Mexican Physical Society
Invited talk given at
Puebla, MEXICO during
the celebration of
Einstein centenary, 1979.

INTERFERENCE AND REALITY

Chandrasekhar Roychoudhuri

TRW
DEFENSE AND SPACE SYSTEMS GROUP
One Space Park
Redondo Beach, California 90278

ABSTRACT

Analogy of classical optical microscope and double-slit (two beam) interference patterns are routinely used to "explain" the concept behind quantum mechanics. We show that these analogies are mostly misleading and some of the interpretations contradict classical observations. Interference is causal and local in classical optics. This leads to the speculation that a better model for classical interference and diffraction phenomena as well as for "single particles" should be developed before a complete understanding of particle interference can be achieved.

INTRODUCTION

The spirit of this talk on Einstein's centenary derives from his lifelong pursuit of reality of this universe independent of the existence of observers like homosapiens. "The belief in an external world independent of the percipient subject is the foundation of all science. But sense perception informs us only indirectly of this external world, of Physical Reality. It is only by speculation that it can become comprehensible."[1] Such conviction of Einstein led him to consistently interpret that Quantum Mechanics (QM) does not represent complete reality of an individual particle,[2-3] and correspondingly, to his lifelong disagreement with the founders of QM. The subject of interpretation of QM has been riddled with questions since the very birth of the theory which, in itself, is unique compared to all other theories of physical sciences. Although everybody agrees on the towering success of quantum formalism within its bounds, there is still no single agreed upon interpretation after more than half a century of the inception of the theory. The various interpreters, however, can be loosely grouped into two: the Copenhagen School and the Statistical School,[4-10] and both the schools use a few classical optical experiments as analogies or to clarify their side of quantum interpretation. The purpose of this talk is to revisit these experiments from a purely classical point of view and show that the analogies were unfortunately more misleading than clarifying the "muddle" of quantum interpretation. Surprisingly, some of these quantum interpretations contradict classical observations even though the analogy started with classical experiments. However, this talk does not claim to demystify various quantum interpretations or offer a coherent alternative, neither is it an attempt to derive alternative theories as various people have been attempting with partial success.[11-14] The main point of the talk is to emphasize the possibility of further exploration from the platform of classical interference and diffraction experiments if we approach them with simple but "speculative" minds.

In the following two sections we first consider the microscope imaging and the far-field single slit pattern that are used to illustrate Heisenberg's uncertainty theorem, then we consider the double slit interference experiment, its various equivalents and modifications to illustrate that some of the interpretations contradict classical experimental observations. None of the experiments we discuss are "gedanken" type; they are routinely carried out in optics laboratories in some form or other. Most of these experiments can also be carried out with particle beams. The reason for not using any "gedanken" experiment is as follows. The truth or falsity of a "gedanken" experiment can be proved only on the basis of existing theories. If we are questioning the completeness of these very theories, unperformed "gedanken" experiments certainly can not take us beyond them.

HEISENBERG'S MICROSCOPE AND SINGLE SLIT DIFFRACTION PATTERN

To interpret Heisenberg's uncertainty theorem, starting with Heisenberg himself,[15] everybody brings in the analogy of classical image formation by a microscope and the far-field single-slit diffraction pattern (Figure 1). From the standpoint of classical diffraction theory (based essentially on Huygen's-Fresnel principle) or diffraction theory of image formation, the above two experiments are identical and there is nothing uncertain about the pattern they form. The image of a point source formed by a microscope or the far-field diffraction pattern formed by a slit is uniquely given by the Fourier transform of the wavefront limiting aperture-function of the system: the aperture of the objective for the microscope and the slit opening for the other. In one dimension the decaying but oscillatory pattern is given by $\sin x/x$ with the first zero at $\lambda/\sin\varepsilon$ where ε is the angle subtended by the objective or the slit. It is true that Rayleigh and other people defined, as a "rule-of-thumb," that the resolution is limited by the width of the strong central lobe. But as far as classical theory is concerned, there is no limit of resolution. If the impulse response[16] (Fourier transform of the limiting aperture) is known, one can always deconvolve (use analytic continuation when necessary) it from the image degraded by diffraction spreading. If the diffraction spreading is to be considered as the cause of uncertainty in the position and momentum, then theoretically it (uncertainty) should be divergent because the diffraction spread extends indefinitely (some 3000 fringes due to a single slit have been measured experimentally[17]). In fact, such is the finding of Beck and Nussenzveig[16] when they used for Δx and Δp the root-mean-square deviation instead of the width of the central peak. So, in our view it is a misleading attempt to "explain" the quantum mechanical indeterminacy relation by using classical diffraction pattern.[18]

DOUBLE-SLIT AND TWO BEAM INTERFERENCE PATTERN

The next optical experiment that is extensively used to "explain" quantum concept is the double-slit interference or the equivalent Michelson's two-beam interference effect (Figures 2-5). It is generally assumed today that even if a single particle is sent at a time through such systems, the two-beam cosine fringes will appear when the total number of particles sent is very large. We shall not deal with the question of single particle interference here. But it is worth noting its logical implications -- self-interference. A particle can make itself interactable (with detector atoms) or not or redirect itself in a generalized curved path with an a priori knowledge of the alternative paths of propagation produced by slits or mirrors or their equivalents at distinctly different space time points. This may lead to questions like whether the phenomenon of interference (principle of superposition) involve instantaneous action at a distance. Extensive list of references on arguments and counter arguments can be found from Jammer,[7] Bastin,[8] Bunge,[9] d'Espagnat.[10] But let us concentrate on a few specific points accepted by both the schools of interpretations.

