Available online at www.sciencedirect.com

SCIENCE DIRECT®

Optics Communications 263 (2006) 60–64

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Passive intra-cavity phase locking of laser channels

Liran Shimshi *, Amiel A. Ishaaya, Vardit Ekhouse, Nir Davidson, Asher A. Friesem

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

Received 19 September 2005; received in revised form 4 January 2006; accepted 4 January 2006

Abstract

A new approach for stable intra-cavity phase locking of several laser channels is presented. In this approach, special interferometric couplers are incorporated inside a laser resonator to obtain efficient self phase-locking between separate laser channels. We analyze the approach and demonstrate experimentally phase-locking of two and of four laser channels, that are derived from Nd:YAG lasers, with 92% and 83% power efficiencies respectively.

Keyword: Phase locking

1. Introduction

Laser systems emitting high output power concomitantly with good beam quality are needed for variety of applications. Such systems can be obtained by properly phase locking several low power lasers so as to enable their coherent addition. This approach allows for high combined output power while maintaining the good beam of a single low power laser. Many approaches for phase locking have been proposed and investigated. These include evanescent wave coupling of laser beams from the separate laser channels [1,2], exploiting Talbot or Fourier transform resonators [3], active feedback control [4], the incorporation of fiber couplers [5,6] and introducing diffractive or phase elements into the combined laser resonator cavity [7,8].

Several of these approaches were found to be rather impractical, and posed difficulties in achieving optimal phase locking with high efficiency. For example, sequential phase locking with fiber couplers is relatively cumbersome, and is difficult to upscale. The complexity of active feedback control may limit the number of laser channels that can be phase locked. Evanescent wave coupling techniques may be further up-scaled but are difficult to incorporate into both high-gain and low-gain lasers, and the scalability to large numbers of laser channels is questionable. In general, most phase locking techniques have excessive losses and require very accurate relative alignment between the individual laser channels in order to ensure efficient and stable phase locking.

In this paper, we present a new phase locking approach in which one or more interferometric couplers are inserted into a multi-channel laser resonator. The interferometric couplers efficiently couple light in a coherent manner from one laser channel to others and vice-versa, so that phase locking between all channels is achieved. Each coupler is formed on a single substrate, so the needed alignment accuracies and robustness is readily achieved. The use of similar plane parallel interferometric couplers in a common resonator ensures that the optical path difference between coupled channels is identical, hence all channels will operate with the same longitudinal modes. Moreover, the level of coupling can be controlled by varying the transmittances of the different dielectric layers that are deposited on the substrate. The ability to control the coupling strength between the laser channels enables optimal phase locking of both high gain and low gain lasers, and the number of laser channels that could be phase locked is relatively large.

* Corresponding author. Tel.: +972 8 934 2695/2051; fax: +972 8 934 4109.

E-mail address: liran.shimshi@weizmann.ac.il (L. Shimshi).

0030-4018/$ - see front matter
doi:10.1016/j.optcom.2006.01.002

2. Principle of operation

The basic configuration of our approach is schematically illustrated in Fig. 1. As shown, a single interferometric coupler is inserted into the cavity of n independent and separate laser beams. The coupler is formed by coating discrete regions of the left (L) and right (R) surfaces of a parallel plate substrate with dielectric layers of different transmittivities $T_1^L, \ldots, T_n^L$ and $T_1^R, \ldots, T_n^R$.

