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A Ring-Cavity for a Quadrupled Nd-Yag Laser.

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Summary. — A new high-powered ultraviolet laser system is proposed. The system doubles the infrared light from a Nd-Yag laser mode-locked at 100 MHz, injects this light into a storage-ring cavity to accumulate a high power in the visible and then doubles this into the ultraviolet at 2600 Å. The power levels anticipated at this wavelength are much larger than those of commercially available c.w. lasers. The new system can have a far-reaching impact in basic research and, even more so, in a great many industrial applications.

PACS 42.65.Ky – Harmonic generation, frequency conversion, parametric oscillation, and parametric amplification.

In the course of designing a short-wavelength high-powered laser for the laser electron gamma source (LEGS) facility at BNL [1], a new technique has been conceived which is expected to provide UV power levels that are much greater than what is now commercially available.

The new technique involves converting infrared light from a CW mode-locked Nd-Yag laser to green by frequency doubling in a nonlinear crystal, while simultaneously injecting into an optical cavity that acts as a storage ring for the light (see fig. 1). The green that has been generated propagates around the ring and is partially converted into UV in a second doubler. The residual green continues around the ring to the first doubler where, if the ring transit time matches exactly with the repetition frequency of the mode-locked IR laser, it adds coherently with the green generated by the next IR pulse.

The idea that a mechanism like this could be used to enhance the efficiency of a second harmonic generation has been recognized in the past [2]. Moreover, a coherent enhancement in the frequency doubling of IR light from a Nd-Yag laser following two passes through a $LiNbO_3$ crystal has already been reported in the literature [3].

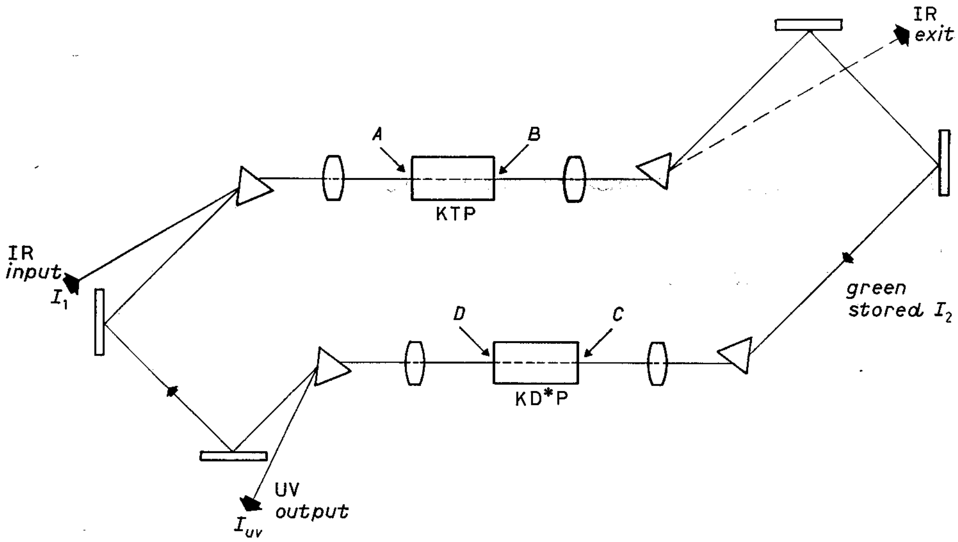

Fig. 1. – Basic scheme for the laser ring cavity.

In the present paper we show that a more general multipass geometry can be associated with the idea of a storage ring for photons in complete analogy with the customarily used storage rings for electrons and protons. We claim that this combination can potentially lead to a unique method for producing unexpectedly high-power UV-laser beams.

In order to construct the power build-up inside the ring, let us first consider an infrared rectangular pulse of power density I_1 which is projected through a KTPcrystal located between A and B. The generated I_2 green pulse is injected into the ring and is subsequently converted into UV in a KD*P-crystal located between C and D (see fig. 1).

The conversion efficiencies of the two crystals depend upon the impinging power

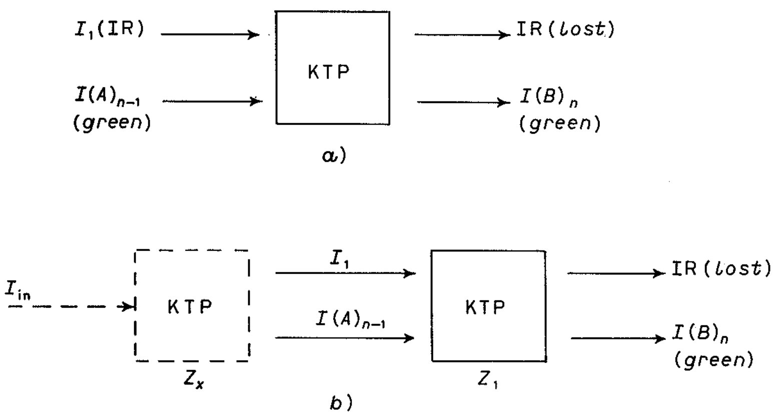

Fig. 2. – Light composition at the KTP-crystal (a)), and the equivalent circuit with the auxiliary crystal of length Z_x (b)).

