Passive intracavity coherent addition of nine laser distributions

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A highly efficient intracavity coherent addition of nine individual laser distributions is presented. It is achieved with two passive interferometric combiners that are introduced into the combined laser cavity. The results reveal that the combined output power is greater by almost a factor of 9 compared to that of the single laser distributions, while the beam quality is the same. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2167392]

The potential for high output power concomitantly with good beam quality has led to the development of many methods for phase locking and the coherent addition of lasers over the past several decades. These include 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,[12,13] and the incorporation of fiber couplers.[14,15] In general two major difficulties must be overcome when performing coherent addition. The first results from the need for proper phase locking which requires very accurate relative alignment between the lasers. The second, and somewhat related difficulty, results from the need to accurately control the relative phase so as to obtain constructive interference between the laser distributions.

In the past, we demonstrated an approach for efficient coherent addition of two Gaussian laser distributions, using relatively simple intracavity interferometric combiners.[16] The ability to scale this approach in a compact manner to coherently add multiple beam distributions is of great practical importance. Here we extend this approach, to coherently add larger arrays of laser distributions, using somewhat more complicated interferometric combiners. Specifically, we first extend the approach in order to obtain efficient coherent addition using a single sequential interferometric combiner that is designed to deal simultaneously with three laser distributions. This is followed by the coherent addition of nine laser distributions, using two such interferometric combiners that are orthogonally oriented inside the combined laser cavity. Essentially, similar combiners as those introduced here can be used to coherently add larger arrays (4×4, 5×5, etc.) using only two interferometric combiners, thus enabling compact laser configurations with high output power.

The single-substrate interferometric combiner and how it coherently adds three parallel laser beams along a line, is presented in Fig. 1. The interferometric combiner is formed of a high precision plane parallel plate, with specially designed coatings. Specifically, a third of the front surface is coated with an antireflection layer, a third with a 50% beam splitter layer, and the remaining third with a 66% (reflectance) beam splitter layer. Two thirds of the rear surface are coated with a highly reflecting layer and the remaining third is coated with an antireflection layer. As shown in Fig. 1, beam 1 enters the interferometric combiner, reflected from the backsurface and intercepts beam 2 at the 50% beam splitter layer. The reflected part of beam 1 interferes constructively with the transmitted part of beam 2, while the remaining parts of the two beams interfere destructively towards the direction of loss channel 1*a*. The combined beam, composed of reflected beam 1 and transmitted beam 2, propagates towards the backsurface, where it is reflected and intercepts beam 3 at the 66% beam splitter layer. The reflected part of the combined beam interferes constructively with the transmitted part of beam 3, while the remaining parts of the two beams interfere destructively towards the direction of loss channel 2*a*. The overall combined beam, hence, composed of all three beams, emerges from the output interface of the interferometric combiner. With two such interferometric combiners, oriented orthogonally with respect to each other, a two-dimensional array of nine laser distributions can be coherently added.

As is well known, phase locking and coherent addition self-occurs due to the inherent ability of the combined laser resonator to select the mode of operation with minimal losses, but only if all the individual laser distributions have some common longitudinal modes. In general, as the number of laser distributions that must be coherently added increases, the probability for obtaining common longitudinal modes may rapidly decrease.[12] Such a decrease is alleviated with our interferometric combiners, whose constant thickness ensures that the path difference between sequential laser distributions is always the same.

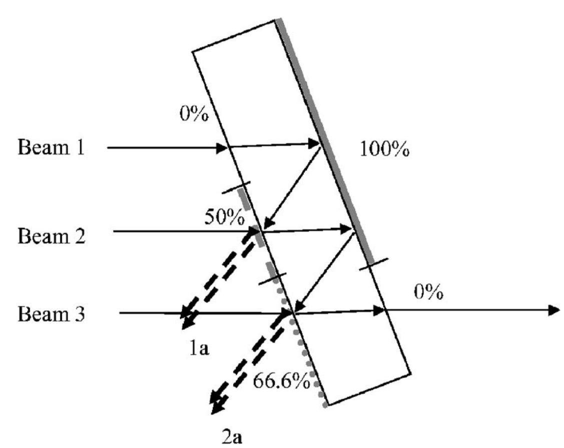

FIG. 1. Interferometric combiner for coherently adding simultaneously three laser distributions. Beams 1*a* and 2*a* present the loss channels.

