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DESCRIPTION

[0001] The present invention relates to an optical system comprising a fiber amplifier, and in particular, an optical system for efficient generation of ultra-short high-energy pulses and/or high-power optical supercontinuum.

[0002] Supercontinuum radiation is a phenomenon whereby narrowband light propagating through a non-linear medium is transformed into a signal with very broad spectrum. Optical fibers are a natural choice of non-linear media.

[0003] Jie Jiang et al., "Tunable coherent Raman soliton generation with a Tm-fiber system", CLEO, pages 1-2, 1 May 2011, demonstrates wavelength tunable coherent Raman soliton generation.

[0004] US 2002/0168161 A1 teaches a source of optical pulses and methods of generating optical pulses, particularly tunable pulses, by use of the Soliton-self-frequency shifting effect in an optical amplifier based on doped holey fiber.

[0005] J. Swiderski and M. Michalska, "Mid-infrared supercontinuum generation in a single-mode thulium-doped fiber amplifier" *Laser Phys. Lett.* 10 (2013) 035105 (6pp), discloses a supercontinuum source comprising thulium-doped fibers. The wavelength of the output spectrum of the supercontinuum source extends from 1.75 to 2.7 μm. The method disclosed therein is as follows. Firstly, nanosecond seed pulses are amplified in a cascade of erbium and erbium:ytterbium fiber amplifiers. The amplified pulses are then passed into a single-mode fiber and are shifted to about 2.4 μm using soliton self-frequency shifting. The spectrum is extended above 2.4 μm by using a core-pumped thulium-doped fiber amplifier, and that radiation is then amplified in another section of thulium-doped fiber amplifier to produce the output supercontinuum. Increasing the pump power broadens the spectrum of the supercontinuum.

[0006] It will be appreciated that the above system is rather complex, and it would thus be advantageous to provide a simpler and more versatile fiber amplifier.

[0007] According to the invention, there is provided an optical system as defined in claim 1, and a method as defined in claim 11 of operating an optical system. Embodiments are set out in the dependent claims.

[0008] The optical system comprises a fiber amplifier comprising an optically active doped fiber; a source of seed pulses; and a pump source, wherein the doped fiber is doped with one or more active element(s) selected such that the seed pulses are amplified in intensity; the doped fiber has a negative (anomalous) group velocity dispersion in the region from the wavelength of the seed pulses to a threshold wavelength at which the magnitude of the optical loss of the doped fiber is greater than a gain due to stimulated Raman scattering, so that due to stimulated Raman scattering, formation of a Raman soliton occurs, the Raman soliton is further shifted in the wavelength domain, and the shifting of the soliton in the wavelength domain is stopped at the threshold wavelength; the fiber is doped with thulium (Tm), the fiber has a negative group velocity dispersion in the region of 1.8 to 2.6 μm; the pump source is arranged to pump at a wavelength from 0.77 to 0.82 μm; the source of seed pulses provides pulses having wavelengths from 1.8-2.1 μm; the duration of the seed optical pulses is limited to less than 100 ps; the threshold wavelength is longer than the wavelength of the seed pulses; and the optical system is operable to generate a series of spectrally separated soliton pulses in the region from the seed pulse wavelength to 2.6 μm.

[0009] By virtue of the invention, in use, formation of a Raman soliton occurs due to stimulated Raman scattering. The Raman soliton is then shifted in the wavelength domain. The shifting of the Raman soliton is stopped at the threshold wavelength.

[0010] Thus, there is disclosed herein an optical system for outputting an optical output comprising: a fiber amplifier comprising an optically active doped fiber; a source of seed pulses; and a pump source; wherein the doped fiber has a negative (anomalous) group velocity dispersion in the region from the wavelength of the seed pulse to the desirable threshold wavelength and it is doped with one or more active element(s) selected such that the seed pulse is amplified in intensity so that due to stimulated Raman scattering a formation of a Raman soliton occurs and a further shift of the soliton in the wavelength domain which is preferably stopped at a threshold wavelength at which the magnitude of the optical loss of the doped fiber is greater than a gain due to the stimulated Raman scattering.

