Intracavity coherent addition of Gaussian beam distributions using a planar interferometric coupler

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We present a compact and practical combined laser resonator configuration in which several Gaussian beam distributions are efficiently combined. It is based on intracavity coherent addition of pairs of Gaussian beam distributions with a planar interferometric coupler. The principle, configuration, and experimental results using pulsed Nd:YAG laser beams are presented. The results reveal more than 92% combining efficiency with a nearly Gaussian output beam, in free running and Q-switched operation. © *2004 American Institute of Physics*.
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The beam quality, stability, and heat dissipation of high-power lasers are typically inferior to those of low power lasers. This suggests that a combination of several low-power lasers may be advantageous over a single high-power one. Such a combination, namely addition, could be performed either incoherently or coherently. When the field distributions of several laser output beams are incoherently combined, the resulting beam-quality factor (M^2) is relatively poor with low optical brightness. But, when the field distributions are coherently added, with the proper phase relations, the combined beam quality factor can be as good as that of a single low-power laser, while the combined power is greater by a factor equal to the number of the combined lasers.

When coherently combining two or more laser output fields two major difficulties are encountered.[1] The first results from the need for proper coupling between the individual laser fields, so as to enable relative phase locking between them. Such coupling typically introduces excessive losses to each laser field, and requires very accurate relative alignment. The second (and somewhat related) difficulty results from the need for accurately controlling the relative phase between the different laser fields, so as to ensure constructive interference between them. This requires that the distances between the participating optical components must be very accurately controlled, causing the output power to be extremely sensitive to thermal drifts and acoustic vibrations.

These difficulties can be alleviated if the phase locking among several channels is self-produced within the laser cavity. Techniques for achieving intracavity phase locking of laser beams have been extensively investigated over the years. These involve Vernier-Michelson cavities,[2,3] intracavity amplitude diffractive components,[4–6] Talbot cavities and Fourier transform resonators,[7,8] phase diffractive components,[9] evanescent waves,[10] antiguiding waves,[11] phase conjugation,[12] and birefringent and polarization components.[13] With several of these techniques successful phase locking of laser beams was demonstrated in the lab, generating a coherent superposition of the beams or various *supermodes*. However, most of these techniques are generally difficult to implement in practice due to the rather severe alignment and stability requirements. Recently, with the advent of fiber lasers, several intracavity methods for successfully combining coherently two and more individual Gaussian field distributions were reported.[14–17] These are based on the Vernier–Michelson type cavity,[2] exploiting standard fiber couplers.

In this letter we present an alternative compact, stable, and practical method in which an intracavity planar interferometric coupler is used to phase lock and coherently combine individual Gaussian field distributions. Specifically, we show how to coherently combine two Gaussian field distributions in a combined laser resonator, where all the optical components are common, and demonstrate experimentally the operation in a pulsed Nd:YAG laser configuration. Unlike other laser configurations that exploit discrete elements for intracavity coherent addition, the use of the interferometric coupler and common end mirrors is of great advantage. Together they alleviate the complexity of alignment and significantly improve the stability, thereby allowing for practical implementation in laser systems.

A basic configuration for intracavity phase locking and coherent addition of two Gaussian laser field distributions is schematically presented in Fig. 1. The resonator is composed of a flat rear mirror, an output coupler which could be either flat or concave for stable laser operation, a common gain medium, a double aperture with diameters suitable for independent fundamental TEM_{00} operation in each of the two channels, and a planar interferometric combiner coupler. The coupler is comprised of a high precision plane parallel plate, with specially designed coatings. For channels with equal gain, half of the front surface is coated with an antireflection layer, and the other half with a 50% beam splitter layer, while half of the rear surface is coated with a highly reflecting layer and the other half is coated with antireflection (AR) layer (in case of different gain in each channel, an appropri-

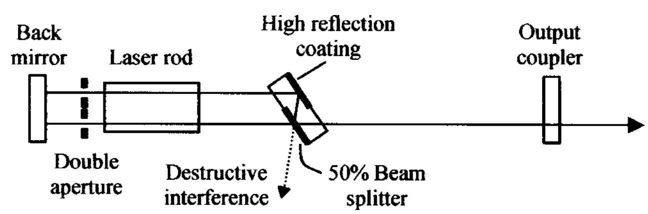

FIG. 1. A configuration for intracavity coherent addition of two Gaussian beam distributions using a single interferometric coupler.

