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SECOND EDITION

Edited by ROBERT M. BESANÇON

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PREFACE TO SECOND EDITION

This second edition of the *Encyclopedia of Physics* follows the same general plan as was used for the first edition; that is, each article is written so as to be of primary value to the type of reader who is most apt to look for the particular topic. There are articles on major areas of physics which are at a low technical level, so as to be of maximum value to the reader with little prior knowledge of physics. There are also articles on major divisions and subdivisions of these areas. In general, these latter start with an introduction intended to define the topic and describe the concepts involved. This is followed by more detailed and advanced treatment for the reader with a stronger background in physics.

To cover more of physics, the book has been considerably expanded, both by adding new articles and by including new material on topics in the first edition. Many of the articles have been completely rewritten, others received major changes, while others, particularly those on major areas of physics, required little or no change.

As in the first edition, the major credit for any success the book may achieve belongs to the authors, many of whom not only contributed a tremendous amount of time and effort in preparing articles, but made valuable suggestions for other parts of the book.

The editors at the Van Nostrand Reinhold Company contributed a great deal to the readability and accuracy of the book, and to my wife, Leigh, goes credit for much careful proofreading, for the preparation of the extensive index, and for the typing and detailed record-keeping required in assembling a book of this magnitude.

To all of these workers my heartfelt thanks are due.

ROBERT M. BESANÇON

Dayton, Ohio
April 10, 1974

PREFACE TO FIRST EDITION

THE AIM of this book is to provide in one volume concise and accurate information about physics. It should be of use to physicists who need information outside of their own special areas of interest, to teachers and librarians who must answer inquiries, to students who wish to add to their funds of knowledge, and to engineers and scientists who encounter physical concepts in pursuit of their professions. The book has been made possible by the thoughtful and generous cooperation of more than 300 authors, both in this country and abroad, who have unstintingly contributed their time, skill and knowledge. Their names and affiliations are shown immediately before this preface.

The most challenging problem for the editor was deciding which topics to include and which to leave out, since the space available was very limited compared with the vast amount of knowledge that could have been included. The approach used was to provide short introductory articles on physics, on the history of physics, on measurements, and on symbols, units and nomenclature, plus general articles on the major areas of physics: heat, light, mechanics, acoustics, etc. To these were added entries on divisions and subdivisions of the major areas; these are more detailed and pitched at somewhat higher technical levels than the broader, more general articles. Other topics lie on the interfaces between major areas of physics or are on subjects that include both physics and other disciplines. These include, among others, astrophysics, geophysics, biophysics, and mathematical biophysics. Finally, a few articles cover sciences that are so closely related to physics that the differences are frequently merely matters of emphasis.

Each article attempts to provide not just a definition of a term but an explanation of an area of physics. No attempt was made to hold all articles at the same technical level; on the contrary, the level for each entry was aimed at those readers who would be most apt to look for information on that specific topic. The contents of each article was left to the discretion of the author as the one most capable of making the proper selection. Some of the authors found it necessary to use mathematics, as is done in many books on physics. However, the reader with a limited mathematical background will find many articles with no mathematics at all, and others with very little, while the reader who is so inclined can sink his teeth into the more mathematical paragraphs.

Most of the authors have provided references to summary articles and books, and in addition, cross-references to other articles in this book have been added wherever it was felt that they might be of particular help to the reader. A few cross-references are shown by the use of small capitals in the body of the text (thus, MECHANICS); others are listed at the end of the article. The index should serve to locate particular topics that might not be subjects of complete articles.

I should like to extend by heartfelt thanks to the authors who contributed so much and to Mr. G. G. Hawley and Mr. H. Simonds of the Reinhold Publishing Corporation who invited me to compile and edit this book as one of the series of scientific and technical encyclopedias published by that company. I also owe a very great deal to Mrs. Alberta Gordon and her staff, who did much of the editing and proofreading, and to my wife, Leigh, who contributed the bulk of the tremendous amount of clerical work involved as well as adding a great deal of enthusiasm and inspiration.

