

(51) International Patent Classification:
G02F 1/39 (2006.01)

(21) International Application Number:

PCT/EP2017/057340

(22) International Filing Date:

28 March 2017 (28.03.2017)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

1605165.8 28 March 2016 (28.03.2016) GB

(71) Applicants: **FUNDACIÓ INSTITUT DE CIÈNCIES FOTÒNIQUES (ICFO)** [ES/ES]; Parque Mediterráneo de la Tecnología, Av. Carl Friedrich Gauss, 3, 08860 Castelldefels, Barcelona (ES). **INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS (ICREA)** [ES/ES]; Pg. Lluís Companys, 23, 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, 08860 Castelldefels, Barcelona (ES). **KUMAR, Suddapalli Chaitanya**; C/o Fundació Institut De Ciències Fotòniques (ICFO), Parque Mediterráneo de la Tecnología, Av. Carl Friedrich Gauss, 3, 08860 Castelldefels, Barcelona (ES).(74) Agent: **STRATAGEM INTELLECTUAL PROPERTY MANAGEMENT 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, DJ, 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, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, 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, ST, SZ, TZ, 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))

(54) Title: APPARATUS COMPRISING AN OPTICAL PARAMETRIC OSCILLATOR

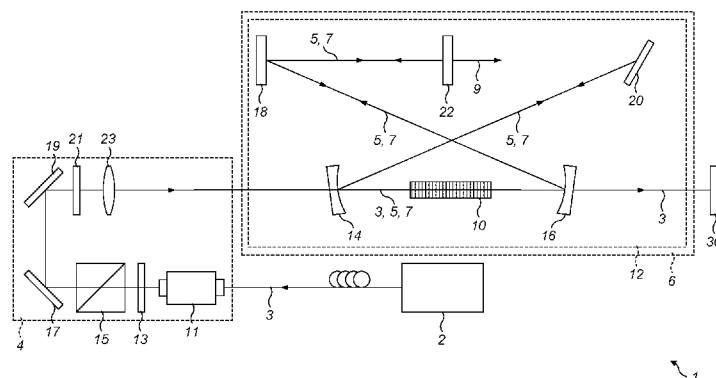


FIG. 1

(57) Abstract: Apparatus (1) comprises: an optical parametric oscillator (6) comprising: a nonlinear optical element (10) configured to produce degenerate or near-degenerate signal and idler waves (5, 7) in response to a pump wave (3); and an optical cavity (12) configured to be doubly-resonant in relation to the signal and idler waves (5, 7) and to provide an output wave (9) corresponding to the signal and idler waves (5, 7); wherein the optical cavity (12) is formed from optical elements and at least one of the optical elements comprises a diffraction grating (20); wherein the diffraction grating (20) is configured to stabilise wavelengths and/or powers of the signal and idler waves (5, 7).

Title

Apparatus comprising an optical parametric oscillator

Field

5 The present invention relates to apparatus comprising an optical parametric oscillator, particularly a laser source.

Background

10 There is an ongoing effort to develop further practically-applicable laser sources for certain wavelengths of interest, including wavelengths of around 2 μm , and with certain desired performance characteristics.

Summary

15 According to a first aspect of the present invention, there is provided an apparatus comprising: an optical parametric oscillator comprising: a nonlinear optical element configured to produce degenerate or near-degenerate signal and idler waves in response to a pump wave; and an optical cavity configured to be doubly-resonant in relation to the signal and idler waves and to provide an output wave corresponding to the signal and idler waves; wherein the optical cavity is formed from optical elements and at least one of the optical elements comprises a diffraction
20 grating; wherein the diffraction grating is configured to stabilise wavelengths and/or powers of the signal and idler waves.

Thus, the apparatus can provide output waves with more stable wavelengths and more stable powers in the normally-unstable circumstances of double resonance and (near-) degeneracy.
25 This, in turn, can enable alternative, more straightforward and/or better-performing laser source for certain wavelengths to be provided.

Optional features are specified in the dependent claims, and further advantages are described below.

30

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:

Figure 1 schematically illustrates apparatus comprising an optical parametric oscillator.

Figure 2 shows pulse energy as a function of repetition rate of various known Tm/Ho-lasers around 2 μm wavelength. The solid lines represent the corresponding average power. The squares represent the fiber lasers, and the circles represent the bulk lasers. The star represents pulse energy as a function of repetition rate for an example apparatus.

Figure 3 shows (a) normalized parametric gain ($\text{sinc}^2(\Delta kL/2)$ with $-2\pi < \Delta kL < 2\pi$) provided by a 50-mm-long MgO:PPLN crystal near degeneracy, when pumped at 1064 nm, as a function of the QPM grating period; and (b) group velocity dispersion of MgO:PPLN near 2.1 μm .

Figure 4 shows output power scaling and pump depletion as a function of the pump power to the example apparatus.

Figure 5 shows long-term power stability of the output from the example apparatus. Inset: 2D and 3D spatial profile of the output beam.

Figure 6 shows beam quality measurement of the output from the example apparatus in the (a) horizontal and (b) vertical directions.

Figure 7 shows beam pointing stability of the example apparatus measured over 1 hour.

Figure 8 shows long-term spectral stability of the example apparatus.

Figure 9 shows high-resolution spectrum of (a) second harmonic generation from the example apparatus and (b) the pump laser used in the example apparatus.

Figure 10 shows a typical interferometric autocorrelation trace of the output pulses from the example apparatus, confirming a pulse duration of ~ 20 ps (assuming Gaussian temporal shape). Inset: variation of the pulse duration as a function of the cavity delay.

Figure 11 shows (a) a pulse train and (b) pulse-pulse stability of an output from the example apparatus.

Figure 12 shows (a) wide-span radio frequency spectrum, and (b) fundamental beat-note of output pulses from the example apparatus.

Detailed Description of the Certain Embodiments

5 *Apparatus*

Referring to Figure 1, an apparatus 1 will now be described. The apparatus 1 can be used as a laser source with certain advantageous characteristics.

10 The apparatus 1 includes a pump source 2, a first set of optical elements 4 and an optical parametric oscillator (OPO) 6.

The pump source 2 is configured to provide a pump beam 3.