densities I, according to the expressions

$$\begin{cases} \varepsilon_1 = \varepsilon(\text{KTP}) = \text{tgh}^2\left(Z_1\sqrt{K_1 I}\right), \\ \varepsilon_2 = \varepsilon(\text{KD*P}) = \text{tgh}^2\left(Z_2\sqrt{K_2 I}\right), \end{cases} \tag{1}$$

where the appropriate nonlinear conversion constants for the two crystals are $K_1 = 2.525 \cdot 10^{-7}/\text{W}$ and $K_2 = 7.6 \cdot 10^{-9}/\text{W}$ [4] and Z_1, Z_2 are the two crystal lengths, respectively.

At each passage through the KPT crystal the situation appears as shown in fig. 2*a*), where $I(A)_{n-1}$ is the green power stored at the $(n-1)$-th passage in the position A and $I(B)_n$ is the one obtained at the n-th passage in the position B.

In the hypothesis that no phase-shift between the old and the new greens is introduced by the cavity, one can imagine an equivalent circuit in which the two densities I_1 (IR) and $I(A)_{n-1}$ (green) are produced by an initial IR-power density I_{in} converted in a crystal of length Z_x (see fig. 2*b*)). In this case, one can write

$$\begin{cases} I_{\text{in}} = I_1 + I(A)_{n-1}, & I(A)_{n-1} = \varepsilon_1(Z_x) I_{\text{in}}, \\ I_1 = (1 - \varepsilon_1(Z_x) I_{\text{in}}), & I(B)_n = \varepsilon_1(Z_x + Z_1) I_{\text{in}}, \end{cases} \tag{2}$$

and

$$\beta^2 = \varepsilon(Z_x) = \frac{I(A)_{n-1}}{I_{\text{in}}} = \text{tgh}^2\left(\sqrt{K_1 I_{\text{in}}}\, Z_x\right), \tag{3}$$

$$\sqrt{K_1 I_{\text{in}}}\, Z_x = \frac{1}{2} \ln \frac{1+\beta}{1-\beta}. \tag{4}$$

On the other hand, by virtue of eq. (4) one has

$$\varepsilon_1(Z_x + Z_1) = \text{tgh}^2\left(\sqrt{K_1 I_{\text{in}}}\,(Z_x + Z_1)\right) = \xi(\delta, x), \tag{5}$$

where

$$\delta = \frac{1-\beta}{1+\beta}, \qquad x = \sqrt{K_1 I_{\text{in}}}\, Z_1, \qquad \xi(\delta, x) = \left(\frac{e^x - \delta e^{-x}}{e^x + \delta e^{-x}}\right)^2. \tag{6}$$

Finally, by inserting eq. (5) into eq. (2) one obtains

$$I(B)_n = I_{\text{in}}\, \xi(\delta, x). \tag{7}$$

It is clear from these considerations that the effective IR $\rightarrow$ green conversion efficiency, defined as

$$\bar{\varepsilon}(\text{KTP}) = \frac{I(B)_n - I(A)_{n-1}}{I_1} = \frac{\varepsilon_1(Z_x + Z_1) - \varepsilon_1(Z_x)}{1 - \varepsilon_1(Z_x)} = \frac{\xi(\delta, x) - \beta^2}{1 - \beta^2}, \tag{8}$$

is effectively enhanced by the presence of the previous green pulse. As a matter of fact, one can see that, in the limit of a big build-up into cavity (*i.e.* $I(A)_{n-1} \gg I_1$ in eq. (2) $\beta \rightarrow 1$, $\delta \rightarrow 0$, and eq. (8) tends to 1. If this condition is fully satisfied, the whole IR-pulse is converted into green and stored inside the cavity.

However, this can never be the case, because the extent of the build-up strongly depends upon the total cavity losses which necessarily include the green-to-UV conversion.

