The invention concerns an adapter for outputting a laser beam having wavelength between 1300 nm and 1350 nm. The invention is characterized in that the adapter has directing means for directing the laser beam into an optical fiber. Also an arrangement comprising the adaptor and a method of producing a supercontinuum laser beam using the adapter are disclosed.
COMPACT SUPERCONTINUUM LASER SOURCE

TECHNICAL FIELD OF INVENTION

The invention relates to a laser system with an output of a broad spectrum supercontinuum.

BACKGROUND OF THE INVENTION

Supercontinuum laser sources are finding increasing use in many areas of science and industry. Despite their highly desirable properties they have been limited in their use by the complexity, size, and cost of the supercontinuum sources found in the prior art.

A supercontinuum radiation source is a light source which exhibits broad flat "white" spectrum and laser-like properties of high output power and high degree of spatial coherence compared to thermal light sources.

Conventionally supercontinuum optical radiation is generated by propagating sub-nanosecond ($<10^{-9}$ s) single wavelength laser pulses through a nonlinear material. For sufficiently intense ($>10^{10}$ W) laser pulses, which can be achieved by high power lasers, a supercontinuum of optical radiation will be generated in the nonlinear material. Virtually any nonlinear material can be applied, including e.g. water.

Interactions of the laser radiation and the nonlinear material generating a supercontinuum include nonlinear processes such as self-phase modulation (SPM), cross-phase modulation (XPM), stimulated Raman scattering (SRS), and four-wave mixing (FWM) all of which may contribute to the generated supercontinuum.
For a nonlinear material in form of a high quality optical fiber confining light in a small cross sectional area over long distances, a supercontinuum can be generated by low power laser sources.

For short pulses e.g. less than about 10 picoseconds all of the above mentioned nonlinear interactions can be responsible for supercontinuum generation in optical fibers. The extent to which each interaction contributes to the spectral broadening is determined by a combination of the characteristics of the laser radiation and the fiber parameters.

In order for four-wave mixing to efficiently contribute to the formation of the supercontinuum the interacting fields must be phase matched. It has long been understood that this requires a pump wavelength close to the zero dispersion wavelength of the optical fiber in use. For standard telecommunications fiber this wavelength is usually near 1300 or 1550 nm in the infrared. The recent development of so called photonic crystal, microstructured, or holey fiber has resulted in fibers with much shorter zero dispersion wavelengths around 800 nm. These fibers, combined with expensive mode -locked titanium sapphire pump lasers, have demonstrated broad supercontinuum sources in the visible region of the spectrum.

However, mode locked lasers are complicated and expensive. It is thus desirable to produce supercontinuum sources using longer pulse lasers such as Q-switched lasers or purely continuous wave lasers. For the case of lasers with pulses longer than several tens of picoseconds or continuous wave output, the effects of self and cross -phase modulation on the spectral width of the input pulse are negligible for the purpose of super continuum generation.

Stimulated Raman scattering (SRS) and four-wave mixing are thus the interactions which can be utilized. SRS does not require phase -matching and hence can be used for the generation of new frequencies with basically any pump wavelength/fiber combination. However, the resulting spectrum is not
smooth, with peaks at intervals spaced by the characteristic frequency shifts of the fiber material. In addition, the spectrum is primarily shifted to wavelengths longer than the pump.

US patent 4,847,850 discloses stimulated Raman scattering using compact acousto-optically Q-switched pump lasers operating at 1064 or 532 nm and standard single-mode fibers. In the case of 532 nm pumping, a continuum which extends from green to the near infrared was generated. With pumping at 1064 nm, a continuum in the infrared which extends to 1500 nm was generated. This patent relies exclusively on SRS (Stimulated Raman Scattering) for spectral broadening which results only in red shifted light with separate bands instead of smooth spectrum.

Provino et. al. "Compact broadband continuum source based on microchip laser pumped microstructured fiber", Electronic Lett. 37, 558 -559, 2001 discloses visible supercontinuum generation in photonic crystal fibers with a 532 nm passively Q-switched pump laser from JDSU which filters out the longer wavelengths. In addition to SRS they observed four-wave mixing processes phase matched through higher order fiber modes which resulted in the generation of wavelengths shorter than the pump. The supercontinuum extended as short as 400 nm but with low efficiency due to the poor mode overlap of the interacting fields. The output beam was also not diffraction limited which is undesirable for many applications. The characteristic of the fiber used is however not specified.

US patent 6,097,870 discloses broadband continuum generation in the visible spectrum using an optical fiber with a zero-dispersion at a visible wavelength and use of 100 fs pulses at 780 nm with 8 kW peak power. However, the continuum band is narrow and it is achieved using special microstructured optical fiber.

