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CONSTRUCTION FEATURES OF THE HIGH-PRECISION LASER RANGEFINDER LIGHT MODULATOR

The issues related to the development of a light modulator operating on the electro-optical effect of laser rangefinders by the modulation method are considered. To reduce the modulation power, it is proposed to lower the modulation frequency to 750-800 MHz, while simultaneously increasing the modulation quality to Q = 1000. The study of the phase determination error of a high-precision laser rangefinder depending on temperature showed that it is rational to construct the light modulator by radial installation of the KDP electro-optical crystal, with separated modulation and demodulation channels, while on combined resonators.

***Keywords**: Modulation power, modulator quality, longitudinal and transverse electro-optical effects, coaxial resonator.*

Introduction

The use of optical radiation for distance measurement has long been known, and the first high-precision measurements were implemented by the interference method. The development of laser technology has further enhanced the role of interference measurement method. However, interference measurements are extremely laborious, are difficult technically and organizationally and require detailed preliminary works [1]. Therefore, such measurements are still used for solving special issues. It should also be noted that the certification and operation of an interferometer is a complex technical issue.

This has led to using other methods to perform high-precision linear measurements. The modulation method has become the primary method for high-precision linear measurements and the light modulators in high-precision laser rangefinders operate on the linear electro-optical effect [2]. In this regard, the study of the specificity of modulator operation and the discovery of ways to effectively use light modulators constructed on KDP electro-optical crystal allows wider application of laser rangefinders in various fields of science and technology.

Further development of UHF (ultra-high frequency) rangefinders is related not only to the development of new measurement principles and methods, but also the improvement of different units of light rangefinders, which will allow to implement the potential opportunities of this or that method. For the construction of a high-precision light rangefinder with measurement error in the range of (0.05… 0.2) *mm*, it is necessary to solve several problems, the main of which are the choice of optical radiation modulation and phase-detection methods**.**

Main Part

After certification and testing of CD-1200 model [4] modernized on the basis of the DVCD-1200 [3] laser rangefinder, a number of questions arose, which are considered in the present paper.

Multiple measurements taken at different comparators aimed at the determination of the device phase - m_k and device constant - m_k errors, showed that for compensation rangefinder $m_\varphi = m_k = 0.07$ *mm* was obtained. It was also confirmed that to implement biphasic mode of the modulation method, the potential accuracy of the phase measurement may be $m_\varphi = 0.01…0.03$ *mm* and such device is capable of self-certification.

All this shows the possibility to build a reference rangefinder, which is necessary for studying the movements of the Earth's crust and controlling the length of national bases and comparators. It is possible to build a reference rangefinder under the following conditions:

- Reduction of modulation power, to decrease the heating of the light modulator-demodulator (modem) crystal, which causes phase emissions in frontal part of the modulated light, installation of receiver optics which not only increases the intensity of light coming from the area, but also averages the modular phase emissions.
- It is necessary to exclude the imposition of a transverse electro-optical effect (EOE) to longitudinal electro-optical effect in the electro-optical KDP crystal during the modulation-demodulation process, which is caused by the curvature of the electric field lines passing through the crystal. The longitudinal electro-optical effect takes place when the direction of light propagation coincides with the direction of the electric field, and the transverse electro-optical effect happens when their directions are perpendicular to each other.
- To maintain the optimum parameters of the dimensional resonator of light modem with a KDP crystal, the scale frequency UHF auto generator should not be combined with the light modem in the same resonator.

Consider the peculiarities of the above-mentioned conditions, focusing primarily on the reduction of modulation power, using the well-known expression [5]

$$P_m = \frac{U^2 \cdot G_m}{2} = \frac{U^2 \cdot \omega_m c_m tg\delta}{2} = \frac{U^2 \cdot \omega_m c_m}{2Q_m} \quad , \tag{1}$$

where U is the voltage applied on the crystal, Q is the modulation quality, c is the capacity, $\omega = 2\pi f$, where f is the modulation frequency.

