Very high-order pure Laguerre-Gaussian mode selection in a passive Q-switched Nd:YAG laser

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Abstract: An intra-cavity phase element, combined with a passive Q-switch saturable absorber and a suitable intra-cavity aperture, can provide extremely high mode discrimination, so as to obtain laser operation with single, pure, very high order Laguerre-Gaussian mode. With a Nd:YAG laser setup, well controlled and extremely stable Q-switched operation in the degenerate Laguerre-Gaussian TEM_{04}, TEM_{14}, TEM_{24}, TEM_{34}, and TEM_{44} modes was obtained. The measured output energy per pulse for each of these modes was 5.2mJ, 7.5mJ, 10mJ, 12.5mJ, and 13.7mJ respectively, compared to 2.5mJ for the Gaussian mode without the phase element (more than a five fold increase in output energy). Correcting the phase for these modes, so that all transverse lobes have uniform phase, results in a very bright and narrow central lobe in the far field intensity distribution that can theoretically contain more than 90% of the output energy.

OCIS codes: (140.3410) Laser resonators; (140.3300) Laser beam shaping

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Received 22 April 2005; revised 11 June 2005; accepted 13 June 2005

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1. Introduction

Pure high order transverse mode operation in laser cavities has been originally suggested in the 1960’s, and since then experimentally investigated in various types of laser configurations [1] - [7]. In recent years rather efficient and robust high-order transverse mode selection in laser resonators was achieved by resorting to intra-cavity phase elements [8, 9]. When placed in the resonator, the phase element introduces high losses to undesired modes and low losses to the selected mode. A limiting aperture is also used in the conventional manner to further discriminate against higher transverse modes. With such phase elements, efficient selection of pure TEM_{01}, TEM_{02}, TEM_{03} and helical TEM_{01^*} Laguerre-Gaussian (LG) modes was experimentally demonstrated, leading to an increase up to a factor of 2 in output power with respect to the fundamental TEM_{00} mode. This was shown for CW and pulsed operation, and for different gain mediums (CO_2, Nd:YAG). Since the entropy of a single high-order mode is equal to that of the fundamental mode [10], it is thermodynamically possible to efficiently transform a single high order mode into a Gaussian beam, thereby achieving excellent beam quality as well as high output power. Such a transformation can be performed externally by means of two specially designed phase elements [11], or, as demonstrated recently, by coherently adding various transverse parts of the mode [12].

When trying to select *very* high-order modes, it is necessary to discriminate against many lower order modes. Such discrimination is difficult to achieve with a single intra-cavity phase element. Thus, the ability to select a pure transverse mode in a laser resonator seemed to be practically limited only to relatively low order modes, and hence resulted only in a modest increase in output powers compared to TEM_{00} operation.

A passive Q-switch saturable absorber, where the transmission is intensity dependent, can provide additional discrimination between laser modes [13, 14]. Indeed, in some cases, a passive Q-switch saturable absorber can serve as a dynamic spatial filter [15] and force TEM_{00} operation even with intra-cavity apertures that are larger than needed for such operation. Further increase of the aperture size typically results in extremely erratic high-order or multimode lasing. This inability to obtain large mode volume in passive Q-switched lasers, either in a single high-order mode or multimode operation, poses a practical limit to the effective power extraction from such lasers.

In this article we show how an intra-cavity phase element, combined with the properties of a passive Q-switch saturable absorber and with a suitable intra-cavity aperture, can provide extremely high modal discrimination, enabling extremely stable and controlled operation of very high order LG modes (with as much as 40 lobes). These modes have a significantly larger mode volume than that of the Gaussian mode, resulting in more than 5-fold increase in output power. We further show that correcting the phase of these modes, so that they have transverse uniform phase, results in a bright central lobe in the far field.

