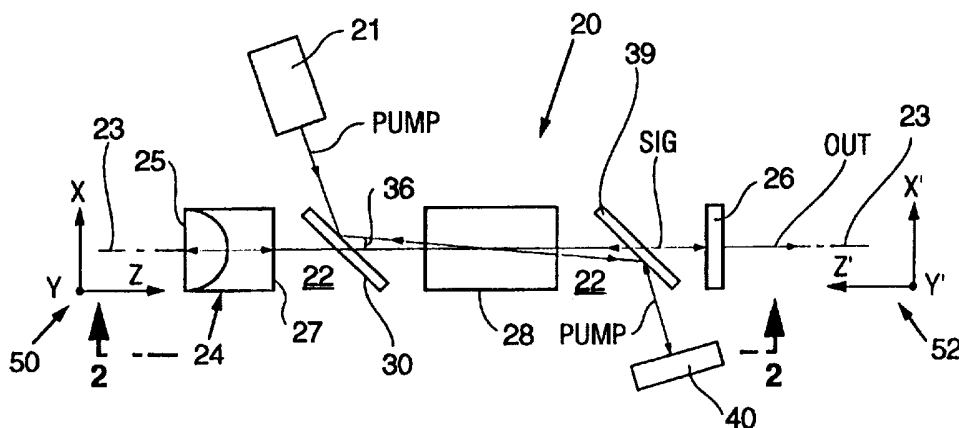




INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

<p>(51) International Patent Classification ⁶ : G02F 1/39</p>	<p>A1</p>	<p>(11) International Publication Number: WO 97/46910</p> <p>(43) International Publication Date: 11 December 1997 (11.12.97)</p>
<p>(21) International Application Number: PCT/US97/08914</p> <p>(22) International Filing Date: 27 May 1997 (27.05.97)</p> <p>(30) Priority Data: 08/657,104 3 June 1996 (03.06.96) US</p> <p>(71) Applicant: COHERENT, INC. [US/US]; 5100 Patrick Henry Drive, Santa Clara, CA 95056-0980 (US).</p> <p>(72) Inventors: NABORS, C., David; 848 Corvallis Drive, Sunnyvale, CA 94087 (US). FRANGINEAS, George; 235 Quinalt Way, Fremont, CA 94539 (US).</p> <p>(74) Agents: STALLMAN, Michael, A. et al.; Limbach & Limbach L.L.P., 2001 Ferry Building, San Francisco, CA 94111 (US).</p>		<p>(81) Designated States: JP, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).</p> <p>Published <i>With international search report.</i></p>

(54) Title: OPTICAL PARAMETRIC OSCILLATOR WITH PORRO PRISM CAVITY



(57) Abstract

An optical parametric oscillator or OPO (20) includes an elongated resonant cavity (22) for signal light, having a parametric gain medium (28) disposed therein for converting pump light to signal light. The resonant cavity has an output coupling device (26) at one end thereof and a Porro prism (2) at the opposite end thereof. The OPO includes an optical arrangement (30, 39 and 40) for directing pump light to make counterpropagating initial and return passes longitudinally through the gain medium at an angle (36) to the axis (23) of the resonant cavity.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

OPTICAL PARAMETRIC OSCILLATOR WITH PORRO PRISM CAVITY

Inventors: C. David Nabors and George Frangineas

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to
5 optical parametric oscillators (OPOs). The invention
relates in particular to an OPO arranged such that a
pump beam counterpropagates through a gain medium in
a resonant cavity at an angle to the cavity axis, and
wherein the resonant cavity is terminated at one end
10 thereof by a Porro prism.

DISCUSSION OF BACKGROUND ART

Optical parametric oscillators (OPOs) are based
on the combination of an optically pumped parametric
gain medium, which provides optical gain, disposed
15 within an optical resonant cavity. The parametric
gain medium is typically an optically nonlinear
crystal.

A parametric mixing process in the non-linear
crystal provides gain by converting pump light at a
20 frequency w_{pump} to light at optical output frequencies
 w_{signal} (signal light) and w_{idler} , according to the
following expression.

$$w_{\text{pump}} = w_{\text{signal}} + w_{\text{idler}} \quad (1)$$

The optical resonant cavity provides feedback of
25 amplified signal light which leads to sustained
oscillation or resonating of the signal light, and
the production of usable signal light output. The
signal light may be defined as laser-like light

The frequencies of the signal light and idler
30 beams can be tuned over a wide range by adjusting
angular alignment and/or temperature of the non-

linear crystal, which affects the indices of refraction. The output frequencies are a function of the indices of refraction. OPOs are thus useful sources of tunable laser-like light.

5 For several potential applications which might benefit from such a light source, the signal light output beam of prior art OPOs has too great a divergence. Further, even if line-narrowing elements such as diffraction gratings are incorporated in the
10 resonant cavity, output spectral linewidth of the signal light may still be too great for several applications.

For an optical parametric gain medium, signal light rays (resonating along a resonant cavity axis)
15 that are noncolinear with pump light rays have phasematched wavelengths that are shifted toward the blue from colinear phasematched rays. The angular acceptance of the gain medium for noncolinear rays at a given wavelength is also far less than for colinear
20 rays, having to satisfy a critical (linearly sensitive) rather than a noncritical (quadratically sensitive) angle condition for divergent rays in the signal-pump plane. For Type I nonlinear interactions in uniaxial crystals, this is true for noncolinearity
25 in either the horizontal or vertical planes with respect to the crystal orientation. The imaging properties of conventional OPO resonant cavities, however, make it difficult to exploit this narrow acceptance angle feature of noncolinear
30 phasematching.

SUMMARY OF THE INVENTION

The present invention is directed to a noncolinear pumped OPO including an elongated resonant cavity for signal light. The resonant
35 cavity has a parametric gain medium disposed therein

for converting pump light to signal light. The resonant cavity is terminated at one end thereof by a Porro prism.

