| (51) International Patent Classification $^5$ : | | (11) International Publication Number: **WO 94/26008** |
|---|---|---|
| **H01S 3/10, H03F 7/00** | **A1** | (43) International Publication Date: 10 November 1994 (10.11.94) |

(72) Inventors: POWERS, Peter, E.; 305 Wyckoff Avenue, Ithaca, NY 14850 (US). CHENG, Lap, Kin; 66 Cypress Bridge Place, Bear, DE 19701-1014 (US). PELOUCH, Wayne, S.; 4725 Mesa Marcada Court, NW, Albuquerque, NM 87120 (US). TANG, Chung, L.; 225 Berkshire Road, Ithaca, NY 14850 (US).

(74) Agents: COOPER, George, M. et al.; Jones, Tullar & Cooper, Suite 1002, 2001 Jefferson Davis Highway, Arlington, VA 22201 (US).

(54) Title: OPTICAL PARAMETRIC OSCILLATION USING KTA NONLINEAR CRYSTALS
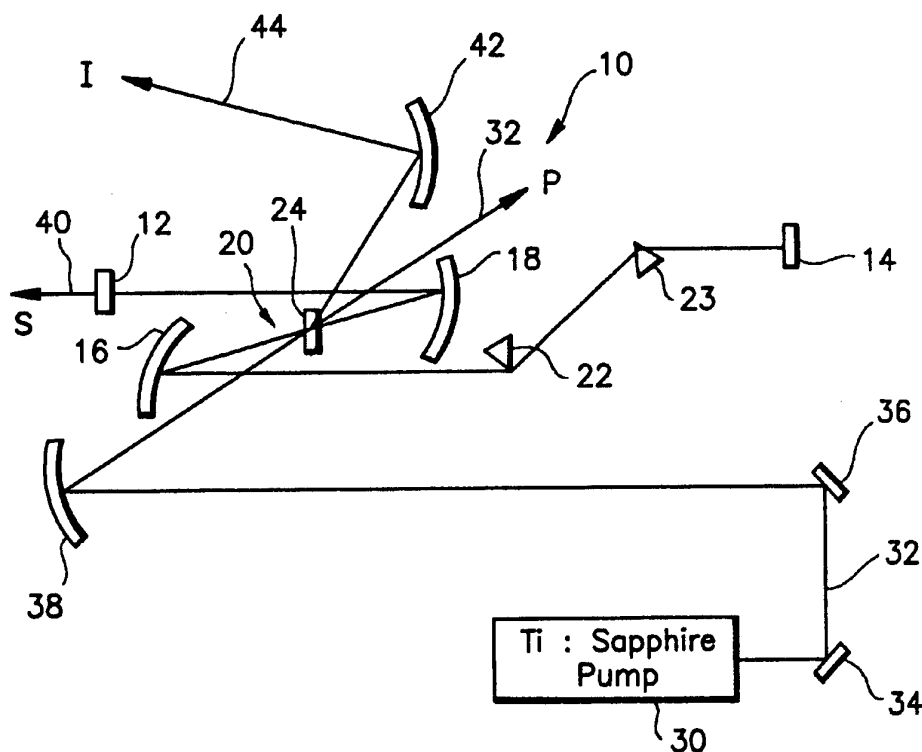
(57) Abstract

    A continuous wave tunable femtosecond optical parametric oscillator (10) includes an oscillator cavity including a pumping cavity (20). A nonlinear KTiOAsO crystal (KTA) (24) is located in the pumping cavity (20) and is pumped by a Ti:sapphire laser (30) to produce output pulses having widths as short as 85 femtoseconds at wavelengths in the range 1.0 $\mu$m to 5.0 $\mu$m.

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## OPTICAL PARAMETRIC OSCILLATION USING KTA
## NONLINEAR CRYSTALS

This is a continuation of copending
5    application serial number 08/055,110, filed on
May 3, 1993.

