Available online at www.sciencedirect.com

SCIENCE DIRECT®

C. R. Physique 7 (2006) 244–253

COMPTES RENDUS

PHYSIQUE

http://france.elsevier.com/direct/COMREN/

High power fiber lasers and amplifiers/Lasers et amplificateurs à fibre de puissance

Coherent combining of fibre lasers

Agnès Desfarges-Berthelemot *, Vincent Kermène, David Sabourdy, Johan Boullet, Philippe Roy, Jerôme Lhermite, Alain Barthélémy

XLIM, UMR CNRS 6172, 123, avenue Albert Thomas, 87060 Limoges cedex, France

Abstract

Recent development of fibre lasers makes them good candidates to supplant bulk lasers especially for high power applications. A solution for power scaling consists in combining several standard fibre lasers emitting moderate power. Coherent combining techniques can be classified in two broad classes: aperture-filling methods and collinear interferometric summation methods. For the first, the phase-locking of the different emitters leads to a power combining only in the far field, whereas for the second, the power combining is obtained in both near field and far field. ***To cite this article: A. Desfarges-Berthelemot et al., C. R. Physique 7 (2006).***

Résumé

Combinaison cohérente de lasers à fibres. Le développement récent des lasers à fibres les rend attractifs pour supplanter les lasers massifs notamment dans le domaine des hautes puissances. Une solution pour la montée en puissance consiste à combiner de manière cohérente plusieurs lasers fibrés de puissance modérée, déjà optimisés et utilisant une technologie éprouvée. Les techniques de combinaison cohérente se divisent en deux grandes catégories : celles exploitant la notion de densification de pupilles pour lesquelles la combinaison se produit en champ lointain et celles utilisant un résonateur multiaxes construit autour d'un interféromètre. Dans ce cas, l'émission est unimodale. ***Pour citer cet article : A. Desfarges-Berthelemot et al., C. R. Physique 7 (2006).***

Keywords: Coherent combining; Fibre lasers

Mots-clés : Combinaison cohérente ; Laser à fibre

Version française abrégée

Grâce à leur compacité, leur haute efficacité de conversion opto/optique et la bonne qualité spatiale des faisceaux émis, les lasers à fibres sont des sources très attractives pour de nombreuses applications industrielles et scientifiques. Cependant, l'émission du mode fondamental gaussien limite le diamètre du cœur des fibres lasers à quelques micromètres, entraînant un fort confinement spatial de l'onde dans le guide. La principale conséquence lors de la montée en

---

* Corresponding author.
E-mail address: adesfar@ircom.unilim.fr (A. Desfarges-Berthelemot).

1631-0705/$ – see front matter © 2006 Académie des sciences. Published by Elsevier SAS. All rights reserved.
doi:10.1016/j.crhy.2006.01.019

puissance de ces sources, est l'apparition d'effets non linéaires parasites qui peuvent dégrader sensiblement la qualité spectrale du faisceau émis ainsi que le rendement de conversion opto/optique du laser.

Les fibres à large section modale [1–3] (LMA : Large Mode Area) ont été développées ces dernières années pour augmenter le seuil d'apparition des effets non-linéaires ainsi que la puissance de saturation. Une alternative consiste à réaliser la combinaison cohérente de l'émission de plusieurs lasers de puissance modérée. Alors que pour les diodes lasers [4,5] ou les lasers tout solide [6,7] des systèmes de combinaison ont été étudiés depuis de nombreuses années, les lasers à fibres n'en bénéficient que depuis peu. Dans cet article, les méthodes de combinaison ont été répertoriées selon deux grandes catégories : soit le co-phasage des différents émetteurs conduit à une combinaison de puissance seulement en champ lointain, soit dans les deux espaces de Fourier.

Dans le premier cas de figure, différentes méthodes ont été expérimentées. L'une d'entre elles est basée sur le contrôle de façon active, par rétroaction, du déphasage relatif entre les amplificateurs à combiner. La configuration typique consiste en un oscillateur maître dont le rayonnement est équi-réparti et amplifié en parallèle dans N fibres actives distinctes. La figure de diffraction résultante à l'infini dépend de l'arrangement transversal des extrémités des N fibres et des phases relatives entre les faisceaux issus de ces fibres. Une analyse de front d'onde associée à une boucle de rétroaction permet de contrôler ces déphasages. Avec cette technique, la combinaison cohérente de sept fibres amplificatrices dopées aux ions néodyme a été expérimentée pour aboutir à une puissance totale de 1,4 Watt dans le lobe principal du champ lointain [11]. D'autres méthodes, basées sur l'utilisation d'une unique cavité laser à bras multiples, pour lesquelles les différents faisceaux sont combinés en champ lointain ont été étudiées. Ce type de source laser comporte N miroirs de fond de cavité et un miroir de sortie commun. Le verrouillage en phase des rayonnements issus des différentes fibres actives unimodales est imposé par un élément d'optique diffractive. Les phases relatives et le spectre de fréquences temporelles sont automatiquement optimisés de façon à minimiser les pertes intracavité et obtenir le maximum de la puissance totale sur l'ordre zéro de diffraction du composant recombineur. Ce type de configuration a permis d'obtenir 70% de la puissance totale émise par trois fibres dopées aux ions néodyme dans l'ordre zéro de diffraction du composant d'optique diffractive utilisé [12].