Q_m is presented as the result of the parallel connection of an electro-optical crystal Q_{kp} and resonator Q_p

$$Q_m = \frac{Q_{kp} \cdot Q_p}{Q_{kp} + Q_p}.$$

During the calculation of the light modulator, the output data is the modulation frequency, the reduction of which leads to a significant decrease in the modulation power. At the same time, the phase determination error is conditioned by the magnitude of the modulation frequency with the following regularity: $m_\varphi = (10^{-3} \dots 10^{-4})\lambda$, according to which an increase in frequency leads to the decrease of phase determination error.

The problem solution can be provided with the application of a new biphasic modulation method, in which two signals deviated from each other by 180° are generated optically and the position of the equality of their amplitudes is recorded. That is, the record of the measurement result is implemented in the average linear area of the demodulation characteristics (the dependence of the relative intensity of light coming from the area on distance). In this case, the phase determination error - m_ϕ is significantly reduced and there is an opportunity to reduce the frequency f. At this stage, the application of the biphasic method allows to reduce the frequency from 1200 *MHz* to 800… 1000 *MHz* [6,7].

According to [3], the voltage U on the light modulator crystals in case of low powers can be provided under the conditions of high quality Q modulator.

At frequencies below 800 *MHz*, the coaxial resonator sizes are considerably larger, which reduces the quality of the light modulator. At high frequencies (1200 *MHz* and more) the resonance resistance of the modulator decreases due to losses in the electro-optical crystal and the quality is in the range of Q = 800. At 800… 1000 *MHz* frequencies the sizes of the resonator are not large and the modulator quality is within the limit of half of the KDP crystal (Q_{KDP} = 2000) quality, Q = 1000.

In a coaxial resonator, according to Fig. 1, depending on the D/d ratio, there is a certain gap size Δ where the KDP crystal is placed, in case of which the electric power lines of the TEM field reach the end of the resonator without curving. The *Δ* gap size is equal to crystal length ℓ_{kp}, and is determined from the condition of the crystal optimal length $\ell_{kp_{opt}} = \lambda_M / 5.5 n_0$.

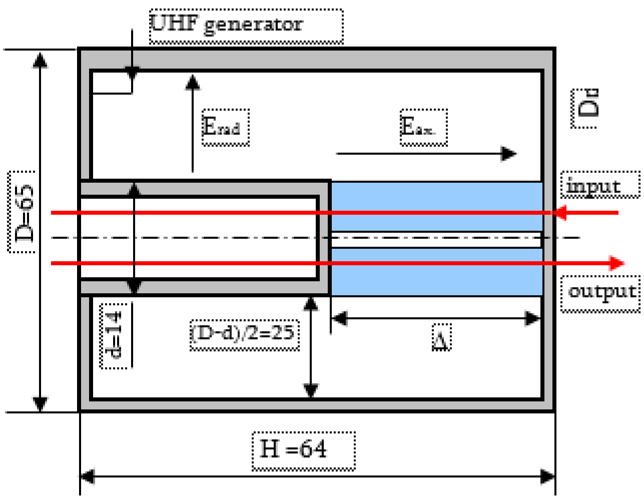

Fig. 1. *The main dimensions of the coaxial resonator*

However, the concept of the optimal length of the crystal should not be used for obtaining longitudinal electro-optical effect, but the nature of the *E* electric field power lines should be taken into account.

The *E* field power lines in *Δ* gap are closed on the resonator cylinder, as shown in Fig. 2 (the given dimensions correspond to the DVCD-1200 light modem). In this case, for a coaxial resonator, starting from the $\Delta \geq \frac{D-d}{2}$ condition, the expected decrease in length H from *λ/4* does not depend on the *Δ* gap size and the *λ/4* length of the resonator can be equal or greater than as for the modem in Fig. 2., where *λ/4*= 250 *mm* (f_m = 1200 *MHz*). In the DVCD -1200 modulator, a 35 *mm* electro-optical KDP crystal placed in a *Δ*=35 *mm* gap, which is 10 *mm* larger than the *(D-d)/2* gap.

This results in the simultaneous operation of longitudinal and transverse electro-optical effects. The presence of a longitudinal electro-optical effect leads to an increase in the thermal dependence of the light modulation phase, which causes phase emissions in the frontal part of the modulated light. This is one of the main reasons for the high value of phase determination error - m_φ= 0.25…0.3 of the DVCD -1200 rangefinder.

