(54) Title: SUPERCONTINUUM GENERATION USING RAMAN PUMPED OPTICAL CAVITY

(57) Abstract: Apparatus (10) for generating a supercontinuum (SC) in an optical cavity (18) by increasing the power of pump radiation having a first wavelength to cause broadening of laser radiation having a second wavelength, i.e., the Stokes shifted wavelength, in the cavity to generate an output that is a SC. The first wavelength may be selected to cause stimulated Raman scattering in the cavity to generate the laser radiation. The Raman amplification in the cavity may improve the efficiency of the SC generation because the input power, e.g., the power of the source used to pump the cavity, may be distributed over a range of wavelengths. In combination with other effects caused by non-linear optical properties of the cavity, the Raman amplification may generate a SC which exhibits a flat power profile across its broad spectral range.
SUPERCONTINUUM GENERATION USING RAMAN PUMPED OPTICAL CAVITY

FIELD OF THE INVENTION

The invention relates to supercontinuum generation using optical fibres. For example, the invention relates to apparatus for generating a supercontinuum from a continuous wave (CW) source.

BACKGROUND TO THE INVENTION

Supercontinuum (SC) generation in optical fibres has found applications in fields as diverse as time-resolved spectroscopy, optical coherence tomography, multi-wavelength optical sources and optical frequency metrology.

Conventional SC generation using a continuous wave (CW) source makes use of non-linear properties of the optical fibre. In particular, such SC generation requires selecting a wavelength for the CW source at which the fibre exhibits low anomalous dispersion to induce efficiently modulation instability (MI). This MI produces the break-up of the CW into a series of pulses, after which a combination of stimulated Raman scattering (SRS) and parametric processes in the fibre trigger nonlinear broadening over a broad bandwidth, leading to SC emission [1].

WO 2006/096333 discloses a supercontinuum emitting device in which a SC is generated from an effective CW source in an optical fibre using a combination of SRS and four-wave mixing. In this particular example, the non-linear properties are varied for successive fibre segments, e.g. by providing a higher zero dispersion wavelength in each successive fibre segment. This technique may generate a SC output having a ~15 dB (from output peak) spectral bandwidth of 240 nm.

Many of the CW-pumped SC sources in conventional fibres have been developed using highly nonlinear dispersion-shifted fibres (HN-DSFs), e.g. as demonstrated in [2]. Other approaches include the use of dispersion decreasing fibres, which can enhance the width of the generated continuum generation [1], or the use of specifically designed Photonic Crystal Fibre (PCF). Using PCF a SC with 29 W of output power over 600 nm at 8 dB has been demonstrated using a 50 W CW Yb fibre pump source [4]. Using more conventional fibres, a CW-SC source with a 20 dB width in
excess of 232 nm in the 1.2-1.5 µm region was recently achieved [3] using a pump power of the order of 8.7 W.

SUMMARY OF THE INVENTION

At its most general the invention proposes generating a supercontinuum (SC) in a Raman pumped optical cavity by broadening the lasing radiation, i.e. the Stokes wavelength, whereby the output of the cavity is a SC. The Raman amplification in the cavity may improve the efficiency of the SC generation because the input power, e.g. the power of the source used to pump the cavity, may be distributed over a range of wavelengths. In combination with other effects caused by nonlinear optical properties of the cavity, the Raman amplification may generate a SC which exhibits a flat power profile across its broad spectral range. A SC output with a flat power profile may be desirable for use in wavelength division multiplexed transmission.

According to the invention, there may therefore be provided apparatus for generating a supercontinuum, the apparatus comprising: an optical source, and a Raman fibre optic cavity, wherein the source is arranged to pump the cavity above its threshold at a power level arranged to broaden the spectrum of lasing radiation therein into a supercontinuum.

The apparatus is thus operable to generate and amplify a Stokes wavelength in the fibre optic cavity. The supercontinuum may be formed based on the broadening of this Stokes component, e.g. caused by nonlinear properties of the cavity.