BACKGROUND OF THE INVENTION
        This invention was made with government
support under Grant No. ECS-9108570, awarded by
10   the National Science Foundation and Contract No.
F49620-90-C-0039 awarded by the Joint Service
Electronic Program (Air Force). The government
has certain rights in the invention.
        The present invention relates, in general, to
15   a continuous wave femtosecond optical parametric
oscillator (OPO) having high power, short pulses,
and broad tunability. More particularly, the
invention is directed to an optical parametric
oscillator with enhanced performance which
20   utilizes a KTA nonlinear crystal.
        The recent development of externally pumped
high-repetition-rate femtosecond (fsec) optical
parametric oscillators using $KTiOPO_4$(KTP) has
demonstrated the feasibility of a broadly tunable
25   high-repetition-rate femtosecond light source.
Laser pulses in the femtosecond time domain; i.e.,
pulses having widths of $10^{-15}$ to $10^{-13}$ seconds, are
important tools for use in studying extremely
short-variation events such as chemical reactions,
30   for by directing femtosecond pulses at reacting
chemicals, for example, researchers can capture
spectroscopic information about the structure and
behavior of short-lived molecular intermediates of

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the reactions.    Femtosecond lasers are also
important for studying the dynamics and the
ultimate limits of high-speed semiconductor
electronic and optical devices. However, numerous
ultrafast phenomena have been inaccessible to
direct optical study due to a lack of light
sources having appropriate wavelengths or other
suitable characteristics such as tunability or a
high repetition rate. The potential tuning range
of the femtosecond KTP optical parametric
oscillator, which is such a high-repetition-rate
femtosecond source, is from approximately .95$\mu$m to
about 4$\mu$m with an absorption band around 3.5$\mu$m,
and such a source has been extremely valuable in
conducting a variety of optical studies. However,
there is a need for a high power source of optical
pulses which will not only be tunable, but which
will have a range beyond that presently available
from currently available KTP optical parametric
oscillators, and which will have pulse widths as
short as 84 fsec.

SUMMARY OF THE INVENTION
        Briefly, the present invention is directed to
a femtosecond optical parametric oscillator
utilizing a KTiOAsO$_4$ (KTA) nonlinear crystal.
Such a crystal may be located, for example, in a
pumping cavity of a linear optical parametric
oscillator and may be optically pumped with, for
example, a Ti:sapphire laser.   KTA has a
transparency range extending out to 5.3$\mu$m, with no
absorption in the 3.5$\mu$m region, and can be tuned
over its whole transparency range, thereby
permitting it to produce outputs in the important
4 to 5$\mu$m region, which is inaccessible to KTP.

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KTA can also tune in the 3.5μm region, where KTP
has an absorption band, so that this material has
the potential for tuning to wavelengths not
available with KTP optical parametric oscillators.

5    BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and additional objects,
features and advantages of the invention will
become apparent to those who are skilled in the
art from a consideration of the following detailed

10   description of a preferred embodiment thereof,
taken in conjunction with the accompanying
drawings, in which:

Fig. 1 is a diagrammatic illustration of a
Ti:sapphire-pumped femtosecond KTA optical

15   parametric oscillator in accordance with the
invention;

Fig. 2 illustrates the pertinent angles of
the crystal used in the oscillator of Fig. 1;

Fig. 3 illustrates a tuning curve for a type

20   II interaction in KTA using a noncollinear angle
of 2.0°;

Figs. 4A and 4B illustrate a small portion
the spectra of the signal and idler waves,
respectively, for a samll portion of the tunning

25   range of the oscillator of Fig. 1; and

Fig. 5 illustrates an intensity
autocorrelation of a 183 femtosecond idler pulse
at 1.77μm, the inset in the figure showing the
interferometric autocorrelation.

30   DESCRIPTION OF PREFERRED EMBODIMENT

Referring now to Fig. 1, an optical
parametric oscillator (OPO) generally indicated at
10 includes a linear cavity defined by a pair of
flat end mirrors 12 and 14, and a pair of

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intermediate curved mirrors 16 and 18. The two
curved mirrors 16 and 18 each have a radius of
curvature of, for example, r=10cm and a high
reflection coating from 1.2 to 1.5$\mu$m, and define
a pumping cavity 20 which includes a nonlinear KTA
crystal (to be described). Flat mirror 12 is a 1%
output coupler which, in one example of the
invention, covers a range from 1.3 to 1.4$\mu$m, while
flat mirror 14 is a high reflector with the same
coating as the curved mirrors. An intracavity
dispersion compensating prism sequence consisting
of two SF 14 prisms 22 and 23 is located in the
cavity, for example between mirrors 14 and 16, the
prisms being spaced at 20cm and arranged so that
they can be inserted or removed from the
cavity 10.