15 In one example (hereinafter referred to as the “first example apparatus”), which was used to obtain the experimental results described below, the pump source 2 is a Yb-fiber laser (*Fianium FP1060-20*). This Yb-fiber laser delivers ~20 ps pulses, at a 79.3 MHz repetition-rate, at a central wavelength of 1064 nm, with a full width at half maximum (FWHM) spectral bandwidth of ~1 nm. As will be explained below, in the first example apparatus 1, the pump source 2 is used to synchronously pump the OPO 6.

20 In other examples, the pump source 2 and/or the pump beam 3 may be different. The pump beam 3 may have any suitable properties, for example any suitable frequency/wavelength. The pump beam 3 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. In the case of picosecond or femtosecond pulses, the OPO 6 is generally synchronously pumped. In the case of a continuous-wave or microsecond or nanosecond
30 pulses, the OPO 6 may be non-synchronously pumped.

The optical elements 4 are configured to prepare the pump beam 3 for the OPO 6.

In the first example apparatus 1, the optical elements 4 include a Faraday isolator 11, a first half-wave plate 13, a polarizing beam splitter 15, two mirrors 17, 19, a second half-wave plate 21 and a lens 23. The pump beam 3 is provided to the optical elements 4 in this order. The isolator 11 is configured to protect the pump source 2 from any back reflections. The optical elements 4 are configured to give the pump beam 3 a suitable polarization for phase-matching in the nonlinear optical element 10 (described below) of the OPO 6. In the first example apparatus 1, the polarization of the pump beam 3 is arranged to be *extraordinary* (*e*) with respect to the optical axis of the crystal 10 (described below). The optical elements 4 are also configured to systematically control the power of the pump beam 3. The lens 23 is configured to focus the pump beam 3 in relation to the nonlinear optical element 10. In the first example apparatus 1, the lens 23 is configured to focus the pump beam 3 to a waist radius of $w_0 \sim 130 \mu\text{m}$ at the center of the crystal 10.

In other examples, the first set of optical elements 4 and/or the properties (e.g. the polarization, focused waist radius in the crystal) of the pump beam 3 provided to the OPO 6 may be different. For example, one or more of the abovedescribed optical elements 4 may be omitted or replaced by a suitable alternative.

The OPO 6 includes a nonlinear optical element 10 configured to produce degenerate or near-degenerate signal and idler waves 5, 7 in response to the pump beam 3. "Near-degenerate" means, for example, that the waves 5, 7 have wavelengths that are within about 15% or 10% or 5% or 1% of each other. For instance, in the first example apparatus 1, in which the pump beam 3 has a wavelength of 1064 nm, the signal and idler wave 5, 7 are (exactly) degenerate when they each have a wavelength of 2128 nm and can be described as "near-degenerate" when they have wavelengths between 2 and 2.2 μm .

In the first example apparatus, the nonlinear optical element 10 is a 50-mm-long MgO:PPLN crystal 10. This crystal 10 is operated near wavelength degeneracy at 2.128 μm . The crystal 10 incorporates a single quasi-phase-matched (QPM) grating period of $\Lambda = 32.16 \mu\text{m}$ and is maintained at a constant phase-matching temperature of 72 °C for degenerate operation under type 0 (*ee*→*e*) interaction. The end-faces of the crystal 10 are antireflection (AR) coated for high transmission ($R < 0.5\%$) at 1.064 μm and over 2.050-2.150 μm .

The high nonlinearity ($d_{\text{eff}} \sim 16 \text{ pm/V}$) and long interaction lengths available in MgO:PPLN have been shown to enable high output coupling, hence large average output power and extraction efficiency, in picosecond OPOs in singly resonant operation (SRO) configuration. For parametric generation near degeneracy close to $2.1 \mu\text{m}$, when pumped at $1.064 \mu\text{m}$, MgO:PPLN also exhibits large phase-matching gain bandwidth, as shown in Figure 3(a), further enabling the use of long interaction lengths to achieve high gain and conversion efficiency in the presence of broad or structured pump spectrum. Moreover, MgO:PPLN has a negative GVD of $-60 \text{ fs}^2/\text{mm}$ at $2.1 \mu\text{m}$, as depicted in Figure 3(b), which can be advantageous in compensating for any positive GVD contribution due to mirrors in the OPO cavity, particularly in the presence of shorter few-picosecond and sub-picosecond pump pulses.

In other examples, the nonlinear optical element 10 may be differently controlled (e.g. maintained at a different temperature or controlled using another parameter), may have different properties (e.g. different dimensions and/or different (constant or varying) grating periods) and/or may correspond to a different type of crystal (e.g. different periodically-poled or birefringent crystals). The nonlinear optical element 10 may be formed from magnesium oxide-doped periodically-poled lithium tantalite (MgO:PPLT), cadmium silicon phosphide (CdSiP_2), orientation-patterned gallium phosphide (OP-GaP), silver gallium selenide (AgGaSe_2) or silver gallium sulphide (AgGaS_2), for example. These materials are particularly suitable where the pump beam wavelength is 1064 nm . The nonlinear optical element 10 may be formed from orientation-patterned gallium arsenide (OP-GaAs) or zinc germanium phosphide (ZnGeP_2), for example. These materials are particularly suitable where the pump beam wavelength is greater than 1064 nm . Generally, any material can be used if it can be phase-matched to operate at degeneracy for a particular wavelength of the pump beam 3, i.e. at twice the wavelength of the pump beam 3.

The OPO 6 also includes an optical cavity 12 configured to be doubly-resonant in relation to the signal and idler waves 5, 7 and to provide an output beam 9.

The optical cavity 12 is formed from several optical elements (hereinafter referred to as "cavity elements") 14, 16, 18, 20, 22 configured to suitably transmit and/or reflect waves. The properties of these optical elements 14, 16, 18, 20, 22 and their arrangement is configured such that the signal and idler waves 5, 7 are both resonant (e.g. form sufficiently stable waves) in the optical cavity 12. At least one of the cavity elements includes a diffraction grating 20.

The diffraction grating 20 is configured to help form the optical cavity 12, e.g. to reflect the signal and idler waves 5, 7, and also to stabilise wavelengths and/or powers of the signal and idler waves, and hence the output wave 9, as will be described below. In many examples, the diffraction grating 20 has a fixed orientation relative to the signal and idler waves 5, 7. This is in contrast to known systems in which diffraction gratings are used for tuning the wavelength(s) of the signal/idler waves 5, 7 and have variable orientations.