A supercontinuum may refer to an output of broadband radiation, e.g. having a wavelength range of 100 nm or more, from a single frequency source in which the spatial coherence of the source may be maintained.

The optical source may be a continuous wave (CW) pump arranged to input optical radiation into the fibre optic cavity. The optical radiation may have a single input wavelength.

The fibre optic cavity may comprise a pair of reflective elements bounding a length of optical fibre e.g. to create a closed cavity, the reflective elements being arranged to cause the cavity to exhibit a high Q value at a Stokes shifted wavelength slightly higher than the zero dispersion wavelength of the optical fibre. The input wavelength and Stokes shifted
wavelength (i.e. the wavelength at which the cavity exhibits its highest Q value) may be selected according to the desired wavelength range of the SC and taking into account the magnitude of the Stokes shift associated with Raman scattering in the optical fibre used for the cavity.

The Stokes shift is similar in most types of silica based optical fibre with a value of approximately 13.2 THz. To efficiently generate a SC having a desired range of wavelengths, the wavelength of the optical pump source may be two Stokes shifts higher in frequency than the frequency range of the SC. The pump generates Stokes shifted lasing radiation within the cavity which is one Stokes shift lower in frequency that the pump source which in turn generates the SC radiation a further Stokes shift lower in frequency.

A method of arranging the apparatus to exhibit SC generation according to the invention may comprise the steps of: selecting a frequency/wavelength range for the supercontinuum output; arranging the cavity to exhibit a reflection spectrum displaced by one Stokes shift (e.g. 13.2 THz for silica fibre) higher in frequency that a centre frequency of the selected frequency range; selecting an optical fibre for the cavity which has slightly anomalous dispersion at a wavelength equivalent to one Stokes shift higher in frequency than the centre frequency of the selected frequency range (i.e. matched with the cavity’s reflection spectrum); and selecting an optical source (pump) with a frequency that is displaced one Stokes shift higher than the cavity’s reflection spectrum, i.e. two Stokes shifts higher than the centre frequency of the selected frequency range.

The reflection spectrum of the cavity may be selected using the optical properties of the reflective elements.

In one specific example, a supercontinuum may be desired in the optical communications C Band, which is the wavelength range from 1530 nm to 1565 nm (i.e. approximately 197 - 191 THz). If a conventional silica fibre (e.g. TrueWave® fibre) is used, the Stokes shift is about 13.2 THz. The cavity may therefore be defined using fibre Bragg gratings as the reflective elements. The grating wavelengths are chosen to be shifted by the equivalent of 13.2 THz from the centre frequency of the C Band range, i.e. the grating wavelength was about 1455 nm. The optical source was arranged to have a pump wavelength displaced by the equivalent of a further 13.2 THz, i.e. to about 1365 nm.
The location of the zero dispersion wavelength of the optical fibre that makes up the cavity is important for efficient supercontinuum generation. To ensure that the cavity exhibits anomalous dispersion at the correct level to facilitate SC generation, e.g. by efficiently inducing modulation instability, the zero dispersion wavelength may be slightly lower than the Stokes shifted wavelength, e.g. 10-20 nm less than the Stokes shifted wavelength.

In the example given above, the zero dispersion wavelength of the optical fibre of the cavity was 1443.5 nm, which is less than the wavelength of the Stokes shifted wavelength (about 1455 nm).

The optical source may include a laser, e.g. a Raman pump laser.

The reflective elements may be reflective for a radiation having limited range of wavelengths and non-reflective, e.g. transmissive, for radiation having wavelengths outside of the limited range. The limited range may be 1 nm, e.g. the limited range may be defined as a 3 dB bandwidth around a central wavelength.

The optical source may be arranged to input optical radiation having a pump wavelength to the fibre optic cavity, the pump wavelength being further from the zero dispersion wavelength of the optical fibre than the Stokes shifted wavelength. The zero dispersion wavelength is thus between the pump wavelength and the Stokes shifted wavelength. In other words the pump wavelength may not be part of the generated SC. The wavelength of radiation reflected in the cavity may be matched to the zero dispersion wavelength of an optical fibre within the cavity to promote SC generation from the lasing radiation.