Ces techniques qui combinent les différents faisceaux élémentaires uniquement en champ lointain ont l'avantage d'être compatibles avec de forts niveaux de puissance. L'amplification est réalisée dans plusieurs fibres actives différentes et la combinaison est obtenue hors de ces fibres et hors cavité. Cependant, ces configurations à sorties multiples engendrent une figure de diffraction à l'infini dont les lobes secondaires inutiles peuvent porter une large part de la puissance totale.

Pour palier ce problème, plusieurs groupes [13–21] ont développé une méthode de combinaison par interférométrie vers un faisceau unique correspondant au mode fondamental gaussien. Cette méthode est basée à la fois sur les propriétés d'auto-organisation d'un laser, sur sa propension à émettre sur les modes longitudinaux de moindres pertes, et sur une architecture laser de type interféromètre. La configuration la plus simple comporte deux fibres amplificatrices indépendantes connectées à un coupleur fibré standard 50 : 50 où est réalisée la sommation cohérente des champs. Une des voies de sortie du coupleur est refermée par un miroir de sortie (réseau de Bragg ou réflexion de Fresnel sur la face clivée droite de la fibre) alors que l'autre voie du coupleur est clivée en angle pour éviter toute rétroaction parasite dans la cavité. Le laser oscille spontanément sur les pics de gain correspondant aux interférences constructives des champs sur la voie commune du résonateur (voie du coupleur où se trouve le miroir de sortie du laser à 2 bras). Le déphasage entre les deux bras du résonateur laser liés aux perturbations environnementales est compensé par un auto-ajustement des raies lasers qui glissent dans la bande spectrale d'émission. Les premiers résultats ont été obtenus avec des lasers en configuration Michelson puis Mach–Zehnder pour lesquelles une efficacité de combinaison de 98% a été atteinte [13]. Depuis, jusqu'à huit lasers tout fibrés ont été combinés avec une efficacité minimale de 85% pour une puissance totale de 2,65 Watts sur le mode fondamental gaussien [14].

Le principal avantage de ce type de combinaison par interférométrie est sa capacité à combiner la puissance de plusieurs lasers fibrés avec une très haute efficacité vers un faisceau de très bonne qualité spatiale en utilisant uniquement des composants standards. Cependant, comme la puissance totale est finalement réunie au bout d'une fibre monomode unique, la montée en puissance peut être problématique en terme de tenue au flux. L'utilisation de composants de couplage massifs peut s'avérer nécessaire dans ce cas là.

Ces dernières années une nouvelle génération de fibres à coeurs multiples a été conçue. Ce type de structure multicoeur est attractif dans le cas des fibres à double gaine afin d'améliorer l'absorption du faisceau de pompage grâce au bon recouvrement entre celui-ci et les cœurs dopés. D'autre part, la répartition de la puissance du faisceau laser sur l'ensemble des cœurs permet de diminuer de façon significative les effets non-linéaires dans la fibre composite.

Jusqu'à présent, dans ce type de structure, l'émission était répartie sur un supermode de forte divergence comparée au mode fondamental gaussien [22–26].

Récemment, la méthode de combinaison interférométrique a été expérimentée avec succès sur une fibre laser à double cœur dopée aux ions ytterbium [27]. Le verrouillage en phase des rayonnements provenant des deux guides était réalisé dans un coupleur fabriqué par fusion étirage directement dans la fibre à deux cœurs. 96% de la puissance de sortie totale était alors émise sur un seul des deux cœurs.

La combinaison cohérente de lasers à fibre est un domaine de recherche important pour ces prochaines années. Obtenir une émission à la fois de forte brillance et de forte puissance est d'un grand intérêt pour de nombreuses applications. Jusqu'à présent, les méthodes de combinaison ont été démontrées pour des lasers ne délivrant que quelques Watts. Les perspectives et les défis à relever concernent maintenant la montée en puissance de ces procédés de combinaison.

1. Introduction

Thanks to their compactness, good heat dissipation, high conversion efficiency, and high beam quality, fibre lasers are very attractive sources for many applications such as free space communications, range finding, or manufacturing applications. However, to ensure fundamental mode laser emission, the fibre core diameter cannot exceed a few micrometers which limits the available output power. Indeed, the higher the amount of doping ions in the core, the higher the saturation power. Moreover, small core diameter involves tight confinement of the signal wave leading to non linear effects so that the spatial and spectral features of the laser beam may be dramatically altered.

Numerous efforts have been made to design new fibres with large doped core emitting diffraction limited beams. They gave birth to Large Mode Area (LMA) fibre lasers delivering high powers, in the kilowatt range, with good beam quality [1–3]. As laser diode [4,5] or solid-state laser [6,7] combining has been widely studied and has given promising results in terms of beam quality and combining efficiency, analogous methods for fibre lasers have been recently developed. Combining techniques are of interest because they extent the use of an available technology and of an already optimised laser. Two main categories of beam combining techniques exist: one is using wavelength multiplexing, the other one is based on coherent processes. The most obvious difference concerns the output spectra: wavelength combined systems have a multi-wavelength output whereas coherently combined systems can have single-frequency output [8]. The use of one or the other method is highly dependent on the application. In this article, we will only discuss coherent beam combining techniques. They can be split in two broad classes: aperture-filling methods and collinear interferometric summation methods. For the first category, the phase-locking of the different emitters leads to a power combining only in the far field whereas for the second one, the power combining is at the same time obtained in the near field.

