have been constructed by numerical integration.

We see from this table that most of the parameters of the Earth-Moon system are determined more accurately from laser than from optical observations. However, the expected accuracies have not yet been attained. This involves the insufficient number of measurements and their not fully rational distribution in time. And in turn, this involves the shortage of working time at the telescope ZTSh-2.6, which is overloaded with astrophysical studies.

One of the most important results seems to us to be the determination of the coordinates of the observation point. This is the basis for geodesic constructions and for solving many geodesic problems. In particular, the chord from the Crimean Observatory to the MacDonald Observatory has been determined with an error of about 2 m on the basis of the laser observations performed in the USSR and the USA.[11]

The results that have been obtained allow us to presume that in the near future the laser location of the Moon will become one of the most accurate methods of studying the Earth-Moon system. Today these results have already far surpassed what N. D. Papaleksi at one time expected from this method. However, undoubtedly, the ideas that he expressed many years ago are the basis of the contemporary studies in this field. And this is a brilliant example of the capacity for scientific foresight that N. D. Papaleksi possessed in high degree.

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Parametric infrared generator

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The principle of parametric amplification and generation of electromagnetic waves in the optical range was set forth and developed in 1962 in the studies of S. A. Akhmanov and R. V. Khokhlov,[1] Kingston,[2] and Kroll.[3] Reports on the first successful experiments to study parametric light generation appeared in 1965–1966.[4-6] This initiated the construction of sources of frequency- (or wavelength-) tunable coherent radiation. The range of continuous tuning of wavelength of parametric light generators (PLGs) that has been covered at present amounts to 0.4–16.4 μm.[24,31] This can be made possible by the existence of only four nonlinear crystals: ADP, $LiNbO_3$, $AgAsS_3$, and CdSe.

The scope of this report does not allow us to treat however briefly all the varieties of PLGs existing at present, which are described in a number of reviews.[7-16] Hence we shall restrict the treatment of PLGs only to one example of a parametric infrared generator based on a CdSe crystal that was built in the oscillation laboratory of the Institute of Physics of the Academy of Sciences.

But before proceeding to describe the CdSe-crystal PLG, we must turn to the works of Academician Nikolaĭ Dmitrievich Papaleksi on parametric generators of electric oscillations. Most of these studies were performed by him jointly with Academician L. I. Mandel'shtam. N. D. Papaleksi's studies in the field of parametric phenomena exerted a great influence on the development of parametric generators and amplifiers in the UHF range, whose widespread application started in the fifties, and then on the invention of a PLG in the optical range at the beginning of the sixties. We should note that, although parametric excitation of mechanical oscillations was known even in the last century (Melde's experiment, 1859), L. I. Mandel'shtam and N. D. Papaleksi first pointed out the possible employment of parametric phenomena for amplifying and generating electric oscillations. The first parametric generators of electric oscillations with mechanical variation of the inductance or capacitance in an oscillator circuit containing no sources of emf nor current were experimentally realized by L. I. Mandel'shtam and N. D. Papleksi in 1931–1933.[17-19] They also developed a detailed theory of the phenomena that can be observed when electric oscillations are excited and maintained in the oscillator circuit as the result of periodic variation of the magnitude of one of the reactive parameters of

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the circuit and at the expense of the work done by the mechanical force that varies the reactive parameter. This phenomenon is called parametric resonance, and it arises whenever the ratio of the circular frequency ω_0 of the eigenoscillations of the circuit to the circular frequency ω of the variations of the parameter becomes close to $n/2$, where $n = 1, 2, 3, \ldots$ Then undamped oscillations arise in the circuit with a frequency close to ω_0 and exactly equal to $\omega/2$, ω, $3\omega/2$, etc., for $n = 1, 2, 3, \ldots$, respectively. An important feature of this method of exciting oscillations is the existence of frequency *regions* near the values $\omega_0/\omega = n/2$ that can be excited in the circuit. Here the frequency interval of these regions broadens with increasing relative variation of the reactive parameter of the oscillator circuit.

The existence of damping in the circuit has the result that the amplitude of the variations of the reactive parameter must exceed a certain value. That is, parametric excitation is a threshold type of process. The case $n = 1$, at which the frequency of the excited electric oscillations is half that of the variation of the reactive parameter, is characterized by the lowest excitation threshold.