ROBERT M. BESANÇON

Dayton, Ohio
November 1, 1965

A

ABERRATIONS

The two sections of this article give a theoretical treatment. For an introductory discussion, see the article entitled LENS.

Geometrical Theory When a light wave passes through an instrument, the wave front suffers deformation due to the imperfection of the instrument. The optical distance between the emerging wave front (actual) and the converging wave front (ideal) when the mapping of object points is perfect is a measure of the aberration of the instrument. For an ideal instrument, the mathematical relation of such a mapping is given by the equations

$$\bar{x}_i = Mx_i \quad (1a), \qquad \bar{\xi}_i = m\xi_i \quad (i = 1, 2, 3), \quad (1b)$$

where M, m are constants characterizing the optical instrument and $(x_i, \bar{x}_i)$, $(\xi_i, \bar{\xi}_i)$ are the coordinates and optical direction cosines of a ray in the object and image space respectively. If the z-coordinates are fixed, $x_3 = z_0$, $\bar{x}_3 = z_1$, the ray enters the object plane z_0 and exits from the image plane z_1.

In general, the above relationship between the object and image points is not realized in actual practice and instead of (1a), (1b) we have

$$\bar{x} = Mx_i + f(x_i, \xi_i) \qquad (2a)$$

$$\bar{\xi}_i = m\xi_i + g(x_i, \xi_i) \qquad (2b)$$

where $f(x_i, \xi_i)$, $g(x_i, \xi_i)$ are complicated functions of the arguments. The functional dependence of these functions on x_i and ξ_i characterizes the optical instrument. These are called the aberrations of the optical instrument or system.

For a given optical system, such as a lens or a number of lenses as in a microscope or telescope objective, the aberrations can be calculated by tracing rays from the object plane to the image plane—object and stop positions—using the law of refraction. This method of computing the aberrations numerically is very laborious and does not yield a clear picture of the various types of aberrations even in simple optical systems. On the other hand, when the Hamilton characteristic functions are introduced, representing the actual emerging wave fronts, one obtains an analytical expression for the aberration function of an instrument and furthermore is able to classify various types of aberrations caused by an optical system. The so-called point characteristic expressing the distance from a point on the object plane to the corresponding point of the same ray on the stop plane is hardly used in actual practice. However, the mixed characteristic W, which is a function of the object position of a ray and its emerging direction on the image or stop plane, forms the basis of the Hamilton, Seidel, and Schwarzschild theory of aberrations, and the fourth characteristic of Hamilton, the angular characteristic, is taken as the basis of the Smith theory.[11] However, the derivation of an explicit form of the mixed or angular characteristic is a very difficult mathematical problem and only in a few simple optical systems has the characteristic function been calculated in a closed form. For rotational systems, the characteristic functions (the point, the two mixed, and the angular characteristic) depend on three variables or invariants, and when the aberration is small they are expanded in power series of the invariants. In the following section on diffraction theory we give the expansion of the mixed characteristic $W(x_i, \xi_i)$ in two different forms, known as the standard and the Zernike-Nijboer expansions, and explain briefly the various classifications of the terms of the series arranged according to the powers of the invariants. For an extended analysis of the geometrical aberrations and their classifications we refer the reader to the general references listed, in particular, to recent studies[11,12,13,14] and to the following comprehensive treatises on the subject: M. Herzberger, "Modern Geometrical Optics," New York, Interscience Publishers, 1958, and H. Buchdahl, "Optical Aberration Coefficients," Oxford, Oxford University Press, 1954, where references to their researches and to more recent developments are to be found.

