Imposing a Gaussian Distribution in Multichannel Laser Resonators

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***Abstract*—Intracavity coherent addition of several laser channel distributions where one is a Gaussian distribution and the others are multimode distributions is investigated. It is shown experimentally that the Gaussian distribution is inherently imposed on all the channels. A model for analyzing coherent addition of two or four beams is developed and used to support the experimental results.**

***Index Terms*—Coherent addition, laser arrays, lasers.**

I. INTRODUCTION

COHERENT addition of several separate lasers, each with a low output power and good beam quality, can lead to a practical and compact overall laser system having a high output power concomitantly with good beam quality. Indeed, a number of methods for phase locking and coherent addition of lasers have been developed [1]–[12]. These involve specialized laser resonator configurations such as Talbot or Fourier transform resonators [1], [2], Vernier–Michelson resonators [3]–[5], evanescent waves coupling [6]–[8], and the introduction of amplitude and phase diffractive components or polarization elements into the resonator [9]–[12]. In these methods only identical Gaussian distributions were coherently added with high efficiency once their phases are properly locked.

In this paper we investigate coherent addition of two as well as four laser channel distributions that, when operated separately, one channel has a Gaussian field distribution and the others have multimode field distributions. In such a configuration, the modal composition, and the phase and amplitude of each mode influence phase locking and coherent addition. We show that for a laser configuration with multichannels, the Gaussian distribution is imposed on all other channels, enabling efficient coherent addition and a nearly Gaussian output beam distribution. The phase locking between the channels needed for coherent addition is achieved by using an intracavity planar interferometric combiner, which enables coupling between the different laser distributions [5]. The overall combined laser configuration is relatively compact and robust, and could potentially be incorporated into practical laser systems.

In the following we begin by describing the principle of operation of coherent addition of several laser distributions, where one differs from all other distributions. Then we present our experimental multichannel laser configuration, and describe the experimental procedure and results. To support the experimental results we then develop a theoretical model for calculating the combined output distribution from a laser that contains several coupled channels. We apply this model to evaluate coherent addition of two as well as four coupled channels, that when operated separately one has a Gaussian distribution and the others multimode distributions. Finally we present some concluding remarks [15].

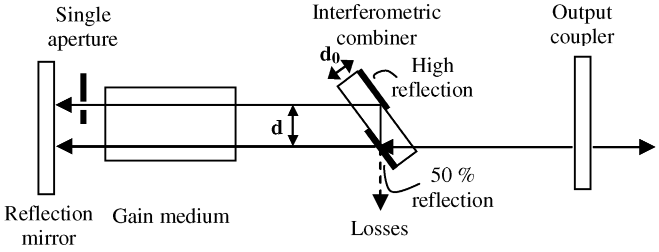

Fig. 1. Basic configuration for coherent addition of two laser distributions.

II. PRINCIPLE OF OPERATION

A basic configuration for coherently adding two laser distributions with a single interferometric combiner is schematically shown in Fig. 1. It is essentially a two arm resonator, where the two arms are coherently combined on a 50% beamsplitter. Such a configuration can be considered as two separate laser resonators with common reflection and output coupler mirrors. The interferometric combiner is a parallel substrate that is coated with high reflective layer on part of one surface and with 50% reflective layer on part of the other surface. The light reflected from the output coupler is divided by the combiner into two beams propagating in parallel inside the laser gain medium. After reflection from the rear end mirror, they are recombined to form one beam by the interferometric beam combiner.

The distance between the two parallel beams inside the gain medium depends on the thickness and the angular orientation of the combiner substrate. This distance is: $d = 2d_0 \cos(\alpha) \tan[\arcsin(\alpha/n)]$, where d_0 is the thickness of the substrate, α is the angular orientation of the substrate relative to the laser resonator axis, and n is the refractive index of the substrate material. If the two parallel beams are incoherent with each other then each will suffer a 50% loss while passing through the combiner, and typically no lasing will occur. If, on the other hand, they are coherently added at the beamsplitter then complete destructive interference is obtained in the loss

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channel (illustrated with a dashed line in Fig. 1), so the losses introduced by the combiner are completely suppressed. Typically, when certain longitudinal mode constraints are fulfilled [5], the overall laser tends to lock the relative phase between the two beams so as to operate at minimum losses.

It is known that two identical Gaussian laser distributions can be coherently added with high efficiency to obtain a combined output with a nearly Gaussian distribution but double the power, provided that common longitudinal modes exist [5]. But what would be the combined output distribution when we try to coherently add a Gaussian distribution with a multimode distribution? This can be done, as shown in Fig. 1, by inserting a small circular aperture in the path of one channel so as to obtain a nearly Gaussian mode distribution, and no aperture in the other channel so as to obtain multimode distribution. Intuitively, we can argue that the phase of the Gaussian mode distribution in the channel with the multimode distribution will lock to the phase of the Gaussian distribution in the other channel, thereby suppressing losses of these two Gaussian distributions at the interferometric combiner. Yet, the phases of the other modes in the channel with the multimode distribution will not lock to the Gaussian distribution in the other channel (since these modes are nearly orthogonal), so these other modes will suffer a $\sim 50\%$ loss at the combiner and consequently will be suppressed. Essentially, the Gaussian distribution of the one channel is thus imposed on the other channel.