This effect can be accounted for by tracking the time evolution of successive pulses over many passes around the ring. At the n-th passage of the pulse through the cavity one has

$$(9)\qquad \begin{cases} I(B)_n = (I(A)_{n-1} + I_1)\,\xi(\delta, x)\,, \\ I(C)_n = \left(1 - \dfrac{\alpha}{2}\right) I(B)_n\,, \\ I(D)_n = I(C)_n\left[1 - \mathrm{tgh}^2\left(Z_2\sqrt{K_2 I(C)_n}\right)\right] = I(C)_n - I_n(\mathrm{UV})\,, \\ I(A)_n = \left(1 - \dfrac{\alpha}{2}\right) I(D)_n\,, \end{cases}$$

where α = total cavity losses and I(UV) is the obtained UV power density. The equilibrium condition is obtained when

$$(10)\qquad \begin{cases} I\,(\text{any position})_{n-1} = I\,(\text{any position})_n\,, \\ I_{n-1}(\mathrm{UV}) = I_n(\mathrm{UV}) \end{cases}$$

and can be computed by iterating over the system of eq. (9) for a sufficient number of times.

This iteration procedure has been applied to the case of a pure TEM_{00} Gaussian-like pulse, assuming the following numerical values:

$$(11)\qquad \begin{cases} \text{average IR power: } P^{\mathrm{IR}}_{\mathrm{AVG}} = 30\,\mathrm{W}\,, \\ \text{IR pulse width (FWHM)} = 100\,\mathrm{ps}\,(\sigma_t = 42.5\,\mathrm{ps})\,, \\ \text{repetition frequency} = 100\,\mathrm{MHz}\,, \\ Z_1 = 0.5\,\mathrm{cm}\,,\quad Z_2 = 1\,\mathrm{cm}\,,\quad \alpha = 0.15 \end{cases}$$

and the obtained results are summarized in table I. Figure 3 shows the IR $\to$ UV

TABLE I. – *Calculated performances of the ring cavity.*

σ_{IR} (μm)	D (MW/cm^2)	$P^{\mathrm{UV}}_{\mathrm{AVG}}$ (W)	$P(C)$ (W)	ε(IR $\to$ UV)
154.5	1.88	1.52	74.0	0.05
109.0	3.78	3.51	88.7	0.12
69.0	9.42	7.53	94.5	0.25
49.0	18.7	11.2	90.4	0.37
34.5	37.7	14.9	81.4	0.50
28.0	57.2	17.0	74.8	0.57
24.5	74.7	18.3	70.5	0.61
22.0	92.7	19.2	67.0	0.64
20.0	112.0	20.0	63.9	0.67
18.5	131.0	20.6	61.4	0.69

σ_{IR} = sigma of the IR-power transverse distribution;

D = IR energy/pulse/$\left(\sqrt{2\pi}\sigma_t \cdot 2\pi\sigma^2_{\mathrm{IR}}\right)$;

$P^{\mathrm{UV}}_{\mathrm{AVG}}$ = obtained UV-average power;

$P(C)$ = green average power impinging on the (KD*P) crystal;

$\varepsilon(\mathrm{IR} \to \mathrm{UV}) = P^{\mathrm{UV}}_{\mathrm{AVG}}/P^{\mathrm{IR}}_{\mathrm{AVG}}$.

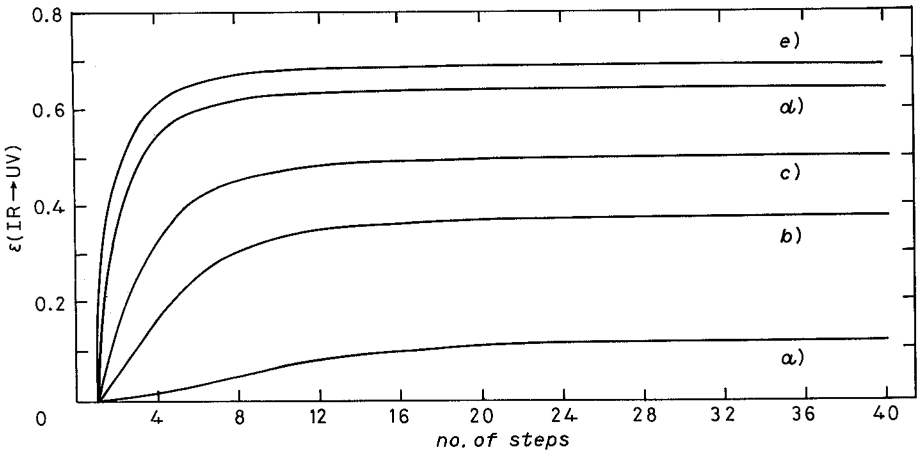

Fig. 3. – IR→UV conversion efficiency *vs*. number of steps necessary to reach equilibrium. Curves *a*), *b*), *c*), *d*), *e*) correspond to IR-power densities of 3.8, 18.7, 38, 93, 131 MW/cm^2.

conversion efficiency *vs*. the number of iteration steps for different values of the power density.