5 The Porro prism replaces a conventional mirror having very high reflectivity for signal light, which is typically used in prior art OPOs. Such a Porro prism terminated cavity OPO has a narrower gain acceptance angle than a corresponding prior art OPO. This allows an OPO in accordance with the present
10 invention to operate with a narrower output beam divergence than a corresponding prior art OPO.

In one preferred embodiment of an OPO in accordance with the present invention, the OPO comprises an elongated resonant cavity for signal
15 light, and a parametric gain medium disposed within the resonant cavity for converting a pump light beam to a signal light beam. The signal light beam resonates along a cavity axis extending longitudinally through the gain medium. The resonant
20 cavity has a Porro prism at one end thereof for fully reflecting the signal light beam, and a signal light output coupling device at the other end thereof for partially reflecting the signal beam and coupling an output portion of the signal light beam out of said
25 resonant cavity. The OPO includes an optical arrangement for directing the pump beam to make first and second counterpropagating passes generally longitudinally through the gain medium along a path noncolinear with the cavity axis in two mutually
30 perpendicular planes.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, schematically illustrate a preferred
35 embodiment of the invention and, together with the

general description given above and the detailed description of the preferred embodiment given below, serve to explain the principles of the invention.

5 FIG. 1 is an elevation view schematically illustrating a preferred embodiment of a noncolinear repumped OPO in accordance with the present invention, including a resonant cavity having a parametric gain medium therein and formed from a Porro prism and an output coupling device.

10 FIG. 2 is a plan view of the noncolinear repumped OPO of FIG. 1 seen generally in a direction 2-2 of FIG. 1.

15 FIG. 3 is a side elevation view of another embodiment of a noncolinear repumped OPO in accordance with the present invention having an output coupling arrangement including a mirror and a reflective diffraction grating in a Littman configuration.

20 FIGS 4, 5 & 6 are respectively side and end elevation views and a plan view schematically illustrating optical functions of the Porro prism in the OPO of FIG. 1.

25 FIG. 7 is an angle-space diagram schematically illustrating forward and return pump beams as seen by sequential oscillations of a signal beam in the gain medium of the noncolinear repumped OPO of FIG. 1.

FIG. 8 is a graph schematically illustrating resonating wavelength as a function of noncolinearity

of pump beam path and resonant-cavity axis in an OPO in accordance with the present invention.

5 FIG. 9 is a graph schematically illustrating relationship of signal light bandwidth to angular gain acceptance of an OPO in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Turning now to the drawings, wherein like components are designated by like reference numerals, 10 FIG. 1 and FIG. 2 schematically illustrate a preferred embodiment 20 of a noncolinear pumped OPO in accordance with the present invention, arranged for Type I phasematching. A resonant cavity (or resonator cavity) 22 for signal light is formed from 15 a Porro prism 24 having a roof-edge 25, and a signal light output coupling device 26.

It should be noted here that, in general terms, above-discussed equation (1) states that pump light in the parametric gain medium generates light of two 20 wavelengths. Either of these wavelengths can be selectively resonated to provide signal light, the other being defined as the idler. It is usually, but not necessarily, the shorter of the two wavelengths which is selected to be resonated. Throughout this 25 description and appended claims, the term signal light refers to that light wavelength which is selected to be resonated, whether or not it is the longer or shorter wavelength.

Continuing now with reference to FIGS 1 and 2, 30 output coupling device 26 is represented in FIGS 1 and 2 as a planar optical element which is partially reflective and partially transmissive for laser light. Porro prism 24 reflects light by total internal reflection and is essentially fully

reflective for the signal light. Preferably, entrance face 27 of Porro prism 24 is antireflection coated for signal light.

5 A parametric gain medium (typically an optically nonlinear crystal) 28 is disposed in cavity 22. Signal light generated by optically pumping gain medium 28 oscillates (resonates) along a cavity axis 23 as indicated by arrowed line SIG, coincident therewith. A portion (OUT) of the oscillating signal light is coupled out of resonant cavity 22 via output coupling device 26.

10 Referring to FIG. 3, in another embodiment 20A of an OPO in accordance with the present invention, a combination 41 of reflective diffraction grating 43, at grazing incidence to axis 23, and a mirror 45 are used as an output coupling device in place of partially reflective, partially transmissive element 26. A portion (OUT) of the oscillating signal light, here, is coupled out of resonant cavity 22 via the 0th order reflection of diffraction grating 43. Mirror 45 is tiltable about an axis 7 (as indicated by arrow T) for tuning signal light wavelength. Signal light bandwidth is narrowed by the grating. This configuration of mirror 45 and grating 43 is referred to by practitioners of the art as a "Littman" configuration or mode of the diffraction grating.

25 In both embodiment 20 and embodiment 20A, pump light (PUMP) is directed, from a pump-light source 21 transversely into cavity 22 and is incident on a beamsplitter element 30 which is highly reflective for pump light and highly transmissive for signal light. Beamsplitter 30 directs the incident pump light to make an initial longitudinal pass through gain medium 28 at an angle 36 to axis 23 in a plane parallel to roof-edge 25 of Porro prism 24, and an

30

35

angle 38 to axis 23 in a plane perpendicular to roof-edge 25 of Porro prism 24. Given the relatively small diameter of a resonating signal light beam, it is important that roof-edge 25 of Porro prism 24 be essentially a knife-edge.

5 A beamsplitter 39, highly reflective for pump light and highly transmissive for signal light, and a mirror 40 highly reflective for pump light, are arranged to redirect the pump beam on a return longitudinal pass through gain medium 28 along the same path as the initial-pass. Such two-pass pumping is usually referred to by practitioners of the art as repumping. Pumping at an angle to the resonant--cavity axis in two mutually perpendicular planes may be referred to as bi-noncolinear pumping. Although in FIGS 1 and 2 pump light is depicted as being directed initially through gain medium 28 from the side thereof facing Porro Prism 24, pump light may, alternatively, be directed from the side of the gain medium facing output coupling device 26, being returned, of course, from the opposite side of the gain medium.