First, it is generally accepted that no particle arrives at the dark point of the fringes, as if the phenomena of diffraction and interference are actually quantum mechanical scattering processes (what is the force of interaction?). The question of scattering in interference can be eliminated by shifting to various alternative arrangements of this experiment. For example, replacing the double-slit system by a Michelson interferometer or illuminating the double-slit with two narrow laser beams produced by a tilted Fabry-Perot (Figures 4-5) and, hence, finally eliminating the need to use two slits. As a matter of fact, a multiple-slit grating effect can be simulated at the focus of the lens without using a grating at all.[19] Regarding nonarrival of the particle at the dark points of fringes we make the following observations. If one follows Figure 2c beyond the double slit, one would find both the laser beams are maintaining their uniform gaussian amplitude characteristics in every region. At the region of real physical superposition of the two beams, detectors, like photographic plates, would show bright and dark fringes. Beyond the region of superposition, the two beams maintain their original gaussian characteristics as if no interaction has taken place. It is logical to assume that the photons did not change their course in the region of superposition to disappear from the dark fringes. (Simulation of these experiments with particle beams of non-zero rest mass would show modified beam distribution after the region of interaction because of scattering due to weak, electromagnetic or strong interactions relevant for the particles besides regular interference.) Classically, there is no conflict to assume that the superposition of two equal field quantities in opposite phase at a space time point make themselves undetectable to systems that require absorption of energy for interaction. The conceptual difficulty in accepting that no particles arrive at the dark regions becomes even more accute when one considers the interference of two coaxial beams propagating in exactly opposite directions. With light beams and high resolution photographic plates one can record three dimensional parallel layers of bright and dark fringes. Certainly, the photons had to cross the dark fringes without being detected.

The second generally accepted point is that any attempt to determine which slit the particle has passed through would destroy the very interference. This is not true, at least in classical experiments, as long as the attempt to identify a specific beam has introduced an accountable steady (in contrast to irregular) exchange of momentum and energy. Consider the modified double-slit experiment of Figure 6 using an incident light beam of frequency ν_1. An acousto-optic modulator is placed behind one slit which causes the light passing through it to change its frequency to ν_2 by Doppler effect (due to reflection from propagating acoustic waves). At the regular observation plane is a pinhole to select a point on any one of the bright fringes. The light through the pinhole passes through a Fabry-Perot spectrometer that helps separate the different frequencies in space detected by separate detectors. Without the modulator working, the interference fringes are stationary in the X-plane and all the light after the Fabry-Perot is detected by channel 1 (Figure 6). With the modulator working, the interference fringes are the same cosine type at the X-plane but are moving laterally. This can be observed at low modulator frequency and verified at high modulator frequency by using an array of detectors placed with a spacing of the stationary fringes; when one set of alternate detectors detects light, the other alternate set does not. But this time the light passing through the Fabry-Perot is detected by both the channels 1 and 2. The light detected by channel 2 of frequency ν_2 has to come through slit 2 and similarly for channel 1. Interference is not destroyed by tracking one of the interfering beams. Moving one of the mirrors of the Michelson interferometer (Figure 5) or of the tilted Fabry-Perot (Figure 4) will be equivalent to adding the modulator because of Doppler shift produced by the moving mirror. Similar experiments to track one of the beams can also be carried out with monoenergetic particles with the modulator replaced by a local velocity changer and the spectrometer by velocity selector.

Another outcome of the explanation of the quantum concept is that interference is not a local phenomenon. In fact, d'Espagnat[20] explicitly says, ". . . the local effect of these waves is certainly not a correct hypothesis" (see also consequences of Bell's theorem[21]). But observation in classical optics is precisely the opposite, the phenomenon of interference is essentially local. The effect of superposition is observable only when, in time and space, more than one wave carrying different information like amplitude, phase and frequency, are superposed in the real physical sense. The observable effects of superposition can be confined into a small region or extend indefinitely depending purely on the characteristics of the interfering waves generated in a particular experiment. Recall the experiment of Figure 2c, where the fringes are visible only in the region of superposition (crossing) of the two beams. Consider a different experiment along the same spirit. A spatially confined collimated beam can illuminate only a part of an N-slit grating, say, covering only two slits. The generated pattern is of two-slit type rather than N-slit type because the incident light beam has been modified into two diffracted beams only. In this context Lande's[22] argument that the grating knows its spatial periodicity in space and acts in unison to exchange a series of quantized momenta (Duane's rule[23]) with the particle is very hard to accept. Examples of experiments where the effect of interference extends indefinitely are more numerous. The grating considered above, whether two or all of its slits are covered by the illuminating beam, the effect evolves in space (also in time for an incident short pulse) from near-field Fresnel pattern to far-field Fraunhofer pattern as each of the component interfering waves evolves through its natural propagation still overlaping each other. But the effect of interference is still local and each local pattern is uniquely given by the superposition of the local component waves. Spatially evolving interference pattern due to interferometers can also be understood in the same way whether they are two-beam type (Michelson, Mach-Zehnder) or multiple-beam type (Fabry-Perot, Lumner-Gehrcke). It should be noted that in the case of gratings when the spatial frequency of the amplitude or phase modulating lines is extremely high (not very large compared to the wavelength of light), the far-field pattern can be reached within a short distance from the grating. Such is the case for particle diffraction by atomic crystals. Further, when the number of diffracting "slits" within the beam is very high, the far-field secondary minima are negligible and there appears clean and discrete (main) diffraction orders as if they were due to quantized momenta exchanged with the entire grating without any gradual evolution of the pattern.

