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Spectral purity of high-intensity laser beams

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Three experiments are described in which high-intensity ruby and Nd:glass laser beams were analyzed for spectral purity. The aim of the experiments was to verify whether the nonlinear relation for photon energy $\epsilon = h\nu/[1-\beta_\nu f(I)]$, previously used to explain ionization phenomena in gases irradiated with laser beams, admitted an interpretation in terms of change of light frequency as a function of intensity. Standard methods of frequency measurement, namely spectroscopic, interferometric, and filtering methods, were used. The results consistently exclude the idea of monochromatic laser beams and seem to indicate that, at the intensities used in the experiments, which ranged from a few hundred kilowatts/cm^2 to a few gigawatts/cm^2, the laser line is broadened by several hundred angstroms.

I. INTRODUCTION

In recent years, a controversy seems to have developed on the correct interpretation of experimental results of interaction of high-intensity laser light and matter. We refer in particular to interaction leading to ionization in gases. The large body of experimental results does not seem to fit into the classical multiphoton picture and it is common to read, even in very recent papers, "The discrepancy between the theoretical results and experimental measurements is not explained in spite of . . . ,"[1] and "The disagreement with experiment, however, persists."[2] This occurs ten years or more after the publication of the first papers on multiphoton theory[3,4] and after more than a hundred articles have been written on the subject in an attempt to bring the theory in line with experiment.

The situation in addition is aggravated by the inability of the complementary theory, namely cascade, to explain in a convincing manner breakdown phenomena in gases irradiated with laser beams, although here one has to admit that a particular functional dependence, that of breakdown laser intensity on gas density, is correctly explained by the theory.

It is certainly premature at the present time to pass judgment on the validity of the two classical interpretations, and undoubtedly more refined experimentation needs to be done with improved, both spatially and temporally, laser beams, and purer gases. However, in view of the large number of applications of laser light, the most important of which is laser fusion, it seems quite appropriate to seek alternate solutions, if they exist, to the present problem. An approach advocated by this author for some time now[5-7] originated from the simple remark that the advent of lasers has introduced two new elements in the experiments of light-matter interaction: high coherence of the light source and extremely high light intensities or photon densities. Although the coherence element could not be ruled out as a possible cause of the divergence of experimental results and classical theories (on the contrary, we believe that it plays a great role), the intensity element was deemed to be the decisive component of the cause of such divergence. It was implicitly argued that either nonlinearities in the light field[8-10] appear much earlier than expected or that quantum electrodynamics breaks down at high photon densities. Whatever the reason, the consequence was postulated to be a variation of photon energy with photon density, according to an exponential law

$$\epsilon = h\nu \exp[\beta_\nu f(I)] \simeq h\nu/[1-\beta_\nu f(I)], \qquad (1)$$

where the symbols conserve the definition given in my first paper.[5]

One of the main and strong objections tacitly advanced against assumption (1) is that it violates the principle of conservation of energy. It has been argued that if photon energy increases with photon density, but the total number of photons remains constant, then a photon traveling towards the focal point of a lens, where the photon density is higher, will have its energy raised without reference to a possible source of energy gain. This objection is not valid because it fails to recognize that relation (1) does not make any assumption on the number of photons undergoing an energy increase. It just states that some photons gain energy without precluding that the gain can be achieved, through a collective process, at the expense of energy loss from the surrounding photons, or by some other means. More specifically, Eq. (1) suggests that photons have a certain energy distribution, which depends on photon density, and that only the more powerful photons in the "tail" of the distribution are able to yield ionization in gases.

Another objection[11,12] is that if (1) is to replace Planck's equation $\epsilon = h\nu$, then we must also change Einstein's equation for photon energy $E = mc^2$ in order to have a de Broglie wavelength for photons, or alternatively, we must change de Broglie's equation in order to continue to write $E = mc^2$. This is because de Broglie's equation $\lambda = hp^{-1}$, where p is photon momentum, is obtained by equating the two expressions for photon energy, photoelectric and relativistic, substituting $c\lambda^{-1}$ for ν in order to obtain the photon wavelength in terms of h and mc, and then generalizing mc to photon momentum. We believe that this objection is valid as it goes to the very root of the problem, whether the basic principles of wave mechanics, which were established for a system of isolated, noninteracting particles,[13] can be extended to a collection of particles at close distance, which presumably interact. If the principles cannot be extended, then either the energy expression or momentum should be revised.

No matter how strong, numerous, and plausible the objections are to the adoption of relation (1), they can be resolved only through experimentation. This article is thus entirely devoted to an exposition of the experimental methods we employed for the experimental verification of the validity of relation (1). The experiments are based on the assumption that, when Eq. (1) is written

$$\epsilon = h\nu/[1 - \beta_\nu f(I)] = h\nu(I),$$

then a photon energy variation with light intensity should appear as a light-frequency change. We used three conventional methods of light-frequency measurement: filtering, spectroscopic, and interferometric. Obviously, the effect being more pronounced at high light intensities, laser beams were used throughout.

