Intracavity coherent addition of single high-order modes

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We report on efficient intracavity coherent addition of several single high-order mode distributions in a multichannel laser resonator. The phase locking and coherent addition is achieved by using an intracavity interferometric beam combiner. The principle, configuration, and experimental results with pulsed Nd:YAG Laguerre–Gaussian TEM_{01} and TEM_{02} laser beam distributions are presented. The results reveal more than 95% combining efficiency with a nearly pure high-order mode output beam distribution in both free-running and Q-switched operation. © 2005 Optical Society of America

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High laser output power combined with good beam quality can be achieved by operating a laser in a single high-order transverse mode. In recent years, high-order mode selection by use of intracavity phase elements was experimentally demonstrated in CO_2 and Nd:YAG lasers, with a 50–100% increase in output power over that of fundamental TEM_{00} mode operation.[1,2] Because of the well-defined amplitudes and phases of single high-order mode beam distributions, their beam quality can be efficiently improved by transforming them externally into a nearly Gaussian distribution.[3,4] Intracavity coherent addition of laser beams is also a promising approach to increasing the output power while maintaining good beam quality.[5] Efficient coherent addition of several Gaussian distributions has been recently demonstrated both in bulk solid-state lasers[6,7] and in fiber lasers,[8,9] with more than 90% combining efficiency. In this Letter we combine both single high-order mode operation with coherent addition, demonstrating that output powers higher than those from each approach separately can be obtained.

A basic configuration for intracavity coherent addition of two single high-order modes is schematically presented in Fig. 1. It is essentially a two arm plano–concave resonator, where two separate laser channels are coherently combined with an interferometric beam combiner to form a single output channel. The use of common end mirrors and gain medium provides improved stability and ease of alignment. Single high-order degenerate Laguerre–Gaussian (LG) mode operation in each channel is obtained by inserting inside the laser resonator cavity a binary phase element along the combined channel and an aperture in each separate channel. Alternatively, the binary phase element can be inserted along one of the separate channels, whereby the desired high-order mode operation will also be imposed on the other channel.[10] The binary phase element consists of π phase steps, corresponding to the uniform phase regions of the desired degenerate LG mode distributions. The combination of the phase element and apertures ensures low losses for the desired modes and significant losses to all other modes.[2] The coherent addition is achieved with a planar interferometric beam combiner composed of a high-precision plane parallel plate with specially designed coatings.[7] Half of the front surface is coated with an antireflection (AR) layer and the other half with a 50% beam splitter layer, whereas half of the rear surface is coated with a highly reflecting layer and the other half with an AR layer. Such an intracavity interferometric combiner allows for self-phase-locking and coherent addition of the two channel distributions.[7]

To analyze coherent addition of high-order modes in the configuration shown in Fig. 1, we exploited a relatively simple one-dimensional model that is based on matrix manipulation and provides solutions to the combined eigenvalue kernel equation for a bare resonator (i.e., no gain).[10] With this model we calculated the field amplitude distribution and round-trip losses of the combined global eigenmodes for a case in which the phase element is placed in the combined channel and for a case in which it is placed in one of the two separate channels. In these calculations a binary phase element for selection of the LG TEM_{01} mode was used for each of the two cases discussed, using a 70 cm long plano–concave resonator with a concave output coupler having a radius of 1.0 m. Figure 2 shows the round-trip losses of the combined TEM_{00} and TEM_{01} eigenmodes as a function of the aperture diameter for both cases. As is evident, there is good discrimination between these two modes with aperture diameters around 1.6 mm for both cases. Also evident is the improved modal discrimination when the phase element is inserted into

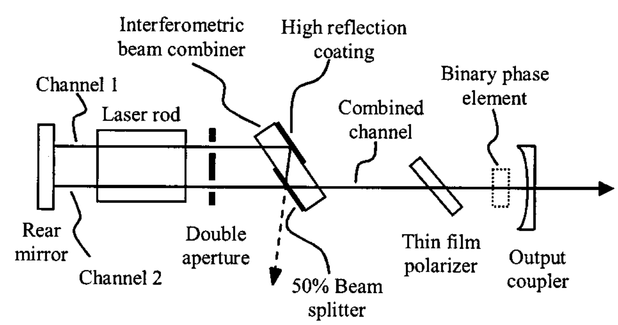

Fig. 1. Configuration for intracavity coherent addition of two high-order mode laser beam distributions.

