Available online at www.sciencedirect.com
ScienceDirect
Optics Communications 276 (2007) 139–144
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Suppression of thermal lensing effects in intra-cavity coherent combining of lasers

Sharona Sedghani *, Vardit Eckhouse, Asher A. Friesem, Nir Davidson

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

Received 31 August 2006; received in revised form 13 March 2007; accepted 17 April 2007

Abstract

An efficient approach to suppress thermal lensing, when coherently combining several laser distributions, is presented. It is based on incorporating a compensating lens inside the laser cavity. The results reveal that with compensation the overall efficiencies can be more than 80% when combining four laser distributions and more than 90% when combining two laser distributions even at relatively high pulse repetition rates. A model for analyzing coherent combining is developed, where predicted results are in good agreement with the experimental results.

1. Introduction

Coherent combining of several separate lasers, each with a low output power and good beam quality, can lead to practical and compact overall laser systems, having a high output power concomitantly with good beam quality [1–10]. Coherent combining requires that the individual lasers be phase-locked, and this in turn leads to very strict requirements on the relative alignment between them. In particular, for efficient phase locking and coherent combining, the required parallelism between the individual laser distributions must be a significantly less than their diffraction limited divergence angles. This, for typical solid state lasers, implies parallelism of few microradians. As a result, laser systems that involve coherent combining are very sensitive to thermal drifts and acoustic vibrations.

During the past few years, we have investigated new configurations for coherently combining several pulsed Nd:YAG laser distributions [5,11–13]. In these configurations, interferometric couplers, formed on single parallel substrates, were inserted inside the laser for phase locking and coherent combining of several individual laser distributions. Typically the back mirror, output coupler mirror, and gain medium, were common to all the individual laser distributions, and the combined laser operated at low pulse repetition rate of about 1 Hz. Consequently, relative misalignments of the individual laser distributions, due to vibrations and drifts, were substantially eliminated, and we were able to successfully demonstrate efficient coherent combining of up to 16 laser distributions [14].

Unfortunately, for more practical laser systems, where a higher pulse repetition rate is needed, thermal lensing becomes prominent and degrades the coherent combining efficiency. Specifically, since thermal lensing may differ for each individual laser distribution, the angular orientation of each will also differ. Consequently, the required parallelism of all laser distributions cannot be maintained, so phase locking is poorer, resulting in significant reduction of combining efficiency.

In this paper, we present a method in which the thermal lensing effects are suppressed by adding a proper compensating lens inside the laser cavity close to the laser rod. With such suppression, we demonstrate that efficient phase locking and coherent combining can be obtained even for pulse repetition rate of ~15 Hz. Our method is applicable where arrays of beam distributions pass through a single gain medium that is symmetrically pumped. The advantage

* Corresponding author.
E-mail address: Sharona.sedghani@weizmann.ac.il (S. Sedghani).

0030-4018/$ - see front matter
doi:10.1016/j.optcom.2007.04.012

of using configurations with a single gain medium and symmetric pumping is that they alleviate the complexity of alignment and significantly improve the stability. Such configurations were used both for coherent combining as well as for improving beam quality [12,15–17]. We present a model for predicting the loss of the combined laser output due to thermal lensing, and show that the predicted results are in good agreement with our experimental results.

2. Experimental procedure and results

Our experimental set up for coherent combining four laser distributions is shown in Fig. 1. It includes a 62 cm long plano-concave resonator, with a concave output coupler having a radius of 1.5 m and 40% reflectivity at 1064 nm, and a flat reflector mirror with >99% reflectivity. The laser gain medium is a Nd:YAG rod of 5 mm diameter and 10 cm length, with 1.1% doping, placed in a diffusive ceramic pump chamber, and pumped with a ~200 μs flash lamp pulse at constant level throughout the experiments. The laser rod acts as a positive thermal lens with focal length, which depends on the pulse repetition rate (at the flash lamp). For a specific focal length, it is possible to add a negative lens close to the rod, in order to compensate for the thermal lensing.