The first two methods will be described in detail and the results discussed at length. The third method will be given only a summary presentation, as it is the subject of an article to appear soon in the literature.[14]

II. FILTERING METHOD (REF. 15)

The underlying idea of this experiment has been to generate first an intense beam of ruby laser light, then to focus it in vacuum by means of a lens, and finally to filter out of the focussed beam any photon of frequency different from the ruby frequency.

The experimental arrangement is described in Fig. 1. Light from a rotating-prism ruby laser, able to deliver pulses of 40-nsec duration at $\simeq 3$ MW cm^{-2} peak intensity, is sent into a vacuum chamber (residual pressure $\simeq 0.05$ Torr) where it is focussed by means of a simple plano-convex lens. The beam is then turned back by a dielectric mirror reflecting the ruby wavelength (reflection 0.990 at $\lambda = 6943$ Å) and is absorbed by the black anodized chamber walls. Photons of different wavelength can, however, pass through the dielectric mirror. In order to detect them, outside the chamber, immediately after the dielectric mirror, is located an interference filter centered at a wavelength different from that of the ruby, for instance $\lambda = 6305$ Å. Finally, a diffuser and an ITT-F4000 calibrated photodiode (photocathode diameter, 1.75 in. = 4.45 cm) with $S1$ response constitute the detector able to measure the amount of light, if any, of wavelength different from the fundamental ruby wavelength.

All components of the system, i.e., mirror, filter, diffuser, and photodiode are calibrated so as to have results in quantitative form. Moreover, in order to make certain that the light entering the chamber has the ruby frequency, an interference filter centered at the ruby wavelength 6943 Å (peak transmission, 81%; half bandwidth, 80 Å) is placed immediately after the laser. A splitter and a calibrated EG and G SGD-100 silicon photodiode are used to monitor the laser output and an iris is used to restrict the light entering the vacuum chamber to a circular area of 3-mm diameter.

To complete the details of the experimental setup we should mention that the laser beam divergence was 4×10^{-3} rad full width at half maximum (FWHM)

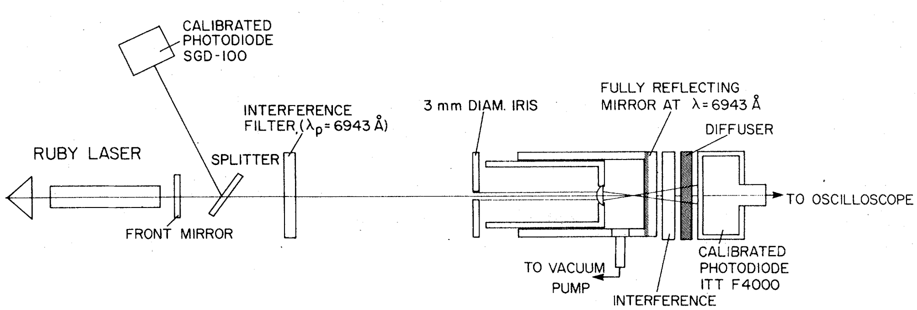

FIG. 1. Experimental setup used in the filtering method of frequency deviation measurement.

(a)

(b)

(c)

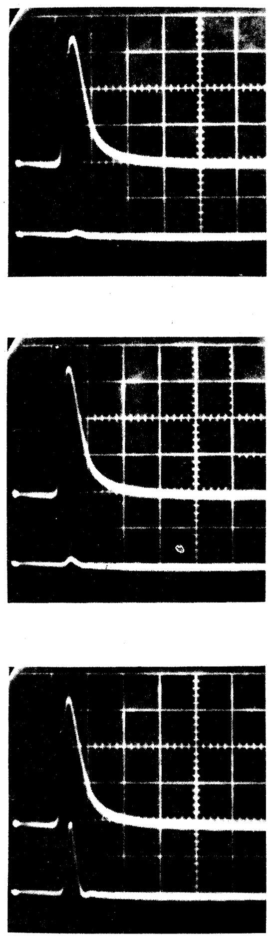

FIG. 2. Upper trace: laser pulse (7.33×10^5 W cm^{-2}/div). Lower trace: signal obtained with (a) unfocussed beam; (b) beam focussed with a 29.5-mm focal length lens (peak intensity 1.6×10^9 W cm^{-2}); (c) beam focussed with a 10.7-mm focal length lens (peak intensity 1.22×10^{10} W cm^{-2}). Time scale: 0.1 μsec/div; voltage scale 0.5 V/div.

and that photodiode SGD-100 had 4-nsec risetime whereas photodiode ITT F4000 had a risetime of 0.5 nsec. The speed of both devices was however offset by the 15-nsec risetime of the dual beam 555 Tektronix oscilloscope and type *L* plug-ins used to monitor the signals.

The dielectric mirror and interference filter in front of the photodiode do not entirely reject the 6943-Å laser light. Therefore, before each experiment, we monitored the leakage laser light reaching the photodiode. Figure 2(a) shows, on the lower trace, a typical leakage signal when the straight (unfocussed) laser beam enters the vacuum chamber through a flat window and crosses an interference filter centered at $\lambda = 6305$ Å (peak transmission, 74%; bandwidth, 80 Å) placed in front of the photodiode. The upper trace shows the laser pulse, as monitored through photodiode SGD-100. As one can see, the leakage signal is negligible.

