Gaussian). A flat-top beam reference angle is used. An example of the encircled beam energy as a function of the far-field angle is shown in Figure 2 for a flat-top beam input ($sg_{exp}=100$). As Figure 1 shows, quoting the quality of a beam as M^2 TDL can be misleading depending on the irradiance profile of the test beam and the chosen reference beam. Also note a Gaussian input beam has approximately twice the peak near and far-field intensity as the flat-top beam (assuming $\omega_0 = d/2$, constant beam energy). Therefore a definition of beam quality based on the peak far-field irradiance or Strehl can be equally misleading. Because a relatively flat-top beam is desired to pump the OPO a flat-top normalization will be used for the beam quality discussions here.

3.2 OPO description

In order to investigate the effect aberrated input beams have on the OPO performance a singly resonant OPO (SRO) with flat cavity mirrors is assumed. The pump laser is a pulsed Nd:YAG laser at 1.064 μm . The input pump field is aligned with the axis formed by the cavity mirrors. There are no losses in the cavity and the reflective (transmissive) coatings are ideal. Thus the pump and idler (3.61 μm) fields make a single pass in the cavity. The input mirror is 90% reflective at the signal frequency (1.51 μm) and the output mirror is 50% reflective. The mirrors are spaced 10 cm apart, perfectly aligned, and a 3 cm LiNbO₃ is centered between them. The LiNbO₃ crystal is oriented at the phase-matching angle of $\sim 47^\circ$ from the c-axis. The cavity is stabilized at a cavity mode of the signal frequency.

The input pump field has a waist of 3 mm and is super-Gaussian in shape,

$$E(r) = E_0(t) \exp \left[- \left(\frac{r^2}{\omega_0^2} \right)^{sg_{exp}} \right] \quad (2)$$

with a super-Gaussian exponent of 5. The pump is Gaussian in time with a 20 ns FWHM. The signal field is seeded with a steady-state Gaussian beam at 500 μW having a 3 mm waist.

3.3 Aberration description

The aberrations investigated are described by Zernike polynomials. Any phase front can be described by a series expansion of Zernike polynomials as

$$\Delta\Phi(r, \theta) = \sum_{n,m} C_{n,m} Z(n,m) \quad (3)$$

where $C_{m,n}$ is the coefficient in waves and $Z(m,n)$ is the Zernike polynomial described by a product of a radial function and an angular function (see references 1 and 2). Zernike polynomials are convenient because the lower order terms have physical interpretations. The lower order polynomials are summarized in Table I. Aberrations starting with defocus are investigated. Although defocus can be considered simply an error in beam collimation and not an aberration (it can be corrected with spherical optics) it is included to compare its effect relative to the other aberrations. Tilt errors, which are simply misalignments relative to the cavity (and crystal), are not considered. Tilt errors would correspond to beam pointing errors.

Table I. Lower-order Zernike polynomials and their interpretations.

n	m	Zernike polynomial	Aberration Type
1	1	$\rho \cos \theta$	x tilt
1	-1	$\rho \sin \theta$	y tilt
2	0	$2\rho^2 - 1$	defocus
2	2	$\rho^2 \cos 2\theta$	third-order 0° astigmatism
2	-2	$\rho^2 \sin 2\theta$	third-order 45° astigmatism
3	1	$(3\rho^3 - 2\rho) \cos \theta$	third-order x coma
3	-1	$(3\rho^3 - 2\rho) \sin \theta$	third-order y coma
3	3	$\rho^3 \cos 3\theta$	third-order x clover
3	-3	$\rho^3 \sin 3\theta$	third-order y clover
4	0	$6\rho^4 - 6\rho^2 + 1$	third-order spherical
4	2	$(4\rho^4 - 3\rho^2) \cos 2\theta$	fifth-order 0° astigmatism
4	-2	$(4\rho^4 - 3\rho^2) \sin 2\theta$	fifth-order 45° astigmatism
4	4	$\rho^4 \cos 4\theta$	four-leaf x clover
4	-4	$\rho^4 \sin 4\theta$	four-leaf y clover

The M^2 value using a flat-top beam with 6 mm diameter is used as a reference to compare beam qualities of the OPO input and output fields. For the pump beam this yields a beam with a half-angle divergence of ~0.2 mRad (84% energy contained) for a beam quality of 1 TDL. The unaberrated super-Gaussian pump beam input has an angular divergence of ~0.14 mRad and thus with this normalization has a beam quality of 0.7 TDL. Pumping the OPO with this unaberrated pump produces output signal and idler fields which are ~1 TDL using this normalization, making it convenient for comparison to the aberrated input cases.

