Some lecture domonstrations on the statistical properties of wave fields

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In a general physics course, the parts devoted to statistical phenomena in optics, to the influence of the coherent properties of light fields on the interference of waves, etc., are unfortunately among the most complicated and least developed from the methodological point of view. In particular, the absence of suitable lecture demonstrations makes it hard for students to get a clear idea of the structure of randomly modulated waves and of the fundamental role of the time-lag properties of the measuring device in the observation of an interference pattern. The point is that the well-known optical interference experiments[1] do not permit one, for example, to vary directly during the demonstration the scale of the time coherence, and because of the specific features of the optical range of wavelengths all observations are of necessity noninstantaneous, and there is no possibility of demonstrating the "train" nature of the oscillations of a light field.

In this connection, it would seem to be worthwhile to have demonstration experiments that simulate these phenomena in the radio range.

The basic ideas of such experiments have already been set forth by Gorclik in his monograph Oscillations and Waves[2]. Below, we briefly describe an improved setup developed in the demonstration physics laboratory of Gor'kiĭ University and possessing greater possibilities. We hope that such a demonstration setup will be of interest for physics laboratories in other post-secondary educational institutions.

In order to have the possibility of simulating interference effects over a wide range—from white to quasi-monochromatic light—it is convenient to obtain randomly modulated oscillations by transmitting a noise signal through a filter with an adjustable band.

A block diagram of the setup is shown in Fig. 1 (here, 1 is the noise generator, 2 is a synchronous filter with a tunable pass band, 3 is a phase shifter, 4 is an adder, and 5 is a linear detector with a controllable time constant).

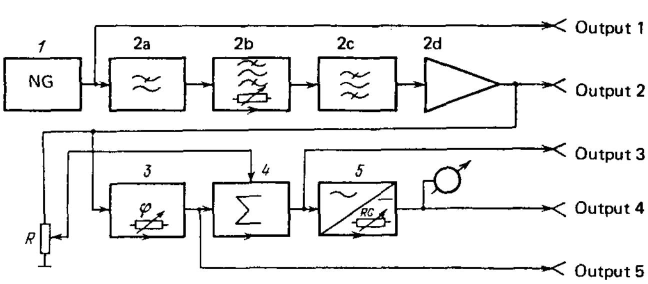

FIG. 1.

As the source of the noise signal, we have used the standard low-frequency noise generators of the type G2-1 or G2-12. If these are not available, one can readily construct simple noise generators by amplifying the shot noise in a resistor or a thyratron, or the avalanche noise of a p-n junction of a noise diode.[3]

The key element is the filter 2. In order to be able to demonstrate the effects using readily available low-frequency oscillographs with a comparatively large screen and also to make possible acoustic perception of the nature of the noise signal and the filtered signal, it is desirable to have a fairly low resonance frequency f_0 of the filter. In our case, $f_0=1$ kHz. At such frequencies, it is difficult, using resonance circuits or RC filters, to ensure a high Q factor (and, thus, good monochromaticity of the filtered signal), and therefore we used a synchronous filter. Omitting a detailed description of such a filter, the principle of which is explained in Ref. 4, we mention only that it is a comb filter, which cuts out from the signal a number of discrete frequencies by means of a special commutator with definite period. The commutator is based on microcircuits of the K115 series, and KT316B transistors are used as switches. The filter contains four sections, the variable resistor and capacitors in it being chosen to achieve a Q factor between 5 and 10^3. To cut out the higher harmonics, the additional LC filters 2a and 2c with $Q\approx 3$–5 and tuned to the same frequency $f_0=1$ kHz are inserted; the signal is then fed to the amplifier 2d, which has gain $K=100$. After the amplifier 2d, the filtered oscillation $u_1(t)$ is fed from the output 2 to the oscillograph, on the screen of which we observe a quasimonochromatic, randomly modulated oscillation, and also to the loudspeaker. In addition, the signal is sent in parallel to the input of the phase shifter 3, by means of which one can vary the amount of the delay from 0 to π. The adder 4 makes it possible to add the oscillation $u_1(t)$ from the filter output to the same oscillation $u_2(t)$ delayed in the phase shifter, and thus demonstrate the superposition of two coherent randomly modulated oscillations. The result of this superposition can be observed directly on the screen by feeding the signal from the output 3 directly to the screen input, or after the detector 5, by feeding the signal to the second input of a dual-beam oscillograph. The time constant $\tau_0=RC$ of the detector can be varied in the range from 0.1 to 20 sec.

