Optical parametric oscillators with high pulse energy and beam quality

Gunnar Rustad, Øystein Farsund, Gunnar Arisholm

Gunnar Rustad, Øystein Farsund, Gunnar Arisholm, "Optical parametric oscillators with high pulse energy and beam quality," Proc. SPIE 7721, Solid State Lasers and Amplifiers IV, and High-Power Lasers, 77210J (17 May 2010); doi: 10.1117/12.854958

Event: SPIE Photonics Europe, 2010, Brussels, Belgium

Optical parametric oscillators with high pulse energy and beam quality

Gunnar Rustad[1], Øystein Farsund, Gunnar Arisholm
FFI (Norwegian Defence Research Establishment), P.O.Box 25, NO-2027 Kjeller, Norway

ABSTRACT

A new method for obtaining high beam quality from high pulse energy optical parametric oscillators (OPOs) is demonstrated. By using different nonlinear crystals that have walk-off in orthogonal directions but are type 2 phase matched for the same interaction, the strong beam asymmetry that is common in critically type 2 phase matched OPOs is removed. Experimentally, this was demonstrated by adding BBO crystals to a type 2 phase matched KTA OPO, where the beam quality improved from $M^2 \approx 2 \times 12$ in the KTA OPO to $M^2 \approx 2 \times 2$ from the KTA-BBO OPO.

Keywords: Optical parametric oscillator, beam quality, high pulse energy

1. INTRODUCTION

Nonlinear frequency down conversion of a laser beam in an optical parametric oscillator (OPO) is a well known method to obtain coherent optical beams at new wavelengths. Properly designed, such conversion can be made efficient, and the beam quality of the pump laser may in many cases be maintained or even improved. However, for conversion of high energy (several millijoule) Q-switched laser pulses of nanoseconds duration it is difficult to obtain both high efficiency and good beam quality in the OPO. In this work we propose and demonstrate a new method to solve this problem.

To have high conversion efficiency in a pulsed OPO, the build-up time needs to be short compared to the pump pulse length, as the part of the pump pulse that passes during the build-up time cannot be converted in the OPO. This calls for high round trip gain in the OPO as well as a short resonator round trip time. To avoid optical damage in the OPO, the pump beam size must be large enough for the total fluence in the OPO to be below the damage threshold. This combination of a short resonator and wide pump beam, leads to a high Fresnel number for the resonator and potentially poor beam quality. In an OPO with low pump energy, this problem is much less pronounced as the beam diameter, and hence Fresnel number, can be much smaller.

Besides the pump beam quality and the resonator Fresnel number, the acceptance angles for the interacting beams, and hence the walk-off between them, are important for the beam quality of the generated beams. It has been shown that walk-off between signal and idler beams, which occurs in critical type 2 phase matching, improves the spatial coherence of both beams in the direction of walk-off [1], but not in the other (non-critical) direction. In an OPO with a large Fresnel number, this may lead to asymmetric beams, where the beam quality in the critical direction is much better than in the non-critical direction. There are a few reported solutions to reduce this beam asymmetry in the literature. These include the use of a non-collinear geometry to induce walk-off between the generated signal and idler beams in both directions [2, 3], and the RISTRA geometry in which the image of the signal beam is rotated 90º for each round trip of a non-planar ring resonator to increase the spatial coherence in the non-critical direction [1]. Here, we propose an alternative and simple design that can remove the asymmetry of the generated beams in a collinearly type 2 phase matched linear OPO.

2. ORTHOGONAL CRITICAL PLANES

The approach uses two different types of nonlinear crystals in the same OPO. The crystals are chosen such that they are type 2 phase matched for the same set of polarizations and wavelengths, but with orthogonal critical planes. For uniaxial crystals, this can be achieved by using one positive and one negative crystal. In this design, the walk-off between the signal and idler beams is in orthogonal directions in the two crystals. The proposed OPO configuration is sketched in Figure 1.