Each reflective element bounding the cavity may be a fibre Bragg grating having a high reflectivity at the Stokes wavelength.

To further broaden the generated SC, the power level may be selected to cause the lasing radiation in the cavity to include first and second order Stokes components. In this arrangement Raman amplification is used as a mechanism to transfer energy from the optical source to two different wavelengths from where other processes cause spectral broadening to achieve the SC. This is in contrast to conventional SC generation methods where the whole SC is broadened from a single spectral peak. With such
conventional systems it may be difficult to achieve flatness of the SC spectrum because the input power is concentrated at a single point. The invention may overcome this disadvantage by using the Raman amplification process to distribute input energy between different wavelengths (e.g. the first and second order Stokes wavelengths) in the spectrum. This may permit generation of SC spectra with improved flatness.

The fibre optic cavity may comprise a length of conventional single mode silica fibre, e.g. a TrueWave® fibre or the like. However, the fibre cavity may include a highly nonlinear optical fibre, e.g. an optical fibre having a nonlinear coefficient of 10 (Wkm)^{-1} or more. Introducing a highly nonlinear region may enable the cavity to be shorter. The cavity may be made solely of a conventional optical fibre, TrueWave® fibre, or may be made from a combination of conventional optical fibre and highly nonlinear optical fibre. For example, the fibre optic cavity may comprise a first optical fibre length at an end of the cavity closer to the optical source optical connected to a second optical fibre length, wherein a nonlinear coefficient of the second optical fibre length is an order of magnitude higher than that of the first optical fibre length. Moreover, the first optical fibre length may have a zero-dispersion wavelength lower than the central wavelength of the reflective element, so that the fibre exhibits low anomalous dispersion to efficiently induce modulation instability and to facilitate SC generation.

Grading the dispersion and nonlinearity in this manner may improve the efficiency of the SC generation, e.g. by controlling the order in which different nonlinear processes exhibit an effect on the lasing radiation.

The fibre optic cavity may be ultra long, e.g. have a length of 5km or more, or 10 km or more. The length of the fibre optic cavity may be one parameter usable for optimising the SC output, e.g. by selecting a length where the combined effect of the nonlinear processes responsible for broadening the spectrum produces a desirable spectral shape.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples of the invention are described in detail below with reference to the accompanying drawings, in which:
Fig. 1 is a schematic view of supercontinuum generation apparatus that is a first embodiment of the invention;

Fig. 2 illustrates spectra generated using the apparatus of Fig. 1 with a solely TrueWave® cavity at different powers;

Fig. 3 illustrates spectra generated using different cavity setups; and

Fig. 4 illustrates spectra generated with and without a cavity.

**DETAILED DESCRIPTION; FURTHER OPTIONS AND PREFERENCES**

Fig. 1 is a schematic diagram showing supercontinuum generation apparatus 10 that is an embodiment of the invention. The apparatus shown is an experimental setup which enables the spectra shown in Figs. 2-4 to be measured. An embodiment of the invention need not possess all of the features illustrated in Fig. 1.

The present invention arises from the realisation by the inventors that a new breed of Raman lasers with ultra-long cavities [5] opens the possibility for a new kind of CW-pumped SC generation architecture, which offers the possibility of improved spectral flatness and SC bandwidth whilst also allowing an increase in SC generation efficiency.

In the illustrated embodiment, the apparatus 10 comprises an optical source comprising a Raman pump laser 12 operating at 1365 nm in optical communication with a fibre optic cavity 18. The cavity is defined between two highly reflective (~98% reflectivity) fibre Bragg gratings 14, 16. Each grating has a 3 dB bandwidth of 1 nm, centred at 1455 nm. The pump laser 12 forward pumps the cavity 18 such that a high-Q cavity is formed to efficiently trap the Stokes shifted wavelength. The wavelength of the gratings 14, 16 may be chosen to match the first order Stokes wavelength to increase the power conversion efficiency of the apparatus.