15 Angles 36 and 38, are preferably about equal and are typically less than about five degrees (5°) external to gain medium 28, such that desired portions of what is essentially a cone of signal light radiation generated by the passage of pump light through the gain medium can be resonated within cavity 22. Preferably angles 36 and 38 are about 1.00 external to gain medium 28, that being equivalent to about 0.6° inside the gain medium. Thus, pump light beams, while not exactly axially propagating through the gain medium, may still be properly defined as longitudinally propagating.

30 Referring now to FIGS 4, 5, and 6, action of Porro prism 24 with respect to signal light incident

thereon is illustrated. Porro prism 24 is preferably made from solid glass or solid fused silica. Porro prism 24 may be a conventional Porro prism, wherein roof angle 29 thereof is nominally exactly ninety
5 degrees. Preferably, however, the roof angle is made about eight seconds of arc less than ninety degrees, i.e., about eighty-nine degrees, fifty-nine minutes and fifty-two seconds of arc ($89^{\circ}59'52''$).

FIG. 4 illustrates signal light (SIG) incident, nonnormally with respect to entrance face 27, at an
10 angle (INC) on Porro prism 24 in a plane parallel to roof-edge 25 thereof. The incident signal light is reflected from prism face 25A or 25B at a reflection angle (REF) equal to the angle of incidence. This is
15 the well known incidence/reflection angle law for a mirror in any plane of incidence. Porro prism 24 differs from a mirror in that, in a plane perpendicular to roof-edge 25 thereof, an incident beam at any angle is retroreflected, i.e, it is
20 returned along a reflection path parallel to its incidence path as illustrated in FIG. 6.

It can be seen from the foregoing discussion that a Porro prism simply provides an optical device which functions as a mirror for light incident
25 thereon in a first plane and as retroreflector for light incident thereon in a second plane perpendicular to the first plane. Those familiar with the optical art will recognize that, in theory at least, other optical arrangements may be devised
30 will act in a similar manner, for example two plane mirrors inclined at 90° to each other and forming a "hollowcorner". Porro prism 24 is preferred, however, because it provides for essentially lossless, complete reflection of signal light at
35 angled reflecting surfaces 25A and 25B thereof; does not require any fixtures or adhesives to maintain a

precise angular relationship between reflecting faces; and provides that the angled reflecting faces may be joined, inseparably, at an essentially zero-thickness joint, i.e., roof-edge 25.

5 Continuing with reference again to FIGS 1 and 2, as illustrated by coordinate systems 50 and 52, signal light rays and pump light rays propagating from left to right (the +z direction) have their angles specified by $0_x'$ and 0_{y1} . Those propagating
10 from right to left (the +z' direction) have their angles to the cavity resonant axis 23 specified by 0_x and 0_y .

If the forward or initial pump beam has angular coordinates $(0_{pumpx'}, 0_{pumpy'})$, then the return pump beam
15 angular coordinates are determined by the following expression.

$$(0_{pumpx1}, 0_{pumpy1}) = \{-0_{pumpx}, 0_{pumpy}\} \quad (2)$$

A reflection of signal light off output coupling mirror 26 causes the reflected signal rays to
20 transform from unprimed coordinate system 50 to the primed coordinate system 52 in accordance with the following transformation.

$$(0_x, 0_y) ==> 0_{x1} = 0_x, 0_{y1} = -0_y \quad (3)$$

Signal light retroreflected from Porro prism 24
25 has angular coordinates transformed differently. The transformation can be defined by as follows

$$(0_{x1}, 0_{y1}) ==> 0_x = 0_{x1}, 0_y = 0_{y1} \quad (4)$$

Referring now to FIG. 7, the beam divergence reducing effect of the combination of noncolinearity
30 of pump beams, the reflection properties of a Porro prism, And double-pass pumping is illustrated in an

angle-space diagram (a Cartesian coordinate system in which the x and y axes are in dimensions of angle) representing any transverse plane in gain medium 28, with respect to coordinate systems 50 and 52. The forward-going (initial) pump direction is indicated by a small circle (FWD) in the third quadrant $Q3$ $0_x < 0$, $0_y < 0$. The return pump direction is indicated by a small circle (RET) in the fourth quadrant $0_{x1} > 0$, $0_{y1} < 0$. The initial and return pump direction is noncollinearly aligned with optical cavity axis 23 which forms the origin of the coordinate systems. The z and z' axes are perpendicular to the plane of the illustration of FIG. 7.

Pump light is typically supplied in the form of a high energy pulse of relatively short duration, for example a few nanoseconds. As nanosecond class OPOs have very few round trip times compared to the length or duration of the pump pulse (typically 5 to 50), the first few round trips where signal light builds up in the resonant cavity are critical to determining which oscillating mode will be established in the cavity. As the gain per pass is very high (often > 100), signal light that sees even a single additional pass worth of gain will overwhelm other light in the cavity. Porro prism 24 has the effect of providing more than a second pass of gain occurs in only a narrow angle-space of the gain medium. This results in the very narrow beam divergence characteristic of an OPO in accordance with the present invention. The manner in which this occurs is discussed in further detail hereinbelow.

Signal light is generated by pump light passing through gain medium 28 in the form of a cone of signal light rays propagating generally in the same direction as the pump light. The signal light is generated in a relatively broad spectrum of

wavelengths, the longest wavelength thereof being on the axis of the cone, with wavelengths decreasing with increasing (off axis) angles from the axis of the cone.

5 Measured optical parametric gain wavelength vs. (off-axis) angle in the gain medium for a beta barium borate (P-BaB₂O₄ or BBO) crystal gain medium, for pump light at 355 nm wavelength, is illustrated (curve WL) in FIG. 8. Pump light angle was 32.65 degrees with
10 respect to the c-axis of the crystal. In order to resonate a specific wavelength, the off axis angle for that wavelength would be the noncolinear angle (in the gain medium) between the pump beam path and the resonating signal light path, i.e., between the
15 pump beam path and the resonant-cavity longitudinal axis.

