Eye Safe Laser Using Optical Parametric Oscillation

[1,]Kireet Semwal , [2,]S. C. Bhatt
[1,]Applied Science Department, GB Pant Engineering College, Pauri (Garhwal)-246194, Uttarakhand, India
[2,]Department of Physics, HNB Garhwal Central University Srinagar (Garhwal)-246174, Uttarakhand, India

ABSTRACT

It is found that laser with operating wavelengths in the region of approximately 0.4 µm to 1.4 µm (i.e. visible and near infrared) is the eye hazardous portion of optical spectrum, because in this region it is transmitted by the cornea and the lens serves to focus the laser beam on the retina. Thus, the actual laser power density entering the eye can be increased by some 10^5 by the time the light gets to the retina, and burn it without any time lag. This hazardous wavelength region often called ocular focus region. Whereas wavelengths beyond this region are absorbed in the cornea, lens, and vitreous humor of eye, and therefore laser cannot make direct impact on the retina. In this region our eye is relatively safe, and there is only thermal injury to eye. Therefore retinal damage is often more severe than corneal damage. Eye damage may not only result from laser light coming directly from the laser, but may also by light coming from secondary light path i.e. reflection, refraction, scattering etc. For extremely high-power laser, even diffuse reflections may be capable of causing eye damage.

KEYWORDS: *Eye safe laser, MPE for Eye, Optical Parametric Oscillator, KTP crystal.*

I. INTRODUCTION:

Laser application have proliferate in recent years and, as to be expected, their presence is no longer confined to the laboratory or places where access to their radiation can be controlled. Military operations are obvious applications where various devices such as laser range finders, target designators, and secure communications equipment elevate the risk of exposure, specifically eye exposure, to unacceptable levels. It is found that laser with operating wavelengths in the region of approximately 0.4 µm to 1.4 µm (i.e. visible and near infrared) is the eye hazardous portion of optical spectrum, because in this region it is transmitted by the cornea and the lens serves to focus the laser beam on the retina. Thus, the actual laser power density entering the eye can be increased by some 10^5 by the time the light gets to the retina, and burn it without any time lag. This hazardous wavelength region often called ocular focus region [1]. Whereas wavelengths beyond this region are absorbed in the cornea, lens, and vitreous humor of eye, and therefore laser cannot make direct impact on the retina. In this region our eye is relatively safe, and there is only thermal injury to eye. Therefore retinal damage is often more severe than corneal damage. The hazards from the laser vary with the wavelength, intensity, and duration of the output or length of exposure and it is difficult to generalize. However, operating procedures and precautions can be specified over the various ranges of outputs of available lasers. Lasers present potential safety hazards but can usually be guarded against with a few simple precautions [2].The effect of exposure to high power or prolonged exposure at low power over the region 0.4 µm to 1.4 µm where the front part of the eye is transparent, may be to damage the retina tissue and in particular the pigment epithelium, causing lesions and leading to permanent blindness. Additional damage may also occur due to absorption in the cornea and surrounding areas [3].

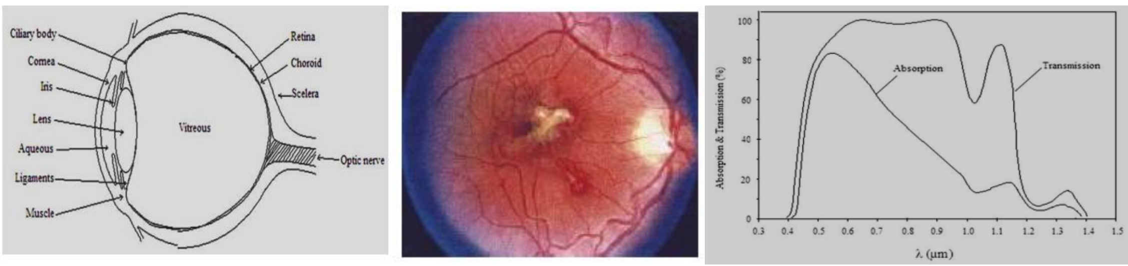

FIGURE 1. a) Construction of eye and eye injury by laser b) Eye transmission and absorption