In the first example apparatus 1, the optical cavity 12 is configured in a standing-wave X-cavity, with two plano-concave mirrors, 14, 16 ($r = 200$ mm), a plane mirror, 18, and a plane output coupler 22 in one arm. In the first example apparatus 1, the diffraction grating 20 is made from aluminum, has 400 grooves/mm and corresponds to a blazed grating with a blaze wavelength of $2.1\text{ }\mu\text{m}$. This diffraction grating 20 serves as the other end mirror in the cavity, but also enables control of the spectrum of the OPO 6 at degeneracy. All mirrors 14, 16, 18 are highly transmitting for the pump ($T > 90\%$) at $1.064\text{ }\mu\text{m}$ and highly reflecting ($R > 99\%$) over 1.800 to $2.150\text{ }\mu\text{m}$, resulting in doubly-resonant oscillator (DRO) operation in the vicinity of degeneracy. The output coupler 22 has partial transmission ($T \sim 87\%$) at $2.1\text{ }\mu\text{m}$ and is used to extract the output beam 9 from the OPO 6. The total round-trip optical length of the optical cavity 12 is ~ 3.78 m, corresponding to a repetition rate of ~ 79.3 MHz, ensuring synchronization with the repetition rate of the pump source 2.

In other examples, the optical cavity 12 may be differently formed. For example, the cavity elements may be different, they may have different properties (e.g. transmittance and/or reflectance) and/or may be they differently arranged (e.g. to form a different type of standing-wave cavity, a ring cavity, etc.).

In many examples, the diffraction grating 20 corresponds to a blazed grating with a blaze wavelength substantially equal to the wavelengths of the signal and idler waves 5, 7. The wavelengths of the signal and idler waves 5, 7 may be different from those described above, and so the blaze wavelength may also be different. The blaze wavelength may be within about 15% or 10% or 5% or 1% (or within the grating bandwidth) of the wavelengths of the signal and idler waves 5, 7. Moreover, in many examples, the diffraction grating 20 has a Littrow configuration and is arranged such that the signal and idler waves 5, 7 are incident on the diffraction grating 20 at its blaze angle such that the signal and idler waves 5, 7 are reflected

back along the same path. In this way, the diffraction grating 20 may be used in forming a standing-wave cavity 12. In other examples, the optical cavity 12 may correspond to a travelling wave cavity (e.g. a bow-tie cavity) and the diffraction grating 20 may be configured differently such that the paths of the incident and diffracted signal and idler waves 5, 7 are different. In these examples, the efficiency of the diffraction grating 20 is generally reduced. In some examples, the diffraction grating 20 may not be blazed or may have a different structure.

The apparatus 1 may also include additional components. For instance, the first example apparatus 1 includes a dumper 30 for the pump beam 3 passing straight through the optical cavity 12. The apparatus 1 may also include an output system (not shown) for processing the output beam 9 before it is provided e.g. to another apparatus, or a system (not shown) to double-pass the pump beam 3 through the crystal 10 to reduce the threshold and increase the output power of the apparatus 1. In most examples, further intracavity elements (e.g. self-phase locking elements) for control of the spectral characteristics of the OPO 6 are not needed.

Experimental results

Experimental results were obtained for the first example apparatus 1.

In order to characterize the first example apparatus 1, measurements of power scaling were performed, the results of which are shown in Figure 4. The high nonlinearity of MgO:PPLN together with long interaction lengths, in combination with picosecond pump pulses, enable high conversion efficiency and output power from picosecond OPOs (see S. Chaitanya Kumar et al., "High-power, widely tunable, room-temperature picosecond optical parametric oscillator based on cylindrical 5%MgO:PPLN," Opt. Lett. 40, 3897-3900 (2015)). Such OPOs can afford high output coupling losses providing extraction efficiencies of >57% in SRO configuration (see S. Chaitanya Kumar et al., "Interferometric output coupling of ring optical oscillators," Opt. Lett. 36, 1068-1070 (2011)). In a degenerate OPO, owing to the large parametric gain, even higher output coupling can be employed to maximize the overall extraction efficiency. As such, by using the 87% output coupler 22, as much as 7.1 W of average output power at 2.1 μm for a maximum available pump power of 18 W at a pulse repetition rate of 79.3 MHz was able to be extracted. The linear fit to the data results in an estimated slope efficiency of 49%. This corresponds to a maximum extraction efficiency of 39.4%, and an external photon conversion efficiency of ~79%, resulting in an internal quantum efficiency of ~91% with respect of the input pump power. The pump depletion is recorded to be >48% near the maximum input pump

power, while the threshold pump power is ~ 3.2 W. Further, the output polarization in a parametric process is strictly determined by the phase-matching condition. In this degenerate OPO 6, all the interacting waves are identically polarized in order to satisfy the quasi-phase-matching condition in MgO:PPLN. Hence, the generated radiation 5, 7 from the degenerate OPO 6 at $2.1\ \mu\text{m}$ is also *extraordinary* polarized with respect to the optic axis of the MgO:PPLN crystal 10, resulting in a linear output polarization. Using a Brewster plate, the linearity of the output beam polarization at $2.1\ \mu\text{m}$ was measured to be $>99.5\%$.

The long-term stability of the output beam 9 from the first example apparatus 1 recorded at an extracted power level of ~ 6 W at $2.1\ \mu\text{m}$ is shown in Figure 5. The example apparatus 1 exhibits a passive power stability better than 1% root mean square (rms) over 15 hours as compared to 0.13% rms for the pump source 2 over the same measurement time. Also shown in the inset of Figure 5 are the 2- and 3-dimensional spatial profiles of the output beam 9 measured at a distance of ~ 1 m from the optical cavity 12, indicating a single-peak Gaussian intensity distribution with TEM₀₀ mode profile. Figure 6 shows the M^2 quality measurements of the output beam 9. Using a CaF₂ lens of focal length $f=150$ mm and scanning beam profiler, the beam diameter across the Rayleigh range were recorded and the M^2 values were estimated, resulting in $M_x^2 < 3.5$ and $M_y^2 < 3$ in horizontal and vertical directions, respectively.

