(57) Abrégé/Abstract:
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Title: TWO-STAGE BRIGHTNESS CONVERTER

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TWO-STAGE BRIGHTNESS CONVERTER

TECHNICAL FIELD

The present description relates to the generation of optical signals and, more specifically, to brightness conversion.

BACKGROUND OF THE ART

Fiber lasers are nowadays emerging as the most powerful solid-state laser technology because of their compactness, reliability, efficiency of operation, and their high output power levels. A fiber laser can be seen as a single stage brightness converter.

One approach for designing a brightness converter uses a laser cavity (see, for example, A. Liem et al., “1.3 kW Yb-doped fiber laser with excellent beam quality” Proc. of CLEO 2004, CPDD2, Vol. 2, pp. 1067-1068, (2004)). In such a brightness converter, a large number of multimode pump diodes are coupled into a rare-earth-doped Double Cladding Optical Fiber (DCOF) using a Tapered Fiber Bundle (TFB) which is also known as a pump combiner. A laser cavity is formed by using a Fiber Bragg Gratings (FBGs) at each end of the DCOF to create a laser effect. Usually, a high reflectivity FBG is used at the input of the laser cavity and a low reflectivity FBG is used at the output of the laser cavity to only partially reflect the signal and allow some power extraction from the cavity. Pump power is absorbed by the doped core of the DCOF and a high brightness optical signal is generated. Theoretically, the output power of the laser is directly proportional to the pump power.

Another approach for designing a brightness converter uses a Master Oscillator Power Amplifier (MOPA) (see, for example, Y. Jeong, J.K. Sahu et al, “Ytterbium-doped large-core fiber laser with 1.36kW continuous-wave output power,” Optics Express, V.12 no.25, pp 6088-6092, (2004)). The MOPA configuration is a more complex brightness converter because it requires more components. A MOPA consists of a laser diode, which is known as a seed, coupled to a given number of
cascaded optical amplifier stages. An optical isolator is typically inserted between the laser diode and the first optical amplifier stage as well as in-between the optical amplifier stages in order to protect the laser diode and each amplifier stages from any back reflection, which could induce damage. The principle of a MOPA does not rely on a laser effect. The optical signal from the laser diode is rather amplified by the cascade of amplifier stages until the desired output power is obtained. Each optical amplifier stage typically consists of a doped optical waveguide pumped using multiple pump diodes which are coupled to the optical waveguide using a TFB.

These two configurations have been used to manufacture fiber lasers and, nowadays, a fiber laser with an output power of several kilowatts is a reality. However these configurations have some limitations.

Regarding the configuration based on a laser cavity, one drawback of this technique is related to a practical limitation of the maximum pump power available for the system, which is critical in high power fiber lasers. This limitation has two causes: the TFB and the maximum brightness produced by a single emitter pump diode. A TFB is an optical component which enables the coupling of pump power propagating into several optical fibers, known as pump arms, into a single fiber, known as the signal fiber. However, there is a theoretical limitation to the number of pump arms that can be used. The state of the art sets this value to 31. While it is possible to increase the number of pump arms by cascading two TFBs, the maximum of available pump arms is then limited to 49. This limitation in the number of pump arms induces a limitation in the maximum pump power available, which is close to 1 kW considering the state of the art single emitter pump diodes. Another limitation related to TFBs is its thermal limitation. The TFB induces an insertion loss. Lost pump power is then absorbed by the package and induces a rise in temperature which may result in a component failure. Usually, with an insertion loss of the TFB of about 0.1 dB, the maximum pump power that may be used for safe operation is about 1 kW. Finally, the maximum pump power is also limited by the brightness of the pump diodes. The initial brightness of the pump diodes should be carefully chosen in order to have an efficient and powerful
system. Some pump diodes which are able to deliver much power are commercially available but their brightness is low with a delivery fiber that is quite large, i.e. 600 μm or higher. This complicates the development of an efficient and powerful fiber laser.

Another drawback of the configuration based on a laser cavity is the achievable beam quality. The absorption of the pump power propagating into the inner cladding of the DCOF is proportional to the ratio between the areas of its core and of its inner cladding. In order to accommodate the use of a low brightness pump diode, the radius of the inner cladding should be increased, which consequently decreases pump light absorption. In order to counter-balance this effect, one can increase the radius of the fiber core. Unfortunately, this solution leads to a degradation of the beam quality of the signal.