Maximum Permissible values of Exposure

The effect of pulsed lasers is dependent on the intensity and duration of the pulse. For the same energy output the hazards due to Q-switched or mode-locked lasers are generally greater than pulsed outputs at the same energy output. Maximum permissible values of exposure (MPE) based on damage to the retina derived from measurements of damage over the visible region, are given in table-1 for cw laser and in table-2 for pulsed laser [4][5][6]. The corresponding maximum permissible exposure levels at the cornea in table-2 are derived from table-1 by multiplying the values by 5×10^5 based on the relaxed eye over the visible range. Where a series of repetitive pulses are used the peak pulse energy and the continuous energy levels should not be exceeded.

TABLE 1. Ocular MPE Values for cw Laser

Laser Type	Wavelength (μm)	MPE (watt/cm^2)	Exposure duration (sec)
He:Cd	0.4416	2.5×10^{-3}	0.25
Argon	0.4880, 0.5145	10^{-6}	$> 10^4$
HeNe	0.632	2.5×10^{-3}	0.25
HeNe	0.632	1×10^{-3}	10
HeNe	0.632	17×10^{-6}	$> 10^4$
Krypton	0.647	2.5×10^{-3}	0.25
Krypton	0.647	1×10^{-3}	10
Krypton	0.647	28×10^{-6}	$> 10^4$
InGaAlP	0.670	2.5×10^{-3}	0.25
GaAs	0.905	0.8×10^{-3}	> 1000
Nd:YAG	1.064	1.6×10^{-3}	> 1000
InGaAsP	1.310	12.8×10^{-3}	> 1000
InGaAsP	1.55	0.1	> 10
CO_2	10.6	0.1	> 10

TABLE 2. Ocular MPE Values for Pulsed Laser

Laser Type	Wavelength (μm)	Pulse length (sec)	MPE (J/cm^2)
ArF	0.193	2×10^{-8}	3×10^{-3}
KrF	0.248	2×10^{-8}	3×10^{-3}
XeCl	0.308	2×10^{-8}	6.7×10^{-3}
XeF	0.351	2×10^{-8}	6.7×10^{-3}
Ruby (free-running)	0.6943	1×10^{-3}	1×10^{-5}
Ruby (Q-switched)	0.6943	$5\text{-}100 \times 10^{-9}$	5×10^{-7}
Rhodamine 6G	0.500-0.700	$5\text{-}18 \times 10^{-6}$	5×10^{-7}
Nd:YAG (free-running)	1.064	1×10^{-3}	5×10^{-5}
Nd:YAG (Q-switched)	1.064	$5\text{-}100 \times 10^{-9}$	5×10^{-6}
CO_2	10.6	1×10^{-3}	100×10^{-7}

Below about 0.4μm and above about 1.4μm damage to the cornea is the principal hazard. Since focusing at the retina does not take place the threshold levels can be considerably relaxed; however, little available data exists on threshold values outside the visible region. Outside the visible light region below a wavelength of about 0.4μm the safe exposure level recommended by BS4803 (British Standard) should not exceed 130 J/m^2 per day, or 2.16 W/m^2 for 1 minute, or a corresponding higher density over a shorter period. At infrared wavelengths above about 1.4 μm the maximum density from a single pulse should be limited to 1kJ/m^2 and for continuous exposure the average level should be limited to 500 W/m^2 [5].