These results show that even at relatively modest IR-power densities of ≈ 100 MW/cm^2 and perfect phase matching, the overall IR-to-UV conversion efficiency approaches values of 0.65 very rapidly, *i.e.* after 12 passes around the ring. This means that at equilibrium most of the IR power is converted into green ($\bar{\varepsilon}$(KTP) = 0.94) and a comparable amount must leave the cavity as UV.

The crucial question in this discussion is the assumption that the IR and the recirculated green pulses are exactly in phase at the position of the first doubler. Since this is in practice impossible to achieve, one has to evaluate the extent of the out-of-phase effect that can be tolerated without spoiling the coherent superposition of the two pulses.

This can be seen by considering the equations for the harmonic and fundamental electric fields E(green), E(IR), in the second harmonic generation process.

Following the procedure outlined in ref. [5] and [6], at perfect phase matching one has

$$\begin{cases} \dfrac{\mathrm{d}E\,(\text{green})}{\mathrm{d}z} = i\sqrt{K_1}\,E^2(\text{IR})\,, \\[2ex] \dfrac{\mathrm{d}E\,(\text{IR})}{\mathrm{d}z} = i\sqrt{K_1}\,E\,(\text{green})\,E^*(\text{IR})\,. \end{cases} \tag{12}$$

With the positions E(green) $= \rho_2 \exp[i\phi_2]$ and E(IR) $= \rho_1 \exp[i\phi_1]$ this system can be rewritten in terms of their amplitudes and phases:

$$\begin{cases} \dfrac{\mathrm{d}\rho_1}{\mathrm{d}z} = \sqrt{K_1}\rho_1\rho_2 \sin(2\phi_1 - \phi_2)\,, & \dfrac{\mathrm{d}\rho_2}{\mathrm{d}z} = -\sqrt{K_1}\rho_1^2 \sin(2\phi_1 - \phi_2)\,, \\[2ex] \dfrac{\mathrm{d}\phi_1}{\mathrm{d}z} = \sqrt{K_1}\rho_2 \cos(2\phi_1 - \phi_2)\,, & \dfrac{\mathrm{d}\phi_2}{\mathrm{d}z} = \sqrt{K_1}\,\dfrac{\rho_1^2}{\rho_2} \cos(2\phi_1 - \phi_2)\,. \end{cases} \tag{13}$$

This system admits the two constants of integration:

$$\rho_1^2 + \rho_2^2 = \text{const}\,, \qquad \rho_1^2\rho_2 \cos(2\phi_1 - \phi_2) = \text{const}\,. \tag{14}$$

The first represents the power flow conservation and the second the phase relationship that exists between the two fields during the harmonic generation through the crystal.

Since without loss of generality one can always assume $\phi_1 = 0$ at the crystal entrance, eqs. (13) and (14) indicate that, when $\rho_2(0) = 0$, the green is always generated in quadrature with the infrared ($\phi_2 = \pi/2$). This would hold in all the subsequent passages through the crystal only if the cavity would not introduce any optical phase difference ($\phi = 0$). In this case the solution of system (13) would immediately lead to eq. (7) as expected.

For $\phi \neq 0$, the equilibrium conditions in the cavity can only be found with an iterative procedure where system (13) is solved with the appropriate initial conditions at each recirculation through the crystal.

Numerical results of this procedure for a rectangular pulse are shown in fig. 4.