Finally, another drawback of the configuration based on a laser cavity is related to thermal management. In practice, there is propagation loss in the DCOF, which generates heat. In a laser cavity brightness converter, a low index polymer is generally used in the outer cladding of the DCOF in order to achieve a proper Numerical Aperture (NA), which is not achievable with silica. While pure silica is able to handle temperatures of up to 1500°C and even higher, low index polymers can only handle temperatures of up to about 120°C. Accordingly, the pump power cannot be increased beyond a certain limit for the polymer not to be subject to damage caused by heat.

All of the limitations described above regarding the configuration based on a laser cavity also apply to the brightness converter configuration which is based on a MOPA. Moreover, there are additional limitations which come from the complexity of the scheme. First, because a MOPA consists of a cascade of amplifier stages, it is generally more costly compared to the laser cavity configuration. Second, special care should to be taken to perfectly control the gain of each amplifier stage in order to obtain an optimum and efficient operation. Third, each amplifier stage should also be isolated one from another using an optical isolator. However, at the present time, there exists no commercially available isolator which is able to handle an optical
power of more than tens of watts. When such power levels are reached, MOPAs are operated without isolators, which could eventually cause dramatic failures.

Considering the drawbacks of the prior art described above, there exists a need for a brightness converter which allows the use of low brightness pump diodes to achieve good beam quality.

**SUMMARY**

According to one aspect, there is provided a two-stage brightness converter. A first brightness conversion stage has a first laser cavity having a first optical waveguide doped with an active ion defining a first optical band with optical absorption, a second optical band with optical absorption and optical gain, and a third optical band with optical gain. The first laser cavity is pumped with a pump power having a wavelength in the first optical band to generate an intermediate optical signal in the second optical band. A second brightness conversion stage which is in cascade with the first brightness conversion stage comprises a second optical waveguide doped with the same active ion. The second brightness conversion stage is pumped with the intermediate optical signal to obtain a high brightness optical signal in the third optical band.

According to another aspect, there is provided a brightness converter which comprises a first brightness conversion stage having a laser cavity to increase the beam quality of a low brightness pump signal to provide an intermediate optical signal, with a high efficiency and a good thermal management; and a second brightness conversion stage to convert the intermediate optical signal into a high brightness optical signal with high efficiency and good thermal management.

The provided two-stage brightness converter allows the generation of an optical signal having good beam quality with the use of a low brightness pump diode while maintaining efficient thermal management.
In accordance with one embodiment, the second stage of the two-stage brightness converter is a laser cavity and, in accordance with another embodiment, the second stage of the two-stage brightness converter uses a configuration based on a Master Oscillator Power Amplifier (MOPA).

In a particular case, the two-stage brightness converter uses all-glass Double Cladding Optical Fibers (DCOFs). Because no low index polymer is used in the DCOFs, they are able to withstand high temperatures.

Furthermore, the provided two-stage brightness converter allows the use of a very low brightness pump diode. Accordingly, compared to techniques of the prior art, a two-stage brightness converter allows an increase of the maximum available pump power.

The provided brightness converter also allows the use of a single pump source, thereby requiring only one launching point for the pump power and eliminating the need for a Tapered Fiber Bundle (TFB) or any other pump combiner.

According to another aspect, there is provided a pump generator for producing a secondary pump power. The pump generator comprises a laser cavity having an optical waveguide doped with an active ion. The optical waveguide has a first optical band with optical absorption, a second optical band with optical absorption and optical gain, and a third optical band with optical gain. The pump generator also comprises a pump source coupled to the laser cavity for generating a primary pump power in the first optical band to pump the laser cavity in order to produce a secondary pump power in the second optical band. The optical waveguide is multimode at a wavelength corresponding to the secondary pump power such that the secondary pump power propagates with multiple modes in the optical waveguide.

According to yet another aspect, there is provided a method for generating a high brightness optical signal. The method comprises: i) Pumping with a pump power a laser cavity having a first optical waveguide doped with an active ion defining a first optical band with optical absorption, a second optical band with optical absorption
and optical gain, and a third optical band with optical gain. The pump power has a wavelength in the first optical band; ii) Generating an intermediate optical signal in the second optical band in the laser cavity as a result of the pumping; iii) Pumping with the intermediate optical signal a second optical waveguide doped with the same active ion; iv) Obtaining within the second optical waveguide a high brightness optical signal in the third optical band as a result of the pumping with the intermediate optical signal; and v) Outputting the high brightness optical signal from the second optical waveguide.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic view illustrating a two-stage brightness converter which is based on a cascade of two laser cavities;

Fig. 2 is a cross-sectional view of a generic example of a Double Cladding Optical Fiber (DCOF);

Fig. 3 is a schematic view illustrating the relative dimensions of the delivery fiber of the pump diode, the optical waveguide of the first stage and the optical waveguide of the second stage of the brightness converter of Fig. 1;