FIG. 9 shows, the wavelength versus angle curve (WL) of FIG. 8 twice superimposed onto an arbitrary axis 63 of FIG. 7 passing through centers 66 and 64
20 of annuli S2 and S3 respectively. Resulting curves WL' and WL", having origins 66 and 64 respectively, have opposite slopes (wavelength v. angle) which intersect on axis 23 at the nominal signal light wavelength. The relationship between signal light
25 bandwidth (BW) and the restricted angle-space band in which resonance occurs is also schematically shown. Lines S2/S3 here corresponding generally to the center thickness of lens-shaped region 60 of FIG. 7, lines S2/S3 are defined by projections of the
30 resonating bandwidth BW. The angular gain acceptance represented by FIG. 9 is the angular separation of lines S2/S3. it should be noted, however, that, for clarity of illustration, bandwidth BW and the angular gain acceptance are shown greatly exaggerated in
35 width compared with what they would actually be in an OPO in accordance with the present invention.

Continuing with reference again to FIG. 7, the solid annulus (S1) centered on pump beam FWD represents the signal light or parametric fluorescence in the bandwidth BW produced by an initial pass of the pump beam. The dashed annulus (S2) is the same light, angles of which have been transformed by reflection from the output coupling mirror, as determined by equation (5). This light contained in annulus S2 is subsequently amplified by the return pump light. The region of angles in the $(0_{x1}, 0_{y1})$ space that derive gain from the return pump are indicated by the dotted annulus (S3).

It can be seen in FIG. 7 that there is a lens-shaped overlap region 60 of the possible offset angles of signal light resulting from the return pump light with the possible offset angles of reflected signal light from the initial pump light. This lens shaped region is thus a region in which initially generated signal light undergoes two passes of gain or amplification.

Twice amplified light from this lens-shaped region is reflected by Porro prism 24 according to the transform rule of equation (4), which does not change its orientation in the coordinate scheme of FIG. 7. This retroreflected, twice-amplified light thus returns, in the forward (+z) direction, through the lens-shaped region. Within the lens-shaped region, there is a generally rectangular region 62 which is defined by the overlap of lens-shaped region 60 with the annular region, S1, of light generated by the initial pass of the pump beam. Rectangular region 62 thus represents a restricted angle-space region in which the twice amplified light undergoes an additional, (third) pass of gain or amplification. Considering signal light originating from the return or repump, it can be seen that after reflection from

Porro prism 24 and a gain pass from the forward pump, the two-pass overlap region is already the same as the region resulting from the above-described three gain-passes.

5 A Porro prism terminated cavity OPO in accordance with the present invention provides that more than a second gain pass through the gain medium can only occur in a restricted angle-space within the gain medium. Because of this, the net angular gain-
10 acceptance the OPO cavity is significantly less than that which would be obtained from prior art OPO resonant cavities. This leads to a more narrow divergence of the output signal and superior beam quality factor, both of which are desirable for many
15 applications.

 The decrease in the gain acceptance angle in the cavity has the beneficial effect of reducing the bandwidth of the output signal light, as wide angular acceptance is coupled through phasematching
20 relationships to wide frequency acceptance. Because of this, a noncolinear pumped, Porro prism terminated cavity OPO in accordance with the present invention operates with significantly smaller spectral
25 bandwidth than prior art noncolinear pumped OPOs.

 In one example of a Porro prism terminated cavity, bi-noncolinear pumped OPO in accordance with the present invention, having a general arrangement similar to OPO 20 of FIGS 1 and 2, the pump
30 wavelength was 355 nm, and the nonlinear crystal was a BBO crystal between about ten 15 millimeters (10 mm) and 15 mm in length, oriented for type I phasematching with a crystal cut angle of approx 28'. This combination allowed for a signal light
35 wavelength tuning range of 420-710 nanometers (nm) with corresponding idler wavelengths of 710-2300 nm. The noncolinear angle for both the horizontal and

vertical planes was approximately 10 external to the crystal. The divergence of the output beam was about one milliradian. When the signal wave was resonated in a cavity similar to cavity 22A, including a
5 Littman configuration grating and angle-adjustable tuning mirror as discussed above with reference to FIG. 3, the Porro-prism-terminated cavity OPO produced a tunable output of several millijoules (mJ) with a linewidth of $< 0.1 \text{ cm}^{-1}$, and an output beam
10 divergence consistent with output beam (OP) being a few times diffraction limited. In all cases, it was found that the near-field beam quality is improved by having the roof angle of the Porro prism be less by about 8 arc seconds than an exact 90° angle that
15 usually defines a Porro prism.

While in the above-described example, a BBO crystal was used as parametric gain medium, principles of the present invention are applicable to any parametric, gain medium. Preferred gain media
20 include the group consisting of BBO, lithium niobate (LiNbO_3), potassium niobate (KNbO_3) lithium iodate (LiIO_3), potassium titanium phosphate (KTiOPO_4 or KTP), lithium borate (LiB_2O_5 or LBO) and potassium dihydrogen phosphate (KDP), and isomorphs of KDP.

25 In summary, the present invention is directed to a noncolinearly-pumped optical parametric oscillator having a resonant cavity terminated at one end thereof by a Porro prism. The combination of the Porro prism-terminated resonant cavity and
30 noncolinear pumping provide for output beam divergence and spectral bandwidth that are narrower than are typical of prior art noncolinear cavity OPOs.

35 The present invention has been described in terms of a preferred and other embodiments. The invention is not limited, however, to the embodiments

described and depicted. Rather the invention is limited by the claims appended hereto.

WHAT IS CLAIMED IS:

1. An optical parametric oscillator,
comprising

5 a resonant cavity for signal light and a
parametric gain medium disposed in said resonant
cavity for converting pump light to signal light,
said resonant cavity being terminated at one end
thereof by a Porro prism, and said resonant cavity
10 arranged such that said signal light resonates along
a longitudinal axis of said resonant cavity; and

means for directing said pump light to make
generally longitudinally counterpropagating initial
and return passes through said gain medium along a
path noncolinear with said longitudinal axis.

