Improving the output beam quality of multimode laser resonators

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Abstract: Multimode laser operation is usually characterized by high output power, yet its beam quality is inferior to that of a laser with single TEM_{00} mode operation. Here we present an efficient approach for improving the beam quality of multimode laser resonators. The approach is based on splitting the intra-cavity multimode beam into an array of smaller beams, each with a high quality beam distribution, which are coherently added within the resonator. The coupling between the beams in the array and their coherent addition is achieved with planar interferometric beam combiners. Experimental verification, where the intra-cavity multimode beam in a pulsed Nd:YAG laser resonator is split into four Gaussian beams that are then coherently added, provides a total increase in brightness of one order of magnitude. Additional spectral measurements indicate that scaling to larger coherent arrays is possible.

OCIS codes: (140.3410) Laser resonators; (140.3290) Laser arrays.

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1. Introduction

Laser resonators operating with only the fundamental TEM_{00} mode provide excellent output beam quality but typically with relatively low output power. Increasing the output power can be readily achieved by resorting to multimode operation, where several transverse modes oscillate simultaneously and exploit a larger volume of the laser gain medium. Unfortunately, the multimode beam does not have well defined phase and amplitude distributions, so the beam quality is relatively poor when compared to that of the TEM_{00} mode beam, and there is no increase of the optical brightness.

In this paper we propose and experimentally demonstrate an approach for significantly increasing the optical brightness of multimode laser resonators. It is based on splitting the intra-cavity multimode beam into an array of high quality beam distributions, which are coherently added within the resonator to form a single high-power high-quality output beam. Intra-cavity coherent addition of separate laser distributions was achieved with discrete beam splitters and difractive components [1, 2, 3, 4, 5], and more recently with fiber couplers [6, 7]. In our approach, the coupling between several beam distributions, and their coherent addition, is achieved with intra-cavity planar interferometric beam combiners [8, 9]. As the individual distributions are more tightly ”packed”, i.e. with high fill factor, the brightness is found to increase considerably.

2. Basic principles

We describe our approach with the aid of the three laser resonator configurations shown schematically in Fig. 1. The most basic configuration is that in Fig. 1(a). It is comprised of a high reflecting rear mirror, a partially transmitting output coupler, a gain medium, and an intra-cavity aperture with a large enough diameter to sustain transverse multimode operation. The output power P from this type of resonator increases linearly with the aperture area, but in general, the one dimensional beam quality factor M_x^2, defined as the ratio between the space bandwidth products of the beam to that of a Gaussian beam [10], also increases linearly with the aperture diameter. This means that although the output power increases with the diameter, the brightness of the output beam, which is proportional to $P/M_x^2 M_y^2$, is not increased.

Now, as shown in Fig. 1(b), let the intra-cavity (multimode) aperture be replaced with an array of four apertures, each suitable for selection of the fundamental TEM_{00} mode, so as to obtain four individual laser beam distributions with high quality. If these apertures are spaced sufficiently apart then each distribution will be independent and incoherent from the others. Since the relative phases of these distributions is random, the output beam quality of the total array will be poor. In order to improve the beam quality and thereby increase the brightness of the output beam, we now introduce two identical interferometric beam combiners [8, 9] into the resonator, as shown in Fig. 1(c). These combiners ensure that all four distributions are phase locked and coherently add to obtain a single output beam with good beam quality. The first combiner coherently adds the two upper beam distributions with the two lower ones, and the second combiner coherently adds the resulting right and left beam distributions.

Each combiner consists of a plane parallel plate with 50% beamspliter layer on one half of its front surface, a high reflecting layer on the second half of its rear surface, and an anti reflecting layer on the remaining halves of both surfaces. The first combiner is tilted vertically at an angle θ, and the second combiner is tilted horizontally at the same angle. The angle θ

#5910 - $15.00 US Received 1 December 2004; revised 20 March 2005; accepted 24 March 2005