The principle of operation is based upon proper coupling between the laser beams, i.e., complete destructive interference and consequently low losses in the direction of the loss channels. For example, consider a configuration for phase locking two laser beams with a simple two-channel interferometric coupler, with $n = 2$, $T_1^L = T_2^R = 100\%$, and T_1^R and T_2^L coated with partially reflecting layers. As shown in Fig. 1, beam 1 enters the interferometric coupler, and is partially reflected from the back surface at the T_1^R beam splitter layer and intercepts beam 2 at the T_2^L beam splitter layer. The reflected part of beam 1 interferes constructively with the transmitted part of beam 2, while the remaining parts of the two beams interfere destructively towards the direction of loss channel L_1. The combined beam, composed mostly of transmitted beam 2, along with reflected beam 1, emerges from the output interface of the interferometric coupler. The principle is identical for beams entering the interferometric coupler from the other side, for hen entering the coupler from the left each channel receives light from channels above and transfers light to channels below, while entering the coupler from the right the opposite occurs, light is received from channels below and transferred to channels above. With two interferometric couplers, oriented orthogonally with respect to each other, two-dimensional array of four laser channels can be phase locked. This procedure can be extended to the larger number of channels, shown in Fig. 1, and can be further extended to a two-dimensional configuration, by resorting to a two-dimensional array of lasers and including two orthogonally oriented interferometric couplers.

Prior to the insertion of the interferometric coupler, the individual beams are incoherent with each other, with no definite phase relation between them. After insertion of the coupler into the cavity, the combined laser system would normally have inherent losses that result from the reflectivities $R = 1 - T$ of each coated region, yielding a round-trip loss of $1 - (T_i^L T_i^R)^2$ for the beam i. However, the inherent property of a laser resonator to operate at minimal losses, induces a self phase-locking mechanism, whereby the losses are minimized by destructive interference of light at each partially reflecting surface of the interferometric coupler. For identical beams, total destructive interference essentially occurs, i.e., no losses, when all T_i are the same, except for T_1^L and T_n^R whose transmittances are 100% (AR coating).

The effect of the interferometric coupler can be analytically represented by the one way transfer matrix M, written as

$$M = \begin{pmatrix} \sqrt{T_1^L T_1^R} & 0 & \ldots & 0 \\ \sqrt{T_1^L(1-T_1^R)(1-T_2^L)T_2^R} & \sqrt{T_2^L T_2^R} & \ldots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ M_{n-1}^1 & M_{n-1}^2 & \ldots & 0 \\ M_{n-1}^1\left(\frac{(1-T_{n-1}^R)(1-T_n^L)T_n^R}{T_{n-1}^R}\right)^{\frac{1}{2}} & M_{n-1}^2\left(\frac{(1-T_{n-1}^R)(1-T_n^L)T_n^R}{T_{n-1}^R}\right)^{\frac{1}{2}} & \ldots & \sqrt{T_n^L T_n^R} \end{pmatrix}, \quad (1)$$

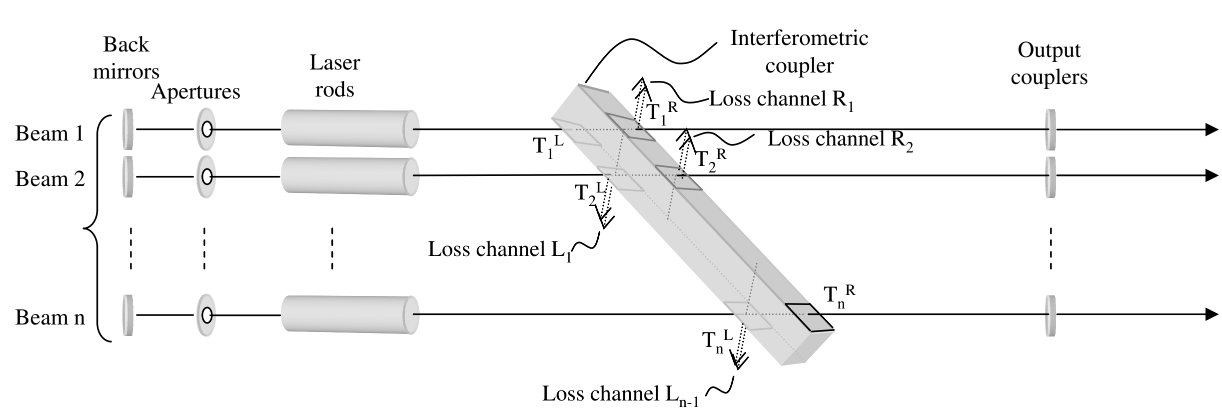

Fig. 1. Configuration for intra-cavity phase locking of several laser channels with a single interferometric coupler.

