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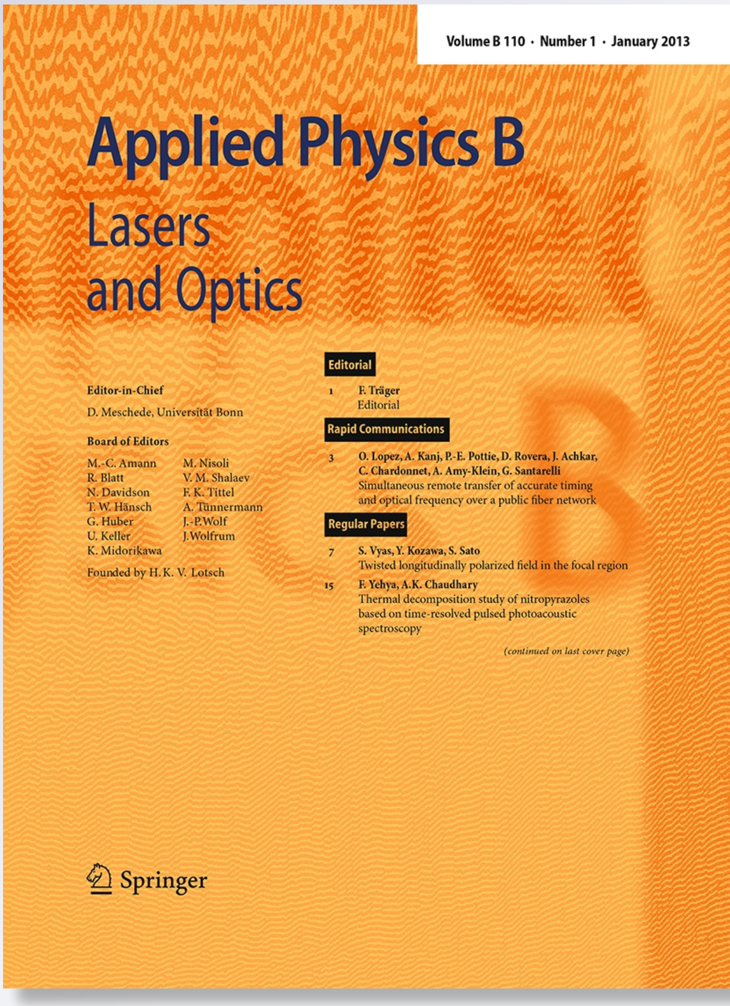

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About comparison of combination of different laser beams at a target to the performance of an equivalent single laser

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Abstract In this work, it is shown that different lasers' beams, of the same frequency, having, however, randomly different phases and polarizations at the output, combine at a target by a statistical distribution with a mean and a standard deviation, both, of the same order of magnitude as the incoherent sum of their intensities. This disadvantage does not occur in an "equivalent" single laser operation. Therefore, it delivers a much higher intensity at the target.

1 Introduction

Much effort has been recently applied to investigation of combining different laser beams at a spot on a target, for scientific, industrial and also civil-military purposes [1–4]. In any of these purposes, a certain threshold intensity that may cause damage, desirable or undesirable in a point of a target should be achieved or avoided, respectively. The reason for this effort rests on losing beam quality due to nonlinear effects in solid and fiber lasers of power higher than ~ 1 kW (that are commercially available). A system of combined laser beams will be addressed as a multi-laser system. An equivalent single laser operates in the same frequency and emits the same intensity as would have emitted the combined lasers, should they all have the same phase and polarization. Next follow the assumptions applied in this work: (a) The multi-laser system operates in the same transversal mode as the equivalent single laser system. This assumption is in favor of the multi-laser performance. (b) The combination of different laser beams at a target, is studied assuming the lasers operate at the same frequency, each of the lasers being a cw coherent source, though each of the lasers has a random phase and polarization at the output, which remain constant during the coherence time, while the coherence length is equal or larger than the range to the target [5]. (c) The coherence time of statistical spread of the lasers is narrow. (d) In favor of the multi-laser system, all the beams are transmitted by the same output mirror. (e) The diffraction, absorption, scattering, jitter, atmospheric turbulence, and thermal blooming act the same way in deteriorating the beam quality for both, the multi-laser and the single laser systems. This assumption is evidently in favor of the multi-laser system. The purpose of this work is to show that a multi-laser system delivers a much smaller intensity at the target than an equivalent single laser. Next the effect of random phases is studied. Then the influence of random polarizations is also included. Discussion of the advantage of a single laser system concludes this work.