---

[1] gunnar.rustad@ffi.no, phone +47 6380 7380, www.ffi.no

Solid State Lasers and Amplifiers IV, and High-Power Lasers, edited by Thomas Graf, Jacob I. Mackenzie,
Helena Jelinková, Gerhard G. Paulus, Vincent Bagnoud, Catherine Le Blanc, Proc. of SPIE Vol. 7721,
77210J · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.854958

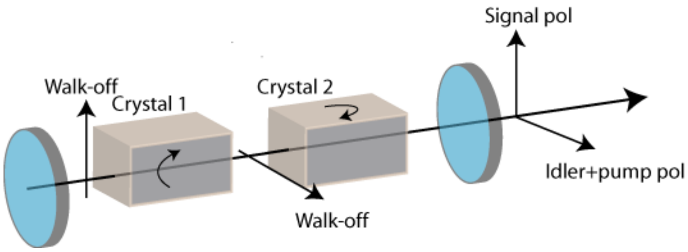

Figure 1. Sketch of directions of polarization for critical collinear type 2 phase matching in the approach proposed in this work. In the simulations and experiments, crystals 1 and 2 are replaced by walk-off compensating crystal pairs

The OPO has been designed and studied using our state-of-the-art numerical simulation tool that accounts for all relevant effects in the OPO [4, 5]. To examine the effect of orthogonal critical planes, we first simulated an OPO with artificial crystals for which we could choose all parameters independently. Two pairs of walk-off compensating crystals were assumed in the simulations, and both the cases with parallel and orthogonal walk-off directions of the two pairs were simulated and compared. With the exception of the walk-off direction, the crystals were identical. The length was 5 mm, the effective nonlinearity was set to 4 pm/V, and the walk-off angle was 2.3º. The OPO was single resonant with single pass pump, and was type 2 phase matched for 1.064 µm to 1.6 µm + 3.2 µm generation. A single longitudinal mode pump with a super-Gaussian order 6 transverse profile with 3 mm beam diameter was assumed. The pulse length was 5 ns and the pump energy was set to 70 mJ. With 50% reflectivity on the 1.6 µm signal wavelength, the resulting peak fluence in the OPO was ~1.7 J/cm^2. We note that when the OPO is single-pass pumped, walk-off compensating pairs of crystals are necessary to avoid angular dispersion [6] and to obtain optimal beam quality [1]. Figure 2 shows the simulated near and far fields of the signal beam from the OPOs with parallel and orthogonal walk-off directions, as well as the pump beam. We notice the large improvement in beam symmetry that is obtained with the proposed method, and also the fact that beam quality in the best direction of the OPO with parallel walk-off directions is not reduced.

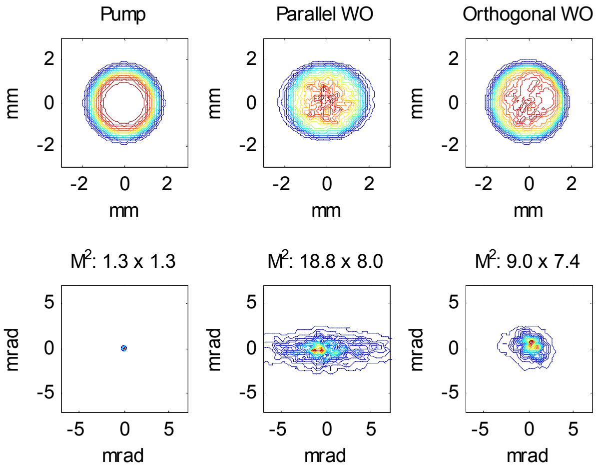

Figure 2. Simulated near (top row) and far fields (bottom row) of the signal beam of OPOs with two walk-off compensating crystal pairs with parallel (center column) or orthogonal (right column) walk-off directions. For comparison, the pump beam is shown to the left (the center of the pump near field is nearly flat at peak power, order 6 super-Gaussian)

2.1 Walk-off angle

In the example above the walk-off distance through a crystal was only 0.2 mm, which is less than 10% of the beam diameter. A greater walk-off distance can increase the correlation area of the beams and improve the beam quality. The walk-off distance is proportional to the walk-off angle and crystal length, and we study the effect by varying the walk-off angle in the simulation. Other parameters were chosen to keep the nonlinear coupling constant for the set of simulations. Figure 3 shows the calculated pulse energy and beam quality as function of walk-off angle for an OPO with two walk-off compensated crystal pairs where the two pairs have orthogonal walk-off direction and the crystals are all 5 mm long. The pump beam was the same as in the previous example. We notice that the beam quality depends rather strongly on the walk-off angle in this case. Therefore, in an actual experiment, it is important to choose crystal type and length to get a suitable walk-off distance compared to the beam size.