Diffraction Theory The starting point of the modern theory of diffraction of optical instruments may be traced to the famous paper on diffraction theory of the phase contrast method by Zernike.[1] The extension to the diffraction theory of aberrations was carried out by him in collaboration with his pupils, especially, Nijboer.[2] Since then, many advances have taken place, both in theory and experimental observation leading to important applications in the improvement of optical instruments. However, prior to Zernike's pioneering work, some significant contributions to the theory were made by a number of authorities, notably Ignatowski, Fischer, Steward,[3] and Picht.[4]

The basis of the diffraction theory of optical instruments is founded on Kirchhoff's integral or a modified form of it, namely

$$U(P) = -\frac{ikn}{2\pi}\iint_S \sqrt{K}\,U_0(Q) \cdot \exp ik\,[W + (\mathbf{r}\cdot\mathbf{s})]\,dS \quad (1)$$

where $U_0(Q)$ is the value of the field on the wave surface (front) S, K and s are respectively the Gaussian curvature and optical normal vector of S, n is the refractive index of the medium in the image space, and W is the Hamiltonian mixed characteristic of the optical system. The image field $U(P)$ at an image point $P(x, y, z)$ is the geometrical optics wave solution of the scalar wave equation, or Maxwell equations.

A more convenient form of Eq. (1) used frequently in actual problems is

$$U(P) = -\frac{ik}{2\pi}\int\int_{p^2+q^2\leqslant n^2} g(p,q)\exp ik\phi(P;p,q)\,dp\,dq,$$

$$\phi(P;p,q) = W + (\mathbf{r}\cdot\mathbf{s}) \quad (2)$$

where a point Q on the wave surface $S(Q)$ is represented parametrically in terms of (p, q), $x = -W_p + \lambda p$, $y = -W_q + \lambda q$, $z = \lambda\sqrt{n^2 - p^2 - q^2}$, $\lambda = \lambda(p,q)$. Here p,q and $(n^2 - p^2 - q^2)^{1/2}$ are the optical direction cosines (components) of the normal vector s. The amplitude function $g(p,q) = |n||\Delta|^{1/2} \cdot U_0(p,q)$ remains constant along a ray $(p \cdot q)$ in image space, and Δ is the discriminant of the second differential form of S. Equations (1) or (2) are known as the Picht-Luneburg integrals.[4,5]

The above formulas give all the information about the image produced by an optical instrument for a monochromatic source. Thus the problem is reduced to the evaluation of such integrals over the arbitrary wave front S. In general, W is not known explicitly (closed form) on S, so instead of the wave surface S one takes a reference surface S_0, usually a spherical wave front with center at the Gaussian image point of the optical system, and expands W in a Taylor series in the parameters. In practice S_0 is the aperture (entrance or exit-pupil) of the instrument. For rotational symmetric systems, most frequently employed in practice, W depends on three invariants, $u_1 = x_0^2 + y_0^2$, $u_2 = p^2 + q^2$, $u_3 = x_0 p + y_0 q$, and an additional invariant $u_4 = x_0 q - y_0 p$ for electron optical systems. Therefore, the expansion of W is of the form

$$W = W_0 + \Sigma a_i u_i + \Sigma a_{ij} u_i u_j + \Sigma a_{ijk} u_i u_j u_k + \cdots, \quad (i, j, k = 1,2,3),$$

$$= W_0 + \sum_{\rho=1}^{\infty}\sum_{n=1}^{\infty}\sum_{m=1}^{n} b_{lnm}\sigma^{2l+m}\rho^n\cos^m\phi =$$

$$W_0 + \sum_{n=1}^{\infty}\sum_{m=0}^{n} f_{nm}(\sigma)\rho^n\cos^m\phi \quad (3)$$

l,n,m are positive integers, $n - m$ even > 0 and $u_1 = \sigma^2$, $u_2 = \rho^2$, $u_3 = \sigma\rho\cos\phi$. The individual constants b_{lnm} are the aberration coefficients. This standard development has been used by Steward and others in their treatment of diffraction of aberrations. However, even for individual aberrations of lower order, the evaluation of the diffraction integral leads to complicated expressions for the image field or intensity distribution, since the various orders of a single type aberration are not separated; consequently, it is difficult to separate the contributions of each order to the total intensity in the image plane. For these reasons, both Steward and Picht and later Born obtained incomplete figures of the intensity distributions of the image. On the other hand, Nijboer, following Zernike's ideas, was able to calculate to a great degree of accuracy (unknown before) the intensity distribution for several types of aberrations and high orders. The experimental observations made at Zernike's laboratory, as well as those made at McGill University on microwaves[2a] are in agreement with Nijboer's figures or with those calculated by Nijboer's method.[2a]