[0011] By virtue of the present invention it is possible to produce as an output of the optical system an optical supercontinuum and/or a high-energy pulse shorter than the seed pulse and preferably comprising the predominant part of the output amplifier radiation without spectral filtering and spectrally shifted to the longer wavelength direction.

[0012] In preferred embodiments, the optical system is operable in a first and second mode, wherein in the first mode the optical system is operable to generate as the output a high-energy pulse shorter than the seed pulse and comprising the predominant part of the output amplifier radiation without spectral filtering and spectrally shifted to the longer wavelength direction, and wherein in the second mode the optical system is operable to generate as the output an optical supercontinuum. In such embodiments, it is preferably possible to change between the first operational mode and the second operational mode by changing at least one of the duration or intensity of the seed pulses, or changing the pump rate.

[0013] The duration of the seed optical pulses is less than 100 ps, in order to provide more efficient generation of the Raman soliton.

[0014] Preferably, the doped fiber has a steeply increasing optical loss at the threshold wavelength, the threshold wavelength being longer than the wavelength of the seed pulse. The magnitude of the optical loss is preferably chosen to overcome the gain due to stimulated

Raman scattering at the peak intensity of the desired output pulse.

[0015] Preferably the fiber is silica-based. Alternatively, the fiber may be a germanate glass fiber, or a fiber with high (preferably >50%) germanium oxide content, or any other fiber with negative (anomalous) dispersion in the desired wavelength range, including but not limited to fluorozirconate glasses (e.g. ZBLAN), phosphate glasses or chalcogenide glasses.

[0016] The doped fiber may be doped with at least one element producing optical loss at the threshold wavelength. The fiber is doped with thulium. Preferably the fiber is doped with at least one element chosen from the rare-earth group, for example Nd, Er, Yb and Ho.

[0017] Thulium/holmium-doped fiber may be used in order to achieve broader gain which is preferable for supercontinuum generation.

[0018] Holmium-doped fiber may be used in order to decrease the spectral band in order to provide more efficient energy transfer to the soliton comprising the most part of the amplifier output energy. When holmium-doped fiber is used, the pump wavelengths are preferably chosen from the regions of 1.14-1.16 μm or 2-2.1 μm.

[0019] However, in accordance with the invention, the fiber is doped with thulium.

[0020] Therefore, there is provided an optical system comprising: a thulium doped fiber amplifier; a pump source arranged to pump at a wavelength from 0.77 to 0.82 μm; and a source of seed pulses, the seed pulses having wavelengths from 1.8-2.1 μm.

[0021] By means of the invention is it possible to generate a series of spectrally separated soliton pulses in the region from the seed pulse wavelength to 2.6 μm. It is also possible to generate (in a first mode of operation) a soliton pulse in the 2.2-2.8 μm region comprising the predominant part of the amplifier output radiation, and (in a second mode of operation) supercontinuum radiation from 1.8-2.6 μm. Changing from one operational mode to another may be achieved by changing the input parameters of the pump source and seed pulses.

[0022] Thus there is disclosed herein a fiber laser comprising an amplification chain for amplification of optical pulses, which has at least one amplifier cascade realized with an optical fiber doped with an optically active element, the doped fiber having a steep rise of an optical loss at a wavelength longer than that of the seed pulse and having a negative (anomalous) group velocity dispersion in the wavelength region from the seed spectral position to the optical loss edge (referred to also as threshold wavelength, or absorption edge). The optical loss value is chosen so that the optical loss overcomes the Raman gain at the desired peak intensity of the output pulse.