Fig. 4 is a graph showing the emission cross section and the absorption cross section of the rare-earth ion Ytterbium;

Fig. 5 is a graph showing the power distribution along the doped optical waveguide of the first stage of an example brightness converter;

Fig. 6 is a graph showing the population inversion along the doped optical waveguide of the first stage of the example brightness converter;

Fig. 7 is a graph showing the intrinsic gain spectral density of the doped optical waveguide of the first stage of the example brightness converter;
Fig. 8 is a graph showing the power distribution along the doped optical waveguide of the second stage of the example brightness converter;

Fig. 9A is a schematic view illustrating a two-stage brightness converter which is based on a cascade of two laser cavities separated by a Mode Field Adapter (MFA);

Fig. 9B is a schematic view illustrating an example of a Mode Field Adapter (MFA);

Fig. 10A is a schematic view illustrating a brightness converter which is based on a MOPA using cascaded amplifiers; and

Fig. 10B is a schematic illustrating in more detail one of the amplifiers of the cascade of the converter of FIG 10A.

It will be noted that throughout the appended drawings, like features are identified by like reference numerals.

**DETAILED DESCRIPTION**

Before describing specific embodiments, the definition of brightness should be reminded. The brightness of a light source is expressed in $W/(sr.m^2)$ and is defined as the following:

$$B = \frac{P}{NA^2 \cdot \pi \cdot A}$$  \hspace{1cm} (1)

where $P$ is the emitted power from an area of size $A$, and $NA$ is the Numerical Aperture.

State of the art pump diodes typically deliver a power in the order of 20 W into an optical fiber having a core diameter of about 100 $\mu$m and a NA of about 0.15. This leads to a brightness $B$ of $3.6 \times 10^{10} \text{ W/(sr.m}^2\text{)}$ which is typical for a state of the art pump diode. For a low brightness pump diode which delivers around 500 W into an optical fiber having a diameter of about 600 $\mu$m and a NA of about 0.22, the
brightness is rather $1.1 \times 10^{10}$ W/(sr.m$^2$). A low brightness pump diode typically delivers more power but with a compromise on the brightness, which is a major problem when using a single stage brightness converter.

Now referring to the drawings, Fig. 1 shows a two-stage brightness converter 100 which is based on a cascade of a first stage 102 and a second stage 104, each consisting of a laser cavity. It is noted that the symbol ‘x’ placed at various positions in Fig. 1 denotes a fusion splice between components.

First stage 102 is pumped using a low brightness pump diode 106 which produces pump power A available at a delivery fiber 108. First stage 102 uses a rare-earth-doped Double Cladding Optical Fiber (DCOF) 110 as the gain medium, and more specifically an Ytterbium-doped silica DCOF. A high reflectivity Fiber Bragg Grating (FBG) 112 is fusion-spliced at the input of DCOF 110 and a low reflectivity FBG 114 is fusion-spliced at the output of DCOF 110, in order to form a laser cavity. Delivery fiber 108 is fusion-spliced to FBG 112 for injection of pump power A to first stage 102. First stage 102 uses pump power A to generate an intermediate optical signal B. Intermediate optical signal B is available at the output of FBG 114.

Second stage 104 receives intermediate optical signal B from first stage 102 and uses it as a pump to generate a high brightness optical signal C. As first stage 102, second stage 104 comprises a rare-earth-doped DCOF 120 used as the gain medium. The rare-earth ion used in DCOF 120 is the same as in DCOF 110, i.e. Ytterbium. DCOF 120 is also silica based. A high reflectivity FBG 122 is fusion-spliced at the input of DCOF 120 and a low reflectivity FBG 124 is fusion-spliced at the output of DCOF 120, in order to form a laser cavity. Second stage 104 is fusion-spliced to first stage 102 to receive intermediate optical signal B from first stage 102. The generated high brightness optical signal C is available at the output of FBG 124.

Throughout the description, reference is made to the rare-earth ion Ytterbium which is used as the dopant in the gain medium. It is however noted that Ytterbium is used
herein as an example and that other ions such as Erbium or any other active ions may also be used.

Low brightness pump diode 106 typically produces several hundreds of watt of pump power A in an optical fiber having a large core diameter, such as 600 µm or even more. By using such a low brightness pump diode, only one pump diode 106 is necessary in this two-stage brightness converter 100 and there is therefore no need for a Tapered Fiber Bundle (TFB). This addresses at the same time at least some of the problems discussed in the background that are inherent to this component. Considering a silica fiber doped with Ytterbium, the wavelength of pump diode 106 is in the wavelength band of 915 to 976 nm. It is noted that while pumping in the 915-976 nm band is more efficient, pump absorption in Ytterbium-doped optical fibers is also possible over a band extending from about 880 to 985 nm.