A nonlinear optical crystal 24 is located in
the pump cavity 20, between mirrors 16 and 18, and
is aligned with the cavity so that the pump (to be
discribed) is an $o$ wave, the resonated signal (S)
is an $e$ wave, and the nonresonated idler (I) is an
$o$ wave. The polarization direction for the $o$
waves is along the Y axis of the crystal (Fig. 2)
and the polarization direction of the e wave is in
the X-Z plane. The crystal is $KTiOAsO_4$, which is
a crystal similar to KTP, but which has an optical
nonlinearity approximately 20% larger and an
infrared transparency range nearly 1$\mu$m broader.
KTA is a positive biaxial crystal, with $n_z > n_y > \approx n_x$,
where x, y, and z correspond to the piezoelectric
axes of the crystal, illustrated in Fig. 2. In an
experimental version of the optical parametric
oscillator of the present invention, the KTA
crystal was grown from a $K_5As_3O_{10}$ flux. The
crystal was lightly doped (about 0.2 weight

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percentage) with indium to promote single-domain
crystallization, it being found that indium doping
does not affect the optical properties of KTA. As
is the case with KTP, the effective optical
5    nonlinearity $d_{eff}$ of the KTA crystal, differs,
depending on the orientation of the crystal to a
beam of light traveling through it, and is
maximized for a type II interaction (o→e+o). In
the experimental version, phase-matching was
10   carried out in the x-z plane so that direct
comparison of the performance of the KTA optical
parametric oscillator could be made with that of
prior KTP optical parametric oscillators. In this
experimental set-up, $k_p$, $k_s$, and $k_i$ were in the $\Phi=0$
15   plane. Since $d_{24}>d_{15}$ and $(n_z-n_y)<(n_z-n_x)$ in KTA,
this configuration also maximizes the $d_{eff}$
coefficient, which in the x-z plane is given by:
$d_{eff}=d_{24}\sin\Theta$, where $\Theta$ is also illustrated in
Fig. 2. The crystal 24 in the experimental set-up
20   was 1.47mm thick, cut at $\Theta=50°$, and anti-
reflection coated on both surfaces from $1.3\mu m$ to
$1.6\mu m$. The crystal had a reflection loss of 14%
per surface at the pump wavelength.

The optical parametric oscillator 10 is
25   pumped by a Ti:sapphire pump laser 30, the pumping
beam 32 being directed by way of flat mirrors 34
and 36 and focusing mirror 38 into the pump cavity
20 and onto crystal 24. The mirror 38 has, for
example, a curvature of r=15cm, with the curvature
30   of this mirror and pump cavity mirrors 16 and 18
being chosen so that the spot size of the pump and
signal are matched in the crystal 24. The pump
laser 30 preferably is a 1.2W, 90 femtosecond
laser operating at a wavelength of 780nm. This
35   produces a corresponding power inside the crystal

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of 1.0W due to the reflection loss at the front
surface of the crystal.

For the optical parametric oscillator 10, the
e wave, or signal wave 40 is resonated within the
5   cavity.   Resonating the e wave results in a
spacial walk-off of the e wave's Poynting vector
from its wave vector inside the nonlinear crystal
24.  Experimental studies have shown that the OPO
operates so that the Poynting vectors of the
10  resonated wave and the pump wave 32 are collinear.
To accomplish this when resonating the e wave, a
noncollinear phase-matching geometry is employed.
Thus, the cavity mirrors 12, 14, 16, and 18 are
placed so that the angle between the pump 32 and
15  the signal wave 40 within the cavity is the
negative of the Poynting vector walk-off.  As a
result, the Poynting vector of the e wave walks
onto that of the pump.

The tuning curves for KTA calculated for
20  various pump wave lengths are illustrated in Fig.
3.  These curves are for wave lengths of 910nm,
820nm, and 730nm, which are in the Ti:sapphire
laser range.

A collimating mirror 42 is positioned to
25  collimate and couple out the non-resonated o wave
44, which is the idler wave (I).  The signal (S)
in the illustrated embodiment, exits the cavity 10
through coupling mirror 12, while the pump beam
(P) exits the cavity after passing through crystal
30  24.