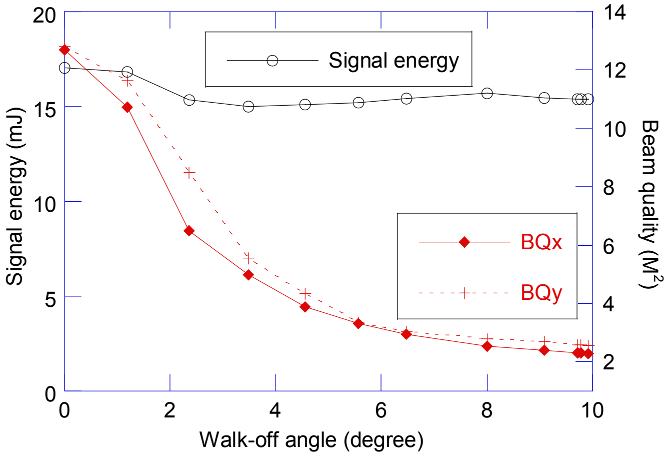

Figure 3. Simulated performance of an OPO with orthogonal walk-off directions as described in the text above as function of walk-off angle

2.2 Idler absorption

The choice of nonlinear crystals for the experimental realization of this OPO is discussed in the Section 3. It turns out that one of the crystals suitable for our experimental OPO has strong absorption at wavelengths above 2 µm, so it is necessary to investigate how idler absorption affects the OPO performance. It turns out that, maybe surprisingly; relatively strong idler absorption has a positive effect on the OPO performance. The main reason for this is that attenuating or removing the idler beam also reduces the back conversion [7], which is the process where the signal and idler beams regenerate the pump beam. Back conversion reduces signal beam energy and beam quality, and avoiding this is important in design of the OPO. Simulations similar to those shown in Figure 2 were performed with 1.5 cm^{-1} idler absorption in all four crystals. The results are shown in Figure 4. We note that the beam quality is improved for both OPO configurations. The signal output energy was slightly higher with idler absorption (~20 mJ vs. ~17 mJ). The

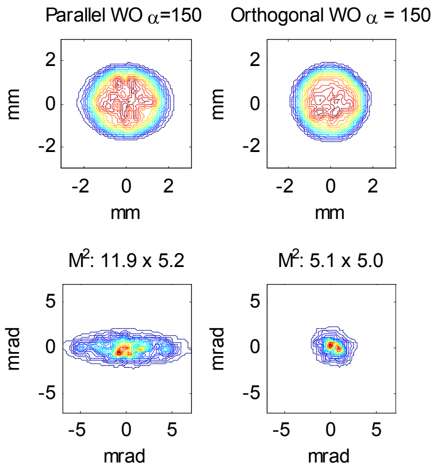

Figure 4. Simulated near and far fields of OPOs with two walk-off compensating crystal pairs with parallel (left graphs) or orthogonal (right graphs) walk-off directions assuming 1.5 cm^{-1} idler absorption

heat load in the OPO with orthogonal walk-off directions, was about 0.6 mJ, 2.6 mJ, 2.8 mJ and 1.6 mJ in the four crystals, respectively. For a low (10 Hz) pulse repetition rate pump laser as is used in this work, this does not affect the performance of the OPO. The simulations also show that if the idler absorption is sufficiently strong (above 4 cm^{-1} in this case), the OPO signal energy is significantly reduced, most likely because it increases the threshold for OPO operation.

3. CHOICE OF NONLINEAR CRYSTALS

A 1.064 µm pump laser was used in the experiments. In Table 1, we have listed potential nonlinear materials that can be used in an OPO for type 2 critically phase matched infrared generation. To have orthogonal walk-off directions, we need one crystal with walk-off in the direction of the slow axis and one crystal with walk-off along the direction of the fast axis (signal and idler beams have orthogonal polarizations in type 2 phase matching, but parallel polarizations in type 1 phase matching). We note that while there are several good candidates for the slow-axis walk-off material, there are fewer and less obvious candidates for the fast-axis walk-off material. BBO has high idler absorption, YCOB has low walk-off, and LNO has a small effective nonlinearity for type 2 phase matching. As was seen in the previous section, relatively high idler absorption may in fact be advantageous for the OPO performance. Therefore BBO was chosen as the "fast" crystal in this work.