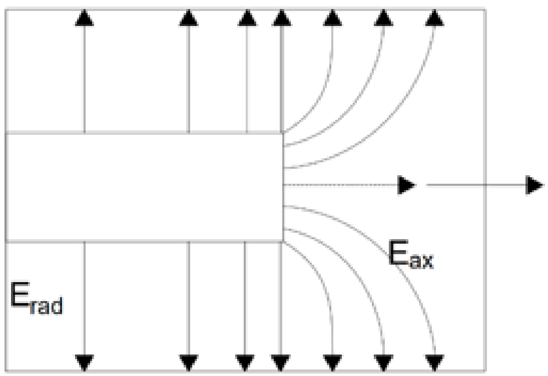

Fig. 2. *The image of E field, when Δ >(D – d) /2*

The nature of the distribution of power lines of the electric field E in a coaxial resonator is also confirmed by a photo taken by a thermal imager (Fig. 3) at the Scientific Research Institute in Kharkov (Ukraine), which shows the distribution of the thermal field in the crystal.The difference in temperature along the 35 *mm* electro-optical crystal is T_1- T_3= 6°*C*, which is the reason for the spread of the modulation phase of ± 0.25 *mm* in the cross section of the modulated light.

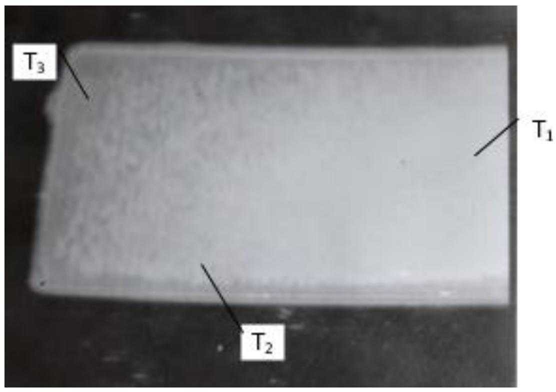

Fig. 3. *Thermal field distribution in the crystal*

This photo proves that the power lines of the Eax field do not reach the end of the resonator, i.e. the *E* field is not applied along the entire length of the crystal. In addition, *E* field is applied in both axial and radial directions. Although the calculation efficiency of the modulation is preserved, according to which the optimal length of the crystal is determined, a part of the modulation efficiency is formed by the transverse electro-optical effect, which is not desirable in phase measurements. To implement only a longitudinal electro-optical effect in the light modulator, it is necessary to place it in the resonator in the radial direction, because distortion of the power lines of E_{rad} electric field does not occur in this direction, reducing the crystal length (Fig. 2). Thus, the crystal length on the longitudinal electro-optical effect must be determined taking into account the minimum losses of the light modulator, which is primarily conditioned by the D/d ratio of the resonator for the selected modulation frequency.

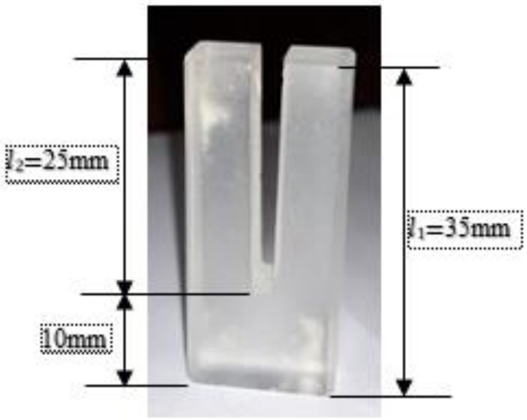

Fig. 4. *KDP crystal form*

Taking into account the fact, that less heating of the crystal reduces the phase emissions of the light received from the area to the front part, a 35 *mm* long crystal with a groove was used in the CD-1200 light rangefinder, Fig. 4 [9]. The implementation of the longitudinal groove along the crystal center allows to form receiver-transmitter channels in the crystal, at the same time maintaining the uniformity of light modulation and demodulation, by separating modulation-demodulation channels optically, as a result of which the penetration of internal reflections from the crystal output front into the analyzer exit as the laser beam passes through the crystal is completely excluded. The groove length l_2 is related to the l_1 crystal length with the following ratio $\ell_2/\ell_1 = 0.7 ... 0.8$.

