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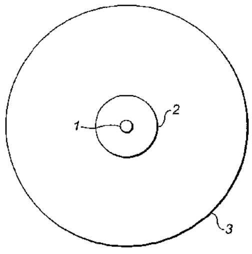
(54) Title: FIBRE LASER OUTPUT AND METHOD OF COMBINING FIBRE LASER OUTPUTS

FIG. 1



(57) Abstract: A method of forming a combiner for combining the output from two or more fibre laser sources is disclosed, comprising providing two or more input fibres, each having a pedestal; bundling the input fibres; strongly tapering the fibres such that the core diameter is less than the core diameter corresponding to the minimum mode-field diameter (MFD) value for the fibres and splicing the bundle of tapered fibres to an output fibre.

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Fibre Laser Output and Method of Combining Fibre Laser Outputs

This invention relates to the output from fibre laser sources and also to a method of combining the outputs from two or more fibre lasers.

Fibre lasers are becoming more and more common. In these, the active gain medium is a doped optical fibre. They can provide relatively high output powers, high optical quality, compact size, reliability and ease of delivery.

The outputs of individual fibre lasers can be combined to increase power by bundling two or more fibres together and coupling these fibres to a single output fibre. However, in combining the source fibres, there would generally be some reduction in the brightness of the beam, due to increased beam diameter and / or increased beam divergence.

More specifically, the combination of high-brightness fibres is limited by the relatively large cladding of these fibres. This restricts how closely the fibres can be packed. One potential solution is to use either smaller diameter fibres (or etch the fibres to remove all or part of the cladding). This solution is undesirable due to the practicalities of individually handling such small fibres.

The present invention arose in an attempt to provide an improved combiner, and method of combining the outputs from two or more fibre lasers.

According to the present invention in a first aspect there is provided a method of forming a combiner for combining the output from two or more fibre laser sources, comprising providing two or more input fibres, each having a pedestal; bundling the input fibres; strongly tapering the fibres and splicing the bundle of tapered fibres to an output fibre.

In this specification, the term 'strong tapering' hereinafter refers to a taper ratio such that the tapered fibre core diameter is less than a_{min}, where a_{min} is the core diameter corresponding to the minimum MFD (Modified-Field Diameter) value for that fibre core.

The fibres may be strongly tapered before, after or during the bundling.

Each input fibre may comprise at least a core having a first refractive index, an outer core or pedestal having a second refractive index lower than the first refractive index and a cladding layer having a lower still refractive index whereby, when the MFD becomes large enough due to strong tapering as described above, laser light escaping from the core is captured and guided by the pedestal and so is confined within a limited region of the fibre.

Preferably, the tapering is performed in an adiabatic manner, wherein increased beam diameter is matched by an equivalent reduction in beam divergence. This allows for the output beam to have a reduced divergence compared with the input beam and thus minimises the reduction in brightness introduced by the combiner. This offers a further advantage over the smaller fibre / etched approach described above.

There may be seven fibres in the input bundle in one embodiment, a central fibre surrounded by six outer fibres, although other embodiments may include any other number of fibres.

The bundle of fibres may be surrounded by an outer capillary that provides a means of handling and protecting the fibre bundle.

The pedestal that provides guiding of the light may itself be tapered further to provide further physical reduction in the diameter of the fibre(s) while still maintaining low-divergence of the light.

According to the present invention in a further aspect, there is provided an output combiner for combining the output from two or more fibre lasers to a single output, comprising a bundle of two or more input fibres, each having a pedestal and being tapered strongly as described above, and an output fibre spliced to the bundle of input fibres.

The input fibres may all be strongly tapered collectively prior to splicing to a single output fibre or alternatively the input fibres could each be tapered separately, assembled into a bundle and then spliced for connection to the output fibre.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 shows a cross-section through a triple-clad (pedestal-type) fibre;

Figure 2 shows relative refractive indices of the fibre of Figure 1;

Figures 3 to 5 show steps in the tapering of a fibre;

Figure 6 shows theoretical variation in mode-field diameter (MFD) when a typical fibre is tapered;

Figure 7 shows a cross-section of a strongly tapered fibre bundle;

Figure 8 shows a combiner; and

Figure 9 shows a cross-section of another strongly tapered fibre bundle.