The phase-matched outputs of the OPO 10 are
the resonated signal 40 and the nonresonated idler
wave 44.  The OPO may be tuned by either rotating
the crystal 24 about its y-axis (angle tuning) or
35  by tuning the pump source 30.  The spectra for a

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small portion of the tuning range of the signal
wave 40 and the idler wave 44 for the KTA optical
parametric oscillator of Fig. 1 are illustrated in
Figs. 4A and 4B, respectively.  The spectra of

5   Fig. 4A illustrate tuning of the device by angle
tuning from 1.29 to 1.44$\mu$m in the signal branch,
while Fig. 4B illustrates angle tuning from 1.83
to 1.91$\mu$m in the idler branch.  Tuning in this
range  is  obtainable  using  one  mirror  set;

10  additional  wave  lengths  can  be  obtained  using
additional  mirrors  to  extend  the  signal  wave
lengths to as high as 5$\mu$m.

The  signal  40  has  two  operating  regimes:
chirped and unchirped.  The chirped regime is

15  encountered when the OPO is operating with a net
positive  group  velocity  dispersion  (GVD).  The
unchirped  regime  is  achieved  by  going  to  net
negative  GVD  using  the  prism  sequence.  The
spectra illustrated in Figs. 4A and 4B are typical

20  of chirped pulses.  The transition from chirped to
unchirped  pulses  when  going  from  positive  to
negative  GVD  is  a  smooth  one.  The  unchirped
regime  is  characterized  by  pulsewidths
approximately 20% longer than the pump pulsewidth

25  and  greater,  depending  on  the  amount  of  negative
GVD.  The  shortest  pulses  are  encountered  near
zero  GVD,  where  signal  pulses  as  short  as  84
femtoseconds  were  measured  in  the  above-mentioned
experimental set up.

30  The  idler  44  is  generated  during  each  pass  of
the  signal  through  the  KTA  crystal  24.  In  tests,
the  interferometric  autocorrelation  of  the  idler
wave shows no sign of chirp regardless of whether
the  signal  pulse  is  chirped  or  unchirped.

35  Similarly,  the  spectra  of  the  idler  when  the

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signal is chirped or unchirped are nearly identical. Figure 5 shows the intensity and interferometric autocorrelation of the idler pulse with a pulsewidth of 183 fsec at a wavelength of 1.77μm and a power of 80 mW. The contrast ratio of the interferometric autocorrelation for the idler pulses is less than 8:1. This is attributed to the scanning arm of the interferometer used in the tests requiring a small corner cube which limits the throughput of that arm. The shortest idler pulses, 148 fsec at a wavelength of 1.89μm and a power of 40mW, were observed for the chirped-pulse signal operation. The total OPO output power (signal plus idler) was greatest for the unchirped signal pulse regime.

Autocorrelation of the signal and idler may be accomplished using a 0.3mm thick BBO crystal. Signal autocorrelation was measured in the experimental set up, using an RCA model C31034 photomultiplier tube (PMT), while an RCA model 7102 PMT was used for the idler autocorrelation.

It was noted that several non-phase-matched outputs accompanied the phase-matched outputs described above. Non-phase-matched second harmonic generation of the signal pulse as well as sum-frequency generation between the pump and signal and between the pump and idler are all present in the cavity 10.

Pulse widths on the order of 200 femtoseconds or less can be generated in the 425μm region of the KTA OPO. The phase matching band width of the signal that will generate idler pulses in this region is approximately 13nm, which is capable of supporting a 95 femtosecond pulse. The inverse group velocity mismatch (GVM) between the signal

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and pump in this region is less than 100 femtosecond per mm so that the signal pulse width should be on the order of 100 femtoseconds. The corresponding idler pulse width is on the same order, since the GVM between the idler and the pump is even less than that between the signal and pump.

The generation of pulses in the range of 84 femtoseconds for signal wave lengths in the 1.25 to 1.5$\mu$m region are also possible with the KTA crystal, and pulses as short as 57 fsec should be possible. The phase matching bandwidth in this region is on the order of 40nm, and the GVM between the pump and signal for KTA is less than 20 femtoseconds per mm, so pulses as short as 57 fsec should be possible. Further, the idler pulsewidth is the shortest fsec idler pulse in the infrared yet reported.

