Lecture demonstrations on the interference of partially coherent light

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A system based on the Mach-Zender interferometer is described. It can be used for lecture demonstrations of interference between light waves with adjustable statistical parameters (degree and time of coherence). The light source is a continuously operating gas laser. Partially coherent light can be produced by modulating with one of the mirrors, using a piezoelectric barium titanate cylinder to establish the required amplitude and frequency. Another method used to vary the degree of coherence continuously from 1 to 0 relies on the introduction of a second, similar laser beam. More accurate quantitative data can be obtained by using a scanning mirror in conjunction with a photomultiplier. This transforms the intensity distribution into a "transverse" pattern on the screen of an oscilloscope. Polarization effects can also be demonstrated.

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Although there is a large number of existing lecture demonstrations of interference between light waves (see, for example, Refs. 1–4), the development of new demonstrations is still of considerable interest. This is so, first, because the systems described in the literature are usually designed for the visual observation of interference patterns on a lecture-room screen and, although they are very effective in their own way, they do not provide sufficiently precise quantitative information on the intensity distribution. Second, the statistical parameters of the radiation (for example, the coherence time τ) cannot be varied during the demonstration, so that, for example, it is not possible to give a clear illustration of the important fact that the visibility of the interference bands depends on the ratio of the coherence time τ to the time constant τ_0 of the detecting device.

In actual fact, the simplified method ordinarily employed in general physics courses neglects amplitude fluctuations,[1-3] so that the intensity of the resultant field recorded by a device receiving two waves with intensities $I_{1,2}$ is assumed to be given by

$$I=I_1+I_2+2\sqrt{I_1I_2}\,\frac{1}{\tau_0}\int\limits_t^{t+\tau_0} p\cos\Delta\varphi\,dt; \tag{1}$$

where $\Delta\varphi$ is the phase difference between the oscillations, p is a parameter that depends on the polarization of the waves (for example, if the interfering waves are linearly polarized at an angle ψ to one another, $p=\cos\psi$), and τ_0 represents the inertia of the method of observation. In optics, $\tau_0 \gg \tau$ (in the case of visual and photographic observation), and interference between independent sources is not observed. However, when the detector is very responsive ($\tau_0 < \tau$), for example, when an image converter is employed, interference can be produced even with independent sources. It is therefore interesting to consider demonstrations in which the ratio of τ_0 to τ could be varied within broad limits (as in the case of simulations of interference experiments in the radio band).[5]

Finally, it is desirable to have a system capable of producing not only the limiting cases of completely coherent (produced by beam splitters) or completely noncoherent (independent sources) waves, but also to vary continuously the degree of coherence.

In view of the foregoing, we have developed a system which, in our view, can be useful for general demonstration purposes. Its main features are as follows: (a) a special modulator which varies the optical path traversed by one of the waves, or two sources with adjustable relative intensity, are used to synthesize radiation with adjustable statistical characteristics (degree of coherence, time of coherence, and so on) and (b) more precise quantitative information on the one-dimensional intensity distribution in the interference pattern is obtained by transforming the distribution into a "transverse" form, namely, the deflection of the beam on the oscillograph screen.

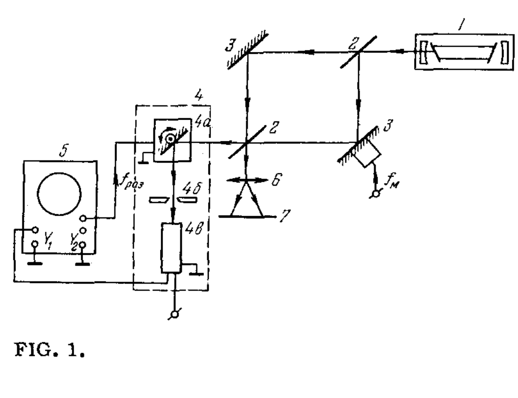

FIG. 1.