2. Aperture-filling methods

2.1. Unfilled apertures

The unfilled aperture designation brings together methods that coherently combine an array of multiple identical laser beams [9–11]. Configuration for which laser beams are spatially separated in the near field and are superimposed in the far field is a common feature of this beam combining technique. The far field intensity distribution depends on the phase relationship between the elementary beams, or sub-apertures, in the near field. Fig. 1 shows a schematic description of the unfilled aperture system. Phase locking of the elementary beams leads to a multi-lobe far field. The goal of these combining methods is to maximize the intensity of the central lobe to enhance the brightness of those composite laser sources. This is what happens when all the elementary fields are in phase. The arrangement of the sub-apertures which are located in a same geometric plane is also important. Sub-apertures must be as close as possible (side by side) to reduce the number of side lobes in the far field otherwise a large part of the total power is spread in these side lobes.

During the last years, several unfilled aperture systems have been developed with fibre laser sources, either by self-adjusting the elementary phases of sub-apertures in a common resonator, or by actively controlling those phases in a Master Oscillator and multiple Power Amplifier configuration.

The general diagram of the latest configuration is depicted on Fig. 2.

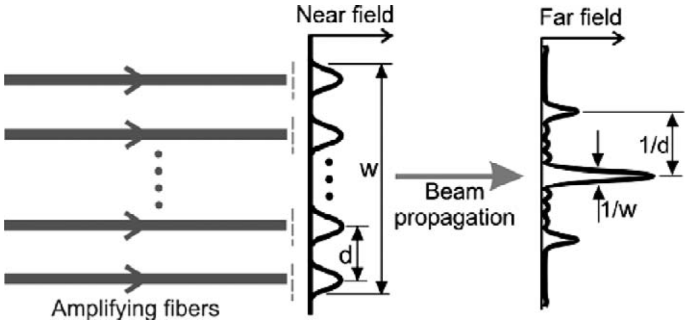

Fig. 1. Unfilled aperture systems: typical near field and far field.

Fig. 1. Dispositifs de combinaison à densification de pupille : allure des champs proche et lointain.

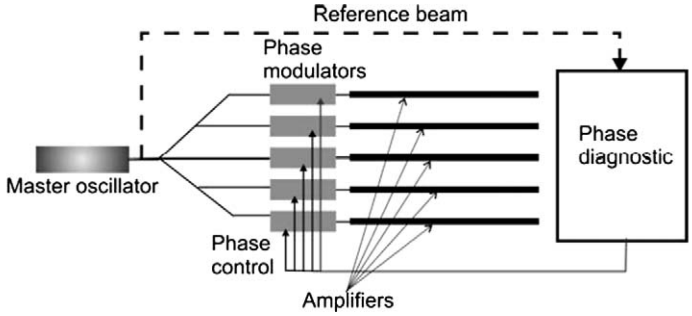

Fig. 2. Active control of phases in a Master Oscillator and multiple Power Amplifier configuration.

Fig. 2. Contrôle actif des phases relatives d'amplificateurs en parallèle par une boucle de rétroaction.

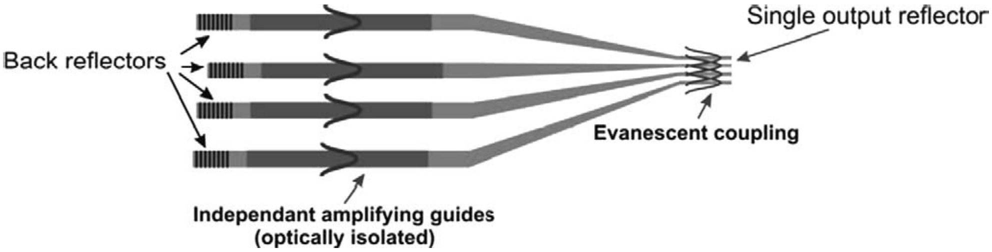

Fig. 3. Co-phasing of amplifiers in a common resonator by evanescent coupling.

Fig. 3. Mise en phase d'amplificateurs dans un résonateur unique par couplage evanescent.

The master oscillator signal is amplified through N fibre amplifiers. The phase relationships are individually monitored via a servo loop fed by a wave front analysis device. In this way, two 10 W Yb fibre amplifiers were recently combined [9] by use of an acousto-optic frequency shifter as a phase actuator. Each sub-aperture was independently locked to the reference oscillator leading to a heterodyne signal error that drove the acousto-optic device. The far field peak intensity nearly doubled when the two beams were phase-locked, the central lobe containing 50% of the total power.

The main drawback of such configuration is that the amplifying fibres and the fibre used for the reference beam must be matched in lengths to within a few millimetres according to the coherence length of the light. Moreover, this kind of combining method requires a complex servo-control system even if the scalability of this system should be good because the elementary phases are referenced to a common source rather than referenced to nearest neighbours.

Evanescent wave coupling method forms also part of the unfilled aperture systems. This is a common-resonator approach where all the N fibre amplifiers are included in a single resonator with $N + 1$ reflectors (Fig. 3). Overlap of the evanescent fields between adjacent emitters introduces wave coupling that results in phase synchronisation.