The beam pointing stability of the first example apparatus 1 at $2.1\ \mu\text{m}$ was also investigated, while operating at maximum power, by recording the centroid position of the output beam 9. The result is presented in Figure 7, confirming a beam pointing stability $< 32\ \mu\text{rad}$ in the x-direction and $< 40\ \mu\text{rad}$ in the y-direction.

Spectral characterization of the first example apparatus 1 was also performed by recording the long-term wavelength stability of the output beam 9 over a period of 1 hour using a spectrometer with a resolution of ~ 7 nm. The results are shown in Figure 8, with a central wavelength of $2.135\ \mu\text{m}$, while operating at 6.5 W of output power. This measurement clearly demonstrates the effectiveness of the technique based on the use of the diffraction grating 20 for control and stabilization of the picosecond OPO output spectrum in degenerate operation. An accurate estimate of the stability and the FWHM spectral bandwidth was not able to be performed due to the poor resolution of the spectrometer. Approximately, the output wave has a spectral stability of better than (e.g. the variation in the center wavelength is less than) about 1% rms over at least 1 hour. In order to further confirm the central wavelength of the

example apparatus 1, single-pass second harmonic generation (SHG) of the output beam 9 at 2.1 μm was implemented in another MgO:PPLN crystal identical to the crystal 10 used in the example apparatus 1. The SHG spectrum at $\sim 1 \mu\text{m}$, measured using a spectrum analyzer with a resolution better than 0.3 nm, is shown in Figure 9(a), along with the spectrum of Yb-fiber pump source 2, shown in Figure 9(b). As evident from Figure 9(a), the SHG spectrum is centered at 1063.7 nm with a FWHM spectral bandwidth of ~ 1 nm. This measurement confirms the central wavelength of the pump source 2 to be 2.127 μm . The spectral acceptance bandwidth for SHG at 2.1 μm in a 50-mm-long MgO:PPLN crystal is calculated to be ~ 1.2 nm, which could be a limiting factor. The SHG spectral bandwidth and the sharp rising edge on the SHG spectrum indicate a FWHM spectral bandwidth > 2 nm at 2.1 μm .

Temporal characterization of the output pulses 9 from the example apparatus 1 was also performed using autocorrelation measurements. Figure 10 shows the typical interferometric autocorrelation of the output pulses 9 at 2.1 μm . The measurement results in a FWHM pulse width of 28.2 ps, corresponding to a Gaussian pulse duration of ~ 20 ps, identical to that of the pump pulses 3 from the Yb-fiber pump source 2. Considering a spectral bandwidth of 2 nm, estimated from the SHG spectrum, these measurements result in a time-bandwidth product of $\Delta\tau\Delta\nu \sim 2.6$ in the absence of dispersion compensation, compared to a time-bandwidth product of $\Delta\tau\Delta\nu \sim 5.3$ for the pump. Implementing intracavity dispersion compensation could improve the time-bandwidth product of the generated pulses. Further, the variation of the pulse duration as a function of the cavity delay is shown in the inset of Figure 10. As the cavity delay is changed from -1.27 mm to perfect synchronization, the output pulse duration varies from 8.3 ps with > 2 W of output power to 20 ps with maximum output power, beyond which it drops down to 13 ps at ~ 0.5 mm.

In order to further study the temporal characteristics of the OPO, the output pulse train 9 from the first example apparatus 1 was recorded using an InGaAs fast photodetector with a bandwidth of 14.5 GHz and a 3.5 GHz oscilloscope, with the result shown in Figure 11(a). The corresponding analysis of the amplitude of the output pulses 9 shown in Figure 11 (b) resulted in a pulse-to-pulse amplitude stability better than 3.4% rms over 2 μsec .

The stability and quality of the generated output pulses was further evaluated from radio-frequency (RF) measurements performed using a RF spectrum analyzer (Agilent EXA signal analyzer 10 Hz-32 GHz). Figure 12(a) shows the wide-span RF spectrum measured with

resolution bandwidth of 10 kHz from DC to 3 GHz, indicating stable single pulse operation. The repetition rate and its harmonics are seen as sharp peaks in the RF spectrum. The high signal-to-noise ratio maintained at high harmonics indicates low timing jitter in the output pulse train. The first beat-note of the RF spectrum is centered at 79.35 MHz, confirming the repetition rate of the 2.1 μm source, while operating a maximum output power is shown in Figure 12(b). This 3-MHz sweep of the RF spectrum, recorded with a resolution bandwidth of 10 kHz, indicates no sidebands at the fundamental frequency, suggesting good pulse train stability with a peak-noise floor ratio of $\sim 45\text{dB}$, with the noise floor of the analyzer shown in blue in Figure 12(b).

Advantages

Thus, the inventors have demonstrated, for the first time, a stable, efficient, high-power, high-repetition rate, picosecond source near 2.1 μm in linear polarization, based on a degenerate OPO in a doubly-resonant configuration pumped by an Yb-fiber laser. By incorporating a diffraction grating for spectral control near degeneracy, also for the first time, the inventors have achieved excellent output stability in wavelength, power, and beam pointing. The OPO provides as much as 7.1 W of output power at 2.1 μm for an available pump power of 18 W at 1.064 μm , corresponding to an extraction efficiency of 39.4%, in 20 ps pulses at 79.3 MHz repetition rate. It exhibits excellent passive power stability better than 1% rms over 15 hours and beam pointing stability $< 40\text{ }\mu\text{rad}$ over 1 hour, in good beam quality with $M^2 < 3.5$. The interferometric autocorrelation measurements resulted in a Gaussian temporal width of $\sim 20\text{ ps}$ under perfect synchronization and pulse duration as short as 8.3 ps were achieved by changing the cavity delay. Further, long-term measurements on the output pulse train along with the RF measurements revealed high temporal stability with low timing jitter. To the best of the inventor's knowledge, this source outperforms any presently commercially available picosecond source near 2 μm . These results confirm the unique and advantageous features of this source as an alternative to Tm-based solid-state and fiber laser technology (discussed below) for many applications, including pumping of long-wavelength OPOs into the deep-IR.