In practice, however, there are several possible complications to this simple intuitive argument. First, the Gaussian distribution in the channel with the multimode distribution inherently differs from that of the (nearly) Gaussian distribution in the other channel, both in shape and intensity, because it does not have an aperture. Such inherent difference reduces the spatial overlap of the two distributions, so complete destructive interference into the loss channel can not occur. Second, even extremely weak high-order modes in the channel with the Gaussian distribution that are not completely suppressed by the aperture can still phase lock with the corresponding high-order modes in the channel with the multimode distribution. Such phase locking affects their losses at the interferometric combiner in a rather complicated manner, and is strongly dependent on the dynamics of the mode competition in the presence of gain. The model which will be discussed further on will allow a better understanding of this issue. Third, longitudinal modes, geometrical misalignments, non uniformities in gain medium and imperfection in reflectivities of interferometric combiner layers must be taken into account.

The configuration shown in Fig. 1 can be expanded to deal with a larger number of channels. For example, four laser distributions can be coherently added by inserting two identical interferometric combiners inside the laser resonator, as shown in Fig. 2. In this configuration, four laser distributions are first coherently added in one coordinate direction, to obtain two laser distributions. The resulting two distributions are then coherently added in the orthogonal coordinate direction to obtain one distribution. The loss mechanism when coherently adding four laser distributions is similar to that of adding two distributions. Thus, if one distribution is Gaussian while the other three have multimode distributions, the Gaussian distribution will be imposed on all, so the combined laser output distribution will have a Gaussian distribution.

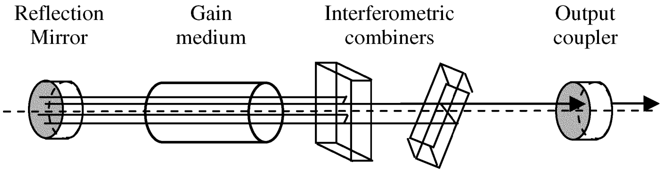

Fig. 2. Configuration for coherently adding four laser distributions with two identical and orthogonal interferometric combiners.

III. EXPERIMENTAL PROCEDURE AND RESULTS

To experimentally demonstrate how one laser distribution is imposed on another with coherent addition, we used the experimental arrangement shown in Fig. 3. It includes a 70-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 high 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 pulse rate of 4 Hz at constant level throughout the experiments. The thermal lensing of the rod under these pumping conditions was measured to be $f = 20$m. A circular aperture of 1.4-mm diameter was inserted in one channel and no aperture in the other. To ensure that light oscillating inside the resonator would be P-polarized in correspondence with the selected reflection layers, a high quality thin film polarizer (TFP) was inserted near the output coupler. The interferometric combiner was a flat parallel plate made of fused silica. Half of one surface was coated with a 50% reflective layer and half of the other surface was coated with a high reflective layer. Its thickness was 3 mm, the refractive index 1.45, and it was oriented at the Brewster angle of 55.4°. The other halves of the surfaces were not coated but reflections from them were negligible because the combiner was set at a Brewster angle and the light was P polarized. A charged-coupled device (CCD) near the output coupler detected the near-field intensity distribution and another CCD camera set at the effective focal plane of a lens, detected the far-field intensity distribution. Both the near and far field distributions were quantitatively analyzed using Spiricon laser beam analyzers.

Initially the interferometric combiner was removed from the resonator and the output coupler was adjusted for each channel separately. The near-field and far-field intensity distributions were detected for each channel, and the corresponding beam quality factor M^2 was calculated in accordance to $M^2 = \sigma_{nf}\sigma_{ff}\pi/4\lambda F$, where F is the effective focal length of the lens, σ_{nf} and σ_{ff} are the second moments of the near and far field distributions, respectively. We ascertained that the value of M^2 was lowest for an aperture diameter of 1.4 mm and higher for other diameters, indicating that the channel with this aperture diameter oscillates with the lowest mode.

Fig. 4 shows the near-field and far-field intensity distributions for the two channels without the interferometric combiner. Fig. 4(a) and (b) show the near-field and far-field intensity distributions of the channel with the aperture, while Fig. 4(c) and (d) those of the multimode distributions in the channel with

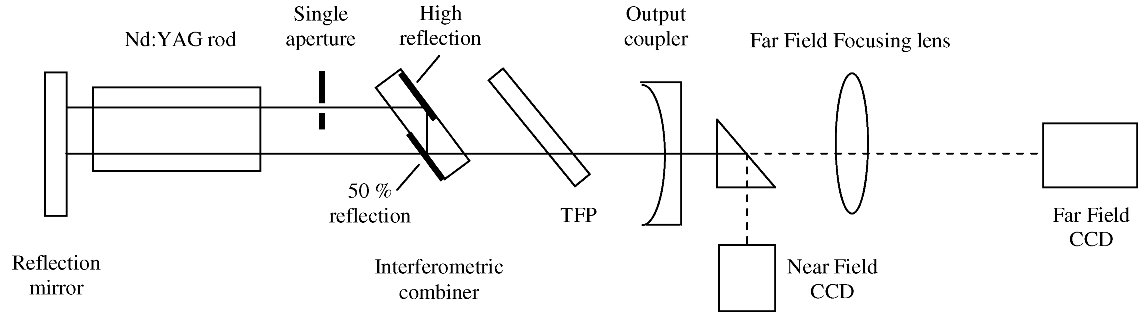

Fig. 3. Experimental arrangement for coherent addition of two-channel distributions. TFP denotes a thin film polarizer.