It is important to de-mystify the effects of gratings and interferometers. It is not the inherent property of gratings and interferometers to redistribute the energy of the incident fields. In classical optics it is the property of the incident field,modified into a regular train of multiplicated beams in the presence of these instruments,to redistribute its detectable energy through superposition of the evolving multiple beams. The phenomenon of diffraction is actually a consequence of the phenomenon of interference coupled with the fact that the mathematical model we have chosen (Huygens-Fresnel principle) to represent a propagating wave as the superposition (interference) of the spherical waves produced from every point on the original wavefront. Any modification, amplitude or phase, array of slits or oscillatory index, will cause a local effect which continues to evolve from spatially varying pattern (Fresnel) in the near-field to a permanent pattern (Fraunhofer) in the far-field. Of course, whether the classical diffraction integral based on Huygens-Fresnel principle represents complete reality of wave propagation and to what extent similar representation can be used for particle beams are legitimate questions to explore.

Locality of interference and diffraction phenomena can also be explored by holographic experiments (Figure 7). With the help of an auxiliary reference beam and double-exposure holographic technique, one can record the pattern (near or far field) of each slit separately of a double-slit system by covering one at a time. Holographic record preserves the relative phase variation of wavefronts even though recorded separately. Then the reconstruction of the hologram can display the effect of double-slit pattern in every detail including its evolution from near to far field, even though one-slit pattern at a time was recorded. One can actually simulate a whole grating by using a single slit and a multiple-exposure holography; between the exposures the slit must be translated by an amount that is equal to the grating-constant of the grating one wants to simulate. In a similar way, at least conceptually, it should be possible to reconstruct an atomic crystal diffractor using a single atom. Holography with particles is feasible.[25,26]

In brief, in classical optics, all possible optical paths created by an interferometer or a grating, are actually traversed by a part of the incident wave. This locality of interference phenomena must be proved to be an illusion or untenable for single particles before discarding this concept.

SUMMARY

We have illustrated the misuse of classical optics in explaining some quantum concepts by pointing out that there is really no theoretical limit of resolution in image formation (Heisenberg's microscope). Some of the generally accepted "quantum mechanical" conclusions derived from two-beam interference experiments are: (a) no particle arrives (or passes through) at the point of dark fringes, (b) impossibility of determining which optical path the particle has followed without destroying the effect of interference and (c) apparently interference and diffraction are not local phenomena. We have shown that these specific conclusions actually contradict classical optical experiments. We have emphasized that classical interference phenomenon is causal and real in the sense that the interfering waves need to be superposed in space and in time.

Then, how does a single particle produce interference pattern? Since experimental verification of particle interference cannot be obtained without using a large number of similarly prepared particles, this is probably not a valid question to Quantum Mechanics, based essentially on statistical probability interpretation. Still, the question is a valid one. But we also do not completely understand the reality and structure of single particles as yet. Then until such time comes we can guide our pure thoughts peacefully along the lines propounded thousands of years ago by Upanishadas,

"In whom the world comes into being
In whom it thrives
In whom it becomes one again
That is to be searched for, that is Bramha".

A major part of this talk is derived from the work done by the author[18,19,27] while at INAOE, Mexico. Thanks are due to the Mexican Physical Society for organizing this centenary seminar series and for their hospitality extended to the speakers.

REFERENCES

1. See "Einstein's theory of knowledge" by V. F. Lenzen in "Albert Einstein, Philosopher-Scientist," ed. P.A. Schilpp (Cambridge U. Press, London, 1970).
2. A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47, 777 (1935).
3. L. E. Ballentine, Am. J. Phys. 40, 1763 (1972).
4. P. K. Feyerabend, Philosophy of Sc., 35, 309 (1968); 36, 82 (1969).
5. H. P. Stapp, Am. J. Phys. 40, 1098 (1972).
6. L. E. Ballentine, Rev. Mod. Phys. 42, 358 (1970).
7. M. Jammer, "The Philosophy of Quantum Mechanics" (Wiley Interscience, New York, 1974).
8. E. W. Bastin, ed., "Quantum Theory and Beyond" (Cambridge University Press, Cambridge, 1971).
9. M. Bunge, ed., "Quantum Theory and Reality" (Springer-Verlag, New York, 1967).
10. B. d'Espagnat, "Conceptual Foundations of Quantum Mechanics" (Benjamin, Menlo Park, California, 1971).
11. T. H. Boyer, Phys. Rev. D 11, 790, 809 (1975).
12. L. de la Peña and A. M. Ceto, Found. Phys. 5, 355 (1975).
13. T. E. Phipps, Found. Phys. 5, 45 (1975); 6, 71, 263 (1976).
14. M. D. Crisp and E. T. Jaynes, Phys. Rev. 179, 1253 (1969).
15. W. Heisenberg, Z. Phys. 43, 172 (1927); "The Physical Principles of Quantum Theory" (Dover, New York, 1949).
16. J. W. Goodman, "Introduction to Fourier Optics" (McGraw Hill, New York, 1968).
17. P. Langlois, M. Cornier, R. Beaulieu and M. Blanchard, J. Opt. Soc. Am. 67, 87 (1977).
18. C. Roychoudhuri, Found. Phys. 8, 845 (1978).
19. C. Roychoudhuri, Am. J. Phys. 43, 1054 (1975); Bol. Inst. Tonantzintla 1, 259 (1975) and 2, 55 (1976).
20. Ref. 10, p. 13.
21. J. F. Clauser and A. Shimony, Rep. Prog. Phys. 41, 1881 (1978).

