Coherent addition of spatially incoherent light beams

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Abstract: We report on efficient coherent addition of spatially incoherent multimode laser beam distributions. Such addition is demonstrated within a multi-channel laser resonator configuration, obtaining more than 90% combining efficiency while preserving the good beam quality. We explain the rather surprising physical phenomenon of coherently adding spatially incoherent light by self-phase-locking of each of the modal components within the multimode beams. Our approach could lead to significantly higher output powers concomitantly with good beam qualities than were hitherto possible in laser systems.

OCIS codes: (140.3410) Laser resonators; (030.1670) Coherent optical effects.

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1. Introduction

Intra-cavity coherent addition of laser beams was originally suggested during the 1960’s, with the introduction of the Michelson-Vernier type resonator [1]. Since then various techniques for achieving intra-cavity phase locking and coherent addition of laser beams have been extensively investigated [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. Recently, with the advent of fiber lasers, coherent addition was also realized in single mode fiber laser resonators, exploiting fiber couplers [13, 14, 15, 16]. Thus far coherent addition of laser beams has only been obtained with spatially coherent Gaussian TEM_{00} beams, having a well defined amplitude and phase distribution. Since incoherent laser light has a multiplicity of transverse and longitudinal modes, with undefined amplitude and phase distributions, it was not considered for coherent addition. In this Letter we present an approach for efficient intra-cavity coherent addition of transverse multimode laser beam distributions, possessing considerably more power than that of Gaussian beam distributions. We further show how one laser beam distribution can imprint its transverse modal content on other beam distributions within a laser cavity. Apart from revealing a surprising physical phenomenon, our approach for coherently adding spatially incoherent light distributions can lead to significantly higher output powers and beam quality than were hitherto possible in laser systems.

2. Basic principles

Typically, the fundamental transverse TEM_{00} mode operation in a laser is achieved by inserting a small aperture in the resonator. Such a mode with a well defined phase leads to excellent output beam quality (i.e. low divergence) but relatively low output power, since only a small volume of the gain medium is exploited. Increasing the diameter of the aperture, results in transverse multimode operation which leads to inferior output beam quality but considerably higher output power. This inherent trade off that exists between output power and output beam quality has played a dominant factor when designing high power lasers. A multimode laser beam distribution, which is comprised of many transverse modes with random relative phase, has no well defined amplitude and phase. Thus, it is generally considered to be spatially incoherent light.

At first glance, the concept of efficient coherent addition of two transverse multimode laser beam distributions does not seem plausible. Indeed, it is not feasible with two independent multimode beams originating from two independent lasers. However, as we will show, this can be achieved within the laser cavity, where two laser channels, each with multimode field distributions, are coherently added, nearly doubling the output power while preserving the beam quality. Into such a laser cavity a loss mechanism, that favors coherent addition of the two multimode field distributions, is inserted. The loss mechanism causes the laser to simultaneously self phase lock all the corresponding transverse modes in the two channels, enabling the coherent addition of the two incoherent beam distributions. This approach, somewhat resembles passive longitudinal mode locking, where an intra-cavity nonlinear effect forces the various frequencies to phase lock such that short intense pulses are produced in the time domain [17].

A basic configuration for intra-cavity coherent addition of two transverse multimode field distributions is schematically presented in Fig. 1. The configuration is essentially comprised of two coupled resonators with a common output coupler. It includes a flat rear mirror, an output coupler that could be either flat or concave for stable laser operation, two channels with gain media and aperture diameters suitable for multimode operation, and a planar interferometric combiner. The combiner is comprised of a high precision plane parallel plate, with specially designed coatings. With equal gain medium, half of the front surface is coated with an anti-reflection 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 with anti-reflection (AR) layer; in case of different gain in each channel, appropriate different beam splitter coatings should be chosen. The light from one channel is directly incident on the beam splitter coating region, while that from the other channel is transmitted through the AR coated region, reflected back from the rear surface, and then reflected from the beam splitter coating so as to be collinear with the other transmitted light. The thickness d of the combiner and its angle relative to the incident light, are designed to match the distance between the incident light beams, so they optimally overlap and propagate collinear after exiting the combiner through the AR region. Similar combiners were recently experimentally exploited for coherent addition of the two lobes of a Hermite-Gaussian TEM_{10} laser beam distribution [18], and for intra-cavity coherent addition of two Gaussian beam distributions [12]. Unlike laser configurations that exploited discrete elements for intra-cavity coherent addition of Gaussian beams [1], the use of the interferometric combiner and common end mirrors in our configuration is of great advantage. Together they alleviate the complexity of alignment and significantly improve the stability of the laser.