where i denotes a region located in the path of beam i, the parameter T_i^L the transmittance of region i on the left surface of the coupler, T_i^R the right surface of the coupler, and n the number of the lasers that are coupled. Note that the matrix M is written in a recursive way, for example $M_n^1 = M_{n-1}^1 \left(\frac{(1-T_{n-1}^R)(1-T_n^L)T_n^R}{T_{n-1}^R}\right)^{\frac{1}{2}}$ is actually composed of a multiplication of n terms.

Some interesting features can be deduced by diagonalizing the round trip matrix, obtained by multiplying the two appropriate one way matrices, and examining the global Eigenmodes of the resonator. By diagonalizing the round trip matrix for different values of coupling, i.e., different values of T_i, we found that the losses of the combined laser system can indeed be essentially eliminated when (1) all T_is are identical except for T_1^L and T_n^R whose transmittances are 100%, and (2) all lasers have the same intensities. These findings suggest to the existence of a phase-locked global Eigenmode with low losses and for inherent phase locking to occur. Moreover, a similar procedure can be exploited to design the coatings for more complex interferometric couplers, taking into account different intensities for each element and deviation of reflectivities from the desired values.

3. Experimental procedures and results

In order to verify the simulated results and demonstrate phase locking with the interferometric couplers, we performed experimental investigations with an available pulsed Nd:YAG laser, whose gain medium rod diameters were sufficiently large to support several independent and separate Gaussian laser distributions. The experimental configurations are shown schematically in Fig. 2. Initially, we performed experiments to demonstrate intra-cavity phase-locking of two Gaussian distributions. This experimental configuration is shown in Fig. 2(a). The resonator, with an overall length of 70 cm, included: (1) a flat back mirror; (2) a flat output coupler with reflectivity of 40%; (3) a dual flashlamp pumped Nd:YAG rod, of length 114 mm and diameter 9.55 mm, placed 16 cm from the back mirror, served as the gain medium; it had a thermal lensing of focal distance 20 m at 1 Hz pulse repetition rate; (4) two apertures, 2.4 mm apart, located 27.5 cm from the back mirror. The diameter of each aperture was 1.4 mm in order to select the TEM_{00} mode; (5) a thin film polarizing plate, located 51 cm from the back mirror and near the output coupler, ensures that the laser operates at a single linear polarization; (6) an interferometric coupler, located 55.5 cm from the back mirror for phase locking between the two channel distribution.

The interferometric coupler was formed of a 3 mm thick high precision plane parallel substrate (parallelism <0.5 arcsec) whose front and back surfaces were half coated with dielectric layers of 80% transmittivity, as illustrated in Fig. 2(a). The transfer matrix parameters for this interferometric coupler were $n = 2$, $T_1^L = 1$, $T_2^L = 0.8, T_1^R = 0.8$ and $T_2^R = 1$. Similar elements, with 50% transmittivity were used for coherent addition of lasers [9]. The interferometric coupler was tilted by 55°, so that the reflected light from the back surface of one beam, will be displaced by exactly 2.4 mm when it reaches the front surface, and thereby coincide with the other incident beam. Accordingly 20% of the light reflected from one laser channel is coupled to the other. If there is no phase locking between the two laser channel beam distributions, then each will suffer 36% loss in a double pass. But, with phase locking, the losses for both channels will be negligible. The optical path length of the beams must be an integer number of half the laser wavelength, so as to ensure proper phase locking between all the laser beams. For the configuration of Fig. 2(a) this length is $\delta L = 2nd\left(1 - \left(\frac{\sin\theta}{n}\right)^2\right) = 7.18$ mm, indicating that