A square array of four apertures each with a diameter of 1.4 mm, results in four separate and independent channels within the cavity, each with a nearly pure Gaussian transverse mode distributions. The separation between adjacent channels was 2.4 mm, and the energy per pulse for each channel was about 6 mJ. The four channels are combined by means of two orthogonally oriented intra-cavity interferometer couplers [12]. Each interferometric couplers was form on a 3 mm thick precision plane parallel fused silica substrate, oriented at the Brewster angle of 55.4°, one vertically and the other horizontally. Half of the front surface of each coupler was coated with a 50% reflective layer and the other half left uncoated, while half of the rear surface was coated with highly reflective layer and the other half uncoated. When four parallel beams, having some common longitudinal modes, are incident on the first interferometric coupler from the left, their relative phase will typically self-adjust. Accordingly, there will be destructive interference into one output path and constructive interference into the other path, so only two beams propagate toward the second interferometric coupler. Then, a similar operation in the second coupler will result in only one beam propagating toward the output coupler mirror. Finally, a thin film polarizer and a 90° polarization rotator ensure that the light incident on each interferometric coupler is P polarized, in order to suppress the reflections from the uncoated areas of the couplers.

We began our experiments by measuring the thermally induced focal length of our laser rod as a function of pulse repetition rate. This was done by letting a collimated beam propagate through the laser rod while it was pumped at different pulse repetition rates and determining the distance between the rod and focus plane at each rate. Since this distance was very large, we used an additional lens, with a known focal length, to bring the focus plane of the thermal lens closer. The experimental results together with exponential fit are presented in Fig. 2. As expected, the thermal lensing is stronger at the higher pulse repetition rates.

We also considered thermal induced birefringence and phase front distortions effects which might influence coherent combining. The birefringence effects were determined by measuring the polarization rotation of a linearly polarized probe after it passed through the Nd:YAG laser rod, first without pumping and then with pumping at a pulse repetition rate up to 20 Hz. We found that the change of polarization was less than 1°. This was repeated for different regions of the rod, with similar results. The phase front distortion was determined by comparing the focal spot sizes, which were obtained by focusing the beams emerging from the Nd:YAG rod with and without pumping. No detectable change of size was observed, indicating that the phase distortion were negligible as well. We note that at much higher pulse repetition rates both thermal induced birefringence and phase front distortions are expected to have a strong influence, and hence may limit our correction scheme.

Next, we investigated the effect of thermal lensing on the coherent combining of four laser distributions, using the configuration of Fig. 1, first without, and then with, a compensating lens. The results are presented in Fig. 3. Fig. 3a shows the measured combining efficiency as a function of pulse repetition rate for the configuration without a compensating lens. As evident, for a low pulse repetition rate of about 1 Hz, a combining efficiency of 85% is obtained. The combining efficiency decreases for the higher pulse repetitions rate, and is only ~30% at 15 Hz. Fig. 3b shows the measured combining efficiency as a function of pulse repe-

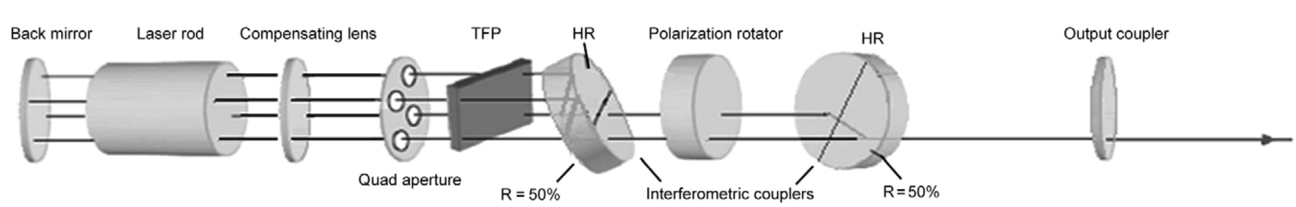

Fig. 1. Configuration for coherently combining four laser distributions with two identical orthogonally oriented couplers. HR: high reflection, TFP: thin film polarizer.

