Limits of coherent addition of lasers: simple estimate

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The coherent combining of single mode lasers using coupled cavities is considered. A simple analytical estimate of the number of lasers that can be efficiently combined in such a way is suggested. In a realistic case, such an estimate agrees with the results of numerical simulations reported recently.

KEYWORDS: coherent beam addition, laser addition, coherent beam combining, power scaling

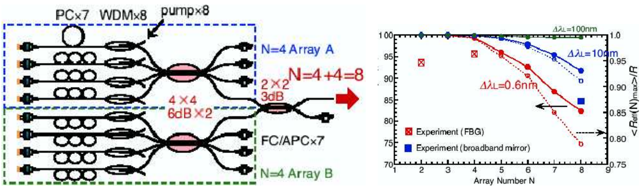

Fig.1. Scheme of combining of lases form[5)] and the resulting efficiency as function of number of lasers combined.

1. Introduction

The interest to the coherent beam combining[1–3)] has revived in the context of powerful fiber lasers, see[4–6)] and references therein. In Fig.1, we show the update of Fig.2 from.[5)] The common cavity with single-mode coupling provides both spectral refinement of the generated light and the scaling of the output power. Fig.1a shows the scheme with binary multiplexing of fibers into a single-mode coupler; however, the sequence of combining may be different; the principal limitations of such a scheme of coupling does not depend on the order of coupling. Lasers could be coupled one by one as well.

The number of lasers that can be coherently combined in such a way is limited, one example of the drop of the efficiency with number of lasers combined in Fig.1b. This figure is corrected version of Fig.5 from Ref.[5)] Each additional laser reduces the variety of the spectral lines at which the system can efficiently oscillate. When the generation becomes single-mode, the ability to add lasers coherently is exhausted, The following increase of number of lasers will cost the loss of the efficiency. The increase of broadband $\delta\lambda/\lambda = k/K$ an order of magnitude allows the addition of few lasers more. Estimates from ref.[4,6,7)] give similar predictions.

The most important parameter the number of lasers which can be combined at a given combining efficiency. The papers[4–7)] show similar estimate of this number for various lasers and couplers, various reflectivities and various regimes of saturation of active elements. Roughly, up to 10 typical fiber lasers can be combined, and it is interesting to understand the origin of this "magic number". Such stability of the maximal number of lasers which can be efficiently combined indicates that some of parameters of the problem have no need to be taken into account in order to get a simple estimate.

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In this paper we suggest a simplified description of the phenomenon of the coherent addition of lasers by the single-mode coupling. The qualitative assumptions leads to the simple estimate of the number of lasers which can be combined in such a way at a given efficiency.

2. Basic assumptions

Assume a certain number N of similar lasers are coupled to the same single-mode feedback. Formally, the coupler of N inputs must also have N outputs; we assume the the losses at other outputs are so high that we have no need to take them into account. The detailed description of the system may include the model for individual lasers (gain versus intensity), and the feedback coefficient. Such a model would return quantitative description of a particular laser system.

The question is, how specific is the efficiency as a function of the number of combined lasers? For example, for the Nd doped finer lasers of several meters long, saturation of coherent addition begins at $N \approx 8$, can we expect the same for combining of some lasers operating at some other frequency? Comparing the results,[4–7)] we could expect this.

Assume that each of the N lasers mentioned above has its own optical round-trip length L_n, and all $L_n \approx L$. Let each laser can operates around wavenumber K, with bandwidth k. Each individual laser is supposed to be already optimized. Assume that each additional nth laser choses the frequency of operation among the frequencies of operation of the system of $n-1$ lasers. However, each additional lasers may slightly shift the frequency of operation of the system in order to realize a mode with minimal losses. Therefore, this assumption may underestimate the efficiency of operation of a combination of 2 or 3 lasers. At larger number of lasers, we may expect such an assumption to lead to a correct estimate.

The assumptions above ignore all the effects of losses in partial lasers, as well as effects of saturation of gain. This allows to estimate the number of lasers what can be efficiently added in a simple close form.

3. Efficiency of adding

If we have the only one laser ($N = 1$), we can expect the generation at the set of frequencies, and have of order of kL spectral lines at the output.