If the value of the losses in the circuit is fixed and the depth of modulation of the reactive parameter is small ($m \ll 1$), the excitation threshold of the parametric oscillations increases as $m^{1/n}$ (with a certain coefficient as cofactor). N. D. Papaleksi (jointly with L. I. Mandel'shtam) was able to observe experimentally not only the first resonance $n = 1$, but also the second parametric resonance $n = 2$. Here the depth of modulation of the inductance had to be increased from the value $m = 0.2$ for $n = 1$ to the value $m > 0.5$ for $n = 2$.[20]

All the features of parametric excitation of electric oscillations that are listed here and are now well known are also manifested in the UHF and in the optical ranges. Just as the external mechanical force causes a time-periodic variation in the value of one of the reactive parameters (inductance or capacitance) that determine the eigenfrequency of oscillations in the circuit, in a nonlinear crystal the intense electromagnetic pump field gives rise to a space-periodic variation of the value of the dielectric permittivity $\varepsilon(\omega, \mathbf{r})$.

The principle of action of a PLG consists of the following (see, e.g., Ref. 7). In an optically transparent medium having a quadratic nonlinearity, the polarization has the form

$$\mathbf{P} = \varkappa \mathbf{E} + \hat{\chi}\mathbf{E}\mathbf{E}. \quad (1)$$

Here $\varkappa$ is the linear and $\hat{\chi}$ the nonlinear susceptibility of the lowest order differing from zero in media lacking an inversion center.

The energy of a high-power light wave of frequency ω_p acting on such a medium gives rise to a spatial modulation of its dielectric permittivity according to the running-wave law

$$\varepsilon(\omega, \mathbf{r}) = \varepsilon_0 \{1 + m(\omega_p)[\exp(i\omega_p t - \mathbf{k}_p \mathbf{r}) + \text{c.c.}]\}. \quad (2)$$

Here the modulation coefficient is $m = 4\pi\chi A_p/\varepsilon_0 \approx 10^{-5}-10^{-6}$, where A_p is the amplitude of the pump wave.

Let us consider two weak waves of frequencies ω_1 and ω_2, which satisfy the relationship

$$\omega_1 + \omega_2 = \omega_p. \quad (3)$$

They do not propagate independently in the nonstationary medium having a variable dielectric permittivity, but interact with one another, since the superposition principle is no longer satisfied. In fact, for the field

$$\mathbf{E}_1 = \mathbf{A}_1 \exp[i(\omega_1 t - \mathbf{k}_1 \mathbf{r})] + \text{c.c.} \quad (4)$$

the displacement at the frequency ω_1 has the form

$$\mathbf{D}(\omega_1) = \varepsilon_0 \mathbf{E}_1 + \varepsilon_0 m \mathbf{A}_2^* \exp\{i[\omega_1 t - (\mathbf{k}_p - \mathbf{k}_2)\mathbf{r}]\}. \quad (5)$$

The displacement at the frequency ω_2 has an analogous form. The interaction between the waves upon passing through the medium will be maximal when the spatial periods of the first and second terms in (5) are equal. This implies the so-called phase synchronization condition

$$\mathbf{k}_p = \mathbf{k}_1 + \mathbf{k}_2. \quad (6)$$

If the conditions (3) and (6) are satisfied, then the nonstationary medium performs positive work on the waves of frequencies ω_1 and ω_2, whose amplitudes increase as they pass through this medium.

The given process is analogous to that of the increase in parametrically excited oscillations in a two-circuit parametric UHF generator with a nonlinear capacitance,[21] that varies according to the law $C = C_0(1 + m\cos\omega_p t)$.

Often one of the waves, e.g., that at the frequency ω_1, is called the signal wave, and the other the idler wave. The source of this terminology is associated with parametric double-circuit UHF amplifiers.[22]

Whenever the amplitude A_p of the pump wave exceeds a certain value (the threshold value), the positive work done by the nonstationary medium exceeds the dissipative losses at the frequencies ω_1 and ω_2, and the medium becomes amplifying at these frequencies. When such an amplifying medium is placed in an open resonator having the Q-factors Q_1 and Q_2 at the frequencies ω_1 and ω_2, one can obtain generation when the condition of self-excitation is satisfied. For small amplifications, the latter has the form[7]

$$\frac{m}{2} > \frac{1}{\sqrt{Q_1 Q_2}}.$$

Upon writing in place of m its expression for the dielectric permittivity, we get[23]