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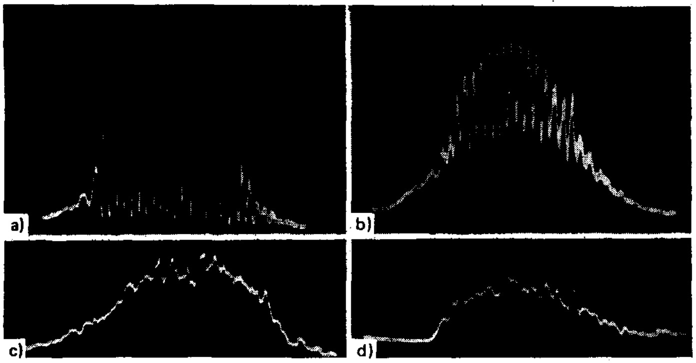

FIG. 2.

The system is based on a somewhat modernized Mach-Zender interferometer.[6] Only slight modifications are necessary to perform different series of demonstrations. One possible arrangement is shown in Fig. 1, where 1 is the source of light (LG-55 or some other continuously-operating single-mode laser), 2 are semitransparent beam splitting cubes (20×20 mm), 3 are front-coated mirrors (20 mm in diameter), 4 is the "transverse" scanning device, and 5 is the oscillograph (S1-19).

One of the advantages of the Mach-Zender interferometer is that it produces two output beams. The second beam can be used for the simultaneous (visual) observation of the interference pattern on the screen 7; the objective 6 is used to magnify the pattern.

The scanning unit 4 consists of a system which periodically sweeps the light beam leaving the interferometer across the fixed optical slit 4*b* (UF-2). This is realized in practice by using the M-320 electromagnetic head from the detection system of a multichannel pen recorder, whose frame carried the small mirror 4*a* with a low moment of inertia. The light beam is intercepted by the photomultiplier 4*c* (FE-27), whose output is displayed on the screen of the oscillograph. The oscillograph time base is synchronized with the mirror scanning process (a more detailed description of the use of this type of device in the observation of the intensity distribution in diffraction patterns is described in Ref. 7).

The averaging time τ_0 of this type of instrument is obviously determined by the slit width d and the angular velocity Ω of the scanning mirror, namely, $\tau_0 = d/l\Omega$, where l is the separation between the mirror 4*a* and the slit; in our system, we have $\Omega \leq 20\ \text{sec}^{-1}$ and $\tau_0 \geq 10^{-4}$ sec.

Before we proceed to a description of the demonstrations, we note that, when the path difference between the interferometer arms is relatively small, the two rays in Fig. 1 are practically completely coherent and the phase difference $\Delta\varphi$ in (1) is independent of time. The visibility of the interference pattern is then $V=1$. To produce (simulate) partial coherence, we produce an artificial change in $\Delta\varphi$ in time by displacing one of the front-coated mirrors with the aid of a piezoceramic cylinder (made from barium titanate), to which a low-frequency voltage from a generator (G3-33) is applied. The effective coherence time τ is, of course, determined by the period T of the modulating voltage, whereas the visibility of the pattern depends on the phase modulation ($\Delta\varphi_M$) and the relationship between τ_0 and T. The simplest situation is that where V is a linear function (more precisely, a sawtooth function) of the form $\Delta\varphi_{(t)} = \Delta\varphi_0 + \alpha t$, where $\alpha = \Delta\varphi_M/t$. To be specific, we suppose that the sweep begins with $t=0$, so that the integral in (1) is

$$\frac{1}{\tau_0}\int_0^{\tau_0} \cos\Delta\varphi\, dt = \frac{\sin(\alpha\tau_0/2)}{\alpha\tau_0/2}\cos\left(\Delta\varphi_0 + \frac{\alpha\tau_0}{2}\right).$$

The visibility of the interference pattern that "appears" as a result of the variation in $\Delta\varphi_{0(t)}$ in the course of scanning with the mirror 4*a* is now $V = \sin(\alpha\tau_0/2)/\alpha\tau_0/2$ and, when $\alpha\tau_0 \ll \pi$, we have $V \to 1$; when $\alpha\tau_0 > 2\pi$, the visibility V tends to zero. In particular, when $\Delta\varphi_M \approx 2\pi$, the interference term in (1) becomes practically zero beginning with $\tau_0 \gtrsim T$. It is readily seen that the qualitatively similar results are obtained for other ways of modulating $\Delta\varphi_{(t)}$, including the sinusoidal modulation ($\Delta\varphi_{(t)} = \Delta\varphi_0 + \Delta\varphi_M \times \cos 2\pi f_M t$). The latter is the simplest to achieve in practice (and was, in fact, used in our demonstrations).