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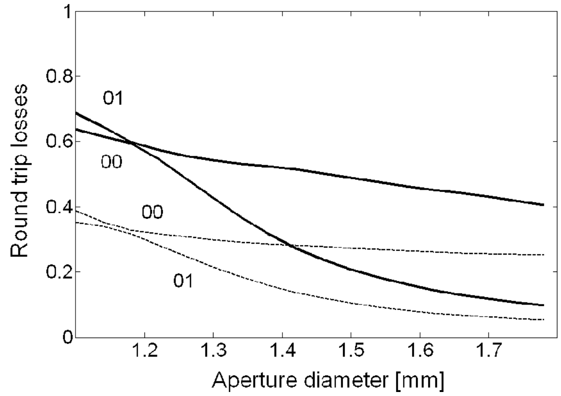


Fig. 2. Calculations of the round-trip losses as a function of the aperture diameter for the two lowest-loss eigenmodes of the resonator of Fig. 1, where the binary phase element is either placed in the combined channel (solid curve) or in one of the separate channels (dashed curve).

the combined channel, rather than in one of the separate channels. The calculated lowest-loss global eigenmode in these two cases has indeed an amplitude distribution of a LG TEM_{01} mode, whereas the next mode has an amplitude distribution of a nearly Gaussian mode.

When the binary element is placed in the combined channel, the selection of the LG TEM_{01} mode operation is not that surprising. It is less intuitive to understand how the TEM_{01} mode operation occurs when the binary phase element is placed in only one of the separate channels. What essentially occurs is that the TEM_{01} mode operation in the channel with the phase element is imposed on the other channel. Specifically, when the two channels are coherently coupled, only the TEM_{01} distribution from each channel will coherently add with little, if any, losses, whereas all other modes suffer losses.

To experimentally demonstrate coherent addition of two high-order mode distributions, we used an arrangement similar to that shown in Fig. 1. It included a 70 cm long plano–concave resonator, with a concave output coupler having a radius of 1.0 m and 40% reflectivity at 1064 nm, and a flat rear mirror with high reflectivity. The typical Gaussian beam diameter in such a resonator is 0.8 mm at the flat rear mirror and 1.4 mm at the concave output coupler. The laser gain medium was 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 pulse rate of either 0.5 or 4 Hz. Two circular apertures were inserted into each of the two separated channels. The interferometric combiner was a 3 mm thick fused silica plane parallel plate (parallelism <1 arc sec), coated with suitable dielectric layers and oriented at Brewster's angle so there is no need for AR layers. Binary phase elements, with the appropriate $0-\pi$ phase regions for selecting the TEM_{01} and TEM_{02} degenerate LG modes, were fabricated using photolithographic and reactive ion etching technologies to form the specific accurate depth profiles and were subsequently coated with AR layers for 1064 nm.[2] A high-quality thin-film polarizer was inserted near the output coupler to ensure p polarization minimize losses at the beam combiner. CCD cameras and a Spiricon laser beam analyzer were used for detecting and characterizing the near- and far-field intensity distributions.

At first, high-order mode pulsed operation (free running) was obtained in a single channel, without the interferometric beam combiner. Optimal selection of the TEM_{01} mode was achieved when a LG TEM_{01} binary phase element was placed 3.7 cm from the output coupler, and the aperture diameter was set to 1.6 mm. An output energy of 3.0 mJ/pulse was measured for the TEM_{01} mode, which is about 42% higher than the measured output energy of 2.1 mJ for the TEM_{00} mode in this laser resonator. Then we inserted the interferometric beam combiner and the second aperture with 1.6 mm diameter while the phase element was placed along the combined channel path. This resulted in combined TEM_{01} mode operation, with a combined output energy of 5.8 mJ/pulse, indicating 97% combining efficiency. The corresponding detected far-field intensity distributions of the output beam, for the single-channel operation and for the combined two-channel operation, are shown in Fig. 3. Since the phase element is located near the output coupler, the TEM_{01} mode acquires a uniform phase when emerging from the resonator, so the far-field intensity distribution has a single central peak in the far field.[2] As is evident, the combined two-channel far-field intensity distribution has indeed the modal structure of the TEM_{01} mode with uniform phase distribution and is almost identical to the distribution obtained with single-channel operation.

Combined high-order mode operation was also achieved by placing the binary phase element along one of the separate channels, near the rear mirror of Fig. 1. The binary phase element, designed to select the LG TEM_{01} mode, was placed 3.7 cm from the rear mirror, together with the same aperture diameters of 1.6 mm. In single-channel operation, without the interferometric beam combiner, the measured output energy for the TEM_{01} mode was 3 mJ/pulse. With two channels and the interferometric beam combiner, allowing for imposing a TEM_{01} mode on both chan-

