



- (51) **International Patent Classification:**
G02F 1/35 (2006.01) *G02F 1/39* (2006.01)
- (21) **International Application Number:**
PCT/EP2014/059018
- (22) **International Filing Date:**
2 May 2014 (02.05.2014)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
1407685.5 1 May 2014 (01.05.2014) GB
- (71) **Applicants:** **FUNDACIÓ INSTITUT DE CIÈNCIES FOTÒNIQUES (ICFO)** [ES/ES]; Parque Mediterráneo de la Tecnología, Av. Carl Friedrich Gauss, 3, Castelldefels, E-08860 Barcelona (ES). **INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS (ICREA)** [ES/ES]; Pg. Lluís Companys, 23, E-08010 Barcelona (ES).
- (72) **Inventors:** **EBRAHIM-ZADEH, Majid**; C/o FUNDACIÓ INSTITUT DE CIÈNCIES FOTÒNIQUES (ICFO), Parque Mediterráneo de la Tecnología, Av. Carl Friedrich Gauss, 3, Castelldefels, E-08860 Barcelona (ES). **BADARLA, Venkata Ramaiah**; C/o FUNDACIÓ INSTITUT DE CIÈNCIES FOTÒNIQUES (ICFO), Parque Mediterráneo de la Tecnología, Av. Carl Friedrich Gauss, 3, Castellde-

fels, E-08860 Barcelona (ES). **ESTEBAN-MARTÍN, Adolfo**; C/o FUNDACIÓ INSTITUT DE CIÈNCIES FOTÒNIQUES (ICFO), Parque Mediterráneo de la Tecnología, Av. Carl Friedrich Gauss, 3, Castelldefels, E-08860 Barcelona (ES). **SUDDAPPALI, Chaitanya Kumar**; C/o FUNDACIÓ INSTITUT DE CIÈNCIES FOTÒNIQUES (ICFO), Parque Mediterráneo de la Tecnología, Av. Carl Friedrich Gauss, 3, Castelldefels, E-08860 Barcelona (ES).

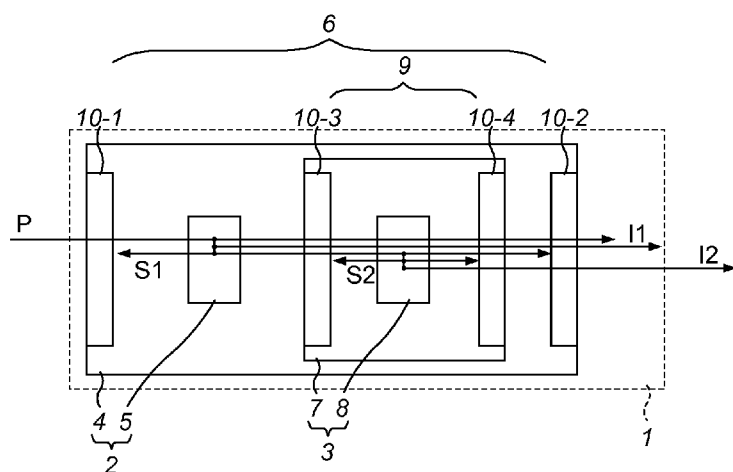
- (74) **Agent:** **TAYLOR, David Matthew Joseph**; Stratagem IPM Limited, Meridian Court, Comberton Road, Toft, Cambridge CB23 2RY (GB).

- (81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,

[Continued on next page]

- (54) **Title:** Internally cascaded optical parametric oscillators



- (57) **Abstract:** Apparatus (1) is configured to provide output light. The apparatus (1) comprises a first optical parametric oscillator (2) to produce first signal light (S1) and first idler light (I1) in response to pump light (P). The first optical parametric oscillator (2) comprises a first cavity (4) and a first nonlinear optical element (5) in the first cavity (4). The first cavity (4) is configured to resonate one (S1) of the first signal light (S1) and first idler light (I1). The apparatus (1) also comprises a second optical parametric oscillator (3) to produce second signal light (S2) and second idler light (I2) in response to the resonated one (S1) of the first signal light (S1) and first idler light (I2), wherein at least one of the second signal light (S2) and second idler light (I2) corresponds to the output light. The second optical parametric oscillator (3) comprises a second cavity (7) and a second nonlinear optical element (8) in the second cavity (7). The second nonlinear optical element (8) is also in the first cavity (4).

FIG. 1



UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

Title

Internally cascaded optical parametric oscillators

Field

5 The present invention relates to optical parametric oscillators that can be described as internally cascaded.

Background

Optical parametric oscillators, which convert input laser light beams with a frequency ω_p into
10 two output laser light beams of lower frequency (ω_s, ω_i) by means of a second-order nonlinear optical interaction, are well known. The output beam with the higher frequency (ω_s) can be designated as the signal, and the output beam with lower frequency (ω_i) can be designated as the idler. These designations are used herein. In some instances, the opposite designations may be used. The sum of the output beams' frequencies is equal to the input beam's
15 frequency, i.e. $\omega_s + \omega_i = \omega_p$.

Summary

According to a first aspect of the present invention, there is provided apparatus configured to provide output light, the apparatus comprising:

20 a first optical parametric oscillator to produce first signal light and first idler light in response to pump light, the first optical parametric oscillator comprising a first cavity and a first nonlinear optical element in the first cavity, wherein the first cavity is configured to resonate one of the first signal light and first idler light; and

a second optical parametric oscillator to produce second signal light and second idler
25 light in response to the resonated one of the first signal light and first idler light, wherein at least one of the second signal light and second idler light corresponds to the output light, the second optical parametric oscillator comprising a second cavity and a second nonlinear optical element in the second cavity;

wherein the second nonlinear optical element is also in the first cavity.

30

Thus, the apparatus can provide greater flexibility to use certain pump sources in combination with certain nonlinear optical materials (in the second optical parametric oscillator), and can do so in an effective way, for example due to the high internal intensity of the first signal light or first idler light resonated by the first cavity.

Optional features are specified in the dependent claims.

Further advantages are described below.

5

Brief Description of the Drawings

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

10 Figure 1 schematically illustrates an apparatus including two optical parametric oscillators that can be described as internally cascaded.

Figure 2 illustrates a system including another apparatus including two optical parametric oscillators that can be described as internally cascaded.

15

Figure 3 shows a part of an apparatus as illustrated in Figure 2 in operation.

Figure 4 shows, for an apparatus as illustrated in Figure 2, the spectral and temporal characteristics of pump light ((a) and (b), respectively) and of signal light produced in the first of
20 the two optical parametric oscillators ((c) and (d), respectively). This ("resonant") signal light is resonated by the cavity of the first of the two optical parametric oscillators and acts as pump light for the second of the two optical parametric oscillators.

Figure 5 shows, for an apparatus as illustrated in Figure 2, changes in the wavelengths of
25 resonant signal light produced in the second of the two optical parametric oscillators. The changes are caused by cavity delay detuning of the second optical parametric oscillator.