We then replaced the flat window with a lens of 29.5 mm focal length and positioned it in such a way that the focal spot was away (≃15 mm) from the surface of the dielectric mirror, in order not to damage it. Everything else remained unchanged and we monitored the signal again. We noticed that it had increased, as shown in Fig. 2(b). However, the most dramatic increase occurred when the lens was replaced with one of shorter focal length, 10.7 mm. Figure 2(c) shows that the signal increased by more than an order of magnitude.

We repeated the experiment with various interference filters centered at different wavelengths on both sides of the ruby wavelength and were able to detect a signal in most cases. The amount of light detected is reported in Table I. It can be seen that the peak power of light detected is not negligible in comparison to the original laser power (equal to 1.75×10^5 W). Moreover, light has been detected even with a filter centered at $\lambda = 5303$ Å, e.g., 1640 Å away from the fundamental ruby wavelength.

In order to convince ourselves that the detected light had really a color different from the ruby color and that only the laser beam was responsible for its appearance, we proceeded with the following experiments.

First, we varied the gas density in the vacuum chamber up to atmospheric density. No variation of any of the signals appeared, which proved that excitation or ionization of air was not responsible for the observed phenomenon.

TABLE I. Peak power of light detected with various interference filters at two laser beam intensities.

Laser peak intensity (W/cm^2)	Peak power (W)					
	$\lambda = 7660$ Å	$\lambda = 7330$ Å	$\lambda = 6305$ Å	$\lambda = 5897$ Å	$\lambda = 5303$ Å	$\lambda = 3497$ Å
1.61×10^9	...	...	8.35×10^2	1.88×10^1	...	...
1.22×10^{10}	...	2.15×10^3	9.44×10^3	3.76×10^2	1.91×10^1	...

Second, we displaced the focussing lens backward by an amount ≃1 focal length and, for both lenses, we did not find any signal variation. This proved that the lens itself, or possible fluorescence excited on it by the laser beam, was not the source of the signal. In fact, if this were the case, the signal would have changed in inverse proportion to the square of the distance of the lens from the photodiode.[16]

Third, we positioned the lens in such a way that the illuminated area on the dielectric mirror was the same as with the unfocussed laser beam. We found that a signal appeared only when the lens was present. We repeated this procedure illuminating the interference filter and the diffuser and again found that a signal appeared only when the lens was present. This proved that neither light from oil, dust particles, etc., generated on the dielectric mirror, interference filter, diffuser, nor possible fluorescence excited on them by the laser beam, was the source of the signal.

Fourth, we inserted calibrated neutral density filters along the beam path immediately after the laser and observed the signal response. We found in all cases that it was linear with light intensity (see Sec. V for a discussion on this point). In other words, the signal varied in proportion to the amount of light entering the vacuum chamber. This proved that the detecting photodiode was a linear device and that a variation of photocathode area illuminated by the lens did not introduce any nonlinearity of response.[17]

Then we fired the laser flashlamp without laser output and found that no signal appeared. This proved that the laser flashlamp was not the cause of the observed signal. (If this were the case, the time constant of the observed signal would at any rate have been greatly increased.)

Finally, we considered the problem of the variation of direction of light incident on the dielectric mirror due to the introduction of the lens along the beam path. The presence of the 3-mm-diam iris along the beam path reduced the angle of incidence to 3° for the 29.5-mm focal length lens and to 8.5° for the 10.7-mm lens. We performed a separate test of reflectivity of the dielectric mirror as a function of laser beam incidence and found that, at least up to ±10°, no significant change occurred. We then ran a computer program to calculate the reflectivity as a function of angle of incidence for the known construction parameters of the multilayer system of the dielectric mirror and found that, up to 21°, no variation of reflectivity should occur at the ruby wavelength.[18] Consequently, the change of direction of the light rays due to the presence of the lens was not the cause of the observed signals.

As a result of all this work we felt that the laser beam was responsible for the signal appearance and that indeed new colors were present in the focal spot of the lens used.

However, still a lot of unanswered questions remained. For instance, could the lens couple interferometrically to the dielectric mirror or the mode pattern of the laser be such as to produce large-angle light incident on the dielectric mirror after focussing, etc.? All these questions had, however, as a common denominator the assumption that the laser light was still monochromatic and that the passage through the filters was facilitated by some unknown mechanism.

In order to answer these questions our line of thought changed and reasoned that, if light had really changed color, we should be able to see it. We then eliminated the photodiode and looked at the diffuser through the filters of safety goggles which are known to reject the red ruby light. When the laser was fired, an unexpected glow appeared on the diffuser which definitely convinced us that light of frequency different from the ruby frequency had been generated.