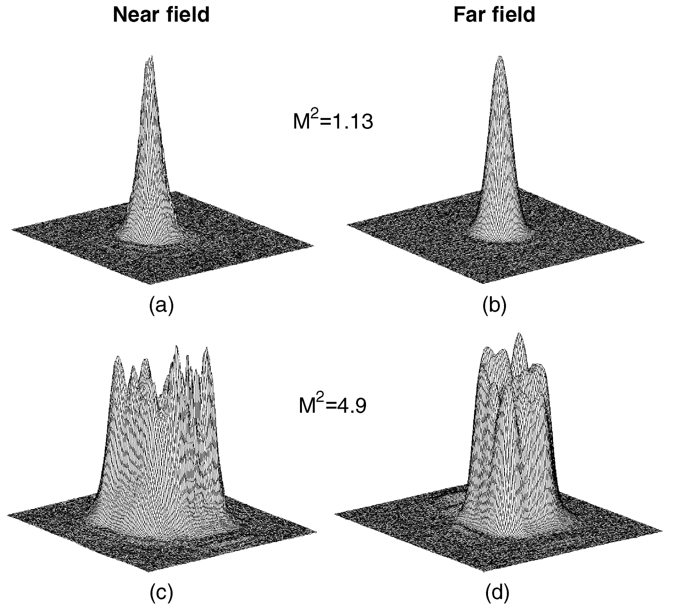

Fig. 4. Experimental near and far field intensity distributions for the separate channels. (a) Near-field intensity distribution for channel with 1.4-mm aperture. (b) Far-field intensity distribution for channel with 1.4-mm aperture. (c) Near-field intensity distribution for channel with no aperture. (d) Far-field intensity distribution for channel with no aperture.

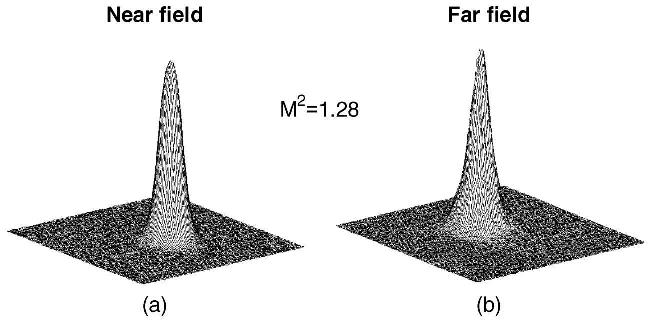

Fig. 5. Experimental near and far field intensity distributions of the combined output when coherently adding two laser channels. Here an aperture of 1.4 mm diameter was used in the channel with the Gaussian distribution. (a) Near-field intensity distribution. (b) Far-field intensity distribution.

no aperture. The laser output energy for the channel with the 1.4-mm aperture was 4.5 mJ per pulse. The calculated M^2 for the channel with the aperture of 1.4 mm was 1.13, indicating a nearly pure Gaussian TEM_{00} distribution. The calculated M^2 for the channel with no aperture was 4.9, indicating, as expected, that several high-order modes distributions are present in addition to the Gaussian distribution.

We then inserted the interferometric combiner inside the resonator. After aligning the combiner and the output coupler we measured an output energy of 10 mJ per pulse. This is more than doubling the energy of the channel with the 1.4 mm aperture. The combined near and far field intensity distributions are shown in Fig. 5. Fig. 5(a) shows the near-field intensity distribution and Fig. 5(b) the far-field intensity distribution. The corresponding calculated M^2 for the combined output was found to be 1.28. The slightly higher M^2 and higher combining efficiency than those expected when coherently adding two pure Gaussian distributions indicate that the combined output also contains some higher order modes. We believe that these added higher order modes result from complicated interference effects that are explained in the next section.

In order to reduce the contribution of the higher order modes to the combined output, the aperture diameter was reduced to 1.3 mm, and the combined intensity distributions were detected and measured. The combined output energy was measured to be 8.5 mJ, i.e. a combining efficiency of 94% (all the combining efficiencies are calculated relative to the energy from the channel with the Gaussian distribution). The detected near-field and far-field field intensity distributions are shown in Fig. 6. The corresponding calculated M^2 in this case was 1.09, indeed indicating a nearly pure Gaussian distribution.

We also coherently added four distributions by inserting two orthogonally oriented identical interferometric combiners (as illustrated in Fig. 2) inside the same experimental arrangement. We added a polarization rotator between the two combiners so they both operate with P-polarized light. The use of two identical interferometric combiners ensures that conditions for the existence of a common longitudinal mode for all four channels is identical to that for a two-channel configuration, and is hence automatically fulfilled [5]. The diameter of the aperture in the channel with the Gaussian distribution was 1.3 mm. The measured energy of the combined output was 17.2 mJ, i.e. a combining efficiency of 95.5%. The detected near-field and far-field intensity distributions are shown in Fig. 7. The corresponding calculated M2 was 1.3 indicating that the output beam was a nearly Gaussian distribution, but again with some contribution from higher order modes. This indicates that the four-channel configuration has even a higher tendency to develop high order

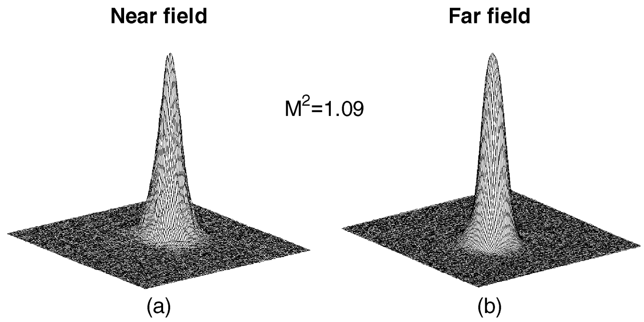

Fig. 6. Experimental near and far field intensity distributions of the combined output when coherently adding two laser channels. Here an aperture of 1.3 mm diameter was used in the channel with the Gaussian distribution. (a) Near-field intensity distributions. (b) Far-field intensity distributions.