15 2. The optical parametric oscillator of claim
1, wherein said noncolinear path is noncolinear with
said longitudinal axis in two mutually perpendicular
planes.

20 3. The optical parametric oscillator of claim
1, wherein said resonant cavity is terminated at an
opposite end thereof by an output coupling device,
said output coupling device including a combination
of a mirror and a reflective diffraction grating in
the Littman configuration.

25 4. The optical parametric oscillator of claim
1, wherein said gain medium is a material selected
from the group consisting of barium borate, lithium
niobate, potassium niobate, lithium iodate, potassium
titanium phosphate, lithium borate, and potassium
30 dihydrogen phosphate, and isomorphs of potassium
dihydrogen phosphate.

5. The optical parametric oscillator of claim 1 wherein said Porro prism has a roof angle of about eighty-nine degrees, fifty-nine minutes and fifty-two seconds of arc.

5 6. An optical parametric oscillator,
comprising:

a resonant cavity for signal light, and a
parametric gain medium disposed within the resonant
cavity for converting pump light to said signal
10 light, said resonant cavity having a longitudinal
axis;

said resonant cavity having an output
coupling device at one end thereof for coupling an
output portion of said signal light beam out of said
resonant cavity and a Porro prism at an opposite end
15 thereof for fully reflecting said signal light beam,
said Porro prism having a roof-edge, and a roof
angle; and

means for directing said pump light to make
20 first and second counterpropagating passes generally
longitudinally through said gain medium along a path
noncolinear with said cavity axis in two mutually
perpendicular planes, a first thereof parallel to
said roof-edge and a second thereof perpendicular to
25 said roof-edge.

7. The optical parametric oscillator of claim 6 wherein said roof angle is about eighty-nine degrees, fifty-nine minutes and fifty-two seconds of arc.

30 8. The optical parametric oscillator of claim 6 wherein said output coupling device includes a combination of a mirror and a reflective diffraction grating in a Littman configuration.

9. The optical parametric oscillator of claim 6, wherein said gain medium is a material selected from the group consisting of barium borate, lithium niobate, potassium niobate, lithium iodate, potassium titanium phosphate, lithium borate, and potassium dihydrogen phosphate, and isomorphs of potassium dihydrogen phosphate.

10. An optical parametric oscillator, comprising

a resonant cavity for signal light and a parametric gain medium disposed in said resonant cavity for converting pump light to signal light, said resonant cavity being terminated at each end thereof by first and second optical devices, and said resonant cavity arranged such that said signal light resonates along a longitudinal axis of said resonant cavity;

means for directing said pump light to make generally longitudinally counterpropagating initial and return passes through said gain medium along a path noncolinear with said longitudinal axis in first and second mutually perpendicular planes;

said first optical device functioning as a mirror for light incident thereon in said first and second mutually perpendicular planes; and

said second optical devices arranged to function as a mirror for signal light incident thereon in one of said first and second mutually perpendicular planes, and as a retroreflector for signal light incident thereon in the other of said mutually perpendicular planes.

11. An optical parametric oscillator,
comprising

5 a resonant cavity for signal light and a
parametric gain medium disposed in said resonant
cavity for converting pump light to signal light,
said resonant cavity being terminated at first and
second opposite ends thereof by respectively first
and second optical devices, and said resonant cavity
arranged such that said signal light resonates along
10 a longitudinal axis of said resonant cavity;

means for directing said pump light to make
generally longitudinally counterpropagating initial
and return passes through said gain medium along a
path noncolinear with said longitudinal axis in first
15 and second mutually perpendicular planes;

said first said optical device arranged to
function as a mirror for signal light incident
thereon in said first plane, and as a retroreflector
for signal light incident thereon in said second
20 plane;

said second optical device arranged to
function as a mirror for signal light incident
thereon in said first and second planes;

said first and second optical devices, said
25 gain medium and said noncolinear pump path arranged
such that, in an angular coordinate plane in said
gain medium transverse to said longitudinal axis,
said pump light on said initial and return passes
generates signal light in respectively first and
30 second gain regions, and signal light generated by
said initial pump-light pass and reflected from said
second optical device passes through a third gain
region, said second and third annular gain regions
overlapping, the overlapping portions thereof to
35 defining a fourth gain region, and said first and
fourth gain region, and said first and fourth gain

regions overlapping, the overlapping portions thereof defining a fifth gain region; and

wherein, only in said fifth gain region may generated signal light undergo three passes of gain.

5 12. An optical parametric oscillator,
comprising

 a resonant cavity for signal light and a
parametric gain medium disposed in said resonant
cavity for converting pump light to signal light,
10 said resonant cavity being terminated at first and
second opposite ends thereof by respectively first
and second optical devices, and said resonant cavity
arranged such that said signal light resonates along
a longitudinal axis of said resonant cavity;

15 means for directing said pump light to make
generally longitudinally counterpropagating initial
and return passes through said gain medium along a
path noncolinear with said longitudinal axis in first
and second mutually perpendicular planes;

20 said first said optical device arranged to
function as a mirror for signal light incident
thereon in said first plane, and as a retroreflector
for signal light incident thereon in said second
plane;

25 said second optical device arranged to
function as a mirror for signal light incident
thereon in said first and second planes;

 said first and second optical devices, said
gain medium and said noncolinear pump path arranged
30 such that, within said gain medium transverse to said
longitudinal axis, said pump light on said initial
and return passes generates signal light in
respectively first and second gain regions, and
signal light generated by said initial pump-light
35 pass and reflected from said second optical device

passes through a third gain region, said second and third annular gain regions overlapping, the overlapping portions thereof defining a fourth gain region wherein signal light may be twice amplified; and

5

said first and second optical devices, said gain medium and said noncolinear pump path arranged such that twice-amplified signal light from said fourth gain region incident on said first optical device is retroreflected thereby back through said fourth gain region, and also arranged such that said first gain region overlaps said fourth gain region and defines, within said fourth gain region, a fifth gain region wherein retroreflected twiceamplified signal light becomes thrice amplified.