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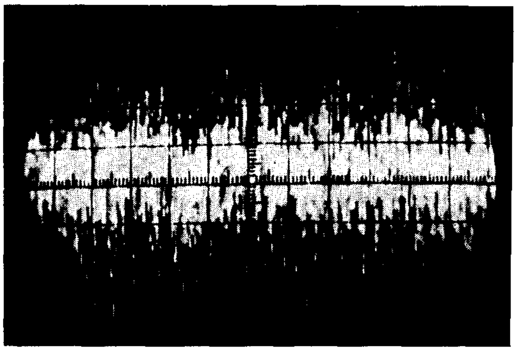

FIG. 2.

The demonstration capabilities of the setup are made clear by what we have said above. For greater clarity and ease of operation, it is desirable to use simultaneously not less than three oscillographs, one of them a dual-beam of the type SI-16 or SI-18, and the other two single-beam of the type SI-1. We do not give the detailed switching and commutation circuits since there are various possibilities. We merely emphasize that the connecting leads must be shielded.

First of all, from output 1 one can feed the noise signal that simulates white light directly onto the screen of one of the oscillographs (Fig. 2). Simultaneously one can listen to this noise by feeding it to an amplifier with loudspeaker at the output (it is convenient to use the sound input of a motion picture projector of the "Ukraina" type). From the output 2 one can also take and observe the filtered randomly modulated oscillation $u_1(t)$. Figure 3 shows oscillograms for different values of the Q factor. It can be seen that for $Q \sim 10^2 - 10^3$ the train structure of the oscillations can be easily observed: such a dependence of the coherence length (i.e., the train length) τ on the pass band of the filter illustrates to some extent the line broadening of the emission of gases depending on the temperature and pressure. Another very characteristic feature is the change in the timbre of the acoustic accompaniment when the band is changed—at small Q the sound has a noise nature, but at higher Q it becomes purer.

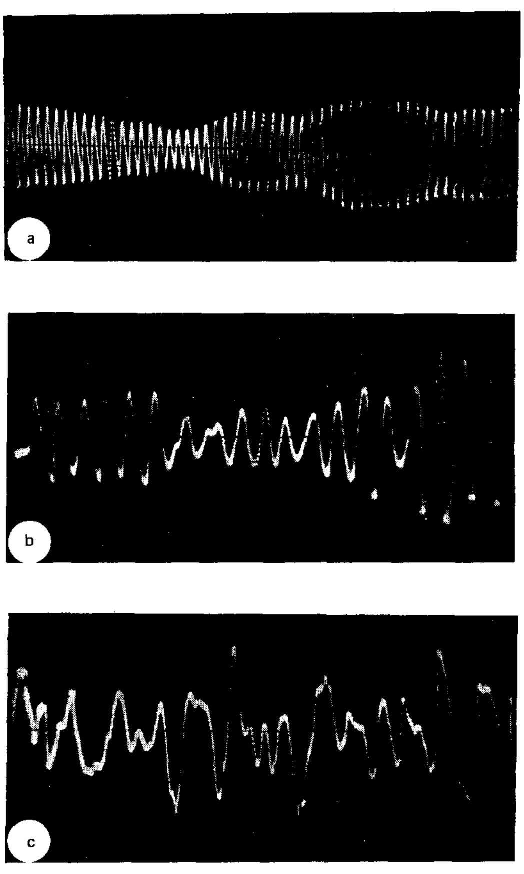

FIG. 3.