Figure 6 shows, for an apparatus as illustrated in Figure 2, changes in the wavelength of the resonant signal light and non-resonant idler light produced in the second of the two optical
30 parametric oscillators. The figure also shows corresponding changes in the power of the signal light. The changes are caused by cavity length tuning of the second optical parametric oscillator. The experimental conditions correspond to those in Figure 5.

Detailed Description of the Certain Embodiments*First apparatus*

Referring to Figure 1, an apparatus 1 (hereinafter referred to as a first apparatus) will now be described. The first apparatus 1 includes two optical parametric oscillators 2, 3 (hereinafter referred to as first and second oscillators) that can be described as internally cascaded, as will be explained in more detail below.

The first oscillator 2 includes an optical resonator or, in other words, a cavity 4 (hereinafter referred to as the first cavity) and a nonlinear optical element 5 (hereinafter referred to as the first nonlinear optical element). The first nonlinear optical element 5 is in the first cavity 4. In other words, at least a portion of the first nonlinear optical element 5 lies in a path 6 (hereinafter referred to as the first path) of a light beam that is resonated by the first cavity 4.

The second oscillator 3 includes a cavity 7 (hereinafter referred to as the second cavity) and a nonlinear optical element 8 (hereinafter referred to as the second nonlinear optical element). The second nonlinear optical element 8 is in the second cavity 7 and is also in the first cavity 4. In other words, at least a portion of the second nonlinear optical element 8 lies in a path 9 (hereinafter referred to as the second path) of a light beam that is resonated by the second cavity 7, and also lies in the first path 6.

The first oscillator 2 is configured to receive (laser) light (hereinafter referred to as pump light) from a pump source (not shown). The pump light may have any suitable frequency. The pump light may be in the form of a continuous-wave or may be in the form of pulses. The pulses may have pulse widths of between about 1 and 1000 microseconds, between about 1 and 1000 nanoseconds, between about 1 and 1000 picoseconds or between about 1 and 1000 femtoseconds. Pulses with these widths are hereinafter referred to as microsecond, nanosecond, picosecond and femtosecond pulses, respectively. The pulse widths may be longer or shorter than this. The first oscillator 2 is preferably configured to receive the pump light in a direction along at least a part of the first path 6.

The first nonlinear optical element 5 is configured to produce signal and idler light (hereinafter referred to as first signal light and first idler light, respectively) in response to the first pump light.

The first cavity 4 is preferably configured to resonate either the first signal light or the first idler light (not both). The resonated one of the first signal light and first idler light is hereinafter referred to as the first resonant light, while the other one is hereinafter referred to as the first non-resonant light. In the example illustrated in the figure, the first cavity 4 is configured to resonate the first signal light.

The first cavity 4 is formed from a plurality of optical elements (hereinafter referred to simply as mirrors 10) configured to transmit and/or reflect incident light as appropriate. In the example illustrated in the figure, the first cavity 4 is formed from two mirrors 10-1, 10-2 (hereinafter referred to as first and second mirrors). However, the first cavity 4 may be formed from any number of two or more mirrors 10.

Preferably, at least one of the mirrors 10 of the first cavity 4 (e.g. the first mirror 10-1) is transmissive (e.g. has a transmittance of greater than about 90%) for the pump light, to enable the pump light to enter the first cavity 4.

Preferably, all of the mirrors 10 of the first cavity 4 are highly reflective (e.g. have a reflectivity of greater than about 99%) for the first resonant light.

Preferably, at least one of the mirrors 10 of the first cavity 4 (e.g. the first mirror 10-1) is transmissive (e.g. has a transmittance of greater than about 90%) for the first non-resonant light, to enable the first non-resonant light to exit the first cavity 4.

In some examples (including the example illustrated in the figure), at least one of the mirrors 10 (e.g. the second mirror 10-2) is transmissive (e.g. has a transmittance of greater than about 90%) for the output light provided by the second cavity 7 (see below), to enable this light to exit the first cavity 4. In other examples (e.g. where the output light provided by the second cavity 7 does not propagate along a path which passes through any of the mirrors 10 of the first cavity 4), this need not be the case.

Because the second nonlinear optical element 8 lies in the first path 6, the first resonant light is incident on the second nonlinear optical element 8. The second nonlinear optical element 8 is configured to provide signal and idler light (hereinafter referred to as second signal light and

second idler light, respectively) in response to the first resonant light. In other words, the first resonant light acts as pump light for the second nonlinear optical element 8.

5 In the figure, the pump light, first signal light, first idler light, second signal light and second idler light are denoted by P, S1, I1, S2 and I2, respectively. In the figure, the paths associated with the different light beams are offset to improve clarity. In actuality, the paths are not offset in this way.

10 The second cavity 7 is preferably configured to resonate either the second signal light or the second idler light (not both). The resonated one of the second signal light and second idler light is hereinafter referred to as the second resonant light, while the other one is hereinafter referred to as the second non-resonant light. The second cavity 7 is preferably configured to provide output light that corresponds to the second non-resonant light. However, the second cavity 7 may be configured to provide output light that corresponds to the second resonant
15 light, for example via a partially-transmitting element, e.g. the mirror 10-4 (see below). In the example illustrated in the figure, the second cavity 7 is configured to resonate the second signal light and to provide the (longer wavelength) second idler light as the output light.

20 The second cavity 7 is formed from a plurality of mirrors 10. In the example illustrated in the figure, the second cavity 7 is formed from two mirrors 10-3, 10-4 (hereinafter referred to as third and fourth mirrors). However, the second cavity 7 may be formed from any number of two or more mirrors 10.

25 In the example illustrated in the figure, the second cavity 7 is formed from mirrors 10-3, 10-4 that are different from the mirrors 10-1, 10-2 of the first cavity 4. However, one or more mirrors 10 may be common to the first and second cavities 4, 7. In some examples (e.g. examples in which the pump light etc. is in the form of a continuous-wave or microsecond, nanosecond or picosecond pulses), the first apparatus may include a single mirror in place of the second and fourth mirrors 10-2, 10-4. This single mirror may provide the abovedescribed
30 functions of the second and fourth mirrors 10-2, 10-4, e.g. highly reflect the first and second (resonant) signal light and highly transmit the first and second (non-resonant) idler light. In these examples, the first and third mirrors 10-1 and 10-3 may also function as described above. This can provide a particularly simple arrangement, which can be used in non-femtosecond-pulse cases.

In the example illustrated in the figure, the second path 9 corresponds to a part of the first path 6 and hence the second cavity 7 can be described as being in the first cavity 4. However, this need not be the case. For example, the first path 6 may correspond to a part of the second path 9, or each of the first and second paths 6, 9 may comprise a part that is common to the first and second paths 6, 9 and a part that is not common to the first and second paths 6, 9.