W. Wadsworth, et. al., "Supercontinuum and four-wave mixing with Q-switched pulses in endlessly single-mode photonic crystal fibers," Opt. Express 12, 299-
309 (2004) discloses supercontinuum generation using a Nd:YAG laser operating at 1.064 microns in combination with photonic crystal fiber with a zero dispersion wavelength in the range of 1.04 - 1.1 microns.

Prior art fails to teach an efficient technique for generating spectrally smooth, single-mode supercontinuum radiation using readily available, low cost components.

OBJECTS OF THE INVENTION

An object of the invention is to provide a supercontinuum source which is compact in size, simple to manufacture, and of low cost.

SUMMARY OF THE INVENTION

The first aspect of the invention concerns a supercontinuum adapter for outputting a laser beam having wavelength between 1300 nm and 1350 nm. The supercontinuum adapter comprises a passive Q-switch. This aspect is characterized in that the adapter has directing means for directing the laser beam into an optical fiber.

The wavelength of the laser beam may be adapted to form a supercontinuum in the optical fiber. The wavelength may be e.g. approximately 1313 nm. The word approximately here may mean e.g. a tolerance of up to 2.5 or 10 nm.

In a preferred embodiment, the connectable optical fiber may comprise e.g. silica glass.

The supercontinuum adapter may further comprise a laser crystal. The laser crystal may comprise at least one of the following materials: Neodymium doped Yttrium Vanadate (Nd:YVO₄), Neodymium doped Yttrium Aluminum Garnet (Nd:YAG) and Neodymium doped Gadolinium Vanadate (Nd:GdVO₄). Yet further, at least a part of a surface of the laser crystal may comprise dielectric coating which provides high reflectivity, e.g. at least 95%, 90% or 85%, for wavelengths
between 1300 nm and 1350 nm. Still further, at least a part of a surface of the laser crystal may comprise dielectric coating which provides high transmission, e.g. at least 95%, 90% or 85%, for wavelengths between 1300 nm and 1350 nm.

The passive Q-switch may comprise at least one of the following materials: Vanadium doped Yttrium Aluminum Garnet (V:YAG) and Co^{2+} doped materials. Further, at least a part of a surface of the passive Q-switch may comprise dielectric coating and which provides high transmission, e.g. at least 95%, 90% or 85%, for wavelengths between 1300 nm and 1350 nm.

The supercontinuum adapter may further comprise an output lens, which may complete a laser cavity, which is comprised of the laser crystal, the passive Q-switch and the output lens. Further, at least a part of a surface of the output lens may comprise dielectric coating which provides partial reflection, e.g. 80%, 90% or 70%, for wavelengths between 1300 nm and 1350 nm.

The supercontinuum adapter further comprise s means, e.g. an optical coupler, a coupling lens or a coupling lens system, for directing said laser beam into said optical fiber.

Another aspect of the present invention is an arrangement comprising a laser source and the adapter of the first aspect of the invention. The laser source may be for example a diode laser producing a laser beam comprising wavelength of approximately 810 nm or 880 nm. The word approximate ly here may mean e.g. a tolerance of up to 2, 5 or 10 nm. The inventor speculates that laser beams of other wavelengths may also be usable.

Yet another aspect of the present invention is a method for producing the supercontinuum laser beam preferably using the adapter of the first aspect of the present invention. The method may also be characterized in that it comprises steps of producing a laser beam having wavelength between 1300 nm and 1350 nm and directing the laser beam into an optical fiber.
The inventor found that directing laser beam pulses of a wavelength between 1300 nm and 1350 nm, especially 1313 nm, into a standard telecommunications optical fiber, the result was surprisingly a smooth, wide spectrum supercontinuum. This provides a significant advantage over prior art solutions which depend on active Q-switch and/or expensive special optical fiber. In the present invention, almost any common silica glass optical fibers can be used. Further, an active Q-switch is much more complicated, more expensive, but not as compact as the passive Q-switch used in the present invention.

BRIEF DESCRIPTION OF DRAWINGS

In the following, the invention is described in greater detail with reference to the accompanying drawings in which

Figure 1 illustrates a view of an embodiment of the invention using a Vanadium doped Yttrium Aluminum Garnet (YAG) based pump laser.

Figure 2 shows a spectrum of the output from a device constructed according to the preferred embodiment.

