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Optical processing in the aid of phase locking laser arrays

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Dedicated to Prof Joseph Shamir

Talbot diffraction and Fourier filtering are incorporated into a degenerate laser cavity to obtain efficient phase locking of hundreds of lasers in a controlled manner. The addition of second harmonic generation converts an array of lasers with out-of-phase distribution into one with in-phase distribution, so the output light can be tightly focused. Simulated and experimental results for square laser arrays are presented.

Keywords: Laser arrays; Phase locking; Talbot and Fourier filtering; Nonlinear optics.

1 Introduction

Phase locking of large arrays of lasers, where all lasers have one or more common frequencies and a fixed phase relationship, results in much more output power than that available from a single laser concomitantly with high output beam quality [1-3]. Moreover, phase locked laser arrays can serve as excellent tools to investigate the properties of coupled oscillators in one or two dimensional arrays [4-6], to study the behavior of frustrated array configurations [7], and the properties of complex networks [8-10].

Most common techniques for phase locking an array of lasers involve either Talbot (or fractional Talbot) diffraction or Fourier filtering [11]. When used separately, these techniques suffer from several disadvantages. Specifically, with Talbot diffraction, efficient phase locking yields an output with out-of-phase distribution that cannot be tightly focused, so additional elements are necessary to obtain in-phase locking [12,13]. With spatial Fourier filtering, using a simple aperture or a mask, the output has an in-phase distribution that can be tightly focused [12,14,15]. However, the efficiency is low (especially for small apertures) due to losses of high order diffraction, the alignment sensitivity is relatively high, and there is a likelihood of damage to the Fourier filter due to strong fields near the edges.

Here we present a new approach where the Talbot diffraction and Fourier filtering are combined so as to obtain either in-phase locking or out-of-phase locking of hundreds of lasers in a controlled manner with high efficiency. The Talbot diffraction is chosen to ensure exact degeneracy between the in-phase and the out-of-phase distributions while the Fourier filter removes the degeneracy and selects either out-of-phase distribution or in-phase distribution without strong fields passing near the edges. We also investigated how to convert an array of lasers with out-of-phase distribution to one with in-phase distribution by resorting to second harmonic generation (SHG) [16]. The SHG results in phase doubling [17-19], so all participating laser outputs, whether in-phase or out-of-phase, will be in-phase. The use of SHG is particularly attractive when visible rather than near infra-red wavelengths as well as tight focusing of output light are needed. The combined approach and the conversion method were successfully incorporated into square laser arrays, with good agreement between calculated and experimental results.

2 Arrangements for obtaining an array of coupled phase locked lasers

The arrangement for obtaining an array of coupled phase locked lasers with both Talbot diffraction and Fourier filtering is schematically presented in Fig 1. In our experiments it was comprised of a modified degenerate cavity laser configuration [7,20] that included two lenses in a 4f telescope, a 10 mm wide flash pumped Nd-YAG gain medium, a high reflecting rear mirror at one end and a mask of holes, and a 95%

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reflectivity output coupler at the other end. The 4f telescope assures that any field distribution will be reimaged after a round trip in the cavity. The mask was an array of holes, whose diameters are 200 μm and distance between them 300 μm, with a specific lattice geometry that corresponded to a square laser array with about 200 lasers. Talbot diffractive coupling between adjacent lasers was introduced by displacing the output coupler away from the mask, where the distance between the mask and the output coupler determines the strength and sign of coupling. This distance, namely the Talbot length, was chosen to ensure exact degeneracy between the in-phase and out-of-phase distributions. An intra-cavity Fourier filter aperture was used to remove the degeneracy. The Fourier filter does not phase lock the laser array and there are no strong intensity peaks at the edges of the filter. Using the combining arrangement shown in Fig 1, we performed simulations and experiments on the square laser arrays. The simulations involved a modified Fox-Li model which included gain with saturation.

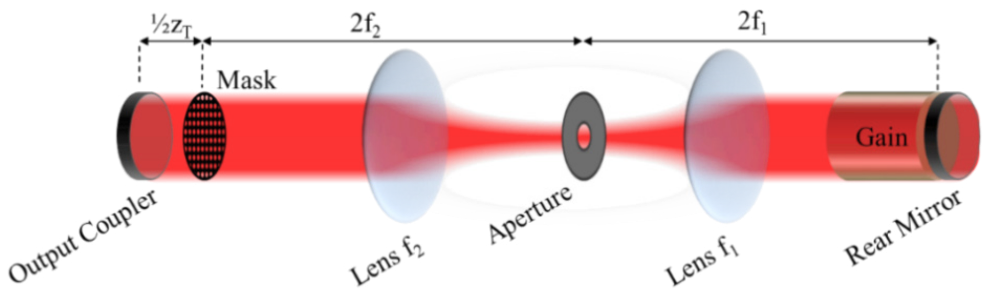

Fig 1. Arrangement for obtaining an array of coupled phase locked lasers with both Talbot diffraction and Fourier filtering.