#7251 - $15.00 USD
Received 22 April 2005; revised 11 June 2005; accepted 13 June 2005

2. Basic principles

A basic configuration for high-order mode selection with a binary phase element and a saturable absorber is schematically shown in Fig. 1. Similar to the case of non Q-switched operation (without a saturable absorber), the phase element, positioned near one of the cavity mirrors, introduces high diffraction losses to all the the undesired modes and very low losses to the desired mode, whereas the aperture provides for discrimination against modes of higher order than desired [8, 9]. The passive Q-switch saturable absorber introduces additional transverse mode discrimination. The additional discrimination due to the passive Q-switch saturable absorber can be attributed to two factors. One is the rather slow opening of the switch (many round trips within the cavity), during which the mode competition introduces transverse discrimination. The other, more dominant factor, results from the fact that the transmission of the absorber depends on the intensity, which varies spatially, forming a dynamic spatial filter. We will now consider the later factor in some detail.

The modal discrimination of the saturable absorber can be intuitively understood by examining a typical transmission curve shown in Fig. 2 [16]. At very low intensity values the transmission is independent of the intensity, and is equal to the initial transmission of the saturable absorber. As the intensity increases, the transmission increases in a rather linear fashion with the logarithm of the intensity. At high intensity values the transmission saturates and the saturable absorber is fully bleached. Accordingly, at low intensity, lasing is inhibited because of the high losses introduced by the saturable absorber. Thus, the modal distribution of the initially formed field in the resonator would be the same as that without the saturable absorber. Specifically, a small diameter of the intra-cavity aperture would lead to a TEM_{00} distribution, whereas larger diameters would lead to multimode distributions.

As the intensity further increases, yet below lasing threshold, the initial modal distribution is altered (peaks become more prominent relative to surrounding field) in accordance to the transmission of the saturable absorber. During the intensity buildup, and when lasing threshold is reached, the intensity induces a transmission distribution in the saturable absorber that acts as a spatially dependent dynamic transmission filter. This filter introduces more losses to certain transverse modes than others, and thus mode discrimination is achieved. The effect of the saturable absorber somewhat resembles a situation where a spatial pump profile is generated in the laser gain medium that favors certain transverse modes [17, 18].

Now, with the addition of the intra-cavity phase element, the actual initial modal distribution will correspond to that obtained with the phase element and the aperture, regardless of the saturable absorber. For example, with an intra-cavity TEM_{04} phase element and an aperture (just of sufficiently large diameter for selecting such high-order mode), the initial modal distribution would be that of a TEM_{04} distribution. This induces a transmission distribution in the saturable absorber that favors TEM_{04} operation. If, however, the aperture diameter is increased, then an initial multimode distribution (probably containing several modes with the same symmetry

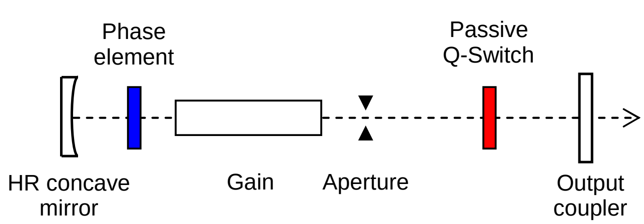

Fig. 1. A basic configuration for high-order mode selection in a laser resonator with an intra-cavity phase element and a passive Q-switch saturable absorber.

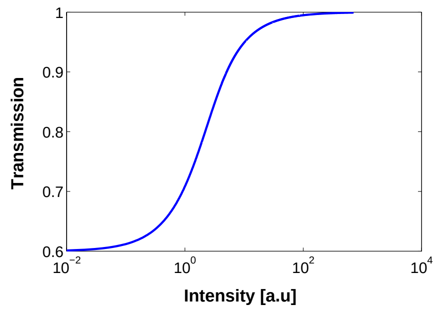

Fig. 2. Transmission of a typical saturable absorber (see ref. [16]).

such as TEM_{14}, TEM_{14}, TEM_{24} TEM_{34}, etc.) would result. This multimode distribution will in turn induce a transmission distribution in the saturable absorber that will favor a different high order mode.