DETAILED DESCRIPTION

Figure 1 illustrates a view of an embodiment of the invention using a Vanadium doped Yttrium Aluminum Garnet (YAG) based pump laser. In this example, the laser has a wavelength of about 810 nm and a power of about 3 watts. The light 101 is focused with lenses (not shown) to a beam radius of about 100 microns within the laser crystal 103 of the supercontinuum adapter 100. Incoming light 101 from the laser source is used as a pump source for the laser crystal 103. The laser crystal 103 can be for example on of the following: Neodymium doped Yttrium Vanadate (Nd:YVO₄), Neodymium doped Yttrium Aluminum Garnet (Nd:YAG) or Neodymium doped Gadolinium Vanadate (Nd:GdVO₄).
On the rear surface 102 of the laser crystal 103, there is a dielectric coating which provides high reflectivity (>95%) at the desired laser wavelength near 1.3 microns. The dielectric coating is also subantially transmissive at the pump laser wavelength of about 810 nm as well as the higher gain laser transitions near 1.06 microns. On the front surface 104 of the laser crystal 103 is a dielectric coating which provides high transmission (>95%) at the desired laser wavelength near 1.3 microns. This arrangement ensures that power from the pump laser at 810 nm wavelength can enter the laser crystal 103 through surface 102 and desired wavelength near 1.3 microns can exit the crystal 103 only through surface 104.

A crystal 105 of Vanadium doped Yttrium Aluminum Garnet (V:YAG) is used as a Q-switching element in this embodiment. Q-switching is a technique, which is used to produce pulsed output from laser to achieve high peak power. The crystal 105 acts as a passive shutter to provide short pulse output from the laser.

Both surfaces 106 and 107 of the V:YAG crystal 105 have dielectric coatings which provide high transmission at the desired laser wavelength near 1.3 microns. The passive Q-switch element operating at zero dispersion wavelengths of regular silica glass single mode optical fibers makes manufacturing of compact and cost efficient supercontinuum laser source possible. Also standard telecommunications optical fibers can be used with the present passive Q-switch element.

An output lens 108 is provided to complete a laser cavity, which is comprised of elements 103-108. In this embodiment, the output lens 108 has a concave surface with a radius of curvature of about 100 millimeters. In another embodiment, the output lens 108 may have non-curved surface. The total length of the laser cavity is 10 millimeters or less. There is a dielectric coating which partially reflects the laser wavelength near 1.3 microns on the surface 109 of the lens 108. In this embodiment the reflectivity is about 80%. The inventor speculates that the reflectivity may also be for instance 70% or 90%.
A laser beam 110 is generated with pulse energy of about 10 microjoules and a pulse width of about 3 nanoseconds resulting in a peak power of about 3 kilowatts. The repetition rate is over 10 kilohertz. The laser beam 110 is directed from the supercontinuum adapter 100 into an optical fiber 112 using an optical coupler or a coupling lens system 111. The optical fiber 112 in this embodiment has a length of about 100 meters and through nonlinear effects such as, but not limited to, four-wave mixing, self-phase-modulation, and stimulated Raman scattering, the output 113 of the fiber 112 is a broad spectrum supercontinuum. The optical fiber 112 is connected to a connector terminal 114.

In the preferred embodiment of the invention, the pump laser is constructed with a Nd:YVO4 or Nd:YAG laser crystal (available from Casix) with mirror coatings suitable to select lasing in the 1300-1350 nm region of the spectrum while suppressing the stronger laser transitions near 1000 nm. Passively Q-switched operation is achieved with either a Vanadium doped YAG crystal (available from Crytur Ltd.) inserted in the resonator or a semiconductor saturable absorber mirror used as one of the cavity end mirrors (available from Reflekon Ltd.). An output coupling mirror completes the laser cavity (available from CVI laser Inc.). By properly choosing the dimensions and optical properties of these elements, the laser will generate output pulses with a peak power in the range of 1000 to 30000 Watts at a wavelength between 1300 and 1350 nm. These pulses are then coupled into standard telecommunications optical fiber (such as SMF-28 available from Corning Inc.) which has a zero dispersion wavelength at about 1300 nanometers and a length of at least 2 meters. Through nonlinear effects such as, but not limited to, four-wave mixing, self-phase-modulation, and stimulated Raman scattering, the initially narrow input spectrum is broadened into a supercontinuum with a spectral width of at least 100 nanometers.

Figure 2 shows a spectrum of the output from a device constructed according to the preferred embodiment. Relative spectral intensity in this embodiment is within ±10 dB tolerance from 800 nm to 1800 nm. The spectrum is clearly wider and smoother than those presented in the prior art.
In an embodiment of the present invention, the supercontinuum adapter may comprise any partial combination or all of the elements 102 - 111 and 114.

It will be appreciated by those skilled in the art that by combining a pump laser similar to that described in the preferred embodiment but with much higher peak power, in the range of 30000 -1000000 Watts, with Large Mode Area (LMA) fiber (available from Liekki Corp. or Nufern), it would be possible to generate high energy supercontinuum pulses without deviating from the scope of the present invention.