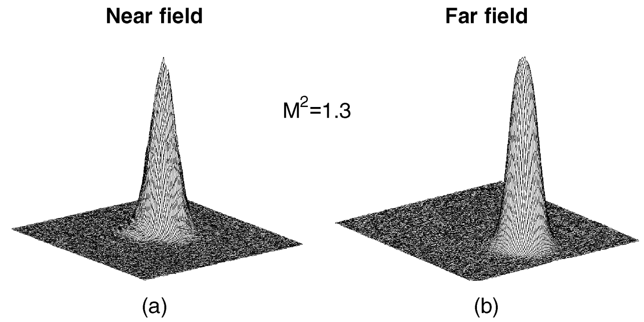

Fig. 7. Experimental near and far field intensity distributions of the combined output when coherently adding four laser channels. Here an aperture of 1.4 mm diameter was used in the channel with the Gaussian distribution, with an aperture of 1.3 mm diameter. (a) Near-field intensity distribution. (b) Far-field intensity distribution.

modes than the two-channel configuration, and both a higher tendency than the single channel configuration.

IV. Model and Calculated Results

We developed a relatively simple one-dimensional model, for analyzing intracavity coherent addition of several laser distributions which are not necessarily identical. The configuration of the basic model is schematically presented in Fig. 8. It has a bare plano-concave resonator that contains two channels, each with independent distribution, that are coupled by an interferometric combiner. The model which is an extension of one that was used for analyzing high-order mode selection in a single channel configuration [13], does not take into account the effect of the laser gain medium and saturation on the light propagation. As shown in Fig. 8, there are four fields $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$, and $\mathbf{d}$ associated with the interferometric combiner and three different planes AC, B, and D at which these fields are determined. The part of the interferometric combiner surface with high reflective layer is treated as a simple mirror, and the part with the beam splitter layer has complex reflection and transmission coefficients of r and t. These coefficients obey the relations

$$r = |r|e^{i\theta_r}; \quad t = |t|e^{i\theta_t}; \quad |r|^2 + |t|^2 = 1 \tag{1}$$

where θ_r and θ_t are the phases of the transmitted and reflected waves. Typically, $\theta_r + \theta_t = \pi/2$. The four fields

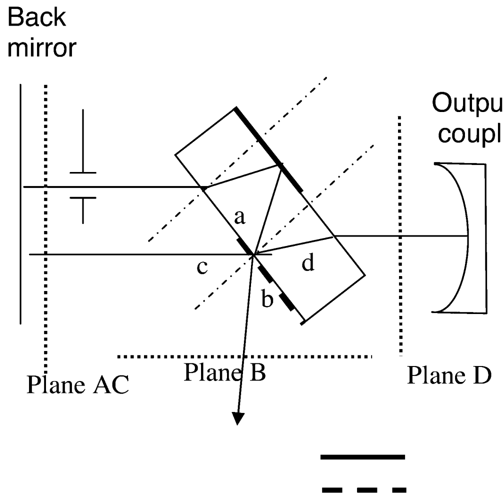

Fig. 8. Configuration of the basic model for analyzing coherent addition of two-channel distributions.

$a(x)$, $b(x)$, $c(x)$, and $d(x)$, which can be separated to incident and outgoing (one-dimensional) fields, are coupled in accordance to

$$\begin{aligned} a(x)_{\text{in}} &= rb(x)_{\text{out}} + td(x)_{\text{out}} \\ b(x)_{\text{in}} &= ra(x)_{\text{out}} + tc(x)_{\text{out}} = 0 \\ c(x)_{\text{in}} &= rd(x)_{\text{out}} + tb(x)_{\text{out}} \\ d(x)_{\text{in}} &= rc(x)_{\text{out}} + ta(x)_{\text{out}} \end{aligned} \tag{2}$$

where the subscript *in* denotes the incident field and *out* the field emerging from the beamsplitter.

We proceed by numerically calculating self-consistently the four coupled fields $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$, and $\mathbf{d}$. This is done by solving the self-consistent round-trip propagation equation

$$KU_n = \gamma_n U_n \tag{3}$$

where the eigenvectors U_n are defined as the resonator global modes, K the round-trip propagation kernel, and γ_n the eigenvalues, with $1 - |\gamma_n|^2$ being the round-trip losses. Eigenvectors U_n contain the four fields in the form

$$U_n = [a_1, \ldots, a_N, b_1, \ldots, b_N, c_1, \ldots, c_N, d_1, \ldots, d_N] \tag{4}$$

where N is the size of the one-dimensional vector representing each of the fields $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$ and $\mathbf{d}$. Accordingly, the size of the eigenvector is $4N$, and the round-trip kernel is a $4N \times 4N$ matrix composed of 16 $N \times N$ blocks. Each diagonal block essentially represents single field propagation (SFP) operator that includes contribution from free-space propagation, lenses, apertures, and phase elements associated with that particular channel [13]. The off-diagonal blocks are operators that can exchange energy between the different fields, which are associated with the beamsplitter.