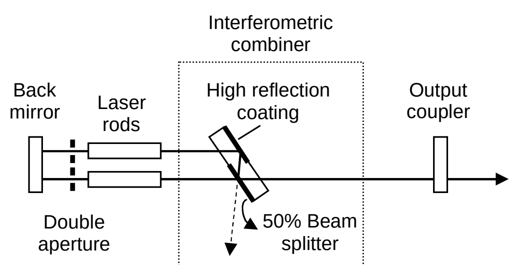

Fig. 1. A combined laser configuration for intra-cavity phase locking and coherent addition of two transverse multimode laser beam distributions using an interferometric combiner. The light from one channel is directly incident on the beam splitter coating region of the combiner, while that from the other channel is transmitted through the AR coated region, reflected back from the rear surface, and then reflected from the beam splitter coating so as to be collinear with the other transmitted light.

In a simplified manner, the operation of our combined laser configuration can be explained as follows. If the two multimode laser beam distributions are incoherent with respect to each other (random relative phase at each location in the beam or different frequencies), then each beam will suffer a 50% loss passing through the interferometric combiner, so, typically, no lasing will occur. Considerable energy is thereby lost as indicated by the dashed line in Fig. 1. On the other hand, if the two multimode beam distributions have similar mode composition, and if each of the transverse modes in one distribution adds coherently with its counterpart in the other beam, then destructive interference occurs, so the losses introduced by the combiner may be completely suppressed. The combined laser configuration tends to operate so that the losses are minimum, whereby the phases of the corresponding individual transverse modes automatically match, so that coherent addition takes place. The combined multimode beam is thus composed of many pairs of phase-locked modes, where the phase difference between the pairs is still completely undefined. This of course is achieved only for those longitudinal modes (frequencies) that are common in the two laser channels. Consequently, care must be taken to imbalance them in such a manner so as to obtain one or more mutual longitudinal modes [14].

If the aperture diameter in one channel is reduced then it is expected that this channel, with the lower transverse mode content, will imprint its modal content on the other channel, obtaining phase locking and coherent addition of the corresponding multimode field distributions. This self-imprinting of the modal content occurs because the higher transverse modes in the channel with the larger aperture diameter do not have corresponding counterparts in the other channel, so they suffer considerable losses by the combiner.

3. Experimental procedure and results

To experimentally demonstrate our approach, we used a pulsed Nd:YAG laser arrangement shown in Fig. 2. It includes a 70 cm long plano-concave resonator, with a concave ($R = 1$ m) output coupler of 40% reflectivity at 1064 nm and a high-reflective flat 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 two channels in the resonator. The rod was pumped with a pulse rate of 0.5 Hz at constant power level throughout the experiments. This power level was about twice that of the threshold pump power. The thermal lensing of the rod under these pumping conditions was measured to be less than $f = 20$ meter. In order to establish the two separate channels a double aperture was used, with two apertures of 2.1 mm diameter each, positioned 2.4 mm apart (between centers). We confirmed that this distance between the two channels was such that spontaneous phase locking, due to partial overlap of the beams [5, 6], did not occur in our configuration. A thin film polarizer was inserted in order to obtain P-polarization operation. The 3 mm thick interferometric combiner was positioned at Brewster's angle. Half of its front surface was coated with a 50% beam splitter coating, and half of its rear surface was coated with a high reflective coating. CCD cameras were used for recording the near and far field intensity distributions.