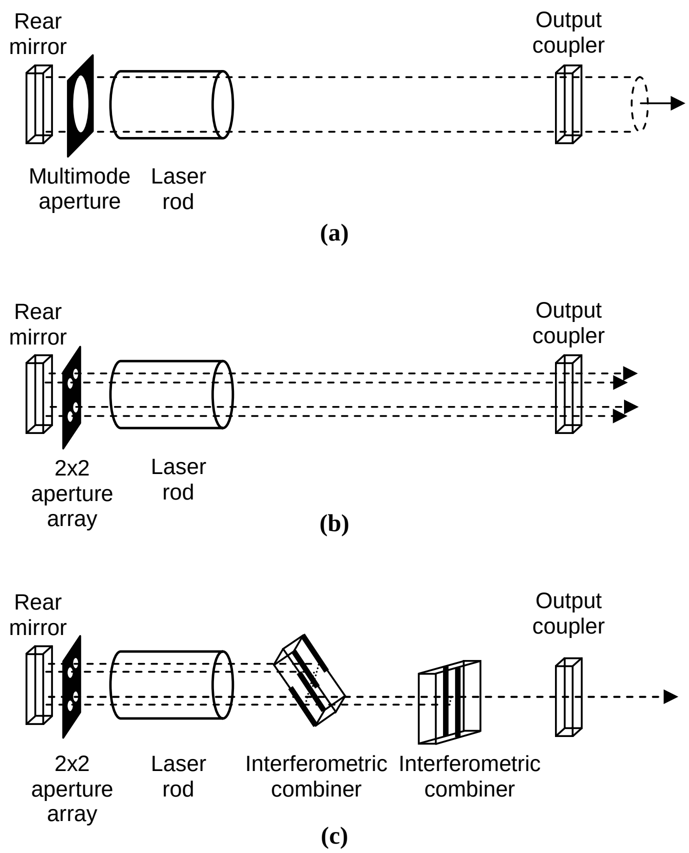


Fig. 1. Laser resonator configurations. (a) a basic multimode laser resonator; (b) a laser resonator with four incoherent laser beam distributions; (c) a laser resonator with two interferometric combiners resulting in phase locking and coherent addition of the four beam distributions.

and the thickness d of the combiner, are designed to match the distance between the individual beams, so they optimally overlap and propagate collinear after exiting the combiner. For an angle θ, d is determined by the simple relation $d = x_o/(2\cos\theta\tan(\arcsin(\theta/n)))$, where x_0 is the distance between adjacent two beams, and n is the refractive index of the combiner material. When the beams in the array are phase locked such that destructive interference occurs at the beamsplitter layer, the losses introduced by the combiner may be completely suppressed, and all four beam distributions will be coherently added into a single output beam.

The configuration shown in Fig. 1(c) should allow efficient phase locking and coherent addition of four individual Gaussian beam distributions within the gain cross section. Yet, the fill factor of the coherent array should also be taken into account when trying to obtain an increase of brightness with regard to the standard multimode configuration. In order to maximize the fill factor it is possible to use one large square aperture, corresponding to four virtual Gaussian sub-apertures, as shown in Fig. 2. In this case the individual laser distributions are essentially formed directly by the beam combiners and the square aperture, namely ”tight packing” of Gaussian distributions. The fill factor in this case can be estimated by dividing the volume under a Gaussian distribution by the volume under a uniform distribution, within a boundary containing 86.5% of the total volume under the Gaussian (where the Gaussian field drops to

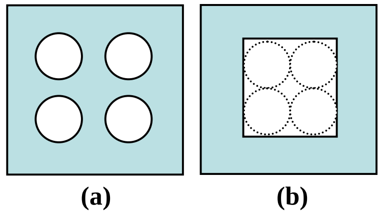


Fig. 2. Intra-cavity aperture array for generating multiple channels within the resonator. (a) A 2x2 spaced aperture array; (b) a single square aperture for generating a tightly packed 2x2 array.

$1/e^2$ of its maximum value). This leads to an estimation of 43.2% for the fill factor. Assuming a combining efficiency of 95%, the expected output power, when replacing the square multimode beam with a tightly packed array of 2x2 Gaussian distributions, would thus be 41% of the original square multimode power. However, the beam quality would be significantly improved.