In some examples (including the example illustrated in the figure), at least one of the mirrors 10 of the second cavity 7 (e.g. the third mirror 10-3) is transmissive (e.g. has a transmittance of greater than about 99%) for the first resonant light, to enable the first resonant light to enter the second cavity 7. Moreover, the transmittance of all of the elements of the apparatus 1 that are within the first cavity 4 (e.g. the third and fourth mirrors 10-3 and 10-4 and the first and second nonlinear optical elements 5, 8) is preferably as high as possible (e.g. greater than 99%) for the first resonant light. This is very important for minimising the intracavity losses of the first resonant light and so maximising the intracavity intensity of the first resonant light so that it is above a threshold intensity for operation of the second oscillator 3 (for which the first resonant light acts as pump light).

In some examples (including the example illustrated in the figure), at least one of the second mirrors 10 (e.g. the fourth mirror 10-4) is transmissive (e.g. has a transmittance of greater than about 90%) for the first non-resonant light, to enable the first non-resonant light to exit the second cavity 7. In other examples (e.g. where the first non-resonant light does not propagate along a path which passes through any of the mirrors 10 of the second cavity 7), this need not be the case.

Preferably, all of the mirrors 10 of the second cavity 7 are highly reflective (e.g. have a reflectivity of greater than about 99%) for the second resonant light.

Preferably, at least one of the mirrors 10 (e.g. the fourth mirror 10-4) is transmissive (e.g. has a transmittance of greater than about 90%) for the second non-resonant light, to enable the second non-resonant light to exit the second cavity 7, thereby forming the output light.

Accordingly, in this example, the first cavity 4 is configured to maximally resonate only one of the first signal light and first idler light, and the second cavity 7 is configured to maximally

resonate only one of the second signal light and second idler light. Thus, the first apparatus 1 can operate stably and with the lowest (or minimal) operation threshold for both oscillators 2, 3.

- 5 The output light may be processed by an output system (not shown) before being provided to further apparatus (not shown).

Second apparatus

Referring to Figure 2, a system 50 will now be described. The system 50 includes a pump
10 source 51, an optical isolator 52, a half-wave plate 53, a lens 54 and an apparatus 1' (hereinafter referred to as the second apparatus). The second apparatus 1' includes features 2'...10' that correspond to the respective features 2...10 of the first apparatus 1.

In this example, the pump source 51 includes a Kerr-lens mode-locked titanium-sapphire laser
15 configured to provide femtosecond pulses of pump light. In other examples, the pump source 51 may include a different type of mode-locked laser, e.g. any mode-locked fibre laser, mode-locked crystalline solid-state laser or mode-locked semiconductor laser. In this example, the pulses include light with a wavelength of 796 nanometres and a spectral bandwidth of about 7
20 nanometres, have a pulse width of about 155 femtoseconds, and have an average power of about 900 milliwatts (the values of spectral bandwidth, pulse width and average power are after transmission through the optical isolator 52). The pulses are substantially transform-limited. In other examples, the pulses may have one or more different parameters. One or more parameters of the pulses may be controllable. In other examples, the pump source 51
25 may be configured to provide continuous-wave light. In other examples, the pump source 51 may be any type of (e.g. solid-state crystalline, fibre, semiconductor, etc.) laser.

The pump light is provided from the pump source 51 to the second apparatus 1' via the optical
isolator 52, the half-wave plate 53 and then the lens 54. The optical isolator 52 is configured to protect the pump source 51 from any back reflections. The half-wave plate 53 is configured to
30 provide pump light with a suitable polarization for phase-matching in the first nonlinear optical element 5'. In this example, the polarisation corresponds to extraordinary polarisation. In other examples, the polarisation may be different. The lens 54 is configured to focus the pump light onto the first nonlinear optical element 5'. In this example, the lens 54 has a focal length of 8 centimetres and focuses the pump light to a waist radius of about 25 micrometres inside

the first nonlinear optical element 5'. In other examples, the lens 54 may be different (or omitted).

In this example, the first nonlinear optical element 5' corresponds to a magnesium oxide doped periodically-poled lithium niobate (MgO:PPLN) crystal, and the second nonlinear optical element 8' corresponds to a cadmium silicon phosphide (CSP) crystal. The CSP crystal is cut at $\theta = 45^\circ$ and $\phi = 0^\circ$. With direct pumping at about 1 micrometre, CSP is able to generate light with wavelengths above about 6 micrometres under noncritical phase-matching at room temperature.

In other examples, one or both of the nonlinear optical elements 5', 8' may correspond to a different type of crystal. For example one or both of the nonlinear optical elements 5', 8' may correspond to a (different type of) periodically-poled crystal. One or both of the nonlinear optical elements 5', 8' may correspond to a (different type of) birefringent crystal. One or both of the nonlinear optical elements 5', 8' may be formed from MgO:PPLN, magnesium oxide-doped periodically-poled stoichiometric lithium tantalite (MgO:sPPLT), periodically-poled potassium titanyl phosphate (PPKTP), periodically-poled potassium titanyl arsenate (PPKTA), periodically-poled rubidium titanyl arsenate (PPRTA), periodically-poled rubidium titanyl phosphate (PPRTP), potassium titanyl phosphate (KTP), potassium titanyl arsenate (KTA), cesium titanyl arsenate (CTA), rubidium titanyl phosphate (RTP), rubidium titanyl arsenate (RTA), lithium triborate (LBO), beta barium borate (BBO), CSP, zinc germanium phosphide (ZnGeP₂, ZGP), or orientation-patterned gallium arsenide (OP-GaAs).

In this example, the first nonlinear optical element 5' is 500-micrometres-long (in a direction parallel to the direction of propagation of the pump light), 3.4-millimetres-wide and 1-millimetre-thick. The first nonlinear optical element 5' includes fan-out gratings, with grating periods varying from about 16 to 23 micrometres across its width. The second nonlinear optical element 8' is 500-micrometres-long. In other examples, one or both of the nonlinear optical elements 5', 8' may have different dimensions. The first nonlinear optical element 5', may have a grating with a grating period that varies in a different way, or is constant.

The first nonlinear optical element 5' (i.e. the MgO:PPLN crystal) may be configured to produce first signal light with a (peak) wavelength of 1024 nanometres and first idler light with a wavelength of 3587 nanometres in response to the first pump light with a wavelength of 796

nanometres. The second nonlinear optical element 8' (i.e. the CSP crystal) may be configured to produce second signal light with a wavelength between 1171 and 1236 nanometres and second idler light with a wavelength between 8049 and 5916 nanometres in response to the first signal light.

5

In this example, the first nonlinear optical element 5' produces the first signal light with extraordinary polarisation and the first idler light with extraordinary polarisation in response to the pump light with extraordinary polarisation (phase-matching type 0). The second nonlinear optical element 8' produces the second signal light with ordinary polarisation and the second idler light with ordinary polarisation in response to the first signal light with extraordinary polarisation (phase-matching type I).

10

In this example, each of the first and second cavities 4', 7' corresponds to a standing wave cavity. In other examples, one or both of the cavities 4', 7' may correspond to a different type of cavity, e.g. a different standing wave cavity or a ring cavity.

15

The first cavity 4' is formed from first, second, third, fourth, fifth and sixth mirrors, 10'-1...10'-6. The second cavity 7' is formed from the same first, second, third, fourth and fifth mirrors 10'-1...10'-5, and a seventh mirror 10'-7. As will be explained in more detail below, an eighth mirror 10'-8 is temporally used in place of the fifth mirror 10'-5.