II. LASER EYE SAFETY:

The recommended eye protection for all people who work with lasers is a pair of goggles that are highly absorbing in the spectral region of the laser. Now this is rather simple for any UV to IR laser, as humans cannot see in these spectral ranges. However, it becomes much more difficult for visible lasers because the glasses that protect the user may also reduce the user's ability to see in the visible spectrum. According to Kuhn [1], the laser safety goggles are characterized by a minimum safe optical density D_λ defined as

$$D_\lambda = log_{10}\left(\frac{H_p}{MPE}\right)$$

Where H_p is the power density (or energy density) of the incident laser beam and MPE is the maximum permissible eye exposure (same unit as H_p)[3][6].

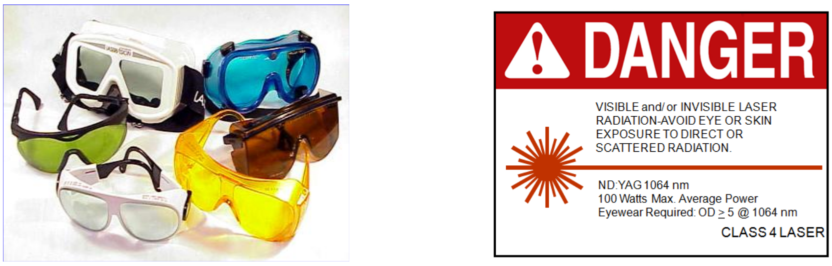

FIGURE 2. Laser Safety Eyewear and Warning Signs

It is essential that everybody concerned with the operation or use of lasers should have knowledge of their potential hazards and the safety procedures involved. A safety officer should be appointed, who should be responsible for records and safety procedures, and for liaising with the medical authorities undertaking surveillance. The safety officer should ideally be one of the operating personnel because of the highly specialist nature of the hazards involved, and work in collaboration with other safety officers. Where operation of an unenclosed or partly closed system (e.g. during maintenance) takes place, the region in which the laser is being operated should be clearly indicated. This should be as small as consistent with safety and contain only personnel working directly on lasers. In the case of industrial laser installation this is best achieved by initially installing the laser in a separate room. At all entrances to this region a cautionary sign should be displayed. Examples of signs recommended by The American National Standards Institute (ANSI) Standard Z136 [5] are illustrated in Figure-2.

During the last many years much effort have been made to develop eye safe lasers (i.e. using materials such as Er:YAG, Er:glass etc.), basically for rangefinders using single pulse of very high intensity, but at a eye-safe wavelength [7]. With lasers of this eye safe kind, range measurement capabilities of 10 km or more have been obtained. The main disadvantage of these rangefinders is their complexity, power efficiency and reliability [8]. Nd:YAG laser removes most of these discrepancies and therefore used as a superior rangefinder. The only problem in using Nd:YAG laser is, its emission in ocular region (i.e., 1.064 μm). Which is particularly in the near infrared region, where the laser often significantly powerful. Thus it is possible to acquire severe retinal damage from a laser beam that we cannot see. Optical parametric devices generate broadly tunable coherent optical radiation by the phase-matched nonlinear interaction of an intense laser beam in a suitable nonlinear crystal. In this process the high energy pump photon is converted into a pair of lower frequency signal and idler photons while conserving the total energy and momentum. Tunability of the signal-idler pair is usually achieved either by changing the crystal birefringence through its temperature dependence or by the angular dependence of the extraordinary index of the crystal. The practical optical parametric oscillator (OPO) device consists of a nonlinear crystal enclosed in an optical cavity resonant at either or both the signal and idler wavelengths and pumped by Nd:YAG laser [9][10].