[0023] There is further disclosed a fiber laser comprising an amplification chain for amplification of seed pulses with spectral intensity maximum in the region of 1.8-2.1 μm, which has at least one amplifier cascade realized on a thulium-doped optical glass fiber with a negative group velocity dispersion in the region of 1.8-2.6 μm pumped at the wavelengths chosen from the region of 0.77-0.82 μm. With this configuration, it is possible to generate an ultra-short soliton pulse in the spectral range of 2.2-2.5 μm which carries the predominant part of the output amplifier radiation without applying a spectral filtering in any form. Moreover, it is possible to generate a series of spectrally separated soliton pulses in the spectral range from the seed laser wavelength up to 2.6 μm. Also, the amplifier can act as a supercontinuum light source in covering the region of 1.8-2.6 μm.

[0024] The optical loss may be natural or introduced by several techniques, such as cut-off of a fundamental mode in a special fiber or doping with chemical elements or introducing bending losses in order to obtain a sharp absorption edge at a desirable wavelength.

[0025] The operation principle of the amplifier is the shifting of the pulse in the wavelength domain due to stimulated Raman scattering which is stopped at a certain spectral point owing to the optical loss overcoming the Raman gain. At a certain threshold pump rate the amplifier produces one or a series of the Raman solitons from each input pulse, whereas the first Raman soliton is spectrally shifted with respect to the pulse, the second Raman soliton is spectrally shifted with respect to the first Raman soliton, and so on.

[0026] In a thulium-doped fiber amplifier, amplification in the $^3H_4$-$^3H_5$ electronic transition band also plays a part in the wavelength shifting of the pulse.

[0027] Depending on the amplifier parameters (fiber composition, core profile, spectral dependence of the light propagation constant, input seed duration, shape and intensity, polarization, bending losses, pump rate, and pump distribution along the fiber), the pulse and the Raman solitons can be completely or partially separated in time.

[0028] In the case that the Raman solitons are completely separated in time (the first mode of operation of the laser), it is possible to generate at a certain pump rate an optical supercontinuum covering the whole spectral region between the input seed and the absorption edge. Further increase in the pump rate will result in the increase of the power of the supercontinuum without broadening of its spectrum.

[0029] In the case that the Raman solitons are partially separated in time (the second mode of operation of the laser), the seed pulse will amplify the first Raman soliton at the expense of its own energy, the first Raman soliton will amplify the second Raman soliton, and so on. The energy transfer will stop at the last Raman soliton whose spectral position is determined by the position of the absorption edge. This Raman soliton will thus accumulate the energy supplied by the pump.

[0030] By changing the pump rate, pump distribution, polarization and seed parameters it is possible to switch between the two described operational modes of one and the same apparatus.

[0031] The technical result is the realization of a high-brightness supercontinuum, and a high energy ultra-short seed pulse accumulating the predominant part of the amplifier output spectral energy, and a device which can switch between these two operational modes.

[0032] The advantage over the prior art, where the increase of the total supercontinuum power leads to the increase of its spectral area rather than increase in its spectral power density (or, brightness), is that the present invention allows to accumulate the energy in the spectral band of interest without its spectral broadening, or, in other words, to increase the spectral brightness of the supercontinuum source.

[0033] Another advantage is the realization of a high-energy pulse comprising the predominant part of the laser output radiation.

[0034] A preferred embodiment of the invention will now be described by way of example only and with reference to the accompanying drawings in which:

Figure 1 shows an optical system in which the present invention can be implemented; and

Figure 2 shows a supercontinuum output spectrum generated by an optical system according to the present invention.

[0035] The optical system 1 of Figure 1 comprises a pump source 2, a source of seed pulses (seed source) for providing seed pulses 3, a combiner 4 and a fiber amplifier 5.

[0036] In operation, the pump source 2 provides pump radiation to the combiner 4, where it is coupled with seed pulses 3 from the seed pulse source. The multiplexed output from the combiner 4 is then input to the fiber amplifier 5, and is output as output pulses 6.

[0037] Figure 2 shows a supercontinuum output spectrum generated by an optical system according to the present invention. The fiber amplifier used was a thulium doped fiber amplifier pumped with pump pulses with a wavelength of 795 nm. The wavelength of the seed pulse was 1970 nm.