Figures 1 and 2 show a typical triple clad optical fibre, for reference. A triple clad (or 'pedestal') fibre comprises a core 1 of first refractive index N1, a pedestal 2 (or inner clad layer) of index N2 less than N1 and an outer cladding layer 3 of index N3 less than N2. Thus, the layer 2 forms a pedestal.

Tapering of optical fibres is quite common. Figures 3 to 5 show respective steps in a typical tapering operation. Figure 3 shows an optical fibre 4 having initial diameter (external diameter) D_0. In a first step, localised heat is applied to an area 5 via any appropriated heating means 6 whilst tension 7 is applied. The tension pulls upon the fibre while the heat is applied. By varying the tension a waist 7 is produced under the localised heat and this has a diameter D_1.

For subsequent use, the fibre might be cleaved at a waist W and this cleaved end can then be spliced to another output fibre, as appropriate.

A parameter, known as 'taper ratio' is equivalent to D_1/D_0. Thus, a taper ratio of 1 equals no tapering and a taper ratio of ½ relates to a tapering to half the original diameter, for example.

A parameter known as the mode-field diameter (MFD) describes the diameter of a propagating light beam within a fibre. For standard fibres, as the fibre is tapered, the MFD initially decreases. However, at a core diameter value a_{min}, the MFD values reaches a minimum. Further tapering of the core leads to a rapidly increasing MFD value. When the MFD value significantly exceeds the core diameter, light can escape from the core. Without a pedestal this would escape into the outer cladding – possibly exit from the fibre and / or be absorbed by external contamination. With a suitable pedestal it is captured by the pedestal.

Figure 6 illustrates how the MFD (in microns) can vary with core diameter when a typical fibre is tapered. The fibre used to obtain these details is one which has an initial core diameter of 20 microns, a core numerical aperture of 0.08 and wavelength of light (laser light) is 1.08 microns. The plot 8 shows the variation of MFD with core diameter and the dashed line 9 relates to values where the MFD equals the core diameter. From an initial value of 16.2 microns (core diameter equals 20 microns; taper ratio equals 1) the MFD decreases slowly to a minimum of approximately 10.9 microns where the core diameter is a_{min}=8 microns and the taper ratio is 0.4 (before increasing more rapidly as the taper ratio/core diameter reduces further).

The term 'strong' tapering refers to a taper ratio corresponding to values where the core diameter is less than the core diameter (a_{min}) corresponding to the minimum value of MFD for that tapered fibre. That is, to a point on the curve 8 situated to the left-hand side of line 9. Thus, for a fibre of initial core diameter 20 microns this corresponds to the core diameter being less than 8 microns (ie a taper ratio of less than 0.4).

In preferred embodiments of the invention, input optical fibres are tapered in this 'strong' manner, ie values to the left of line 9 in the figure. Such strongly tapered fibres are used in embodiments of the invention.

In embodiments, bundles of fibres (or at least collections of two or more fibres), each fibre forming the output of a fibre laser, are used as input fibres to a combiner. The bundles of fibres are strongly tapered as described above, or in any ways. In a preferred embodiment, the 'strong' tapering is done to a bundle of input fibres collectively (ie all the fibres are bundled) and then tapered down and then the tapered bundle is spliced to a single output fibre as will be described further below. In an alternative embodiment, each individual fibre is tapered separately, all the tapered fibres are then assembled into a bundle and the bundle is then spliced to the single output fibre.

Note that the taper ratio D1/D0 shown in Figure 5 for examples describes the ratio of the final cladding to the initial cladding diameters. That is, a 400 micron diameter fibre tapered to a 200 micron one has a taper ratio of 0.5. For an untapered fibre, the taper ratio equals 1 of course. Note that the core and also the pedestal if present also reduce in diameter by the same ratio.

Figure 7 shows a cross-section of a strongly tapered fibre bundle comprising seven fibres, an inner fibre 4a and 6 outer fibres 4b to 4g.