Thus, the setup makes it possible to realize different relationships between the periods of the oscillations $T=1/f_0$, the train length τ, and the time constant τ_0 of the receiving device. For example, the direct reception of the oscillogram of the instantaneous value of the intensity $u_1(t)$ on the oscillograph screen corresponds to lag-free observation ($\tau_0 \ll T \ll \tau$), which is impossible in optics. If the voltage from the output of a linear detector is fed to the oscillograph, and if the detector has a time constant $\tau_0 = 0.1-0.2$ sec and $Q \geqslant 30$, then $\tau \gg \tau_0 \gg T$, i.e., this is a fast-response method of observation: the reading of the instrument can no longer follow the instantaneous value of $u_1(t)$ but reacts to the change in the field amplitude. Figure 4a is an example of such oscillograms of the voltage $u_1(t)$ and its envelope $A_1(t)$ photographed on the screen of the dual-beam oscillograph. At higher Q, the condition $\tau_0 \gg \tau$ can also be ensured for aural perception of the oscillations: the

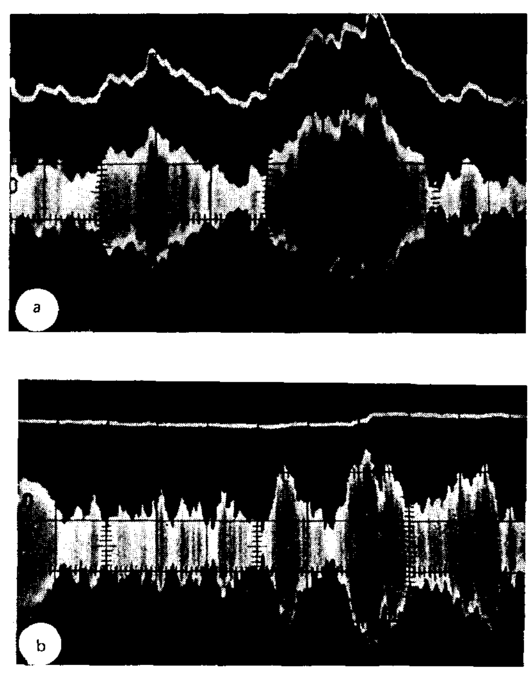

FIG. 4.

resolution time of the ear is $\tau_0 \lesssim 0.1$ sec, and for $\tau \approx 0.3$ sec one can already clearly hear beats that are in time with the oscillations of the acoustic intensity ($\sim A^2(t)$). (Note that in optics $\tau \lesssim 10^{-9}$ sec typically for natural light sources and fast-response observation is possible only if one uses sufficiently good photoelectronic converters.) But if the time constant of the detector is chosen such that $\tau_0 \gg \tau$, the voltage at the output of the detector can no longer follow even the change of the envelope (Fig. 4b); this is the case of strongly delayed observation, typical of the optical range (in visual observation, photography, etc.). Observation of the output voltage by means of a pointer-type instrument is also usually subject to time lag.

By means of the setup, one can realize scalar and vector addition of both coherent and incoherent randomly modulated oscillations. More precisely, the result of scalar addition of coherent oscillations is taken from the output of the adder and fed either directly to an oscillograph, or is taken from the output of the detector to an oscillograph and pointer-type instrument. Using the phase shifter to change the phase shift between the oscillations $u_1(t)$ and $u_2(t)$, one can show that the amplitude of the resulting oscillation takes on values ranging from the sum of the amplitudes $[A_1(t)+A_2(t)]$ to their difference $[A_1(t)-A_2(t)]$; by choosing the amplitude $A_1(t)$ by means of a potential divider R one can in the latter case achieve almost complete quenching of the oscillations.

To obtain vector addition, the filtered and the delayed oscillations are fed, respectively, to the vertical and horizontal inputs of the oscillograph. As a result, one obtains a figure (Fig. 5) that simulates in the general case an elliptically polarized wave.

