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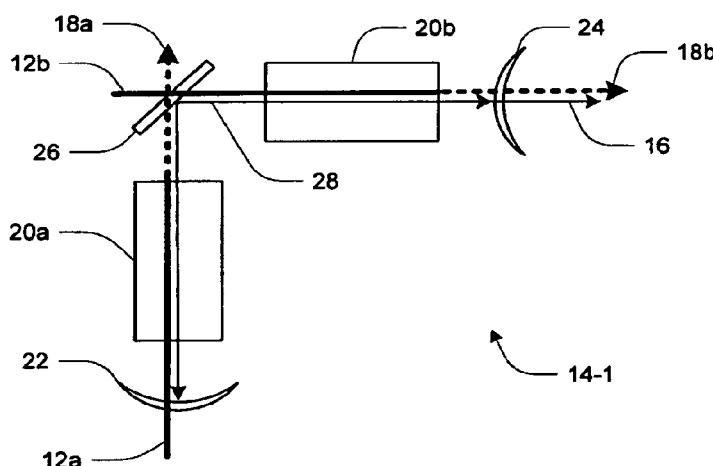
- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))
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(54) Title: MULTI-PORT OPTICAL PARAMETRIC OSCILLATOR



(57) **Abstract:** An optical parametric oscillator (14) includes a source (10) of coherent energetic pump optical signals and an optical resonator cavity which includes a set of optical parametric amplifying (OPA) crystals (20a, 20b) and a set of optical elements (22, 24, 26) such as mirrors disposed along an optical path. The optical elements are configured (1) to direct an oscillation optical signal (28) generated by the OPA crystals along the optical path, (2) to provide input coupling of the energetic pump optical signals (12a, 12b) such that each energetic pump optical signal travels through only one of the OPA crystals to result in a corresponding depleted pump optical signal, and (3) to provide output coupling of the depleted pump optical signals (18a, 18b) to prevent each depleted pump optical signal from traveling through more than one of the OPA crystals. Resonator cavities have multiple-leg configurations, including "L" and "U" shapes, and either linear (or standing-wave) or ring architectures. The pump source may employ wavefront division or alternatively amplitude division of a single relatively high-power optical pump beam.

WO 2007/123781 A1



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MULTI-PORT OPTICAL PARAMETRIC OSCILLATOR

BACKGROUND

One type of nonlinear optical frequency conversion device utilizes the phenomenon of optical parametric amplification in which energy provided at one wavelength in a "pump" optical signal is converted into energy at two other wavelengths of waves commonly referred to as "signal" and "idler" waves. For example, one type of optical parametric amplification (OPA) device employs so-called "quasi-phase matched" (QPM) techniques to produce a phase-matched optical parametric oscillator (OPO) output in the ultraviolet/visible, near infrared or midwave infrared (MWIR) spectral range. QPM devices produce phase-matched output by resetting the phase mismatch of the three optical signals by π radians every "coherence length", which for MWIR OPOs may be in the range of 20-40 microns. One method of resetting the phase mismatch is accomplished by anti-parallel domains of electric polarization that alternate in sign every coherence length. Current QPM technology uses ferroelectric crystals (the electric analogue of a ferromagnet where there is a permanent electric moment along a preferred direction) within which a modulated electric domain structure is induced using a photo-lithographically fabricated periodic electrodes. Very high field strengths, such as in the range of 2 - 20 kV/mm, are utilized to obtain the desired operation. The term "periodic poling" (PP) is used to describe this kind of QPM fabrication.

Current PP QPM technology is limited to crystal structures with thicknesses in the range of 1 - 5 mm. This limit is imposed by the fundamental dielectric breakdown strength of the ferroelectric crystals. This thickness limitation poses a potentially serious constraint on the utility of PP QPM structures for use in OPOs or other nonlinear frequency converters that are used to generate high pulse energy output. The limitation is based on the fact that the limited cross sectional area A of the QPM device (approx. 0.1 - 0.3 cm²) restricts both the maximum pump pulse energy and output pulse energy to a value imposed by a product ($F \cdot A$) of the cross sectional area A and an optical damage limit F for a typical QPM device, which may be in the range of $F = 3 - 10 \text{ J/cm}^2$ for example.