2 Random phases

In order to calculate the intensity of e.g. 100 laser beams at their point of intersection are spot on the target, assuming that each beam has the same frequency and a constant (in time), however, random, phase, the following expression should be evaluated:

$$\mathcal{J} \approx [A(e^{i\varphi_1} + e^{i\varphi_2} + \cdots + e^{i\varphi_{100}})]^*[A(e^{i\varphi_1} + e^{i\varphi_2} + \cdots + e^{i\varphi_{100}})] \qquad (1)$$

where A is the amplitude, "*" denotes the complex conjugate and $\varphi_1, \varphi_2, \ldots, \varphi_{100}$ are random (though constant in

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time, during the coherence time) phases. The result of this evaluation is about 100 (in arbitrary units). It means that the resultant intensity is smaller by a factor of 100 (approximately), than if all the beams would have been in phase with each other, or than if an equivalent single laser would have been used. It should be noticed (Fig. 1) that repeating the calculation many times (e.g., 10^6 times) with random phases gives a large standard deviation that equals approximately the mean, while the most probable case is the case of zero intensity. The probability density function that represents this behavior is given by the exponential distribution as is shown in Fig. 2, where the green curve that is an exact exponential coincides (overlaps) with the blue curve, that is the envelope of the histogram in Fig. 1. (A similar mathematical result, though related to another physical system is shown in Ref. [6].)

The reason for the different approaches in these two cases, the case of multi-laser system with long coherence time and the case of multi-laser system with short coherence time, stems from their different origin. In the first case of laser beams, each phase is random but constant in time (at least during the coherence time that is relatively long). In the second case of incoherent (or thermal) beams, the phases are randomly fluctuating on a very short time scale. Rapid and random fluctuations increase the line-width and affect the monochromaticity and coherence.

If the coherence length of each single laser is shorter than the range to the target, the result of combining n_1 lasers should be similar to that of combining n_1 incoherent beams [1, 2]. In such a case, during the propagation, the phase of each beam is a random function of time. Time averaging applied to non-diagonal terms that appear in the product in Eq. (1) contributes zero, while each of the diagonal terms contributes 1; therefore, the result would be n_1. However, if the coherence length of each single laser is larger than the range to the target, then the phases are constant during the propagation, and time averaging does not apply.

There are two basically different methods for combining laser beams:

(i) Combining the beams while inside the laser system which includes all optical elements that transmit (and may absorb) high energy beams.

(ii) Combining the beams outside the laser system which does not contain any optical element that transmits (and may absorb) high energy beams.

If the combination occurs inside the laser system, as in references [3, 4], components of the system transfer high intensities that cause nonlinear propagation effects. That in turn deteriorates the beam quality.

If the adjustment of frequencies and phases takes place outside the laser systems or at the target, then small differences in the paths of the beams before reaching the target also cause random phase differences. In this case, the considerations that follow Eq. (1) apply as well as the conclusions.

It has been suggested in Ref. [3] that the method described there is scalable and that an output of even 100 kW can be obtained.

In Ref. [4], it is concluded that events with high phase locking levels of over 90 %, in combining a large number of fiber lasers, are rather rare and have no immediate practical use.