22. A. Landé, Am. J. Phys. 43, 701 (1975); "New Foundations of Quantum Mechanics" (Cambridge U. Press, Cambridge, 1965).

23. W. Duane, Proc. Nat. Acad. Sci. (USA) 9, 153 (1923).

24. A. H. Greenway and A. M. J. Huiser, Optik 45, 295 (1976).

25. L. S. Bartell, Optik 43, 373 and 403 (1975).

26. H. A. Ferwerda, Optik 45, 411 (1976).

27. C. Roychoudhuri, J. Opt. Soc. Am. 65, 1418 (1975); Opt. Eng. 16, 173 (1977); Bol. Inst. Tonantzintla 1, 245 (1975) and 2, 101, 165, 187 (1977).

FIGURE CAPTIONS

Figure 1. Due to diffraction through a finite aperture both the position and the momentum of a particle become "uncertain" (see Ref. 15).

Figure 2. Interference due to two point sources produce three dimensional fringes in space. A cross-section through the plane containing the sources shows curved hyperbolas in the near-field which become rectilinear in the far-field.

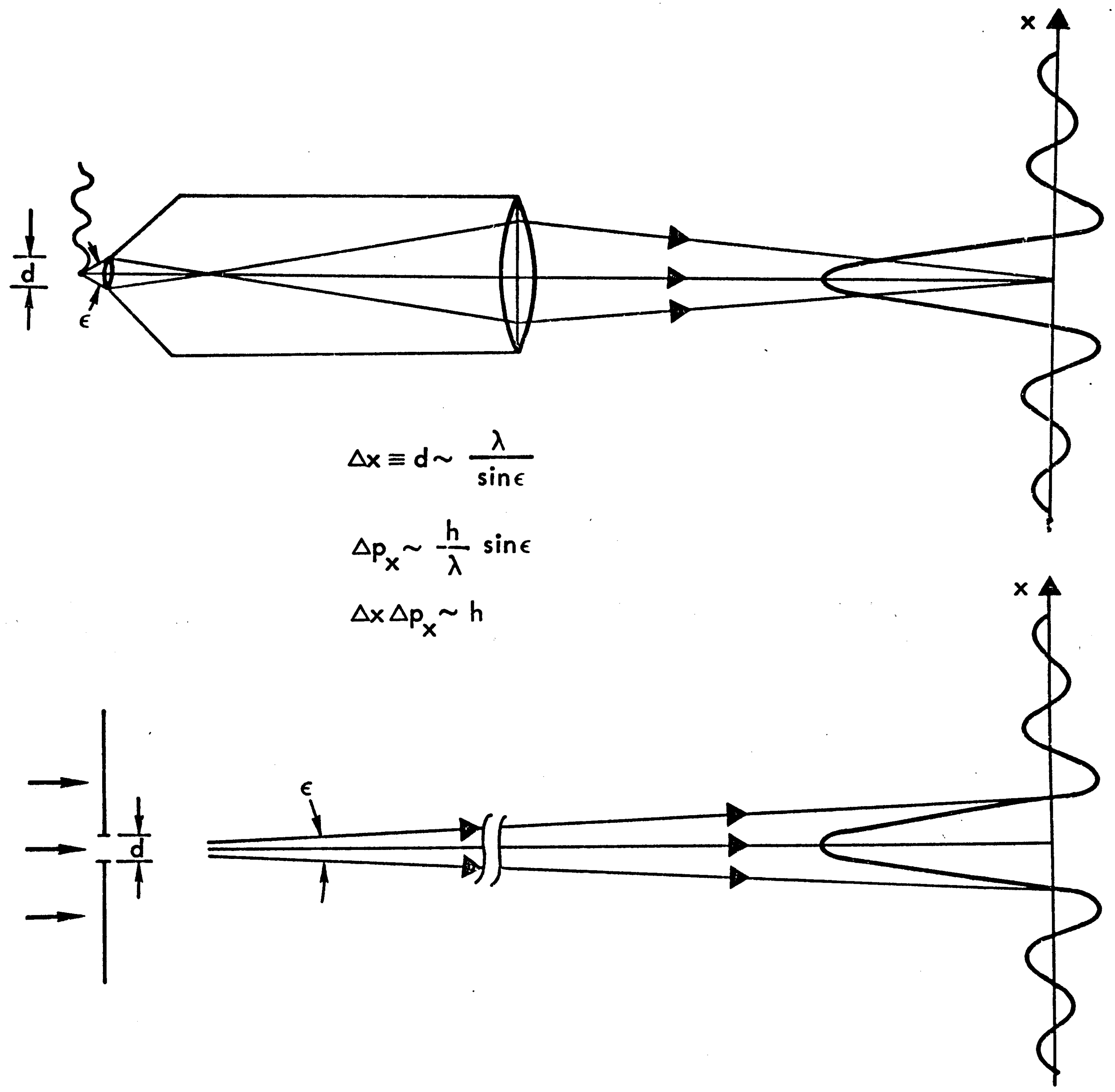
Figure 3. Classical diffraction theory indicates that each slit of a two-slit system produces its own tilted plane wavefront with a sinx/x amplitude and phase distribution. It is the relative tilt (linear phase delay) between the two wavefronts that gives rise to straight cosine fringes in the Fraunhofer plane (in this case simulated at the focal plane of the lens).

Figure 4. A narrow collimated laser beam can be multiplicated into a large number of laterally shifted beams by a pair of parallel but tilted beam-splitters. If two of the beams are allowed to pass through the two slits of Figure 3, cosine fringes are formed at the focal plane of the lens. Outside the focal region the two beams are independently identifiable, emphasizing locality of interference phenomenon.