Table 1. Materials for type 2 phase matched conversion of 1.064 µm to 1.7 µm. The column S/F lists whether slow or fast beam has walk-off (for biaxial crystals crystal plane is also listed), θ/φ is the calculated propagation angle in the crystal and d_{eff} is the corresponding effective nonlinearity. WO lists the walk-off angle between signal and idler beams. The crystal data and acronyms for the crystal names are taken from [8]

Material	S/F wo	θ/φ (º)	d_{eff} (pm/V)	WO (º)
KTP	Slow (XZ)	46/0	2.6	2.8
KTA	Slow (XZ)	43/0	2.9	2.3
BBO	Fast	30	1.6	3.5
BiBO	Slow (XZ)	42/0	2.6	4.8
YCOB	Fast (XY)	90/42	1.3	0.9
LNO	Fast	58	0.6	2.2
LBO	Slow (YZ)	44/90	0.5	0.5

We used KTA as the "slow" crystal in the OPO. It was chosen because of its higher nonlinearity, but it is likely that both KTP and BiBO may perform similarly well. BBO is an unusual choice for an infrared OPO, as the transmittance above 2 µm is poor, as is shown in Figure 5. As the absorption rapidly increases above 2.8 µm, we have chosen to operate the OPO at a signal wavelength of 1.68 µm, corresponding to an idler wavelength of ~2.9 µm and ~2.5 cm^{-1} absorption.

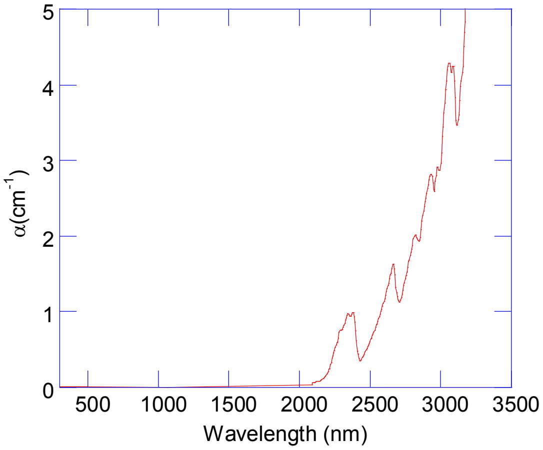

Figure 5. Absorption coefficient in BBO as function of wavelength deduced from [9]

4. DESIGN OF EXPERIMENT

As was seen in Figure 3, the beam quality depends on the walk-off distance. To get a symmetrical beam, crystal lengths should therefore be chosen to have similar walk-off distances. The nonlinear gain also affects this choice, but we found that a BBO/KTA length ratio of 0.7 produced nearly symmetrical beams. The OPO was optimized through simulations, subject to total peak fluence below 2 J/cm^2. It was found that a double-pass pump geometry greatly improved OPO performance, and the output coupling and crystal lengths were optimized for this condition. The OPO design process then resulted in a 50 % signal output coupling (and 100% idler output coupling), two 15 mm KTA crystals and two 10 mm BBO crystals. A double-pass pumped OPO does not need walk-off compensating crystals to avoid angular dispersion [1], so we can make this choice based on efficiency and beam quality. Our simulations indicated that the KTA crystals should be oriented for walk-off compensation for the best performance. Our BBO crystals could not be used in walk-off compensating geometry as this would require a different cut angle for the second crystal to avoid a reversal of the sign of d_{eff} (two *e*-beams in an uniaxial crystal, see [10]). The crystals were placed in an alternating order (KTA-BBO-KTA-BBO), both because it was experimentally convenient, and because distributing the idler loss in the OPO was found to improve the performance.

5. EXPERIMENTAL RESULTS

A 10 Hz pulse frequency multi-longitudinal mode (~20 GHz bandwidth) Quantel Brilliant B Nd:YAG laser was used as pump source in the experiments. The pulse length was approximately 5 ns, and the beam profile was 'top-hat-ish' (see Figure 8). The pump beam was concentrated with a telescope to a beam diameter of ~4 mm, and a rotating half-wave plate and a polarizer made it possible to adjust the pump energy. To avoid optical damage, the maximum pump energy was limited to 70 mJ in the experiments. The experimental set-up is sketched in Figure 6. The energy incident on the OPO was monitored by detecting radiation leakage through one of the folding mirror. The idler beam and residual pump was filtered out from the output beam of the OPO ,and the near and far fields of the signal beam were measured with a pyroelectric camera at 60 mJ pump energy. The far field was measured in the focal plane of an *f* = 1 m lens.