SUMMARY

In accordance with the disclosed technique, a relatively high-energy pump beam is divided into lower-energy pump beam components, and each component is used to pump a different one of a plurality of OPA crystals of an optical parametric oscillator. This may be accomplished for example by "wavefront division" using special graded reflectivity mirrors (GRMs) to reflect a limited sub-aperture of the entire wavefront. Another approach is to divide the pump beam by a reduction in amplitude/intensity using, for example, polarizing or dichroic beam splitters, which is called amplitude division. High-power operation is achieved without surpassing optical damage limits of individual OPA crystals.

Specifically, disclosed is an optical parametric oscillator that includes a source of a set of coherent energetic pump optical signals, and an optical resonator cavity which includes a set of optical parametric amplifying (OPA) crystals disposed along an optical path and a corresponding set of optical elements disposed along the optical path. The optical elements, which may include graded-reflectivity or other mirrors for example, are configured (1) to direct an oscillation optical signal generated by the OPA crystals along the optical path, (2) to provide input coupling of the energetic pump optical signals such that each energetic pump optical signal travels through a corresponding distinct one of the OPA crystals to result in a corresponding depleted pump optical signal, and (3) to provide output coupling of the depleted pump optical signals to prevent each depleted pump optical signal from traveling through more than one of the OPA crystals.

Specific embodiments of the optical parametric oscillator employ resonator cavities having multiple-leg configurations with each leg containing a corresponding OPA crystal. "L"-shaped and "U"-shaped cavities are shown. Also, both linear (or standing-wave) architectures as well as ring architectures are shown. A disclosed pump source employing wavefront division utilizes a set of mirrors offset from each other across the wavefront of a single relatively high-power optical pump beam, whereas an alternative pump source employs amplitude division by extracting the pump optical signals from different points of a laser resonant cavity.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages will be apparent from the following description of particular embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis

5 instead being placed upon illustrating the principles of various embodiments of the invention.

Figure 1 is a block diagram of a multi-port optical parametric oscillator according to an embodiment of the present invention;

10 Figures 2-3 are schematic diagrams of embodiments of an optical cavity in the optical parametric oscillator of Figure 1;

Figure 4 is a schematic diagram of an embodiment of the optical parametric oscillator of Figure 1;

15 Figures 5-6 are schematic diagrams of other embodiments of the optical cavity in the optical parametric oscillator of Figure 1; and

Figure 7 is a schematic diagram of an embodiment of a pump source in the optical parametric oscillator of Figure 1.

DETAILED DESCRIPTION

20 Figure 1 shows an optical parametric oscillator in a generalized form. A pump source 10 generates a plurality of coherent, energetic pump optical signals (ENER PUMP OPT SIGNALS) 12, which are provided to an optical cavity 14 that utilizes the energetic pump optical signals 12 to generate an oscillator optical signal (OSC OPT SIGNAL) 16, which is the desired output of the optical oscillator. The oscillator

25 optical signal 16 is one of either the "signal" or "idler" waves generated in the parametric amplification process, as described in more detail below. The optical cavity 14 also generates depleted pump optical signals (DEPL PUMP OPT SIGNALS) 18 which are by-products of parametric amplification occurring within the optical cavity 14 such as described below.

30 Generally, one benefit of the optical parametric oscillator of Figure 1 is its ability to generate the oscillator optical signal 16 of greater power than can be generated when only a single pump optical signal is utilized. In order to prevent

damage to the optical parametric amplification (OPA) crystals within the optical cavity 14, the optical power density experienced by each crystal is kept below a damage limit. The optical cavity 14 employs multiple OPA crystals pumped by separate pump optical signals, so that each crystal receives only a fraction of the overall pump energy provided by the pump source 10. A high-power output is obtained by utilizing a correspondingly high amount of pump power but distributing this power among multiple crystals such that the power density within each crystal is maintained below the damage limit.