In summary, there has been described a high-repetition rate optical parametric oscillator based on the nonlinear optical crystal KTA. The OPO produces unchirped pulses as short as 84 femtosecond at 1.36$\mu$m and 150 femtoseconds at 1.89$\mu$m. The OPO can be tuned from 1.29 to 1.44$\mu$m in the signal branch and from 1.83 to 1.91$\mu$m in the idler branch with one set of mirrors, and with other mirrors the crystal operates in the 3-5$\mu$m spectral range. A Ti:sapphire based pump allows the OPO to generate high power, broadly tunable pulses in accordance with the present invention. Although the invention is described in terms of a preferred embodiment, it will be apparent that variations and modifications may be made without departing from the true spirit and scope thereof, as set forth in the accompanying claims.

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WHAT IS CLAIMED IS:

1.    A  broadly  tunable  optical  parametric
oscillator, comprising:

        an oscillator cavity including first and
5    second reflectors defining a pump cavity;

        a nonlinear optical crystal located in
said cavity;

        a  laser  pumping  source  producing  an
output pumping beam incorporating high repetition
10   rate femtosecond pumping pulses;

        means directing said pumping beam onto
a surface of said crystal in said pump cavity to
stimulate generation of signal and idler beams in
said crystal;

15            said signal and idler beam having pulse
widths  of  less  than  about  200fs  and  having
wavelengths between about 1μm and about 5μm;

        means directing a selected one of said
signal  and  idler  beams  out  of  said  oscillator
20   cavity;

        means causing the other of said signal
and  idler  beams  to  resonate  in  said  oscillator
cavity; and

        means  transmitting  a  portion  of  said
25   resonant  beam  out  of  said  oscillator  cavity  to
provide a femtosecond oscillator output beam.

2.    The oscillator of claim 1, wherein said
oscillator cavity is a linear cavity having first
and second spaced end mirrors aligned with an axis
30   of said oscillator cavity.

3.    The oscillator of claim 1, wherein said
crystal is a $KTiOAsO_4$ crystal.

4.    The oscillator of claim 3, wherein said
laser pumping source is a Ti:sapphire laser.

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5.   The oscillator of claim 4, wherein said first and second end mirrors are aligned with said first and second reflectors defining said pump cavity.

6.   The oscillator of claim 5, wherein said crystal is doped with indium.

7.   The oscillator of claim 5, wherein said oscillator cavity end mirrors are flat, one of said mirrors being partially transmissive to provide an output coupler for said oscillator.

8.   The oscillator of claim 1, wherein said signal beam is resonated in said oscillator cavity, and said idler beam is directed out of said oscillator cavity.

9.   The oscillator of claim 8, wherein said first and second reflectors are curved and are aligned with said crystal to focus said signal beam for resonance in said oscillator cavity.

10.   The oscillator of claim 9, further including a collimating mirror located to intercept said idler beam.

11.   The oscillator of claim 9, wherein said signal beam has a wavelength range of from about $1\mu$m to about $5\mu$m.

12.   The oscillator of claim 11, wherein said signal beam is a train of pulses having pulse widths in the femtosecond time domain.