This bundle of fibres, whether formed by tapering individual fibres or by tapering the whole bundle, is cleaved and at the waist for example is spliced to an output fibre 18, as shown in Figure 8. Each fibre in the bundle of input fibres 4 is from a separate fibre laser and these all connect to the single output fibre 8. The laser beam therefore travels towards the left in the figure in the direction shown by arrow A.

The resulting combiner is found to minimise the reduction in brightness by the bundle of input fibres being strongly tapered and also by the use of the pedestal surrounding the first core in the fibres. In a typical example, the output fibre is of core diameter 90 microns and outer cladding diameter 400 microns, having core numerical aperture of 0.11.

Each of the input fibres is of core diameter 9, pedestal diameter 105 and outer cladding diameter 125 microns having respective numerical apertures 0.09, 0.20 and 0.45 and tapered down to core diameter 1.8, pedestal diameter 21 and cladding diameter 25 micron.

Note that the fibres are tapered adiabatically. This means that the increased beam diameter is matched by an equivalent reduction in beam divergence. Adiabatic tapering is described in, for example, US 6,324,326 which describes how a single mode input can be preserved as it passes through a tapered region. The taper angle Θ (z) should be sufficiently low to prevent power in the fundamental core mode (LP_{01}) transferring to the closest even core mode (LP_{02}).

$$\Theta(z) < \Theta_{T.max} = r.(\beta_{01} - \beta_{02})/2\pi$$

where r is the core radius and β_{01} and β_{01} are the propagation constant for LP_{01} and LP_{02} core modes respectively. In the present application, an object is to prevent power in the LP_{01} core mode (radius is r) transferring to the LP_{02} pedestal mode (radius greater r). However, if a smaller value for the core radius applies, then the taper falls within the criteria for both core and pedestal and thus is classed as adiabatic.

Note that use of the pedestal provides an additional guiding structure that permits tapering well beyond the MFD minimum while maintaining low loss. This results in overall better brightness preservation.

A beam profile taken directly from a tapered input shows that the beam distributions fit very well with a Gaussian profile and is nearly single mode. The beam divergence is 0.05 rad. As described, the fibre specification in this embodiment is of diameter 9/105/125 NA 0.9/0.20/0.45 tapered down to a diameter of 1.8/21/25 micron.

In essence, a single mode beam in the core is completely coupled into the fundamental mode of the pedestal and remains single mode.

In an embodiment the diameter of the output fibre is 90/400 micron and numerical aperture 0.11/0.45. When this fibre is spliced to a tapered bundle of seven input fibres, the beam divergence from the output fibre is 0.066 rad, ie less than 0.07 rad (half angle) and this corresponds to a BPP (beam parameter product) of about 3mm.mrad (half-angle/radius). The distributions are again very nearly Gaussian. The loss of the device in this case is less than 0.15 dB in both low power and high power tests. The output in the example shown in Figure 10 is from the pedestal of an output fibre with seven input fibres. In this example the seven input fibres are bundled within a capillary having bore of approximately 380microns and outer diameter equal to 1.27mm. The capillary and fibres are then tapered to give a capillary outer diameter of 254 micron.

The beam in the input fibres are then transmitted into the single output fibre for onward delivery.

In some embodiments, it may be desirable to surround the bundle of fibres by an outer capillary. An example is shown in Figure 9. Outer capillary 20 serves to protect the fibre bundles and enables easier handling of it.

Claims

1. A method of forming a combiner for combining the output from two or more fibre laser sources, comprising providing two or more input fibres, each having a pedestal; bundling the input fibres; strongly tapering the fibres such that the core diameter is less than the core diameter corresponding to the minimum mode-field diameter (MFD) value for that fibre and splicing the bundle of tapered fibres to an output fibre.

2. A method as claimed in Claim 1, wherein the fibres are strongly tapered before bundling.

3. A method as claimed in Claim 1, wherein the input fibres are bundled and collectively tapered prior to splicing to the output fibre.

4. A method as claimed in any preceding claim, including a single output fibre.

5. A method as claimed in any preceding claim, wherein each input fibre comprises at least a core having a first refractive index, a pedestal having a second refractive index lower than the first refractive index and a cladding layer having a third refractive index lower than the second refractive index.