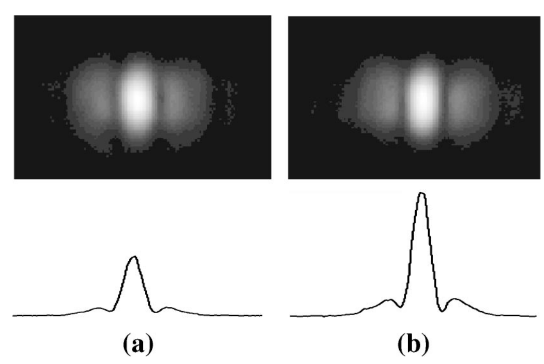
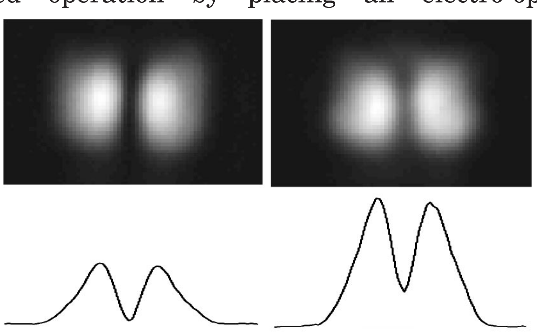


Fig. 3. Experimental far-field intensity distributions and normalized cross-sectional traces for operation with a binary TEM_{01} phase element placed along the combined channel path near the output coupler. (a) Single-channel operation, (b) combined two-channel operation.

nels and their coherent addition, the measured output energy increased to 6.2 mJ/pulse, indicating more than double the energy obtained with single-channel operation. This can be explained by a slightly deteriorated level of purity of the combined mode in this case, evident in the experimental far-field intensity distributions for the single-channel operation and for the combined two-channel operation that are shown in Fig. 4. Qualitatively, the TEM_{01} mode operation is indeed obtained when combining the two channels (since the phase element in this case is placed near the rear mirror, the far-field distribution has the usual two-lobe distribution of the TEM_{01} mode). However, the cross-sectional traces in Fig. 4(b) clearly show that the combined intensity distribution is not zero at the center, indicating the slightly deteriorated level of mode purity compared to the single-channel operation of Fig. 4(a). Comparison between the results presented in Fig. 3 and those presented in Fig. 4 indicate that the modal discrimination is higher when the phase element is placed along the combined channel, in good agreement with the calculations presented in Fig. 2.

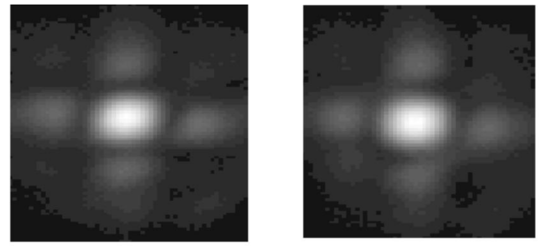
We also performed an experiment for coherent addition of two TEM_{02} mode distributions using a suitable binary phase element. The phase element was placed along the combined channel path, 3.7 cm from the output coupler, and the aperture diameters were chosen to be 1.8 mm for optimal mode selection. A combined output energy of 7 mJ was measured in the TEM_{02} mode compared to 3.7 mJ for single-channel TEM_{02} operation (95% combining efficiency). This output energy in the combined TEM_{02} mode is more than triple the output energy in the Gaussian TEM_{00} mode in this resonator. The corresponding detected far-field intensity distributions of the TEM_{02} mode output beam, for single-channel operation and for combined two-channel operation, are shown in Fig. 5. The bright central peak in the far-field intensity distributions in Fig. 5(a) for the single channel and Fig. 5(b) for the two channels is a clear indication of the purity of these uniform phase TEM_{02} mode beams.

Similar experiments were preformed in Q-switched pulsed operation by placing an electro-optical



(a) **(b)**

Fig. 4. Experimental far-field intensity distributions and normalized cross-sectional traces for operation with a binary TEM_{01} phase element placed in one of the separate channels near the rear mirror. (a) Single-channel operation; (b) combined two-channel operation.



(a) **(b)**

Fig. 5. Experimental far-field intensity distributions with a binary TEM_{02} phase element placed along the combined channel path near the output coupler. (a) Single-channel operation; (b) combined two-channel operation.

$LiNbO_3$ crystal and a $\lambda/4$ retardation plate in the combined channel near the output coupler. The results were essentially the same as for free running, with more than 95% combining efficiency for the TEM_{01} and TEM_{02} mode distributions. In all the experiments described above the combining efficiency was found to be rather insensitive to angular deviations of the interferometric combiner. The effect of cavity and aperture misalignments on the output power was similar to that encountered with a typical plano–concave resonator of the same dimensions.

To conclude, we have demonstrated that two single high-order mode distributions can be selected and coherently added to obtain laser output energies that are significantly higher than those obtained by coherently adding Gaussian distributions. These demonstrations were performed with TEM_{01} and TEM_{02} modal distributions. We expect that using higher-order modal distributions and more intracavity channels would lead to further increase of the combined laser output energies.

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