III. SECOND ORDER NONLINEAR PROCESSES:

In the regime of conventional optics, the electric polarization vector $\boldsymbol{P}$ is simply assumed to be linearly proportional to the electric field strength $\boldsymbol{E}$ of an applied optical wave, i.e.

$$\boldsymbol{P} = \varepsilon_0 \chi E \qquad (1)$$

where ε_0 is the free-space permittivity, χ is the susceptibility of a given medium and a plot of $\boldsymbol{P}$ versus $\boldsymbol{E}$ is a straight line. The relation (1) is valid for the field strengths of conventional sources. The quantity χ is a constant only in the sense of being independent of $\boldsymbol{E}$; its magnitude is a function of the frequency. With sufficiently intense laser radiation this relation does not hold good and has to be generalized to equation (2), which can be written in the vector form, as by a power series

$$\boldsymbol{P} = \varepsilon_0[\chi^{(1)}\boldsymbol{E} + \chi^{(2)}\boldsymbol{EE} + \chi^{(3)}\boldsymbol{EEE} + \text{--------}] \qquad (2)$$

$$\vec{P}_i(\omega_j) = \varepsilon_0 [\sum_j \chi^{(1)}_{ij}(\omega_m) E_j(\omega_m) + \sum_{jk}\sum_{(mn)} \chi^{(2)}_{ijk}(\omega_m, \omega_n) E_j(\omega_m) E_k(\omega_n) + \sum_{jkl}\sum_{(mno)} \chi^{3}_{ijkl}(\omega_m, \omega_n, \omega_o) E_j(\omega_m) E_k(\omega_n) E_l(\omega_0) + ...] \qquad (3)$$

where $\chi_{ij}^{(1)}$ is a second – rank (linear) tensor (9 components *xx*, *xy*, *xz*, *yx*,……..), where $\chi_{ijk}^{(2)}$ is a third -rank (nonlinear) tensor (27 components, *xxx*, *xxy*, *xxz*, *xyx*,…….), and $\chi_{ijkl}^{(3)}$ is a forth-rank (nonlinear) tensor (81 components, *xxxx*,*xxxy*, *xxxz*, *xxyx*,……). The values of the tensor coefficients are functions of frequency and temperature. The subscripts *m*, *n*, and *o* etc. denotes different frequency components, and *i*, *j*, *k* and *l* are Cartesian indices that run from 1 to 3 [1][20]. For small field strength the polarization is proportional to the electric field ***E*** and is accounted for by the polarizatbility tensor $\chi_{ij}^{(1)}$. All of the optics discussed so far has been linear optics encompassed in the term $\varepsilon_0 \chi_{ij}^{(1)}(\omega_m)\boldsymbol{E}_j(\omega_m)$. This term represents optical phenomenon that are proportional to the electric field and are at the frequency of incoming wave.

The term $\chi_{ijk}^{(2)}(\omega_m,\omega_n)\boldsymbol{E}_j(\omega_m)\boldsymbol{E}_k(\omega_n)$ is responsible for all of the two-wave effects. This includes second harmonic generation (two fields at ω to make one at 2ω) and parametric oscillation (one field at ω_1 and other field at ω_2 to create fields at ω_1 - ω_2 and $\omega_1 + \omega_2$). This also includes optical mixing, and the Pocals effect (change of index of refraction with applied electric field). The nonlinear polarization tensor $\chi^{(2)}$ vanishes in the crystals that have a center of symmetry (i.e. crystal symmetry). In these crystals second harmonic generation is not possible. As a result of, many of the components of $\chi^{(2)}$ will be zero or equal to other components of the tensor. Thus the second-order polarization and the corresponding monochromatic components of the optical field:

$$\boldsymbol{P}^{(2)}(\omega = \omega_1 + \omega_2) = \varepsilon_0 \chi^{(2)}(\omega_1,\omega_2)\boldsymbol{E}(\omega_1)\boldsymbol{E}(\omega_2) \quad (4)$$

where $\chi^{(2)}$ denotes the second-order susceptibility that is a third-order tensor.