$$\frac{\varepsilon_n}{\varepsilon_0} > \frac{1}{\sqrt{Q_1 Q_2}}.$$

This is analogous to the condition for self-excitation of a double-circuit parametric UHF generator having the nonlinear capacitance C_n:

$$\frac{C_n}{\sqrt{C_1 C_2}} > \frac{1}{\sqrt{Q_1 Q_2}}.$$

Generally we can take the frequencies of the two waves ω_1 and ω_2 to have any values within the confines of the relationship $\omega_1 + \omega_2 = \omega_p$, and this is the basis of the frequency tuning of a PLG. The restrictions on ω_1 and ω_2 involve the fulfillment of the condition (6) of phase synchronization, and generation in a PLG is possible only when both conditions (3) and (6) are satisfied. The case of equal "parametric" frequencies $\omega_1 = \omega_2 = \omega_n/2$ is called the degenerate case and is analogous to the case of the first parametric resonance $n = 1$ in electrotechnology that was observed by N. D. Papaleksi as early as 1931,[17-19] and which is of great practical significance. We note that, in view of the smallness of the modulation coefficient $m = 4\pi\chi A_p/e_0$ in optics (which involves the smallness of $\hat{\chi}$), here also the first parametric resonance is of practical significance.

Parametric light generators proved to be the first frequency- (wavelength-) tunable sources of coherent radiation. However, tunable dye lasers, high-pressure gas lasers, and injection semiconductor lasers soon appeared. At present this list has been supplemented with tunable lasers based on dimers and on various types of F-centers.

Nevertheless the PLGs continue to be an important variety of tunable lasers, which retain their advantages for a number of problems.

In the visible and the near infrared range, PLGs are inferior to tunable dye and F-center lasers, owing to the relatively simple design of the latter. The advantages of PLGs over dye and F-center lasers are manifested in the infrared range whenever one must have a wide tuning range with a high output power and a relatively narrow generation line, which can be reduced to 0.001 cm^{-1}.

The further prospects of development of PLGs are closely associated with development of new nonlinear crystals and with improvement of the existing ones, and also with construction and improvement of lasers for pumping the PLG.

An example of a PLG in the infrared range is the CdSe-crystal PLG, which is distinguished by a very-long-wavelength tuning region (as far as 16.4 μm[31]). At the time of appearance of the first publications on the CdSe PLG,[25-27] the spectral range covered by other PLGs did not extend beyond 3.7 μm. However, for physical studies such as laser photochemistry, molecular spectroscopy, and atmosphere probing, the yet unconquered 3–16 μm range was of great interest. The broad-band semiconductor crystal CdSe was chosen as the active material for PLGs in order to advance into this spectral range. This choice was dictated by the fact that the uniaxial positive crystal ($n_e > n_0$) CdSe is noncentrosymmetric (point group symmetry 6mm); it has a broad transparency range (0.75–20 μm) with a low coefficient of absorption ($\sim 10^{-2}$ cm^{-1}), a large value of the quadratic nonlinearity [$d_{31}(= (1/2)\hat{\chi}) = 1.9 \times 10^{-11}$ m/V], and a rather high threshold power for optical breakdown (40 MW/cm^2). The CdSe crystal exhibits a singular type of parametric interaction of light waves $o - eo(\mathbf{k}_p^o = \mathbf{k}_1^e + \mathbf{k}_2^o)$. Here the effective nonlinear coefficient that determines the value of the parametric amplification is $d_{eff} = d_{31} \sin\theta$, where θ is the angle between the wave vector $\mathbf{k}_p^o$ of the pump radiation and the C_6 optic axis of the CdSe crystal. The dispersion properties of the refractive index of the CdSe crystal are such that it possesses a 90-degree synchronization. Here the maximal range of tuning of parametric frequencies (wavelengths) is reached upon pumping with radiation with a wavelength of 2.5–3 μm.

In the experiments of Refs. 25 and 27 a single-resonator PLG system (SPLG) with a resonance in the short-wavelength parametric branch was used. In spite of its higher generation threshold, the SPLG is favored over the double-resonator PLG (DPLG) because of its lack of so-called "cluster" structure of the spectrum, which rules out a truly smooth tuning of the frequency of the DPLG. The pump source was a dysprosium laser ($\lambda_p = 2.36$ μm, $T = 77.4$ K), which generated giant pulses of 100-W power in the TEM_{00} mode with a duration of 60 ns and a repetition frequency of 1 Hz.