6. A method as claimed in any preceding claim, wherein the tapering is performed in an adiabatic manner.

7. A method as claimed in any preceding claim, comprising bundling seven fibres into the input bundle.

8. A method as claimed in any preceding claim, comprising cleaving the bundle of input fibres at a waist and splicing the cleaved bundle to the output fibre.

9. A method as claimed in any preceding claim, including a bundle of input fibres and an outer capillary radially surrounding the bundle.

10. An output combiner for combining the output from two or more fibre lasers to a single output, comprising a bundle of two or more input fibres, each having a pedestal and being tapered strongly such that the core diameter is less than the core diameter corresponding to the minimum mode-field diameter (MFD) value for that fibre , and an output fibre spliced to the bundle of input fibres.

11. A combiner as claimed in Claim 10, wherein each input fibre comprises at least a core having a first refractive index, a pedestal having a second refractive index lower than the first refractive index and a cladding layer having a third refractive index lower than the second refractive index.

12. A combiner as claimed in Claim 10 or Claim 11, wherein the input fibres have respective core, pedestal and cladding diameters of 9/105/125 microns and respective numerical apertures of 0.09/0.2/0.5 and are tapered down to respective diameters of 1.8/21/25 microns.

13. A combiner as claimed in any of Claims 10 to12, wherein the output fibre has respective core and cladding diameters of 90 and 400 microns and numerical apertures 0.11 and 0.45.

14. A combiner as claimed in any of Claims 10 to 13, including an outer capillary surrounding the bundle.

15. A method of combining fibre laser outputs substantially as hereinbefore described with reference to, and as illustrated by, the accompanying drawings.

16. A combiner substantially as hereinbefore described with reference to, and as illustrated by, any of the accompanying drawings.