Desmond [19] simplified $\chi_{ijk}^{(2)}$, and replaced by a nonlinear optical coefficient d_{il} (Coulomb/Volt^2), according to the following relationship:

$$d_{il} = \varepsilon_0 \chi_{ijk}^{(2)} \qquad \begin{cases} l = 1,2,3,4,5,6 \\ jk = xx, yy, zz, yz, zx, xy \end{cases} \quad (5)$$

i.e., the nonlinear optical coefficient d_{ijk} is symmetric in *j* and *k* and according to Khun [1] $d_{ij} = \frac{1}{2}\chi_{ijk}^{(2)}$, here, ε_0, is the permittivity of free space, some authors excludes ε_0 from the *d* coefficient, in this case *d* [As/V^2] = 8.855×10^{-12} *d* [m/v]. The conversion from the cgs system to MKS units becomes *d* [As/V^2] = 3.68×10^{-15} *d* [esu]. In most practical situations the tensor equations containing d_{ijk} can be simplified to non-tensor form in which d_{ijk} is replaced by d_{eff}, is the effective nonlinear coefficient for the interaction dependent on crystal symmetry and propagation direction in the medium.

3.1 Second Harmonic Generation:

The simplest second-order process is that of second-harmonic generation (SHG). In this process, an intense laser beam of angular frequency ω_1 (= ω) is passed through a crystal having nonzero value of $\chi^{(2)}$, such that the beam emerging from the crystal contains the angular frequencies ω_1 of the input beam and also $\omega_2 = 2\omega_1$, twice the frequency of the input beam. This can be shown to occur by considering the second nonlinear polarization term $P^{(2)}$.

3.2 Optical Sum and Difference Frequency Generation:

In the second-harmonic generation, considered the combination (addition) of two photons of the same frequency to produce a single photon of twice the frequency. It can now to generalize this process to allow for the case in which the two photons have different frequencies ω_1 and ω_2. These include second harmonic terms (involving $2\omega_1$ and $2\omega_2$), and two new terms involving $\omega_1 + \omega_2$ and $\omega_1 - \omega_2$. The new term involving $\omega_1 + \omega_2$ generates a new frequency that is the sum of the two original frequencies and is thus known as *sum frequency generation*. The term involving the difference between the two frequencies, $\omega_1 - \omega_2$, is referred to as *difference frequency generation*. In the process of difference frequency mixing, the frequency ω_2 is amplified while the frequency ω_3 is being generated. In the process of optical parametric oscillation (OPO) the intense input laser beam at frequency ω_p is known as the *pump* frequency, when passes through a nonlinear material, generates the desired frequencies ω_s (signal frequency) and the frequency ω_i (idler frequency) [20].The amplification can be enhanced by placing the optical harmonic (nonlinear) crystal within an optical cavity in which the mirrors are specifically made reflective at either one of these two frequencies, or for both. Thus the intensity at those frequencies will build up within the cavity, by Fabry-Perot interferometer. Such an amplification process is known as an optical parametric oscillator (OPO). Of course, either ω_s or ω_i can be tunable laser to generate amplified tunable output. This process is used most often in the infrared frequency range, where tunable lasers are not as readily available as in the visible portion of the frequency spectrum [13]. The output of an optical parametric oscillator (OPO) is similar to that of a laser. The energy conservation requires that

$$\omega_p = \omega_s + \omega_i \qquad (6)$$

Here ω_p, ω_s, and ω_i are the frequencies of the pump, signal and idler wave. For a given ω_p, there can be a continuous range of choices of ω_s and ω_i. This, in fact, is the origin of the tunability of the optical parametric oscillator. The specific pair of frequencies that will be emitted is dictated by the momentum conservation condition, or phase matching condition: $\boldsymbol{k}_p = \boldsymbol{k}_s + \boldsymbol{k}_i$, that must also be satisfied in order to ensure that the signal waves generated in different parts of the nonlinear crystal are in phase and add coherently [12]. For collinearly propagating waves this may be written

$$\left.\begin{aligned} \frac{n_p}{\lambda_p} &= \frac{n_s}{\lambda_s} + \frac{n_i}{\lambda_i} \\ \omega_p n_p &= \omega_s n_s + \omega_i n_i \end{aligned}\right\} \qquad (7)$$

