Q-SWITCHED LASER ARRANGEMENT

arrangement are controlled externally with respect to the laser cavity.

For two-letter codes and other abbreviations, refer to the "Guideance Notes on Codes and Abbreviations" appearing at the begining of each regular issue of the PCT Gazette.

Abstract: A Q-switched laser arrangement comprising a laser medium; a saturable absorber; one or more optical elements defining a laser cavity, the laser cavity including the laser medium and the saturable absorber; a pump laser optically coupled to the laser medium for pumping the laser medium; a driver controlling generation of pump laser pulses by the pump laser such that Q-switched laser pulses generated by the laser
Q-SWITCHED LASER ARRANGEMENT

FIELD OF INVENTION

The present invention relates broadly to a Q-switched laser arrangement and to a method of generating Q-switched laser pulses.

BACKGROUND

Q-switching is a method to obtain laser pulses of high peak power by accumulating and storing electron energy in the excited state so that the population inversion is higher than the threshold gain value before emission. This is achieved by initially increasing the cavity losses due to the absorption, polarization or diffraction of light by a Q-switch element, thus preventing the onset of lasing to allow the stored energy and gain to significantly exceed the inherent cavity losses other than those introduced by the Q-switch element. The Q-switch element losses are then quickly lowered, i.e. switched off, producing a large net round trip amplification and causing laser power to build up in the cavity. The laser power begins to decay after the stored energy in the laser material has been extracted, and the gain once again drops below the cavity losses and lasing ceases.

Q-switching can be achieved mechanically, acoustic- or electro- optically utilising modulators, and such Q-switching is typically referred to as active Q-switching. Alternatively, saturable absorbers can be used in so-called passive Q-switching. Compared to active Q-switching or switches, passive Q-switching does not require high voltage or radio frequency (RF) drivers, thereby reducing the size and complexity of the total laser system and improving the power efficiency. Passive Q-switching has been attracting more and more attention since the diode-pumping technology was introduced, which makes it possible to construct Q-switched micro chip lasers for short laser pulses.

A saturable absorber operates as a passive Q-switch by having a transmission that varies with the incident light intensity, and typically increases with increasing light intensity. When the intensity is low, the transmission of the saturable absorber is low, resulting in high cavity losses and thus an energy built up in the cavity. This energy built up causes in an increase in the light intensity,
which in turn leads to decreasing absorption in the saturable absorber, until the saturable absorber becomes transparent. At that point, the cavity losses become low, and an intense Q-switch light pulse can be generated.

In general, passively Q-switch lasers have some significant inherent deficiencies. These deficiencies include that the pulse generation is based on a self-pulsing mechanism, i.e. the pulses cannot be well controlled externally, and may not be well synchronised. This is a disadvantage for most applications of Q-switch lasers as most applications require laser pulses to be synchronised, e.g. in processes such as marking. Furthermore, time instability up to 10% of the pulse period with a large jitter in repetition rate have typically been observed due to fluctuations in the environment and thermal effects. Another deficiency relates to the fact that pulses generated with existing passive Q-switching techniques are typically not as powerful as those achievable by active Q-switching techniques.

A need therefore exists to provide a passive Q-switching technique that addresses at least one of the above mentioned problems.

SUMMARY

In accordance with a first aspect of the present invention there is provided a Q-switched laser arrangement comprising a laser medium; a saturable absorber; one or more optical elements defining a laser cavity, the laser cavity including the laser medium and the saturable absorber; a pump laser optically coupled to the laser medium for pumping the laser medium; and a driver controlling generation of pump laser pulses by the pump laser such that Q-switched laser pulses generated by the laser arrangement are controlled externally with respect to the laser cavity.

The pump laser may be optically coupled to the laser medium for end-pumping the laser medium.

The driver may control the pump laser pulses such that a repetition rate of the Q-switched laser pulses is externally controlled.

The driver may control the pump laser pulses such that a single Q-switched laser pulse is generated for each pump laser pulse.