Two incoherent oscillations can be obtained by taking the voltage from a second filter that is identical to the first. As in the foregoing, one can here obtain scalar and vector addition of these oscillations. In demonstrations of these experiments, it is above all appropriate to draw the attention of the students to the circumstance that the resulting oscillation has the same statistical structure as the original (component) oscillations; in particular, the same characteristic duration of the trains. Moreover, it is just this experiment that clearly demonstrates the fundamental importance of the time constant of the detecting instrument in observing interference of two independent (incoherent) waves. In the case of fast-response observation ($\tau_0 \ll \tau$) the amplitude of the resulting oscillation over a time of the order of the train length τ also varies randomly in the range $|A_1(t) \pm A_2(t)|$, i.e., interference occurs, and rapid adjustment of the phase of one of the oscillations by means of the phase shifter influences the instantaneous amplitude of the total oscillation. It is only in the case of the slow-response method of observation ($\tau_0 \gg \tau$) that the interference disappears. In this case, averaging occurs, which leads to addition of the oscillation intensities: $\overline{A^2(t)} = \overline{A_1^2(t)} + \overline{A_2^2(t)}$, and this is conveniently demonstrated quantitatively by means of a voltmeter connected to the detector output. The position of the phase shifter control no longer influences the magnitude of the signal. In the case of vector addition, one can here also note the elliptical structure of the resulting oscillation if $\tau_0 \ll \tau$; in the opposite case, even for equal mean intensities of the added oscillations one obtains the picture shown in Fig. 6, which simulates natural (unpolarized) light.

In the case of vector addition of incoherent unfiltered oscillations (noise), we observe on the screen a spot with axial symmetry without clear indication of the presence of a set of rapidly varying ellipses (Fig. 7). The result of scalar addition is a noise voltage that hardly differs from that of the added voltages.

Finally, we point out some possibilities of further

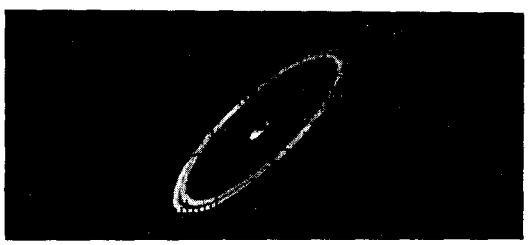

FIG. 5.

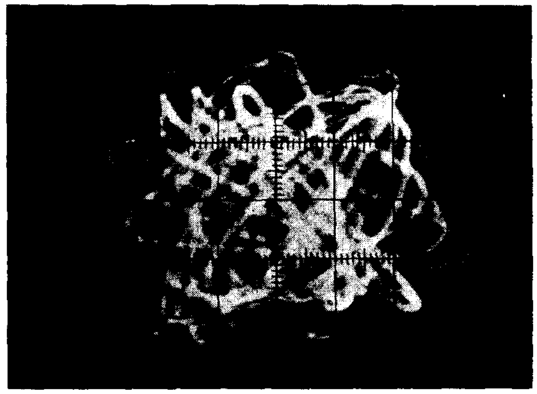

FIG. 6.

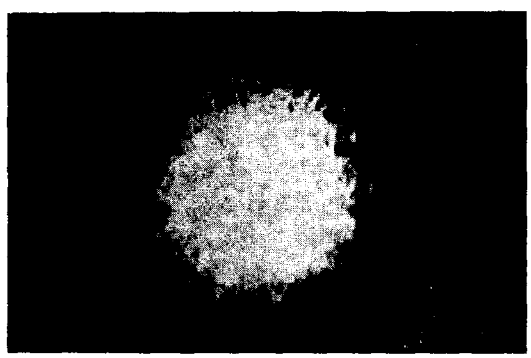

FIG. 7.

improvement of the setup. Using it, one can also observe the case of interference of partly coherent oscillations. For this, instead of the phase shifter (or in series with it) one must connect an additional delay unit that makes it possible to obtain a delay time comparable with the coherence time. Such a unit can be most readily realized by using electroacoustic conversion by means of a dynamic loudspeaker and a microphone separated from it by an adjustable distance.

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Translated by Julian B. Barbour