The free-space propagation matrix is calculated by using the angular spectrum propagation [14]. Apertures, lenses, and phase elements for each field are all simply represented by appropriate

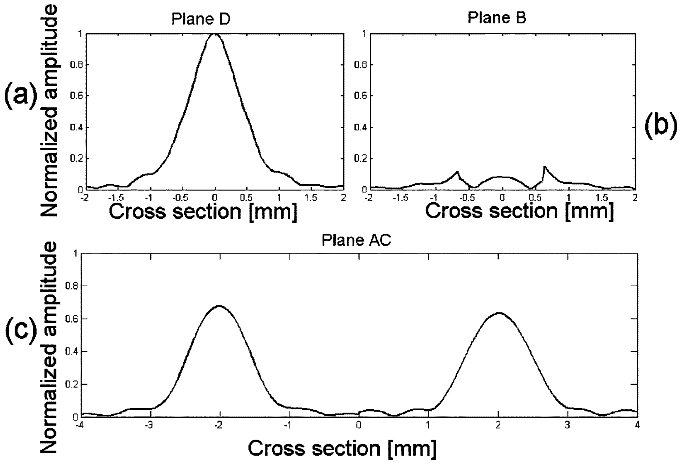

Fig. 9. Calculated fields at specific planes for the configuration shown in Fig. 8. (a) Field $\mathbf{d}$ at plane D. (b) Field $\mathbf{b}$ at plane B. (c) Field $\mathbf{a}$ and $\mathbf{c}$ at plane AC.

diagonal $N \times N$ matrices. The round-trip propagation kernel K is formed by multiplying several matrices, each having the form

$$\begin{bmatrix} \mathrm{SFP\_}a & a-b & a-c & a-d \\ b-a & \mathrm{SFP\_}b & b-c & b-d \\ c-a & c-b & \mathrm{SFP\_}c & c-d \\ d-a & d-a & d-c & \mathrm{SFP\_}d \end{bmatrix} \tag{5}$$

where e.g., $\mathrm{SFP\_}a$ represents single channel propagation matrix of field $\mathbf{a}$, and a-b represents a $N \times N$ unit matrix multiplied by the transmission coefficient between fields $\mathbf{a}$ and $\mathbf{b}$. Equation (3) was solved numerically by diagonalizing the round-trip kernel, to obtain a self-consistent solution for the four different fields (global mode of the resonator) and the round-trip losses. We found that for convergence, $N = 100$ is sufficient, requiring the diagonalization of a 400 × 400 matrix.

Initially, the model was exploited for calculating the fields $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$, and $\mathbf{d}$ at planes AC, B, and D for the basic two-channel configuration shown in Fig. 8. An aperture of 1.3 mm was placed in one channel and no aperture in the other. The difference in propagation distances for the two channels was chosen such as to ensure destructive interference into the loss channel. The calculated results for the cross section of the field (square root of the intensity) of the lowest order mode are presented in Fig. 9. Fig. 9(a) shows field $\mathbf{d}$ at plane D; this field is a coherent combination of the distributions of the two channels. Fig. 9(c) shows the fields $\mathbf{a}$ and $\mathbf{c}$ at plane AC, where the distributions from two channels are spatially separated; a slight difference is seen between the fields $\mathbf{a}$ and $\mathbf{c}$, which results from aperture diffraction of field $\mathbf{a}$. Fig. 9(b) shows the field $\mathbf{b}$ at plane B; this field represents the losses, and results from imperfect destructive interference, due to the slight difference between the fields $\mathbf{a}$ and $\mathbf{c}$.

Next, we extended the model to deal with coherent addition of four-channel distributions. In this extension two interferometric combiners are inserted inside the resonator configuration, as illustrated in Fig. 2. The second combiner for the orthogonal coordinate direction can be treated as two identical beamsplitters each for a different channel from the first combiner, as illustrated in the configuration of Fig. 10. As evident, there are 10 different fields in this extended configuration. Each beamsplitter has four fields and there are two common fields. Each field is represented by a vector of the size of N. The size of the eigenvectors U_n is $10N$and the round-trip kernel is a $10N \times 10N$ matrix with 100 $N \times N$ blocks. As before, each $N \times N$ block is an operator that modifies the fields that propagate through the resonator. Specifically, the diagonal blocks represent free space propagation, lenses, mirrors and phase elements, which can differ for each channel, and the off diagonal blocks are operators that can exchange energy between the different fields, that are associated with the beamsplitters.

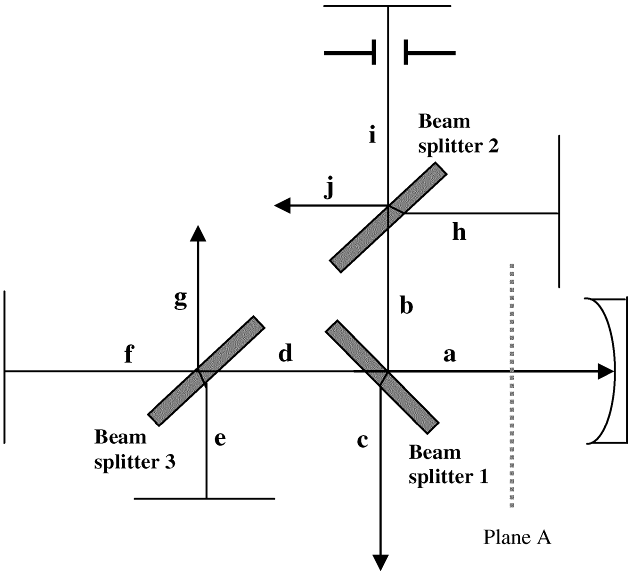

Fig. 10. Extended configuration of the model for coherent addition of four-channel distributions.

We are now in a position to determine how a Gaussian distribution of one channel is imposed on other channels, which independently would have multimode distributions. Specifically, we evaluate the special case where one channel has an aperture to obtain a Gaussian distribution while the others have no aperture. We consider three different configurations—a single channel, two channels, and four channels. The single channel configuration simply has a conventional resonator with one aperture. The two-channel configuration includes a resonator in which one interferometric combiner is inserted, and one aperture in one of the channels to obtain a Gaussian distribution. The four-channel configuration includes a resonator in which two interferometric combiners are inserted, and one aperture in one of the four channels to obtain a Gaussian distribution. All resonator configurations were plano-concave, where we assumed a flat reflection mirror and a radius of curvature of 1.5 m for the output coupler.

