Can one passively phase lock 25 fiber lasers?

Moti Fridman\textsuperscript{a}, Micha Nixon, Nir Davidson and Asher A. Friesem

Weizmann Institute of Science, Dept. of Physics of Complex Systems, Rehovot 76100, Israel

\textsuperscript{a}Corresponding author: moti.fridman@weizmann.ac.il

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Phase locking of many fiber lasers has been attracting much attention, mainly because it enables their coherent addition so as to obtain high output brightness beyond the limit of a single fiber laser [1–10]. In order to achieve phase locking, the fiber lasers must have at least one longitudinal mode that is common to all [5]. Unfortunately, since the length of each fiber laser cannot be accurately controlled, the probability for having such common longitudinal modes rapidly decreases as the number of coupled fiber lasers increases. Indeed, a theoretical upper limit of 8 to 12 fiber lasers for efficient phase locking was predicted [1–4]. Experimentally, none of the approaches for passive phase locking or coherent combining of separate fiber lasers have exceeded this theoretical limit (see e.g. [6]).

In this letter we present a new configuration for coupling and phase locking up to 25 fiber lasers, each with a different cavity length. With this configuration we investigated in some detail the phase locking level as a function of the number of fiber lasers and the connectivity between them. We show that the average phase locking level reduced significantly for more than ten fiber lasers, in agreement with the theoretical predictions of [1–4]. However, the instantaneous phase locking level fluctuates rapidly and on some rare occasions it can exceed 90% even for 25 fiber lasers. This is because the cavity lengths of the fiber lasers typically fluctuate [8], mainly due to thermal and acoustic variations, so on an instantaneous basis all lengths can match.

Our experimental configuration for phase locking up to 25 fiber lasers is presented schematically in Fig. 1. It is composed of 25 fiber lasers as shown in the left inset. Each fiber laser was comprised of $1.5m \pm 0.2m$ of Ytterbium doped double clad fiber, a high reflection fiber Bragg grating (FBG) that served as the rear mirror, and a low reflection FBG (5%) that served as the front mirror; the spectral bandwidth of either FBGs was $1nm$ with a central wavelength of $1070nm$. Each laser was pumped through the rear FBG with a $975nm$ stabilized diode laser of $100mW$, and the front end was attached to a collimator. The collimators of all the 25 lasers were accurately aligned to form a $5x5$ square array, as shown in the upper inset, to obtain 25 parallel beams with parallelism better than $0.1mrad$. The separation between adjacent lasers was $3.6nm$.

The coupling between the fiber lasers was achieved by means of four coupling mirrors denoted as $r_1$, $r_2$, $r_3$ and $r_4$ with reflectivity of $40\%$ for $r_1$ and $r_3$ and reflectivity of $100\%$ for $r_2$ and $r_4$. All the coupling mirrors were located close to the focal plane of a focusing lens with $500nm$ focal length. Since there was only enough space for only a pair of mirrors within the Rayleigh range of the focusing lens, we inserted a $50\%$ beam splitter to obtain another focal plane where we placed another pair of mirrors. Finally, we directed about $10\%$ of the light with a partially reflecting mirror (PR), from the collimators array, towards an output coupler (OC), which was placed at a distance equivalent to that of the focal plane of the lens. The OC reflected part of the light from each laser back onto itself with the same delay as the light that is coupled from the other lasers. Such an arrangement ensures that although the coherence length of each laser is shorter than the distance to the coupling mirrors, phase locking can still occur [10]. The near-field intensity distribution at the output coupler is presented at the lower inset of Fig. 1. The intensities of all lasers were about $50mW$ and remained relatively constant.

Now, by controlling the orientation of the coupling mirrors $r_1$, $r_2$, $r_3$ and $r_4$, we could realize variety of connectivities for the fiber lasers array. Each coupling mirror connects pairs of lasers that are symmetric around the self reflecting point of the mirror. Representative connectivities for the array of 25 fiber lasers (denoted as red circles) with three different orientations of the four coupling mirrors are presented in Fig. 2. Figures 2(a), (d) and (g) show the self-reflecting point of each coupling mirror on the array (denoted as blue stars). Figures 2(b), (e) and (h) show the corresponding couplings connections that are imposed by the coupling mirrors. Figures. 2(c), (f) and (i) illustrate more clearly the corresponding coupling connection after we rearranged the lasers locations in the array. As evident, there is great flexibility for the coupling connections. These include the effective 1D connectivity as shown in Fig 2(c), 2D connectivity as shown...
Fig. 1. Experimental configuration for phase locking 25 fiber lasers. BS - Beam splitter, OC - output coupler, PR - partially reflecting mirror.