20

The first, second, third and fourth mirrors 10'-1...10'-4 correspond to concave mirrors. The first and second mirrors 10'-1, 10'-2 are arranged as a pair. The third and fourth mirrors 10'-3, 10'-4 are arranged as a pair. In this example, the third and fourth mirrors 10'-3, 10'-4 each have a radius of curvature of 100 millimetres and are separated by 100 millimetres. In this example, the first and second mirrors 10'-1, 10'-2 also have a radius of curvature of 100 millimetres. The first nonlinear optical element 5' is arranged between the first and second mirrors 10'-1, 10'-2. The second nonlinear optical element 8' is arranged between the third and fourth mirrors 10'-3, 10'-4. The fifth, sixth, seventh and eighth mirrors 10'-5...10'-8 correspond to plane mirrors. All of the mirrors 10'-1...10'-8 are broadband highly reflecting (with a reflectivity of greater than 99.8 %) for the wavelength range 980 to 1640 nanometres, and highly transmissive (with a transmittance of greater than 90 %) for the wavelength range 710 to 840 nanometres.

25

30

Accordingly, the first cavity 4' is configured to resonate the first signal light with the wavelength of 1024 nanometres, but not the pump light with the wavelength of 796 nanometres nor the first idler light with the wavelength of 3587 nanometres. The second cavity 7' is configured to resonate the second signal light with the wavelength between 1171 and 1236 nanometres, but not the second idler light with the wavelength between 8049 and 5916 nanometres.

The first and second cavities 4', 7' include an element (hereinafter referred to as a discriminant 11) configured to receive the first and second resonant light propagating along a common path, and to provide the first and second resonant light propagating along different paths, and vice versa. Accordingly, the discriminant 11 can act as an interlink between common and separate parts of the first and second paths 6', 9'. In this example, the discriminant 11 corresponds to a thin film-polarizer 11. In other examples, the discriminant 11 may correspond to another type of optical element, e.g. a mirror or dichroic filter. In this example, the discriminant 11 is highly reflective (with a reflectivity of greater than 99 %) for wavelengths between 1000 and 1100 nanometres and highly transmissive (with a transmittance of greater than 98%) for wavelengths between 1150 and 1350 nanometres. This applies for both extraordinary and ordinary polarizations. Accordingly, the first resonant (signal) light with the wavelength of 1024 nanometres is reflected by the discriminant 11 and the second resonant (signal) light with the wavelength between 1171 and 1236 nanometres is transmitted by the discriminant 11. As will be explained in more detail below, the discriminant 11 is positioned such that the first resonant (signal) light propagates from the fourth mirror 10'-4, via the discriminant 11, to the sixth mirror 10'-6 (and back), whereas the second resonant (signal) light propagates from the fourth mirror 10'-4, via the discriminant 11, to the seventh mirror 10'-7 (and back).

As will be explained in more detail below, in this example, the discriminant enables the cavity lengths of the first and second cavities 4', 7' to be separated so that they can be adjusted independently of each other. In some examples, there may be more than one discriminant 11.

The second apparatus 1' preferably includes two prisms 12-1, 12-2 in a common part of the first and second paths 6', 9'. The prisms 12-1, 12-2 are configured to compensate for group delay dispersion. In this example, the prisms 12-1, 12-2 are separated by a distance of 21.6 centimetres. In other examples, the second apparatus 1' may include different elements for dispersion compensation, such as suitably dispersive bulk crystal elements, or suitably

chirped mirrors used in place of some or all of the first, second, third, fourth, sixth, seventh and eighth mirrors $10'-1...10'-4$, $10'-6...10'-8$.

In the figure, the pump light, first signal light, first idler light, second signal light and second idler light are denoted by P, S1, I1, S2 and I2, respectively. In the figure, the first and second paths $6'$, $9'$ are offset to improve clarity. In actuality, the paths $6'$, $9'$ are not offset in this way.

The pump light is provided to the first nonlinear optical element $5'$ through the first mirror $10'-1$.

The first resonant (signal) light produced by the first nonlinear optical element $5'$ propagates along the first path $6'$. In particular, the first resonant (signal) light propagates from the first nonlinear optical element $5'$ to the second mirror $10'-2$, the prisms 12-1, 12-2, the fifth mirror $10'-5$, the prisms 12-1, 12-2, the second mirror $10'-2$, the first nonlinear optical element $5'$, the first mirror $10'-1$, the third mirror $10'-3$, the second nonlinear optical element $8'$, the fourth mirror $10'-4$, the discriminant 11, the sixth mirror $10'-6$, the discriminant 11, the fourth mirror $10'-4$, the second nonlinear optical element $8'$, the third mirror $10'-3$, the first mirror $10'-1$, and then back to the first nonlinear optical element $5'$, etc.

The pump light, and the first non-resonant (idler) light produced by the first nonlinear optical element $5'$, exits the first cavity $4'$ predominantly through the second mirror $10'-2$.

The second resonant (signal) light produced by the second nonlinear optical element $8'$ propagates along the second path $9'$. In particular, the second resonant (signal) light propagates from the second nonlinear optical element $8'$ to the fourth mirror $10'-4$, the discriminant 11, the seventh mirror $10'-7$, the discriminant 11, the fourth mirror $10'-4$, the second nonlinear optical element $8'$, the third mirror $10'-3$, the first mirror $10'-1$, the first nonlinear optical element $5'$, the second mirror $10'-2$, the prisms 12-1, 12-2, the fifth mirror $10'-5$, the prisms 12-1, 12-2, the second mirror $10'-2$, the first nonlinear optical element $5'$, the first mirror $10'-1$, the third mirror $10'-3$, and then back to the second nonlinear optical element $8'$, etc.

The second non-resonant (idler) light produced by the first nonlinear optical element $5'$ exits the first cavity $4'$ predominantly through the third and fourth mirrors $10'-3$, $10'-4$. This light corresponds to the output light. This light propagates in two directions because the first signal

light (which acts as the pump light) resonates in both directions in the standing-wave-type first cavity 4'.

During an initial phase in which the second apparatus 1' is being set up, the prisms 12-1, 12-2
5 can be removed from the first and second paths 6', 9', such that the first and second resonant light propagates directly from the second mirror 10'-2 to the eighth mirror 10'-8 (and back). This can facilitate the setting up.

Furthermore, the second nonlinear optical element 8' can be optimally positioned in relation to
10 the focus of the third and fourth mirrors 10'-3, 10'-4 by adjusting the position of the second nonlinear optical element 8' to maximise the power of the second signal light and second idler light. The second nonlinear optical element 8' is preferably mounted on a translation stage (not shown).