Here n_p, n_s and n_i are the refractive indices of the pump, signal and idler wave and λ_p, λ_s and λ_i there corresponding wavelengths respectively. The pump signal is usually provided by a laser and, therefore λ_p is fixed. However, if the refractive indices are varied, the signal and idler frequencies will tune. Under an appropriate arrangement for the angle (or temperature) of a given nonlinear crystal, the above two requirements (Eq. (6) & (7)) can be satisfied and oscillations at two different frequencies ω_s, and ω_i can be achieved. Based on this working condition, if we slightly change the angle or temperature of the crystal, the refractive index relation between these three waves will be changed; therefore the oscillating frequencies will be smoothly tuned to different values [10][14].

The requirements of nonlinear crystals for optical parametric oscillation are essentially the same as that for SHG. In other words, the nonlinear materials must be non-centrosymmetrical crystals, highly transparent for pump, signal, and idler beams, able to fulfill the phase matching by using angle-tuning or temperature-tuning. In principle, all commonly used SHG crystals used for OPO purpose. A possible simple implementation of the optical parametric oscillator is shown schematically in Figure-3.

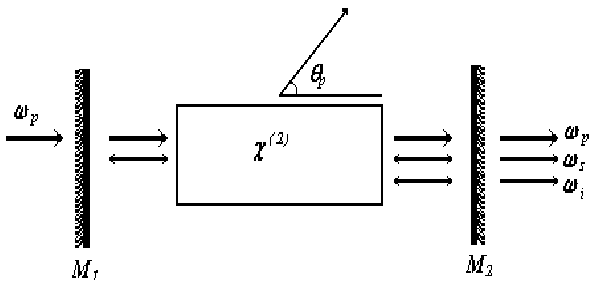

FIGURE 3. Singly-Resonant Optical Parametric Oscillator

It is consist of a suitably oriented nonlinear optical crystal in a Fabry-Perot cavity. The cavity mirrors are coated to transmit the pump wave and reflect either the signal wave only or both the signal and idler waves.

In the former case, the oscillator is known as the singly resonant oscillator, and, in the latter case, it is known as the doubly resonant oscillator. After passing through the output-coupling mirror the transmitted pump beam is blocked by a filter. The further separation between the signal beam and idler beam can be done by using appropriate spectral filters or optical dispersive elements. Various optical cavity designs, including stable, unstable, or metastable cavity configurations, can be employed for OPO purpose. The criteria of selection of cavity designs are same as that for laser cavity devices [20].

3.3 Nonlinear Optical Materials

For generating new frequencies from existing lasers via harmonic generation and difference generation, they must (1) be resistant to optical damage, (2) have high mechanical hardness, (3) exhibit good thermal and chemical stability, (4) be capable of being grown in useful sizes, and (5) have the appropriate phase-matching properties. The second harmonic crystals must have no inversion symmetry (i.e. non-centrosymmetric). Bulk second-order nonlinear materials are generally inorganic crystals. A number

Property	KTP	BBO	LBO	CLBO
Nonlinear coefficient (pm/V)	3.1	1.94	1.16	1.11
Transmission range (μm)	0.35 - 5.5	0.19 - 3.5	0.16 – 2.6	0.16 – 2.6
Damage threshold (GW/cm^2)	> 0.5	1.5	2.5	> 2.5
Angular acceptance (mrad-cm)	20	< 1	2	1.4
Spectral acceptance (mm-cm)	0.5	0.5	0.8	1
Walk-off angle (degree)	1.3	5.5	<1	1.8
Damage resistance to moisture	High	Low	Low	Medium