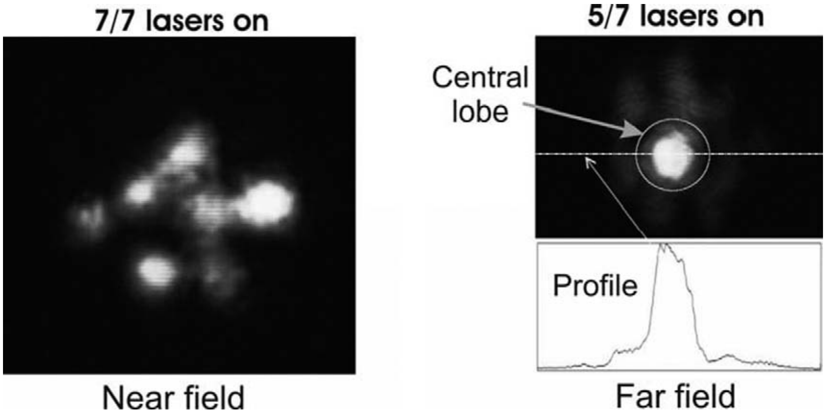

Fig. 4. Near and far field patterns of Nd lasers phase-locked in a common resonator by evanescent coupling in a tapered bundle of randomly positioned fibres. From reference [10].

Fig. 4. Couplage de lasers à fibres dopés Nd dans une cavité unique par ondes évanescentes en réalisant un amincissement de la botte de fibres en extrémité de cavité : champ proche et champ lointain. Extrait de la référence [10].

Relative phases are self adjusted to get minimum threshold in the laser. The fibered nature of the laser system makes evanescent coupling simple by drawing locally the N fibres closer like a fused star coupler that has been cleaved across the narrowest part. Lately, a tapered bundle of seven fibres was connected to seven Neodymium doped fibres (110 mW per laser) to experiment such evanescent wave coupling method [10]. There was no symmetry in the coupler that was made from a twisted bundle of fibres in random position. The cleaved face of the bundle served as the output reflector of the laser array. In this configuration, only five fibres were coupled in-phase (Fig. 4).

This study shows the difficulty to find an arrangement suited to a great number of sub-apertures so that all can be locked in-phase. The advantage of the method is that it requires neither identical lengths of sub-cavity nor active servo-control device.

2.2. Filled apertures

Other techniques which also combine the beams in the far field use filled-aperture systems as illustrated in Fig. 5.

In opposition with the unfilled-aperture systems, the elementary beams are superimposed in the near field on a beam combiner element. This component operates just at the opposite of a beamsplitter. For particular phase and amplitude relationships between the different input beams, corresponding to a good overlap between the fields on both sides of the combiner, the theoretical combining efficiency is close to 100%. Such filled-aperture systems use a single cavity with several arms. The cavity has N independent rear mirrors and a common output one. The phase-locking of radiations emitted by single-mode active fibres is made by the intracavity beam combiner. Indeed, the relative phases of the coupled beams and the frequency spectrum are automatically adjusted in order to get minimum laser threshold for the system. For the proper set of parameters, the far field concentrates on one diffraction order only. Because of the self-adjustment of the frequency spectrum, identical lengths for the N arms of the resonator are

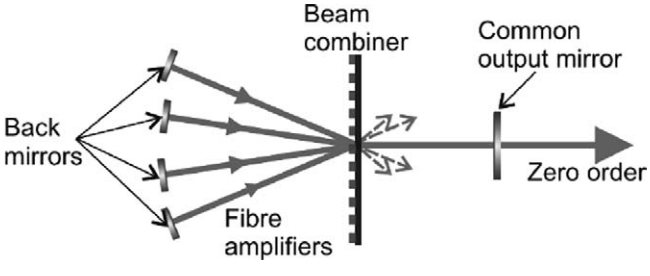

Fig. 5. A schematic representation of field aperture systems.

Fig. 5. Représentation schématique des dispositifs de combinaison utilisant des élements d'optique diffractive.

not required to lock the N emitters. In that configuration, three Nd doped fibres were coherently coupled thanks to an intracavity phase grating [12]. This experiment has led to 70% of the total output power emitted in the zero diffraction order. The frequency spectrum had a fine structure which was produced by the rear mirrors and the output mirror acting as Fabry–Perot etalons. As expected, the authors observed that this fine structure undergoes changes when they slightly modified the path length difference between the arms of the resonator. This is an advantageous property of this combining method: it can correct for dynamical path length changes. The scalability to a large number of emitters is probably limited by the efficiency of the beam combiner which decreases when the number of ports increases.

The main advantage of the aperture-filling techniques which combine the different beams only in the far field is the scalability of this approach to extremely high power. Indeed, the coherent combining is not performed in a single fibre and each elementary fibre only supports moderate power. Nevertheless, these multi-output configurations induce a far field pattern with a large part of power distributed in useless side lobes.