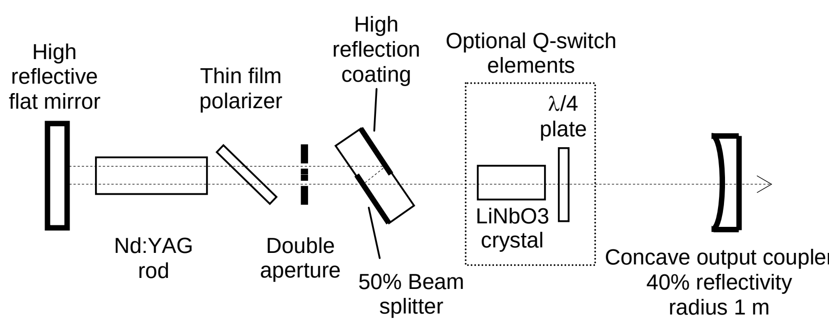

Fig. 2. Experimental arrangement for intra-cavity coherent addition of two transverse multimode laser beam distributions with an interferometric combiner. The two separate transverse multimode distributions were derived from a common gain medium and formed with a double aperture, each of 2.1 mm diameter. The thin film polarizer was used to obtain P polarization in order to minimize losses of the combiner. Optional Q-switch operation was obtained by intra-cavity Q-switch elements.

To confirm that each of our multimode laser beam distribution is indeed spatially incoherent, we first performed a rather simple double slit experiment, where we detected the interference pattern of the light from the two slits that were placed in the beam. This was done, without the interferometric combiner, for the multimode distribution as well as for a Gaussian distribution, as schematically shown in Fig. 3. With the spatially coherent Gaussian field distribution the expected fringe pattern appears at the far field, whereas with the multimode field distribution the fringe pattern is averaged out by the rapid amplitude and phase variations across the beam distribution.

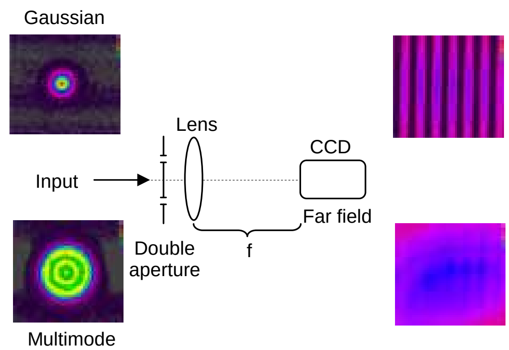

Fig. 3. A double slit experimental arrangement for confirming the spatially incoherent nature of one transverse multimode laser beam. Two circular pinholes, each with a diameter of 100 μm and spaced 1 mm apart served as slits. The 4-sigma widths of the Gaussian and multimode distributions, at the slits plane, were 1.7 mm and 3.6 mm, respectively. The far field intensity distributions, at the focal plane of the lens, were detected with a CCD array. With the input of Gaussian distribution from a pulsed Nd:YAG laser ($M^2 = 1.1$) a fringe pattern appears at the far field. Whereas with an input of multimode distribution from the same laser ($M^2 = 4.6$), no fringes appear.

We then independently characterized the two channels in free running operation without the interferometric combiner. 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 19.5 mJ for one channel and 20 mJ for the other. Figure 4 shows the detected intensity distributions. Figures 4(a) and 4(b) show the near and far field intensity distribution for channel 1 and Figs. 4(c) and 4(d) the near and far field intensity distribution for channel 2. In order to characterize the beam quality we used the beam quality parameter M^2, defined as the ratio between the space bandwidth products of the beam to that of a Gaussian beam [19]. Measuring the second order moments of the intensity distributions in the near and far fields and using the explicit definition for M^2, resulted in values of $M_x^2 = 4.43$ and $M_y^2 = 4.84$ for the first channel, and $M_x^2 = 4.41$ and $M_y^2 = 4.69$ for the second channel, indicating a multimode beam with more than 13 transverse modes in each of the channels.