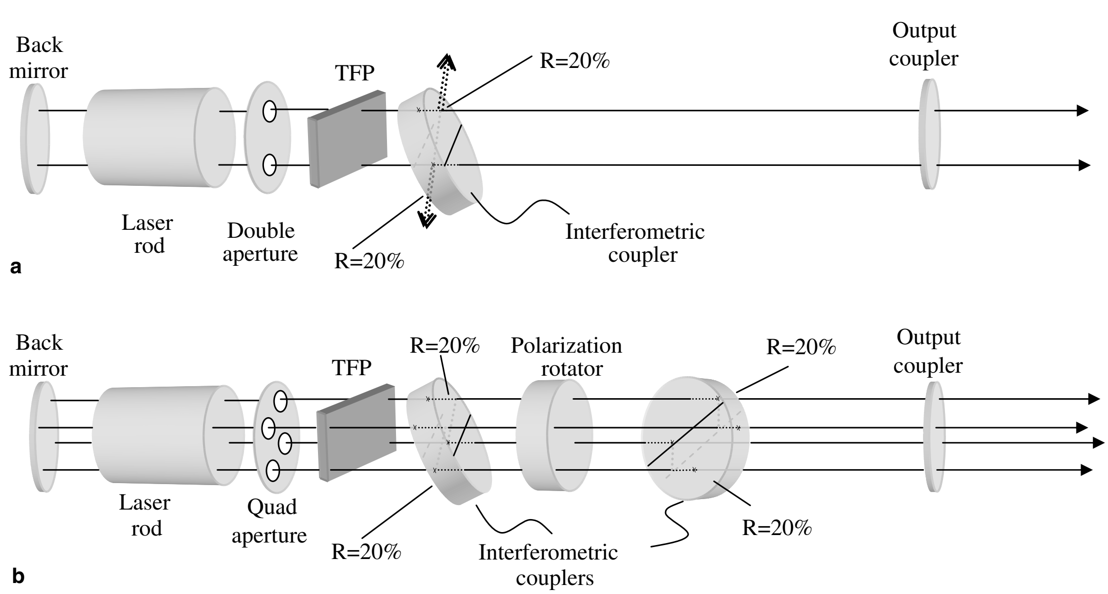

Fig. 2. Experimental configurations for phase-locking the distributions of several laser channels: (a) for two channels; (b) for four channels.

phase locking is possible for special bands separated by $\frac{c}{2\delta L} = 20.9$ GHz. Since this separation is considerably smaller than the 120 GHz natural bandwidth of our gain medium, there is always a wavelength within the gain bandwidth for which phase locking is possible. Moreover, even if the number of channels to be phase locked is increased, the use of a single plane parallel plate interferometric coupler ensures that the optical path length difference between all the channels is always an integer number of the same δL, and hence the existence of common longitudinal modes for all the channels. Experimental spectral analysis we recently conducted on a similar configuration confirms this fact [10].

Next, we performed experiments to demonstrate intra-cavity phase locking of four Gaussian distributions. This experimental configuration is shown in Fig. 2(b), where a second interferometric coupler was incorporated. The resonator used was similar to the the prior (Fig. 2(a)). Instead of the two apertures, we used four apertures allocated in a square pattern, 2.4 mm apart. The diameter of each aperture was again 1.6 mm. The second interferometric coupler, oriented at the same angle in the orthogonal plane to that of the first coupler, was inserted at a distance of 59 cm from the back mirror. To ensure correct polarization suitable for the dielectric coatings of the couplers, a polarization rotator was placed between the two interferometric couplers, 57 cm from the back mirror.

We used two methods to verify that phase locking indeed occurs. First, we compared the output intensity distribution and output energy from each laser, before and after insertion of the interferometric coupler. When they are essentially the same, then efficient phase coupling is indicated. Second, we detected the combined far field intensity distribution. When it contains an interference pattern, corresponding to the number, location and phase of the individual laser outputs, then phase coupling is verified. The near field intensity distribution for the configuration was detected with a CCD camera placed close to the laser output, and the far field intensity distribution with another CCD camera placed at the focal plane of a collecting lens. The pulse energies of the independent and phase-locked channels were measured with a power-meter.