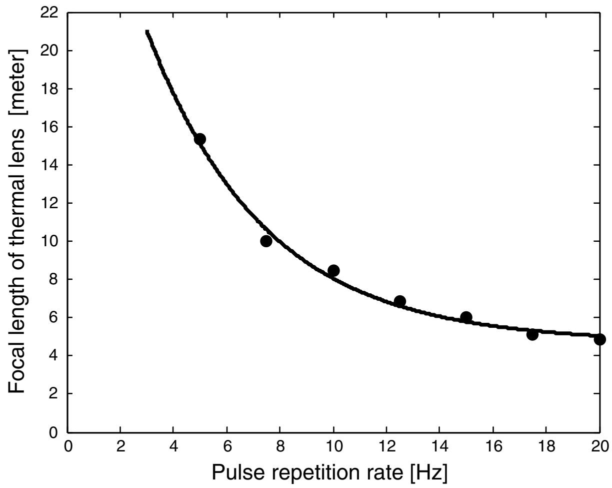

Fig. 2. Measured focal length of thermal lens as a function of pulse repetition rate. Dots—experimental; solid curve—exponential fit.

tition rate for the configuration with a compensating lens of focal length $f = -6$ m located 12.5 cm from the center of the Nd:YAG rod. As shown, the combining efficiency is now indeed maximal at pulse repetition rate of 15 Hz, where the deleterious effect of the thermal lens of the laser rod is now cancelled by the negative compensating lensing. The efficiency is nearly identical to that measured for the configuration without a compensating lens when using pulse repetition rate of 1 Hz. As pulse repetition rate increases beyond this optimal value of 15 Hz, the combining efficiency again decreases, indicating that our simple compensation method can be successful only for a narrow and predetermined range of pulse repetition rates.

The near-field and far-field intensity distributions were detected, using CCD cameras. The corresponding beam quality factor M^2 was then calculated in accordance to $M^2 = \sigma_{nf}\sigma_{ff}\pi/(4\lambda F)$, where F is the focal length of the far-field lens, and σ_{nf} and σ_{ff} are the second moments of the near and far-field distributions. We found that the M^2 of the combined output distribution from the configuration without the compensating lens at pulse repetition rate of 1 Hz was about 1.3. The M^2 was essentially the same for the combined output distribution from the configuration with the compensating lens and pulse repetition rate of 15 Hz. These values, as well as the far-field distributions presented as insets in Fig. 3a and b, indicate very good beam quality and near Gaussian beam distribution in both cases.

We repeated the same experiment for coherent combining of two laser distributions, by removing one of the interferometric combiners and polarization rotator from the configuration of Fig. 1. The results were essentially identical to those of Fig. 3, except that the maximal efficiencies without the compensating lens at pulse repetition rate of 1 Hz as well as with the compensating lens at pulse repetition rate of 15 Hz, were improved to above 90%.

3. Theoretical model and results

In the intra-cavity coherent combining configuration of Fig. 1, the effect of thermal lensing is that the laser rod acts as an off-axis lens on each laser channel distribution. This results in two loss mechanisms. First, the off-axis thermal lens deflects the light from each channel so it will not completely pass through its corresponding aperture (for single channel resonators, the light is usually centered along the axis of the laser rod, so typically it is not deflected laterally by thermal lensing). Secondly, since the light of each channel is deflected to a different direction by the independent thermal lenses, the laser distributions from the four channels are no longer parallel. Thus, complete destructive interference into one path or complete constructive interference into the output path could be less than distributions that are from parallel channels.