3. Collinear interferometric summation methods

3.1. Principle

To overcome the drawback of the previous methods, an interferometric combining technique leading to a fundamental mode emission is developed by several groups [13–21]. It is based on laser self organization properties, ensuring emission of modes of lowest losses, and on the use of an interferometric resonator configuration. For a two arm configuration depicted in Fig. 6(a), two independent fibre amplifiers are connected to a 2×2 coupler which performs a field coherent addition. This coherent combining occurs by using one of the coupler output ports to close the laser cavity whereas the other output port is angle cleaved. The laser spontaneously oscillates on the frequencies which correspond to constructive interferences towards the flat output port of the coupler. Therefore, the emitted spectrum is modulated with a period inversely proportional to the path length difference ΔL between the two arms of the resonator. Changes in the interferometer phase-shift due to environmental perturbations are compensated by an automatic adjustment of the oscillating frequencies.

The first results were obtained with a Michelson type resonator and then with a Mach–Zehnder type laser (Fig. 6): a 98% combining efficiency was achieved and the combined power in a fundamental mode was of 90 mW [13]. Power fluctuations obtained with the Mach–Zehnder fibre laser have been measured versus the optical path length difference ΔL and have been compared to those of a standard Fabry–Perot laser made with the same components. Fig. 7 shows that these fluctuations are significant when ΔL is lower than 2 mm corresponding to a spectrum modulation of the same order or larger than the laser gain bandwidth. Provided the active interferometer has a sufficiently large difference in the length of its arms, the laser exhibits no power instabilities.

3.2. Performances

The main advantages of collinear interferometric summation methods with respect to aperture-filling ones are (i) the use of standard components only to perform the combining operation and (ii) the capability of achieving high combining efficiency in the fundamental Gaussian mode. As coherent combining occurs in both far field and near

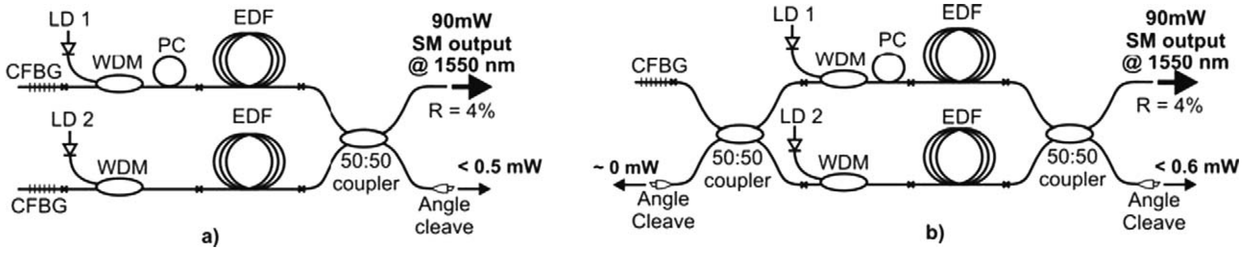

Fig. 6. Experimental setup of: (a) Michelson fibre laser, (b) Mach–Zehnder fibre laser. LD1, LD2: 980 nm pump laser diodes; EDF: erbium-doped fibre; CFBG: chirped fibre Bragg grating at 1550 nm; WDM: wavelength division multiplexer; PC: polarization controller.

Fig. 6. Schémas des lasers fibrés : (a) Michelson, (b) Mach–Zehnder. LD1, LD2 : diodes lasers de pompage à 980 nm ; EDF : fibre dopée Erbium ; CFBG : Réseau de Bragg fibré large bande à 1550 nm ; WDM : multiplexeur en longueurs d'onde ; PC : contrôleur de polarisation.

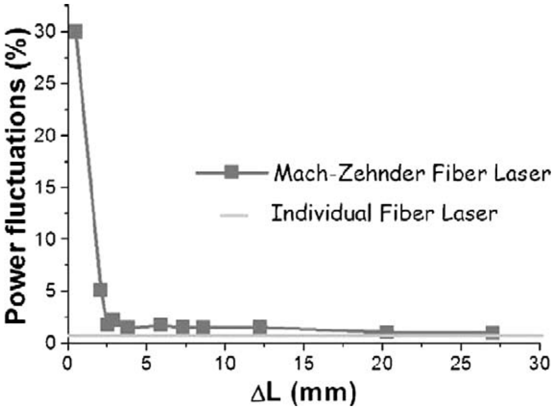

Fig. 7. Power fluctuations of the Mach–Zehnder fibre laser versus the path length difference ΔL compared with those of an individual fiber laser. From Ref. [19].

Fig. 7. Comparaison des fluctuations temporelles des puissances émises par les lasers fibrés Mach–Zehnder et standard en fonction de la différence de marche ΔL. Extrait de la Réf. [19].

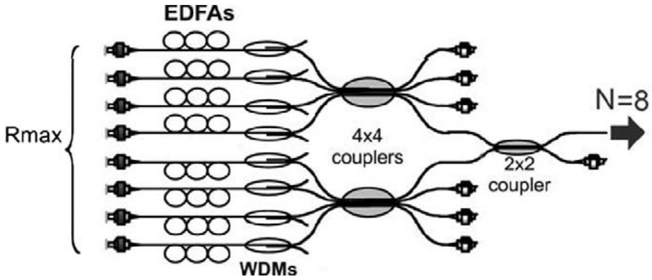

Fig. 8. Experimental setup of a 8 coherently coupled fibre laser array.

Fig. 8. Schéma d'un laser arborescent à 8 voies amplificatrices.