High-power ultrafast laser sources near the 2 μm spectral range are of great interest for a variety of applications including LIDAR and remote sensing. The favorable water absorption in this region also enables several biomedical applications. Further, such high-power sources, particularly at wavelengths slightly above 2 μm , are highly desirable for long-wavelength nonlinear frequency conversion processes such as pumping of optical parametric oscillators, which are versatile sources of coherent radiation over extended spectral regions. Mid-infrared

(mid-IR) OPOs covering the 3 to 10 μm wavelength range are based on nonlinear materials such as ZnGeP_2 (ZGP) and orientation-patterned GaAs (OP-GaAs), which require pumping beyond 2 μm to avoid two-photon absorption. As such, high-power laser sources in linear polarization and good beam quality, operating slightly beyond 2 μm , are of great demand for pumping such mid-IR OPOs.

There has been substantial effort to develop various conventional laser technologies near 2 μm . In particular, the wide gain spectrum of the rare-earth doped bulk and fiber gain media based on Thulium (Tm) from 1.8 to 2.1 μm , and Holmium (Ho) from 2.05 to 2.15 μm , are attractive for the development of ultrafast lasers in the 2 μm wavelength range. A survey of the state-of-the-art ultrafast lasers with picosecond and sub-picosecond pulse duration operating near 2 μm , showing the output pulse energy as a function of repetition rate, is presented in Figure 2. It can be seen that almost all bulk solid-state lasers operate at high repetition rates >70 MHz, while the large majority of fiber lasers operate at repetition rates <50 MHz. All of the known bulk solid-state and fiber lasers have deployed passive mode-locking techniques using semiconductor saturable absorber mirrors (SESAMs), carbon nanotubes and graphene, where the low power handling capability of such elements partly limits the attainable output power. Although the known bulk lasers produce desirable output pulse durations (of <50 ps) at high repetition rates, their low average power remains a major limitation for many applications, including their deployment as pump sources for subsequent nonlinear frequency conversion stages. While the high Tm^{3+} concentration can enable efficient cross-relaxation processes, leading to high quantum efficiencies, most of the 2 μm Tm-fiber lasers are randomly polarized and operate at repetition rates <50 MHz, as can be seen in Figure 2, owing to the compromise between doping concentration and quenching, requiring long lengths of fibers. Moreover, the majority of the Tm- and Ho-fiber lasers rely on silica fibers as the host medium. For wavelengths around 2 μm , silica glass fibers have negative group velocity dispersion (GVD), enabling Tm-mode-locked fiber lasers without any dispersion control. However, operation beyond 2 μm suffers from propagation losses in the silica fiber host, which poses a major setback for power scaling of 2 μm lasers in this architecture. As a result, new host fibers such as tungsten tellurite glass are also being investigated. Against this backdrop, a suitable practical picosecond laser source in simplified design, useful for many applications including pumping mid-IR OPOs, was not previously readily available.

Access to the 2.1 μm spectral range using OPOs is challenging because of the proximity of the output wavelength to degeneracy when pumped at 1064 nm. Deploying an OPO in a doubly-resonant oscillator (DRO) configuration operating near degeneracy is generally considered undesirable, particularly in picosecond and nanosecond timescales and continuous-wave operation, as it can lead to unacceptable spectral and output power instabilities of the OPO, rendering the technique impracticable for many applications. For this reason, all practical picosecond OPOs to date have been developed exclusively in the singly-resonant oscillator (SRO) scheme.

However, as explained above, the inventors have demonstrated the effective deployment of a diffraction grating as a feedback element in a picosecond OPO for spectral and output power stabilization near degeneracy. Even in a DRO configuration with its inherent instabilities, and the large bandwidths associated with degenerate operation, the use of a diffraction grating can provide remarkable spectral and power stabilization of the OPO output as well as high spatial quality and excellent beam pointing stability, together with high average power and conversion efficiency. Without being bound to any theory, it is proposed that the high bandwidth of the OPO at degeneracy is controlled/limited to the bandwidth of the diffraction grating thereby stabilizing the spectrum of the waves in the OPO.

Furthermore, since in this approach both the pump at 1064 nm and the generated output wavelength at 2.1 μm lie well within the transparency range of MgO:PPLN, there is negligible residual absorption in the crystal, thus minimizing any thermal effects detrimental to the OPO operation.

Modifications

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

For instance, the apparatus need not be provided with an included pump source.

The apparatus may have spectral or power stabilities of better than 10%, 5%, 1%, 0.5% or 0.1% over a period of about one or five or 10 or 15 or more hours.

CLAIMS

1. Apparatus comprising:
an optical parametric oscillator comprising:
5 a nonlinear optical element configured to produce degenerate or near-degenerate signal and idler waves in response to a pump wave; and
an optical cavity configured to be doubly-resonant in relation to the signal and idler waves and to provide an output wave corresponding to the signal and idler waves;
wherein the optical cavity is formed from optical elements and at least one of
10 the optical elements comprises a diffraction grating;
wherein the diffraction grating is configured to stabilise wavelengths and/or powers of the signal and idler waves.
2. Apparatus according to claim 1, wherein the output wave has a wavelength of between
15 2 and 2.2 micrometres.
3. Apparatus according to claim 1 or 2, wherein pump wave is provided by an ytterbium fibre laser and has a wavelength of 1.064 micrometres.
- 20 4. Apparatus according to any preceding claim, wherein the nonlinear optical element comprises magnesium oxide doped periodically-poled lithium niobate.
5. Apparatus according to any preceding claim, wherein the diffraction grating has a fixed orientation relative to the signal and idler waves.
25
6. Apparatus according to any preceding claim, wherein the diffraction grating is blazed and has a blaze wavelength substantially equal to the wavelength of the signal and/or idler waves.
- 30 7. Apparatus according to claim 6, wherein the optical cavity corresponds to a standing-wave cavity, the diffraction grating has a Littrow configuration, and the angle of incidence of the signal and idler waves is substantially equal to the blaze angle.

8. Apparatus according to any preceding claim, wherein the output wave is comprised in ultrashort pulses, preferably picosecond pulses, more preferably a Gaussian pulse duration of about 20 picoseconds.

5 9. Apparatus according to any preceding claim, wherein the output wave has a passive power stability of better than about 1 percent root mean square over 15 hours.

10. Apparatus according to any preceding claim, wherein the output wave has a spectral stability of better than about 1 percent root mean square over 1 hour.

10

11. Apparatus according to any preceding claim, wherein the output wave has a full width at half maximum spectral bandwidth of less than about 2 nanometres.

12. Apparatus according to any preceding claim, wherein the output wave has a beam pointing stability of better than about 40 microradians over 1 hour.