III. SPECTROSCOPIC METHOD

In order to have a confirmation of the filtering results, we then proceeded with a spectroscopic method of frequency measurement. The experimental apparatus is shown in Fig. 3. The same laser previously used was fired into a Jarrel-Ash plane grating spectrograph Mod. 75-000. The resolution of the instrument was 10 Å/mm. The beam was focussed onto the entrance slit by means of a cylindrical lens of 12.7 mm focal length. The slit aperture was 400 μm which permitted the focussed beam to enter the spectrograph unobstructed by the slit. All spectra were recorded on Polaroid type-57 film.

Figure 4 shows a few typical records taken under different amounts of spectroscope illumination. Figure 4(a) shows the spectrum of the full-intensity laser beam, unimpeded by any filter. The spectrum of Fig. 4(b) was obtained by placing an interference filter centered at the ruby wavelength 6943 Å along the beam path. Figures 4(c)–4(e) show spectra of the laser beam obtained after inserting neutral density filters along the beam path of transmission, respectively, 72, 40, and 1.3%. The intensity of light falling on the grating ranged from $\simeq 1.35\times10^{6}$ W cm^{-2}, with the unimpeded beam, to $\simeq 1.75\times10^{4}$ W cm^{-2}, with the beam filtered with the lowest-transmission neutral density filter. At the end of the experiment we opened the spectroscope, inspected it for damage and found that neither the mirrors nor the grating had in-

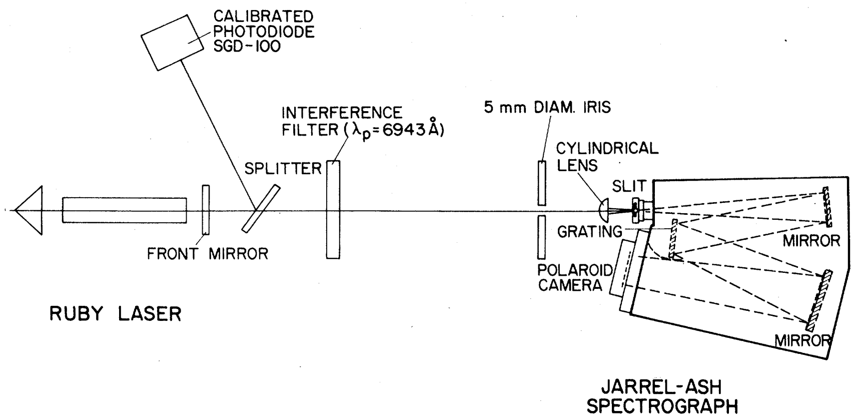

FIG. 3. Experimental setup used in the spectroscopic method of frequency measurement.

curred any damage whatsoever.

The analysis of the spectra leads us to the following considerations:

(i) Spectrum (b) obtained by shining the filtered laser beam into the spectroscope has structure not much different from spectrum (a) obtained with the unfiltered beam. Therefore the laser itself or the flashlamp cannot be held responsible for the appearance of such spectra, which are due solely to the laser beam.

(ii) Overexposure of spectra (a)–(d) is not the cause of the spectra. To prove this point let us recall[19] that photographic reproduction is affected by two elements: (a) optical behavior of the sensitive layer during its exposure and (b) adjacency effects occurring during processing. The optical behavior of the sensitive layer is determined by the multiple light reflections, refractions, and scattering within the layer itself with the resulting diffusion modifying the distribution of the exposing light. This diffusion is a spherical characteristic, i.e., it has no preferred direction. Adjacency effects during processing, which are due to migrations of developer component from nonexposed to exposed areas, is also a three-dimensional phenomenon.

Overexposure makes more apparent the general diffusion of light in all directions. Consequently, on examination of spectra (a)–(d), which are sharply confined within the exit slit edges, one must conclude that the spectra are not overexposed except at the position of the 6943-Å line and the immediate vicinity (±70 Å).

(iii) *Overlapping of orders*. As far as visible light is concerned (4000–8000 Å) the first- and second-order grating spectra cannot overlap.[20] Our grating is blazed for the first-order wavelength. Therefore, the observed spectra are not due to overlapping of orders.

(iv) *Grating scattering*. It is undoubtedly present. However, it is well known that a pulsed ruby laser has a coherence length of only a centimeter, at most. Any scattered light cannot interfere at the spectroscope exit slit with the light diffracted by the grating because the path difference would be larger than the coherence length. Therefore, grating scattering can be responsible only for the continuum background light in the spectra, not for the appearance of the several lines on both sides of the ruby line.