The arrangement with which we converted an array of lasers with out-of-phase distribution to one with in-phase distribution is schematically shown in Fig 2. It consisted of three main parts. The first part was comprised of a modified degenerate cavity laser configuration as described above but without an intra-cavity aperture and with a mask whose lattice geometry corresponded to a square laser array of about 330 lasers. In order to obtain an array of negatively coupled phase locked lasers (out-of-phase distribution), the distance between the output coupler and the mask was set at a quarter Talbot length ($z_T/4$) [21,22]. The second part included a second telescope which focused the output light from the degenerate cavity laser onto a 5 mm cube KTP type two nonlinear crystal so as to obtain second harmonics. The third part was comprised of lenses, filters and a camera for detecting the near-fields and far-fields of the first and second harmonics.

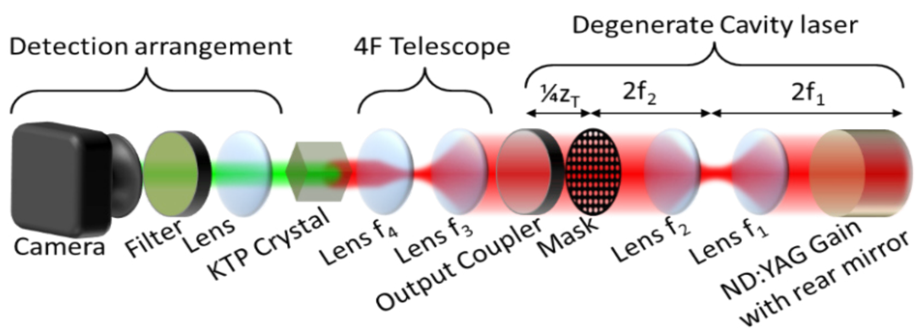

Fig 2. The arrangement for obtaining an array of negatively coupled phase locked lasers, forming first and second harmonics and their detection.

3 Results and discussion

The overall phase distribution in a square laser array is essentially a continuously repeated phases of four adjacent basic lasers. Any coherent superposition between the two in-phase and the two out-of-phase distributions can exist in the cavity as long as the lasers are in saturation and have uniform intensity distribution at the near-field. Representative results for a square laser array of about 200 lasers with one Talbot length (z_T) coupling and combined with different Fourier filters are presented in Fig 3. Figure 3 (a) shows schematic illustrations of the phase distributions of the basic four lasers. Figure 3 (b) shows specific simulated realizations of near-field phase distributions. Figure 3 (c) shows simulated far-field intensity distributions, where the red circles denote the boundaries of the Fourier filters. Figure 3 (d) shows the corresponding experimental far-field intensity distributions.

With a Fourier filter aperture of radius 0.9 order (where 1 order is the distance between adjacent peaks in the far field), the phases of the four adjacent basic lasers have an out-of-phase distribution. With a Fourier filter of a mask of holes with radii 0.5 order and distance between them of 1 order, the phases of the four adjacent basic lasers have an in-phase distribution. Note that for infinite arrays, the efficiency of phase locking with z_T is equivalent to that with $z_T/2$. Also, phase locking with z_T is possible for any phase distributions, while with $z_T/2$ phase locking is possible only for out-of-phase distribution.