The calculated results are presented in Figs. 11–15. Fig. 11 shows the fields of the three lowest order modes near the output coupler, calculated for a conventional single channel resonator configuration with an aperture of 1.4 mm. The fields are normalized according to the lowest order TEM_{00} mode and the round-trip losses were taken into account. Fig. 12 shows the fields of the three lowest order modes, near the output coupler (plane D in Fig. 8) for a two-channel resonator configuration, where an aperture of 1.4-mm diameter is inserted in one of the channels. Here again the fields are normalized according to the

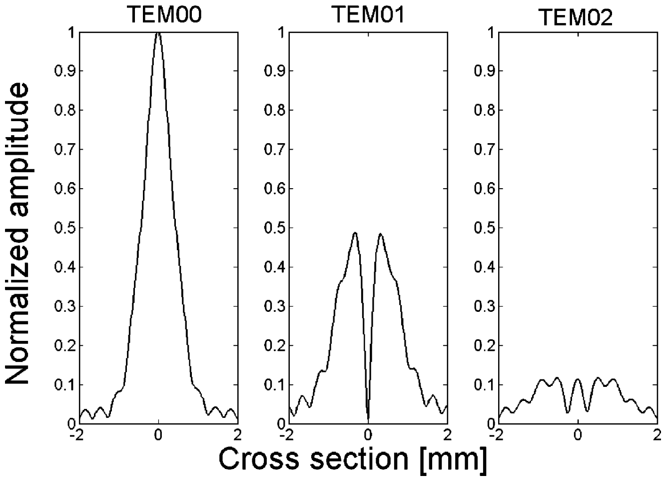

Fig. 11. Calculated field distributions of TEM$_{00}$, TEM$_{01}$, and TEM$_{02}$ modes for a single channel resonator configuration with an aperture of 1.4 mm.

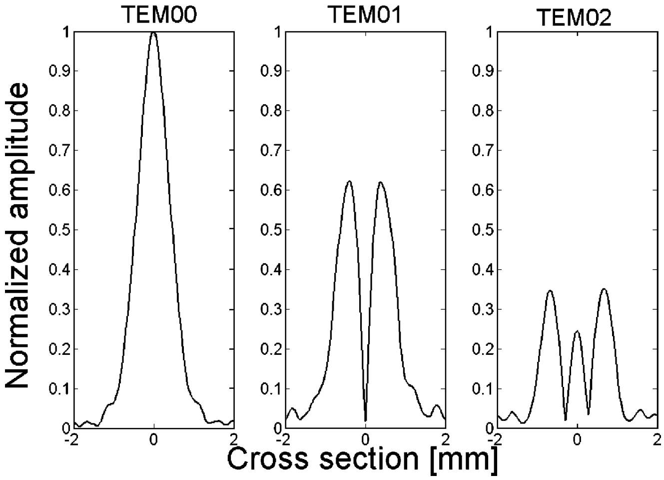

Fig. 12. Calculated field distributions of TEM$_{00}$, TEM$_{01}$ and TEM$_{02}$ modes for a two-channel resonator configuration with an aperture of 1.4 mm.

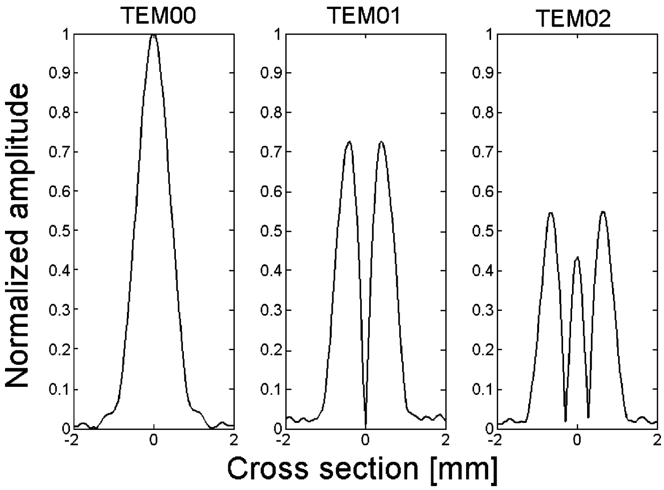

Fig. 13. Calculated field distributions of TEM$_{00}$, TEM$_{01}$, and TEM$_{02}$ modes for four-channel resonator configuration with an aperture of 1.4 mm.