15

13. Apparatus according to any preceding claim, wherein the output wave has a beam quality factor of better than 3.5.

20 14. Apparatus according to any preceding claim, wherein the output wave is comprised in a pulse train having an amplitude stability of better than 3.4 percent root mean square over 2 microseconds.

25 15. Apparatus according to any preceding claim, having an extraction of efficiency of at least about 40 percent.

16. Apparatus according to any preceding claim, wherein the output wave is comprised in ultrashort pulses and has an average power of at least about 7 watts and /or a repetition rate of at least about 80 megahertz.

30

17. Apparatus according to any preceding claim, wherein the output wave is more than 99.5 percent linearly polarized.

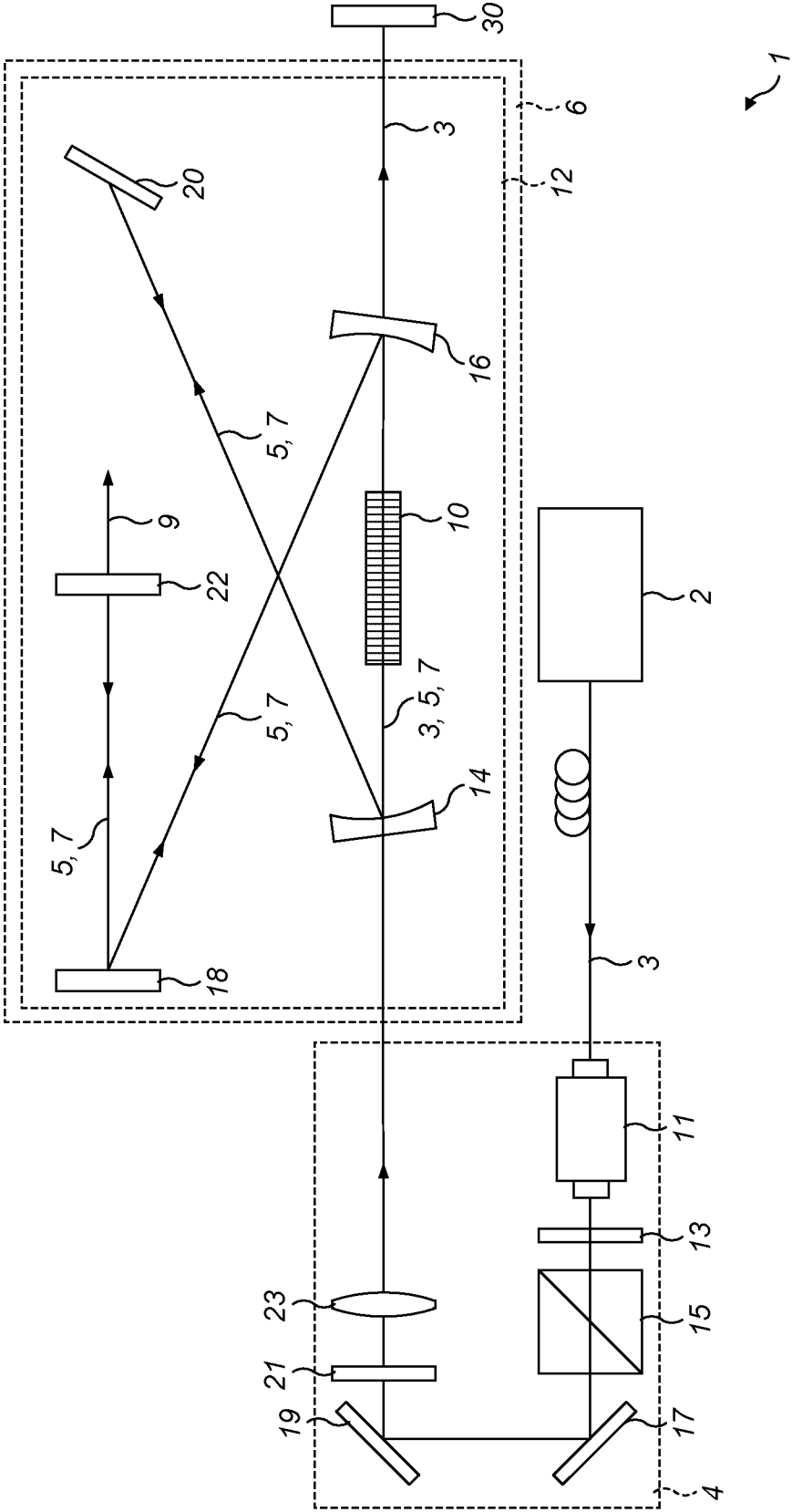


FIG. 1

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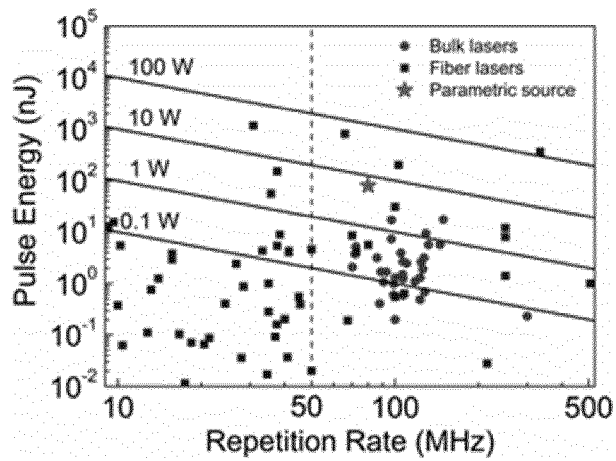