Although 5… 7% modulation efficiency loss takes place in the crystal, the phase error decreases to the value m_φ = 0.07 *mm*. The study of this issue showed that the size of the coaxial resonator gap Δ should be determined according to the Δ/D curve presented in Fig. 5 [5].

For the resonator shown in Fig. 1, $D/d \approx 4.7$, or d/D = 0.215 and respectively Δ/D = 0.15 or Δ = 0.15 • 65 = 10 *mm*. In this case, the capacity of the gap, according to the curve shown in Fig. 5 will be

$$C_\Delta = FD = 0.05 \cdot 6.5 = 0.325pF.$$

Since in coaxial resonators the direction of the power lines of E_{rad} electric field does not depend on the size of the gap Δ and according to the magnitude of the voltage the radial and axial components of the electric field *E* are equal to each other - $E_{rad} = E_{ax}$, and the concentration of the power lines in the axial direction is higher, for light modulation-demodulation it is rational to place the crystals radially, because in case of the same modulation efficiency the radial crystal heats up less, i.e. it consumes less UHF power than in the case of axial installation of a KDP electro-optical crystal. If the modulation efficiencies are equal in case of axial and radial installations of the crystals during the experimental measurements, it will be possible for the high-precision rangefinder to build a light modulator with separated modulation and demodulation channels on connected resonators, which will allow to connect the transmitter-receiver optics directly to the light modem. The length of the radially installed crystal should be determined from the condition of the optimal resonator capacity, the size of which for the given gap is determined by the curves shown in Fig. 5.

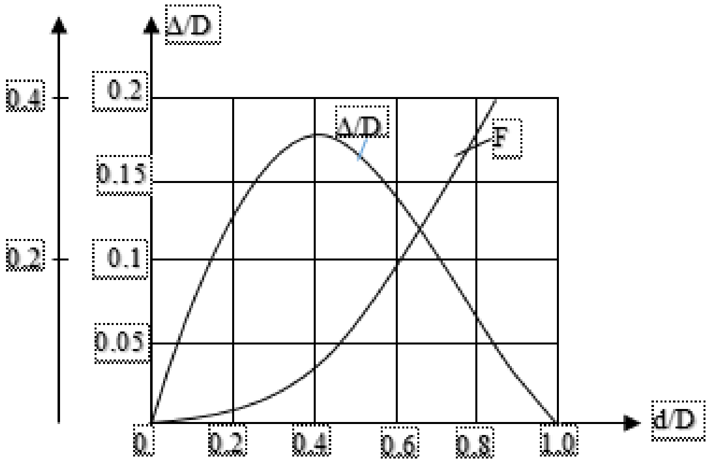

Fig. 5. *Curves for modulator calculation*

Focus on the issues of the light modulator structure. The first results of the light modulator study led to the conclusion that by dividing the resonator into 2 parts, where the gaps are proportional to the half of the crystal length $\frac{l_{kp}}{2}$, it is possible to combine 2 resonators with radially installed crystals. We will get a light modem with split channels of modulation and demodulation (Fig. 6) on the combined resonators. To excite the modulator, a large-scale UHF generator can be connected to the "aa" attachment line. The peculiarity of the two-side coaxial resonator is that the modulator can be excited in 2 modes – synchronous and antiphase. A strong electric field in the gap of the resonator allows to carry out modulation frequency addition in a significant range by introducing *V* volume dielectric. The distance D_{avr} between electro-optical crystals is D_{avr} = 30 *mm*, which is the average diameter of the receiver-transmitter optics.