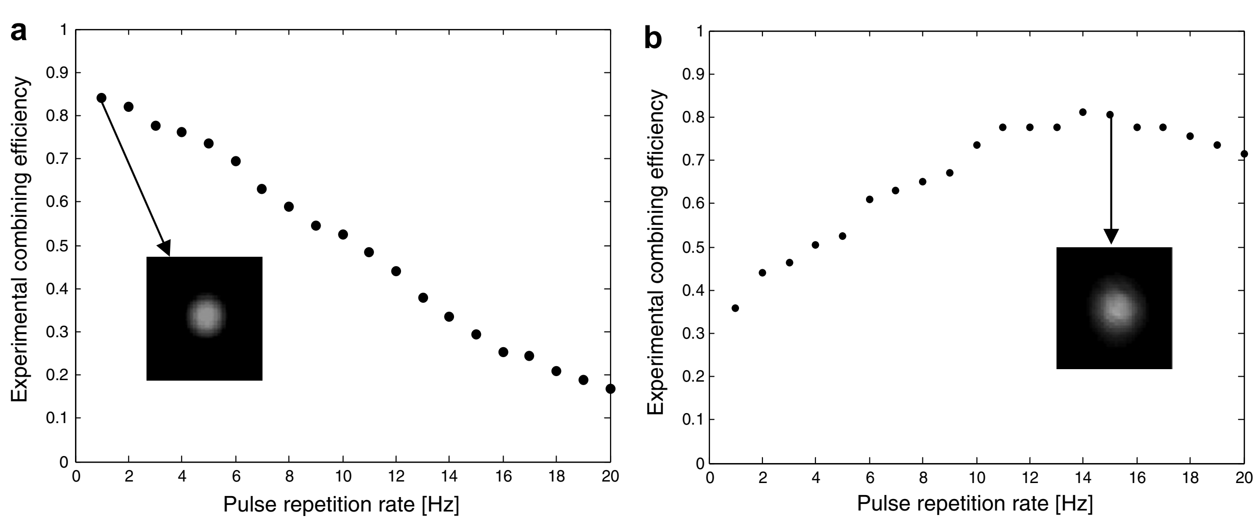

Fig. 3. Measured combining efficiency as a function of pulse repetition rate for coherent combining of four laser distributions. (a) Without compensating lens. (b) With compensating lens of focal length of 6 m. Insets: far-field distributions, indicating nearly Gaussian distributions for both cases.

To evaluate the first loss mechanism of thermal lensing, we first calculated the round-trip cavity loss for a single channel distribution, corresponding to the configuration of Fig. 1 with three of the apertures blocked and no interferometric couplers, and compensating lens. The round trip losses are found by solving the self-consistent round trip propagation equation in the matrix form

$$KU_N = \gamma_N U_N, \tag{1}$$

where the eigenvectors $U_N = [a_1, \ldots, a_N]$ are the amplitudes of the resonator modes (in one transverse dimension), γ_N the eigenvalues, with $1-(\gamma_1)^2$ being the round trip loss for the mode of minimal-loss ($N=1$), and K the round trip propagation matrix that includes contribution from free-space propagation, mirrors, lenses, apertures and effects of thermal lensing [18]. We simulate the thermal lensing in the laser rod, as a thin lens where focal length corresponds to pulse repetition rate according to the exponential fit shown in Fig. 2. Using Eq. (1) we calculated $(\gamma_1)^2$ (i.e. "1-loss") as a function of pulse repetition rate.

To evaluate both the first as well as second loss mechanisms, we calculated how the thermal lensing affects the efficiency and output beam quality when coherently combining four laser distributions. We used a two dimensional model [11] to fully account for the round trip propagation of each channel (as done above for the single channel case), as well as for the phase locking between the channels that is obtained by the interferometric couplers. For the model, we used the expanded configuration shown in Fig. 4. Since the light of each channel passes through a different part of the laser gain medium, each will undergo a shifted thermal lensing effect. We included these differences by inserting a lens of proper off-axis in each of the four channels.