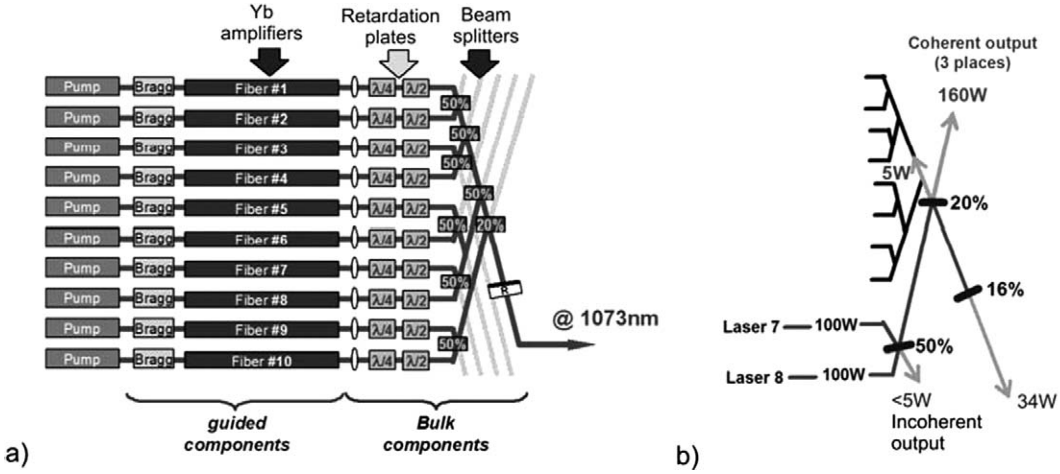

Fig. 9. Hybrid (fibered and bulk components) configurations: (a) 10 moderated power fibre lasers coherently coupled, (b) 2 high power fibre lasers coherently coupled.

Fig. 9. Configurations hybrides (composants fibrés et massifs) : (a) combinaison cohérente de 10 lasers fibrés de puissance modérée, (b) combinaison cohérente de 2 lasers fibrés de forte puissance.

field, all-fibre configurations with a single fibre output are well-suited to emission of moderate powers. Shirakawa et al. [14] have recently demonstrated the coherent combining of eight fibre lasers thanks to a tree arrangement (Fig. 8). An output power of 2.65 W was obtained from one fibre port with an efficiency of 85%.

For high power operation, coupling schemes with a single fibre output can suffer non-linear effects even if large mode area fibres are used. Hybrid configurations with free-space couplers were experimented in order to overcome this drawback [15]. Ten lasers emitting about 2 W were combined in the tree arrangement of Fig. 9(a) with an efficiency greater than 90%. When only two of the ten lasers were turned on and pushed to deliver a maximum output power of 100 W, a still high combining efficiency of 95% was preserved as deduced from measurement of the different coherent outputs (Fig. 9(b)).

Concerning the scalability to a larger number of combined lasers, a theoretical study [14] showed that the combining efficiency monotonically reduces when the number N of lasers increases. In fact, firstly, the number of allowed frequencies decreases due to the Vernier effect. Secondly, it becomes difficult for the reflectivity transfer function in intensity of the device (without gain and output mirror) to reach 100% within the laser bandwidth. However, a carefully design of the array lengths increasing the number of lasing frequencies may enable efficient coherent addition.

Another element limiting the combining efficiency is the power of each individual fibre laser. Recent experimental results [15] showed that combining efficiency decreased when individual laser powers were raised. A possible explanation for such behaviour is the gain nonlinearity saturation which induces phase changes incompatible with a high combining efficiency.

In conclusion about collinear interferometric summation methods, we can notice the simple nature of the optical device which includes only standard components leading to a very high combining efficiency. Despite the interferometric nature of the resonator, the laser operates without any output instabilities if the path length differences between the sub-cavities are high enough. Indeed, the frequency spectrum self-adjusts in real time in order to minimize cavity losses.

4. Coherent combining with multiple core fibre lasers

Another attractive way to perform coherent combining consists in designing cladding pumped multicore fibre lasers. Because of a large overlap between doped cores and pump radiation, high pump absorption is achieved with these fibre lasers. The previously described aperture-filling and collinear interferometric summation techniques can be used to phase-lock the radiations emitted by the different cores.

4.1. Aperture-filling

The composite fibre is usually made-up of several amplifying cores either electromagnetically coupled or not [22–26]. Whatever the case considered, most of the time, an external device is necessary to phase-lock all the elementary emitters. A Talbot resonator architecture was tried for this purpose. In such resonators one makes use of the fact that a coherent periodic field distribution self-images after the so-called Talbot distance Z_T. A feedback mirror placed at $Z_T/2$ distance of the end face of the multicore fibre provides only high reflection when fields from the cores are phase-locked. 18 singlemode cores (Nd-doped) periodically arranged along a ring pattern were coupled thanks to the Talbot effect [23] (Fig. 10(a)). A microstructured output mirror was also required to suppress the side lobes in the far field (Fig. 10(b)). The output power of the phase-locked multicore fibre exceeded 5 W, only 10% of which are confined in the central lobe of the far field, at a pump power of 36 W. The weak slope efficiency can be explained by the high intracavity losses due to the radial divergence of the emitted beam which are not compensated by the Talbot effect.