Furthermore, the length of the first and second cavities 4', 7' can be independently adjusted
15 such that the first nonlinear optical element 5' is synchronously pumped by the pump light and the second nonlinear optical element 8' is synchronously pumped by the first resonant (signal) light. The position of the sixth mirror 10'-6 can first be adjusted to achieve oscillation in the first cavity 4' and to maximise the power of the first signal light and first idler light, and then the
20 position of the seventh mirror 10'-7 can be adjusted to achieve oscillation in the second cavity 7' and to maximise the power of the second signal light and second idler light. Each of the sixth and seventh mirrors 10'-6, 10'-7 is preferably mounted on a precision linear translation stage (not shown).

25 *Experimental results*

Experimental results were obtained for a system 50 as described above.

Figure 3 shows an image of a part of the second apparatus 1' in operation. The second
nonlinear optical element 8' is towards the centre of the image.

30

Figures 4(a) and (b) respectively show the spectral and temporal characteristics of the pump light. The pump light has a (centre) wavelength of 796 nanometres and a bandwidth of 7 nanometres. The pulses of pump light have pulse widths of about 155 femtoseconds. Figures 4(c) and (d) respectively show the spectral and temporal characteristics of the first signal light.

The first signal light has a (centre) wavelength of 1024 nanometres and a bandwidth of 7.3 nanometres. The pulses of first signal light have pulse widths of about 210 femtoseconds.

With the wavelength of the first signal light constant at 1024 nanometres, the wavelength of the second signal and idler light was controlled by way of cavity length tuning, i.e. cavity delay detuning. In particular, the position of the seventh mirror 10'-7 was adjusted to adjust the length of the second cavity 7', thereby controlling the wavelength of the second resonant (signal) light and also the second non-resonant (idler) light.

Figure 5 shows changes in the spectrum of second signal light that were brought about by way of the cavity delay detuning. Figure 6 shows the corresponding changes in the (peak) wavelength of the second signal light and second idler light as a function of the change in the length of the second cavity 7'. Figure 6 also shows the average power of the second signal light as a function of the change in the length of the second cavity 7'. The wavelength of the second signal light can be changed from 1170 to 1235 nanometres by changing the cavity length/delay by about 100 micrometres. The corresponding tuning range for the second idler light is in the mid infrared and is from 8050 to 5920 nanometres. Accordingly, for a second signal tuning range of about 70 nanometres, the second idler (output) tuning range is about 2100 nm. For a fixed angle of incidence of the first resonant (i.e. "pump") light on the second nonlinear optical element 8' and for a fixed temperature of the second nonlinear optical element 8' etc., this output tuning range of greater than 2 micrometres is unprecedented for a CSP-based optical parametric oscillator.

Further advantages of the apparatus

Thus, the apparatus 1⁽ⁱ⁾ can provide greater flexibility to use certain pump sources in combination with certain nonlinear optical materials. For example, the apparatus 1⁽ⁱ⁾ can enable pump sources to be used with nonlinear optical materials that absorb light at the pump laser wavelengths. This can be achieved by using a suitable first nonlinear optical element 5⁽ⁱ⁾ in the first cavity 4⁽ⁱ⁾. Moreover, because the first and second oscillators 2⁽ⁱ⁾, 3⁽ⁱ⁾ are internally cascaded as described herein, this can be achieved in an effective way. For example, the intensity of the first resonant light inside the first cavity 4⁽ⁱ⁾ can be high relative to the intensity of light which might be extracted from the first cavity 4⁽ⁱ⁾. Accordingly, threshold intensities required for operation of the second oscillator 3⁽ⁱ⁾ can be achieved more effectively. Furthermore, the internally cascaded arrangement of first and second oscillators 2⁽ⁱ⁾, 3⁽ⁱ⁾ can be

more practical and robust compared to arrangements involving e.g. externally cascaded oscillators in series. For example, the first and second oscillators $2^{(i)}$, $3^{(i)}$ can share common elements, e.g. mirrors $10^{(i)}$. Also, the first and second oscillators $2^{(i)}$, $3^{(i)}$ can be controlled independently of each other, and so, unlike externally cascaded arrangement, the requirement
5 for stabilisation of the cavities $4^{(i)}$, $7^{(i)}$ is greatly reduced.

By using a Kerr-lens-mode-locked titanium-sapphire pump source 51 (or similar) with a periodically-poled lithium niobate (PPLN) crystal (or similar) as the first nonlinear optical element $5^{(i)}$, the apparatus $1^{(i)}$ can open up new avenues in relation to various nonlinear optical
10 materials that normally require a pump source that provides a wavelength of about 1 micrometre or longer. Because PPLN is transparent up to about 4.5 micrometres, the entire wavelength range from about 1 to 4.5 micrometres can be made accessible for pumping the second nonlinear optical element $8^{(i)}$. Moreover, Kerr-lens-mode-locked titanium-sapphire lasers and PPLN can have the advantage of being well-established technologies. Furthermore,
15 using a Kerr-lens-mode-locked titanium-sapphire pump source 51 (or similar) can enable femtosecond operation.

By also using a CSP crystal (or similar) as the second nonlinear optical element $8^{(i)}$, the apparatus $1^{(i)}$ can provide an effective way of realising a source of mid-infrared light,
20 particularly light with a wavelength of between about 4 and 12 micrometres. CSP absorbs light with wavelengths below 1 micrometre and so cannot normally be used directly with a Kerr-lens-mode-locked titanium-sapphire pump source. Compared to known systems, the apparatus $1^{(i)}$ can also enable tuning over a wide range of wavelengths between about 4 and 12 micrometres. Moreover, this tuning can be performed continuously, rapidly, and statically by
25 way of cavity delay detuning.

The above is particularly significant in light of the scarcity of sources of mid-infrared laser light and various limitations with known ways of producing mid-infrared light using optical parametric oscillators. For example, systems involving oxide-based birefringent nonlinear
30 materials are generally limited to wavelengths below about 4 micrometres due to multi-phonon absorption by these materials. Systems involving other materials (e.g. orientation-patterned gallium arsenide (OP-GaAs) and chalcopyrite crystals such as ZnGeP_2) can provide longer wavelengths, but generally require longer pump wavelengths (e.g. above 2 micrometres for OP-GaAs or ZnGeP_2) to avoid absorption. Accordingly, these systems are generally not used

with neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers (or similar), which operate at wavelengths near 1 micrometre.

Modifications

- 5 It will be appreciated that many other modifications may be made to the embodiments hereinbefore described.

For instance, the apparatus 1⁽ⁿ⁾ may include an internally cascaded third oscillator, etc.

- 10 Furthermore, the wavelengths of the first signal light and first idler light and/or the wavelengths of the second signal light and second idler light (and hence the output light) may be controllable in another way, e.g. by controlling the temperature of the first and/or second nonlinear optical elements 5⁽ⁿ⁾, 8⁽ⁿ⁾, rotating the first and/or second nonlinear optical elements 5⁽ⁿ⁾, 8⁽ⁿ⁾ to control the angle of incidence of their pump light, and/or, where the first and/or
- 15 second nonlinear optical elements 5⁽ⁿ⁾, 8⁽ⁿ⁾ have fan-out gratings, by re-positioning the first and/or second nonlinear optical elements 5⁽ⁿ⁾, 8⁽ⁿ⁾ relative to the path of their pump light.