If the cavity is pumped above its threshold, lasing of a stable Stokes component at 1455 nm is observed. To generate a SC, the power level of the pump laser 12 is increased to facilitate broadening of the lasing radiation due to dispersion and other nonlinear processes in the cavity 18.

In the embodiment the fibre optic cavity 18 consists of 11 km of TrueWave® (i.e. conventional single mode) fibre 20 followed
by 1.1 km of a highly nonlinear fibre 22. The TrueWave® fibre 20 has a zero-dispersion wavelength of ~1443.5 nm, a dispersion slope of 0.046 ps/nm²/km and a nonlinear coefficient of ~1.84 (W/km)^1 at 1550nm. The highly nonlinear fibre 22 has a zero dispersion wavelength of ~1464.5 nm and a nonlinear coefficient of more than 10 (W/km)^1.

To measure the spectrum generated in the cavity 18, a 99:1 coupler 24 was placed at the output grating 16. The coupler 24 communicates the generated SC power and spectrum to an optical spectrum analyzer 26 having resolution of ~0.07 nm.

Beyond the output grating 16 the signal from the cavity was split between a output spectrum analyser 28 and a power meter 30 for measuring the output spectrum and output power respectively.

Fig. 2 illustrates the evolution of the generated radiation inside the cavity 18 as pump power increases. In this example the cavity consists only of the 11 km length of TrueWave® fibre 20. The vertical line 32 indicates the zero-dispersion wavelength of the fibre 20. It may be seen that the first Stokes wavelength 34 is much closer to the zero dispersion wavelength than the pump wavelength 36. This is because the apparatus is arranged to generate a SC based on the lasing radiation; to introduce efficiently modulation instability for initiating SC generation, the wavelength of interest on which the SC is based may be provided near to the zero dispersion point of the fibre.

Fig. 2 shows that for input powers up to 3 W the bandwidth of the SC radiation increases but for powers higher that this threshold the first Stokes wave is depleted and the efficiency of the SC generated spectrum is degraded.

These results show that through the process of stimulated Raman scattering the primary 1365 nm pump may generate a first order Stokes component around the wavelength of the gratings (1455 nm). With increasing power clear signs of modulation instability and broadening of the wings of this spectral component are observed. With nearly 1 W of input pump power the generation of a second order Stokes component 38 at 1555 nm may also be observed. By increasing the injected pump radiation inside the cavity, generation of a supercontinuum spectrum ranging from 1440 to 1670 nm can be observed. This SC was generated without any specialist fibre: Fig. 2 illustrates an arrangement in which the cavity 18 consists only of 11 km of conventional TrueWave® fibre.
Fig. 3 shows SC spectra for three different fibre configurations operating at their optimum launch powers, i.e. the power at which the spectrum exhibit the most flatness over a broad spectral range. The first configuration corresponds to the arrangement used for Fig. 2, i.e. 11 km of TrueWave® fibre 20 only. The second configuration corresponds to that illustrated in Fig. 1, i.e. a cavity 18 having 11 km of TrueWave® fibre 20 followed by an additional 1.1 km of highly nonlinear fibre 22. The third configuration (not illustrated) is similar to the second but provides the highly nonlinear fibre 22 first in the cavity, i.e. at the optical source end of the cavity.

The highly nonlinear fibre 22 is provided with a view to enhancing the range and flatness of the supercontinuum radiation from the TW fibre alone.

To optimise the arrangement, the spectrum at various powers is monitored to find a flat SC output. In each configuration of the embodiment the output pump power was optimised at 1.72 W.

The spectra in Fig. 3 show that the efficiency of the SC generation is maximized for a cavity in which conventional (lower nonlinearity) fibre precedes specialist (higher nonlinearity) fibre, i.e. corresponding to the second configuration. In this case the bandwidth of the SC output for the second configuration extended beyond 1700 nm which was the limit of the analyzer. Moreover, for this configuration the power variation of the output was less than 1 dB over a range of 180 nm from 1490 to 1670 nm for an input pump power of only 1.72 W.