Figure 2 illustrates an embodiment 14-1 of the optical cavity 14. The optical cavity 14-1 has an "L" configuration having two separate legs lying along different geometric axes. Each leg includes a respective OPA crystal 20 (shown as crystals 20a, 20b for legs "a" and "b" respectively). Also included are end mirrors 22, 24 and an internal mirror 26. In the illustrated embodiment, the end mirrors 22, 24 are spherical sections such that the overall cavity forms an unstable resonator, as that term is known in the art. At the frequency of the oscillator optical signal 16, the end mirror 22 as well as the internal mirror 26 are fully reflective, and the end mirror 24 is only partially reflective. As generally known in the art, this provides for the out-coupling of the desired oscillator optical signal 16 as well as feeding back some fraction of the optical energy generated within the cavity to maintain oscillation (indicated by reference number 28). The oscillator optical signal 16 may be either the so-called "signal" or "idler" wave generated in the optical parametric amplification process, and is also referred to herein as the "resonated wave". It is preferred that the non-resonated wave (e.g., the idler wave if the signal wave is resonated) generated within a given OPA crystal 20 be coupled out of the optical cavity 14 and not enter other OPA crystals 20 of the oscillator. Although the non-resonated wave is not explicitly shown, in the embodiment of Figure 2 the non-resonated wave generated within OPA crystal 20a exits via mirror 26, and the non-resonated wave generated in OPA crystal 20b exits via mirror 24. Extracting the non-resonated wave in this manner insures that a desired phase synchronization between all three waves will be retained. In the remaining description below it is to be understood that the non-resonated wave is being extracted from the cavity 14.

A respective energetic pump optical signal 12 (12a, 12b) is passed through each crystal 20. This is accomplished partly by the geometry of the oscillator as well as the characteristics of the mirrors 22, 24 and 26. Each energetic pump optical signal 12 is directed along an axis along which the corresponding crystal 20 lies, and the mirrors 22, 24 and 26 provide for both input coupling of the energetic pump optical signals 12 as well as the output coupling of the depleted pump optical signals 18 such that each energetic pump optical signal 12 is used to pump only one crystal 20. Thus energetic pump optical signal 12a, for example, passes through end mirror 22 and the crystal 20a, and exits crystal 20a as depleted pump optical signal 18a which then exits the cavity 14 through the internal mirror 26. Similarly, energetic pump optical signal 12b passes through internal mirror 26 and the crystal 20b, and exits crystal 20b as depleted pump optical signal 18b which then exits the cavity 14 through the end mirror 24.

Any of a variety of OPA crystals 20 may be utilized. General classes include phase-matching materials and so-called "quasi-phase-matched" or QPM materials. QPM crystals may be of the "periodically poled" type and/or utilize a variety of OPA materials such as lithium niobate.

Figure 3 illustrates an embodiment 14-2 of the optical cavity 14 that has a "U" configuration employing three legs (a, b and c). It will be appreciated that the approach can be extended to an arbitrary number of legs each having an independently pumped crystal 20. The arrangements can be two-dimensional as those of Figures 2 and 3, or three dimensional in alternative embodiments.

Figure 4 illustrates an embodiment of the oscillator of Figure 1 that employs a technique referred to as "wavefront division" for generating the energetic pump optical signals 12. A single relatively high-power pump optical signal 30 impinges on a set of mirrors 32 (shown as 32a - 32c) that are offset from each other across the width of the pump optical signal 30. Each successive mirror 32 reflects the corresponding portion of the wavefront of the pump optical signal 30 to generate the corresponding energetic pump optical signal 12 (e.g., signal 12a is generated by mirror 32a, etc.). Mirrors 34 (shown as 34a - 34c) operate to transmit the optical energy 28 within the cavity while reflecting the pump beams 12 and 18 such that each energetic pump optical signal 12 is steered through a corresponding optical parametric device

36 and the depleted pump optical signals 18a, 18b are directed out of the cavity after exiting the corresponding device 36.

Figure 4 also illustrates a configuration of the overall oscillator in which one leg (the leftmost leg "a" in Figure 4) includes an optical parametric device 36a that is configured as an optical parametric oscillator, while in successive downstream legs ("b" and "c" in Figure 4) the optical parametric devices 36 are configured as optical parametric amplifiers only (as in the embodiments of Figures 2-3). It will be appreciated that each optical parametric device 36 includes one or more OPA crystals (not shown) such as crystals 20, and that the optical parametric device 36a configured as an optical parametric oscillator includes mirrors and/or other elements (not shown) that contribute to maintaining oscillation.

Figures 5 and 6 illustrate alternative oscillators 14-3 and 14-4 respectively that employ a ring architecture versus the linear or "standing wave" architecture of the oscillators 14-1 and 14-2. The desired oscillatory optical energy 28 is shown circulating in a clockwise direction, with the oscillator optical signal 16 exiting via one of the mirrors 26. In each oscillator 14-3 and 14-4, a collimated beam expander 38 is utilized in the non-pumped leg.