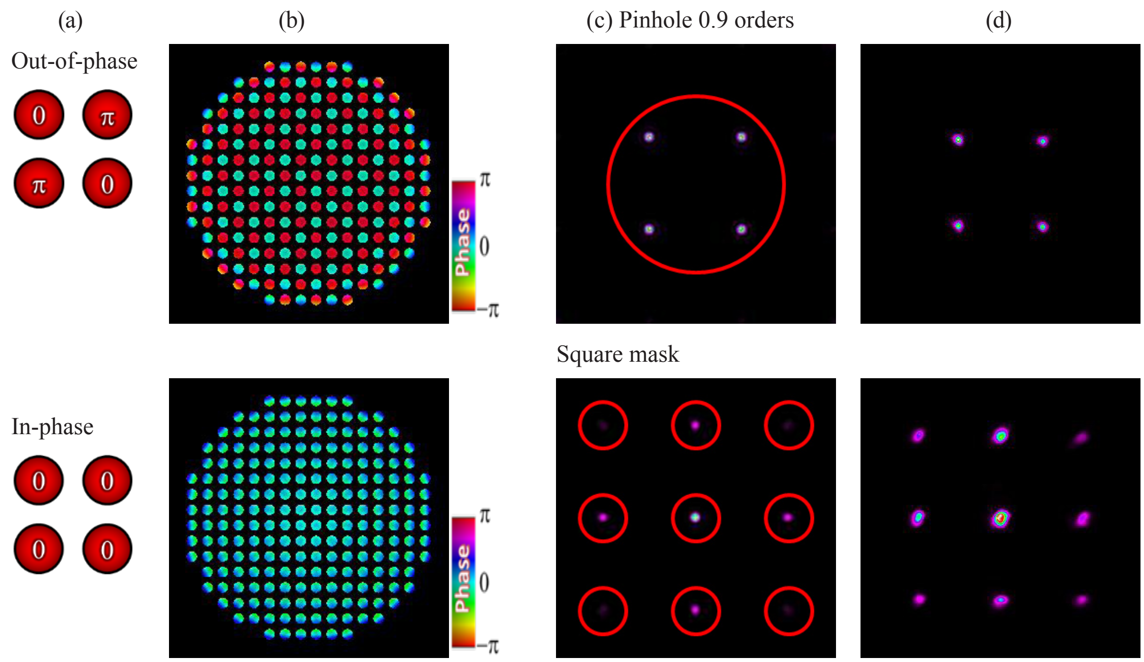

Fig 3. Results for a square laser array of about 200 lasers with one Talbot length (z_T) coupling and combined with different Fourier filters. (a) Illustration of the phase distributions for the four basic lasers. (b) Simulation of specific realizations of near-field phase distributions. (c) Simulated far-field intensity distributions, where the red circles denote the boundaries of the Fourier filters. (d) Experimental far-field intensity distribution.

Representative results of out-of-phase distribution to in-phase distribution for a square laser array of about 330 lasers with half Talbot length ($z_T/2$) are presented in Fig 4. Figure 4 (a) illustrates phase shift doubling in the second harmonics. Figure 4 (b) shows the experimental intensity distribution in the near-field and the far-fields of the first and second harmonics. The darkness in the center of the first harmonic indicates out-of-phase locking (π phase shift between neighboring lasers), and the bright lobe in the center of the second harmonic indicates in-phase locking (2π phase shift).

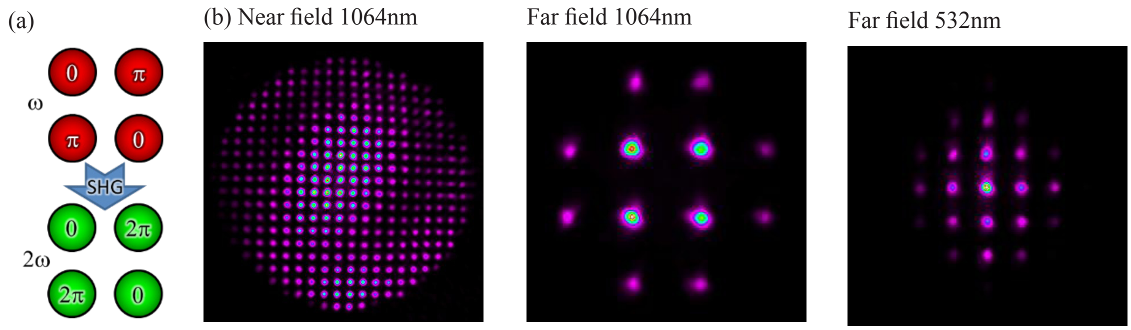

Fig 4. Conversion results of out-of-phase distribution to in-phase distribution for a square laser array of about 330 lasers with half Talbot length $(l/2)z_T$ coupling and second harmonics generation. (a) Schematic illustration of phase shift doubling in the second harmonics, where an out-of-phase locking (π phase shift) in the first harmonic is converted into an in-phase locking (2π phase shift) in the second harmonic. (b) Experimental intensity distributions for the near and far fields of first and second harmonics.

4 Concluding remarks

We have shown both by simulation and experiments that using combined Talbot diffractive coupling and Fourier filtering it is possible to efficiently phase lock laser array of square geometry with different phase distributions. For a laser array of square geometry with one Talbot length coupling, we demonstrated two different phase distributions including in-phase distribution and out-of-phase distribution. We believe that our approach of combining Talbot diffraction with Fourier filtering is suitable for many types of lasers and array geometries, including diode laser arrays and multicore fiber arrays. In addition, we have shown that second harmonics can be exploited to convert an array of out-of-phase locked lasers into in-phase locked lasers so as to allow for tight focusing. Our experimental arrangement is relatively simple and can easily be adapted to various arrays of negatively coupled lasers.

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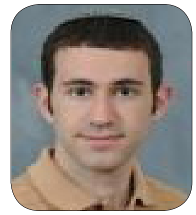

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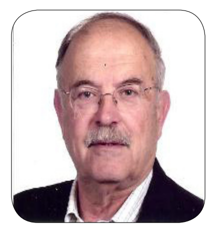

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