Fig. 4 shows optical power spectra of a generated SC with and without the gratings in place, i.e. with and without a lasing cavity 18. Thus, Fig. 4 illustrates the effect that the use of the cavity has on the generated supercontinuum.

Both spectra correspond to pump powers of 2.65 W, but the broadening is significantly enhanced inside the cavity due to the Stokes wave trapping and more efficient generation of the 1455 nm Stokes component, which translates also into an increased SC output power.

In addition, four wave mixing processes caused by the interaction of the large number of longitudinal modes may have an important influence in the first stages of SC generation within the cavity.

The apparatus of the invention may thus show an improvement in SC generation efficiency though the use of ultra-long cavity
Raman amplification. In one embodiment a spectrum exhibiting flatness within 1 dB over a 180 nm range from 1490 nm to 1670 nm was achieved with an input pump power of only 1.72 W using hybrid cavity comprising a combination of conventional (lower nonlinearity) fibre and specialist (higher nonlinearity) fibre. In another embodiment a pump power of 2.65 W was used to achieve a SC having an average power output of 1.15 W and a ~15 dB bandwidth of more than 260 nm from 1440 to more than 1700 nm.

REFERENCES

CLAIMS

1. Apparatus for generating a supercontinuum, the apparatus comprising:
an optical source, and
a Raman fibre optic cavity in optical communication with
the source,
wherein the source is arranged to pump the cavity above its
threshold at a power level to generate a spectrum of Stokes
shifted radiation, and the cavity is arranged to broaden the
spectrum of Stokes shifted radiation therein into a
supercontinuum.

2. Apparatus according to claim 1, wherein the cavity
comprises a pair of reflective elements bounding a length of
optical fibre, the reflective elements being arranged to cause
the cavity to exhibit a high Q value at a Stokes shifted
wavelength that is slightly more than the zero dispersion
wavelength of the optical fibre.

3. Apparatus according to claim 2, wherein the optical
source is arranged to input optical radiation having a pump
wavelength to the fibre optic cavity, the pump wavelength being
further from the zero dispersion wavelength of the optical fibre
than the Stokes wavelength.

4. Apparatus according to claim 2 or 3, wherein each
reflective element is a fibre Bragg grating having a high
reflectivity at the Stokes shifted wavelength.

5. Apparatus according to claim 4, wherein the Stokes
shifted wavelength is displaced by another Stokes shift from a
centre frequency of the supercontinuum.

6. Apparatus according to any preceding claim, wherein
the optical source includes a laser.

7. Apparatus according to any preceding claim, wherein
the power level is selected to cause the Stokes shifted radiation
in the cavity to include first and second order Stokes
components.
8. Apparatus according to any preceding claim, wherein the fibre optic cavity comprises a length of optical fibre having a nonlinear coefficient of 10 $\text{Wkm}^{-1}$ or more.

9. Apparatus according to any preceding claim, wherein the fibre optic cavity comprises a first optical fibre length at an end of the cavity closer to the optical source optical connected to a second optical fibre length, wherein a nonlinear coefficient of the second optical fibre length is an order of magnitude higher than that of the first optical fibre length.

10. Apparatus according to any preceding claim, wherein the fibre optic cavity has a length of 10 km or more.
Fig. 3

Fig. 4
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01S3/30 G02F1/365
ADD. H01S3/067

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbol)

H01S G02F

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

Electronic data base consulted during the international search (name of data base and, where practical, search items used)

EPO-Internal, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category* Citation of document, with indication, where appropriate, of the relevant passages Relevant to claim No.


the whole document figure 1 pages 114204-2, right-hand column - pages 114204-3, right-hand column

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X Further documents are listed in the continuation of Box C.

* Special categories of cited documents:

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"Y" document member of the same patent family

Date of the actual completion of the international search

5 November 2009

Date of mailing of the international search report

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