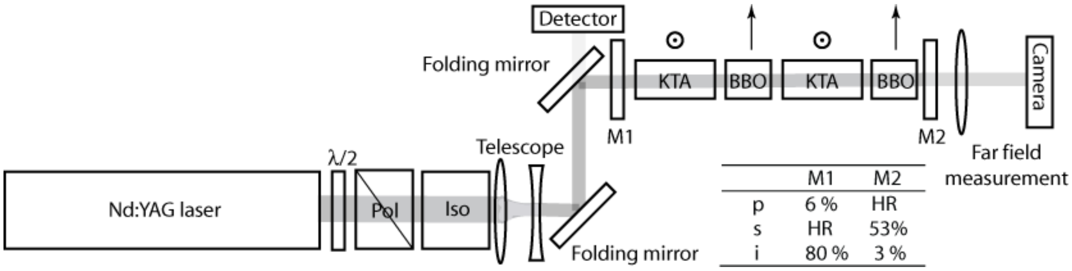

Figure 6. Sketch of the experimental setup. The details are explained in the text

The KTA OPO was tuned to 1.68 µm signal wavelength and was optimized with respect to signal energy. The BBO crystals were then inserted and tuned without tuning the previously installed crystals. The measured signal energy is show in Figure 7 both for the KTA OPO and for the KTA-BBO OPO. Also shown are results from simulations, showing a good agreement with the experimental results. Although the OPO was designed to be singly resonant, the mirror coatings reflected part of the idler beam, so the OPO is not perfectly singly resonant. However, the high idler absorption in BBO (~10 absorption lengths round trip) and the bandwidth of the pump laser, reduced the effect of idler reflection [11].

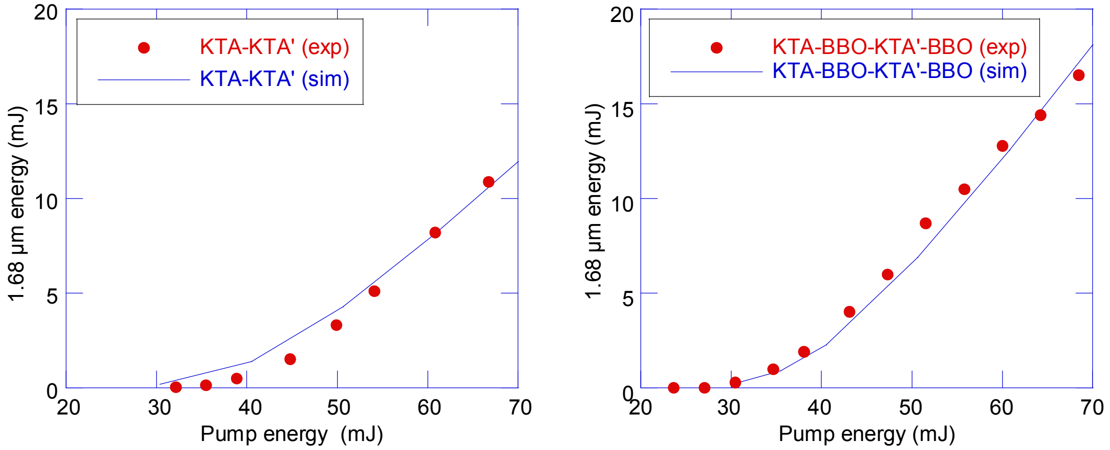

Figure 7. Comparison of simulations and experimental results for the KTA OPO (left) and the KTA-BBO-OPO (right)

Figure 8 shows the measured near and far fields from the pump, the KTA OPO and the KTA-BBO OPO. We notice that adding the BBO crystal greatly improves the symmetry of the signal beam. There was significant baseline noise from the camera making exact beam quality calculations difficult. However, by filtering the images through an aperture with approximately twice the diameter of the visible spot in the near and far fields, we estimated the beam qualities for the pump to be $M^2 \approx 2 \times 2$, for the KTA OPO to be $M^2 \approx 2 \times 12$, and for the KTA-BBO OPO to be $M^2 \approx 2 \times 2$.