Figure 5. Michelson's two-beam interferometer also gives cosine fringes as in Figures 3 and 4. Here the paths of the two interfering beams are more easily controllable. For example, motion of mirror M_2 with a velocity v could give Doppler shift to one beam by $\delta\nu = 2v\nu/c$ and produce beat fringes at the observer's position.

Figure 6. A Doppler shifting acousto-optic modulator placed immediately behind one slit of a two-slit system produces identical cosine fringes at the Fraunhofer plane as in Figure 3, but the effect of beat translates the fringes laterally in time. Light collected from the Fraunhofer plane, when spectrum analyzed, would show two different frequencies ν_1 and ν_2 coming through slits 1 and 2, respectively.

Figure 7. In classical optics each slit produces its own diffracted wavefront evolving in space. Each of these waves can be independently recorded and reproduced by holographic technique at any state of its evolution. A double exposure hologram reproducing both the beams simultaneously will show the evolution of two-slit pattern.



$$\Delta x \equiv d \sim \frac{\lambda}{\sin\epsilon}$$

$$\Delta p_x \sim \frac{h}{\lambda}\sin\epsilon$$

$$\Delta x\, \Delta p_x \sim h$$

FIG.1

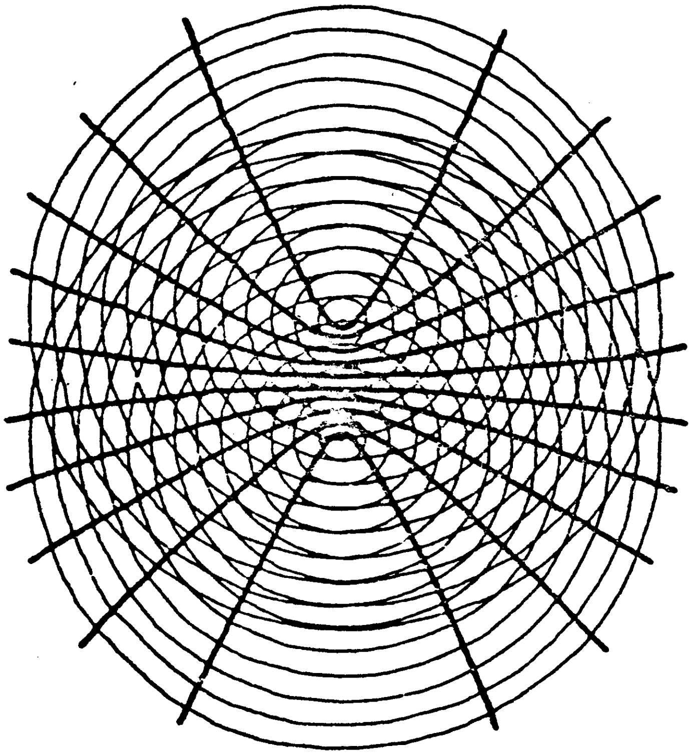


FIG.2

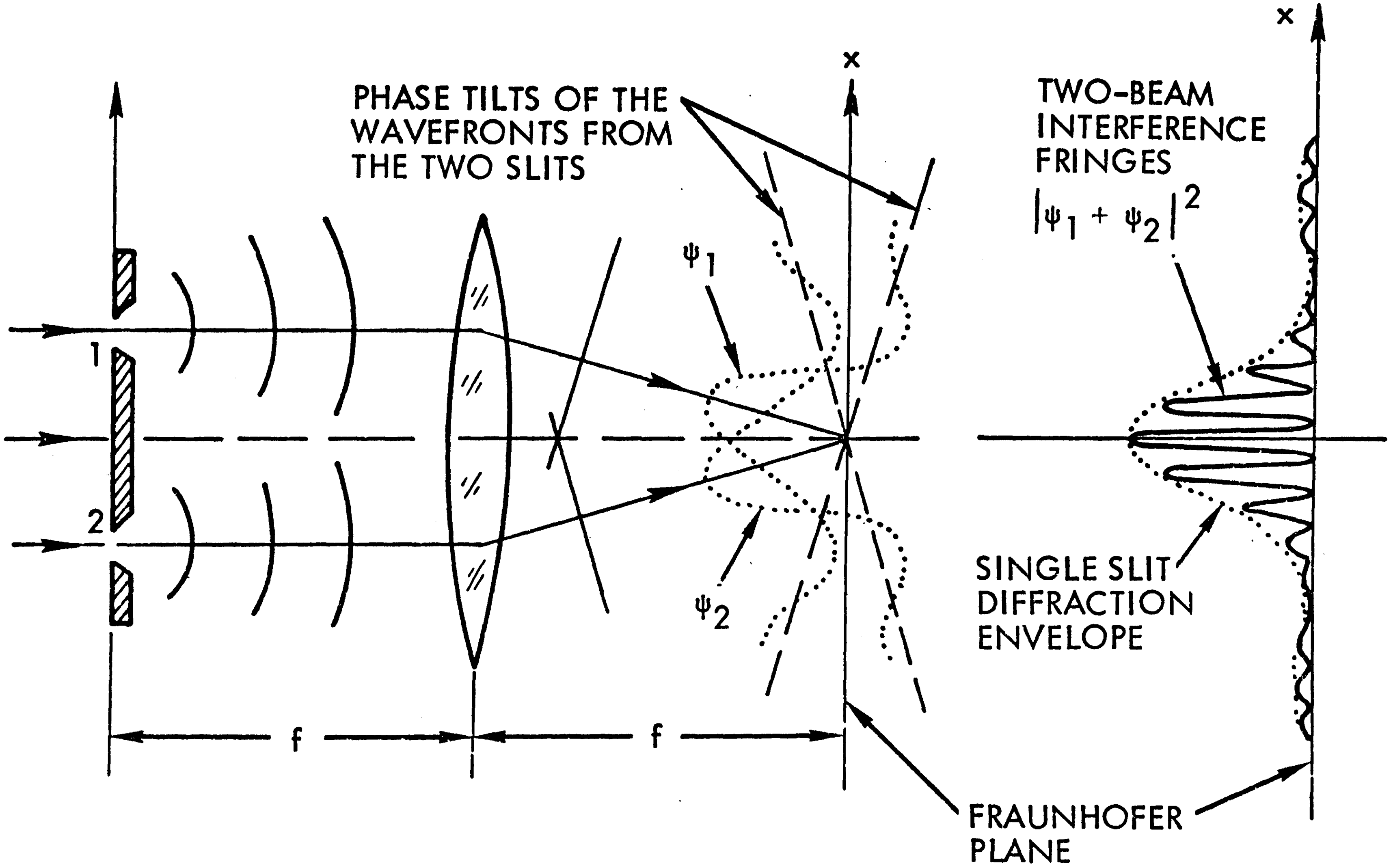

PHASE TILTS OF THE WAVEFRONTS FROM THE TWO SLITS
x
x
TWO-BEAM INTERFERENCE FRINGES
$|\psi_1 + \psi_2|^2$
ψ_1
1
2
ψ_2
SINGLE SLIT DIFFRACTION ENVELOPE
f
f
FRAUNHOFER PLANE