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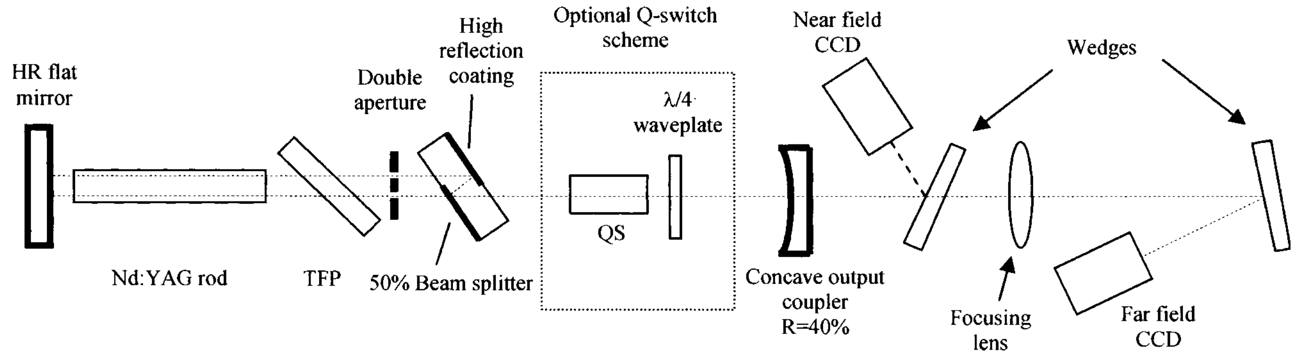

FIG. 2. Experimental pulsed Nd:YAG laser setup for intracavity coherent addition of two Gaussian beam distributions.

ate beam splitter transmission should be chosen). The beam of one channel is directly incident on the beamsplitter coating region, while the beam of the other channel is transmitted through the AR coated region, reflected back from the rear surface, and then is incident on the beam splitter coating so as to be collinear with the other transmitted beam. The thickness d of the coupler and its angle relative to the beams are designed to match the distance between the beams, so the two beams optimally overlap and propagate collinear after exiting the coupler through the AR region. For an incident angle α, d is determined by the simple relation $d = x_0/\{2 \cos \alpha\, tg[\text{acrsin}(\sin \alpha/n)]\}$, where x_0 is the distance between the two beams, and n is the refractive index of the coupler material. Similar couplers were successfully exploited recently for external coherent combining two lobes of a high order mode distribution, emerging from a laser.[18]

In a simplified manner, the operation of our combined resonator can be explained as follows. If the two Gaussian beam distributions are incoherent (random relative phase between the beams or different frequencies), then each beam will suffer a 50% loss passing through the coupler, so, typically, no lasing will occur. On the other hand, if the beams add coherently, then the losses introduced by the coupler may be completely suppressed. Specifically, to the right of the beam splitter constructive interference occurs with little, if any, losses, while destructive interference occurs in the lower path from the beam splitter, as shown in Fig. 1. Indeed, the combined laser will tend to operate so that the losses are minimum, whereby the phases of the individual beams will be automatically matched (automatic phase locking) such that coherent addition takes place. This of course can be achieved only for those longitudinal modes (frequencies) that are common in the two laser channels. Thus, care must be taken to imbalance the optical length of the two resonator channels in such a manner so as to obtain one or more mutual longitudinal modes.

To verify our combined laser resonator design, we performed experiments with a Nd:YAG laser setup shown in Fig. 2. The resonator was basically a ~70-cm-long plano-concave resonator, with a concave (R=3 m) output coupler of 40% reflectivity at 1064 nm and a high-reflective flat mirror. A Nd:YAG rod of 5 mm diameter and 10 cm length, with 1.1% doping, was 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. The resonator included a double aperture with two apertures of 1.6 mm diameter each, positioned 2.4 mm apart (between centers), and a high quality thin film polarizer. The 3-mm-thick interferometric combiner coupler was positioned at Brewster's angle. Half of its first surface was coated with a 50% beam splitter coating, and half of its second surface was coated with a high reflective coating (no AR coatings). An arrangement comprised of an electro-optical LiNbO3 crystal and a $\pi/4$ retardation plate was used for Q-switching (free running experiments were done without these elements). The CCD cameras and Spiricon Laser Beam Analyzers were used for detecting and characterizing the near and far field intensity distributions.

In order to independently characterize the two channels in free running operation we first operated the laser without the combiner coupler. The concave output coupler was aligned separately for each channel, and the output pulse energy, and the near and far field intensity distributions of each channel were detected. The output pulse energy was 9.75 mJ for each of the two independent channels. Figure 3 shows the detected field distributions. Figures 3(a) and 3(b) show the near and far field intensity distribution for channel 1 and Figs. 3(c) and 3(d) the near and far field intensity distribution for channel 2. The calculated M^2 for these individual beams, which was obtained by measuring the second-order moments and using the explicit definition for M^2,[19] was M_x^2=1.15 and M_y^2=1.20 for the first channel, and M_x^2 =1.14 and M_y^2=1.21 for the second channel, indicating a nearly pure Gaussian TEM mode beam in both channels.