CLAIMS

1. Apparatus configured to provide output light, the apparatus comprising:
a first optical parametric oscillator to produce first signal light and first idler light in
5 response to pump light, the first optical parametric oscillator comprising a first cavity and a first
nonlinear optical element in the first cavity, wherein the first cavity is configured to resonate
one of the first signal light and first idler light; and
a second optical parametric oscillator to produce second signal light and second idler
light in response to the resonated one of the first signal light and first idler light, wherein at
10 least one of the second signal light and second idler light corresponds to the output light, the
second optical parametric oscillator comprising a second cavity and a second nonlinear optical
element in the second cavity;
wherein the second nonlinear optical element is also in the first cavity.
- 15 2. Apparatus according to claim 1, wherein the output light corresponds to mid-infrared
light.
3. Apparatus according to claim 1 or 2, wherein the output light has a wavelength of
between about 4 and 12 micrometres.
- 20 4. Apparatus according to any preceding claim, wherein the first nonlinear optical
element comprises a quasi-phase-matched material, preferably a periodically-poled material,
preferably magnesium oxide doped periodically-poled lithium niobate.
- 25 5. Apparatus according to any preceding claim, wherein the second nonlinear optical
element comprises a birefringent material, preferably cadmium silicon phosphide.
6. Apparatus according to any preceding claim, wherein the pump light is provided by a
titanium-sapphire laser.
- 30 7. Apparatus according to any preceding claim, wherein the first optical parametric
oscillator is configured to produce first signal light with a wavelength of between about 1 and
about 2 micrometres and first idler light with a wavelength of between about 2 and about 4.5
micrometres in response to pump light with a wavelength of less than 1 micrometre.

8. Apparatus according to any preceding claim, configured to provide the output light with a wavelength which is controllable by way of cavity length tuning.

5 9. Apparatus according to claim 8, wherein the wavelength of the output light is changeable by more than about 2 micrometres.

10. Apparatus according to any preceding claim, wherein the pump light and the output light is comprised in ultrashort pulses, preferably femtosecond pulses.

10

11. Apparatus according to claim 10, wherein the first cavity has a cavity length such that the first nonlinear optical element is synchronously pumped by the pump light, and the second cavity has a cavity length such that the second nonlinear optical element is synchronously pumped by the resonated one of first signal light and first idler light.

15

12. Apparatus according to any preceding claim, wherein the first cavity and/or the second cavity correspond to a standing wave cavity.

20

13. Apparatus according to any preceding claim, wherein the first nonlinear optical element is arranged substantially at the focus of a pair of concave mirrors forming at least a part of the first cavity, and/or wherein the second nonlinear optical element is arranged substantially at the focus of a pair of concave mirrors forming at least a part of the second cavity.

25

14. Apparatus according to any preceding claim, wherein the first cavity is formed from a first set of optical elements, the second cavity is formed from a second set of optical elements, and the first and second sets include one or more optical elements that are common to the first and second sets and one or more optical elements that are not common to the first and second sets.

30

15. Apparatus according to any preceding claim, wherein the resonated one of the first signal light and first idler light propagates along a first path in the first cavity, wherein the second cavity is configured to resonate one of the second signal light and second idler light, wherein the resonated one of the second signal light and second idler light propagates along a

second path in the second cavity, and wherein each of the first and second paths comprises a path segment that is common to the first and second paths and a path segment that is not common to the first and second paths.

5 16. Apparatus according to claim 15, comprising an element configured to discriminate between the resonated one of the first signal light and first idler light and the resonated one of the second signal light and second idler light, thereby linking the path segments that are common to the first and second paths with the path segments that are not common to the first and second paths.

10

17. Apparatus according to claim 16, wherein the element comprises a thin film polariser.

18. Apparatus according to any one of claims 15 to 17, wherein the lengths of the path segments that are not common to the first and second paths are independently adjustable to enable the length of the first cavity to be adjusted such that the first nonlinear optical element is synchronously pumped by the pump light, and the length of the second cavity to be adjusted such that the second nonlinear optical element is synchronously pumped by the resonated one of the first signal light or first idler light.

15 19. Apparatus according to any one of claims 15 to 18, wherein the lengths of the path segments that are not common to the first and second paths are independently adjustable to enable the length of the first cavity to be adjusted to control the wavelength and/or power of the first signal light and first idler light by way of cavity length tuning, and/or the length of the second cavity to be adjusted to control the wavelength and/or power of the second signal light and second idler light and hence output light by way of cavity length tuning.

20

20. Apparatus according to any preceding claim, wherein first optical parametric oscillator is configured to produce the resonated one of the first signal light and first idler light with an intensity inside the first cavity that is above a threshold intensity for operation of the second optical parametric oscillator.

30

21. Apparatus according to any preceding claim, wherein the apparatus is operable at room temperature.

22. Apparatus according to any preceding claim, wherein the first nonlinear optical element is also in the second cavity.
23. Apparatus according to any preceding claim, wherein the first cavity is configured to maximally resonate only one of the first signal light and first idler light, and the second cavity is configured to maximally resonate only one of the second signal light and second idler light.
- 5