The driver may control the pump laser pulses such that conditions in the laser cavity substantially return to a same state prior to generation of each Q-switched laser pulse.
The laser medium may comprise a solid state crystal.

The solid state crystal may comprise one of a group consisting of Nd:YAG, Yb:YAG, Nd:YVO$_4$, and Nd:GdVO.

The saturable absorber may comprise one of a group consisting of a dye, colour center and solid state crystal.

The solid state crystal may comprise Cr:YAG or Cr:YSGG.

The pump laser may comprise a diode laser.

The diode laser may comprise one or more of a group consisting of a diode bar, a diode stack, an optical fiber coupled diode bar, and an optical fiber coupled diode stack.

The laser arrangement may further comprise a frequency converter for frequency converting the Q-switched laser pulses.

The frequency converter may be provided internal to the laser cavity, or external to the laser cavity.

The frequency converter may comprise a non-linear optical material.

The non-linear optical material may comprise one of a group consisting of KTP, BBO, and LBO.

The optical elements may comprise one or more of a group consisting of a coating on a face of the laser medium, a coating on a face of the saturable absorber, and a separate mirror element.

One of the optical elements may function as an output coupler of the laser arrangement.

The driver for the pump laser may control the pump laser pulses such that the amplitude [I left the amplitude, since we have described increasing the amplitude by increasing the pump power on p. 9. That would be enough support] of the Q-switched laser pulses are externally controlled.

In accordance with a second aspect of the present invention there is provided a method of generating Q-switched laser pulses, the method comprising controlling pump laser pulses for pumping a laser medium of a Q-switched laser arrangement such that the Q-switched laser pulses generated by the laser arrangement are controlled externally with respect to a laser cavity of the laser arrangement.

The method may comprise end-pumping the laser medium.

The method may comprise controlling the pump laser pulses such that a repetition rate of the Q-switched laser pulses is externally controlled.
The method may comprise controlling the pump laser pulses such that a single Q-switched laser pulse is generated for each pump laser pulse.

The method may comprise controlling the pump laser pulses such that conditions in the laser cavity substantially return to a same state prior to generation of each Q-switched laser pulse.

The method may comprise controlling the pump laser pulses such that the amplitude and width of the Q-switched laser pulses are externally controlled.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

Figure 1 is a schematic drawing of a laser arrangement of according to an example embodiment.

Figures 2a to d are graphs illustrating pump pulses and laser pulses according to an example embodiment.

Figure 3 is a schematic drawing illustrating another laser arrangement according to an example embodiment.

DETAILED DESCRIPTION

The example embodiments described provide a passive Q-switching technique that can provide pulse synchronisation with external electronics, control of the pulse period, reduction of jitter in pulse repetition rate, and improvement in the laser output performance.

Figure 1 shows a schematic drawing of a passively Q-switch solid state laser arrangement 100 according to an example embodiment. The solid state laser arrangement 100 includes a laser medium 102, in the example embodiment in the form of a laser crystal such as Nd:YAG, and a saturable absorber 104 comprising Cr^3+:YAG, as a passive Q-switch element. A first mirror or output coupler is provided in the form of a coating 109 on one end face 110 of the saturable absorber 104, having a partial transmission and partial reflection at the lasing wavelengths. A coating 111 is provided at one end face 106 of the laser medium 102 and having a high reflection at the lasing
wavelength and a high transmission at the pump wavelength of a diode pump laser 108. The coatings 109 and 111 define a resonator or cavity of the laser arrangement 100, the cavity including the laser medium 102 and the saturable absorber 104 form the resonator of the laser arrangement 100. It will be appreciated by the person skilled in the art that the cavity may be defined differently in different embodiments, for example by using separate mirror elements rather than coatings.