Figure 7 illustrates an embodiment 10-1 of the pump source 10, specifically a ring unstable cavity laser. In contrast to the wavefront division approach of Figure 4, the illustrated source 10-1 employs "amplitude division", i.e., deriving the energetic pump optical signals 12 as separate amplitude components of a single pump beam. An NdYAG crystal (NdYAG) 40 is employed as a lasing element in one of the legs. A Q switch, polarizer and waveplate (collectively ref. 42) are disposed in another leg, and a collimating beam expander 44 in yet another. Three coherent energetic pump optical signals 12 (12a - 12c) are extracted via respective partially transmissive mirrors 46 (46a - 46c).

While various embodiments of the invention have been particularly shown and described, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

For example, although the above-discussed embodiments employ mirrors such as mirrors 26 and 34 for internal beam steering, it will be appreciated that alternative

embodiments may employ alternative types of optical elements, which may include for example prisms, diffractive elements, etc. Other variations are also possible.

CLAIMS

What is claimed is:

1. An optical parametric oscillator, comprising:

a source of a plurality of coherent energetic pump optical signals; and
an optical resonator cavity including:

a plurality of optical parametric amplifying (OPA) crystals disposed
along an optical path; and

a plurality of optical elements disposed along the optical path, the
optical elements being configured (1) to direct an oscillation optical signal
generated by the OPA crystals along the optical path, (2) to provide input
coupling of the energetic pump optical signals such that each energetic pump
optical signal travels through a corresponding distinct one of the OPA crystals
to result in a corresponding depleted pump optical signal, and (3) to provide
output coupling of the depleted pump optical signals to prevent each depleted
pump optical signal from traveling through more than one of the OPA crystals.

2. An optical parametric oscillator according to claim 1 wherein the source employs
amplitude division of a relatively high-power pump optical signal to generate the
plurality of energetic pump optical signals.

3. An optical parametric oscillator according to claim 2 wherein the source includes a
multiple-leg optical cavity and each of the energetic pump optical signal comprises a
fraction of an optical signal appearing in a corresponding leg of the optical cavity.

4. An optical parametric oscillator according to claim 1 wherein the source employs
wavefront division of a relatively high-power pump optical signal to generate the
plurality of energetic pump optical signals.

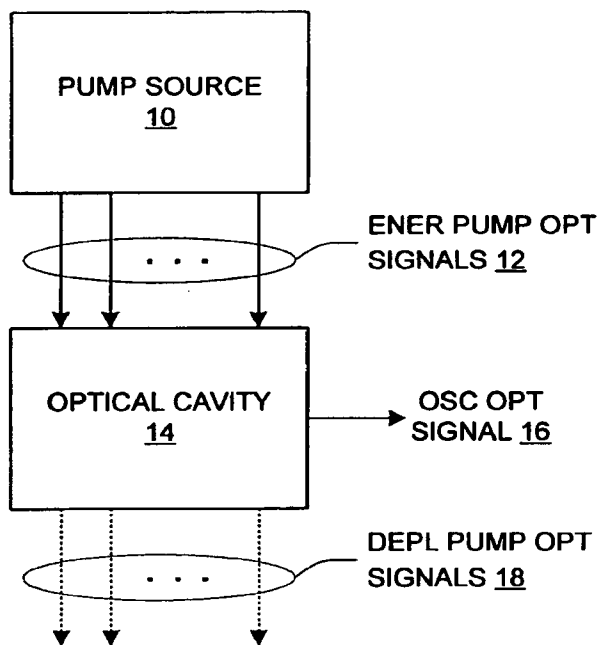
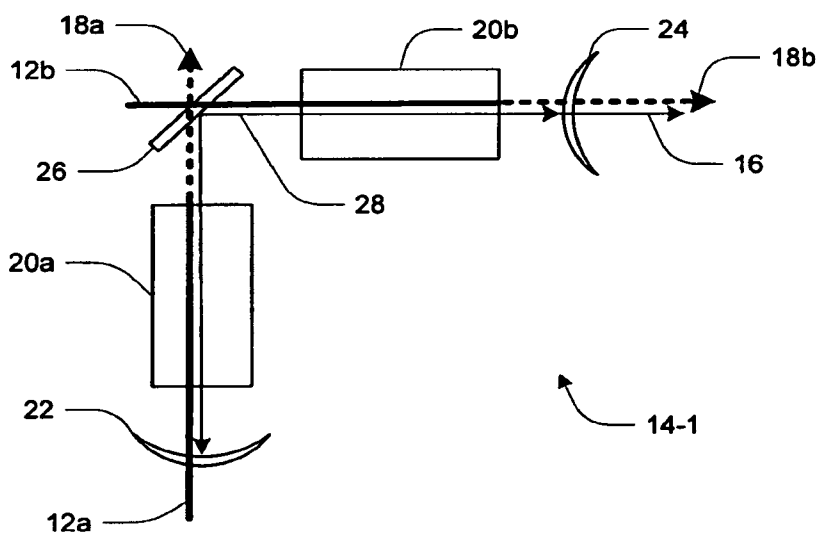
5. An optical parametric oscillator according to claim 1 wherein the source includes a
plurality of mirrors offset from each other across the wavefront of the relatively high-
power pump optical signal, such that each mirror reflects a corresponding portion of