As shown in Fig. 4, the two interferometric couplers are represented by three beam splitters, and there are 10 participating fields **a**, **b**, **c**, **d**, **e**, **f**, **g**, **h**, **i** and **j**. Accordingly, the eigenvectors U_N contain 10 fields, in the form

$$U_N = [a_1, \ldots, a_N, b_1, \ldots, b_N, c_1, \ldots, c_N, d_1, \ldots, d_N, e_1, \ldots, e_N, f_1, \ldots, f_N, g_1, \ldots, g_N, h_1, \ldots, h_N, i_1, \ldots, i_N, j_1, \ldots, j_N], \tag{2}$$

where N is the size of the one-dimensional vector representing each of **a**, **b**, **c**, **d**, **f**, **g**, **h**, **i** and **j** fields. Thus, the size of the eigenvector is 10 N, and the round trip kernel is a 10 N × 10 N matrix composed of 100 N × N blocks. Each diagonal block represents a single field propagation operator for a corresponding channel distribution. The off-diagonal blocks are operators that exchange energy between the different fields, which are associated with the beam splitters.

The calculated results, presented in Figs. 5 and 6. Fig. 5, show the calculated "1-loss" as a function of pulse repetition rate. Fig. 5a shows the results for both a single channel laser as well as for coherent combining

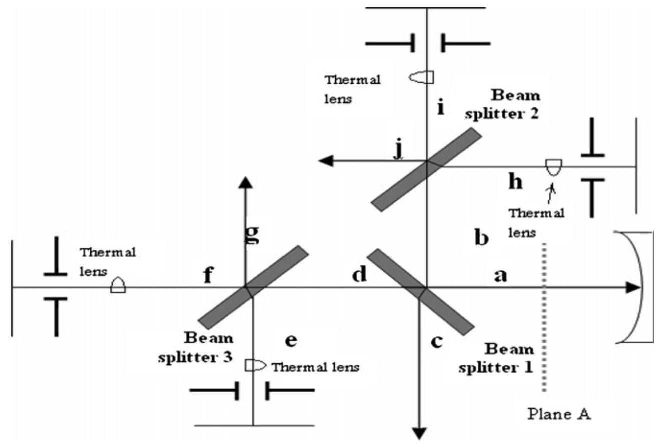

Fig. 4. Extended configuration of the model for coherent combining of four-channel distributions.

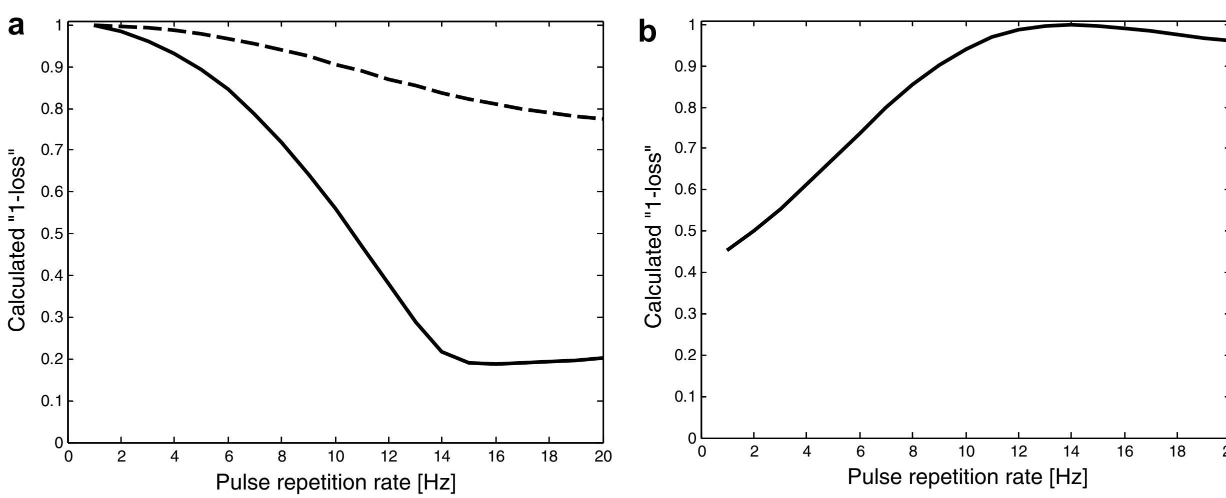

Fig. 5. Calculated "1-loss" as a function of pulse repetition rate. (a) Single laser distribution—dashed curve, coherent combining of four laser distributions without compensating lens—solid curve. (b) Coherent combining of four laser distributions with compensating lens.