Representative experimental intensity distributions with and without phase-locking of two separate independent laser beams of Gaussian distributions are shown in Fig. 3. Fig. 3(a) shows the near field intensity distributions of the two independent beams without phase-locking, and Fig. 3(b) the corresponding far field intensity distribution. Since there is no phase relation between the two channels, the far field intensity is just the incoherent sum of two Gaussian distributions, as expected. Fig. 3(c) shows the far field intensity distribution of the two phase locked beams with the intra-cavity interferometric coupler; it was very stable and robust. We attribute this stability to the use of single-substrate interferometric coupler, and common mirrors to both channels. As evident, there is clearly an interference pattern, which indicates that the two beams distributions are now phase-locked. The efficiency in phase locking the two beams distributions, defined as the output energy with phase-locking, 10.5 mJ, over the output energy without phase-locking, 11.4 mJ, was 92%.

The "missing" energy of 1 mJ was found to emerge from the two "loss channels" of the interferometric coupler (see Fig. 2a dashed arrows), indicating that the loss of efficiency is mainly due to imperfect destructive interference into the loss channels. Such imperfect interference can result from either intensity imbalance, imperfect spatial overlap or imperfect parallelism between the two beams.

We also performed the experiment with an interferometric coupler with 90% transmittivity. Although we could obtain phase locking with this element, it was less stable than with 80% transmissivity, probably due to the lower coupling between the channels.

Representative experimental and calculated intensity distributions with and without phase-locking of four separate independent laser beams of Gaussian distributions are shown in Fig. 4. Fig. 4(a) shows the near field intensity distributions of the four independent beams without phase-locking. Fig. 4(b) shows the far field intensity distribution of the four phase locked beams with the intra-cavity interferometric couplers; again, it was found to be very stable and robust. As evident, there is clearly an interference pattern, which indicates that the two beams distributions are

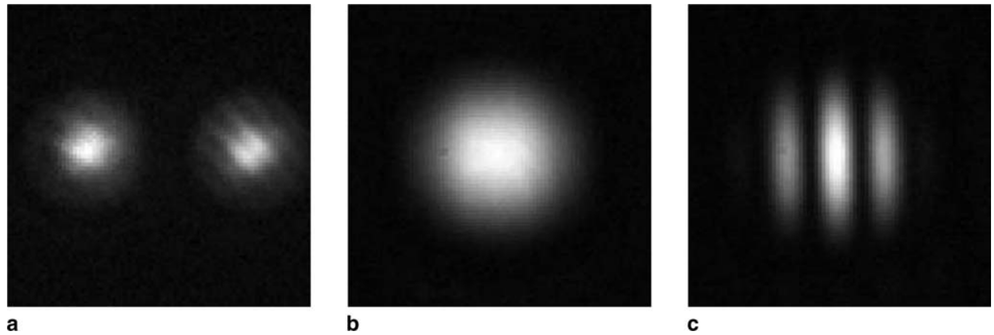

Fig. 3. Experimental intensity distributions with and without phase-locking of two separate independent laser channels of Gaussian distributions: (a) near field output intensity distribution of the independent channels; (b) far field output intensity distribution of the independent channels; (c) far field output intensity distribution of the phase locked channels.