FIG3

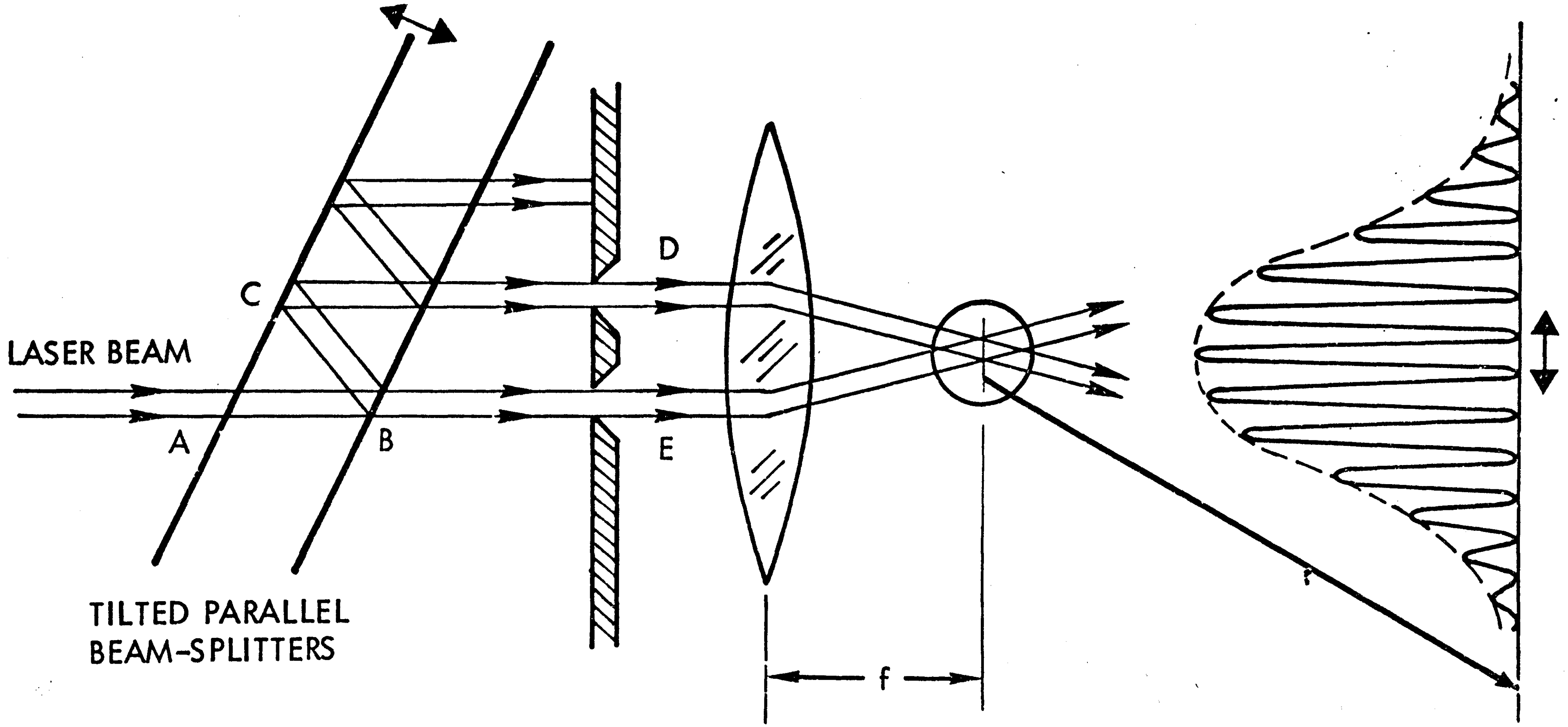


FIG. 4

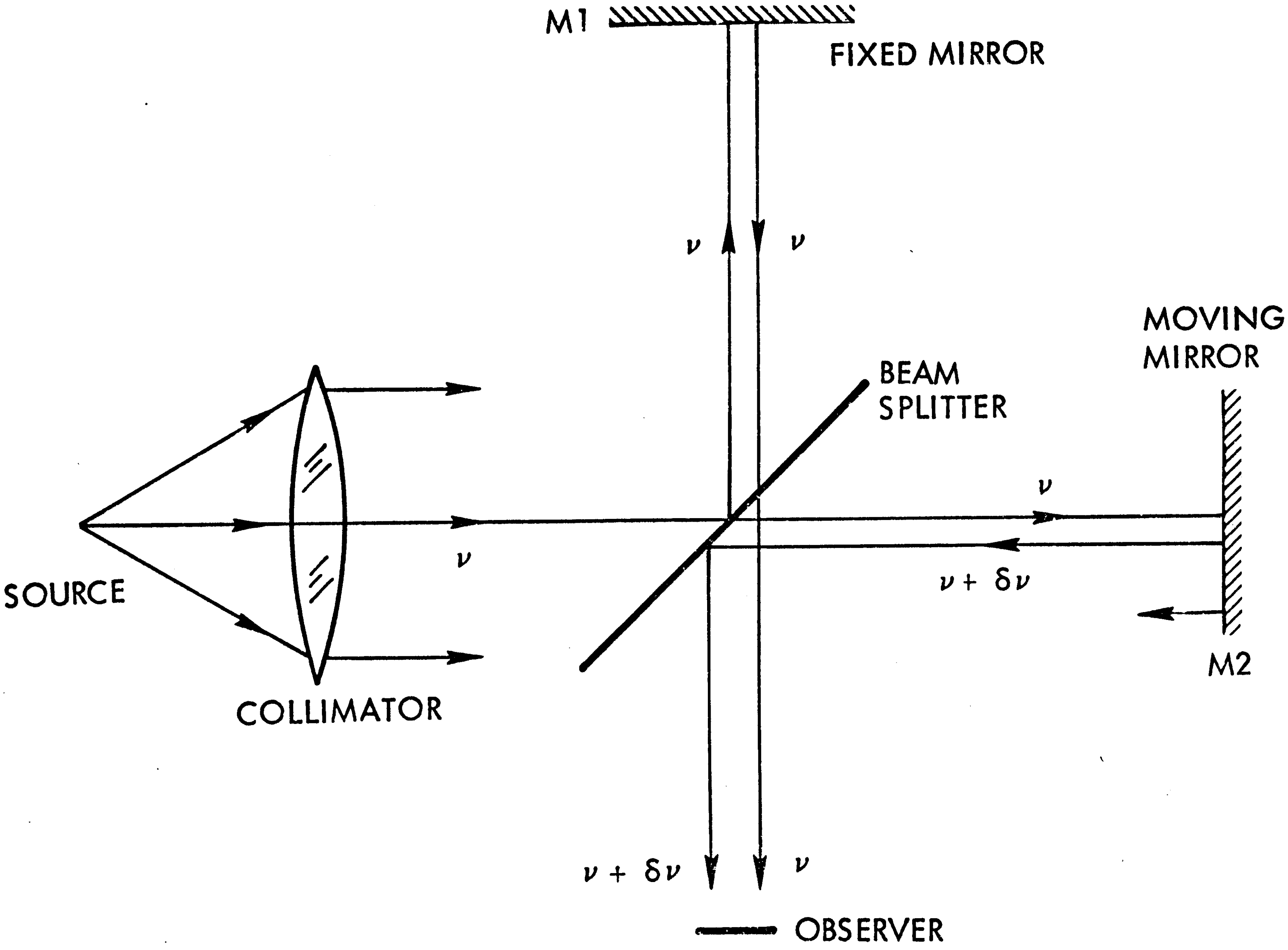

M1
FIXED MIRROR
ν
ν
MOVING MIRROR
BEAM SPLITTER
ν