(v) *Diffraction pattern of the entrance slit*. It is easy to prove that this is not the cause of spectra (a)–(d). In fact, a spectrum line is merely a monochromatic image of the entrance slit. The diffraction pattern of the slit is a function of slit width, the half intensity linewidth varying directly as slit width.[21] We repeated the experiment with various slit widths (400, 200, 100, and 50 μm) and were

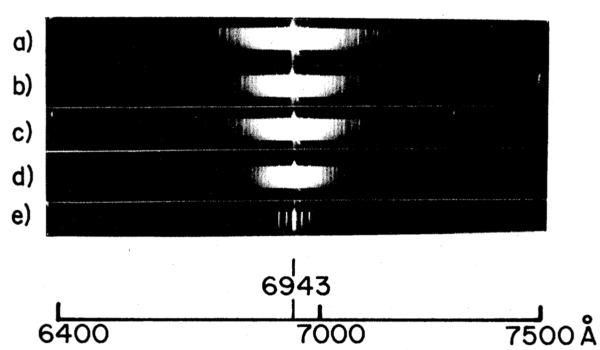

FIG. 4. Spectra of ruby light taken under different intensities of spectroscope illumination: (a) full laser beam of peak intensity $\simeq 1.35\times 10^6$ W cm^{-2} on grating. No filter of any nature placed on beam path; (b) interference filter (λ_p = 6943 Å, half bandwidth 80 Å, transmission 81%) placed along beam path; light intensity on grating $\simeq 1.09\times 10^6$ W cm^{-2}; (c)–(e) interference filter excluded. Neutral density filters of transmission 72, 40, and 1.3%, respectively, inserted along beam path. Intensity of light on grating $\simeq 9.72\times 10^5$, 5.40×10^5, and 1.75×10^4 W cm^{-2}, respectively.

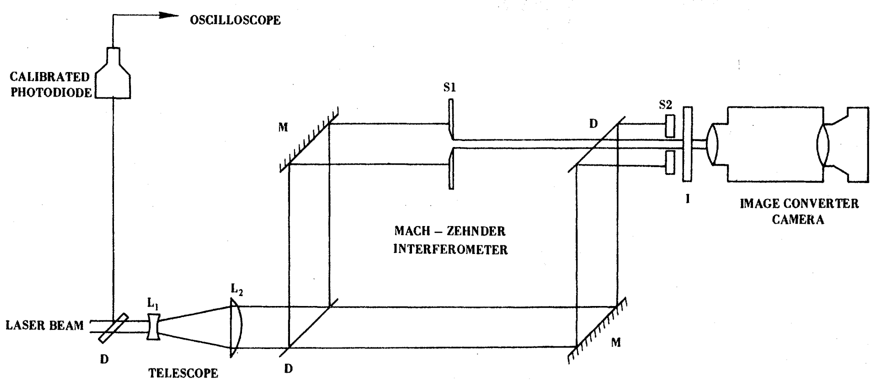

FIG. 5. Experimental setup used in the interferometric method of frequency measurement.

unable to find any variation of the diffraction pattern in all of the spectra. Therefore, the array of lines on both sides of the 6943-Å ruby line does not represent the diffraction pattern of the entrance slit but, rather, seems to be a fine-structure component of the 6943-Å line.

(vi) *Rowland ghost lines.*[21] These are due to intrinsic periodic errors of grating ruling. These lines are present in all our spectra as pairs of lines symmetrically located on both sides of the strong ruby line. They are easily recognizable and do not affect the interpretation of the spectra.

(vii) *Lyman ghost lines.*[21] These are observed at large distances from the parent lines. They are not present in our spectra.

In summary, the foregoing analysis of spectra (a)–(e) leads us to conclude that there are features which cannot be explained within the confines of classical spectroscopy and physics. However, if we adopt a positive attitude, we would be inclined to say that the laser line seems to possess a fine-structure component extending for several hundred angstroms into the blue and red side of the spectrum.

IV. INTERFEROMETRIC METHOD

In this experiment we let light from a Q-spoiled Nd:glass laser illuminate a Mach-Zender interferometer and observed the time history of the interference fringes with an image converter camera. The experimental apparatus is shown in Fig. 5. A 25-MW peak power, 80-nsec duration Nd:glass laser pulse enters a telescopic system of lenses $L_1 L_2$ where it is expanded from the initial 0.5 to 4.2 in. (1.27–10.7 cm) diameter. In this way, the peak light intensity decreases from 19.7 $\mathrm{MW\,cm^{-2}}$ to 278.2 $\mathrm{kW\,cm^{-2}}$. The low-intensity collimated beam then enters the interferometer. A slit $S1$, 1 mm wide, located in one arm of the interferometer, selects a narrow central portion of the beam which proceeds undisturbed out of the interferometer. An additional slit $S2$ outside the interferometer rejects all light coming from the second arm of the interferometer except that part which can interfere with the beam passing through $S1$. A narrow-band filter with peak transmission $\lambda = 10\,600$ Å and half bandwidth 85 Å is placed in front of the camera with the purpose of rejecting all light but that at the Nd:wavelength. The zeroth-order fringes, which are located in the plane of slit $S1$ and are oriented normally to the slit,[22] are imaged by the camera and recorded on Polaroid type-47 film. Finally, a 200-nsec plug-in streak unit, used in conjunction with the camera, provides a film writing speed of 0.25 mm/nsec, and an image time resolution of less than 1 nsec is achieved.