3. Experimental procedure and results

To experimentally investigate mode selection in the presence of a saturable absorber, we used a pulsed Nd:YAG laser arrangement shown in Fig. 3. It includes a 70 cm long plano-concave stable resonator, with a concave ($R = 1.5$ m) output coupler of 40% reflectivity at 1064 nm and a high-reflective flat mirror (the equivalent stability parameters [16] are $g_1 = 1$ and $g_2 = 0.53$). A flash lamp pumped Nd:YAG rod of 5 mm diameter and 10 cm length (1.1% doping) served as the gain medium. Throughout the experiments, the rod was pumped with a pulse rate of 0.5 Hz at a power level suitable for single pulse operation . Under these pumping conditions, the focal length of the thermal lens in the rod was measured to be more than 20 m. A thin film polarizer was inserted in order to obtain P-polarization operation. The intra-cavity aperture diameter was varied between 1 mm and 5 mm in order to allow selection of various transverse modes. A binary phase element with 8 azimuthal sections (see insert in Fig. 3), corresponding to the 0 and π phase regions of the TEM_{04} degenerate LG mode, was positioned 4.5 cm from the rear mirror. This element was made of fused silica and was fabricated using photolithographic and reactive ion etching technologies to form the specific accurate depth profiles. These were subsequently coated with anti-reflection layers for 1064 nm. A plastic dye saturable absorber (BDM, made by Kodak), positioned 6.5 cm from the output coupler, was used for passive Q-switching. The near and far field intensity distributions were detected with CCD cameras, and a fast photodiode connected to an oscilloscope measured the temporal pulse shape and ensured single pulse operation (within one pump pulse).

Initially we operated the laser with the passive Q-switch saturable absorber but without the intra-cavity phase element. Single TEM_{00} mode operation was obtained with intra-cavity aperture diameters as large as 1.8 mm. These values are larger than the 1.4 mm diameter required for selection of the TEM_{00} mode in free-running (non Q-switched) operation. The measured pulse energy was 2.5 mJ. The near and far field intensity distributions of the TEM_{00} mode are shown in Fig. 4. The M^2 values calculated from these distributions were 1.03 and 1.08 for the X and Y directions respectively. Increasing the aperture diameter above 1.8 mm and below 2.3 mm resulted in TEM_{01} operation, but this was very sensitive to alignment of the resonator mirrors. Increasing further the aperture diameter resulted in uncontrolled high-order mode lasing, where in each successive pulse a different mode was observed.

We then inserted the binary phase element for selecting the TEM_{04} mode into the resonator,

#7251 - $15.00 USD Received 22 April 2005; revised 11 June 2005; accepted 13 June 2005

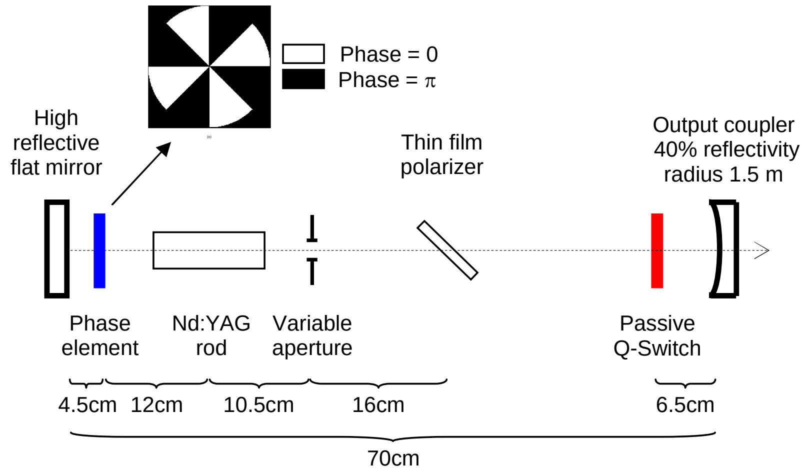

Fig. 3. Experimental passive Q-switched Nd:YAG laser arrangement for intra-cavity high-order transverse mode selection.