1 / 4

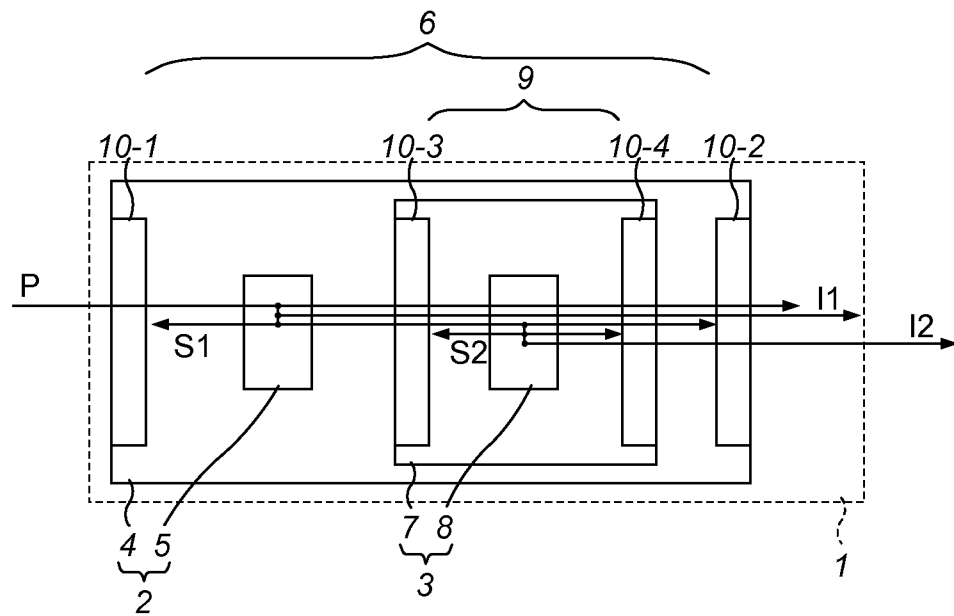


FIG. 1

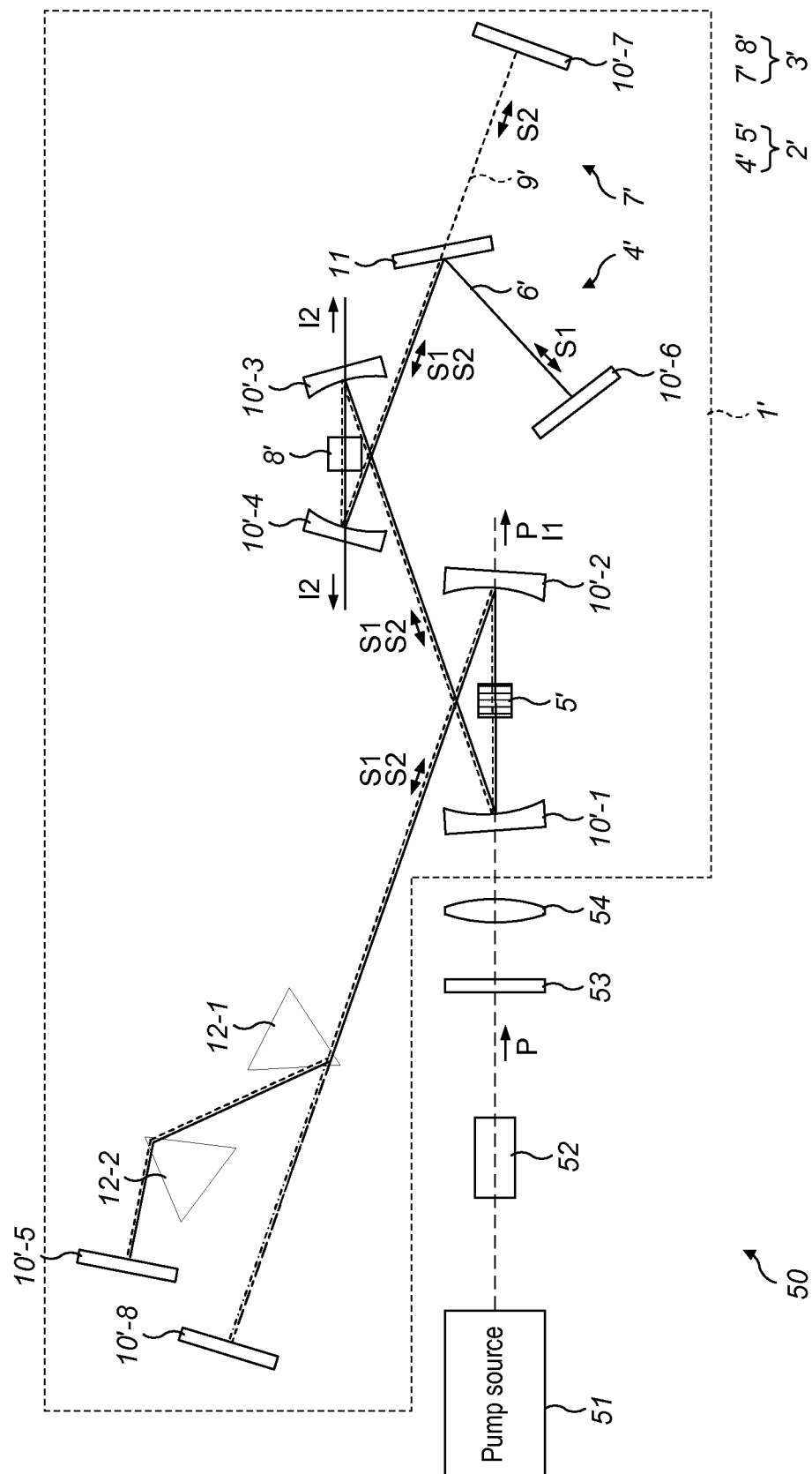
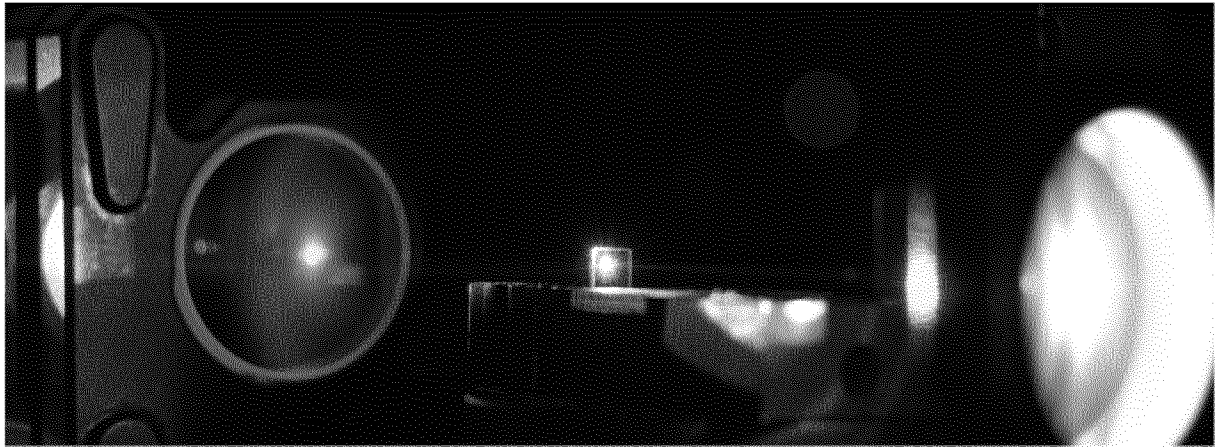
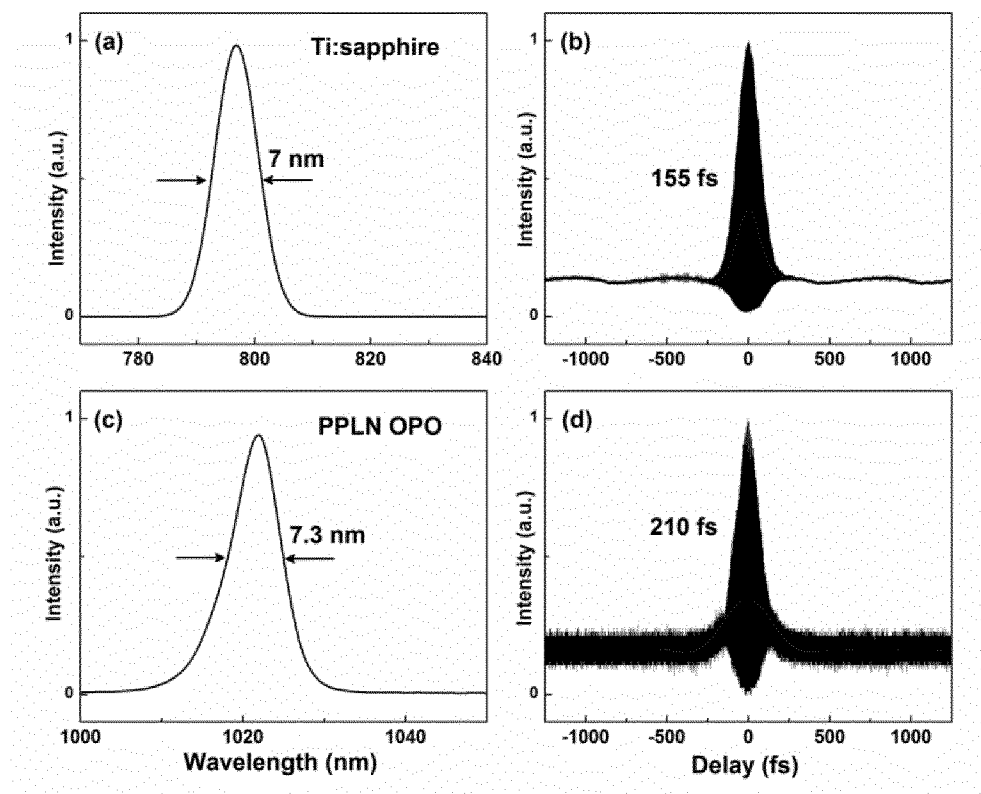