In general, with high order multimode laser operation, a decrease of the intra-cavity aperture by a factor of 2 would lead to an improvement of M^2 in each axis by a factor of 2, so that $M_x^2 \cdot M_y^2$ would be reduced by a factor of 4. However, with low order multimode laser operation, the improvement of the beam quality is even greater. This is particulary so in our case, when comparing the beam quality of a Gaussian distribution to that of a square multimode beam distribution whose width is roughly twice that of the Gaussian distribution. Specifically, if the multimode beam contains only Hermit-Gaussian modes with indexes m,n, such that $m+n<2$ (i.e. $HG_{00}, HG_{10}, HG_{01}, HG_{11}, HG_{20}, HG_{02}$) [11], and the beam quality factors M_x^2 and M_y^2 for each mode equals (1+2m) and (1+2n) respectively, then $M_x^2 \cdot M_y^2$ could be reduced by a factor as high as 25. Taking into account the output power is reduced to 41%, this would be equivalent to an increase in brightness by a factor of 10.3. Essentially, it is possible to design the square aperture to correspond to a tightly packed array of four multimode beam distributions of only few modes (instead of Gaussians), so that coherent addition of multimode beams is exploited [9]. In this case the output power would be greater than with the Gaussian distributions due to the higher fill factor, but the output beam quality would be improved only moderately, so that the increase in the brightness would not be as high.

The phase locking and coherent addition can occur only if all individual beam distributions have common frequencies (longitudinal modes) within the gain bandwidth. To ensure that such common frequencies exist, the difference in the optical length between the individual resonator channels should be accurately controlled. When coherently adding two channels, the optical length difference ΔL need only be greater than a certain value, so it is easy to control for a Nd:YAG laser [2]. But in general, with more resonator channels each with a different optical length L, L+ΔL_1, L+ΔL_2, etc., the probability for having common frequencies within the gain bandwidth is drastically decreased. In our configuration, where the resonator channels end mirrors are common, the beam combiners introduce exact optical length differences,integer number of ΔL, i.e ΔL, $2\Delta L$, $3\Delta L$, etc., between the channels. For example, in our specific 2x2 array configuration, the resonator length of one channel is L, of two channels $L+\Delta L$, and of the remaining channel $L+2\Delta L$. Thus, resorting to length differences of nΔL ensures that common frequency bands equally exist in coherent addition of two channels, four channels, and also of larger number of channels.

Scalability can be achieved by using additional pairs of interferometric beam combiners, where each additional pair increases the number of beams in the array by a factor of 4. The optical length differences between all channels can still be nΔL, thereby ensuring the existence

#5910 - $15.00 US Received 1 December 2004; revised 20 March 2005; accepted 24 March 2005

of common longitudinal modes. For example, a 4x4 array of Gaussian beam distributions can be obtained using a total of 4 beam combiners. In this case the thickness of the interferometric combiners in the second pair should be doubled in order to obtain a displacement twice that of the first pair. In general, the number of channels in the array will scale as 2^N, where N is the number of beam combiners (N= 2, 4, 6, ...).

3. Experimental procedure and results

To experimentally demonstrate our approach, we used a pulsed Nd:YAG laser arrangement shown in Fig. 3. It includes a 70 cm long plano-concave resonator, with a concave ($R = 1.5$ m) output coupler of 40% reflectivity at 1064 nm and a high-reflection flat rear mirror. A flash lamp pumped Nd:YAG rod of 5 mm diameter and 10 cm length (1.1% doping) served as a common gain medium for the four channels in the resonator. The rod was pumped with a pulse rate of 4 Hz at pump power levels between two to four times that of the threshold pump power. The maximum thermal lensing of the rod under these pumping conditions was measured to be $f = 10$ m. In order to establish the four separate channels, four apertures of 1.4 mm diameter, positioned 2.4 mm apart (between centers), were used. We confirmed that this distance between the channels was such that spontaneous phase locking, due to partial overlap of the beams [12, 13], did not occur in our configuration. Two identical 3 mm thick fused silica interferometric beam combiners were positioned at Brewster's angle (55.4°) in the horizontal and vertical directions, respectively, corresponding to the required 2.4 mm beam displacement. Half of their front surface was coated with a 50% beam splitter dielectric coating, and half of their rear surface was coated with a high reflection coating. A thin film polarizer and a polarization rotator were used to ensure P-polarization of the beams incident on both interferometric beam combiners. Optional Q-switch operation was obtained by intra-cavity Q-switch elements. The near and far field intensity distributions were detected with CCD cameras.

We first independently characterized each individual channel distribution in free running operation without the interferometric combiners. The concave output coupler was aligned separately for each channel, and their output pulse energy and near and far field intensity distributions were detected. Next, the vertically tilted interferometric combiner was inserted and two channels were coherently combined (the other two were blocked). Finally, the horizontally tilted combiner was also inserted and coherent addition of four channels was obtained.