FIG. 2

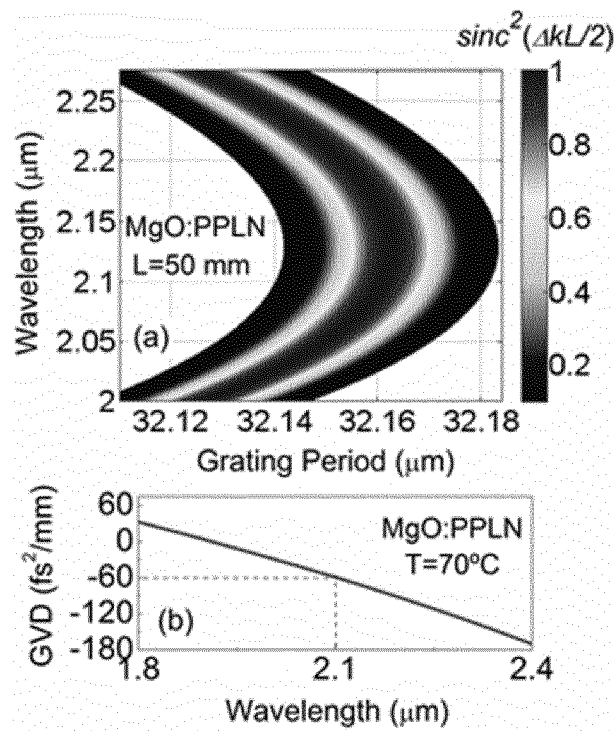


FIG. 3

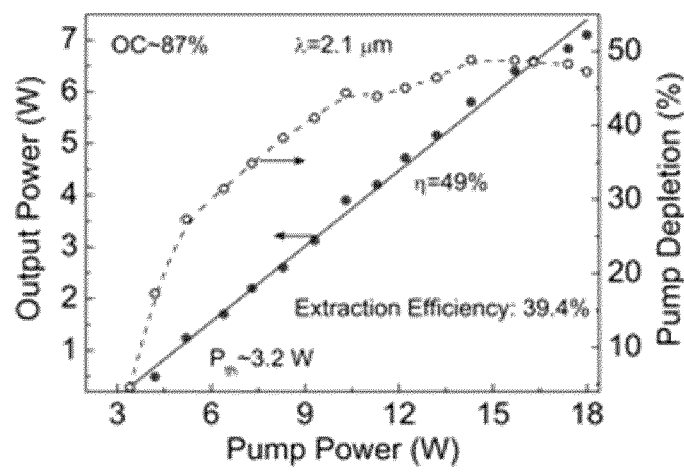


FIG. 4

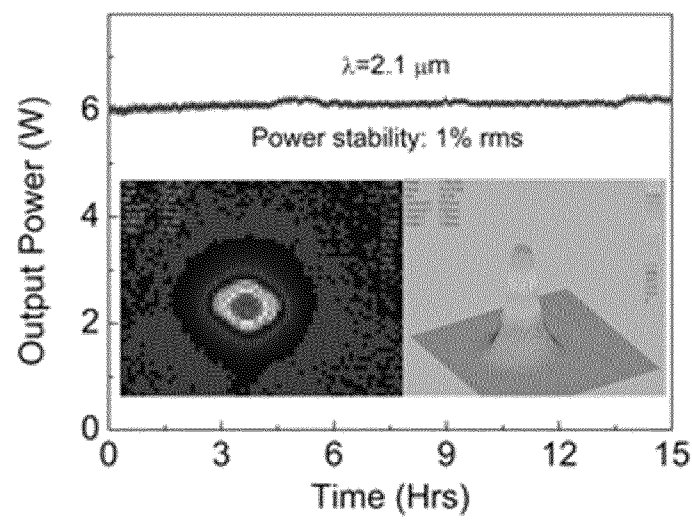
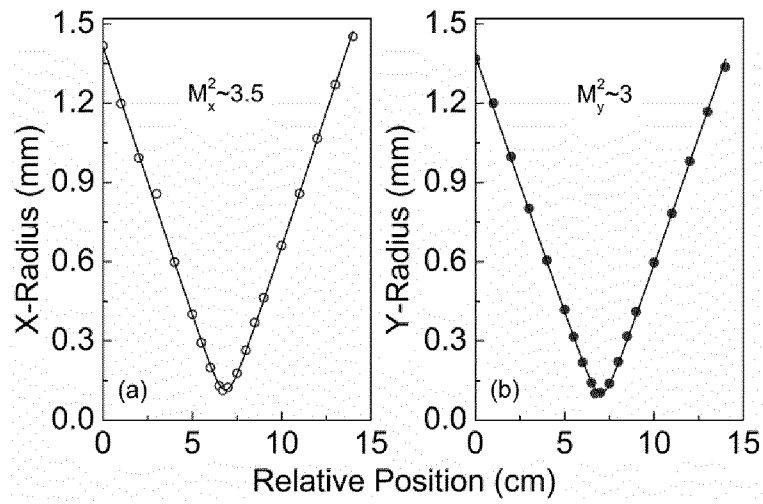
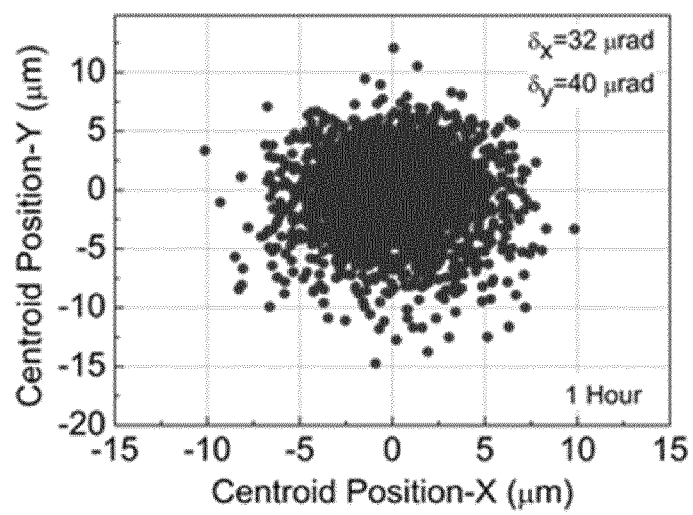
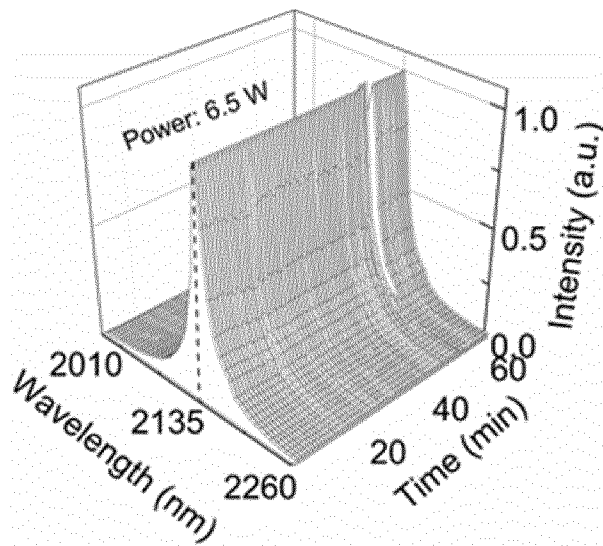
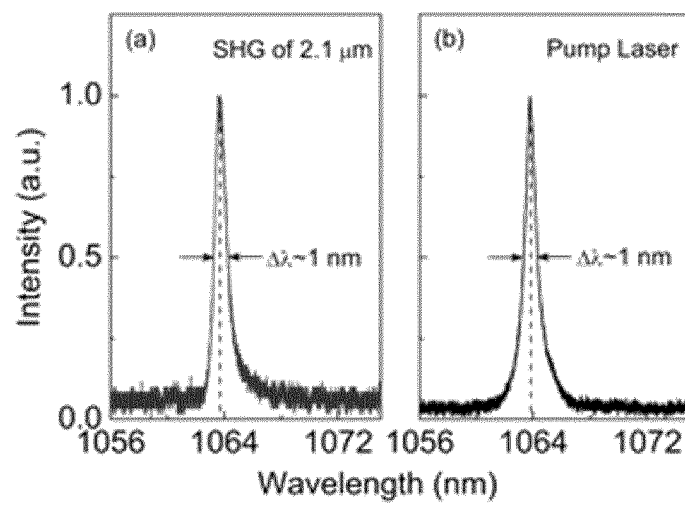