First stage 102 is designed to produce a laser emission at a wavelength \( \lambda_1 \), referred to as intermediate optical signal B. As explained hereinbelow, the wavelength \( \lambda_1 \) of intermediate optical signal B is selected in an intermediate optical band of about 1020 to 1030 nm in this case. Both FGB 112 and FBG 114 have a peak reflectivity at \( \lambda_1 \) for the laser cavity to laze at this wavelength and special care is taken in the design of FBGs 112, 114 in order to ensure that all the optical modes sustained by multimode DCOF 110 are reflected by FGBs 112 and 114.

It is noted that first stage 102 may also be called a pump generator since it is used to generate an optical signal used as a pump in second stage 104.

Second stage 104 receives the intermediate optical signal available at the output of first stage 102 and uses it as pump. Second stage 104 is designed to produce a laser emission at a wavelength \( \lambda_2 \). This laser emission which is of high brightness and high beam quality is referred to herein as high brightness optical signal C. As explained hereinbelow, the wavelength \( \lambda_2 \) is selected at 1080 nm in this case. Both FGB 122 and FBG 124 have a peak reflectivity at \( \lambda_2 \) to form the laser cavity and stabilize the lasing wavelength to \( \lambda_2 \). It is noted that while the first and second stages 102, 104
both use an Ytterbium-doped silica DCOF as the gain medium, the dimensions and characteristics of DCOF 110 and DCOF 120 are different from one another.

Before discussing the specific dimensions of DCOFs 110 and 120, a schematic of a generic DCOF is illustrated in Fig. 2. A DCOF may be regarded as a superposition of two waveguides, i.e. a signal waveguide and a multimode pump waveguide. A DCOF comprises a core 202 which is doped with an active ion, an inner cladding 204, an outer cladding 206 and a jacket 208. The signal waveguide consists of core 202 and inner cladding 204 such that the signal is guided in core 202 using inner cladding 204. The multimode pump waveguide consists of inner cladding 204 and outer cladding 206. The pump power is guided in inner cladding 204 using outer cladding 206. Jacket 208 surrounds outer cladding 206. A DCOF is then able to convert the low brightness and poor beam quality multimode pump power propagating in the pump waveguide into a high brightness and high beam quality signal propagating into the signal waveguide. The pump power is injected into the pump waveguide and during its propagation the pump power overlaps the signal waveguide where it is absorbed by the active ion. Finally, a stimulated emission takes place into the signal waveguide.

Fig. 3 shows the relative dimensions of delivery fiber 108 of pump diode 106 (not shown in Fig. 3), DCOF 110 of first stage 102 (not shown in Fig. 3) and DCOF 120 of second stage 104 (not shown in Fig. 3). Delivery fiber 108 has core 302 and cladding 304. DCOF 110 has core 312, inner cladding 314 and outer cladding 316. DCOF 120 has core 322, inner cladding 324 and outer cladding 326. It is noted that FBGs 112 and 114 have dimensions matching DCOF 110 and FBGs 122 and 124 have dimensions matching DCOF 120. FBGs 112, 114, 122 and 124 are not shown in Fig. 3 for better clarity.

Pump power A available at delivery fiber 108 is coupled to inner cladding 314 of DCOF 110. DCOF 110 is designed such that the diameter of inner cladding 314 matches the diameter of core 302 of delivery fiber 108 such that an optimal coupling is obtained. In one embodiment, this diameter is 600 µm. The diameter of core 312 is
in the order of magnitude of 100 \( \mu \text{m} \) or higher. DCOF 110 therefore operates in multimode. Because the diameter of core 312 of DCOF 110 is smaller than the diameter of core 302 of delivery fiber 108, the brightness of intermediate optical signal B is improved compared to pump power A.

5 In addition, the diameter of inner cladding 324 of DCOF 120 is designed to match the diameter of core 312 of DCOF 110. By having a ratio between the area of inner cladding 324 and the area of core 322 that is in the range of tens of percents, the diameter of core 322 can be kept small enough to insure a single mode operation of DCOF 120. The single mode operation provides a high brightness optical signal C that is diffraction limited. It is noted that a multimode DCOF 120 may rather be used but that some special care should then be taken to operate DCOF 120 in a single mode regime in order to obtain a diffraction limited beam at its output. Slightly multimode operation of the second stage is also possible.

10 It is noted that the parameters of DCOFs 110 and 120 of the embodiment described above allows the use of all-glass optical fibers for both DCOF 110 and DCOF 120. It is however noted that DCOFs using a low index polymer or silicone may still be used. It is also noted that the dimensions described above are given as an example and that these dimensions may be varied to adapt to any other practical applications.