the relatively high-power pump optical signal to generate a corresponding one of the plurality of energetic pump optical signals.

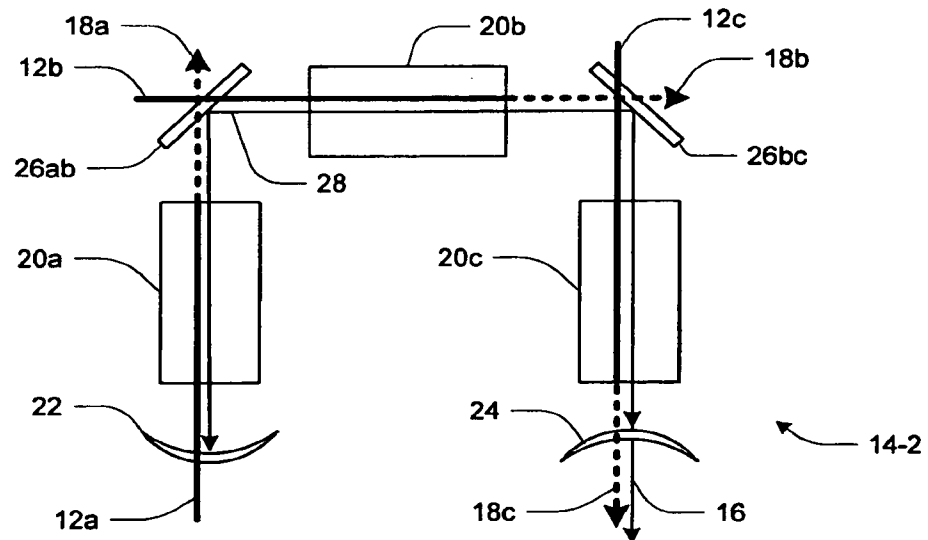
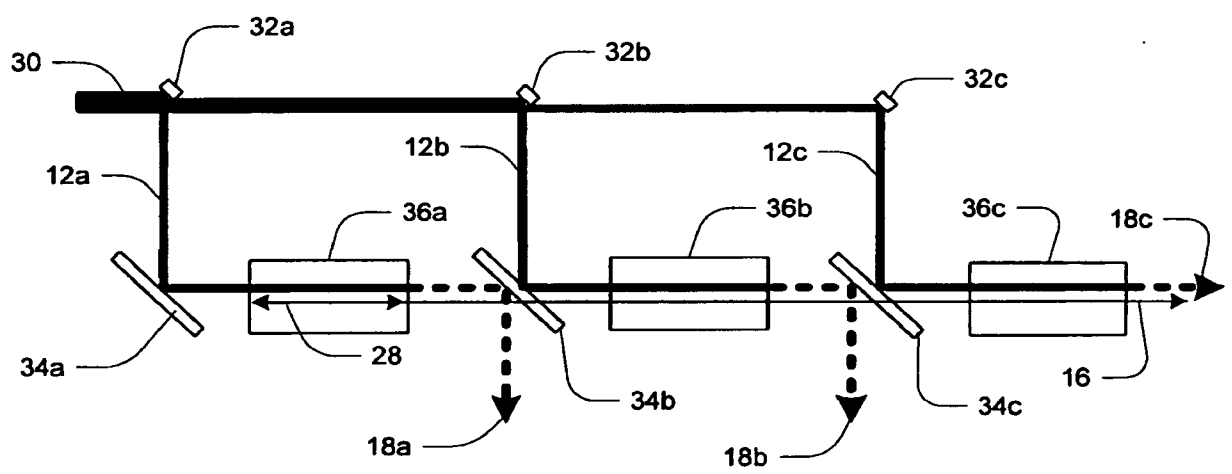
6. An optical parametric oscillator according to claim 1 wherein the optical path of the optical resonator has multiple legs arranged at angles with respect to each other, and wherein corresponding ones of the optical elements comprise mirrors arranged between adjacent pairs of the legs, the mirrors being reflective with respect to the oscillator optical signal but transmissive with respect to the energetic and depleted pump optical signals.