The pump laser diode 108 operates in a quasi continuous wave (CW) mode and is optically coupled to the laser medium 102 through the coating 111. The laser arrangement 100 is thus end-pumped with the at least one quasi CW diode laser 108. The diode laser 108 may be beam shaped, coupled into an optical fiber or bundle of fibers, or both. In the example embodiment, the pump beam from the diode laser 108 is further manipulated by an optics unit 112, which, in the example embodiment, includes a set of lenses for collimating and re-focusing so that the pump beam can be matched with the fundamental transversal mode of the laser arrangement 100. In the example embodiment, the pump diode laser 108 preferably has a well-matched wavelength with the absorption band of the laser medium 102. For example, in the case of the laser medium comprising a neodymium ions-doped crystal such as Nd³⁺:YAG or Nd³⁺-YVO₄, the wavelength of the pump diode laser 108 is preferably approximately 808 nm.

In the following, the operation of the laser arrangement 100 will be described in detail. In conventional passive Q-switching, the repetition rate cannot be conveniently controlled externally as it is dominated by an inherent self-pulsing mechanism. When the pump power is far above threshold, the self-pulsing repetition rate can be written as:

\[
J_{\text{rep}} = \frac{g_o}{2AR_{TL}}
\]  

(1)

where \(\tau_L\) is the upper-state-level lifetime of the laser medium, \(M\) the modulation depth of the saturable absorber, and \(g_o\) the small signal gain, which is proportional to the pump power. From equation (1) it can be seen that the repetition rate \(\frac{1}{\tau_p}\) of a conventional passively Q-switched laser is dependent primarily on
two internal parameters of the laser, \( \tau_L \) and \( \Delta R \), and one external parameter, \( g_o \), which is controlled by the pump power. Since a change in the pump power in order to control the repetition rate would result in undesirable variation in pulse energy and pulse width, the pulse repetition rate is therefore practically non-controllable externally.

In the example embodiment, the pump diode laser 108 delivers a quasi CW laser beam, where the diode driver (not shown) operates in a pulse configuration and drives the diode laser 108 with a pulse current (curve 200) as shown in Figure 2a. Therefore, the pump laser beam is essentially a train of pulses with the power amplitude and pulse repetition rate being controlled by the diode driver. Within the pump pulse duration \( T \) (Figure 2a) the lasing conditions are the same as those in a conventional passively Q-switched laser, i.e. the pulse repetition rate can still be represented by equation (1). However, when the pump pulse is turned off, i.e. in the periods between pulses, there is no pump signal available to produce a laser pulse in the solid state laser arrangement 100 (Figure 1). As a result, laser pulses e.g. 202 are only produced during the pump pulse duration \( T \), as shown in Figure 2b. It will be appreciated by a person skilled in the art that the number of pulses 202 produced within one cycle of the pump pulse is approximately proportional to the product of the pump pulse duration \( T \) and the inherent repetition rate \( f_{rep} \) of equation (1), and an effective repetition rate \( f_{eff} \) of the quasi CW pumped laser in the example embodiment can be estimated as:

\[
f_{eff} = N \frac{f_{rep}}{D_{cyc}}
\]  

(2)

where \( N \) is the laser pulse number produced within each pump pulse and \( D_{cyc} \) is the duty cycle of the pump pulse, which is the ratio of the pump pulse duration \( T \) to the period \( P \) of the pulse current (curve 200) of the diode driver, as shown in Figure 2a. As \( D_{cyc} \) i.e. \( T \) and \( P \), are parameters of the pulse current of the diode driver, \( \frac{N}{\Delta N} \) represented by equation (2) can be readily controlled with the external circuit of the diode driver in the example embodiment.

An automatic and accurate control of the laser pulse number \( N \) in equation (2), hence the repetition rate \( f_{eff} \) can e.g. be realized by photo detecting the laser pulses and trigging the diode driver. In this process, a fast photo detector sensitive only at the laser wavelength is usually used to detect the laser pulse other than the pump pulse, and the laser diode driver current will be immediately cut off once a
desired number of laser pulses are detected. It is noted that the repetition rate may also be controlled by manually changing the pump pulse width based on prior experimental data. However, such a manual method may not be reliable as lasing conditions change with a lot of factors such as room and cooling temperatures, pump power density in the laser crystal, laser diode degradation and duty circle, etc.