15 The provided brightness converter allows for flexibility in the choice of the characteristics of the optical waveguides used. When using DCOFs, the Numerical Aperture (NA) and the diameter of core 312 of DCOF 110 of the first stage may be carefully chosen to maximize core absorption in DCOF 120 of the second stage while keeping inner cladding 324 of DCOF 120 of the second stage small enough. The core 322 of DCOF 120 of the second stage may then be kept small enough for single mode operation in the second stage, thereby providing a diffraction limited output beam.

20 Fig. 4 shows the absorption cross section 410 and the emission cross section 420 of the rare-earth ion Ytterbium and is used to describe the operation of the two-stage
brightness converter 100 of Fig. 1. The absorption and emission cross sections 410, 420 are related to the optical gain and their study gives us insight on how a signal is amplified inside a laser cavity. Fig. 4 also shows three spectral bands that will be described below and which correspond to a first optical band 431, a second optical band 432 and a third optical band 433. The first optical band 431 extends between about 915 and 976 nm and corresponds to an optical absorption band. The second optical band 432 extends between about 1020 and 1030 nm, where both absorption and gain may occur. The third optical band 433 extends around 1080 nm which corresponds to an optical gain band.

In a single stage brightness converter, pumping is typically performed in the first optical band 431 extending between 915 and 976 nm where the absorption cross section is the highest. The lasing wavelength is then set in the third optical band 433, i.e. around 1080 nm.

However, one can note that the absorption cross section is not negligible in the second optical band 432 extending between 1020 and 1030 nm as it is the case in the third optical band extending around 1080 nm. In the second optical band 432, both absorption and gain are possible. This observation is important for the two-stage brightness converter 100 which specifically uses this band. First stage 102 is pumped using low brightness pump diode 106 in the first optical band 431, i.e. between 915 and 976 nm, and is designed to generate intermediate optical signal B with a wavelength in the second optical band 432, i.e. between about 1020 and 1030 nm. Pump power A propagates in inner cladding 314 (see Fig. 3) of doped DCOF 110. Intermediate optical signal B which is generated in the second optical band 432 propagates in core 312 (see Fig. 3). Intermediate optical signal B in the second optical band 432 has an improved brightness compared to pump power A. Because the absorption in the second optical band 432 is not negligible, the intermediate optical signal B generated by first stage 102 may be used to pump second stage 104 to generate high-brightness optical signal C in the third optical band 433. Moreover, the brightness improvement in first stage 102 allows keeping the fiber core of DCOF
120 small enough to have single mode operation in the third optical band 433, i.e. at 1080 nm. Second stage 104 therefore generates a laser signal at 1080 nm with a diffraction limited beam, thanks to the single mode operation of DCOF 120.

As noted above, while pumping in the 915 to 976 nm band is more efficient, pump absorption in Ytterbium-doped optical fibers is also possible over a larger band extending from about 880 to 985 nm. Accordingly, the first optical band 431 may also be expended to this range. Similarly, the second optical band 432 may also be expended from about 1000 to 1050 nm where both absorption and gain exist. The third optical band 433 may also be expended from about 1060 to 1100 nm where an efficient gain is possible.

The two-stage brightness converter 100 addresses at least some of the limitations related to the thermal management of fiber lasers. First, in most cases, doped DCOFs 110 and 120 may be made all-glass with no need for any low index polymer. In single-stage brightness converters based on a laser cavity, the doped DCOFs typically use a low index polymer in order to increase the NA of the pump waveguide to match the NA of the delivery fiber of the Tapered Fiber Bundle (TFB), which is about 0.46. However, most of the commercially available low brightness pump diodes have a delivery fiber with an NA close to 0.22 and since no TFB is used in this embodiment, an NA of 0.22 may be achieved in DCOF 110 using a low index glass. By avoiding the use of a low index polymer in the design of DCOFs 110 and 120, problems related to thermal failures are eliminated.

Moreover, a two-stage brightness converter 100 provides an improved thermal management over the prior art configurations described above. The quantum efficiency of a single-stage brightness converter varies between 85% and 90%. With two-stage brightness converter 100 of Fig. 1, the quantum efficiency will typically vary between 88% and 95% for first stage 102, and between 88% and 94% for second stage 104. As higher quantum efficiency leads to a lower heat generation, low heat generation is achieved in each of stages 102 and 104. Even lower heat generation is achieved in first stage 102 because of the large core diameter of DCOF 410 which is
typically close to or greater than 100 μm. As heat generation is inversely proportional to the square of the core radius, a low heat generation is achieved in first stage 102.