As an example, Fig. 2 shows the oscillograms, photographed from the oscillograph screen, for a few values of f_M (fixed τ_0 and $\Delta\varphi_M \approx 2$; $p=1$, $I_1 = I_2$); (a) $f_M = 0$, so that $V \approx 1$; (b) $f_M = 15$ kHz; (c) $f_M = 20$ kHz; here $V \to 0$ and the interference bands vanish almost completely. We note that the small intensity spikes that can be seen in Fig. 2c against the Gaussian background are due to irregularities in the laser beams themselves and are present even when a single beam is recorded (Fig. 2d).

Similar interference patterns are obtained for fixed frequency f_M by varying the amplitude of the oscillations of the mirror and, correspondingly, the modulus of $\Delta\varphi$ and the degree of coherence of the rays; in our experiments, the values of $\Delta\varphi_M$ approached 4π.[1)]

[1)]We note that, in principle, the deterioration in the visibility of the interference pattern due to the oscillations of the mirror can also be interpreted as the Doppler effect associated with reflection by a moving mirror. However, under our conditions, the Doppler shift was much smaller than the laser linewidth, so that the above quasistatic treatment in

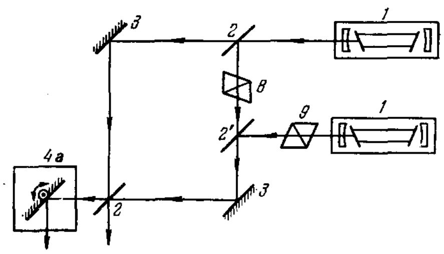

FIG. 3.

In the other method of producing partially coherent waves, a semitransparent plate 2′ is used to introduce radiation from a second laser, identical with the first, into one of the interferometer arms (Fig. 3). The attenuators 8 and 9 are used to ensure that the intensity I_2 in the lower arm is held equal to I_1. It is well known (see, for example, Ref. 2) that the degree of coherence (and, correspondingly, the visibility of the interference pattern) is then simply equal to the ratio I_2'/I_1', where I_2' corresponds to the intensity arriving from the second laser.

The attenuators were in the form of closely spaced dichroic polaroids (depolarization coefficient ~0.01); the intensity transmitted by these polaroids was varied by rotating one of them, whilst the other (more distant along the beam) defined the initial direction of polarization. The detection system was the same as before and is not shown in the figure. The coherence time τ was determined by the laser linewidth and was of the order of 10^{-7} sec, so that slow-response detection was, in fact, used ($\tau_0 > \tau$). As a result, so long as only the first (upper) source is operating, we have complete coherence between the interference beams and the interference pattern is the same as in Fig. 2a. However, as the fraction of power introduced by the second laser is increased, the degree of coherence decreases continuously and patterns similar to those shown in Figs. 2b and 2c are obtained.

In the above experiments, the polarization parameter p in (1) was taken to be unity. By introducing the quarterwave plate and a polarizer (in the form of a polaroid film) into one of the interferometer arms, we can illustrate the dependence of the interference pattern on the angle between the planes of polarization. When $I_1 = I_2$ (an attenuator introduced into the other arm), we again obtain oscillograms similar to those shown in Fig. 2a ($\psi = 0$), Fig. 2b ($\psi \approx \pi/4$) of Fig. 2c ($\psi = \pi/2$). In the last case, it is instructive to show, in addition, that, if a further polaroid is introduced into the path of the beam leaving the interferometer, the interference pattern appears again. Maximum visibility is obtained when the additional polarizer is at 45° to the plane of polarization of the two beams. This illustrates the fact that the concepts of coherence can be extended to the case of fields that are orthogonal in space.

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which the observed effect is interpreted as being due to the phase-difference modulation $\Delta\varphi_{(t)}$ is more satisfactory (see, for example, Ref. 8).

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Translated by S. Chomet