In order to phase lock and coherently combine the two individual channels distributions, the interferometric combiner was inserted into the overall 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 6 common longitudinal mode frequency bands in both channels to be within the gain bandwidth (out of several hundreds longitudinal modes) [11]. A combined output energy of 36 mJ was measured, indicating a 91% combining efficiency. The 9% loss can be attributed to the imperfect coatings on the combiner and inexact overlap of the two channel distributions. The near and far field intensity distributions of the combined laser output are shown in Figs. 4(e) and 4(f). The calculated M^2 values for the combined output beam were $M_x^2 = 4.17$ and $M_y^2 = 4.72$, indicating that the original beam quality was not only preserved, but even slightly improved. We found that slowly tilting the combiner 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

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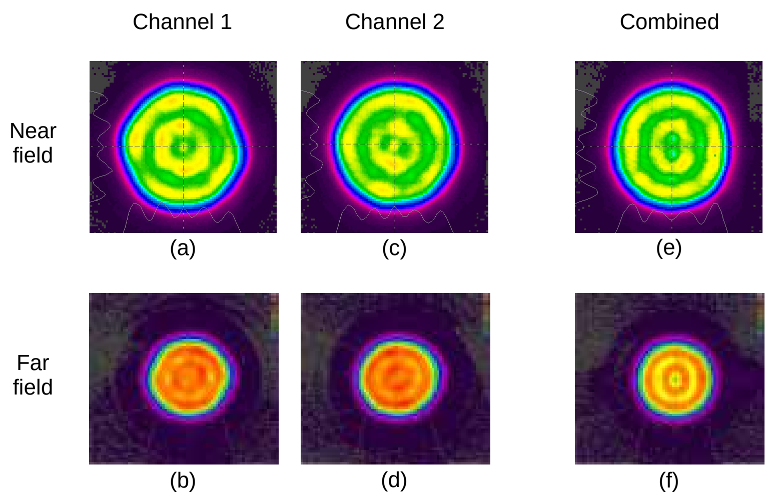

Fig. 4. Experimental intensity distributions of the separate transverse multimode channels, and the combined laser output beam distribution obtained using the interferometric combiner. (a) and (b) near and far field intensity distributions of the first channel; (c) and (d) near and far field intensity distributions of the second channel; (e) and (f) near and far field intensity distributions of the combined laser output, using the interferometric combiner.

mechanism of the laser in this configuration, and its insensitivity to geometrical displacements of the combiner.

We also investigated how a low transverse mode content channel imprints its modal content on a high transverse mode content channel. This was done by reducing the aperture diameter in one of the channels to 1.2 mm, such that only the Gaussian mode is allowed in that channel. At the combined output we detected a Gaussian mode profile ($M^2 = 1.05$) with slightly more than twice the output power of the independent Gaussian channel. This result indicates that the high order modes in the channel with the larger aperture are completely suppressed, and this otherwise multimode channel is forced to operate in a Gaussian mode. The higher than expected output power can be explained by the absence of a limiting aperture for the Gaussian in the multimode channel.

Similar experiments were performed in active Q-switched operation, using an electro-optical LiNbO3 crystal and a $\lambda/4$ retardation plate (see Fig. 2). The results in Q-switched operation reveal essentially the same behavior as for free running operation. These indicate that the phase locking mechanism is also effective for 20 nsec pulse durations of Q-switched operation.

4. Concluding remarks

We have demonstrated a new practical approach for phase locking and coherent addition of transverse multimode laser field distributions. With this approach, self-phase locking is achieved within a laser cavity, enabling the rather surprising coherent addition of spatially incoherent multimode field distributions. The basic resonator design can be scaled to addition of more than two multimode beam distributions. This can be done by using several two-beam interferometric combiners for adding each pair of channels, or alternatively using a single interferometric combiner that includes several beam splitter sections with appropriate reflectivities for sequentially adding multiple channels. From a practical point of view, our approach can be incorporated in a wide variety of lasers, especially in newly developed high-power multimode fiber lasers, leading to significantly high output power and good beam quality.

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