Application of the different Zernike aberrations to a field produces different amounts of angular divergence or beam qualities for the same input coefficient (magnitude in waves). This can be seen from the divergence values listed in Table II. The middle two columns in Table II present the beam divergence for the specified aberration level (in waves of phase-front error) while the last column is the Zernike coefficient (in waves) needed to produce a 2 TDL input beam. The Zernike normalization radius used for the calculations here is taken equal to the beam radius of 3 mm. Note that a one wave aberration level can reduce the beam quality to 3-7 TDL depending on the nature of the aberration. Conversely, less than a half wave of defocus, third-order coma, third-order spherical, or fifth-order astigmatism produces a 2 TDL beam. Only the $m \geq 0$ polynomials are presented in Table II because the

polynomials with $m < 0$ generate the same far field distribution as those with $m > 0$ but rotated and hence have the same angular divergence.

Table II. Effect of Zernike aberrations on the angular divergence of the input pump field.

Zernike	$M^2 (C_{m,n} = \lambda/2)$	$M^2 (C_{m,n} = 1 \lambda)$	$C_{m,n} (M^2 = 2 \text{ TDL})$
$z(2,0)$	2.9	5.5	0.32
$z(2,2)$	1.6	2.9	0.65
$z(3,1)$	2.3	4.6	0.40
$z(3,3)$	1.9	3.5	0.55
$z(4,0)$	3.9	6.6	0.27
$z(4,2)$	2.5	4.6	0.39
$z(4,4)$	2.0	3.9	0.50

4. ABERRATED OPO OUTPUT

Two possible approaches to investigate the effect of the different aberrations on the performance of the OPO are holding the Zernike aberration magnitude constant or holding the input beam divergence constant. Although both have been used the general tendencies can be seen by presenting the results of pumping the OPO with a constant input beam divergence equivalent to 2 TDL. This requires aberration magnitudes varying from approximately a quarter of a wave for third-order spherical to two thirds of a wave of astigmatism as seen in Table II. The summary results with an aberrated input pump beam are given in Figures 3-6 as a function of the input pump energy. Figure 3 presents the output idler energy, Figure 4 is the pump conversion efficiency, Figure 5 is the output signal divergence or beam quality, and Figure 6 is the output idler beam quality. Note that as discussed earlier there are no losses treated in this study of pump phase aberrations and the pump intensity profile is a smooth super-Gaussian with a diameter (6 mm) significantly greater than the pump walk-off distance in the LiNbO_3 crystal (1 mm in a 30 mm long crystal). Therefore conversion efficiencies are expected to be higher than would be expected experimentally.

The oscillation threshold is seen to increase only a few to at most 10% going from diffraction limited to 2 TDL with any of the aberration forms. However, the aberrated beams can lead to significantly reduced output energy, particularly if the available pump energy is only marginally above threshold. At 100 mJ pump energy, or about 1.3 times threshold, the diffraction limited input generates 5.4 mJ of idler while the aberrated inputs generate as low as 2 mJ. The poorest energy conversion occurs with the third-order x-coma aberration [$z(3,1)$] in which the largest gradients are oriented in the crystal walk-off direction (the x-direction). Conversely the third-order y coma has the largest gradients oriented normal to the walk-off direction and has high conversion efficiency. As seen in Figure 4, with sufficient pump energy the OPO can produce efficient energy conversion with a 2 TDL input pump beam. Even for the worst aberration ~30% pump depletion efficiency is possible.