It is noted that the diameter of the core of the optical fiber used to manufacture of FBGs 112, 114 should match the diameter of the core of DCOF 110, i.e. typically in the order of magnitude of 100 μm. One should note that the writing of FBGs uniformly across such a large core can be difficult. It is however noted that it is not mandatory that the FBGs be uniformly written across the core since a non-uniform inscription will cause unequal reflection of the various modes, simply resulting in less efficient FBGs.

Example:

An example of a specific design of a two-stage brightness converter according to Fig. 1 is now given. It should be understood that the parameters of the converter specified below are simply given for illustration and that there exist many other possible designs of such a two-stage brightness converter.

First stage 102 of the brightness converter should be designed with care in order to obtain a laser emission within the second optical band, i.e. between 1020 and 1030 nm. First stage 102 should be designed with the goal of having a maximum gain spectral density within the second optical band in order to obtain an efficient laser emission.

Such an efficient laser emission within the second optical band, i.e. between 1020 and 1030 nm, is obtained with a strong population inversion within DCOF 102 of first stage 102. In order to obtain the desired strong population inversion a short cavity and a large ratio of the core diameter to the inner cladding diameter are used such that a strong absorption of the pump power is obtained.

In order to obtain a strong absorption of the pump power, one may want to use a heavily doped DCOF. It is however noted that incorporating too much rare earth ions in a glass matrix may result in the crystallization of the glass matrix with the consequence of increasing the background loss. In the case of Ytterbium, a
concentration of $3 \times 10^{26}$ to $6 \times 10^{26}$ ions/m$^3$ is acceptable. In this example, a concentration of $3 \times 10^{26}$ ions/m$^3$ is used with a fiber length of 1 meter.

Next, in order to obtain an efficient laser cavity, the choice of the wavelength of the pump power is important. As seen in Fig. 4, the first optical band 431, which corresponds to the typical pumping band of Ytterbium-doped optical fibers, extends between 915 and 976 nm. One should note that the closer the wavelength of the pump is to the wavelength of the laser emission, the more efficient the laser is. However, because the absorption bandwidth is very narrow at this wavelength, a pump wavelength close to 976 nm would require a pump laser diode that is very stable in wavelength. For this reason, a pump wavelength of 965 nm is rather selected.

A low brightness pump diode delivering a power of 1000 W at 965 nm in a delivery fiber having a core diameter of 400 $\mu$m and a NA of 0.22 may be obtained, for example, from Laserline GmbH located in Germany. The brightness of such a pump diode is $5 \times 10^{10}$ W/(sr.m$^2$).

Then, in order to match the diameter of the delivery fiber of a typical low brightness laser diode, the diameter of the inner cladding is 400 $\mu$m and the diameter of the core is 100 $\mu$m, for a core to inner cladding diameter of 0.25.

Finally, the lasing wavelength is set to 1027 nm.

Figs. 5 to 7 show the result of a simulation of first stage 102 according to the above described design. The simulation is performed using the rate equation modeling (see Rare-Earth-Doped Fiber Lasers and Amplifiers, 2nd Edition, Michel J.F. Digonnet, Marcel Dekker Inc., 2001, p. 341-344)

Fig. 5 shows the power distribution along DCOF 110 of first stage 102; Fig. 6 shows the population inversion along DCOF 110; and Fig. 7 shows the intrinsic gain spectral density of DCOF 110. As can be seen in Fig. 6, the population inversion is close to 50% which is two to three times stronger than inversions typically used for classic
double cladding fiber lasers emitting at wavelengths around 1080 nm. As shown in Fig. 7, the maximum intrinsic gain of first stage 102 is reached at a wavelength of about 1020 nm which is close to the lasing wavelength of 1027 nm. The nice match between the maximum intrinsic gain and the lasing wavelength results in a good laser efficiency of 93%, as can be observed in Fig. 5.

Now, second stage 104 converts intermediate optical signal B at 1027 nm into a high brightness optical signal C. The diameter of the inner cladding of DCOF 120 of second stage 104 is selected to match the diameter of the core of DCOF 110 of first stage 102. Accordingly, the diameter of the inner cladding of second stage 104 is 100 µm. In order to obtain a high-brightness optical signal C that is diffraction limited, DCOF 104 is designed to be single-mode. The diameter of the core is 15 µm and the numerical aperture is 0.08 which result in a v-number of 3.5 which is close enough to 2.405 for a single mode operation of DCOF 120. The Ytterbium concentration is equal to 3x10^{28} ions/m^3 in order to obtain good laser efficiency while keeping the background loss at an acceptable level.