In addition, besides the "end pumped" laser geometry described in Figure 1, other diode pumped laser geometries are equally suitable including, but not limited to, side pumping, edge pumping, or "thin -disk" geometries. It will also be clear to those skilled in the art that substituting laser or passive Q-switch materials other than those described in the preferred embodiment (such as Nd:YAP for laser crystals and Co$^{2+}$ doped materials for Q-switching) does not deviate from the scope of the invention. The passively Q-switched design presented here is for illustrative purposes.

For a person skilled in the art, the foregoing exemplary embodiments illustrate the model presented in this application whereby it is possible to design different methods and arrangements, which in obvious ways to the expert, utilize the inventive idea presented in this application.
CLAIMS

1. A supercontinuum adapter (100) for outputting a laser beam of a wavelength between 1300 nm and 1350 nm, comprising a passive Q-switch, characterized in that the supercontinuum adapter (100) has directing means for directing the laser beam into an optical fiber (112).

2. An adapter (100) according to claim 1, characterized in that the wavelength of the laser beam is adapted to form a supercontinuum in said optical fiber (112).

3. An adapter (100) according to claim 2, characterized in that said wavelength is approximately 1313 nm.

4. An adapter (100) according to claim 1, characterized in that said optical fiber (112) comprises silica glass.

5. An adapter (100) according to claim 1, characterized in that said adapter (100) comprises a laser crystal (103).

6. An adapter (100) according to claim 5, characterized in that said laser crystal (103) comprises at least one of the following materials: Neodymium doped Yttrium Vanadate (Nd:YVO₄), Neodymium doped Yttrium Aluminum Garnet (Nd:YAG) and Neodymium doped Gadolinium Vanadate (Nd:GdVO₄).

7. An adapter (100) according to claim 5, characterized in that said laser crystal (103) comprises a dielectric coating (102) which provides reflectivity for wavelengths between 1300 nm and 1350 nm.

8. An adapter (100) according to claim 5, characterized in that said laser crystal (103) comprises a dielectric coating (104) which provides transmission for wavelengths between 1300 nm and 1350 nm.

9. An adapter (100) according to claim 1, characterized in that said adapter (100) comprises a connector terminal (114) for connecting said optical fiber (112).
10. An adapter (100) according to claim 1, characterized in that said passive Q-switch (105) comprises at least one of the following materials: Vanadium doped Yttrium Aluminum Garnet (V:YAG) and Co $^{2+}$ doped materials.

11. An adapter (100) according to claim 1, characterized in that said passive Q-switch comprises at least one of dielectric coatings (106) and (107) which provide transmission for wavelengths between 1300 nm and 1350 nm.

12. An adapter (100) according to claim 1, characterized in that said adapter (100) comprises an output lens (108).

13. An adapter (100) according to claim 9, characterized in that said output lens (108) comprises a dielectric coating which provides partial reflection for wavelengths between 1300 nm and 1350 nm.

14. An adapter (100) according to claim 1, characterized in that said adapter (100) comprises at least one of the following: an optical coupler, a coupling lens and a coupling lens system (111), for directing said laser beam into said optical fiber (112).

15. An arrangement comprising a laser source and the adapter (100) of any of the claims 1-14.

16. An arrangement according to claim 15, characterized in that said laser source is a diode laser producing a laser beam comprising wavelength of approximately 810 nm.

17. A method for producing a supercontinuum laser beam, characterized in that the method comprises the steps of producing a laser beam having wavelength between 1300 nm and 1350 nm and directing the laser beam into an optical fiber.
## INTERNATIONAL SEARCH REPORT

**International application No**

PCT/ FI 2008/050564

### A. CLASSIFICATION OF SUBJECT MATTER

**INV.**  G02F 1/35  H01B3/11

According to International Patent Classification (IPC) or to both national classification and IPC.

### B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G 02 F  
HOIS

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

### C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of Box C

See patent family annex

**Date of the actual completion of the international search**

10 February 2009

**Date of mailing of the international search report**

04/03/2009

**Name and mailing address of the ISA/ European Patent Office, P B 5618 Patentlaan 2 NL - 2280 HV RUSWICK Tel (+31-70) 340-2040, Fax (+31-70) 340-3016**

Boubal, François
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<td>WO 2005/071483 A (KOHERAS AS [DK]; BUCHTER SCOTT CHARLES [FI]; LUDVIGSEN HANNE ELISABETH) 4 August 2005 (2005-08-04) page 1, line 1 - line 14 page 6, line 18 - line 26 page 11, line 4 - line 8 page 16, line 15 - page 18, line 32 figures 1a, 3</td>
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