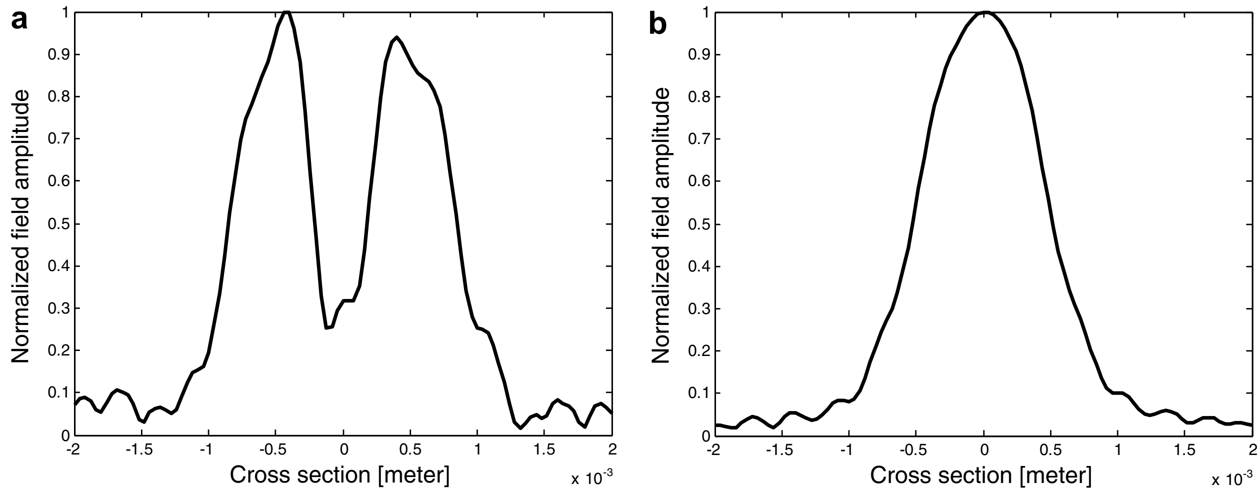

Fig. 6. Calculated cross-section of output beam for coherent combining of four laser channel distributions at a repetition rate of 15 Hz (a) without compensating lens and (b) with compensating lens.

of four laser distributions. As evident, the decrease in "1-loss" as pulse repetition rate increases is relatively moderate for the single channel. This is as expected for the first loss mechanism. It should be noted that even though the propagation mode is shifted in order to suppress the loss due to aperture, there was still distortion that results in some measurable losses. When coherent combining four laser distributions, the thermal induced losses are much stronger than those for the single channel, indicating that the main thermal loss mechanism is the relative misalignment between the channels. Such misalignment (loss mechanism 2) is greater than the misalignment between each channel and its corresponding aperture (loss mechanism 1). Fig. 5b shows the calculated "1-loss" as a function of pulse repetition rate for coherent combining of four lasers distribution after adding off-axis compensating concave lenses with focal lengths of -6 m a distance of 12.5 cm from each thermal lens in the model. As expected, the compensating lens results in a shift of the region with the lowest losses to a higher pulse repetition rate of $\sim$15 Hz where the lens exactly compensates for the thermal lensing of the laser rod.

As evident, the calculated result of "1-loss" as a function pulse repetition rates shown in Fig. 5 are in good agreement with the experimental results of combining efficiency as a function of pulse repetition rates shown in Fig. 3. This is expected, since the output power of our laser which corresponds to the combining efficiency is essentially proportional to "1-loss" [19].

Fig. 6 shows the calculated cross-section of the output beam at pulse repetition rate of 15 Hz. Fig. 6a shows the cross-section for a configuration without a compensating lens and Fig. 6b with a compensating lens. As evident, without the compensating lens the cross-section of the output beam is severely distorted due to the thermal lensing, whereas with the compensating lens it is nearly Gaussian as in the experimental results shown in Fig. 3.

4. Concluding remarks

When coherently combining several lasers distribution from pulsed solid state lasers, the combining efficiency is severely reduced due to thermal lensing, which occurs at high pulse repetition rates. We discussed the effects of thermal lensing and showed, both experimentally and theoretically, how they can be fully suppressed by using compensating lens. Such suppression leads to high combining efficiency as well as to improvement of the combined output beam quality, even for high (predetermined) pulse repetition rates. We expect that the suppression with compensating lenses would also be valid for coherent combining of several multimode laser distributions and for several CW laser distributions, where thermal lensing can be very strong.

References

[1] F.X. D'Amato, E.T. Siebert, C. Roychoudhury, Appl. Phys. Lett. 55 (1989) 816.
[2] S. Menard, M. Vampouille, B. Colombeau, C. Froehly, Opt. Lett. 21 (1996) 1996.
[3] M. DiDomenico Jr., Appl. Phys. Lett. 8 (1) (1966) 20.
[4] D. Sabourdy, V. Kermene, A. Desfarges-Berthelemot, M. Vampouille, A. Barthelemy, Appl. Phys. B 75 (2002) 503.
[5] A.A. Ishaaya, N. Davidson, L. Shimshi, A.A. Friesem, Appl. Phys. Lett. 85 (2004) 2187.
[6] J. Xu, S. Li, K.K. Lee, Y.C. Chen, Opt. Lett. 18 (1993) 513.
[7] L. Fabiny, P. Colet, R. Roy, D. Lensta, Phys. Rev. A 47 (1993) 4287.
[8] M. Oka, H. Masuda, Y. Kandeda, S. Kubot, IEEE J. Quant. Electron. 28 (1992) 1142.
[9] S. Menard, M. Vampouille, A. Desfarges-Berthelemot, V. Kermene, B. Colombeau, C. Froehly, Opt. Commun. 160 (1999) 344.
[10] T.Y. Fan, IEEE J. Quant. Electron. 11 (2005) 567.
[11] V. Eckhouse, A.A. Ishaaya, L. Shimshi, N. Davidson, A.A. Friesem, IEEE J. Quant. Electron. 41 (2005) 686.
[12] A.A. Ishaaya, V. Eckhouse, L. Shimshi, N. Davidson, A.A. Friesem, Opt. Express 13 (2005) 2722.
[13] L. Shimshi, A.A. Ishaaya, V. Ekhouse, N. Davidson, A.A. Friesem, Appl. Phys. Lett. 88 (2006) 041103.

[14] V. Eckhouse, A.A. Ishaaya, L. Shimshi, N. Davidson, A.A. Friesem, Opt. Lett. 31 (50) (2006) 350.
[15] M. Brunel, A. Le Floch, F. Bretenaker, J. Opt. Soc. Am. B 13 (5) (1996) 946.
[16] R. Oron, S. Blit, N. Davidson, A.A. Friesem, Appl. Phys. Lett. 77 (21) (2000) 3322.
[17] Q. Tang, O. Yu, Q. Hu, Chin. Opt. Lett. 5 (1) (2007) 34.
[18] R. Oron, N. Davidson, A.A. Friesem, E. Hasman, Prog. Opt. 42 (2001) 325.
[19] A.A. Ishaaya, N. Davidson, G. Machavariani, E. Hasman, A.A. Friesem, IEEE J. Quant. Electron. 39 (2003) 74.