In Fig 2(i) and an intermediate connectivity as shown in Fig 2(f).

Using the configuration shown in Fig. 1, we measured the phase locking level as a function of time for different number of lasers in the array and for different connectivities. This was done by continuously detecting the far-field intensity distribution of the total output light from the array with a CCD camera and calculating the average fringe visibility along the x and y directions, namely the phase locking level that range from 0% to 100%, over a period of 10 hours to obtain about 300,000 measurements. These measurements were then repeated for different number of lasers in the array and for different connectivities. The results are presented in Figs. 3 - 5. Figure 3 shows 650 representative measurements of the phase locking level as a function of time, for 25 lasers with the 2D connectivity shown in Fig 2(i). As seen, the phase locking level rapidly fluctuates with essentially no correlation between adjacent measurements, as ascertained in the auto correlation plot shown in the inset [8]. A striking feature seen in Fig. 3 is that although the average phase locking level is rather low (30%) there are occasionally high spikes which we denote as the maximal phase locking level.

Figure 4 shows the average phase locking level (red crosses) and the maximal phase locking level (blue stars) as a function of the number of lasers in the array for the 2D connectivity. As predicted, the average phase locking level indeed drops as the number of lasers increases [1–4]. However, the instantaneous maximal phase locking level remains high regardless of the number of lasers in the array. Figure 4 also includes representative far-field intensity distributions of two fiber lasers (inset a), of 25 fiber lasers with instantaneous maximal phase locking level (inset b), and of 25 fiber lasers with average low phase locking level (inset c). These results indicate that as the
number of lasers in the array increases, the probability to find common longitudinal modes rapidly drops as predicted. However, since the length of each fiber laser fluctuates randomly (modulus $\lambda$) due to thermal and acoustic variations, there is a certain probability for instantaneously obtaining a common longitudinal mode for all fiber lasers. We found that the probability for obtaining phase locking levels above 90% drops rapidly. Specifically, the probability is 0.1% for 12 lasers, 0.012% for 16 lasers, 0.004% for 20 lasers and 0.001% for 25 lasers.

We calculated the effective reflectivity as a function of number of lasers in the array [9]. Specifically, we calculated the maximal effective reflectivity within the bandwidth of our FBG as a function of the number of coupled fiber lasers whose lengths were randomly distributed between 2.8$m$ to 3.2$m$. Then we repeated the calculations 1000 times, each time choosing a different random realization of the fiber lasers lengths, and determined the average of the results. These provide a measure of the phase locking level for lasers with many longitudinal modes [5], and are plotted as the solid curve in Fig. 4. The agreement between the experimental and calculated results indicates that the reduction of the average phase locking level is related to the random cavity lengths of the fiber lasers in the array.

We also determined how the average phase locking level is related to the connectivity of the fiber lasers in the array. Specifically, we measured the average phase locking level of an array of 25 fiber lasers as a function of the average number of coupled neighbors to each fiber laser, for different coupling connectivities. The results are presented in Fig. 5. We started with 1D connectivity of the full array, shown at the left inset, in which the average number of coupled neighbors to each fiber laser is only 1.9. Then, we varied the connectivity and increased the average number of coupled neighbors and measured the average phase locking level of the array in each case, up to a 2D connectivity where the average number of coupled neighbors is 3.2. As evident, there is a monotonic increase in the average phase locking level of the array from 21% up to 29%. These results manifest that connectivity influences the phase locking level, consistent with the expected increase of an order parameter with dimensionality for all coupled oscillators [11].

To conclude, we showed that while the average phase locking level drops as the number of lasers in an array increases, there are still rare events with high phase locking levels of over 90%. These rather rare events have no immediate practical use, but are significant as a first conclusive proof for the ability to phase lock a large number of fiber lasers whose cavity lengths are matched. We also showed that the average phase locking level increases when increasing the connectivity, suggesting that by further increasing the connectivity in the array, even higher phase locking efficiencies may be obtained.

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