Fig. 8 shows the result of a simulation of second stage 104 according to the above described design. Again, the simulation is performed using the rate equation modeling. It shows the power distribution along DCOF 120. An efficiency of 80% is observed in second stage 120, which leads to an overall laser efficiency of 75%.

This example two-stage brightness converter produces a power of 750 W, which gives a brightness of more than 2x10^{14} W/(sr.m^2) for a NA of 0.08. This corresponds to an improvement in brightness from pump power A to high-brightness optical signal C of a factor higher than 4000.

Fig. 9A shows a variation from the two-stage brightness converter 100 of Fig. 1. Two-stage brightness converter 900 of Fig. 9A is mostly identical to the brightness converter 100 of Fig. 1 and similar components are therefore not repeatedly described. Two-stage brightness converter 900 comprises a pump diode 906, a first stage 902 with a DCOF 910 and a second stage 904 with a DCOF 920. Two-stage
brightness converter 900 includes an additional component, i.e. a Mode Field Adapter (MFA) 930, inserted between first stage 902 and second stage 904.

In some embodiments, the brightness of pump diode 906 is so poor that the diameter of the inner cladding of DCOF 910 of first stage 902 needs to be increased in order to obtain an optimum lasing effect in the second optical band. In this particular scenario, the ratio between the area of the inner cladding of DCOF 910 and the area of the core of DCOF 920 would be decreased such that it becomes smaller than unity and absorption of power in DCOF 920 would then decreases. One solution would be to increase the diameter of core of DCOF 920 but this would then result in an undesired multimode operation of DCOF 920. In order to overcome this problem, MFA 930 is inserted between stages 902 and 904. As can be seen in Fig. 9B which details MFA 930, a MFA is a section of optical fiber where the diameter is gradually decreased. It can be compared to a buffer between an optical fiber with a large diameter and one with a smaller diameter. Usually, if the two diameters are close enough, this adaptation can be done without severe insertion loss.

It is noted that a MFA may alternatively or additionally be inserted between the pump diode and DCOF of the first stage in the case of a pump diode having a delivery fiber with a large diameter. This allows maintaining a low diameter of the inner cladding of the DCOF of the first stage.

Fig. 10A and 10B shows another embodiment of a brightness converter 1000 which is based on cascaded Master Oscillator Power Amplifiers (MOPAs). In the brightness converter of Fig. 10A, a laser seed 1002 at 1080 nm, is amplified by a cascade of amplifiers 1004, 1006 separated by optical isolators 1008. It is noted that the number of amplifiers may vary. Brightness converter 1000 varies from state of the art MOPAs mostly by the configuration used for each amplifier 1004 and 1006 as shown in Fig. 10B. Each amplifier 1004 and 1006 has a first stage 1010 and a second stage 1020. First stage 1010 generates pump power at a wavelength in the 1020-1030 nm band, which is used to pump second stage 1020. Second stage 1020 consists of an
amplifier that amplifies seed laser 1002 using the pump power generated in first stage 1010.

First stage 1010 comprises a DCOF 1012 doped with an active ion, Ytterbium in this case, which is pumped using a low brightness pump diode 1014. High and low reflectivity FBGs 1016 and 1018 are used to form a laser cavity and stabilize the emission wavelength of the laser to $\lambda_1$, which lies in the 1020-1030 nm band. Because of a laser effect at wavelength $\lambda_1$, a beam brightness improvement is obtained in first stage 1010 as in the first stage of brightness converter 100 of Fig. 1. The pump power generated in first stage 1010 is used to pump second stage 1020. Second stage 1020 is a MOPA and consists of a DCOF 1022 doped with an active ion, Ytterbium in this case. The pump power is coupled to DCOF 1022 a pump combiner 1024. Because of the improved beam brightness obtained from first stage 1010, DCOF 1022 may be operated in single mode, resulting in an optimum amplification of laser seed 1002. As in the embodiment of Fig. 1, the use of a two-stage brightness converter in the MOPA configuration of Fig. 10A allows to overcome the pump power limitation because it uses a low brightness pump diodes which can typically deliver more power than pump diode with better brightness. Furthermore, as in the embodiment of Fig. 1, all-glass DCOFs may be used in the brightness converter of Fig. 10A, thereby improving thermal management compared to the configurations of the prior art. Finally, the configuration of Fig. 10A also does not require the use of a TFB. A simple pump combiner is rather used, which addresses at least some of the limitations related to the use of TFBs.

While the embodiments described herein use optical fibers as waveguides, it is noted that any other type of optical waveguides, such as planar optical waveguides, may also be used.