17. Laser fibre apparatus comprising a combiner as claimed in any of Claims 10 to 14 and 16.

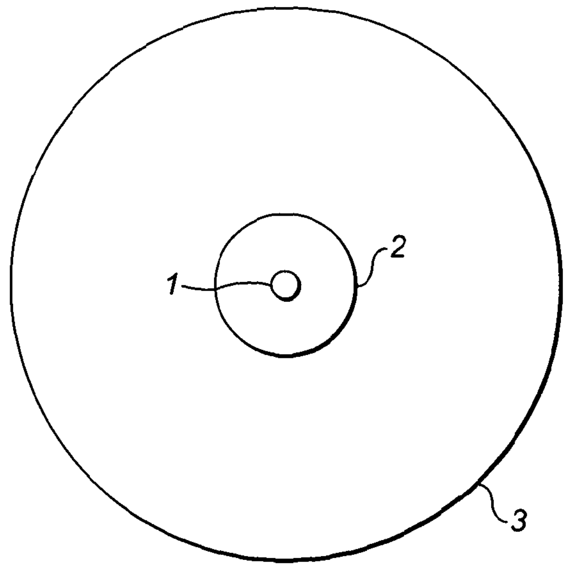

FIG. 1

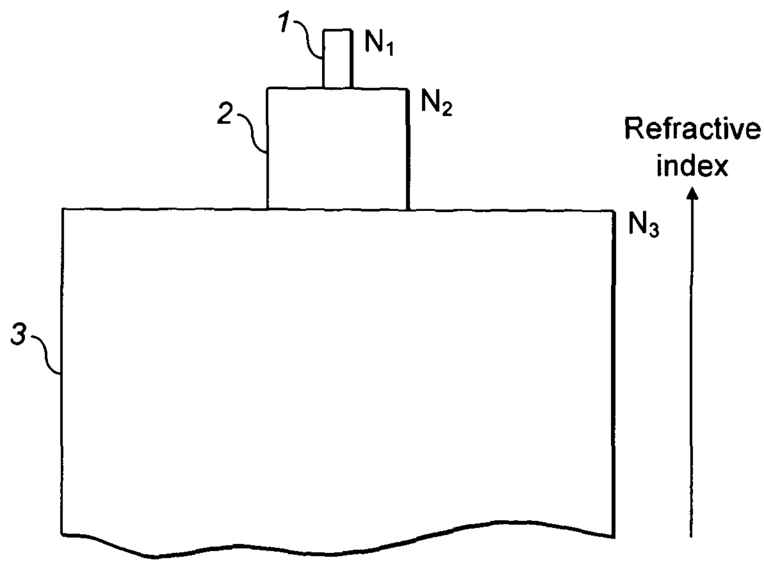

FIG. 2

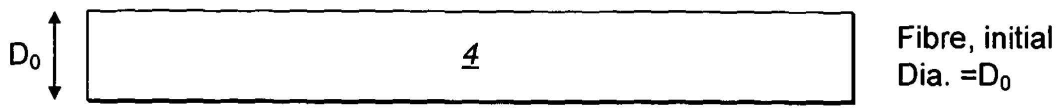

FIG. 3

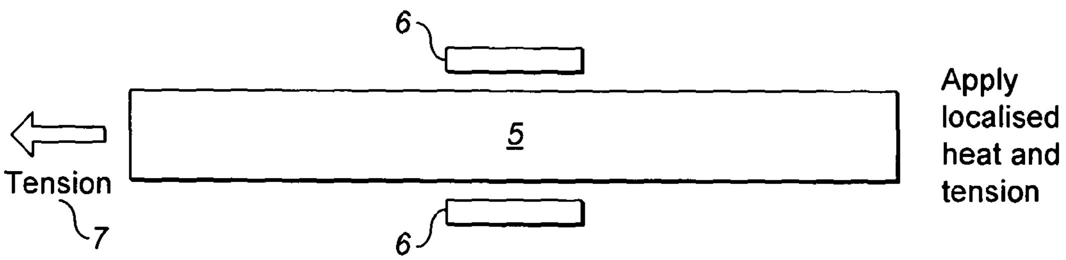

FIG. 4

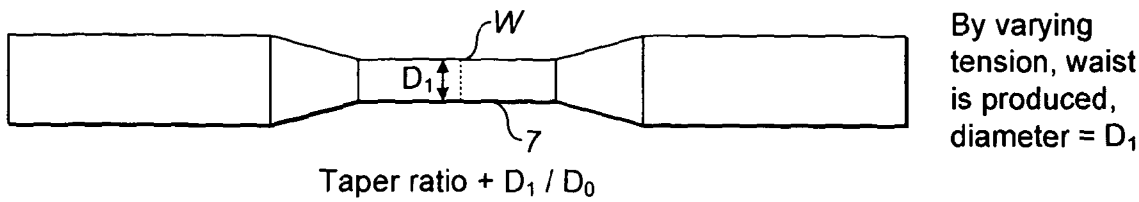

FIG. 5

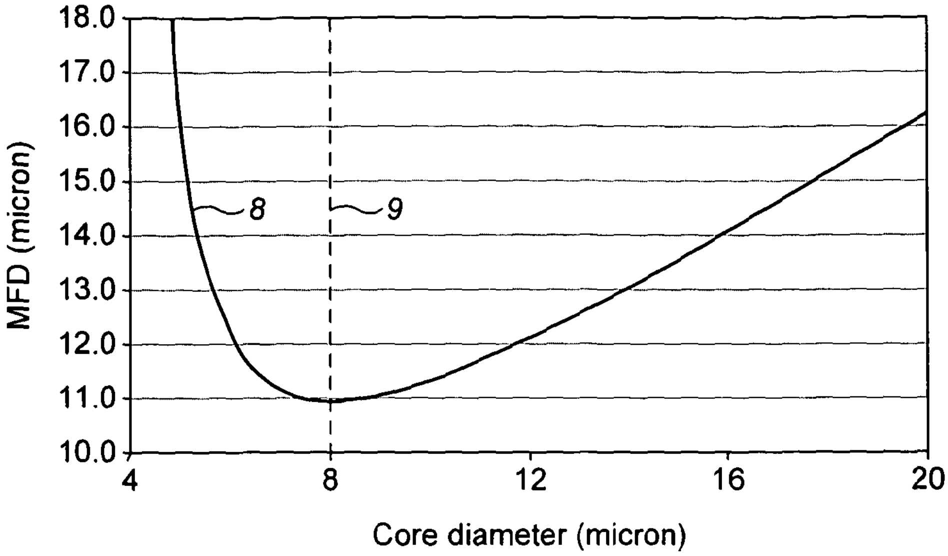
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
MFD (micron)
8
9
4
8
12
16
20
Core diameter (micron)