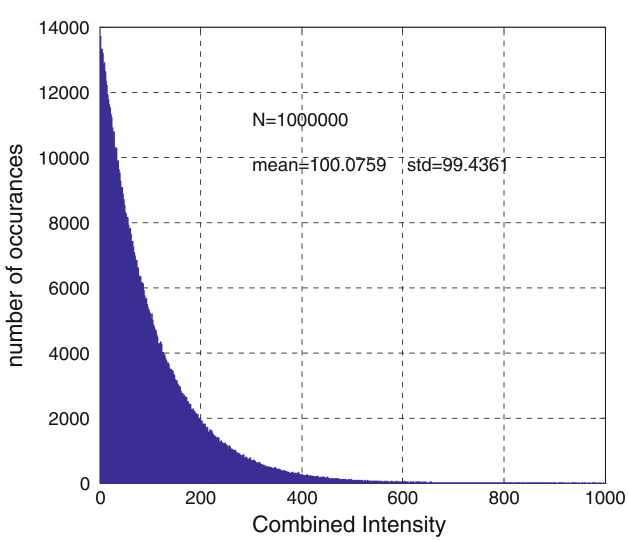

Fig. 1 Histogram of 10^6 calculations of Eq. (1) for the combined intensity of 100 lasers. The mean and the standard deviation are indicated

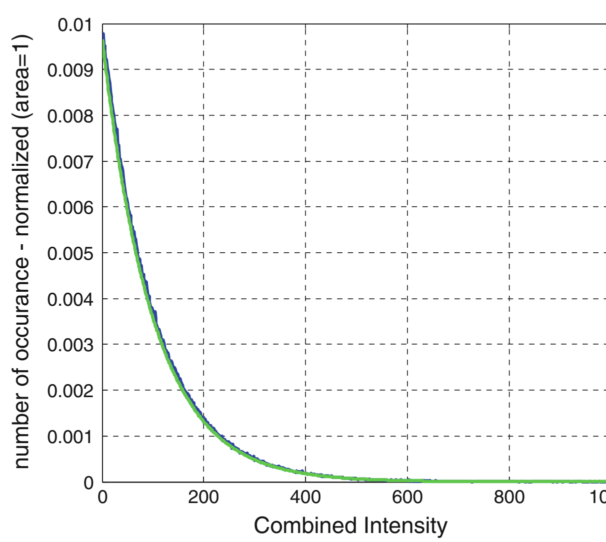

Fig. 2 Comparison of the envelope of the histogram of Fig. 1 (*blue curve*) to the exponential distribution function (*green curve*). Both curves coincide

3 Random polarizations

If random polarizations are included in addition to random phases, the following expression should be evaluated:

$$\mathcal{J} \approx [\mathrm{A}(\hat{\epsilon}_1 e^{i\varphi_1} + \hat{\epsilon}_2 e^{i\varphi_2} + \cdots + \hat{\epsilon}_{100} e^{i\varphi_{100}})]^* [\mathrm{A}(\hat{\epsilon}_1 e^{i\varphi_1} + \hat{\epsilon}_2 e^{i\varphi_2} + \cdots + \hat{\epsilon}_{100} e^{i\varphi_{100}})] \tag{2}$$

Here $\hat{\epsilon}_i$ is the polarization unit vector, randomly oriented in the plane that is perpendicular to the direction of propagation of the laser number "i" radiation. "*" denotes complex conjugate, and the product of the two parts of Eq. (2) is the dot product. The statistical result of repeating 10^6 random calculations is summarized in Figs. 3 and 4. In Fig. 4, it is shown that the envelope of the histogram in Fig. 3 may be approximated by a product of a linear expression of intensity and a Gaussian.

Because of practical considerations, the following equation has been used:

$$N(\mathcal{J}) = a(\mathcal{J} + d)\exp\{-[(\mathcal{J} - b)/c]^2\} \tag{3}$$

The fitting of this expression (the red curve in Fig. 4) to the envelope of the histogram (the blue curve in Fig. 4) is obtained by the least square method with iterations applying right guessing. A general result that determines the parameters of Eq. (3) is obtained:

$b = -n_1/2$, $c = (4/3)n_1$, $d = n_1/5$ where n_1 is the number of lasers, and a is normalized equating the area under the curve $N(\mathcal{J})$ to 1. By this approach, Eq. (3) becomes the probability distribution function that gives the probability to get a total intensity at the target between the values $\mathcal{J}$ *and* $\mathcal{J} + d\mathcal{J}$.