Figures 6 and 7 show the experimental results. Figure 6(a) shows the time history of the interference fringes when laser light experiences a large rate of intensity variation ($\simeq 7\ \mathrm{kW\,cm^{-2}\,nsec^{-1}}$ within the interferometer), whereas Fig. 7(a) shows the fringes when the intensity varies little in the course of time. The form of the light pulses is

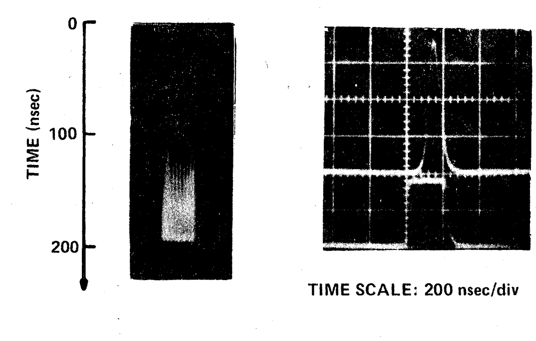

FIG. 6. (a) Time history of the interference fringes when the laser pulse experiences a large intensity variation; (b) oscilloscope record of laser emission (upper trace: 6.74 MW/div) and camera open time (lower trace).

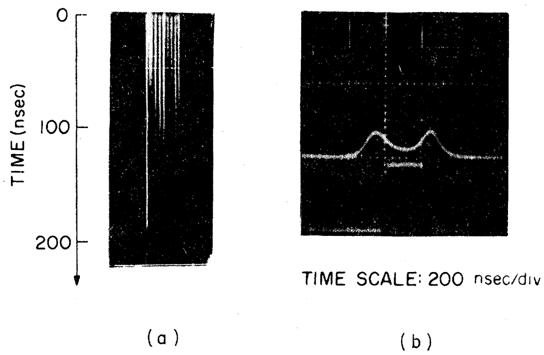

FIG. 7. (a) Time history of the interference fringes when the laser intensity is almost constant with time; (b) oscilloscope record of laser emission (upper trace: 6.74 MW/div) and camera open time (lower trace).

displayed in the upper trace of Figs. 6(b) and 7(b), while the camera open time is reported in the lower traces of the same figures.

Examination of Figs. 6 and 7 indicates that the time evolution of the interference fringes, in the case of variable light intensity, has a behavior different from the case of constant light intensity. When the intensity remains constant, or almost constant, in the course of time (Fig. 7) the fringes appear, as expected, straight and parallel. Knowing that the fringe spacing is proportional to light wavelength, it can be concluded that the light wavelength (or frequency) does not vary in this case. On the contrary, when the intensity experiences a large increase in the course of time (Fig. 6), the fringes seem to contract and a wavelength decrease of ≃2000 Å appears.

These interferometric results were analyzed in depth in the paper mentioned in the Introduction.[14] It suffices to repeat here that the wavelength shift was proved to be a true effect, no alternate interpretation being possible, such as self-induced phase modulation in the laser glass, distortion of the electron optics within the image converter camera, or laser beam divergence effect. On the other hand, the spectroscopic and filtering results are in general agreement with the interferometric results. They show that photons do not maintain their frequency but undergo frequency fluctuations according to light intensity.

V. DISCUSSION

If we take an overall view of the experimental results, the immediate remark to be made is that all three methods of frequency measurement consistently exclude the idea of a monochromatic laser beam and support the hypothesis of a beam with a large frequency distribution. The broadening of the laser line is clear in the spectroscopic and filtering results. It is less apparent in the interferometric results because the narrow-band filter in front of the image-converter camera (Fig. 5), centered at the laser frequency, permits sufficient transmission for recording only to the blue-shifted high-intensity region of the beam.

The second remark to be made is that the laser frequency does not seem to be a function of the instantaneous laser intensity. In fact, if we compare the interferometric and spectroscopic results, we note that, although the laser intensity in the spectroscopic measurements was as high as 1.35×10^{6} W cm^{-2}, e.g., ≃5 times larger than in the interferometric measurement, the wavelength shift was larger in the latter case than in the former. This general behavior is confirmed by the filtering results. A displacement of the focussing lens, with consequent variation of intensity of light at the position of the dielectric mirror, does not yield a change in the amount of light detected of color different from the fundamental laser color. In other words, it seems that photons of shifted wavelength do not return immediately to the original frequency when the intensity decreases, but have a certain "lifetime," which is a function of the overall intensity distribution in the light pulse.

We further note that, despite our efforts, the reported results are qualitative and not quantitative. Quantitative results can be obtained only if one is able to measure the amount of light contained in a small frequency interval away from the laser frequency. We have not been able to do so. In fact, the interferometric results yield information on wavelength shift only. The spectroscopic results also suffer from the same drawback. Even if we had used a calibrated film to record the spectra, a quantitative analysis would be impossible because of the presence of scattered light and "ghost" lines. We are now working on an arrangement consisting of a specially made filter and a calibrated photomultiplier to replace the film on the spectroscope. The band-stop filter will only reject ruby light, in which we are not interested, but will allow all other wavelengths to pass through and to be detected by the photomultiplier. In this way, we hope to have a quantitative plot of intensity distribution as a function of wavelength.