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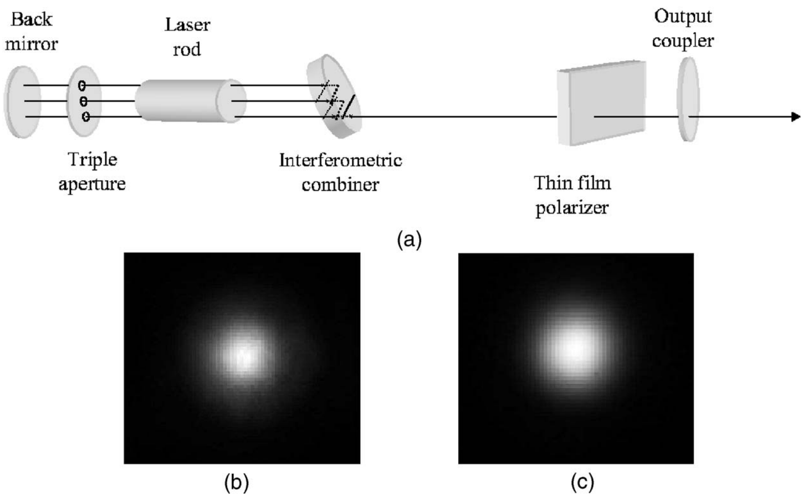

FIG. 2. Coherent addition of three laser distributions: (a) Experimental configuration; (b) near-field intensity distribution of the combined output; and (c) far-field intensity distribution of the combined output.

We performed experimental investigations with available pulsed Nd:YAG lasers, whose gain medium rod diameters were sufficiently large to support several independent and separate Gaussian laser distributions. Initially, we performed experiments to demonstrate intra-cavity coherent addition of three Gaussian distributions. This experimental configuration and results are shown in Fig. 2. Figure 2(a) shows the resonator of length 71 cm, with a flat rear mirror and a concave output coupler mirror of 40% reflectivity, and a radius of curvature of $R=1.50$ m. The resonator included: (1) A gain medium of a single flashlamp pumped Nd:YAG rod with a of length 102 mm and diameter 5 mm, placed 10 cm from the rear mirror. The gain medium demonstrated thermal lensing of focal distance 20 m at 1 Hz repetition rate. (2) Three apertures, placed along a line and 1.6 mm apart, located 25 cm from the rear mirror. The diameter of each aperture was 1.4 mm in order to select the TEM_{00} mode; (3) A thin film polarizing plate, located 50 cm from the rear mirror and near the output coupler, ensures that the laser operates at a single linear polarization; (4) A three-channel interferometric combiner, formed from a 3-mm thick high precision plane parallel plate (parallelism ¡ 0.5 s) with the coatings illustrated in Fig. 1, located 30 cm from the rear mirror and titled by 24 deg. It yielded a displacement of the reflected beams of exactly 1.6 mm, the distance between the laser distributions—to enable coherent addition of the three laser distributions.

The near-field and far-field detected intensity distributions of the combined output are shown in Figs. 2(b) and 2(c). The energy of the output beam was measured as 7.06 mJ per pulse, compared to the 2.52 mJ per pulse for a single channel, indicating 92% combining efficiency. The beam quality factor $M^2=\sigma_{\mathrm{nf}}\sigma_{\mathrm{ff}}\pi/4\lambda f$ (where σ_{nf}, σ_{ff} are the second moments of the near-field and far-field distribution and f is the focal length of the lens used to detect the far-field) was measured using these distributions. We found that $M^2=1.03$ for the combined output beam, nearly identical to the $M^2=1.06$ measured for each channel distribution separately.