FIG. 6

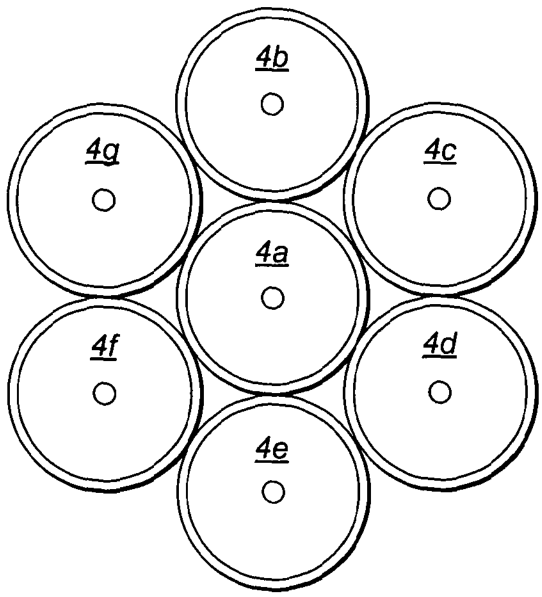
4b
4g
4c
4a
4f
4d
4e

FIG. 7

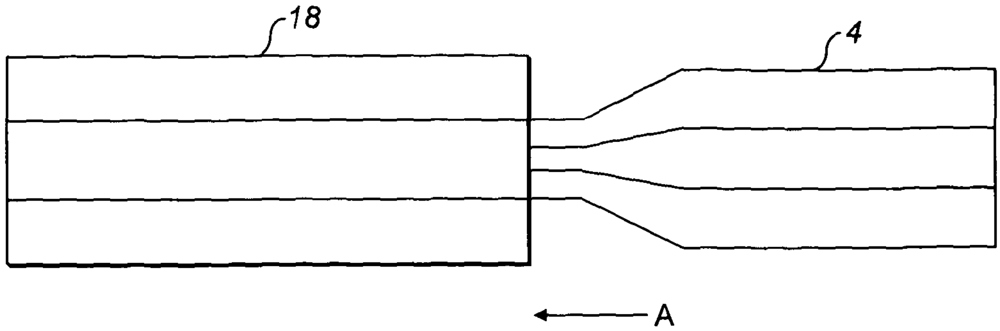

FIG. 8

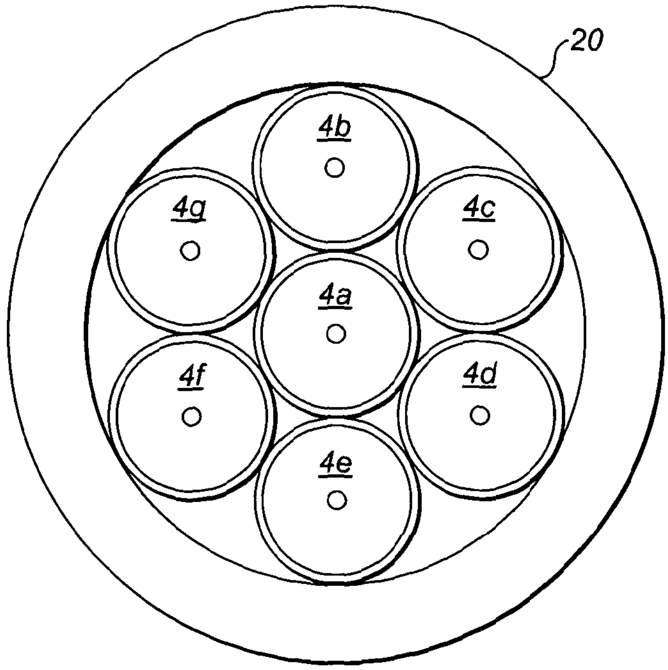

FIG. 9