Now, let us add one additional laser, and somehow discriminate modes with the coupling efficiency less than R. This R can be interpreted as the efficiency of combining;

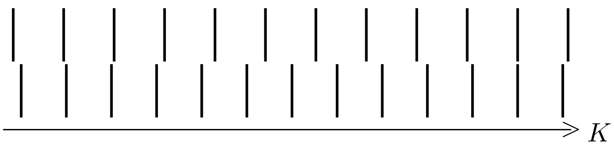

Fig.2. Occasional coincidence of spectral lines of two lasers.

$1-R$ is coefficient of loss; this portion of power goes to other outputs of the coupler and presumably cannot be used for the single-mode operation. This portion of power is lost. Assume that $1-R \ll 1$. The laser still can emit many spectral lines, but now the number of longitudinal modes is limited by the condition of occasional synchronism. In Fig.2 we show two sets of spectral lines of two independent lasers. However, as they are coupled together, they have to oscillate at some frequency which is close enough to some spectral line of each of lasers. At each round-tirp, the partial mode of an added laser should rotate the angle

$$\phi = |K(L_1 - L_2) + 2\pi m| \qquad (1)$$

for some appropriate integer m. At the coupling, the $(1-\cos\phi)$ part of the intensity is lost.

The number of spectral lines which allow the efficient operation can be estimated as follows:

$$n(1) = kL \qquad (2)$$

$$n(2) = \frac{n(1)}{2\pi}\int_{-\pi}^{\pi} \vartheta(\cos(\phi) > R)\, \mathrm{d}\phi = = \frac{kL}{\pi}\arccos(R) \approx \frac{kL}{\pi}\sqrt{2(1-R)} \qquad (3)$$

where ϑ is unit step function.

The coherent addition of lasers reduces the spectral width of generation. The efficiency of addition of a new laser can be estimated as $\cos(\phi)$ where ϕ is relative phase the field of the laser has to rotate at each round-trip, in order to be in-phase with other lasers. The probability of each mode of the system be in-phase with an added laser can be estimated as

$$p_1 = \frac{\sqrt{2(1-R)}}{\pi} \qquad (4)$$

However, the expression depends on R which gives the criterion, what case is called "in phase".

We add $N-1$ lasers, and want all to them to be in phase. The expectation of amount of phased modes can be estimated as $kL\, p_1^{N-1}$. We would like to have at least one mode with high efficiency; this gives an equation

$$kL\, p_1^{N-1} = 1 \qquad (5)$$

Taking the logarithm, we get

$$N-1 = \frac{\log(kL)}{\log\left(\frac{\pi}{\sqrt{2(1-R)}}\right)} = \frac{\log(kL)}{\log\left(\frac{\pi}{\sqrt{2}}\right) + \frac{1}{2}\log\left(\frac{1}{1-R}\right)} \qquad (6)$$

In the typical case, the length L of the lasers is of order of 10m; and the bandwidth k is of order of $10^4\mathrm{cm}^{-1}$. If we require that the efficiency of combining $R > 0.9$, we get the estimate $N-1 \approx \frac{\log(10^7)}{\log(2.23)+0.5\log(10)} \approx 8$. About 9 lasers can be efficiently combined in such a way. An extra laser drops the efficiency of the system. Such an estimate agrees with previous results.[4–7]

The increase of the amount of lasers combined requires exponential grow of the effective length L of the lasers and/or their bandwidth k. We expect, the simplicity of the eq.(6) makes it useful for the design of powerful laser systems.

4. Conclusion and discussion

The assumptions of combining of lasers one by one and adjustment of frequency of each new laser to some of frequencies of the rest of the system leads to the simple estimate (6) of number of lasers that can be efficiently combined. In typical case, about 9 lases can be combined. The increase of the bandwith and/or length of laser orders of magnitude allow to add only few more lasers at the given efficiency.

The additional abilities of coherent combining of lasers appear is we vary the mutual optical lengths of the partial lasers. However, the optimal conditions for generation take place at sporadic moments of time when the lasers happen to be synchronized. Such a system can be used for generation of pulses; in particular, of random pulses. Such a random synchronization allows to add a few additional lasers to a system keeping the high efficiency.

The following increase of the amount of lasers combined requires the artificial adjustment of at least one of resonant frequencies of each partial laser to some common frequency. The detuning should be small enough to cause the phase less than $\sqrt{1-R}$ per round-trip. We expect such a synchronization to be useful for scaling of power of laser systems.

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