13.   The oscillator of claim 12, wherein the wavelength of said signal beam is tunable over said wavelength range.

14.   The oscillator of claim 1, wherein said crystal is a $KTiOASO_4$ crystal, and wherein said signal beam is resonated in said oscillator cavity to produce an output beam comprising a train of pulses having wavelength tunable from about $1\mu$m to
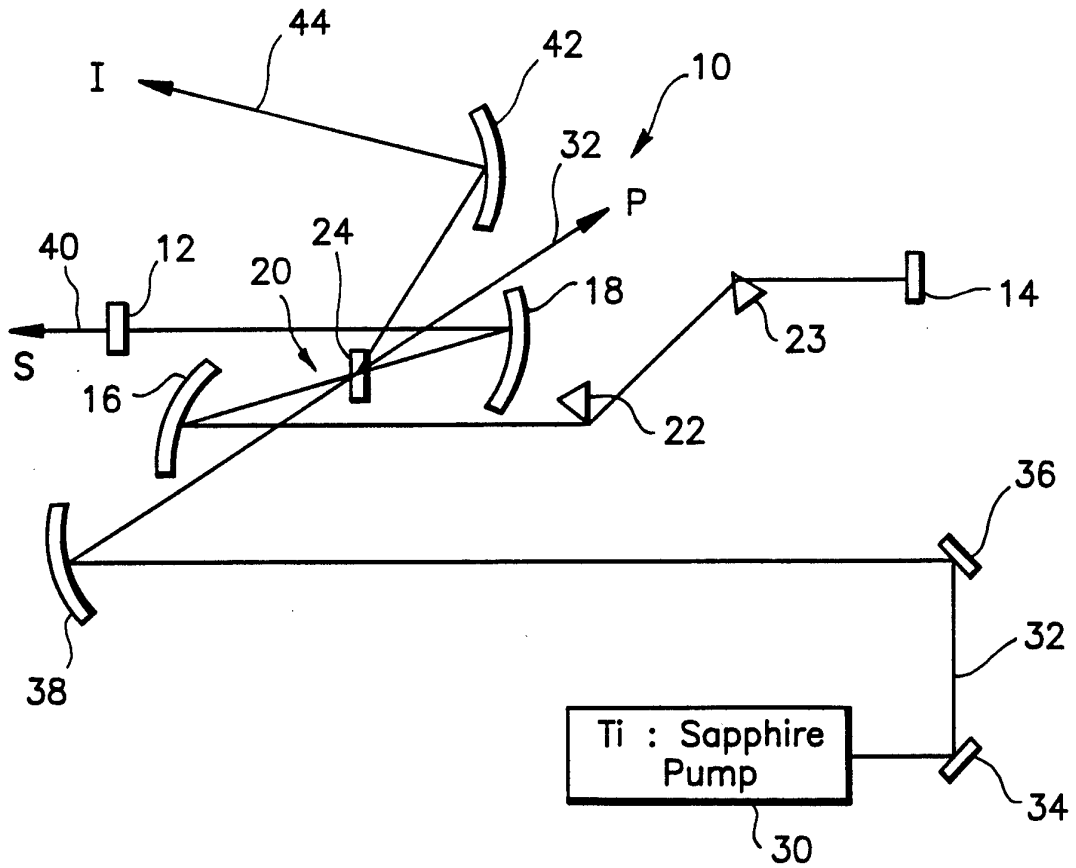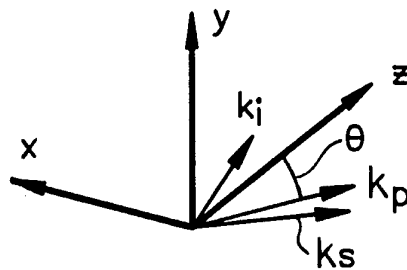
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about  5$\mu$m  and  having  pulse  widths  in  the
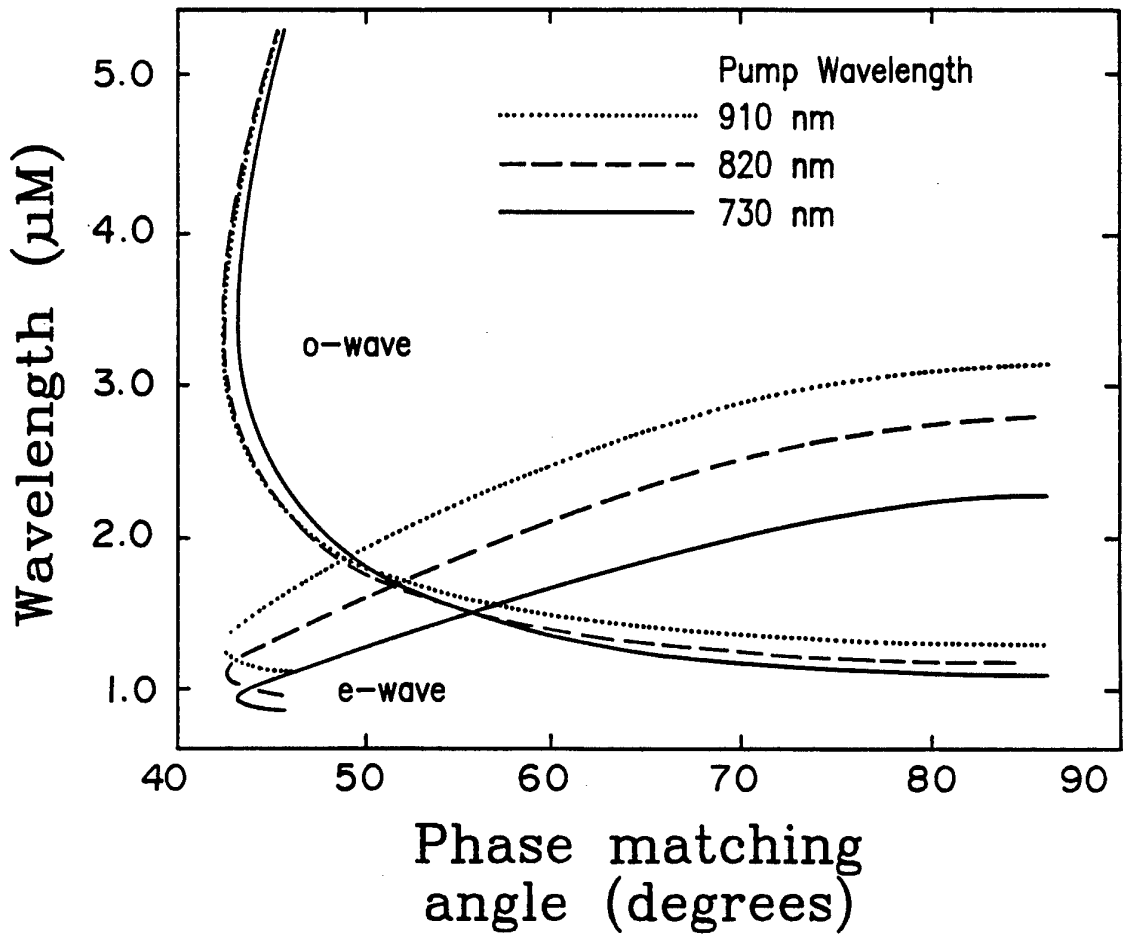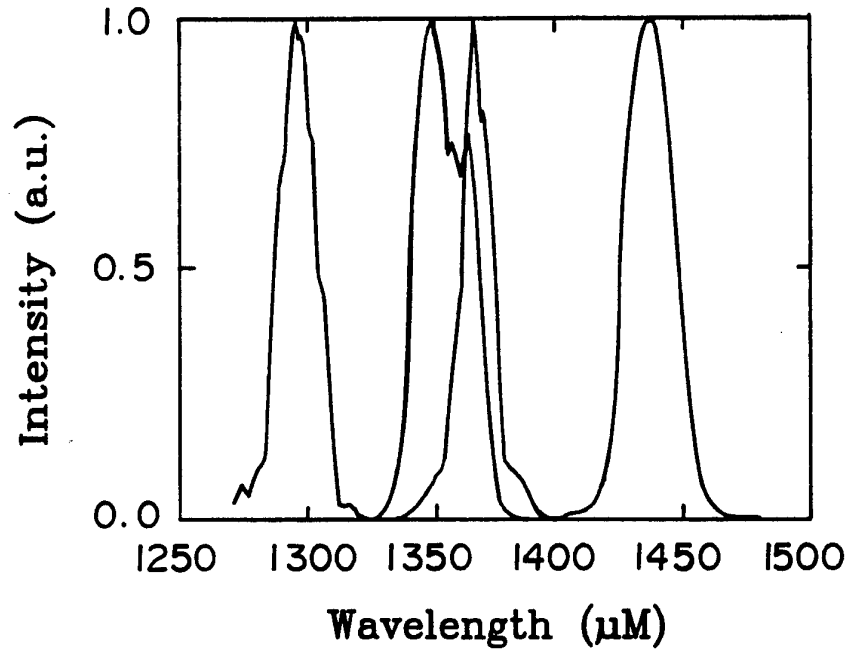femtosecond time domain.