7. An optical parametric oscillator according to claim 1 wherein the OPA crystals comprise periodically poled, quasi-phase-matched crystals.

1/4

**Fig. 1****Fig. 2**

2/4

**Fig. 3****Fig. 4**

3/4

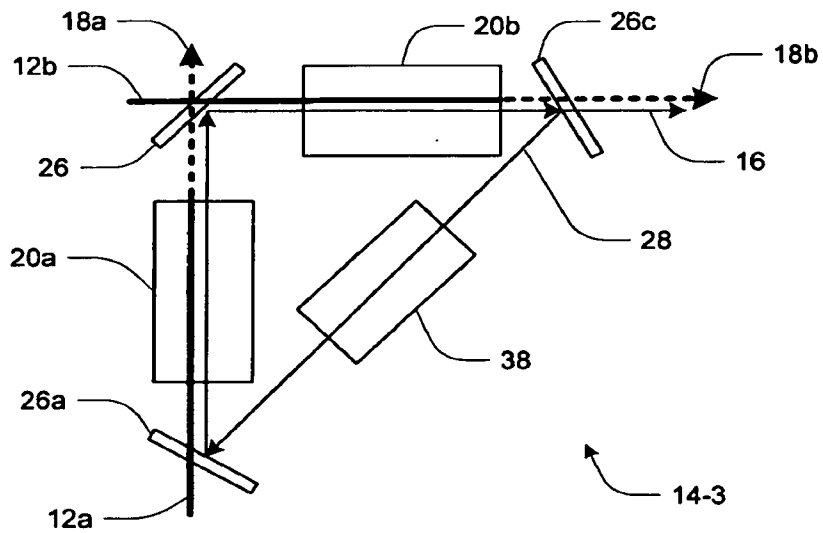


Fig. 5

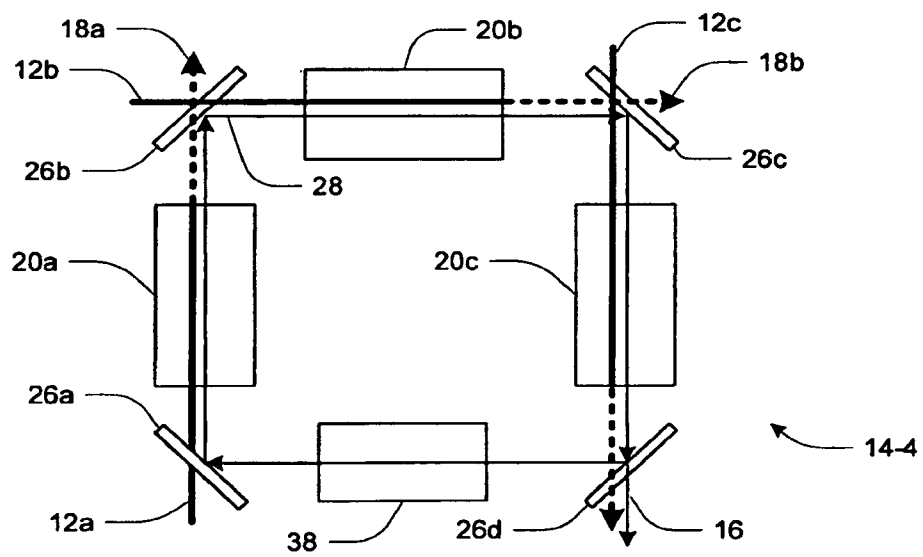
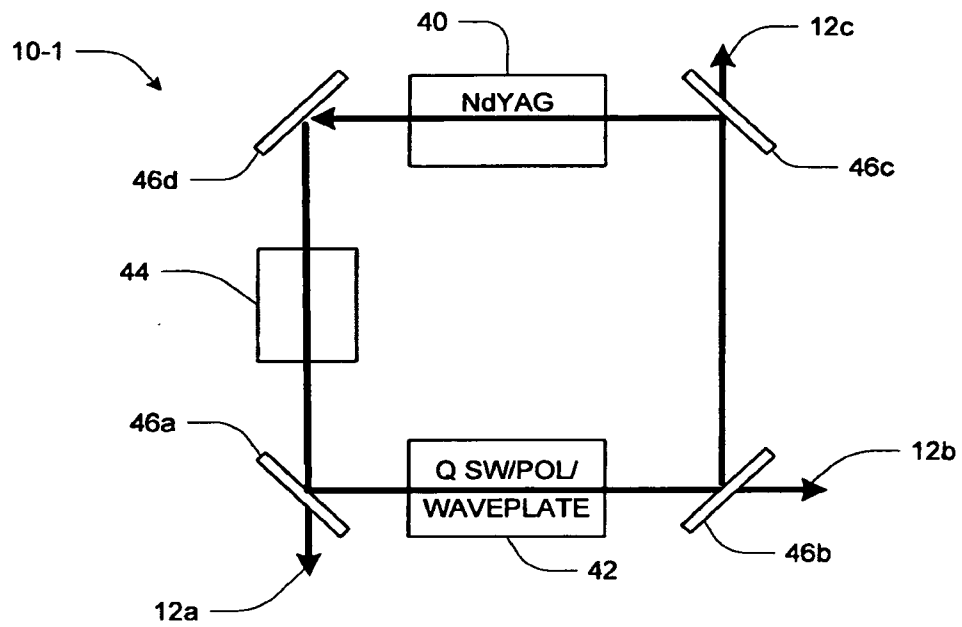


Fig. 6

4/4

**Fig. 7**

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2007/008040

A. CLASSIFICATION OF SUBJECT MATTER

INV. G02F1/39
ADD. H01S3/08 H01S3/083

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 practical, search terms used)

EPO-Internal, COMPENDEX, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2004/109323 A2 (ELOP ELECTRO OPTICAL IND LTD [IL]; ANSHEL ISRAEL [IL]; KRUPKIN VLADIM) 16 December 2004 (2004-12-16) paragraphs [0109] - [0111]; figure 14	1,2,4,6,7
Y	WO 2004/049056 A (UNIV MACQUARIE [AU]; ORR BRIAN JOHN [AU]; HE YABAI [AU]) 10 June 2004 (2004-06-10) page 36, line 19 - page 38, line 15 page 49, line 25 - page 51, line 14 figures 3,21	1,2,4,6,7
A	US 2003/112493 A1 (JOVANOVIC IGOR [US] ET AL) 19 June 2003 (2003-06-19) paragraphs [0022] - [0030]; figures 1,2 ----- -/-	1,2

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