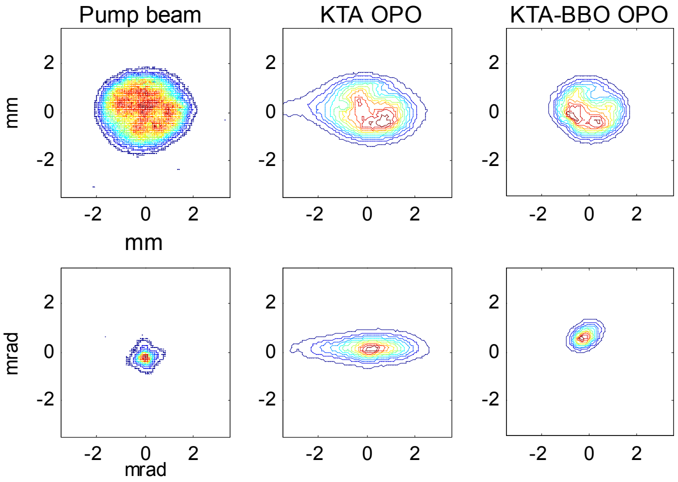

Figure 8. Measured near (top row) and far (bottom row) field for the pump, KTA OPO and KTA-BBO OPO (left, middle, right)

6. CONCLUSIONS

In conclusion, we have demonstrated a method to obtain improved and symmetric beam quality from a linear OPO with large beams. Using the fact that walk-off between signal and idler improves beam quality in the direction of walk-off, we have used two different type 2 phase matched crystals with walk-off in orthogonal directions. In an OPO based on KTA and BBO pumped with a 4 mm diameter pump beam, the beam quality was improved to $M^2 \approx 2 \times 2$ compared to $M^2 \approx 2 \times 12$ for the OPO with only KTA.

REFERENCES

[1] Smith, A.V. and Bowers, M.S. "Image-rotating cavity designs for improved beam quality in nanosecond optical parametric oscillators", J. Opt. Soc. Am. B, 18 (5), 706-713 (2001).

[2] Anstett, G., Goritz, G., Kabs, D., Urschel, R., Wallenstein, R., and Borsutzky, A. "Reduction of the spectral width and beam divergence of a BBO-OPO by using collinear type-II phase matching and back reflection of the pump beam", Appl. Phys. B, 72 (5), 583-589 (2001).

[3] Nabors, C.D. and Frangineas, G. "Optical parametric oscillator with bi-noncolinear, porro prism cavity", OSA Trends in Optics and Photonics Series vol 10, 90-93 (1997).

[4] Arisholm, G. "General numerical methods for simulating second-order nonlinear interactions in birefringent media", J. Opt. Soc. Am. B, 14 (10), 2543-2549 (1997).

[5] Arisholm, G. "Advanced numerical simulation models for second-order nonlinear interactions", Proc. SPIE, 3685 86-97 (1999).

[6] Alford, W.J., Gehr, R.J., Schmitt, R.L., Smith, A.V., and Arisholm, G. "Beam tilt and angular dispersion in broad-bandwidth, nanosecond optical parametric oscillators", J. Opt. Soc. Am. B, 16 (9), 1525-1532 (1999).

[7] Lowenthal, D.D. "CW periodically poled $LiNbO_3$ optical parametric oscillator model with strong idler absorption", IEEE J. Quantum Electron., 34 (8), 1356-1366 (1998).

[8] Nikogosyan, D.N. [Nonlinear optical crystals: a complete survey]. Springer, New York, (2005).

[9] Eimerl, D., Davis, L., Velsko, S., Graham, E.K., and Zalkin, A. "Optical, Mechanical, and Thermal-Properties of Barium Borate", J. Appl. Phys., 62 (5), 1968-1983 (1987).

[10] Armstrong, D.J., Alford, W.J., Raymond, T.D., Smith, A.V., and Bowers, M.S. "Parametric amplification and oscillation with walkoff-compensating crystals", J. Opt. Soc. Am. B, 14 (2), 460-474 (1997).

[11] Arisholm, G. and Stenersen, K. "Optical parametric oscillator with non-ideal mirrors and single- and multi-mode pump beams", Opt. Express, 4 (5), 183-192 (1999).