The measured output pulse energies as a function of the pump power for a single channel and the four channels are presented in Fig. 4. As expected, when coherently adding four channels, the output energy is increased considerably. The combining efficiency was measured to be

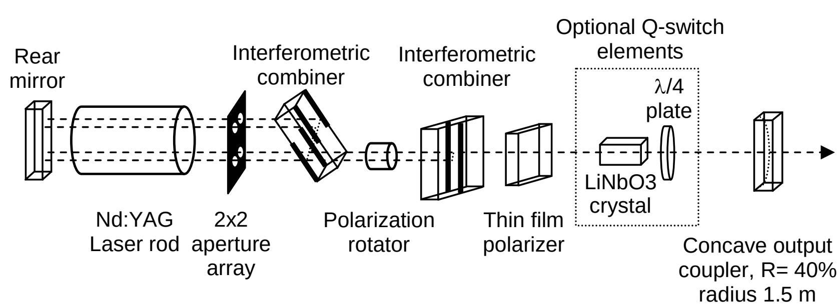


Fig. 3. Experimental resonator configuration. A 2x2 coherent phased array of Gaussian distributions is generated within the gain medium using four apertures and two interferometric beam combiners. Coherently adding the beams in the array produces a single output beam with high brightness.

#5910 - $15.00 US
Received 1 December 2004; revised 20 March 2005; accepted 24 March 2005

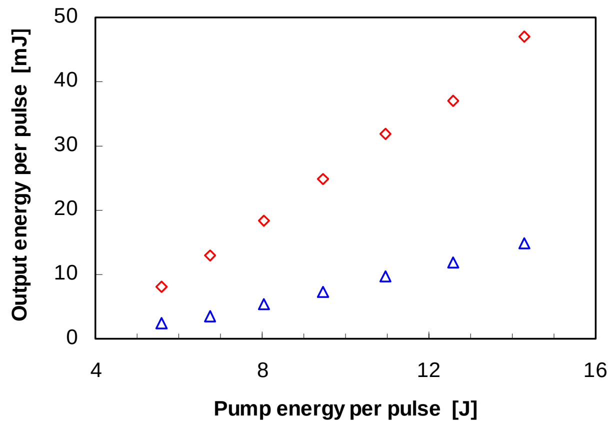


Fig. 4. Measured output pulse energy as a function of the pump power for a single Gaussian channel laser operation (△), and for intra-cavity coherent addition of four Gaussian channels (◇).

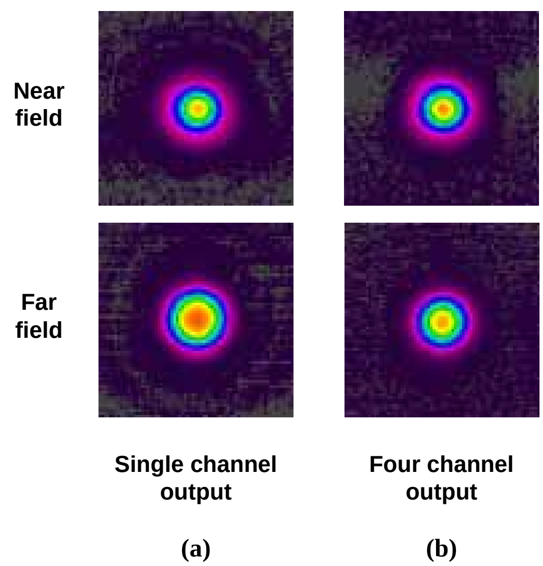


Fig. 5. Experimental near and far field intensity distributions of the single and four channels output beam. (a) a single Gaussian channel without an intra-cavity interferometric beam combiner; (b) four Gaussian channels that are coherently added with two intra-cavity interferometric combiners.

more than 90% at low pump powers (7 J). At high pump powers the measured combining efficiency decreased to 80%, probably do to the effect of thermal lensing within the rod which introduces an asymmetric phase to the beam distributions. The effect of thermal lensing on the combining efficiency can be reduced by inserting a compensating lens into the resonator. Figure 5 shows the detected intensity distributions. Figure 5(a) shows the near and far field intensity distribution for a single Gaussian channel, and Fig. 5(b) shows the near and far field intensity distribution for coherent addition of four channels (two interferometric combiners). The calculated one dimensional beam quality parameter M_x^2 for one and four channels, was

1.15 and 1.02, respectively. As evident, there is even a slight improvement in beam quality when coherently adding four channel distributions. Similar results were obtained when a single aperture for selection of the Gaussian mode was placed in the common arm of all channels (instead of the 4 separate apertures).