As to the filtering results, we do not think we have really measured intensity of light at the filter wavelength. This is because a filter selects its own wavelength for transmission only when the direction of the impinging rays is perpendicular to the filter surface or deviates by a small angle, say ±10°. In our case photons undergoing a frequency shift do so after scattering from the focal region. Consequently, their direction of travel is likely to be outside the ±10°-aperture central cone having apex at the focal point. Since the transmission wavelength of an interference filter decreases when the filter is tilted relative to perpendicular rays, some of the scattered rays of wavelength shorter than the original central wavelength are allowed to cross the filter. In other words, the filter, on a crude approximation, behaves as a short-wave pass, rather than a narrow-band device, the cutoff wavelength being the wavelength for perpendicular rays. The matter is further complicated by the fact that the quantum efficiency of the detector, the ITT photodiode, varies with wavelength. Hence, the results of Table I are just an indication that light of frequency different from the fundamental laser frequency was detected by the photodiode, but they do not represent in any way a measurement of the amount of light at the filter wavelength.

One final point is worth discussing. In the filtering measurements we found that, by inserting calibrated neutral density filters along the beam path, the signal varied linearly with light intensity. It is easy to prove that this result is in agreement with the predictions of relation (1). In fact, consider a laser pulse of peak intensity I_p. Knowing that a filter really behaves, on a first approximation, as a short-wave pass, we need to calculate the number of photons which, according to Eq. (1), have wavelength λ shorter than λ_f, the filter wavelength. We shall write

$$h\frac{c}{\lambda_f} \leq \frac{hc/\lambda_0}{1-\beta_\nu I_p^\alpha e^{-\alpha a r^2}}, \qquad (2)$$

where λ_0 is the laser frequency, and the spatial light distribution has been assumed to be Gaussian $I = I_p e^{-ar^2}$. As before[5] we have taken $f(I) = I^\alpha$. Photons of $\lambda \leq \lambda_f$ are located in a circle of radius r deduced from (2):

$$r \leq [(1/a)\ln(I_p/I_m)]^{1/2}, \qquad (3)$$

where I_m is the peak intensity of a laser beam which contains only one photon (located at $r=0$) of $\lambda = \lambda_f$. The total number of photons of $\lambda \leq \lambda_f$ is then

$$N_p(I_p) = \frac{2\pi\lambda_0}{hc}\int_0^{[(1/a)\ln(I_p/I_m)]^{1/2}} I_p e^{-ar^2} r\,dr$$

$$= (\pi\lambda_0/hca)(I_p - I_m),$$

$$= (\pi\lambda_0/hca) I_p (1 - I_m/I_p). \qquad (4)$$

Knowing that our laser beam had intensity $I_p \gg I_m$, we can write

$$N_p(I_p) \propto I_p,$$

which is what we found.

VI. CONCLUSION

The experimental results reported in this article suffer from a residual uncertainty as to the degree of influence played by the detector on the measurement. We cannot resolve this uncertainty. We can only say that we tried to perform experiments in which the detector played a minor role and tried to interpret the results by taking into proper account the role of the detector.

Historically, the situation is not new. For instance, when white light was first decomposed into colors by means of a prism, the question immediately arose as to whether the prism, rather than the original white light, might be the source of the new colors. As is well known, several experiments done with different dispersive instruments solved this doubt and proved that white light was indeed a blend of all colors. Similarly, we believe that the doubts surrounding our results will disappear when several independent experiments, done under different conditions, will bring results of converging interpretation.

As to the possibility that the results reported here undermine the unity of physics and leave the entire field of quantum theory in great disarray, we would like to point out that this is not necessarily so. Allen[12] has demonstrated that the nonlinear relation (1) can be accommodated under standard first principles of quantum mechanics. By assuming the validity of Heisenberg uncertainty principle for photons and decomposing photon momentum in three space, he proves that the energy of focussed photons has a lower bound, the bound being determined by no more than the geometrical focussing parameters. Should this interesting idea, which admits a quick experimental verification, be proved to be correct, then the photoionization processes of gases, which were the motivation and starting point of all our work, will be conclusively demonstrated to be single-photon processes of nonlinear ionization.

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[15]A concise report of this experiment has been presented at the recent meeting of the Plasma Physics Division of the A.P.S. [E. Panarella, Bull. Am. Phys. Soc. 21, 1121 (1977)].
[16]This result rules out also the hypothesis that oil or dust particles at the focus or on the surface of the lens could be the source of the signal.
[17]Irrespective of the property of the light used, a signal response proportional to the amount of light impinging on a photocathode indicates that the photocathode behaves linearly with light intensity. In our particular case, considering that the same linearity appears when the illuminated area changes, it further indicates that the photocathode area variation has no effect on the linearity of response. Therefore, photocathode nonlinearity is absent and the observed signals have a different origin. The only question thus remaining is to verify whether this result is in contradiction to the basic hypothesis of Eq. (1), and this is done in the discussion of Sec. V.
[18]We are indebted to Dr. J. A. Dobrowolski for his assistance in providing us with the computer program.
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[22]For those readers who are not familiar with interferometry, we recall that the fringes in a Mach-Zehnder interferometer can be localized in any plane, even in a plane within the interferometer itself [M. Born and E. Wolf, *Principles of Optics* (Pergamon, Oxford, 1965), pp. 312–316].