Furthermore, in the quasi CW diode end-pumped laser arrangement 100 (Figure 1), stabilisation of the laser pulses can also advantageously be achieved. The laser pulses are characterized with the pulse repetition rate $n_{/ \text{t}}$, represented by equation (1), energy $E$ and width $t$, which can be represented by the following equations:

$$E = \frac{\hbar \nu}{\sigma} AAR \eta_{\text{out}}$$  \hspace{1cm} (3)

$$t \equiv \frac{3.527;}{\Delta R}$$ \hspace{1cm} (4)

where $\hbar \nu$ is the photon energy, $\sigma$ the emission cross-section, $A$ the beam area inside the laser, $T_R$ the cavity round-trip time, and $\eta_{\text{out}}$ the output coupling efficiency. From equations (1), (3) and (4) it can be seen that the in-stability of the laser pulse is mainly due to fluctuation in the small signal gain and the modulation depth $AR$. Those parameters vary with both internal and external environmental conditions such as temperature, thermal effects and photo density distribution in the laser cavity, which lead to different initial conditions between pulses.

In the example embodiment, the influence of those effects on the laser pulses can be mitigated as the laser pulse number within the pump pulse can be controlled in a manner such that the initial conditions of pulse formation can be partially recovered during the pulse pause. In order to fully stabilise the laser pulses, it is advantageous that only a single pulse is generated within a pump pulse. This can be achieved by adjusting the pump pulse width $T$ so that there is only one laser pulse 204 generated within a pump pulse, as shown in Figures 2c and d. In this case, the initial conditions of pulse formation can be advantageously fully recovered to be identical between pulses 204. Therefore, the generated pulses 204 can have an accurate pulse period, pulse width and
pulse energy. Furthermore, the laser pulse repetition rate and jitter are controlled by the diode driver, and thus those parameters should be the same as the corresponding parameters of the diode driver.

Returning to Figure 1, the end-pumping configuration used in the example embodiment has a number of advantages over a side-pumped configuration, including higher efficiency and better beam quality. At the same time, the end-pumped configuration can suffer from stronger thermal effects at high pump power. The thermal effects can deteriorate the laser performance and Q-switching by alternating the resonator's characteristics, modifying the power density in the saturable absorber, and increasing the cavity's diffraction lost because of the aberrated thermal lensing effect. In the example embodiment, the thermal lensing effect is advantageously significantly weakened as the average power absorbed by the laser medium 102 from the quasi CW diode laser 108 is lower than for "true" CW pump sources.

For example, a 100 W quasi CW diode laser at 808 nm delivering pulses of 200 µs at 1 kHz has a thermal loading (due to quantum defect) of one fifth of a true CW diode of the same power. The thermal lensing effect can be further weakened by shortening the pump pulse via the diode driver so that the pump pulse can immediately turn off once a laser pulse is generated. As a result, the quasi CW diode laser 108 can allow high power for end-pumping the passively Q-switched laser 100 without significant thermal effect. The weakening in the thermal lensing effect can also help to stabilise the laser pulses as described above. Therefore, the example embodiment can advantageously provide controllable and high peak power laser pulses in a passively Q-switched solid state laser that is end-pumped with quasi-CW diode laser(s).

In the following, results from experiments conducted utilising example embodiments are provided. In the example embodiment, the laser medium is Nd³⁺:YAG within a plano-plano cavity and the saturable absorber is Cr⁺⁺:YAG inserted near an output coupler. The pump source is a 100W quasi CW diode laser. With a cavity length of 220mm, and a diode current of 80 A (pump power approximately 80W), a single Q-switched laser pulse within a pump pulse duration of 200µs is generated. The pulse energy is 1.93mJ with a delay time of 180µs between the laser pulse and the raising edge of the pump pulse. The pulse energy increases slightly to 2mJ when the pump current increases to 100A (power of light approximately 100W), and the delay time changes to
155 µs. In all the experiments, the pulse width is 13ns, corresponding to laser pulse peak powers of approximately 150OkW. With a cavity length of 65mm, a current of 7OA and pulse width of 200µs, laser pulses have been achieved with a pulse energy of 0.91 mJ and pulse width of 3ns, corresponding to a peak power of 300OkW.