[0038] The preferred embodiment uses a silica-based thulium-doped optical fiber with OH- groups introduced into the fiber during manufacturing. OH- groups will be present to some extent in most optical fibers, but normally their concentration is reduced as much as possible. Leaving OH- in the fiber to some extent allows controlling the cut-off wavelength and loss (i.e., the more OH-, the shorter the cut-off wavelength and the higher the losses). Thus it is worth noting that OH- groups may exist in different optical glass fibers and thus can play the role providing the requisite optical loss, especially the intense absorption peak situated at the wavelength of 2.7-2.8 μm depending on the specific glass composition.

[0039] A supercontinuum or the ultra-short pulses in the wavelength region of 1.8-2.7 μm can be generated by such an optical fiber. Alternatively, a germanate glass fiber or a fiber with high (preferably >50%) germanium oxide content can provide the extension of this spectral range up to 2.8 µm. The silica-based thulium-doped optical fiber is seeded by seed pulses in the region of 1.8-2.1 µm. The preferable pump method is clad-pumping. Clad pumping is important for reaching high output powers and for using direct diode-pumping which is more economical. The pump wavelength is selected from the regions of 0.77-0.82 µm, 1.5-1.65 µm, and 1.18-1.21 µm. Core-pumping method, or any combination of the mentioned above pump possibilities can be used as well. It is possible to generate an ultra-short soliton pulse in the spectral range of 2.2-2.7 µm which carries the predominant part of the output amplifier radiation without applying a spectral filtering in any form.

[0040] The invention can be used in industrial and scientific applications such as fine material processing, oil and gas sensing, environment monitoring, and medicine.

[0041] The advantage of the amplifier is its natural simplicity and reliability as compared to the existing analogues.

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- US20020168161A1 [0004]

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- **JIE JIANG et al.**Tunable coherent Raman soliton generation with a Tm-fiber systemCLEO, 2011, 1-2 [0003]

Patentkrav

1. Optisk system omfattende:

en fiberforstærker (5) omfattende en optisk aktiv doteret fiber;

en kilde af seed-impulser (3); og

en pumpekilde (2), hvor

den doterede fiber er doteret med et eller flere aktive elementer valgt således at seed-impulserne (3) forstærkes i intensitet;

den doterede fiber har en negativ gruppehastighedsdispersion i regionen fra bølgelængden af seed-impulserne (3) til en tærskelbølgelængde ved hvilken størrelsen af det optiske tab af den doterede fiber er større end en forstærkning på grund af stimuleret Raman-spredning, således at i anvendelse på grund af stimuleret Raman-spredning, dannelse af et Raman-soliton sker, Raman-solitonet yderligere forskydes i bølgelængdedomænet, og forskydningen af solitonet i bølgelængdedomænet stoppes ved tærskelbølgelængden;

fiberen er doteret med thulium Tm,

fiberen har en negativ gruppehastighedsdispersion i regionen af 1,8 til 2,6 µm;

pumpekilden (2) er indrettet til at pumpe ved en bølgelængde fra 0,77 til 0,82 µm;

kilden af seed-impulser (3) tilvejebringer impulser med bølgelængder fra 1,8-2,1 µm;

varigheden af de optiske seed-impulser er begrænset til mindre end 100 ps;

tærskelbølgelængden er længere end bølgelængden af seed-impulserne (3); og

det optiske system er virksomt til at generere en serie af spektralt separerede solitonimpulser i regionen fra seed-impulsbølgelængden til 2,6 µm.

2. Optisk system ifølge krav 1, hvor den doterede fiber har et markant stigende optisk tab ved tærskelbølgelængden.

3. Optisk system ifølge krav 1 eller 2, hvor omfanget af nævnte optiske tab er valgt til at overvinde forstærkningen på grund af stimuleret Raman-spredning ved den ønskede topintensitet af Raman-solitonet.

4. Optisk system ifølge et hvilket som helst foregående krav, virksomt i en første og anden tilstand,
hvor i den første tilstand det optiske system er virksomt til at generere som dets output en højenergiimpuls kortere end seed-impulsen og omfattende den dominerende del af outputforstærkerstråling uden spektral filtrering og spektralt forskudt til den længere bølgelængderetning,
og hvor i den anden tilstand det optiske system er virksomt til at generere som dets output optisk superkontinuum.