Analyzing these results shows that the mean is approximately the sum of the intensities (100) and the standard deviation is large (approximately equals to the mean). The most probable case is the case with intensity of approximately half the sum of the intensities (50). This leads to the conclusion that the result of a combination of many ($n_1 = 100$) laser beams at a target delivers an intensity at a target that is much less than the intensity delivered by a single equivalent laser (smaller by a factor of n_1).

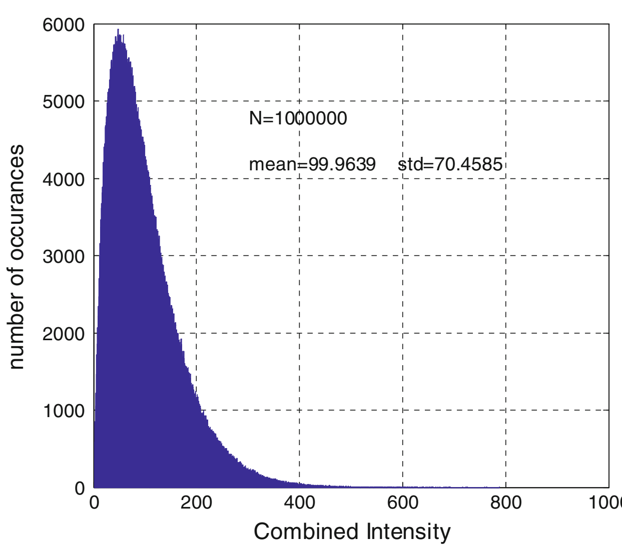

Fig. 3 Histogram of 10^6 calculations of Eq. (2) for 100 lasers. The mean and the standard deviation are indicated

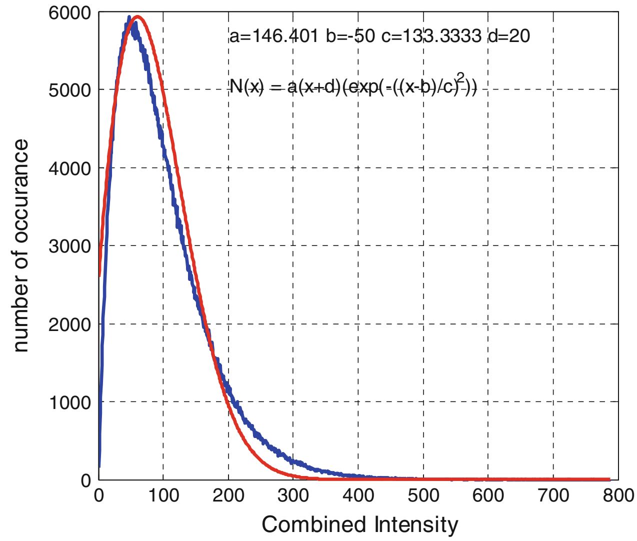

Fig. 4 Fitting the envelope of the histogram that appears in Fig. 3 (*blue curve*) to the distribution calculated using Eq. (3) (*red curve*)

4 Summary and conclusions

In this work, the combination of laser beams at a target has been studied. A distribution function is obtained that is an important part of the probability to achieve a required intensity (or higher) at the target. The distribution function is approximated by a product of a linear expression of the total intensity and a Gaussian. The average intensity appears as approximately equal to the sum of the intensities while the standard deviation is large, and the most probable case is the case with intensity of approximately half the scalar sum of all intensities. Since these disadvantages do not appear in a single laser operation, it is concluded that it is by much preferable as related to the multi-laser system.

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