In a modified the laser arrangement 300 according to another example embodiment, a frequency converter 302 is added to the laser architecture, as shown in Figure 3. Components identical to the components in the laser arrangement 100 (Figure 1) have been labelled with the same numeral as in Figure 1. The frequency converter 302 is formed by at least one non-linear optical crystal, depending on the destination wavelength required. For instance, frequency doubling from 1064nm to 532nm requires only one non-linear optical crystal, single piece element such as Potassium Tytanil Phosphate (KTP), beta-Barium Borate (BBO) and Lithium Triborate (LBO), while frequency tripling requires at least two such single piece elements. The frequency converter 302 is located external to the resonator cavity in the example embodiment, however, it will be appreciated that the frequency converter 302 could be located intra-cavity in different embodiments. In such embodiments, the converter may preferably be inserted between the output coupler and the saturable absorber. The output coupler in such an embodiment may be formed directly on the output surface of the frequency converter 202.

The example embodiments described have a number of advantages over existing technologies. For example, the example embodiments do not require high voltage or RF drivers, thereby reducing the size, cost, and complexity of the laser system and improving the power efficiency. In particular, the use of solid state saturable absorbers such as Cr4+:YAG, suitable for long lifetime of operation of passive Q-switching in diode pump solid state lasers, can be provided in an example embodiment.

Furthermore, the example embodiments can provide a technique to mitigate or fully eliminate the inherent deficiency of conventional passive Q-switching. These deficiencies include power limitation, pulse in-stability and lack of external synchronisation.

Compared with side-pumped configurations, the example embodiment, in using an end-pumped configuration, can provide a number of advantages including higher efficiency, improved beam quality, and improved beam shape.
It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly describe. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

For example, it will be appreciated that different laser media may be used in different embodiments, including solid state crystals such as Nd:YAG, Yb:YAG, Nd:YVO₄ and Nd:GdVO.

Furthermore, different saturable absorbers may be used in different embodiments, including dye, colour centre, and solid state crystals. The solid state crystals may for example include CrYAG and CrYSGG.

Different quasi CW diode sources may be used as pump sources in different embodiments, including diode bars, diode stacks, optical fiber coupled diode bars and optical fiber coupled diode stacks.

Example embodiments may be applied in a number of industrial applications, including in applications such as marking, engraving, micro-drilling, micro-welding and micro-cutting. Other applications include application in the defence sector, such as measurement, targeting, encoding and special communications, and range-finding.
CLAIMS

1. A Q-switched laser arrangement comprising:
   a laser medium;
   a saturable absorber;
   one or more optical elements defining a laser cavity, the laser cavity including the laser medium and the saturable absorber;
   a pump laser optically coupled to the laser medium for pumping the laser medium; and
   a driver controlling generation of pump laser pulses by the pump laser such that Q-switched laser pulses generated by the laser arrangement are controlled externally with respect to the laser cavity.

2. The laser arrangement as claimed in claim 1, wherein the pump laser is optically coupled to the laser medium for end-pumping the laser medium.

3. The laser arrangement as claimed in claims 1 or 2, wherein the driver controls the pump laser pulses such that a repetition rate of the Q-switched laser pulses is externally controlled.

4. The laser arrangement as claimed in any one of the preceding claims, wherein the driver controls the pump laser pulses such that a single Q-switched laser pulse is generated for each pump laser pulse.

5. The laser arrangement as claimed in claim 4, wherein the driver controls the pump laser pulses such that conditions in the laser cavity substantially return to a same state prior to generation of each Q-switched laser pulse.

6. The laser arrangement as claimed in any one of the preceding claims, wherein the laser medium comprises a solid state crystal.

7. The laser arrangement as claimed in claim 6, wherein the solid state crystal comprises one of a group consisting of Nd:YAG, Yb:YAG, Nd:YVO₄, and Nd:GdVO.