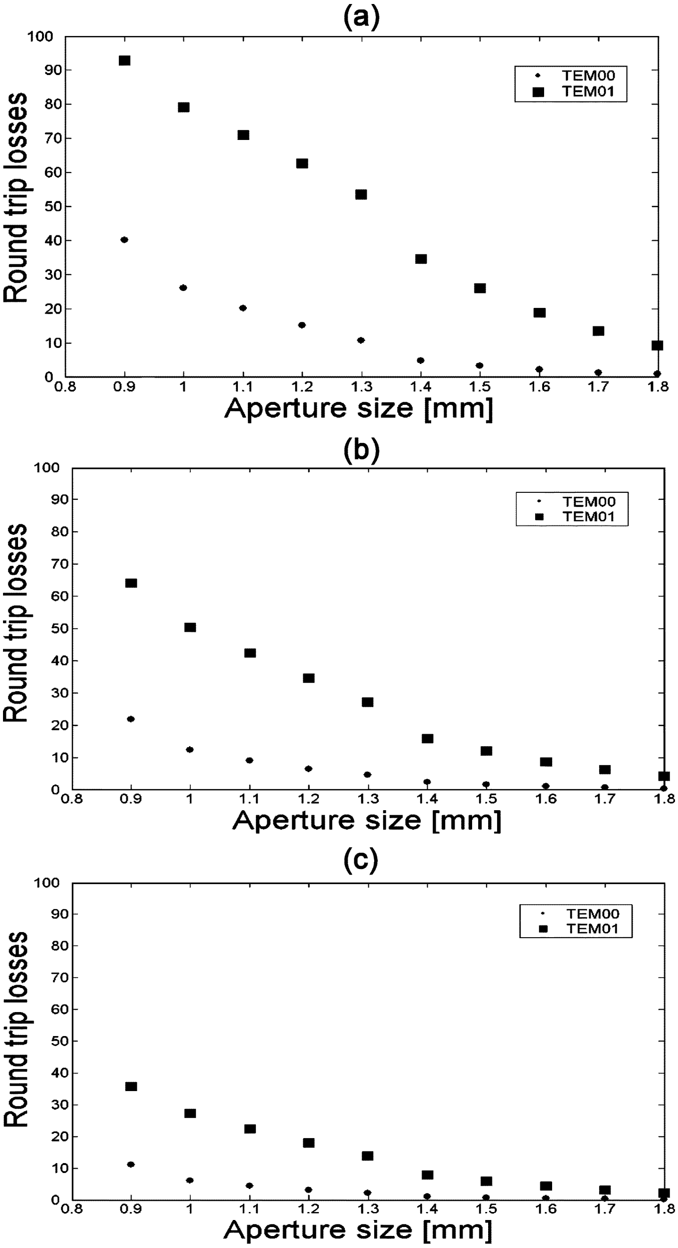

Fig. 14. Calculated round-trip losses of TEM$_{00}$ and TEM$_{01}$ mode distributions as a function of aperture diameter. (a) Single-channel configuration. (b) Two-channel configuration. (c) Four-channel configuration.

lowest order TEM$_{00}$ mode. Fig. 13 shows the normalized fields of the three lowest order modes, near the output coupler (plane A of Fig. 10), for a four-channel resonator configuration, where an aperture diameter of 1.4 mm is inserted in one of the channels. As evident from Figs. 11–13, the amplitudes of the higher modes increase as more channels are coherently added to the channel with the Gaussian distribution. This indicates that the round-trip losses of these higher modes decrease as more channels are coherently added.

Fig. 14 shows the calculated round-trip losses of the TEM$_{00}$ and TEM$_{01}$ modes as a function of the aperture diameter in the channel with the Gaussian distribution for the three resonator configurations (with single channel, two channels and four channels, respectively). As evident, the discrimination between the TEM$_{00}$ and TEM$_{01}$ modes is reduced when more channels are coherently added to the channel with the Gaussian distribution at any fixed aperture diameter. It is also evident that when the aperture size is reduced, the discrimination is

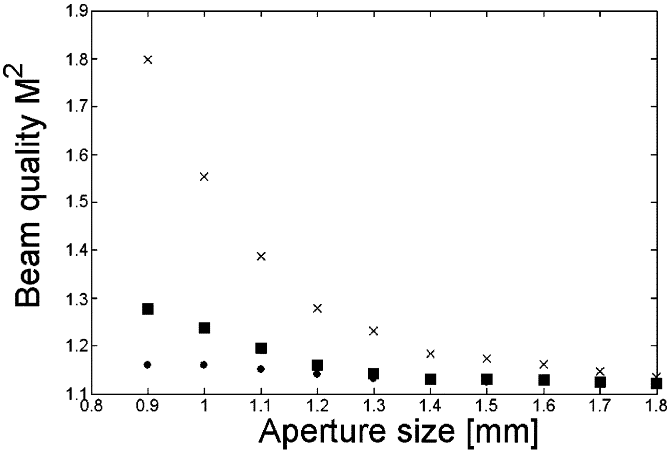

Fig. 15. Beam quality factor M^2 of the combined TEM_{00} mode distribution as a function of aperture diameter for the three resonator configurations: single channel (x), two channels (□), and four channels $(\cdot)$.

increased for the two-channel as well as the four-channel resonator configurations. Thus, in order to ensure that the discrimination is sufficient for obtaining only Gaussian TEM_{00} distributions, the aperture size must be reduced when more channels are coherently added.

Such a behavior is in good agreement with our experimental observations described in the previous section. Specifically, we found that an aperture diameter of 1.4 mm was experimentally needed in order to obtain the Gaussian TEM_{00} distributions shown in Fig. 4(a) and (b) for a single channel. This, together with the results shown in Fig. 14(a), implies that the round-trip losses of the TEM_{01} mode must be at least 30%. Accordingly, the round-trip loss of the TEM_{01} mode must also be approximately 30% in order to obtain a combined Gaussian TEM_{00} distribution of the output. As evident from Figs. 14(b) and 14(c), such a round-trip loss would occur when the aperture diameter is reduced to 1.3 mm in the two-channel configuration and 1.1 mm in the four-channel configuration, in good agreement with the experimental results.

Finally, it is important to understand how the beam quality of the combined TEM_{00} mode distribution is affected when we decrease the aperture diameter. Thus, we calculated the beam quality M^2 of the lowest order TEM_{00} mode as a function of the aperture diameter for the three resonator configurations. The results are presented in Fig. 15. As evident, the beam quality factor M^2 of the combined TEM_{00} mode distribution improves as the number of the coherently added channels increase for a given aperture diameter. Moreover, the M^2 is even better in the two-channel resonator configuration with an aperture of 1.3 mm, and still better in the four-channel resonator configuration with an aperture of 1.1 mm. Thus, in accordance to Figs. 14 and 15, when more channels are coherently added the discrimination does not change and the beam quality improves, if the appropriate aperture diameter is chosen. These calculated results are in good agreement with our experimental results. We applied our model to a configuration where the aperture is inserted in the combined channel, or in the separated channels. In this configuration both channels suffer diffraction losses by the aperture and we will not benefit from the higher beam quality of the open channel. From looking at the experimental and theoretical model results it is clear that when two or four laser distributions are combined the beam quality of the combined beam is better then the beam quality of the separate beams.