☒ See patent family annex.

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11/09/2007

Name and mailing address of the ISA/

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INTERNATIONAL SEARCH REPORT

International application No

PCT/US2007/008040

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2003/137719 A1 (VAN DER VEER WYTZE EEUWKE [US]) 24 July 2003 (2003-07-24) paragraphs [0036], [0037]; figure 1 -----	1
A	RUSSELL S M ET AL: "Optical parametric generation of greater than 30 mJ signal energies in PPLN stacks" CONF LASERS ELECTRO OPT EUR TECH DIG; CONFERENCE ON LASERS AND ELECTRO-OPTICS EUROPE - TECHNICAL DIGEST 2001, 2001, pages xlvii-xlviii, XP002447571 the whole document -----	4,5
A	US 5 390 211 A (CLARK JAMES B [US] ET AL) 14 February 1995 (1995-02-14) abstract; figures 1,3,4 -----	

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2007/008040

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
WO 2004109323	A2	16-12-2004	CA	2527754 A1	16-12-2004
			EP	1629299 A2	01-03-2006
WO 2004049056	A	10-06-2004	NONE		
US 2003112493	A1	19-06-2003	NONE		
US 2003137719	A1	24-07-2003	NONE		
US 5390211	A	14-02-1995	DE	4400095 A1	02-03-1995
			FR	2709381 A1	03-03-1995