The resonator of the CdSe SPLG of length 4 cm was formed using one plane mirror and one spherical mirror of radius of curvature 300 cm. The coefficient of reflection for the radiation of the short-wavelength parametric branch amounted to 97%. The transmission coefficient of the mirrors of the SPLG resonator in the range 6–16 μm amounted to 85%. The length of the CdSe crystal was 3 cm. Under these conditions the threshold pump power proved to be ~ 2.5 MW/cm^2. This is considerably smaller than the threshold power for breakdown. In the 90° orientation of the CdSe crystal ($\theta = 90°$), with the generation threshold exceeded by a factor of four, 15% of the pump energy was converted into parametric radiation of 7.88 μm wavelength. Upon angular tuning of the frequency of the PLG, the efficiency declines with decreasing angle θ, owing to the decrease in the effective nonlinearity $d_{eff} = d_{31} \sin\theta$, so that at $\theta = 65°$ the energy conversion for the long-wavelength parametric branch amounted to $\sim 4\%$. The maximal power conversion, which was recorded by observing the "consumption" of the pump pulse on passing through the CdSe crystal, was as much as 60%. The cited PLG parameters pertain to a regime of operation of the dysprosium pump laser with a repetition frequency of 1 Hz. At a frequency of pulse repetition of 300 Hz, the

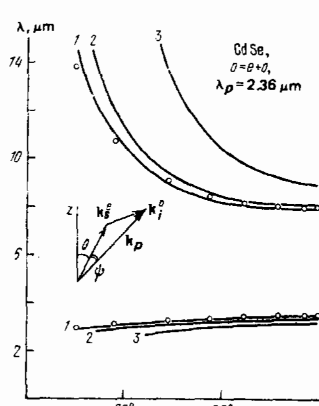

FIG. 1. Tuning curve for the CdSe crystal when pumped with a dysprosium laser ($\lambda_p = 2.36$ μm). 1—collinear interaction ($\psi = 0$); 2, 3—noncollinear interaction ($\psi = 0.5°$ and 1°); $\mathbf{k}_p$, $\mathbf{k}_s^e$ and $\mathbf{k}_i^o$ are the wave vectors of the pump, signal, and idler waves; θ is the angle between $\mathbf{k}_s^e$ and the axis of the crystal; ψ is the angle between $\mathbf{k}_p$ and $\mathbf{k}_s^e$.

mean power of parametric generation amounted to 15 mW at a mean pump power of 500 mW.[30]

Angular tuning in a CdSe SPLG pumped with a dysprosium laser (see Fig. 1) enables one to cover the spectral regions 3.36–2.8 μm (short-wave branch) and 7.88–13.7 μm (long-wave branch) as the angle θ is decreased from 90° to 65°.[27] The spectral region 3.36–7.88 μm remains uncovered because the phase synchronization condition (6) is not fulfilled there. Thus, the CdSe PLG has proved to be the only PLG among those existing now[24] in which a degenerate parametric-generation regime is impossible ($\lambda_1 = \lambda_2 = 2\lambda_p$).

The line width of the CdSe SPLG measured with a scanning Fabry-Perot interferometer did not exceed 1.5 cm^{-1}. Here there were no selective devices inside the resonator of the PLG. Application of such devices enables one to narrow substantially the generation line of a PLG.[32,33]

Some subsequent studies have obtained parametric generation in CdSe by using an HF-laser[28,31] and a laser based on $CaF_2 : Er^{3+}$ crystals[29] to pump the PLG. In contrast to the dysprosium laser, these lasers operate at room temperature. Recently the oscillation laboratory of the Institute of Physics of the Academy of Sciences has developed a new laser based on crystals of yttrium erbium aluminum garnet ($\lambda = 2.94$ μm), which operates at room temperature,[34,35] and which at present is apparently the most suitable pump source for CdSe PLGs.

As an example illustrating the application of a CdSe PLG, we can point to the paper by Rockwood[36] at the Laser Spectroscopy Conference, which was devoted to separation of uranium isotopes.

We should note that the CdSe PLG makes it possible to cover the "window" of transparency of the atmosphere at 8–13 μm, and can serve as the light source in the differential-absorption method for monitoring atmospheric pollution.

The attempt made in this paper to draw parallels and to trace analogies in the processes being described has aimed to show the many common features of phenomena so outwardly different as the generation of electric oscillations in the parametric generators invented a half century ago by Nikolaĭ Dmitrievich Papaleksi and the smooth variation of the wavelength of light in parametric light generators.

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