Next, we performed experiments to demonstrate the intracavity coherent addition of nine Gaussian laser distributions. The experimental configuration and results are shown in Fig. 3. Figure 3(a) shows the experimental configuration. The resonator is similar to that used for the coherent addition of three laser distributions, except for a larger gain medium with a stronger power supply, in order to support nine laser distributions, a different output coupler, an additional interferometric combiner and a 90 deg polarization rotator. Specifically, we used a concave output coupler mirror of 40% reflectivity, and a radius of curvature of $R=1.00$ m, and a dual flashlamp pumped Nd:YAG rod, with a length of 114 mm and diameter 9.55 mm. We used nine apertures allocated in a square grid pattern, 1.6 mm apart. The diameter of each aperture was 1.2 mm in order to select the TEM_{00}

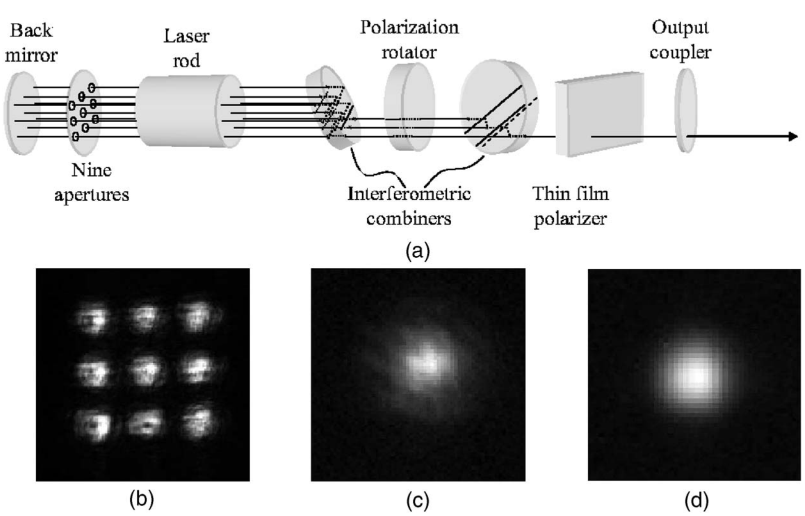

FIG. 3. Coherent addition of nine laser distributions: (a) Experimental configuration; (b) near-field intensity distribution of the residual light escaping from the rear mirror; (c) near-field intensity distribution of the combined output; and (d) far-field intensity distribution of the combined output.

mode. The additional interferometric combiner, located 45 cm from the rear mirror, was oriented orthogonally to the first interferometric combiner, thus enabling coherent addition between channels for the orthogonal axis. The polarization rotator was placed between the two interferometric combiners, 37.5 cm from the rear mirror.

Figure 3(b) shows the near-field intensity distribution of the residual light escaping from the rear mirror. As evident, nine separate laser distributions are clearly detected. The near-field and far-field detected intensity distributions of the combined output are shown in Figs. 3(c) and 3(d). The energy of the output beam was measured as 30.5 mJ per pulse, compared to the 3.9 mJ per pulse for a single channel, indicating 87% combining efficiency. We found that $M^2=1.3$ for the combined output beam, slightly larger than the $M^2=1.2$ measured for each channel distribution separately. We attribute this lower efficiency mostly to the imperfection of our coatings and their imprecise placement upon the interferometric combiners.

To conclude, we presented an efficient and compact method for coherently adding three and nine nearly Gaussian laser distributions. The method used could be extended to deal with the coherent addition of more laser distributions, either by increasing the number of laser distributions that are coherently added by each interferometric combiner (using additional beam splitter coatings, with 75% reflectance for the fourth beam, 80% reflectance for the fifth beam, etc.), or by using more than two interferometric combiners inside the laser cavity. Although the experiments were performed using transverse Gaussian laser distributions, the method can be successfully applied to coherently add many single high-order mode laser distributions as well as to multimode operation, as demonstrated before for two laser distributions.[17,18]

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