The results presented in Figs. 4 and 5 verify that high combining efficiency and high beam quality can be obtained with our approach. Yet there is room for improving the power extraction from the laser by reducing the spacing between adjacent channels, i.e. tight packing with high fill factor. In order to demonstrate a coherent array with a higher fill factor, we replaced the four apertures with a single square aperture of 3.2 mm width. To obtain a 2x2 array of tightly packed Gaussian beam distributions, the radius of the concave output coupler was changed from R=1.5 m to R=3 m, and new combiners of the same thickness (3 mm) but different angular orientation (23.9°) were incorporated to generate the 1.6 mm displacement required for tight packing (instead of a 2.4 mm displacement); with this resonator configuration the aperture needed to select the Gaussian beam is 1.6 mm instead of 1.4 mm. Care was taken to ensure very sharp and precise borders between the coated regions of the new combiners in order to suppress losses in such tight packing configuration.

Operating the laser with the single square aperture and no interferometric combiners, resulted in an output beam with a square multimode distribution. Inserting the two interferometric beam combiners generated a 2x2 array of tightly packed Gaussian distributions, that were phase locked and coherently added to obtain a single Gaussian output beam. The output energy per pulse for the multimode beam was 51.2 mJ while that of the combined Gaussian output beam was 23 mJ, i.e. 45% extraction efficiency. Figure 6 shows the measured near and far field intensity distributions of the output beams in both cases for the same pump power level. The calculated M^2 values for the multimode beam distribution were $M_x^2 = 6.3$ and $M_y^2 = 6.0$ as com-

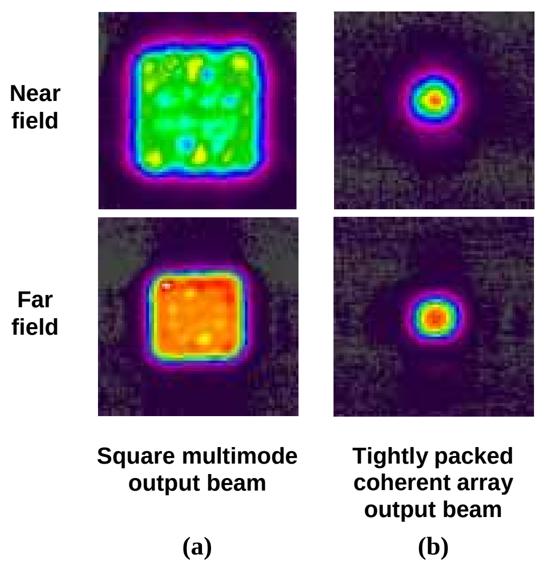
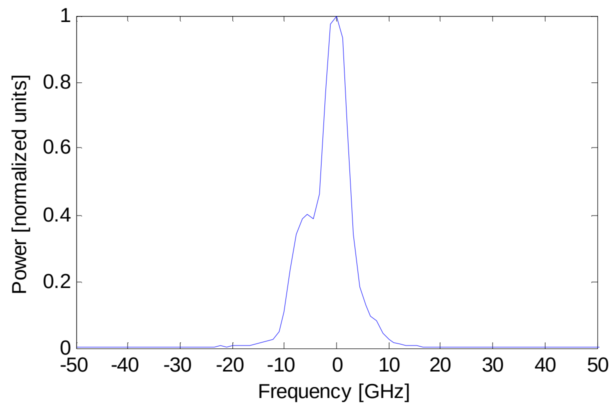


Fig. 6. Experimental near and far field intensity distributions of the multimode output beam and the Gaussian output beam after tight packing. (a) square multimode beam output distributions without an intra-cavity interferometric beam combiner; (b) Gaussian beam output distribution after coherently adding a tightly packed 2x2 array of Gaussian distributions with two intra-cavity interferometric combiners.