FIG. 5

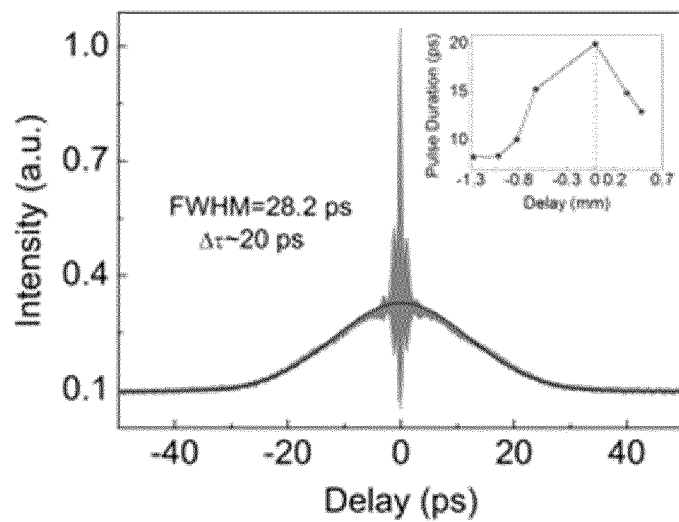
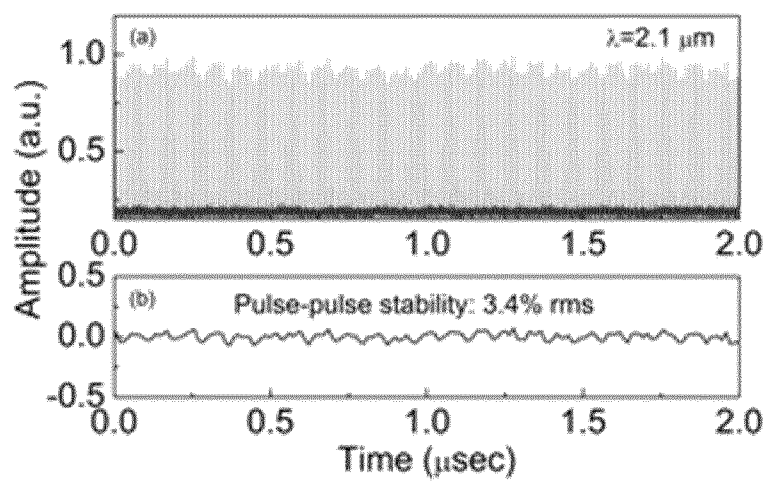
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*FIG. 6**FIG. 7*

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*FIG. 8**FIG. 9*

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*FIG. 10**FIG. 11*

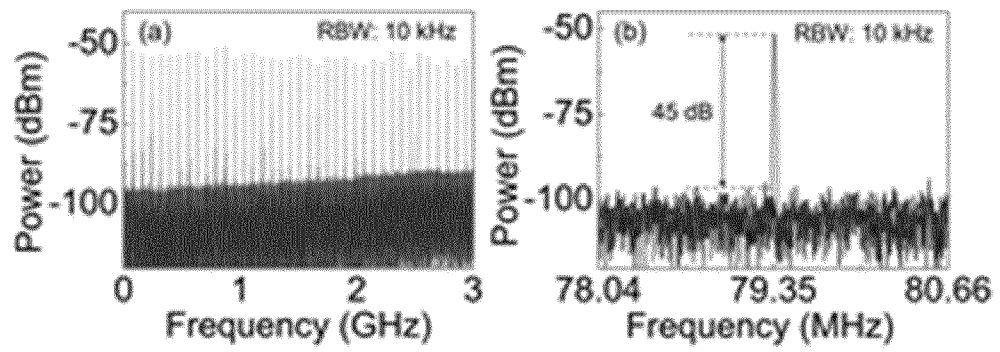


FIG. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/057340

A. CLASSIFICATION OF SUBJECT MATTER
INV. 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, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	US 8 599 474 B1 (KOZLOV VLADIMIR G [US] ET AL) 3 December 2013 (2013-12-03) abstract; claim 1; figure 4 column 2, lines 37-39 column 5, lines 24-29,57-67	1-17
Y	WO 2004/107033 A1 (UNIV ST ANDREWS [GB]; DUNN MALCOLM H [GB]; SPURR MICHAEL B [GB]; STOTH) 9 December 2004 (2004-12-09) abstract page 6, line 3 - page 14, line 13 ----- -/--	1-17



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

30 May 2017

Date of mailing of the international search report

13/06/2017

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

Beugin, Anne

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2017/057340

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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Y	WO 2010/061046 A1 (UNIV HELSINKI [FI]; VAINIO MARKKU [FI]; HALONEN LAURI [FI]) 3 June 2010 (2010-06-03) abstract; figures 13,14 page 21, lines 8-16	1-17
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2017/057340

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