SOURCE
ν
ν + δν
M2
COLLIMATOR
ν + δν
ν
OBSERVER

FIG.5

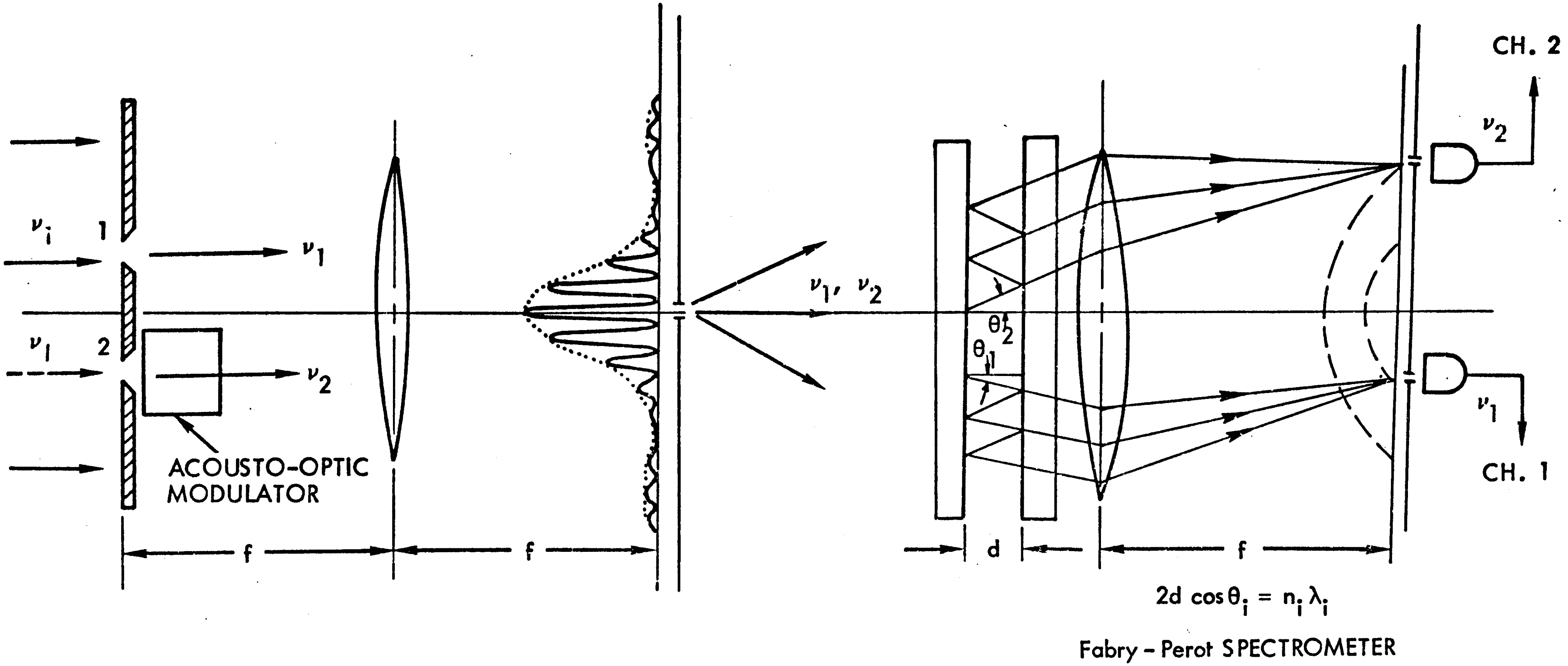

ν_i
1
ν_1
ν_1
2
ν_2
ACOUSTO-OPTIC MODULATOR
f
f
ν_1, ν_2