FIG. 2

3 / 4

*FIG. 3**FIG. 4*

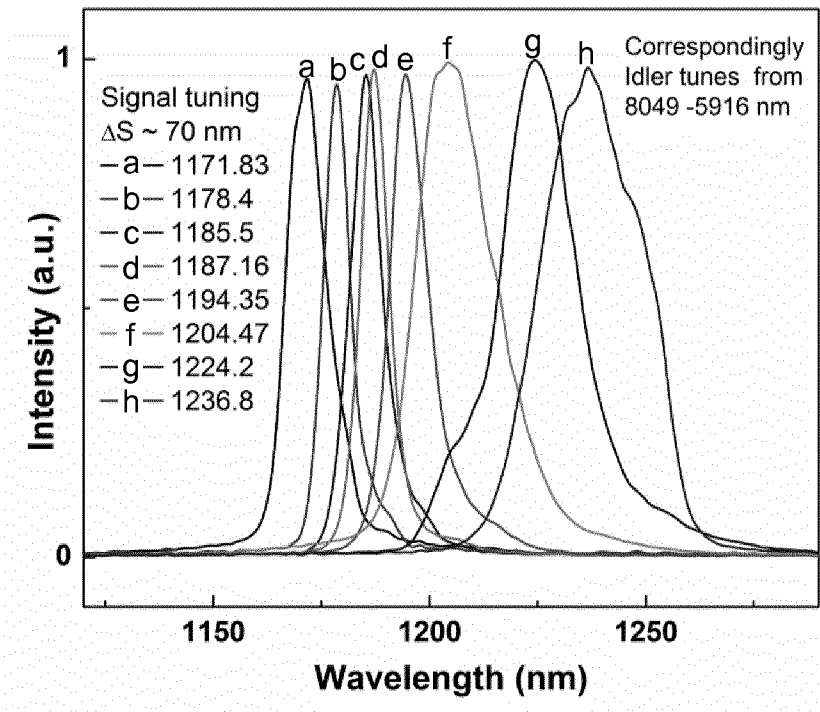


FIG. 5

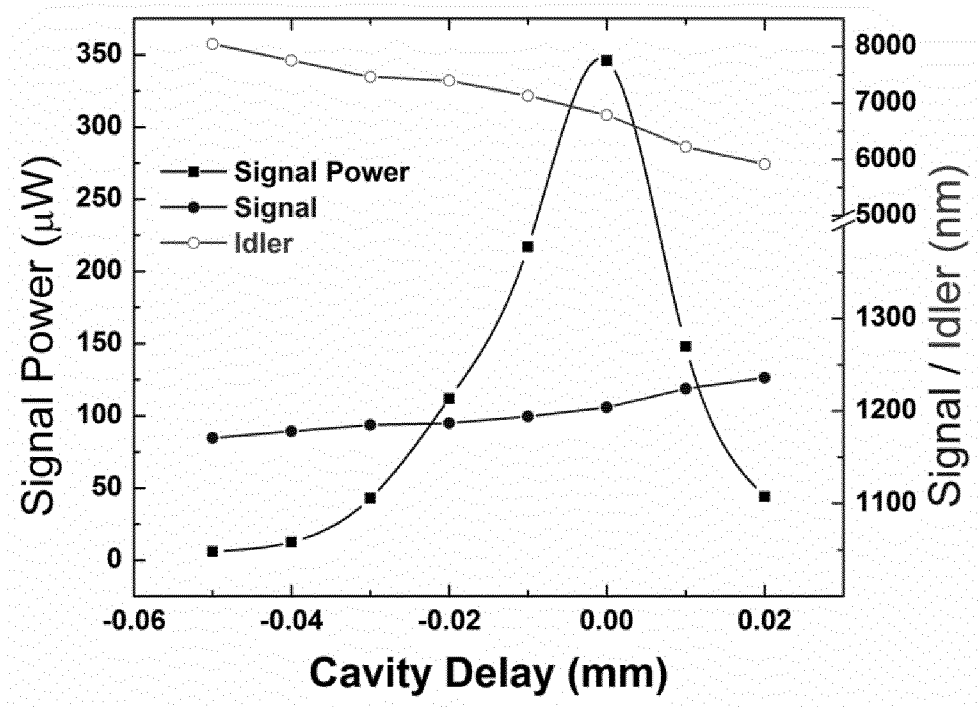


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2014/059018

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02F1/35 G02F1/39
ADD.

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)
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 practicable, search terms used)

EPO-Internal, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2012/126495 A1 (INST CIENCIAS FOTONIQUES FUNDACIO PRIVADA [ES]; INSTITUCIO CATALANA DE) 27 September 2012 (2012-09-27)	1-7,10, 12-23
Y	page 6, line 15 - page 8, line 28 figure 1 ----- -/--	8,9,11



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

9 December 2014

Date of mailing of the international search report

15/12/2014

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Bouba1, François

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2014/059018

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	ZHU JIANG-FENG ET AL: "ELECTROMAGNETISM, OPTICS, ACOUSTICS, HEAT TRANSFER, CLASSICAL MECHANICS, AND FLUID DYNAMICS; Tunable femtosecond laser in the visible range with an intracavity frequency-doubled optical parametric oscillator", CHINESE PHYSICS B, CHINESE PHYSICS B, BRISTOL GB, vol. 22, no. 5, 16 May 2013 (2013-05-16), page 54210, XP020244515, ISSN: 1674-1056, DOI: 10.1088/1674-1056/22/5/054210 the whole document -----	8,9
Y	GERALD T MOORE ET AL: "The Tandem Optical Parametric Oscillator", IEEE JOURNAL OF QUANTUM ELECTRONICS, IEEE SERVICE CENTER, PISCATAWAY, NJ, USA, vol. 32, no. 12, 1 December 1996 (1996-12-01), XP011051528, ISSN: 0018-9197 the whole document -----	11

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2014/059018

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2012126495	A1	27-09-2012	NONE