The Zernike-Nijboer diffraction theory of aberration is based on the development of the aberration function, or W, in terms of orthogonal polynomials (functions) over the region of integration (wave front) which, in their case, was a circle. Instead of Eq. (3), W is expanded in the form

$$W = W_0 + \sum_{n=1}^{\infty}\sum_{m=0}^{\infty} f_{mn}(\sigma)Z_n^m(\rho)\cos m\phi,$$

$$(m = 0,1,\cdots,n;\ n = 1,2,\cdots) \quad (4)$$

where $Z_n^m(\rho)$ are called the Zernike polynomials, which are orthogonal over a unit circle. In this development, a typical aberration term is of the form $b_{lnm}\sigma^{2l+m}Z_n^m(\rho)\cos m\phi$. On account of the orthogonality of Z_n^m, the various orders of a single aberration enter individually (are not mixed) in the expression representing the intensity distribution function; i.e., different aberrations cannot counterbalance each other's contribution for all σ. In general, the amplitude function can also be expanded in Zernike polynomials, or other functions such as Fourier-Bessel, or Dini functions,[10] if the field over the aperture is not constant (coating of lenses). In general, the idea of expanding both the amplitude and the phase function in orthogonal functions over the domain of integration has many advantages over previous methods, since the double integral cannot be reduced into a single integral, except for the simplest type of apertures. However, when only spherical aberration of all orders is considered, the method of integration by parts of the diffraction integral leads to rather simple expression for the image field. This case has been treated exhaustively for both circular and annular apertures by Boivin.[8] The calculation of the diffracted field in the presence of higher order aberrations including the more general problem of nonsymmetric optical systems is given in reference 14.

All the methods discussed above are valid only for small aberrations. For large or moderately large aberrations, one must resort to asymptotic methods, which at present are sufficiently developed to include most of the interesting cases occurring in the theory of diffraction of optical systems. When these analytical methods are combined with the present progress in computational methods, the intensity distribution produced by an optical system can be calculated to any desired degree of accuracy.