FIG. 1



FIG. 2

FIG. 3

FIG. 4A
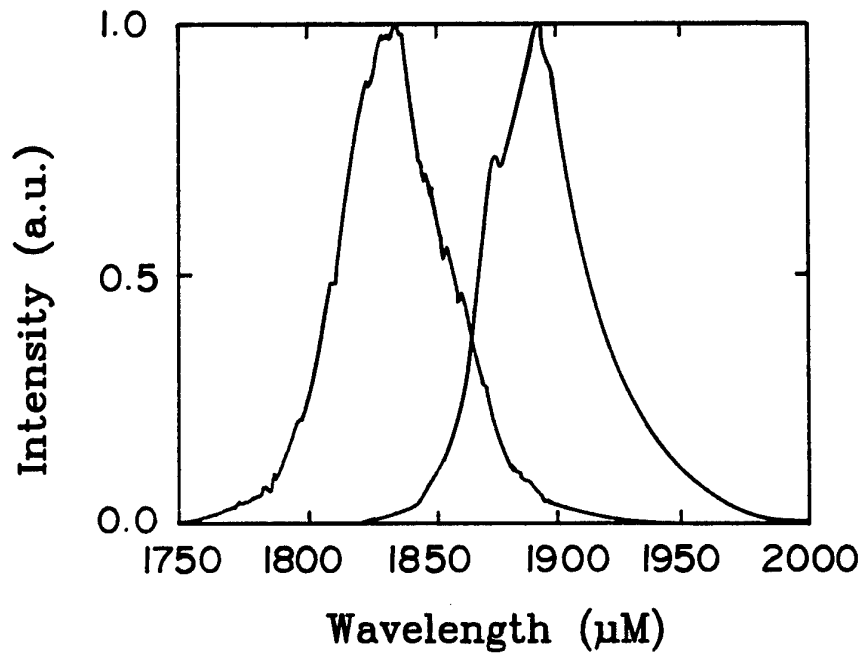


FIG. 4B
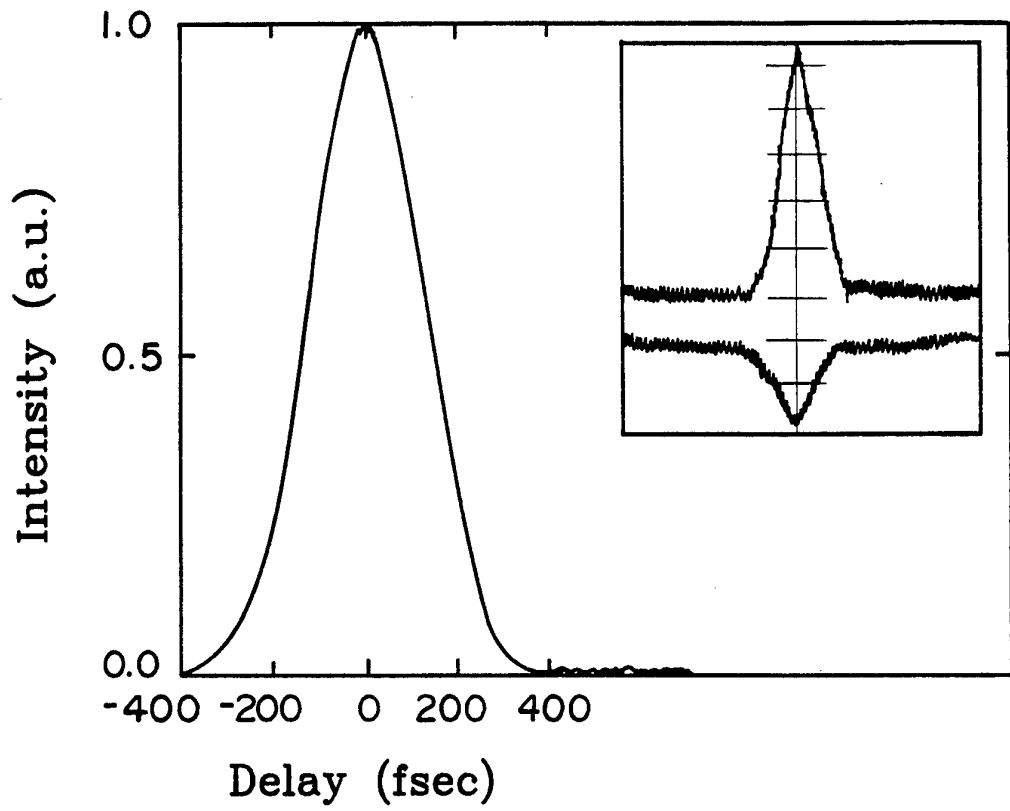
FIG. 5

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(5)  :H01S 3/10; H03F 7/00
US CL  :372/25, 20, 21; 359/330

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)

U.S.  :  372/25, 20, 21; 359/330

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)

APS
search terms: optical, parametric, KTA

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
| --- | --- | --- |
| A,P | US,A, 5,291,503 (GEIGER ET AL) 01 March 1994, entire document. | 1, 2 |
| A | US,A, 5,017,806 (EDELSTEIN ET AL) 21 May 1991, entire document. | 1, 2 |

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

| * | Special categories of cited documents: | "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 |
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| Date of the actual completion of the international search | Date of mailing of the international search report |
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