Fiber Bragg Gratings (FBGs) may also be replaced by other wavelength specific mirrors such as thin film filters for example.
It is also noted that while reference is made herein to optical fibers doped with Ytterbium, other active ions may also be used as dopants. For example, Erbium is one ion that may be used because it shows a first optical band with absorption at 980 nm or around 1480 nm, a second optical band between 1520 and 1550 nm where both absorption and gain take place, and a third optical band with gain between 1550 and 1600 nm. Erbium may then be used in a first stage to generate an intermediate pump in the 1520-1550 nm band from a low brightness pump diode at 980 nm, and in a second stage pumped by the intermediate pump to generate a signal in the 1550-1600 nm band.

The embodiments described herein use a single high-power low-brightness pump diode as a pump source. It is however noted that it is still possible to use instead a plurality of pump diodes each with lower pump power and combined using a pump combiner.

The embodiments described above are intended to be exemplary only. The scope of the invention is therefore intended to be limited solely by the appended claims.
WHAT IS CLAIMED IS:

1. A brightness converter comprising:
   a first brightness conversion stage having a first laser cavity having a first flexible optical fiber with a multi-mode core doped with an active ion defining a first optical band with optical absorption, a second optical band with optical absorption and optical gain, and a third optical band with optical gain, said first laser cavity being pumped with a pump power having a peak wavelength in said first optical band to generate an intermediate multi-mode optical signal in said second optical band; and
   a second brightness conversion stage having a second laser cavity and arranged in cascade with said first brightness conversion stage, said second laser cavity having a second flexible optical fiber with a core doped with said active ion and a cladding surrounding the core, said second brightness conversion stage being coupled to the first brightness conversion stage in a manner that the intermediate multi-mode optical signal emitted by the core of the first flexible optical fiber be pumped into the cladding and the core of the second flexible optical fiber, the second laser cavity thence generating a high brightness optical signal in said third optical band.

2. The brightness converter as claimed in claim 1, wherein said active ion is Ytterbium.

3. The brightness converter as claimed in claim 2, wherein said first optical band comprises wavelengths between 915 nm and 976 nm.

4. The brightness converter as claimed in claim 3, wherein said second optical band comprises wavelengths between 1020 nm and 1030 nm.
5. The brightness converter as claimed in claim 4, wherein said third optical band comprises the wavelength of 1080 nm.

6. The brightness converter as claimed in any one of claims 1 to 5, wherein said first flexible optical fiber and said second flexible optical fiber are each an all glass Double Cladding Optical Fiber (DCOF).

7. The brightness converter as claimed in any one of claims 1 to 6, wherein a diameter of the cladding of the second flexible optical fiber corresponds to a diameter of the core of the first flexible optical fiber.

8. The brightness converter as claimed in any one of claims 1 to 7, wherein said first optical waveguide is multimode when propagating said intermediate optical signal and wherein said second optical waveguide is single-mode when propagating said high brightness optical signal.

9. The brightness converter as claimed in any one of claims 1 to 8, wherein said first laser cavity comprises a high reflectivity fiber Bragg grating positioned at an input of said first optical waveguide and a low reflectivity fiber Bragg grating positioned at an output of said first optical waveguide.

10. The brightness converter as claimed in any one of claims 1 to 9, further comprising a low-brightness pump source coupled to said first laser cavity, for generating said pump power.

11. A method for generating a high brightness optical signal, the method comprising:
pumping with a pump power a laser cavity having a first flexible optical fiber doped with an active ion defining a first optical band with optical absorption, a second optical band with optical absorption and optical gain, and a third
optical band with optical gain, said pump power having a peak wavelength in said first optical band;

generating a multi-mode intermediate optical signal in said second optical band in said laser cavity as a result of said pumping with a pump power;
pumping with said intermediate optical signal a second laser cavity having a second flexible optical fiber doped with said active ion;

obtaining within said second flexible optical fiber a high brightness optical signal in said third optical band as a result of said pumping with said intermediate optical signal; and

outputting said high brightness optical signal from said second flexible optical fiber.

12. The method as claimed in claim 11, further comprising propagating said high brightness optical signal with a single mode within said second flexible optical fiber.

13. The method as claimed in any one of claims 11 or 12, wherein said first flexible optical fiber is an all glass Double Cladding Optical Fiber (DCOF) having a first core, a first inner cladding and a first outer cladding and wherein said second flexible optical fiber is an all glass DCOF having second first core, a second inner cladding and a second outer cladding and wherein said method further comprises propagating said pump power in said first inner cladding, propagating said intermediate optical signal in said first core, propagating said intermediate optical signal in said second inner cladding and propagating said high brightness optical signal in said second core.