NICHOLAS CHAKO

References

1. Zernike, F., *Physica*, **1**, 689 (1934).
2. Nijboer, B. R. A., "The Diffraction Theory of Aberrations," Groningen thesis, 1942. For the experimental part, see the thesis by Nienhuis, K., Groningen, 1948. For microwave experiments see: Bachynski, M. P. and Bekefi, G., *IRE Trans.*, AP-4, No. 3, 412 (1955). "Studies in Microwave Optics," *McGill Univ. Tech. Rept.*, 38 (1957).
3. Steward, G. C., "The Symmetrical Optical System," Cambridge, Cambridge Univ. Press, 1928.
4. Picht, Johannes, "Optische Abbildung," Braunschweig, 1931.
5. Luneburg, R. K., "Mathematical Theory of Optics," Providence, R.I., Brown University, 1944. Reproduced by the University of California Press, Berkeley and Los Angeles, 1964.
6. Linfoot, E. H., "Recent Advances in Optics," London, Oxford Univ. Press, 1955.
7. Born, M., and Wolf, E., "Principles of Optics," New York, Pergamon Press, 1959.
8. Boivin, A., "Théorie et Calcul des Figures de Diffraction de Révolution," Paris, Les Presses de l'Université Laval, Québec and Gauthier-Villars, 1964.
9. Maréchal, A., and Françon, M., Diffraction Structure des Images, Paris, Masson et Cie, Editeurs, 1970.
10. Françon, M., in "Handbuch der Physik," Vol. 24, Berlin, Springer, 1956.
11. Pegis, R. J., "The Modern Development of Hamiltonian Optics," *Progress in Optics*, **I**, Ed. E. Wolf, Amsterdam, North Holland Publ. Co. (1961). Focke, J., "High Order Aberration Theory," *Progress in Optics*, **IV** (1965).
12. "Handbuch der Physik," Vol. XXIX, Ed. S. Flügge, Berlin, Springer Verlag, 1967. Articles by Welford, Walter T., "Optical Calculations and Optical Instruments, An Introduction"; Marechal, Andre, "Methode de Calcul des Systèmes Optiques"; Helmut, Max, "Theorie der Geometrisch-Optischen Bildfehler."
13. Hawkes, P. W., "Quadrupole Optics, Electron Optical Properties of Orthogonal Systems," Springer Series, "Tracts in Modern Physics," Vol. 42, Berlin, 1966.
14. Chako, Nicholas, "Contribution à la Théorie de la Diffraction," Centre d'Etudes Nucléaires de Saclay, CEA-R-3151, Saclay, France, 1969. "Etudes sur les Dévéloppements Asymptotiques des Intégrales Multiples de la Physique Mathématique" (large aberration diffraction), CEA-R-3263, Saclay, France, 1968.

Cross-references: DIFFRACTION BY MATTER AND DIFFRACTION GRATINGS; LENS; OPTICAL INSTRUMENTS; OPTICS, GEOMETRICAL; OPTICS, PHYSICAL.

ABSORPTION SPECTRA

The first experiment in which the light from the sun was dispersed into its spectrum was performed by Sir Isaac Newton in 1666. The chief effect was, obviously, the transformation of the round pinhole image of the sun in white light into a sausage-shaped array of colors, starting with red and ending, further up the wall, with violet. There was only a gradual transition from one color to the next, and apparently no colors were missing between violet and red.

The next step in the new optical topic of spectroscopy was the observation by W. H. Wollaston (1766–1828) in 1802 that the solar spectrum is not complete, but is crossed by a large number of dark lines—apparently missing wavelengths. A dozen years later Joseph von Fraunhofer (1787–1826) again observed these dark lines in the solar spectrum. In 1859 they were explained by Kirchhoff as due to the fact that the elements which, when in the laboratory, give characteristic bright lines in their spectrum, would in the solar atmosphere absorb those very lines—hence relative darkness is apparent at these places in the spectra when viewed from the earth.

Distinctions should be made at this point between several terms used in the discussion of absorption spectroscopy.

The *absorption coefficient* of a material (α) is expressed in the equation, known as the law of absorption and enunciated by Bouguer and Lambert,*

$$I_x = I_0 e^{-\alpha x}$$

*Pierre Bouguer (1698–1758) and Johann Lambert (1728–1777). It was later shown by Beer that the absorption coefficient for a solution is directly proportional to the concentration of the absorbing species. The relationship, known today as Beer's law, is

$$I = I_0 10^{-abc}$$

where a is the *absorptivity*, b is the thickness through which the initial intensity I_0 drops to I, and c is the concentration of the absorbing material.

in which the intensity of an incident plane wave I_0 is shown to decrease as the reciprocal of an exponential function to a value I_x after the energy has penetrated to a distance x in the sample of the material. In other words, the fraction dI/I_0 of the initial intensity is "lost" in traversing the distance dx, since $dI/I_0 = -\alpha dx$.

Absorption is the general phenomenon taking place within the body of the material as measured by the absorption coefficient.

Absorbance is the common logarithm of the ratio of the incident to the transmitted intensities.

Absorptance is the measure of the amount of light that disappears at a single reflection.

No substance has been found to exist that does not strongly absorb some wavelengths if the range be sufficiently extended. Dielectrics usually exhibit three extensive regions of large transmission, one in each of the three distinctive portions of the electromagnetic spectrum—very short wavelengths, intermediate wavelengths, and very long wavelengths.