5. Optisk system ifølge krav 4, omfattende en styreindretning til at styre kilden af seed-impulser (3), fortrinsvis hvor styreindretningen er konfigureret til at ændre mindst en af varigheden eller intensitet af seed-impulserne (3) for at skifte mellem den første driftstilstand og den anden driftstilstand.

6. Optisk system ifølge krav 4 eller 5, yderligere omfattende en styreindretning til at styre pumpekilden (2), hvor styreindretningen er konfigureret til at ændre pumpehastigheden for at skifte mellem den første driftstilstand og den anden driftstilstand.

7. Optisk system ifølge et hvilket som helst foregående krav, hvor den doterede fiber er doteret med mindst et element der producerer optisk tab ved tærskelbølgelængden, eller hvor tærskelbølgelængden tilvejebringes ved at afbryde en grundtilstand eller indføre bøjningstab.

8. Optisk system ifølge et hvilket som helst foregående krav, hvor fiberen er silika-baseret.

9. Optisk system ifølge et hvilket som helst af kravene 1 til 7, hvor fiberen er en germanat-glasfiber eller en fiber med et germaniumoxidindhold større end 50 %.

10. Optisk system ifølge krav 1, virksomt i en første tilstand til at generere en solitonimpuls i 2,2-2,8 µm-regionen omfattende den dominerende del af forstærkeroutputstrålingen og i en anden tilstand til at generere superkontinuumstråling fra 1,8-2,6 µm, hvor det er muligt at skifte fra en driftstilstand til en anden ved at ændre inputparametrene af pumpekilden (2) og seed-impulser (3).

11. Fremgangsmåde til drift af et optisk system omfattende:

at tilvejebringe en fiberforstærker (5) som har en optisk aktiv doteret fiber;

at seede fiberforstærkeren med seed-impulser (3); og

at pumpe fiberforstærkeren (5); hvor

den doterede fiber er doteret med et eller flere aktive elementer; og den doterede fiber har en negativ gruppehastighedsdispersion i regionen fra bølgelængden af seed-impulsen til en ønskelig tærskelbølgelængde, således at i anvendelse på grund af stimuleret Raman-spredning, dannelse af et Raman-soliton sker, Raman-solitonet yderligere forskydes i bølgelængdedomænet, og forskydningen af solitonet i bølgelængdedomænet stoppes ved tærskelbølgelængden ved hvilken størrelsen af det optiske tab af den doterede fiber er større end en forstærkning på grund af den stimulerede Raman-spredning, og hvor

at tilvejebringe fiberforstærkeren (5) er at tilvejebringe en thulium-doteret fiberforstærker, hvor den thulium-doterede fiberforstærker (5) har en negativ gruppehastighedsdispersion i regionen af 1,8 til 2,6 µm;

at seede fiberforstærkeren er at seede den thulium-doterede fiberforstærker med seed-impulser (3) som har bølgelængderne fra 1,8-2,1 µm;

at pumpe fiberforstærkeren (5) er at pumpe den thulium-doterede fiberforstærker ved enhver bølgelængde fra 0,77-0,82 µm;

varigheden af de optiske seed-impulser begrænses til mindre end 100 ps;

tærskelbølgelængden er længere end bølgelængden af seed-impulserne (3); og

det optiske system er virksomt til at generere en serie af spektralt separerede solitonimpulser i regionen fra seed-impulsbølgelængden til 2,6 µm.

12. Fremgangsmåde ifølge krav 11 omfattende at generere en solitonimpuls med en bølgelængde på 2,2-2,5 µm, således at den genererede solitonimpuls bærer den dominerende del af forstærkeroutputeffekten; og fortrinsvis omfattende at generere serien af spektralt separerede solitonimpulser i den spektrale region fra seed-impulsbølgelængden til 2,6 µm.