4.2. Collinear interferometric summation

More recently, the interferometric combining method has been successfully adapted to a multicore fibre laser. This approach makes it possible to benefit of the amplification from the whole doped cores while the total output power is emitted from only one of these cores.

In the experiment, two Ytterbium doped cores embedded in the same fibre [27] were locally coupled through a biconical fused coupler close to one of the fibre end (Fig. 11). As in Section 3.1, the fibre laser architecture is based on the Michelson interferometer configuration which is here integrated in the same component. The core where the combined output beam came from was chosen by tilting the output mirror toward this core. 96% of the total output power was emitted from the core where the feedback was performed and the laser slope efficiency was higher than 70%. In agreement with the principle of the combining method exposed in Section 3.1, the emitted spectrum was modulated with a periodicity that depends on the difference in propagation constant between the modes of the two independent cores of the fibre. When power combining was performed with two distinct fibre lasers [19], a random shift of the spectral modulation inside the laser bandwidth was observed due to fluctuations of the optical path difference between the two arms of the active interferometer, induced by environmental perturbations. In the two core fibre laser, both guides suffer nearly identical external perturbations, as they are embedded in the same cladding, and the position of the spectral modulation remains stable. As the collinear interferometric combining method was already applied to efficiently couple 10 distinct lasers [15], it should be extended to a fibre with a larger number of active cores and equipped with mirrors directly coated on the fibre ends for a better compactness.

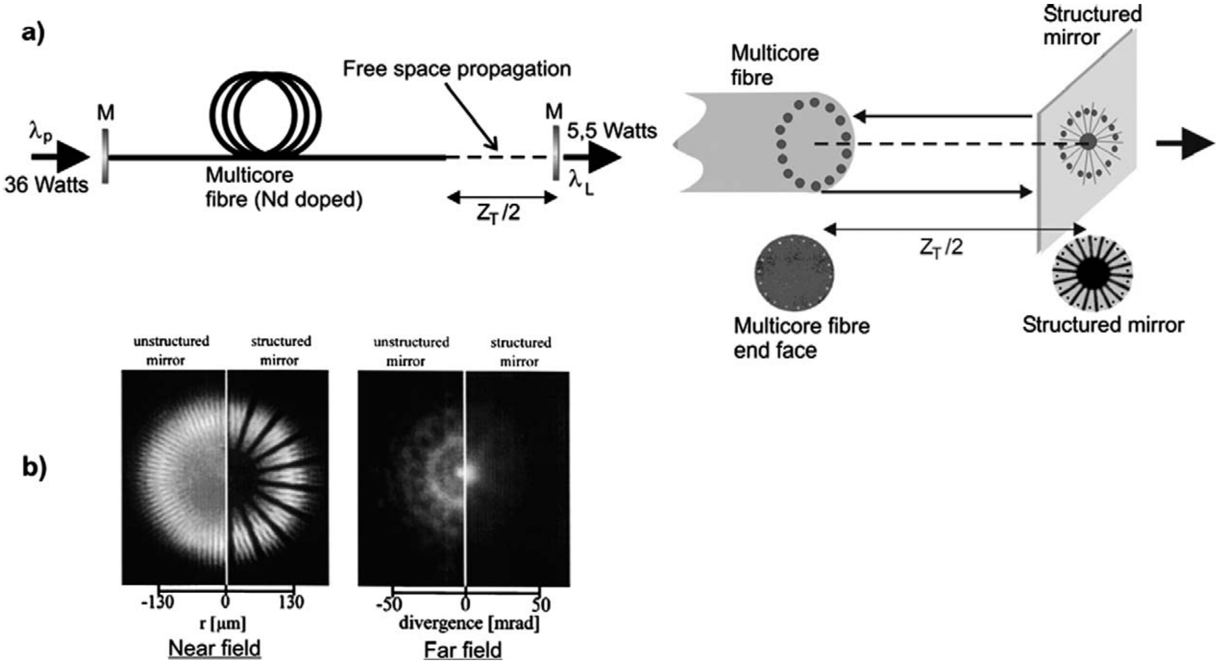

Fig. 10. (a) Experimental setup of a Talbot cavity. (b) Near field and far field patterns obtained with (left) an unstructured mirror and (right) a structured mirror. From Ref. [23].

Fig. 10. (a) Schéma d'une cavité Talbot. (b) Champ proche et champ lointain obtenus avec (gauche) un miroir standard et (droite) un miroir structuré. Extrait de la Réf. [23].

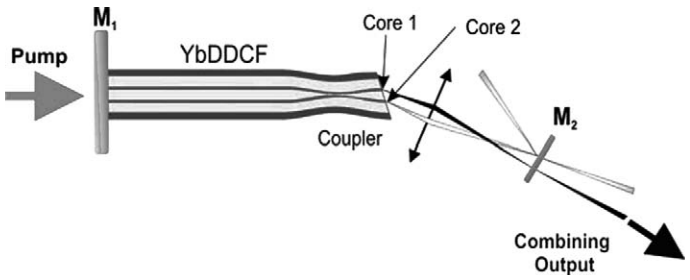

Fig. 11. Experimental setup of a two doped core fibre laser. YbDDCF: Yb-doped double-core fibre. From Ref. [27].