Table-3. Properties of some important nonlinear crystals[6]

of semiconductors are useful for second harmonic generation when used in waveguides. The nonlinear crystals can be classified into two groups according to their physical properties. Crystals grown from water solutions are fragile, hygroscopic, and sensitive to thermal shock. The crystals of this group, to which KDP and its isomorphs belong, are somewhat difficult to handle because the crystals are soft, and the polished faces may be fogged if they are held with bare hands or exposed to humid atmosphere. On the other hand, the crystals are easy to grow, they are available in large sizes, and they are of excellent optical quality. Crystals grown from the melt are relatively hard, nonhygroscopic and less sensitive to thermal shock. Important members of this group crystals are $LiNbO_3$ (LBO) , $Ba_2NaNb_5O_{15}$ (BBO) and $KTiOPO_4$ (KTP). KTP possesses good optical properties, a large acceptance angle, large temperature acceptance, a large nonlinear coefficient, and high optical damage thresholds [9] [10].

IV. CONCLUSION

In summary laser safety research must involve investigation of the effects of laser exposure in the visible and near-infrared. Many civilian and military laser devices involve both visible and near infrared laser sources. Accidental exposure under these conditions may involve a wide range of exposure from acute retinal exposure well above the Maximum Permissible Exposure (MPE), therefore it is required to use precautions. Thus Optical parametric devices generate broadly tunable coherent optical radiation by the phase-matched nonlinear interaction of an intense laser beam in a suitable nonlinear crystals such as KTP etc. In this process the high energy pump photon is converted into a pair of lower frequency signal and idler photons while conserving the total energy and momentum. Tunability of the signal-idler pair is usually achieved either by changing the crystal birefringence through its temperature dependence or by the angular dependence of the extraordinary index of the crystal. The practical optical parametric oscillator (OPO) device consists of a nonlinear crystal enclosed in an optical cavity resonant at either or both the signal and idler wavelengths and pumped by Nd:YAG laser.

REFERENCES

[1] K. J. Kuhn; Laser Engineering, Prentice Hall Pub., 1998.
[2] J. K. Franks; SPIE, 1419, 2-8 (1991).
[3] John E. Harry; "Industrial Lasers and their applications". McGraw Hill, New York.
[4] D. C. Winburn; "Practical Laser Safety", 2d ed. (New York: Marcel Dekker, Inc. 1990.
[5] Americal National Standard for the safe use of Laser, ANSI Z136, 1-1973, Americal National Standards, Inc., New York, USA.
[6] Safety with Lasers, Brit. Med. J., 3(5765), 3-4, 1971.
[7] L. R. Marshall, A. D. Hays, H. J. Kasinski, and R. Burnham; SPIE, 1419, 141-152 (1991).
[8] R. D. Stultz, D. E. Nieuwsma, E. Gregor; SPIE, 1419, 64-74 (1991).
[9] Walter Koechner, Solid State Laser Engineering, 5rh ed., (Springer Berlin 1999).
[10] Willium T. Silfvast, Laser Fundamentals, (Cambridge university Press 1991).
[11] H. K. V. Lotsch; Japan J. Appl. Phys, 4, 435 (1965).
[12] M. Bass, P. A. Franken, J. F. Ward, and G. Weinreich; Phys. Rev. Lett., 9, 446, (1962).
[13] S. Wang, V. Pasiskevicius, J. Hellstrom, F. Laurell, and H. Karlsson, "First-order type-II quasi-phase-matched UV generation in periodically poled KTP", Opt. Lett. 24, 978-980 (1999).
[14] G. E. Francois; Phy. Rev., 143, 597 (1966).
[15] K. Kato; Appl. Phys. Letters, 25, 342 (1974).

[16] K. Kato; IEEE J. Ouant. Electr. QE-10, 622 (1974).
[17] G. Nath, S. Haussuhal; Appl. Phys. Lett., 14, 154 (1969).
[18] J. E. Bjorkholm; IEEE J. Ouant. Electr. QE-4, 970 (1968).
[19] S. Desmond Smith; Optoelectronic Devices, (Prentice Hall Pub., 1995).
[20] W. Boyd, Non-Linear Optics (Boston, MA; Academic Press, (1992).