and increased the aperture diameter to 3.5 mm. As expected, the laser output beam had a TEM_{04} mode distribution. Increasing further the aperture diameter to 4.2 mm, 4.3 mm, 4.5 mm, and 4.8 mm, resulted in laser output beams with the TEM_{14}, TEM_{24}, TEM_{34}, and TEM_{44} degenerate LG mode distributions, respectively. Lasing with these pure high order modes was found to be stable, and rather insensitive to alignment. The near and far field intensity distributions of these output beams are shown in Fig. 5. The measured output energy per pulse for the TEM_{04}, TEM_{14}, TEM_{24}, TEM_{34}, and TEM_{44} mode distributions, were 5.2mJ, 7.5mJ, 10mJ, 12.5mJ, and 13.7mJ respectively. These results indicate that more than a five fold increase in output energy can be obtained as compared to that from a conventional passive Q-switch laser resonator with the Gaussian mode distribution (without the intra-cavity phase element).

Despite the fact that the binary intra-cavity phase element that was used had only azimuthal phase dependence, the results indicate that discrimination and selection of modes with radial phase dependence were also achieved. We believe that the azimuthal discrimination between modes is achieved by the phase element, while the radial discrimination is achieved by the saturable absorber. Thus, the combination of the phase element and the saturable absorber, yielded the high modal discrimination needed in order to select these very high-order pure modes. To verify that the saturable absorber Q-switch is indeed playing an important role in the mode selection process, we repeated these experiments with an active Q-switch arrangement.

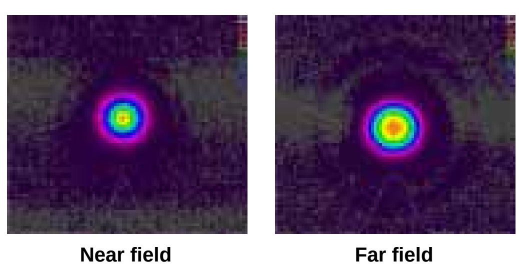

Fig. 4. Experimental near and far field intensity distributions of the Gaussian TEM_{00} mode in passive Q-switched operation. These were obtained with an intra-cavity aperture diameter of 1.8 mm and without an intra-cavity phase element.

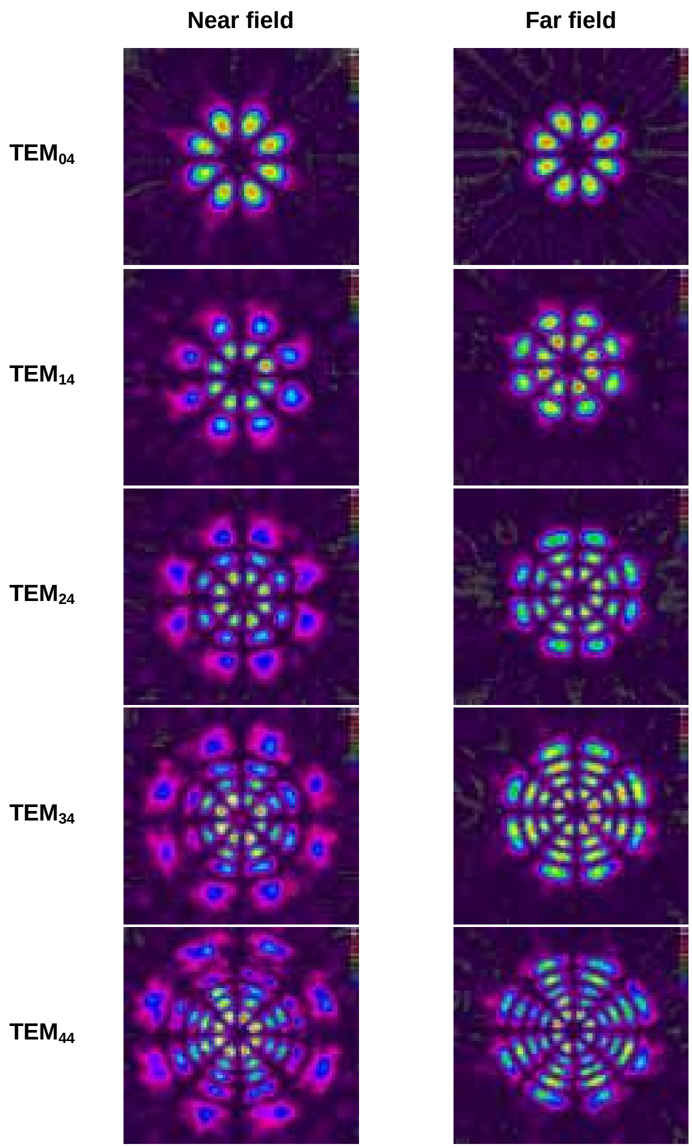

Fig. 5. Experimental near and far field intensity distributions of high order modes (degenerate Laguerre-Gaussian TEM_{04}, TEM_{14}, TEM_{24}, TEM_{34}, and TEM_{44} modes).

The active Q-switch arrangement was comprised of an electro-optical $LiNbO_3$ crystal and a $\lambda/4$ retardation plate, that were placed instead of the passive Q-switch. The far field intensity distribution of the laser output when operating with a 4.8 mm aperture diameter is shown in Fig. 6. As evident, the output in this case is a multimode beam, probably containing simultaneously all of the modes shown in Fig. 5. This clearly indicates that the passive Q-switch introduces the necessary discrimination needed for selection of these pure high-order modes.

As expected, significant correlation was found between the multimode intensity distributions in non Q-switched (and in actively Q-switched) operation and the modes selected in passive Q-switched operation, in the same resonator configuration. This is shown in Fig. 7. Figures 7(a)

#7251 - $15.00 USD
Received 22 April 2005; revised 11 June 2005; accepted 13 June 2005

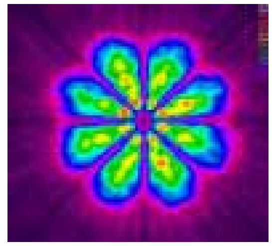

Fig. 6. Far field intensity distribution of the laser output beam when operated with an active Q-switch, a TEM_{04} phase element, and a 4.8 mm intra-cavity aperture diameter.

and 7(b) show the experimentally detected far field multimode intensity distributions in active Q-switched operation, with the TEM_{04} phase element and aperture diameters of 3.5 mm and 4.8 mm respectively. As evident, these two multimode distributions differ significantly. Figures 7(c) and 7(d) show only the peaks of the distributions of Figs. 7(a) and 7(b) respectively (this was obtained by discarding all intensity values below 85% of the maximum intensity). Now, assuming that the initial spatial transmission distribution of the saturable absorber, $T(x,y)$, is proportional to peaks in these multimode distributions, we calculated for each of the two distributions shown in Figs. 7(c) and 7(d) the effective transmission for the LG $TEM_{\rho 4}$ modes, with $\rho = 0,1,2,3,4$. The effective transmission, T_{eff}, for each mode was calculated by multiplying the mode intensity distribution with the spatial transmission T(x,y), and normalizing the result with respect to the mode distribution (see equation in Table I).The waist parameter of the $TEM_{\rho 4}$ modes was extracted from the experimental data in passive Q-switched operation. The calculated effective transmission values for each case are shown in Table I. As evident, the mode with the highest effective transmission in the case of a 3.5 mm aperture diameter is the TEM_{04} mode, and in the case of a 4.8 mm aperture diameter is the TEM_{44} mode; the

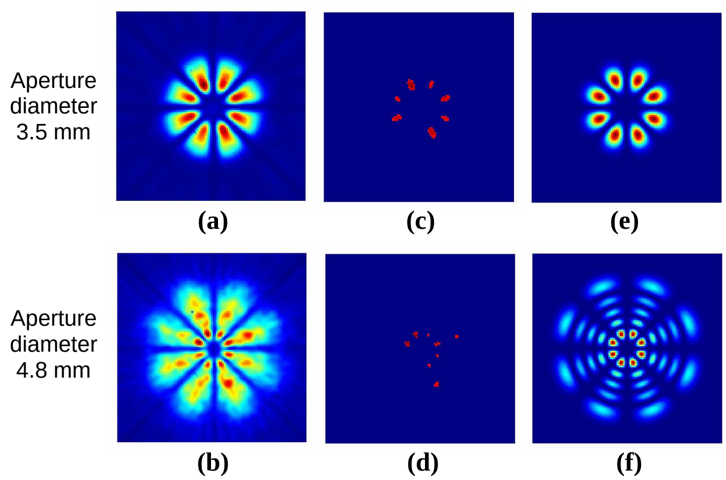

Fig. 7. Experimental multimode intensity distributions in active Q-switched operation and the corresponding selected modes in passive Q-switched operation. (a) and (b) experimental far field intensity distributions in active Q-switched operation for aperture diameters of 3.5 mm and 4.8 mm; (c) and (d) intensity distributions of (a) and (b) above a threshold of 85% of the maximum intensity; (e) and (f) corresponding calculated LG TEM_{04} TEM_{44} mode distributions that fit (c) and (d).

#7251 - $15.00 USD
Received 22 April 2005; revised 11 June 2005; accepted 13 June 2005

Table 1. Calculated effective transmission through the saturable absorber for each LG mode distribution, assuming the induced transmission patterns shown in Figs. 7(c) and 7(d). With $T_{eff} = \frac{\int T(x,y) \cdot I_{mode}(x,y) \cdot dxdy}{\int I_{mode}(x,y) \cdot dxdy}$.

Transverse mode	T_{eff} [a.u] d=3.5 mm	T_{eff} [a.u] d=4.8 mm
TEM_{04}	0.106	0.012
TEM_{14}	0.067	0.020
TEM_{24}	0.033	0.023
TEM_{34}	0.028	0.025
TEM_{44}	0.028	0.026

corresponding calculated intensity distributions of these modes are shown in Figs. 7(e) and 7(f)), and they are in excellent agreement with the experimental results for passive Q-switched operation shown in Fig. 5.

Temporal pulse shape measurements for the high order mode passive Q-switched pulses were also performed. The results, shown in Fig. 8, reveal how the temporal pulse shape depends on the purity of the selected transverse modes. Figures 8(a) and 8(b) show a representative far field intensity distribution for a pure mode and the corresponding pulse shape. The measured pulse width (FWHM) was 44nsec. Figures 8(c) and 8(d) show what happens when a pure mode is not discriminated and selected, i.e. when the aperture diameter is such that two or more modes lase simultaneously. As evident, the far field intensity distribution is not that of a pure mode, and the

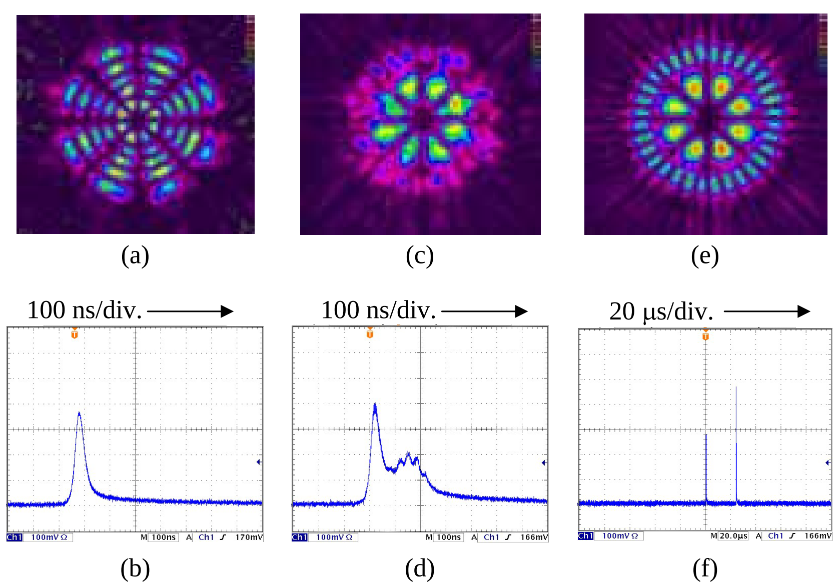

Fig. 8. Experimental far field intensity distributions and corresponding temporal pulse shapes in passive Q-switched operation. (a) and (b) far field intensity distribution and corresponding pulse shape for a pure high-order mode selection; (c) and (d) far field intensity distribution and the corresponding pulse shape, for an impure mode selection; (e) and (f) far field intensity distribution and timing sequence for a double-pulse operation.

#7251 - $15.00 USD Received 22 April 2005; revised 11 June 2005; accepted 13 June 2005

corresponding temporal pulse shape has a double-hump shape, probably corresponding to the lasing of two (or more) participating modes. When the pump power is increased, two discrete laser pulses can be obtained within one pump pulse. In this case two high-order transverse modes lase, as shown in Figs. 8(e) and 8(f), where each of the modes corresponds to one of the pulses. Here a combination of TEM_{04} and $TEM_{0,16}$ was observed in a single CCD camera frame (the time delay between the two pulses was about 24 μsec). We believe that the TEM_{04} mode with the lowest losses lases with the first pulse and depletes the energy in the gain regions that correspond to this mode. Then the $TEM_{0,16}$ mode lases with the second pulse by exploiting energy that is stored in the outer part of the gain region.

The pure high-order LG mode beam distributions shown in Fig. 5, have a relatively high M^2 and large divergence, but in principle can be efficiently converted into a nearly Gaussian TEM_{00} mode [10, 12]. Even without conversion, when these pure high-order modes are corrected so that they have a uniform transverse phase distribution in the near field, the far field intensity distribution has a central lobe with most of the energy contained within it, although M^2 remains the same [19].

We calculated the relative energy as a function of the radius in the far field intensity distribution, for several degenerate LG modes with uniform phase. The results for TEM_{04}, TEM_{14}, TEM_{24}, TEM_{34}, and TEM_{44} modes with uniform phase distributions, are shown in Fig. 9 (the result for the TEM_{00} is also shown for comparison). As evident, in all cases, more than 85% of the total energy is contained in the far field central lobe. For the higher order modes, that have more lobes in the central area, the energy contained in the central lobe increases and the width of the lobe decreases. Specifically, for TEM_{44} with uniform phase distribution the energy in the central lobe exceeds 90%, and it's width decreased by about a factor of 2 when compared to that of the TEM_{00}. In addition, since the far field central lobe closely resembles a Gaussian distribution, using a single aperture in the far field to filter out the side lobes would result in nearly Gaussian beam quality with high peak intensity.

We performed an experiment to obtain a uniform phase distribution, and thereby a high narrow central lobe, for the far field intensity distribution of a laser operating with TEM_{04} mode. In this experiment we placed a TEM_{04} binary phase element in the optical path of the laser output. Figure 10 shows the calculated and experimental far field intensity distributions for two laser outputs. In one the near field distribution was the usual TEM_{04} mode distribution,

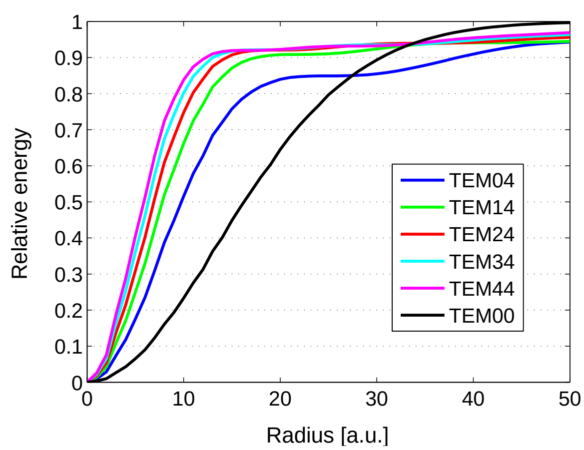

Fig. 9. Calculated energy percentage as a function of radius in the far field intensity distribution for the TEM_{00} mode, and for several high-order LG modes with uniform phase.

Received 22 April 2005; revised 11 June 2005; accepted 13 June 2005

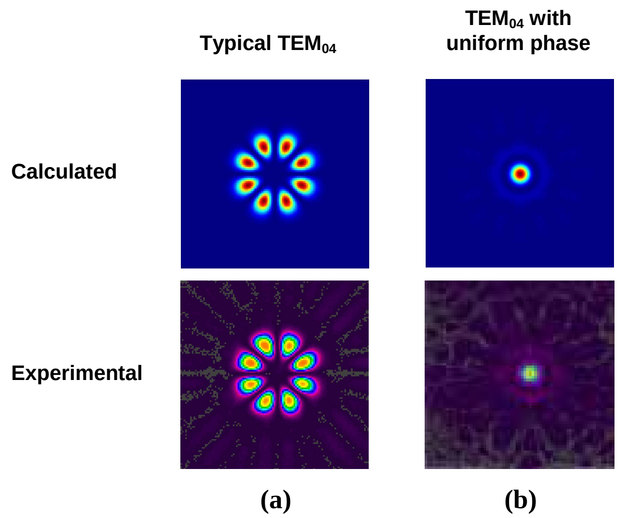

Fig. 10. Calculated and experimental far field intensity distributions for a laser operating with a LG TEM_{04} mode. (a) for typical TEM_{04} with alternating 0 and π phases for adjacent lobes; (b) for TEM_{04} with uniform phase.

and in the other TEM_{04} mode distribution with uniform phase. As expected, we obtained a central bright lobe for that with the TEM_{04} with the uniform phase distribution. The measured energy percentage contained in the central lobe was 73%, somewhat lower than the calculated percentage of 85%. This reduction can be attributed to imperfections in the external phase element or to a slight impurity of the selected mode (in phase or amplitude). Thus, although it was shown that applying a uniform phase to laser modes by use of binary phase elements does not improve the M_2 [19], far field distributions with most of the energy in the central lobe can be obtained. Accordingly, the energy-in-the-bucket criterion would be more suitable than the M_2 criterion for characterizing the beam quality. Finally, it should be noted that the need for an external phase element in this case could be eliminated by placing the intra-cavity phase element near the output coupler [9].

4. Concluding remarks

The combination of an intra-cavity phase element, a passive Q-switch saturable absorber, and a suitable intra-cavity aperture, can provide extremely high transverse mode discrimination. This was demonstrated with a passive Q-switched Nd:YAG laser, that operated stably in TEM_{04}, TEM_{14}, TEM_{24}, TEM_{34}, and TEM_{44} degenerate LG modes. The results revealed that more than 5-fold increase in output energy as compared to TEM_{00} operation can be obtained. Such output energies in passive Q-switched lasers were difficult to achieve in the past, due to the inability to obtain stable operation with either multimode or single high-order mode. We further showed that correcting the phase of these modes would result in a very bright and narrow central lobe in the far field distribution that can theoretically contain more than 90% of the energy. Experimentally we showed that the energy in the central lobe for a a TEM_{04} mode with uniform phase reached 73%. We expect that for higher order modes the energy in the central lobe will increase as predicted by theory. Moreover, exploiting phase elements with both radial and azimuthal dependence could lead to even higher modal discrimination than demonstrated, and would allow for suitable phase correction of very high order modes resulting in a far field intensity distribution with one central lobe where most of the energy is contained. Finally, the very high order modes with uniform phase should be useful in a variety of applications, such as compact laser range-finders, requiring high peak intensity with low divergence.

Acknowledgments

The authors would like to thank E. Galun, V. Krupkin, E. Luria, I. Pe'er, I. Shoshan and M. Sirota, from Elop Electro-optics Industries, for the passive Q-switch and helpful discussions.