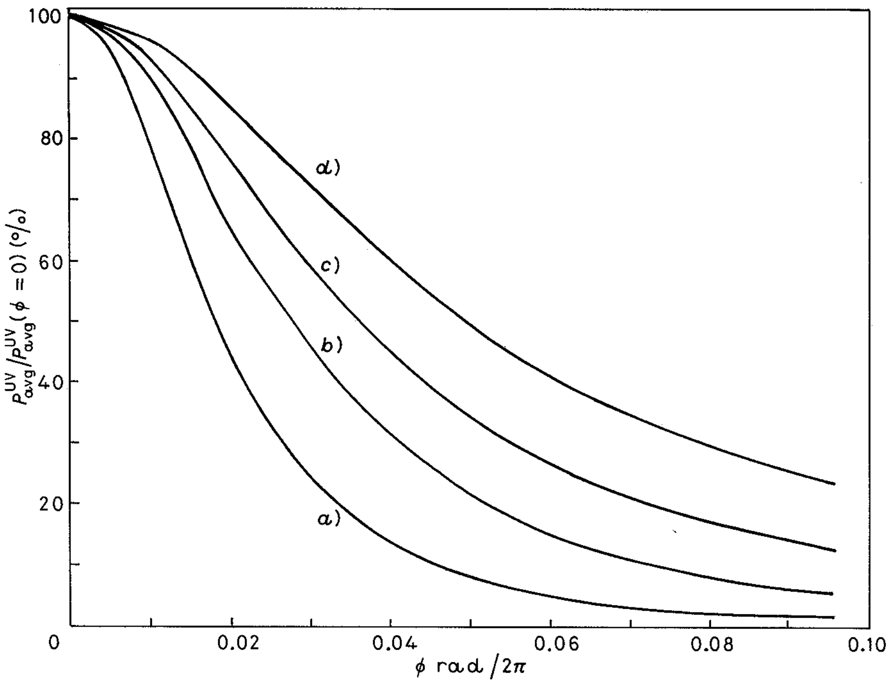

Fig. 4. – Effect of the cavity phase lag ϕ on the UV power at equilibrium. Curves *a*), *b*), *c*) *d*) correspond to IR power densities of 2, 5, 10, 40 MW/cm^2.

As an example, a lag of phase of $\phi = 10°$ would cause a power degradation effect of 50% at 10 MW/cm^2 and of 30% at 40 MW/cm^2. This means that the coherent enhancement can be almost fully preserved only if the path length of the cavity is controlled well within a fraction of a wavelength.

Admittedly, this is a hard thing to do, but there are several possible approaches to the problem. Essentially they must be implemented in a feedback loop in which a small fraction of green power that leaks through one of the ring's mirror is monitored and the path length varied to maintain a maximum. Alternatively one can think to derive an error signal by taking advantage of the dephasing effect on the IR pulse at the exit of the KTP-crystal that results from the optical phase difference ϕ introduced by the cavity.

There are many other technological problems like the effects of heat deposition, temperature control of the crystals, distortion of the wavefronts, etc. that can be seriously challenging, but we do not think that they can be appropriately addressed in the present paper.

However, another reason that makes this scheme so special is that any effect that results in a drop of the single-pass conversion efficiency has little impact on the power levels reached at equilibrium. The less the instantaneous conversion efficiency, the more passes around the ring are required to build up what is roughly the same equilibrium conversion efficiency. For example, by reducing both K-values in eq. (1) by a factor of 2, the UV power at equilibrium diminishes by approximately 13% with an IR power density of 40 MW/cm^2. Correspondingly the number of passes necessary to reach equilibrium goes from 6 to 11, which is always well within the limits imposed by the expected coherence time of the mode-locked Nd-Yag laser.

On the other hand, a K-value 6 times larger than potassium dideuterium phosphate (KD*P) has already been reported for β-BaB_2O_4 that has a damage threshold of 4.6 GW/cm^2 at 1.06 μm [7, 8]. With these considerations, the ring shifts the burden of difficulties from maintaining a high single-pass conversion efficiency to controlling the beam quality and the optical path length. Although this latter is not trivial, it is far less problematic.

In conclusion, we think we have outlined a basic method that can potentially produce power levels at 266 nm much larger than the almost c.w. lasers commercially available today and as such can represent a breakthrough in laser technology.

This new laser system is expected to have a far-reaching impact on basic research and even more so, on a great many industrial and medical applications.

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REFERENCES

[1] A. M. SANDORFI, M. J. LEVINE, C. E. THORN, G. GIORDANO, G. MATONE and C. SCHAERF: *IEEE Trans. Nucl. Sci.*, Vol. **30**, 3083 (1983).
[2] A. A. ASHKIN, G. D. BOYD and J. M. DZIEDZIC: *IEEE J. Quantum Electron.*, QE-2, 109 (1966).
[3] J. M. YARBOROUGH, J. FALK and C. B. HITZ: *Appl. Phys. Lett.*, 18, 70 (1971).
[4] W. KOECHNER: *Solid-State Laser Engineering* (Springer-Verlag, New York, N.Y., 1976) and W. D. FOUNTAIN: private communication.
[5] *Laser Handbook*, Vol. 5, edited by M. BASS and M. L. STITCH (North Holland, Amsterdam, 1985).
[6] J. A. ARMSTRONG, N. BLOEMBERGEN, J. DUCUING and P. S. PERSHAN: *Phys. Rev.*, 127, 1918 (1962).
[7] K. MIYAZAKI, H. SAKAI and T.SATO: *Opt. Lett.*, 11, 797 (1986).
[8] CHEN CHUANGTIAN, WU BOCHANG, JIANG AIDONG and YOU GUIMING: *Sci. Sin. B*, 28, 235 (1985).