A *blackbody* absorbs all of the radiant energy incident upon it—is a perfect absorber—and likewise acts as a perfect radiator. Kirchhoff's law of radiation states that the ratio of the *emissive power* to the *absorptive power* is the same for all bodies at a specified absolute temperature, or E/A = a constant = E_B. E is the total energy radiated per square centimeter of surface per second and A, the *absorptive power*, is the fraction of the incident energy that is not reflected or transmitted by the surface. Obviously, A is unity for a blackbody, and hence the constant in the above equation is E_B, the emissive power of a blackbody at the specified temperature. Absorption lines in a spectrum can be explained on the assumption of RESONANCE of the atoms of the absorbing material to that portion of the incident energy spectrum which presents the same oscillation frequency. The atoms reradiate all of the absorbed energy *but in all directions*, so that the portion in the line of sight of the observer is relatively less than what would have been in that position without the intervening vapor.

A material that reduces the intensity of incident light almost entirely without regard to wavelength is said to exhibit *general absorption*. White light becomes gray. In the instances cited in this article, there is *selective absorption*. Flowers, paints, skin, etc., have color by selective absorption since some of the light penetrates ever so slightly into the body of the material.

The absorption bands in the spectra of solids and liquids are usually continuous, gradually fading out along the wavelength axis, but gases show narrow lines in their absorption spectra as a general rule.

We know from elementary optics that the *index of refraction* (n) of a nonconducting material (dielectric) at a definite wavelength is its essential property, for by its use in Snell's law, we can obtain the sequence of deviations of a ray as it passes through or from an interface bounding two media (see REFRACTION). The case is very different for metals (conductors) due to the presence of free electrons in among the atoms. Strong absorption at once occurs so that metals are opaque, certainly to visible light. When the optical properties of metals are being considered, it is more efficacious to use the quantity known as the *absorption index*, defined for a given wavelength λ by

$$\kappa = \frac{\alpha\lambda}{4\pi n}$$

where n is best determined by the measurement of Brewster's angle. (see POLARIZED LIGHT). For silver at $\lambda = 589.3$nm, $n = 0.177$ and $\kappa = 20.554$.

The theory of dispersion shows that generally, in the visible region, transparent materials exhibit a decrease in refractive index with wavelength (section AB of Fig. 1). This part of the graph (AB) is known as the *normal dispersion curve* for the material and can readily be plotted from data taken with a prism spectrometer. The earliest attempt to relate n to λ was made by Cauchy in 1836, namely,

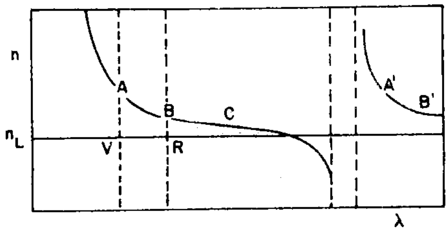

FIG. 1. Index of refraction vs. wavelength for a typical material. Adapted from Fig. 23D of *Fundamentals of Physical Optics*, by Francis A. Jenkins and Harvey E. White, courtesy of McGraw-Hill Book Co., New York, 3rd Edition, 1957.

$$n = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}$$

where A, B and C are constants. Although based, as we now know it, on false assumptions, this relationship has proved valuable as a practical working equation, as long as one keeps far from an absorption band. Considering the effect of the frequency of the incident light (ν) upon the particles of the medium, having a natural frequency ν_0, Sellmeier (1971) derived the more acceptable relation

$$n^2 = 1 + \frac{A\lambda^2}{\lambda^2 - \lambda_0^2}$$

where A is a constant proportional to the number of oscillators affected and λ_0 is the wavelength corresponding to ν_0 in a vacuum. We see from this equation that at resonance (when $\nu = \nu_0$), the index of refraction becomes very large. In