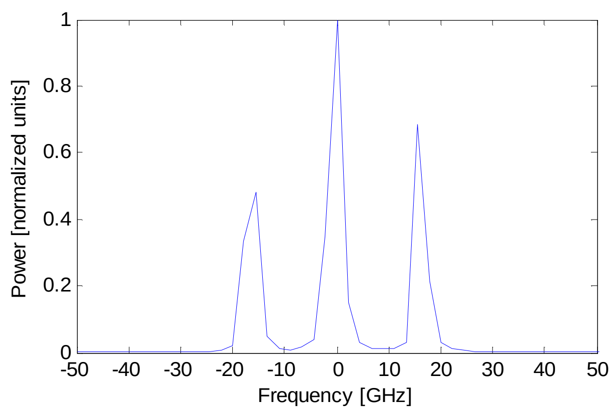
#5910 - $15.00 US
Received 1 December 2004; revised 20 March 2005; accepted 24 March 2005

pared to $M_x^2 = 1.23$ and $M_y^2 = 1.31$ for the nearly Gaussian beam distribution. This corresponds to an increase in brightness $P/M_x^2 M_y^2$ by a factor of 10.5, which is in good agreement with our predicted estimation. Similar experiments were performed in active Q-switched operation (pulse duration of $\sim$20 nsec), using an electro-optical $LiNbO_3$ crystal and a $\lambda/4$ retardation plate (see Fig. 3). The results in Q-switched operation reveal essentially the same behavior as for free running operation (with pulse duration of $\sim$100 μsec).

In order to confirm our prediction that common frequency bands exist when coherently adding two and more laser channels, we measured the spectrum of the output beam. These measurements were performed with a spectrometer comprised of an external grating with 1800 lines per mm, a telescopic optical arrangement for expanding the beam, a focusing lens, and a CCD camera. The resolution of the spectral measurements was about 3 GHz, which was sufficient for resolving the common frequency bands of interest, but not the fine structure of the individual longitudinal mode frequencies (separated by the Free Spectral Range of 214 MHz). The results are presented in Fig. 7. The measured spectrum for single Gaussian operation with



(a)



(b)

Fig. 7. Experimental power spectrum measurements. (a) The power spectrum of the output beam with a single Gaussian channel resonator configuration (without beam combiners); (b) the power spectrum of the coherently combined output beam with a four-channel resonator configuration.

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Received 1 December 2004; revised 20 March 2005; accepted 24 March 2005

no beam combiners is shown in Fig. 7(a). As evident, the natural (homogenously broadened) 120 GHz line width of Nd:YAG [14] is substantially narrowed by longitudinal mode competition to a value of 20 GHz. The measured spectrum of the combined output beam that results from coherent addition of four Gaussian distributions in a tightly packed array is shown in Fig. 7(b). As expected, the power spectrum indeed has several frequency bands which are spaced apart [2]. The measured spacing between the bands is 18 GHz, in excellent agreement with the 8.35 mm optical length difference introduced by our interferometric beam combiner ($\Delta\upsilon = c/2|\Delta L|$). When adding only two Gaussian distributions in the same configuration (using only one combiner and blocking half of the square aperture), we obtained essentially the same distribution of frequency bands.

The similarity between the spectral measurements in the cases of coherent addition of two and four channels confirms that the optical length differences in the case of four channels are exactly ΔL or $2\Delta L$ (see previous section), and that these length differences are stably maintained during lasing. These results indicate that up-scaling to larger arrays in our configuration, using additional interferometric beam combiners, is indeed possible. It is interesting to note that the side lobes in the spectrum, when coherently adding four channels, are not within the line width obtained with a single channel. This indicates that coherent addition influences the longitudinal mode competition dynamics.

4. Concluding remarks

We have presented a practical approach for improving the brightness of multimode laser resonators. With this approach, the multimode beam is replaced with a coherent array of Gaussian distributions, which are phase locked and coherently added within the resonator. We have experimentally demonstrated our approach by coherently adding a 2x2 spaced array of Gaussian beam distributions, with more than 90% combining efficiency while retaining the good beam quality of a single channel. In order to increase significantly the power extraction we further demonstrated coherent addition of a tightly packed 2x2 array, resulting in one order of magnitude increase in the brightness of the output beam (compared to the corresponding multimode beam). Spectral measurements indicate that this could be further up-scaled to larger arrays. Finally, if the requirement on the output beam quality is moderate ($M^2 > 1$), then our approach could be implemented with coherent arrays of multimode distributions instead of Gaussian distributions [9]. This would enable the use of smaller arrays, or alternatively, allow for higher output powers with the same array size. From a practical point of view, our approach can be incorporated into a wide variety of lasers, leading to high output power combined with good beam quality.

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