θ_2
θ_1
d
f
CH. 2
ν_2
ν_1
CH. 1
$2d \cos\theta_i = n_i \lambda_i$
Fabry - Perot SPECTROMETER

FIG. 6

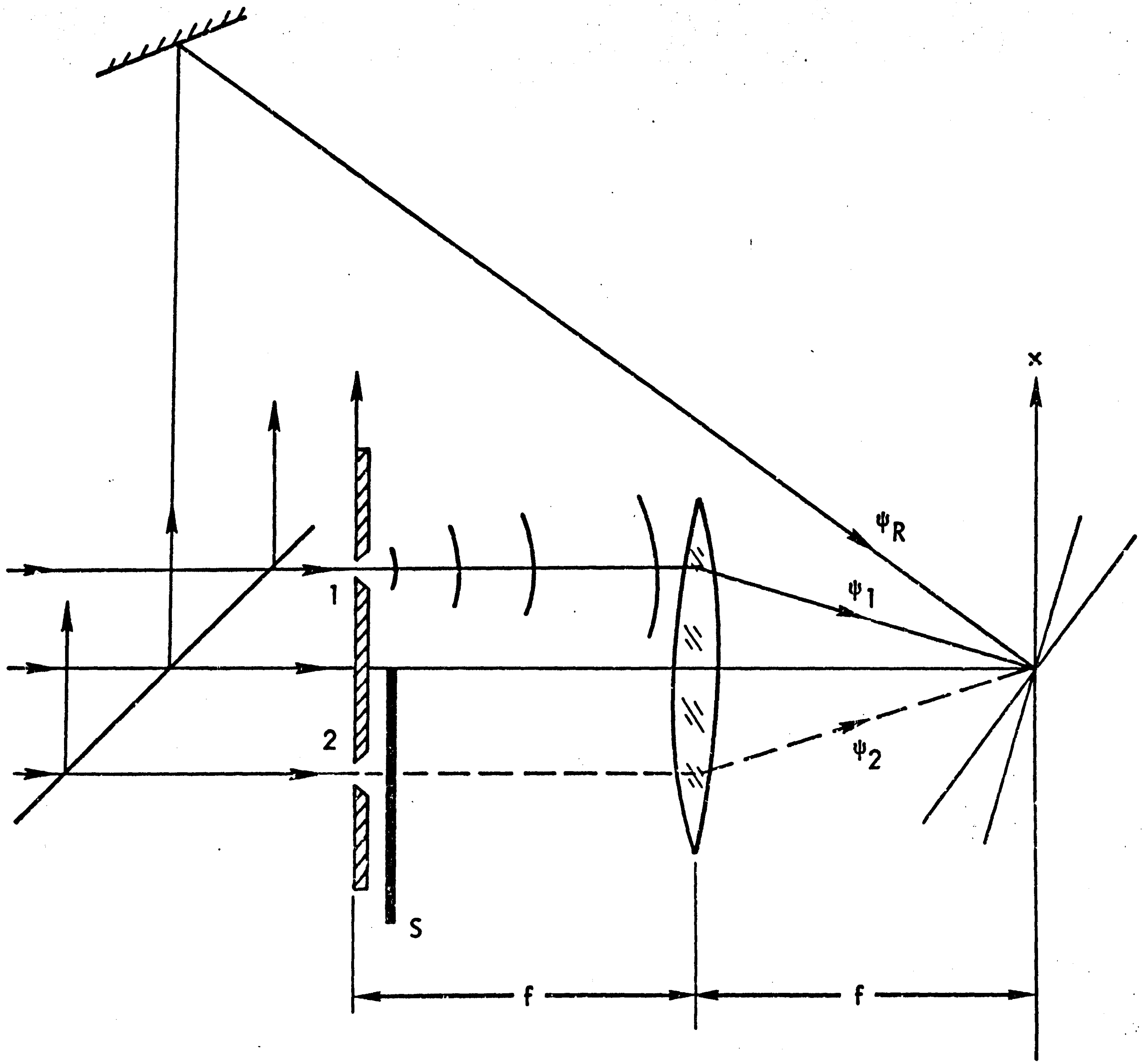


FIG.7