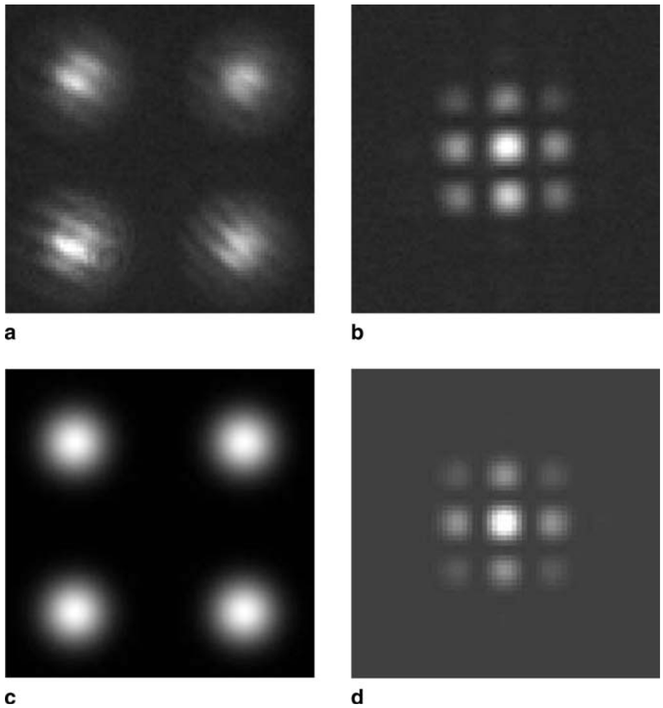

Fig. 4. Experimental and calculated intensity distributions of four separate, independent, and phase-locked channels with Gaussian distributions: (a) experimental near field output intensity distribution of the independent channels; (b) experimental far field intensity distribution of the phase locked channels; (c) calculated near field intensity distribution of the independent channels; (d) calculated far field intensity distribution of the phase locked channels.

now phase-locked. Fig. 4(c) shows the calculated near field intensity distributions of the four independent beams without phase-locking. Fig. 4(d) shows the calculated far field intensity distribution of the four phase locked beams. The calculations were performed in accordance with our model. As evident there is good agreement between the experimental and calculated results. The efficiency in phase locking the four beams distributions, defined as the output energy with phase-locking, 19.2 mJ, over the output energy without phase-locking, 23.0 mJ, was 83%.

4. Concluding remarks

To conclude, we showed how several independent laser channels, can be stably and robustly phase locked with special passive interferometric couplers. The strength of the coupling between channels can be controlled by varying the transmittivity of the interferometric couplers, which can be readily optimized for any laser system. We experimentally verified that two laser channels with with Gaussian distributions, in a Nd:YAG laser resonator, can be phase-locked with 92% efficiency, and with four laser beams with 83% efficiency. More precise fabrication of the interferometric couplers should enable higher efficiencies. We believe that our approach can be up-scaled to phase-lock a higher number of laser beams with either additional two-channel interferometric couplers or with a single interferometric coupler that can simultaneously phase lock many laser beams.

References

[1] T.S. Rutherford, R.L. Byer, in: Proceedings of the 15th International Conference on Lasers and Electooptics, Munich, Germany, 2001.
[2] S. Menard, M. Vampouille, A. Desfarges-Berthelemot, V. Kermene, B. Colombeau, C. Froehly, Opt. Commun. 160 (1999) 344.
[3] A. Desfarges, V. Kermene, B. Colombeau, C. Froehly, M. Vampouille, Opt. Commun. 127 (1996) 372.
[4] S.J. Augst, T.Y. Fan, A. Sanchez, Opt. Lett. 29 (2004) 474.
[5] D. Sabourdy, V. Kermene, A. Desfarges-Berthelemot, L. Lefort, A. Barthelemy, P. Even, D. Pureur, Opt. Express 11 (2003) 87.
[6] A. Shirakawa, K. Matsuo, K. Ueda, CThGG2, in: Proceedings of the Conference on Lasers and Electrooptics (CLEO), San Francisco, CA, USA, 2004.
[7] J. Morel, A. Woodtli, R. Dandliker, Opt. Lett. 18 (1993) 1520.
[8] Y.A. Rubinov, Appl. Opt. 34 (1995) 4235.
[9] A.A. Ishaaya, N. Davidson, L. Shimshi, A.A. Friesem, Appl. Phys. Lett. 85 (2004) 2187.
[10] A.A. Ishaaya, V. Eckhouse, N. Davidson, L. Shimshi, A.A. Friesem, Opt. Express 13 (2005) 2722.