8. The laser arrangement as claimed in any one of the preceding claims, wherein the saturable absorber comprises one of a group consisting of a dye, colour center and solid state crystal.

9. The laser arrangement as claimed in claim 8, wherein the solid state crystal comprises CnYAG or CnYSGG.
10. A laser arrangement as claimed in any one of the preceding claims, wherein the pump laser comprises a diode laser.

11. A laser arrangement as claimed in claim 10, wherein the diode laser comprises one or more of a group consisting of a diode bar, a diode stack, an optical fiber coupled diode bar, and an optical fiber coupled diode stack.

12. The laser arrangement as claimed in any one of the preceding claims, further comprising a frequency converter for frequency converting the Q-switched laser pulses.

13. The laser arrangement as claimed in claim 12, wherein the frequency converter is provided internal to the laser cavity, or external to the laser cavity.

14. The laser arrangement as claimed in claims 12 or 13, wherein the frequency converter comprises a non-linear optical material.

15. The laser arrangement as claimed in claim 14, wherein the non-linear optical material comprises one of a group consisting of KTP, BBO, and LBO.

16. The laser arrangement as claimed in any one of the preceding claims, wherein the optical elements comprise one or more of a group consisting of a coating on a face of the laser medium, a coating on a face of the saturable absorber, and a separate mirror element.

17. The laser arrangement as claimed in any one of the preceding claims, wherein one of the optical elements functions as an output coupler of the laser arrangement.

18. The laser arrangement as claimed in any one of the preceding claims, wherein the driver for the pump laser controls the pump laser pulses such that the amplitude of the Q-switched laser pulses are externally controlled.

19. A method of generating Q-switched laser pulses, the method comprising:

   controlling pump laser pulses for pumping a laser medium of a Q-switched laser arrangement such that the Q-switched laser pulses generated by the laser arrangement are controlled externally with respect to a laser cavity of the laser arrangement.

20. The method as claimed in claim 19, comprising end-pumping the laser medium.
21. The method as claimed in claims 19 or 20, comprising controlling the pump laser pulses such that a repetition rate of the Q-switched laser pulses is externally controlled.

22. The method as claimed in any one claims 19 to 21, comprising controlling the pump laser pulses such that a single Q-switched laser pulse is generated for each pump laser pulse.

23. The method as claimed in claim 22, comprising controlling the pump laser pulses such that conditions in the laser cavity substantially return to a same state prior to generation of each Q-switched laser pulse.

24. The method as claimed in any one of claims 19 to 23, comprising controlling the pump laser pulses such that the amplitude of the Q-switched laser pulses are externally controlled.
Figure 3
INTERNATIONAL SEARCH REPORT

International application No,
PCT/SG2005/000408

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

HOIS 3/113 (2006.01)    HOIS 3/11 (2006.01)

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)

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) -

Q(W)/SWITCH, SATURB+, ABSOR+, PASSIVE, BLEACH, PUMP, PULS+, HOIS 3/-

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<td>WO 2004/034523 A2 (SPECTRA SYSTEMS CORPORATION) 22 April 2004</td>
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<td>Entire document, see abstract, paragraphs 0016 and 0031, Fig.4</td>
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<td>US 6188704 B1 (KWON et al) 13 February 2001, Entire document, see abstract, Fig.2</td>
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[X] Further documents are listed in the continuation of Box C       [X] See patent family annex

* Special categories of cited documents:

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

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Date of the actual completion of the international search

17 January 2006

Date of mailing of the international search report

31 JAN 2000

Name and mailing address of the ISA/AU

AUSTRALIAN PATENT OFFICE
PO BOX 200, WODEN ACT 2606, AUSTRALIA
E-mail address: pct@ipaaustralia.gov.au
Facsimile No. (02) 6285 3929

Authorized officer

CHARLES BERKO
Telephone No: (02) 6283 2169

Form PCT/ISA/210 (second sheet) (April 2005)
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This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

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Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX