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Upscaling coherent addition of laser distributions

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Abstract

We investigate configurations for upscaling the number of laser distributions that can be coherently added by means of intra-cavity interferometric combiners. Experimental demonstrations of coherent addition of 5 and 25 laser distributions are presented. Calculated results indicate that with our configurations upscaling to a large number of coherently added distributions is possible but strongly depends on the tolerances of the interferometric combiners.

Keywords: Coherent addition; Coherent combining; Upscaling

1. Introduction

The quest for finding an efficient method for coherently adding a multiplicity of several laser distributions in order to obtain a high output power concomitantly with good output beam quality has been going on for many years. Several methods have been developed. These involve evanescent waves coupling [1,2], Talbot and Fourier transform resonators [3,4], active feedback control of both CW and ultrafast lasers [5–7], the introduction of diffractive components and phase elements into the laser resonators [8–11], Vernier–Michelson resonators [12], the incorporation of fiber couplers [13,14], and more recently the insertion of intra-cavity interferometric combiners [15–17]. In all these, the main question that arises is whether upscaling to coherently add a larger number of laser distributions can be efficiently achieved.

Here we consider upscaling using specialized interferometric combiners inserted into the cavity of a combined laser system [15–17]. Specifically, we develop a single sequential interferometric combiner for efficient coherent addition of five independent laser distributions. We then show how two such interferometric combiners orthogonally oriented inside the combined laser cavity, can coherently add twenty-five independent laser distributions. Finally, we analyze the dominant factors that affect upscaling in such coherent addition configurations.

2. Principle of operation

The interferometric combiner for coherently adding five parallel laser distributions, equally spaced along a line, is presented in Fig. 1. It is formed of a high optical quality, parallel planar substrate, whose front and rear surfaces are coated with dielectric layers. The front surface is divided into five regions, each with a different reflectivity and transmittivity. Specifically, the first region is coated with an anti-reflection layer, the second with a layer of 50% reflectivity (and 50% transmittivity), the third with a layer of 66.6% reflectivity, the fourth with a layer of 75% reflectivity, and the fifth region with a layer of 80% reflectivity. The rear surface is mainly coated with a highly reflecting layer, except for a small region that is coated with an anti-reflection layer.

The operation principle of the interferometric combiner of Fig. 1 is such that five separated incident laser beams of equal intensities are coherently added to form one output

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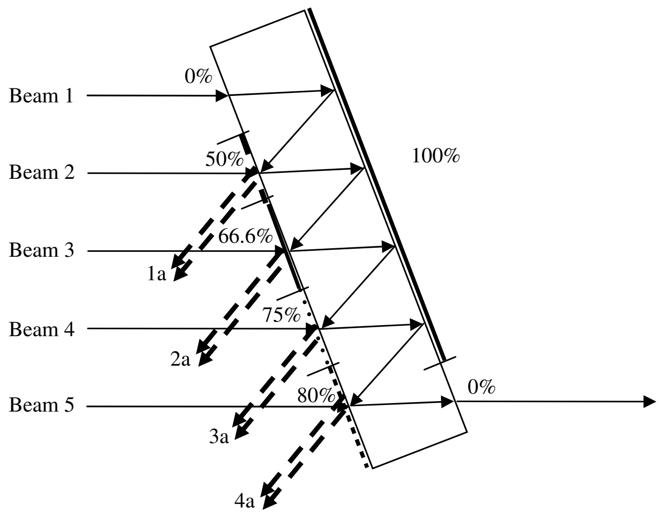

Fig. 1. A five-channel interferometric combiner. Beams 1a, 2a, 3a and 4a represent the loss channels, in which destructive interference occurs. Percentages indicates the amount of light reflected from each region.

beam whose intensity is five times that of the individual beams. It relies on the principles first developed for simpler combiners that coherently add small number of beams [15,16]. Specifically, as depicted in Fig. 1, beam 1 passes through the first region in the front surface of the interferometric combiner, reflected from the rear surface towards the second region of the front surface. There, its phase is such that its reflection from the 50% beam splitter interferes constructively with the transmitted beam 2, and its transmission interferes destructively with the reflected part of beam 2, depicted by the dashed line 1a. The resultant beam, whose intensity is that of the combined incoming beam 1 and beam 2, then propagates towards the rear surface. There, it is reflected towards the third region of the front surface, where it interferes constructively with the transmitted beam 3. The 66.6% reflected part of beam 3 and the 33.3% transmitted part of the combined beam 1 and 2 have equal intensities again, enabling full destructive interference into the loss channel (dashed line 2a). This process is repeated in regions 4 and then 5 of the front surface, so that finally the overall combined beam of all five individual beams, emerges from the output interface region part of the interferometric combiner, where it is coated with anti-reflection layer.

When an interferometric combiner is inserted into the cavity of the combined laser system, its operation principle causes self phase locking of the individual laser distributions. In order to obtain efficient coherent addition, all the individual laser distributions must have equal intensities and some common longitudinal modes that are then phase locked [15] to ensure full destructive interference into the loss channels 1a–4a of Fig. 1. Typically, such full destructive interference and consequently no losses, is difficult to achieve as the number of laser distributions that must be coherently added becomes large [18]. Fortunately, it is achieved with relative ease with our interferometric combiners, whose constant thickness ensures that the path difference between sequential laser distributions is always the same. So, in principle, there is no restriction on the number of laser distributions that can be coherently added. Similar interferometric combiners can be exploited for coherent addition of fiber lasers even though it is practically difficult to ensure that their lengths are the same in order to obtain common longitudinal modes. We expect that this together with the fact that fiber lasers inherently have many longitudinal modes, the length restriction with fiber lasers is significantly alleviated.

3. Experimental procedures and results

We performed experimental investigations with an available pulsed Nd:YAG laser, whose gain medium rod diameter was sufficiently large to support up to twenty-five independent and separate nearly Gaussian laser distributions. Initially, we performed experiments to demonstrate intra-cavity coherent addition of five Gaussian distributions, using the experimental configuration schematically shown in Fig. 2. In our experiments, the overall resonator length was 43 cm, the back mirror was flat with 99.8% reflectivity and the output coupler mirror was concave with a radius of curvature $R = 0.75$ m and 40% reflectivity. The gain medium was a dual flashlamp pumped Nd:YAG rod of length 102 mm and diameter 9.55 mm, placed 10.5 cm from the back mirror. The thermal lensing for this rod was found to have a focal distance of 20 m at 1 Hz pulse repetition rate. An interferometric combiner, depicted in Fig. 1, was inserted inside the resonator cavity at a distance of 24 cm from the back mirror and tilted by 30 degrees. The combiner was formed on a high precision plane parallel fused silica plate of 2.0 mm thickness and parallelism of <0.5 arcsec. Accordingly, the displacement of the beams reflected from the back surface was 1.3 mm at the front surface of the interferometric combiner, which was also the distance between the individual laser distributions. A thin film polarizing plate, located 31 cm from the back mirror and near the output coupler, ensured that the laser operated at a single linear polarization. Finally, a single aperture, with diameter with 0.9 mm located at a distance of 40 cm from the back mirror, ensured that the five laser distributions are separate and independent.

Using a CCD camera with the configuration shown in Fig. 2, we detected the far-field intensity distribution of

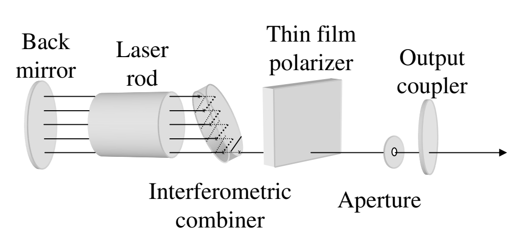

Fig. 2. Schematic configuration for intra-cavity coherent addition of five laser distributions using one sequential interferometric combiner.

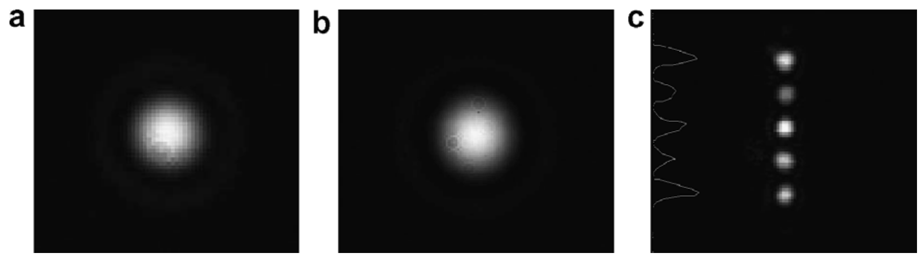

Fig. 3. Experimental coherent addition of five laser distributions: (a) far-field intensity distribution of one individual laser; (b) far-field intensity distribution of the combined output and (c) near-field intensity distributions of the residual light leaking through the back mirror.

one individual laser (without the interferometric combiner) and of the combined output, as well as the near-field intensity distribution of the residual light escaping from the back mirror. The results are shown in Fig. 3. Fig. 3a shows the far-field Gaussian intensity distribution of one of the individual lasers. Fig. 3b shows the far-field detected intensity distribution of the combined output. As evident, the far-field intensity distribution of the combined output is nearly Gaussian. Fig. 3c shows the near-field intensity distribution and corresponding cross-section profile of the residual light escaping from the rear mirror, where five separate laser distributions are clearly detected. As evident, the intensities of the individual laser distributions are similar but not identical. The average beam quality factor was calculated using $M^2 = \frac{\sigma_{\text{nf}}\sigma_{\text{ff}}\pi}{4\lambda f}$, where σ_{nf}, σ_{ff} are the second moments of the near-field and far-field intensity distributions, and f is the focal length of the lens used to detect the far-field. We determined that for the combined output beam $M^2 = 1.24[M_x^2 = 1.22, M_y^2 = 1.25]$ identical to that of each individual laser beam $M^2 = 1.23[M_x^2 = 1.22, M_y^2 = 1.23]$. We also measured the energy of the individual and combined laser distributions. The energy of the combined output beam was 0.82 mJ per pulse, compared to the 0.19 mJ per pulse for an individual laser beam, indicating 86% combining efficiency. This efficiency is less than expected, because the reflectivities of all coatings could not be accurately controlled. In particular, the reflectivity of the back surface was about 95% rather than an ideal reflectivity of 100%.

In order to coherently add twenty-five laser distributions, we inserted another interferometric combiner and a 90 degrees polarization rotator into the resonator cavity configuration shown in Fig. 2. The additional interferometric combiner, located 37 cm from the back mirror, was oriented orthogonally to the first, and the polarization rotator was placed between the two interferometric combiners, 34 cm from the rear mirror. The experimental detected intensity distributions from the expanded configuration are presented in Fig. 4. Fig. 4a shows the far-field detected intensity distribution of the combined output. The combined output had a nearly Gaussian distribution, just the same as each of the twenty-five individual beams, with a beam quality factor of $M^2 = 1.19$. Fig. 4b shows the far-field intensity distribution of the residual light escaping from the rear mirror, where twenty-five separate laser distributions are clearly detected. As shown there are variations in the intensities of the individual laser distributions, more along the horizontal direction than vertical direction. Here again we attribute these non-uniformities to inaccurate reflectivities of the coatings, including that of the back surface which was only about 90%. As a result of these non-uniformities, the energy of the combined output beam was only 1.5 mJ per pulse, when coherently adding 25 individual laser beams, each with 0.19 mJ per pulse.

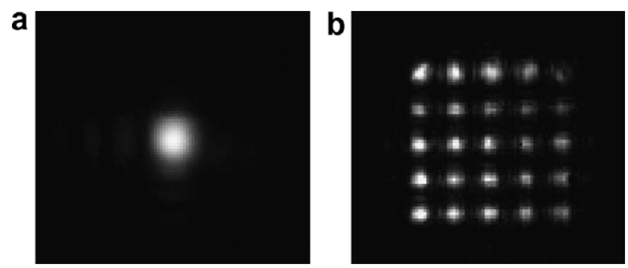

Fig. 4. Experimental coherent addition of twenty-five laser distributions: (a) far-field intensity distribution of the combined output and (b) near-field intensity distributions of the residual light leaking through the back mirror.

4. Imperfections investigations and results

We further investigated how imperfections in the interferometric combiners, such as deviations from perfect parallelism between the front and the rear surface of the substrates and reduction of reflectivities at the rear surface, degrade the combining efficiency and thereby the possible upscaling of our configurations. Specifically, we developed a simple model to help analyze the effect of deviations from perfect parallelism of the interferometric combiner surfaces, taking into account (1) the reorientation of the phase fronts for each laser distribution, (2) displacements of the laser distributions, and (3) phase mismatch between the laser distributions.

For the model we used a plane parallel interferometric combiner of thickness t and determined the effect of angular misorientation α of the back surface. We assumed that each of the laser distributions has a Gaussian shape and a uniform phase front, and considered coherent addition of two, then five and then eight laser distributions, each with a corresponding interferometric combiner. With misorientation, each participating beam will propagate through a different effective thickness at different locations, along the interferometric combiner where a reflection occurs. Specifically, each participating beam k out of a total of p beams will undergo a number of reflections inside the combiner each of which is denoted by j_k. Thus, the effective thickness $t_{\mathrm{eff}_{\{k,j_k\}}}$, for $j_k = p-1$ reflection is

$$t_{\mathrm{eff}_{\{k,j_k\}}} = \frac{d\cos(\theta+(2(p-k)+1)\alpha)\cdot\cos(\theta+2(p-k)\alpha)}{\cos\theta\cdot\cos(\theta+(2(p-k)-1)\alpha)} \quad (1)$$

and for all other j_k it is

$$t_{\mathrm{eff}_{\{k,j_k\}}} = t_{\mathrm{eff}_{\{k,j_k+1\}}}\frac{\cos(\theta+(2(j_k-k)+3)\alpha)}{\cos(\theta+(2(j_k-k)+1)\alpha)}, \quad (2)$$

where θ is the angular orientation of each incident beam inside the combiner after refraction, with respect to the normal to the combiner.

The corresponding local optical path lengths of the beams that propagate inside the interferometric combiner, are

$$l_{\mathrm{int}_{\{k,j_k\}}} = n\cdot t_{\mathrm{eff}_{\{k,j_k\}}}\left[\frac{1}{\cos(\theta+2(j_k-k)\alpha)}+\frac{1}{\cos(\theta+2(j_k+1-k)\alpha)}\right]. \quad (3)$$

Also, the corresponding local optical path length difference l_{diff} between the internally propagating beam and adjacent external beam is

$$l_{\mathrm{diff}_{\{k,j_k\}}} = l_{\mathrm{int}_{\{k,j_k\}}} - l_{\mathrm{ext}}. \quad (4)$$

where $l_{\mathrm{ext}} = 2d\sin\theta_{\mathrm{inc}}\tan\theta$ is just the optical path difference between externally adjacent beams, with θ_{inc} as the external angular orientation of each beam with respect to the normal to the combiner. Finally, with Eqs. (1)–(4) we determined the reorientation of the phase fronts $\Delta\psi$, displacements of laser distributions $\Delta d_{\{k,j_k\}}$, and phase mismatch between laser distributions $\Delta\phi$, as

$$\begin{aligned}&\Delta\psi = 2\cdot j_k\cdot\alpha,\\ &\Delta d_{\{k,j_k\}} = t_{\mathrm{eff}_{\{k,j_k\}}}[\tan(\theta+2(1-k+j_k)\alpha)-\tan(\theta+2(j-k)\alpha)],\\ &\Delta\phi = 2\cdot\pi\cdot\frac{l_{\mathrm{diff}}\,\mathrm{modulo}\,\lambda}{\lambda}.\end{aligned} \quad (5)$$

Using Eq. (5), we calculated the effective reflectivity [13] of our interferometric combiner, which is essentially the same as the combining efficiency for our pulsed laser configurations [19]. This was done by first finding the allowed wavelength λ for which a closed resonator that includes the interferometric combiner has minimum losses. Then, by summing over the energy of all laser distributions that are reflected from a mirror placed after the combiner and dividing by the total energy of original laser distributions; double pass through the combiner determines the effective reflectivity. We determined that the dominant degrading influence is due to phase mismatch which results from the fact that the optical paths over which the laser distributions propagate inside the interferometric combiner are different, when the surfaces of the combiner are not exactly parallel.

The calculated results of combining efficiency as a function of the angle α between the two surfaces of the interferometric combiner are presented in Fig. 5. As evident, the influence of angular deviations significantly increases as the number of coherently added laser distributions becomes larger. In order to obtain a combining efficiency greater than 95%, the angular deviations can be as large as 10 arcsec when coherently adding two laser distributions. The angular deviation must be less than 1 arcsec when coherently adding five laser distributions, and less than 0.25 arcsec when coherently adding eight laser distributions. Fortunately, substrates with such angular deviations are commercially available. Assuming that the losses for two consecutive interferometric combiners inside a cavity simply add, these results also imply combining efficiency of about 90% for

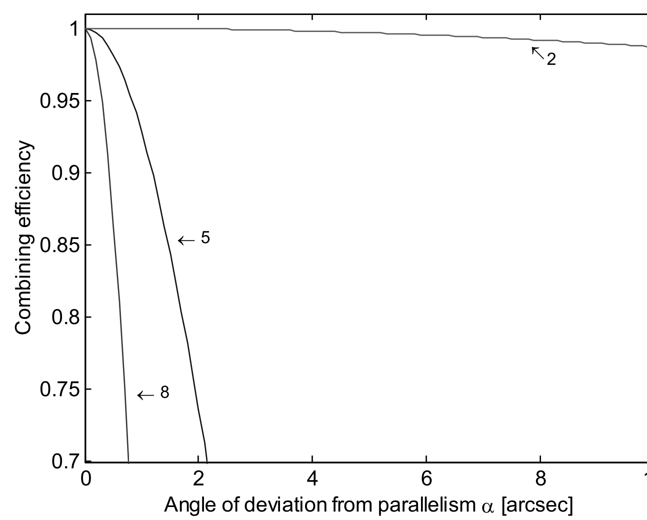

Fig. 5. Calculated combining efficiency as a function of angular deviation from perfect parallelism between the interferometric combiner surfaces for two, five and eight laser distributions.

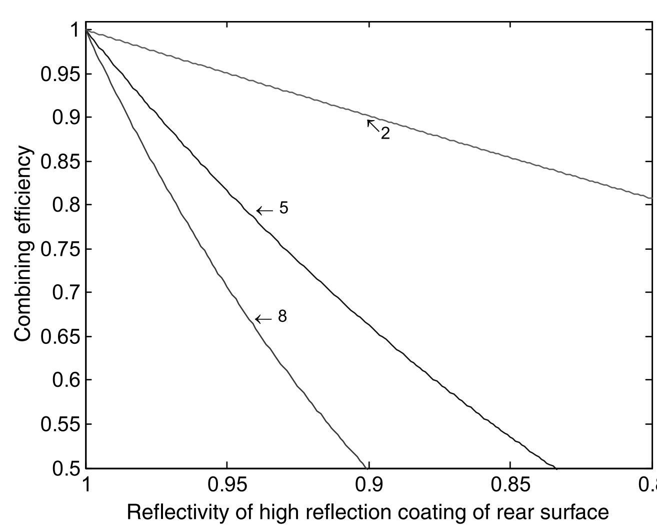

Fig. 6. Calculated combining efficiency as a function of reflectivities of the rear surface of an interferometric combiner, for two, five and eight laser distributions.

both twenty-five laser distributions (with $\alpha = 1$ arcsec) and sixty-four laser distributions (with $\alpha = 0.25$ arcsec).

The same model was extended to determine the influence of reduction of reflectivity from 100% at the rear surface of the interferometric combiner. The results are presented in Fig. 6. As evident, the influence of reflectivity significantly increases as the number of coherently added laser distributions becomes larger. For coherent addition of two laser distributions, a reflectivity of 95% suffices to obtain a combining efficiency of 95%. However, the reflectivity must be better than 98.5% in order to obtain combining efficiency of 95% for coherent addition of five laser distributions, and a combining efficiency of about 90% for coherent addition of twenty-five laser distributions. The reflectivity must be better than 99.5% in order to obtain a combining efficiency of 95% for coherent addition of eight laser distributions, and a combining efficiency of about 90% for coherent addition of sixty-four laser distributions. Such reflectivities are commercially available.

5. Concluding remarks

To conclude, our investigations reveal that upscaling coherent addition to many laser distributions by means of intra-cavity interferometric combiners is both feasible and practical. In our experiments, the combining efficiency was relatively low, when coherently adding 25 laser distributions, because of the relatively low quality interferometric combiners that were used. However, we expect that the combining efficiency can be greater than 90% when geometrical and optical imperfections of the interferometric combiners are minimized.

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