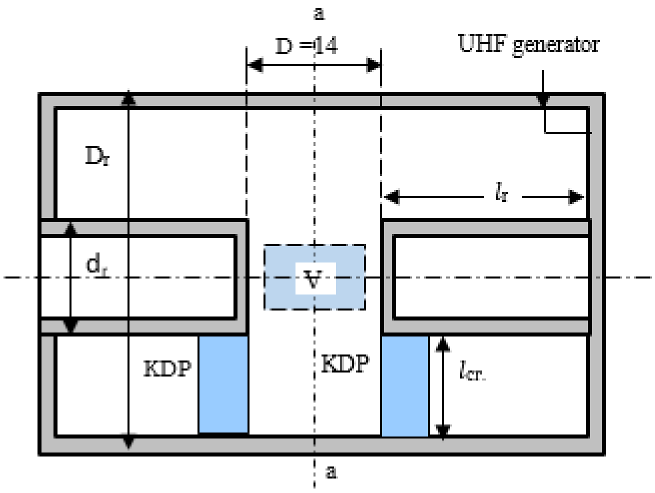

Fig. 6. *Light modem with separate light modulation-demodulation channels*

Estimate the modulation power reduction for the new modulator. For a KDP crystal when the light wavelength is λ = 0,6328μm, the half-wave voltage is $U_{\lambda/2} = \frac{\lambda}{2n_0^3 r_{63}}$ [10], where n_0 is the refractive index of the KDP crystal for a regular wave and n_0 = 1.47,r_{63} is the electro-optical coefficient, r_{63} =10.5•10^{-10}*cm/V*, which results in $U_{\lambda/2}$ = 9500*V*. According to the expression (1), the $P_{\pi\ calc.}$ calculation half-wave power for a frequency of 1200 *MHz* will be:

$$P_{\pi\ calc.} = \frac{(9500)^2 \cdot 2 \cdot 3{,}14 \cdot 12 \cdot 10^8 \cdot 0{,}95 \cdot 10^{-12}}{2 \cdot 800} = 410\ W.$$

The ratio $\frac{I}{I_0}$ of modulated and demodulated light intensities is determined experimentally in the case of P_m of certain modulation powers. Then from the equation $\frac{I}{I_0 = 0{,}5\left[1 - J_0\left(\sqrt{\frac{P_m}{P_\pi}}\right)\right]}$ the value of $P_{\pi exp.}$= 450 *W* is determined. The difference in powers $P_{\pi exp.}$ - $P_{\pi calc.}$ = 40 *W* is due to losses of stable wave coefficient.

Among the well-known solutions that reduce the light rangefinder modulation power, let us point out the biphasic mode of accurate linear measurement, where the optimal ratio U/U_π = 0.54 takes place and the modulation power at the Pm_φ1200 *MHz* frequency is $Pm_\varphi = (0.54)^2 \cdot P_{\pi ex.} = 131\ W$.

If the modulation frequency is reduced to 800 *MHz*, i.e., electro-optical crystal capacity is reduced by 1.5 times and the modulator quality is raised to Q = 1000, the magnitude of the half-wave power will be:

$$P_{\pi\ calc} = \frac{(950)^2 \cdot 2 \cdot 3{,}14 \cdot 8 \cdot 10^8 \cdot 0{,}65 \cdot 10^{-12}}{2 \cdot 1000} = 150\ W.$$

Taking into account the losses, we can assume that P_π=180 *W*. Since $P_m = P_\pi \cdot \left(\frac{U}{U_\pi}\right)^2$, in compensation mode it will be $P_m = 180 \cdot (0.61)^2 = 67\ W$. In the biphasic operation mode we will have:

$$P_m = 180 \cdot (0.54)^2 = 53\ W.$$

Conclusion

Thus, the construction scheme of a high-precision light rangefinder should be based on light modulation-demodulation in biphasic mode, and the electro-optical crystal KDP should be placed in the radial direction in the resonator excited by the TEM wave.

As a result of studies, a new type of light modulator is proposed, which will allow to create a high-precision laser rangefinder, providing a phase error of m_φ = 0.03…0.05 *mm*. If modulators with axial and radial installation of crystals have equal modulation efficiency, it is rational to build the light modem for laser rangefinder on resonators combined with separated modulation-demodulation channels, which will allow to directly connect the receiver-transmitter optics with the light modem.

In a high-precision light rangefinder, it is preferable to perform laser light modulation-demodulation on the electro-optical effect in the frequency range of 750… 800 *MHz*, increasing the modulator quality up to Q = 1000, which will allow to significantly reduce the modulation power.

The study of the temperature-dependent phase error showed that the size of the coaxial resonator *Δ* gap should be determined according to the curves shown in Fig. 5.

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