13. Fremgangsmåde ifølge krav 11, omfattende at generere superkontinuumstråling, som dækker regionen på 1,8-2,6 µm.

14. Fremgangsmåde ifølge krav 11, omfattende at generere serien af spektralt separerede solitonimpulser i den spektrale region fra seed-impulsbølgelængden til 2,6 µm i en første driftstilstand, og i en anden driftstilstand, at generere superkontinuumstråling, som dækker regionen på 1,8-2,6 µm; fortrinsvis hvor i den første driftstilstand, serien består af mindst en solitonimpuls i regionen på 2,2-2,5 µm, som bærer den dominerende del af forstærkeroutputeffekten; og/eller fortrinsvis hvor driftstilstanden skiftes mellem de to tilstande ved at ændre inputparametrene af pumpning og seedning.

DRAWINGS

Fig. 1

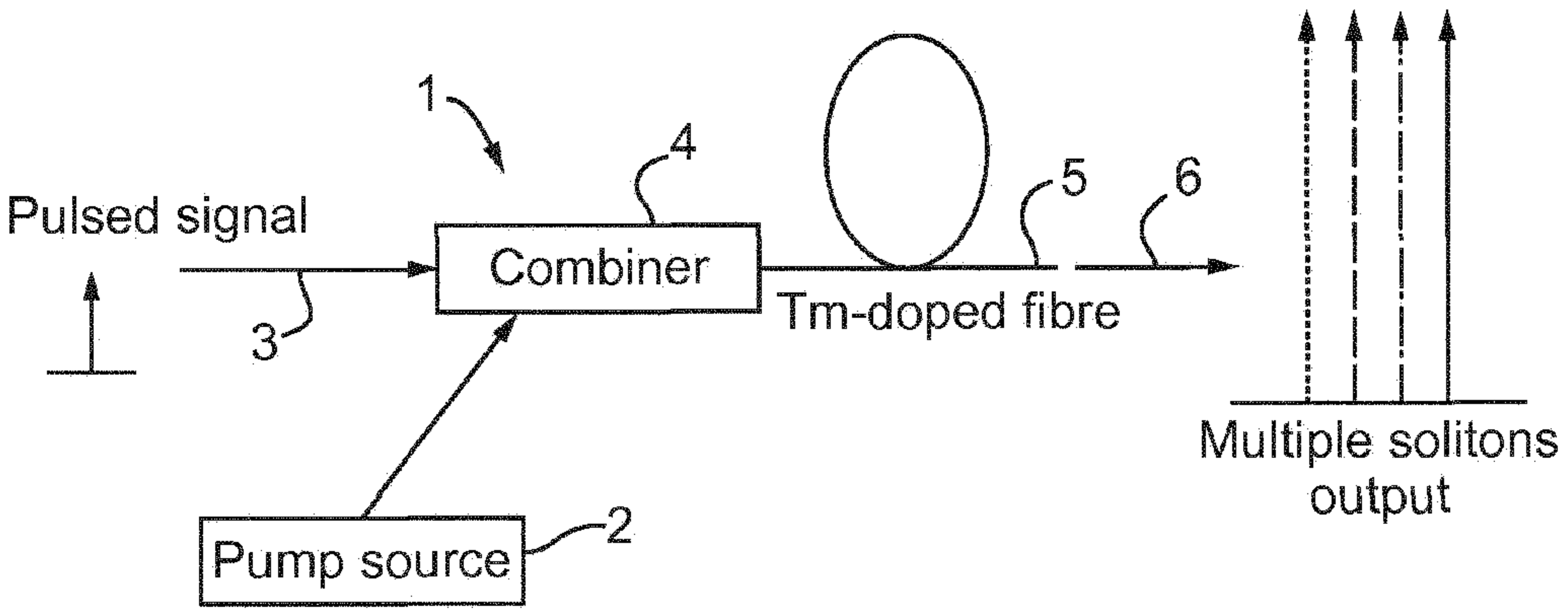

Fig. 2