Fig. 11. Schéma du laser fibré à deux coeurs dopés. YbDDCF : Fibre dopée Ytterbium à double coeur. Extrait de la Réf. [27].

5. Conclusion

Coherent combining of fibre lasers is an important and challenging area of laser science. Achieving a single output of both high-power and high-brightness from many moderate power lasers promises a great number of scientific and industrial applications.

The two broad classes of coherent combining methods reported here have complementary characteristics and performances. When the aperture filling methods require, most of the time, specific components or servo control devices, collinear interferometric summation is based on self organization of laser properties and standard components. Moreover, laser combining occurs in both the far field and the near field with the last combining methods when the former ones only combine in a complex far field pattern. The collinear interferometric summation is also well adapted to coherently combine with very high efficiency. Nevertheless, the aperture-filling methods are intrinsically compatible with high power levels because the total output power is distributed on several amplifying fibres on the contrary to collinear interferometric summation that would require bulk combining components to reach the same performances.

Up to now, most of the combining methods have been only demonstrated for lasers delivering up to few Watts. Perspectives stand now around higher power levels.

References

[1] Y. Jeong, et al., Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power, Opt. Express 12 (2004) 6088–6092.

[2] J. Limpert, et al., High power air-clad large-mode-area photonic crystal fiber laser, Opt. Express 11 (2003) 818.

[3] P. Glas, D. Fisher, Cladding-pumped large mode area Nd-doped holey fiber laser, Opt. Express 10 (2002) 286.

[4] J.R. Leger, G. Mowry, External diode-laser-array with mode-selecting mirror, Appl. Phys. Lett. 63 (1993) 2884–2886.

[5] V. Daneu, et al., Spectral beam combining of a broad-stripe diode laser array in an external cavity, Opt. Lett. 25 (2000) 405–407.

[6] J.R. Leger, et al., Coherent laser addition using binary phase gratings, App. Opt. 26 (1987) 4391–4399.

[7] M. Tondusson, et al., Coherent combination of four laser beams in a multi-axis Fourier cavity using a diffractive optical element, J. Opt. A: Pure Appl. Opt. 3 (2001) 521–526.

[8] T.Y. Fan, A. Sanchez, Coherent (phase array) and wavelength (spectral) beam combining compared, Proc. SPIE 5709 (2005) 157–164.

[9] S.J. Augst, et al., Coherent beam combining and phase noise measurements of Ytterbium fiber amplifiers, Opt. Lett. 29 (2004) 474–476.

[10] M.L. Minden, et al., Self-organized coherence in fiber laser arrays, Proc. SPIE 5335 (2004) 89–97.

[11] H. Bruesselbach, et al., Power-scalable phase-compensating fiber-array transceiver for laser communications through the atmosphere, J. Opt. Soc. Amer. B 22 (2005) 347–353.

[12] J. Morel, et al., Coherent coupling of an array of Nd^{3+}-doped single-mode fiber lasers by use of an intracavity phase grating, Opt. Lett. 18 (1993) 1520–1522.

[13] D. Sabourdy, et al., Power scaling of fibre lasers with all-fibre interferometric cavity, Electron. Lett. 38 (2002) 692–693.

[14] A. Shirakawa, et al., Power summation and bandwidth narrowing in coherently coupled fiber-laser array, in: CLEO/QELS ’04 San Francisco CThGG2.

[15] H. Bruesselbach, et al., 200 W self-organized coherent fiber arrays, in: CLEO/QELS ’05 Baltimore CMDD4.

[16] A. Shirakawa, et al., Coherent addition of fiber lasers by use of a fiber coupler, Opt. Express 10 (2002) 1167–1172.

[17] T.B. Simpson, et al., Extraction characteristics of a dual fiber compound cavity, Opt. Express 10 (2002) 1060–1073.

[18] H. Bruesselbach, et al., Self-organized coherence in fiber laser arrays, Opt. Lett. 30 (2005) 1339–1341.

[19] D. Sabourdy, et al., Efficient coherent combining of widely tunable fiber lasers, Opt. Express 11 (2003) 87–97.

[20] D. Sabourdy, et al., Coherent combining of Q-switched fibre lasers, Electron. Lett. 40 (2004) 1254–1255.

[21] M. DiDomenico, Characteristics of a single-frequency Michelson-type He–Ne gas laser, IEEE J.Q. Electronics QE-2 (1966) 311–322.

[22] M. Wrage, et al., Phase locking in a multicore fiber laser by means of a Talbot resonator, Opt. Lett. 25 (2000) 1436–1438.

[23] M. Wrage, et al., Combined phase-locking and beam shaping of a multicore fiber laser by structured mirrors, Opt. Lett. 26 (2001) 980–982.

[24] M. Wrage, et al., Phase-locking of a multicore fiber laser by wave propagation through an annular waveguide, Opt. Comm. 205 (2002) 367–375.

[25] P.K. Cheo, A high-brightness laser beam from a phase-locked multicore Yb-doped fiber laser array, IEEE Phot. Tech. Lett. 13 (2001) 439–441.

[26] E.J. Bochove, et al., Self-organization in a multicore fiber array, Opt. Lett. 18 (2003) 1200–1202.

[27] J. Boullet, et al., Coherent combining in an Yb doped double core fiber laser, Opt. Lett. 30 (2005) 1962–1964.