10

15

13. An OPO comprising:

a resonant cavity, said resonant cavity including at least first and second reflectors;

20

a non-linear crystal disposed in said resonant cavity;

a source for generating laser pump pulses to excite the crystal and generate and amplify signal light, the resonant cavity arranged such that said generated and amplified signal light resonates along a longitudinal axis of the cavity;

25

means for directing the pump pulses along a path noncolinear with the axis of the cavity;

30

and wherein one of said reflectors of said resonant cavity is defined by a reflector means having two reflecting surfaces disposed at about ninety degrees to each other, with the noncolinear path angle of the pump pulse and the angle of the reflector means being chosen such that generated signal light can undergo multiple amplification

35

passes through the crystal only in a narrow angular

region thereof aligned with the cavity axis, thereby confining resonating signal light beam to said narrow angular region and minimizing the divergence of said resonating signal light.

5 14. An OPO as recited in claim 13, wherein said reflector means is a Porro prism.

 15. An OPO as recited in claim 12, wherein
generated signal light can undergo no more than two
amplification passes outside said narrow angular
10 region of said crystal.

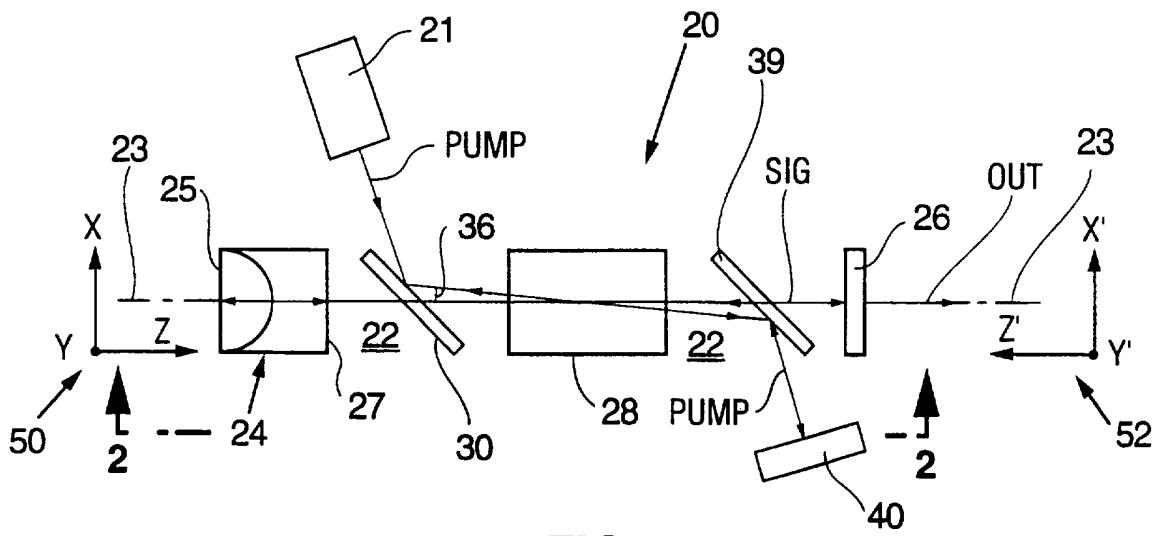


FIG. 1

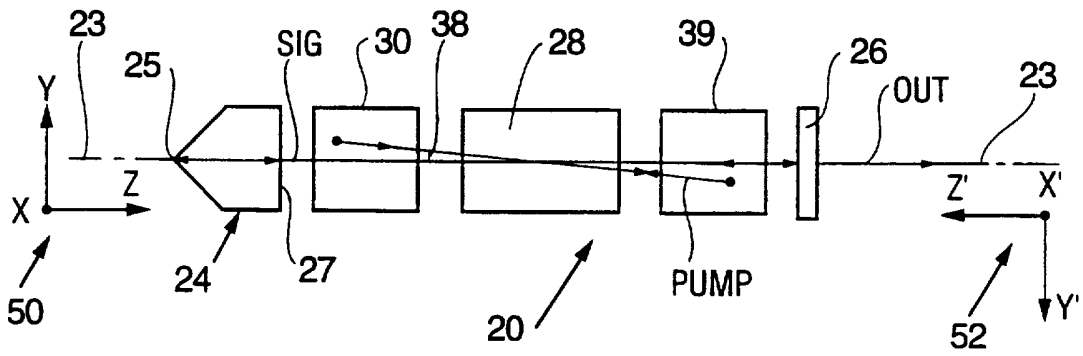


FIG. 2

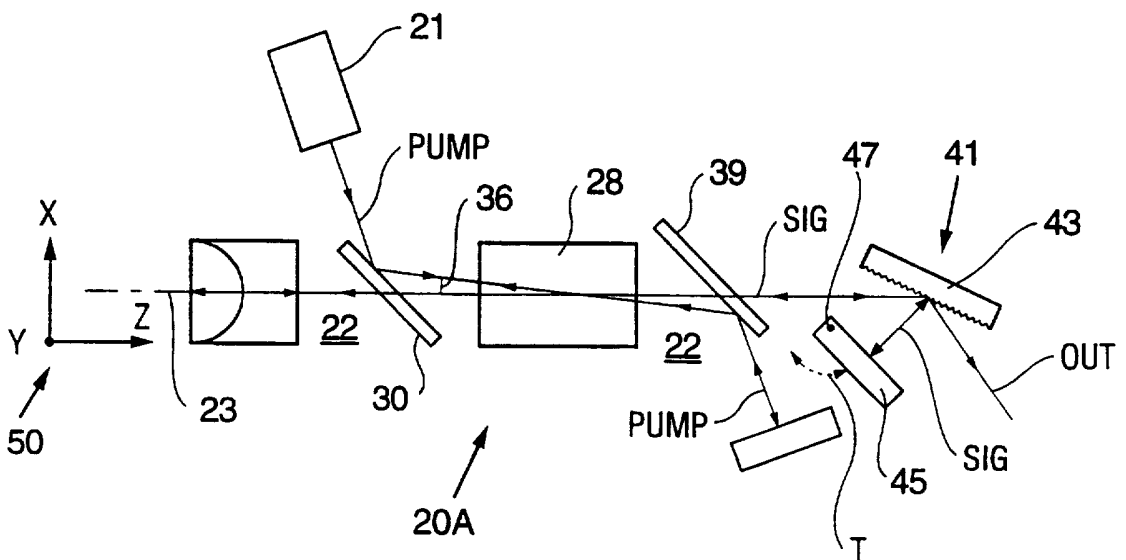


FIG. 3

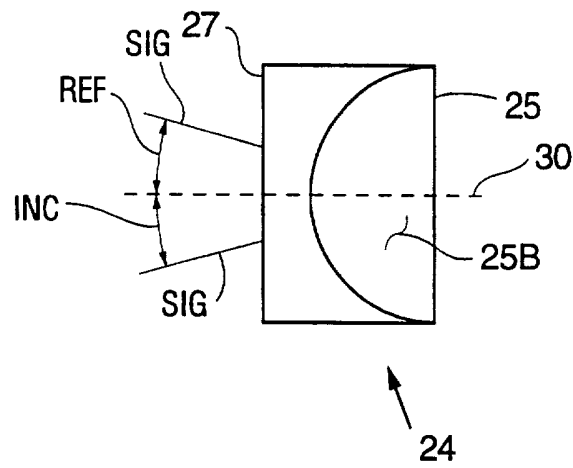


FIG. 4

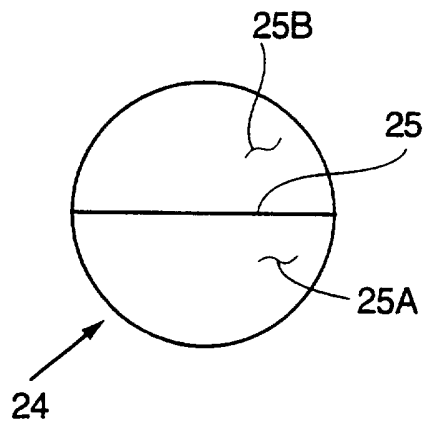


FIG. 5

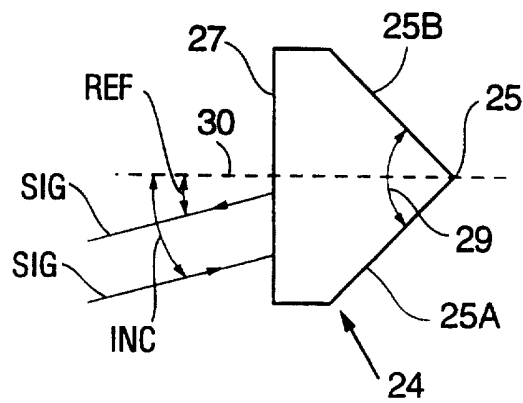


FIG. 6

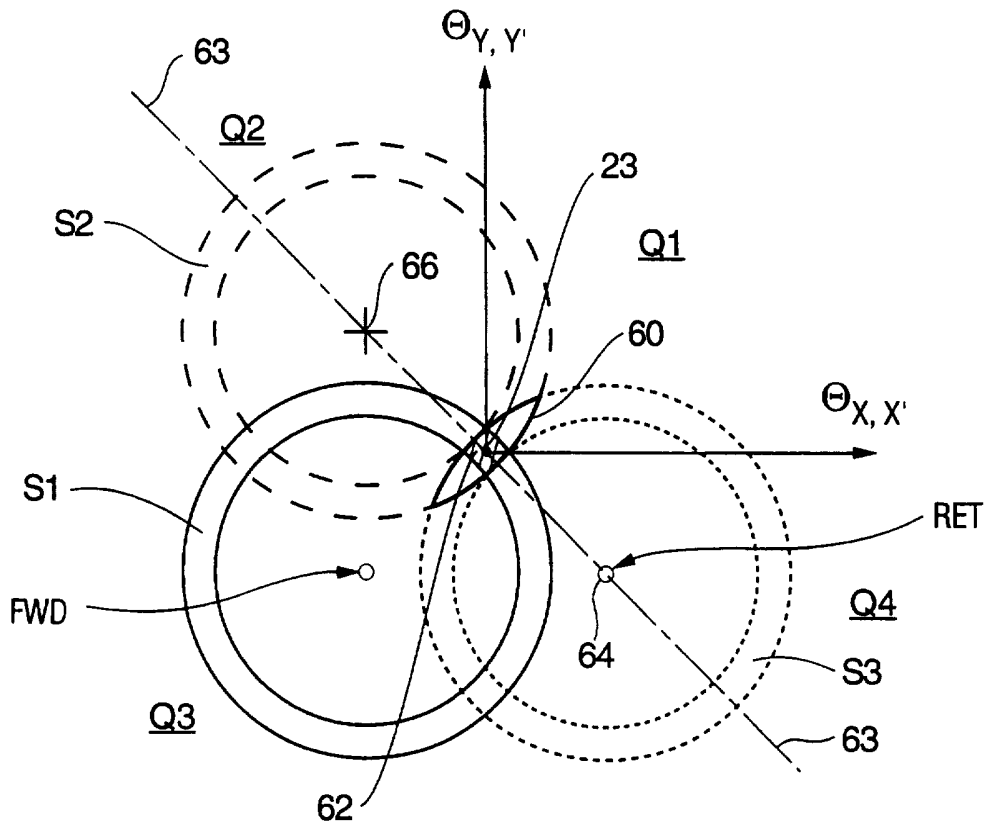


FIG. 7

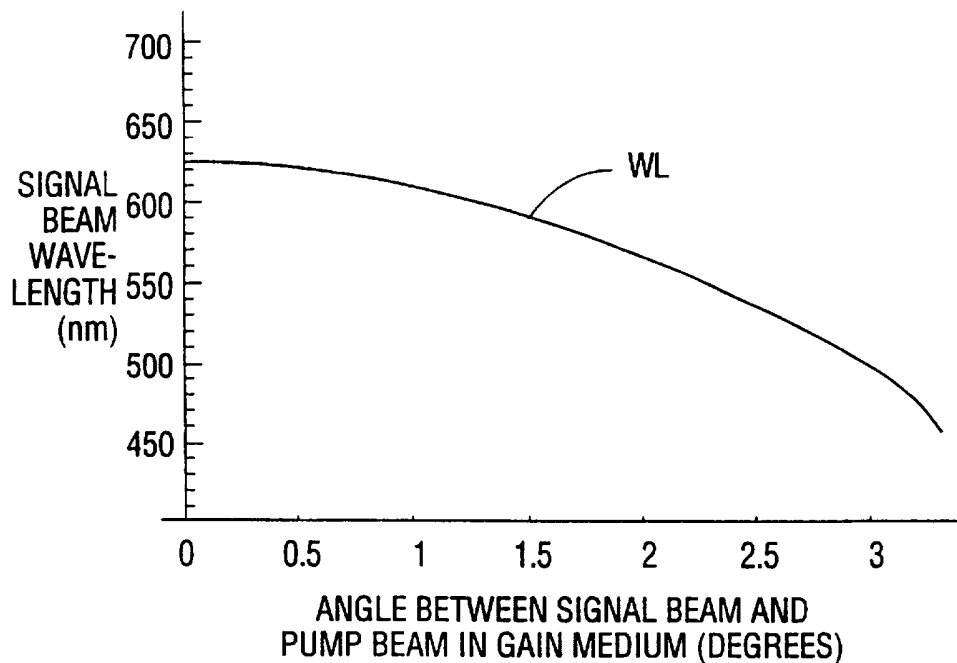


FIG. 8

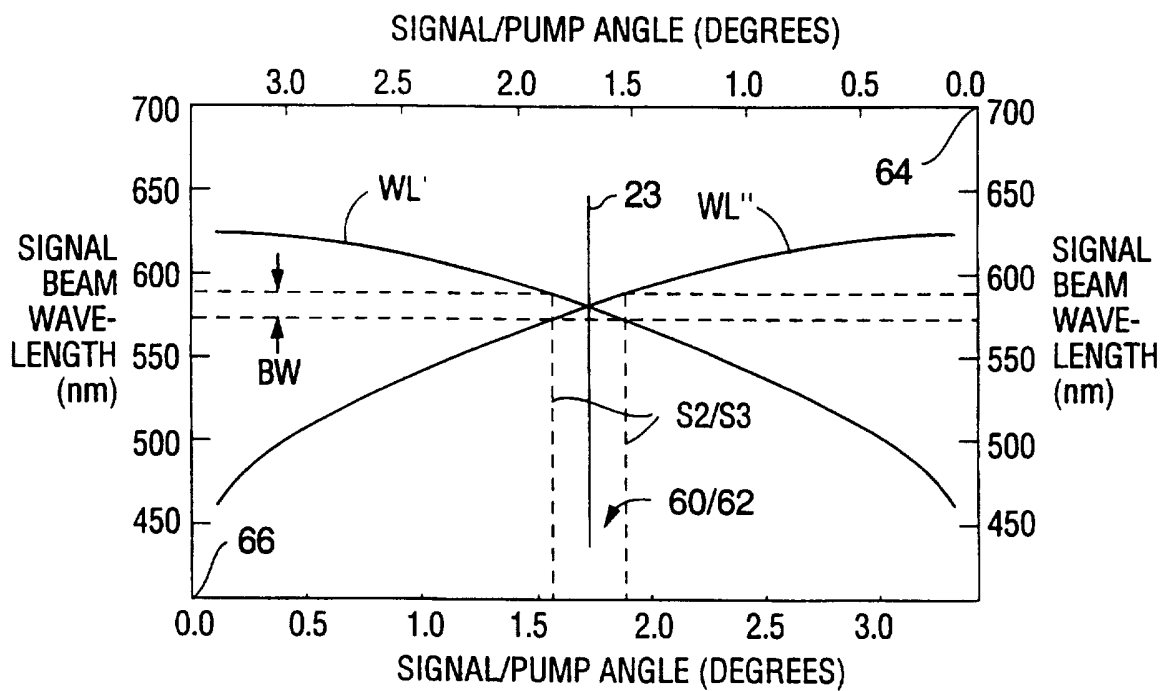


FIG. 9

INTERNATIONAL SEARCH REPORT

Int tional Application No PCT/US 97/08914
--

A. CLASSIFICATION OF SUBJECT MATTER IPC 6 G02F1/39				
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) IPC 6 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)				
C. DOCUMENTS CONSIDERED TO BE RELEVANT				
Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.		
A	US 5 235 456 A (GUYER DEAN R ET AL) 10 August 1993 see column 7, line 13 - column 9, line 10 ---	1-4, 6, 10-13		
A	US 3 654 482 A (MASSEY GAIL A) 4 April 1972 see column 1, line 39 - line 45 ---	1, 6, 10-13		
A	US 3 454 902 A (GIORDMAINE JOSEPH A) 8 July 1969 see figures 1, 5 ---	1, 6, 10-13		
A	US 5 079 445 A (GUYER DEAN R) 7 January 1992 see figure 1 -----	1, 6, 10-13		
<input type="checkbox"/> Further documents are listed in the continuation of box C.				
<input checked="" type="checkbox"/> Patent family members are listed in annex.				
° Special categories of cited documents :				
<table style="width: 100%; border: none;"> <tr> <td style="width: 50%; border: none; vertical-align: top;"> "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document 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 </td> <td style="width: 50%; border: none; vertical-align: top;"> "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 </td> </tr> </table>			"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document 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
"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document 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	Date of mailing of the international search report			
12 September 1997	22/09/1997			
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Galanti, M			