In order to phase lock and coherently combine the two individual beams, the combiner coupler was inserted in the resonator. This resulted in a 7.2 mm optical length difference between the two channels. For a typical Nd:YAG gain bandwidth of 120 GHz, this length difference for a 70-cm-long resonator, would leave about six common longitudinal mode bands in both channels to be within the gain bandwidth (out of several hundreds longitudinal modes).[3] After aligning the combiner coupler and output coupler, a combined output energy of 18 mJ was measured, indicating a 92% combining efficiency. The 8% loss can be attributed to the imperfect coatings on the combiner coupler and inexact overlap of the two channel beam distributions. The near and far field intensity distributions of the combined beam is shown in Figs. 3(e) and 3(f). The calculated M^2 values for the combined output beam were M_x^2=1.12 and M_y^2=1.18, indicating that the original, nearly Gaussian, beam quality was preserved. We found that slowly tilting the combiner coupler at small angles, so as to slightly change the channel length difference, did not affect the output energy or its intensity distribution. This demonstrates the self-locking mechanism of the laser in

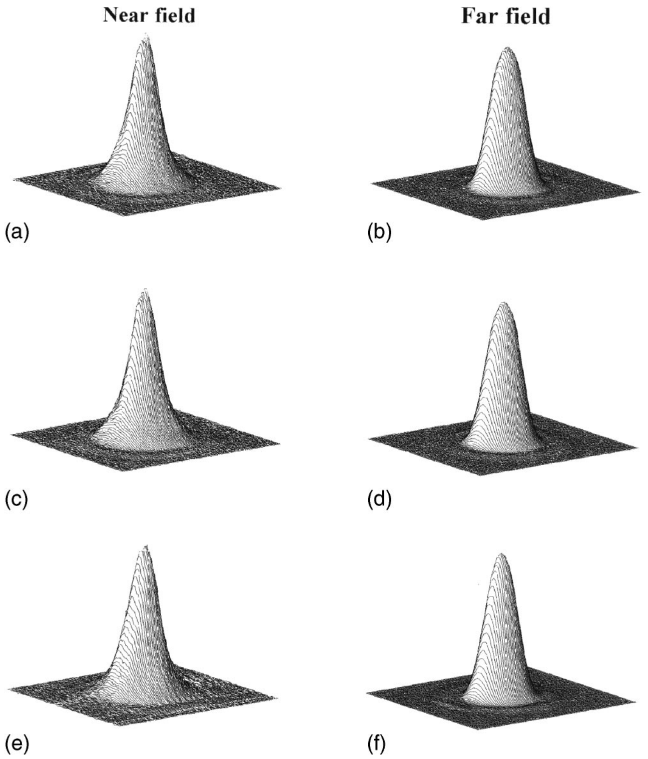

FIG. 3. Experimental intensity distributions of the separate independent Gaussian beams, and the combined output beam obtained using the combiner coupler. (a) and (b) Near and far field intensity distributions of the first channel output beam; (c) and (d) near and far field intensity distributions of the second channel output beam; (e) and (f) near and far field intensity distributions of the combined channel output beam using the combiner coupler.

this configuration, and its insensitivity to geometrical displacements of the combiner coupler.

Similar experiments were performed with the Q-switching arrangement inserted in the resonator (see Fig. 2), revealing essentially the same behavior as for free running operation. Combining efficiency of 93% and a nearly Gaussian output beam ($M_x^2=1.12$, $M_y^2=1.23$) were obtained.

The resonator design for coherently combining two Gaussian beam field distributions can be extended to pairwise addition of more than two Gaussian beams. In Fig. 4, for example, a resonator design for phase locking and coherent addition of four Gaussian beams is depicted. Here, three combiner couplers are used, each responsible for the coherent addition of two beams. In this case the longitudinal modes in the various channels should be carefully considered in order to ensure that at least one common frequency is present. Here also, the insensitivity to geometrical displacements would be ensured by the self-locking mechanism of the laser.

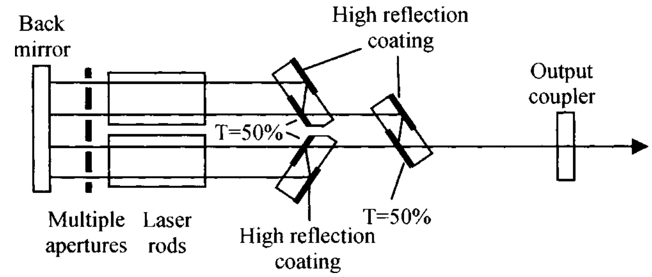

FIG. 4. A configuration for intracavity coherent addition of four Gaussian beam distributions using interferometric combiner couplers.

To summarize, we have presented a compact and practical resonator scheme for efficiently combining two or more Gaussian beam distributions. With this scheme, self-phase locking is achieved, overcoming most of the difficulties encountered when trying to combine laser beams. We verified experimentally its operation for two Nd:YAG Gaussian beams, both in free running and Q-switched operation, obtaining stable lasing with more than 92% combining efficiency, while preserving the original Gaussian beam quality.

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