The OPO output beam quality for the various aberration types is more complicated. In general, the higher above threshold the OPO is pumped the worse the beam quality is. This is true even for the diffraction limited case, although the output beam quality for the diffraction limited input case is still 1.25 TDL at 300 mJ input (~4 times over threshold). Because of the wavelength differences the signal and idler beams are more divergent than the pump beam for the same beam quality. A diffraction limited signal beam has a divergence of ~0.3 mRad and the idler divergence is 0.7 mRad at $M^2=1$.

The pump beam with second order aberrations generates the best output beam quality of the aberrated cases. At pump energies near threshold the pump beam with second order aberrations, astigmatism and defocus, produce

at or better than the 2 TDL input pump beam. This 'beam cleanup' does come at the expense of energy conversion compared to the diffraction limited input case. With the 3rd and 4th-order Zernike aberrated pump input the OPO output beam quality is 2-3 TDL near threshold and ranges from 4-7 TDL at 300 mJ input. The output beam quality behavior of 4th-order aberrated fields is similar for the different Zernike terms. This is not true for the 3rd-order aberrated fields. The 3rd-order clover-aberrated fields behave similarly the coma-aberrated fields produce very different output beam qualities depending on the angular orientation of the aberration. This is consistent with the poor conversion efficiency of the coma-aberrated pump field when the aberration is aligned with the walk-off direction in the crystal.

The continued degrading of output beam quality with increased pump power is believed to be due to the higher angular components of the field going over threshold as the pump energy increases. The output fields can contain complicated angular spectra as is evident from Figure 7 which is the angular spectrum (far-field) of the output undepleted pump and idler generated with a 150 mJ input pump field aberrated with third-order x coma [z(3,1)]. Pump aberrations can also lead to angular displacement between the output signal and idler fields. An example of this is shown in Figure 8 for a input pump beam with third-order 0° astigmatism. The field curvature generates optimal phase matching for the three-wave interaction in a non-collinear arrangement. This effect is also observed for angularly symmetric aberrations, such as defocus, with the angular displacement occurring in the walk-off direction. The angular displacement of the signal and idler beams is opposite in direction relative to the direction of the pump beam which yields a mirror image character to the output signal and idler far-field patterns.

5. SUMMARY

The effects of an aberrated pump field on the output of an SRO have been investigated. The input pump field has a smooth, super-Gaussian irradiance profile and an input beam quality of 2 TDL with the aberrations described by Zernike polynomials. The threshold energy increases by 10% or less for the 2 TDL input beams compared with the diffraction limited input pump. The output idler energy can be significantly decreased with the addition of aberrations if the input pump energy is not far above threshold. This relatively high quality input beam is found to produce significantly more divergent output signal and idler fields particularly as the pump energy increases above ~2 times the threshold energy. The aberration with the most significant effect on the OPO performance is third-order coma when the aberration is aligned with the walk-off direction in the crystal. The aberrated pump fields can also lead to angular displacements between the generated signal and idler fields.

6. REFERENCES

1. M. Born and E. Wolf, *Principles of Optics*, Pergamon, London, p. 464, (1987).
2. W.A. Neuman and J.R. Fincke, *Beam quality of direct nuclear pumped laser amplifiers*, J. Appl. Phys., 69, p. 6789, (1991).

Figure 1. Far-field angular divergence variation with near-field beam profile.

Figure 2. Far-field angular energy of a unaberrated super-Gaussian beam ($sg_{exp}=100$). Figure 3. Idler output energy with a 2 TDL input pump beam divergence.

Figure 3. Idler output energy with a 2 TDL input pump beam divergence.

Figure 4. Pump conversion efficiency with a 2 TDL input pump beam divergence.

Figure 5. Signal field divergence with a 2 TDL input pump beam divergence.

Figure 6. Idler field divergence with a 2 TDL input pump beam divergence.

Figure 7. Undepleted pump (top) and output idler (bottom) far-field irradiance profiles with a 2 TDL input pump field of 150 mJ (third-order x-coma aberration, angular dimension in mRad).

Figure 8. Signal (top) and Idler (bottom) far-field irradiance profiles with a 2 TDL input pump field of 150 mJ (third-order 0° astigmatism aberration, angular dimension in mRad).

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