Although we presented examples of coherent addition of two and four laser channels, our configuration can be extended to deal with larger numbers of lasers. An inherent limit when scaling some configurations is the need for a common longitudinal mode to all channels. Using our configuration there is no such inherent limit since all the optical elements are common and each beam combiner introduce an identical optical length difference between the channels. Unfortunately, presently our model cannot be used to study these effects for much larger number of channels since the size of the matrices we would need to diagonalize rapidly becomes impractical. On the other hand, additional lenses, phase elements and other optical components can be incorporated in each channel, so as to deal with coherent addition of single high-order mode distributions as well as multimode distributions.

V. CONCLUDING REMARKS

We showed experimentally that when a channel with Gaussian distribution is coherently added intracavity to one or more multimode distributions, the Gaussian distribution is imposed on all channels. We have showed that for a small number of channels using a single aperture in one of the channels and imposing its transverse content on the others results in improved beam quality when the lowest mode is selected. Experimentally, such coherent addition leads to a combined laser output with Gaussian distribution, and combining efficiency close to 100 %. A model to support the experiments was developed, and the calculated results for coherent addition of two and four laser distributions are in good agreement with the experimental results. Such model could be extended to deal with coherent addition of more laser distributions. We expect that our approach should be valid for imposing a single high-order mode laser distribution, rather than a Gaussian distribution, on other multimode distributions by intracavity coherent addition.

REFERENCES

[1] F. X. D'Amato, E. T. Siebert, and C. Roychoudhury, "Coherent operation of an array of diode lasers using a spatial filter in a Talbot cavity," *Appl. Phys. Lett.*, vol. 55, pp. 816–818, 1989.

[2] S. Menard, M. Vampouille, B. Colombeau, and C. Froehly, "Highly efficient phase locking and extracavity coherent combination of two diode-pumped Nd:YAG laser beams," *Opt. Lett.*, vol. 21, pp. 1996–1998, 1996.

[3] M. DiDomenico Jr., "A single frequency TEM00 mode gas laser with high output power," *Appl Phys. Lett.*, vol. 8, no. 1, pp. 20–22, 1966.

[4] D. Sabourdy, V. Kermene, A. Desfarges-Berthelemot, M. Vampouille, and A. Barthelemy, "Coherent combining of tNd:YAG lasers in Vernier-Michelson type cavity," *Appl. Phys. B*, vol. 75, pp. 503–507, 2002.

[5] A. A. Ishaaya, N. Davidson, L. Shimshi, and A. A. Friesem, "Intracavity coherent addition of Gaussian beam distributions using a planar interferometric coupler," *Appl. Phys. Lett.*, vol. 85, pp. 2187–2189, 2004.

[6] J. Xu, S. Li, K. K. Lee, and Y. C. Chen, "Phase locking in a two-element laser array: a test of the coupled-oscillator model," *Opt. Lett.*, vol. 18, pp. 513–515, 1993.

[7] L. Fabiny, P. Colet, R. Roy, and D. Lensta, "Coherence and phase dynamics of spatially coupled solid-state lasers," *Phys. Rev. A, Gen. Phys.*, vol. 47, p. 4287, 1993.

[8] M. Oka, H. Masuda, Y. Kandeda, and S. Kubot, “Laser diade pumped phase-locked Nd:YAG laser arrays,” *IEEE J. Quantum Electron.*, vol. 28, no. 4, pp. 1142–1147, Apr. 1992.

[9] T. S. Rutherford and R. L. Byer, “Six beam phase-locked slab laser resonator,” in *Proc. 15th Int. Conf. Lasers and Electrooptics*, Munich, Germany, 2001, p. 39.

[10] S. Menard, M. Vampouille, A. Desfarges-Berthelemot, V. Kermene, B. Colombeau, and C. Froehly, “Highly efficient phase locking of four diode pumped Nd:YAG laser beams,” *Opt. Commun.*, vol. 160, pp. 344–353, 1999.

[11] J. R. Leger, G. J. Swanson, and W. B. Veldkamp, “Coherent laser addition using binary phase grating,” *Appl. Opt.*, vol. 26, pp. 4391–4399, 1987.

[12] M. Brunel, A. Le Floch, and F. Bretenaker, “Multi axis laser eigenstates,” *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 13, pp. 946–960, 1996.

[13] A. A. Ishaaya, N. Davidson, G. Machavariani, E. Hasman, and A. A. Friesem, “Efficient selection of high-order Laguerre-Gaussian modes in a Q-switched Nd:YAG laser,” *IEEE J. Quantum Electron.*, vol. 39, no. 1, pp. 74–82, Jan. 2003.

[14] J. W. Goodman, *Introduction to Fourier Optics*, 2nd ed. New York: McGraw-Hill, 1996.

[15] A. A Ishaaya, L. Shimshi, N. Davidson, and A. A. Friesem, “Coherent addition of spatially incoherent light beams,” *Opt. Exp.*, vol. 12, no. 20, pp. 4929–4934, Oct. 2004.

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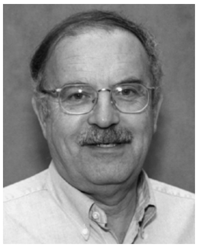

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