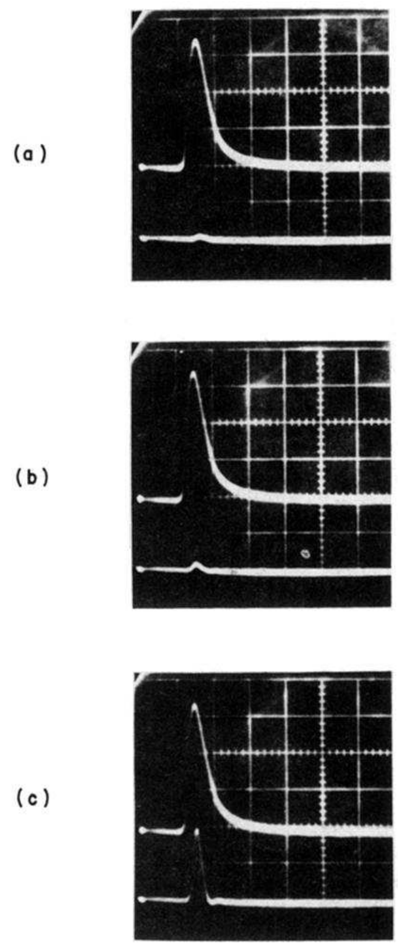

FIG. 2. Upper trace: laser pulse (7.33×10^5 W cm^{-2}/div). Lower trace: signal obtained with (a) unfocussed beam; (b) beam focussed with a 29.5-mm focal length lens (peak intensity 1.6×10^9 W cm^{-2}); (c) beam focussed with a 10.7-mm focal length lens (peak intensity 1.22 $\times 10^{10}$ W cm^{-2}). Time scale: 0.1 μsec/div; voltage scale 0.5 V/div.

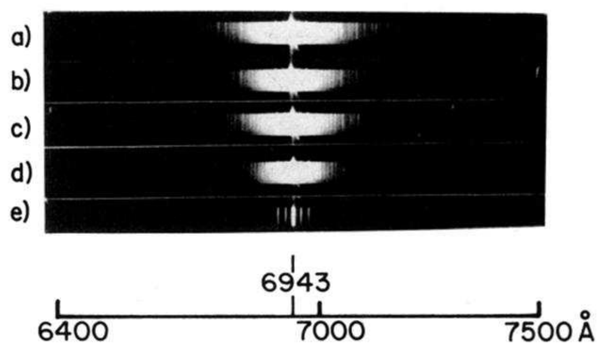

FIG. 4. Spectra of ruby light taken under different intensities of spectroscope illumination: (a) full laser beam of peak intensity $\simeq 1.35\times 10^6$ W cm^{-2} on grating. No filter of any nature placed on beam path; (b) interference filter ($\lambda_p = 6943$ Å, half bandwidth 80 Å, transmission 81%) placed along beam path; light intensity on grating $\simeq 1.09\times 10^6$ W cm^{-2}; (c)–(e) interference filter excluded. Neutral density filters of transmission 72, 40, and 1.3%, respectively, inserted along beam path. Intensity of light on grating $\simeq 9.72\times 10^5$, 5.40×10^5, and 1.75×10^4 W cm^{-2}, respectively.

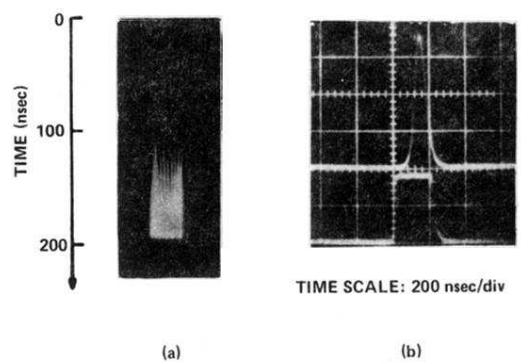

FIG. 6. (a) Time history of the interference fringes when the laser pulse experiences a large intensity variation; (b) oscilloscope record of laser emission (upper trace: 6.74 MW/div) and camera open time (lower trace).

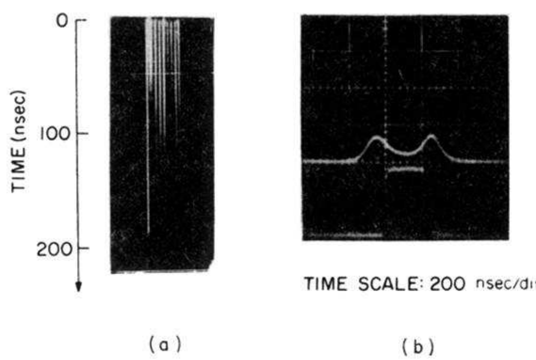

FIG. 7. (a) Time history of the interference fringes when the laser intensity is almost constant with time; (b) oscilloscope record of laser emission (upper trace: 6.74 MW/div) and camera open time (lower trace).