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POLARIZATION: DEFINITIONS AND NOMENCLATURE, INSTRUMENT POLARIZATION

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FOREWORD

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SUMMARY

This report has been prepared as part of the working program of the CIE Committee TC-2.3 to study the effects of polarization on photometric and radiometric characteristics of materials. The terms defined are, in the main, those of particular relevance to photometric considerations and should not be regarded as comprehensive to all aspects of polarization.

The degree of polarization produced in a beam of light by an optical system varies with the complexity of the instrument as well as, in general, being wavelength dependent in a given system. Furthermore, the effect of any polarization on the determination of photometric properties will depend on the actual measurement being undertaken. Thus although polarization can have a very significant effect on many photometric measurements, it is difficult to quantify this in a generalized way.

The report discusses polarization effects in the individual optical components which make up a complete instrument, including the source and detector. In addition, information on the main properties of polarizers, particularly those relevant to photometric considerations, is included.

RÉSUMÉ

POLARISATION:

DÉFINITIONS ET NOMENCLATURE, POLARISATION INSTRUMENTALE

Ce rapport a été préparé comme un élément du programme de travail du TC-2.3 de la CIE, destiné à étudier les effets de la polarisation sur les caractéristiques photométriques et radiométriques des matériaux. Les termes définis sont, pour la plupart, ceux relatifs à des aspects photométriques et ne doivent pas être considérés comme couvrant tous les aspects des phénomènes de polarisation.

Le degré de polarisation d'un faisceau de lumière, créé par un système optique, dépend de la complexité de l'appareil et dépend aussi en général de la longueur d'onde, pour ce système particulier. De plus, les effets de toute polarisation sur la détermination des propriétés photométriques dépendent du type particulier de mesures réalisées. Aussi, bien que la polarisation puisse avoir des effets très significatifs sur de nombreuses mesures photométriques, il est difficile de fixer des valeurs numériques sur ces effets en général.

Ce rapport passe en revue les effets de polarisation dus isolément aux composants optiques d'un instrument complet, comprenant source et détecteur. De plus est incluse une information sur les propriétés principales des polariseurs, particulièrement ceux qui sont liés à des aspects photométriques.

ZUSAMMENFASSUNG

POLARISATION:

DEFINITIONEN UND BEGRIFFE, POLARISATION VON INSTRUMENTEN

Dieser Bericht ist als Teil des Arbeitsprogramms von CIE TC-2.3 verfasst, um den Einfluss der Polarisation auf photometrische und radiometrische Eigenschaften von Materialien zu untersuchen. Die definierten Begriffe sind im wesentlichen für photometrische Betrachtungen von besonderer Bedeutung und gelten deshalb nicht für alle Aspekte der Polarisation.

Der Polarisationsgrad eines Lichtbündels, der durch ein optisches System bestimmt wird, hängt von der Komplexität des Instruments ab und ist im allgemeinen in einem gegebenen System wellenlängenabhängig. Darüber hinaus ist die Wirkung einer Polarisation auf die Bestimmung von photometrischen Eigenschaften von der ausgeführten Messung abhängig. Obwohl die Polarisation viele photometrische Messungen wesentlich beeinflusst, ist es doch schwierig, diese in einer allgemeinen Form zu erfassen.

Dieser Bericht beschreibt Polarisierungseffekte einzelner optischer Komponenten eines vollständigen Gerätes, einschliesslich Lichtquelle und Empfänger. Zusätzlich werden Informationen über wesentliche Eigenschaften von Polarisatoren, besonders der für photometrische Anwendungen, mitgeteilt.

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PART 1 DEFINITIONS AND NOMENCLATURE

1.1. INTRODUCTION

The fundamental phenomena of polarization can be explained on the concept that light is a transverse wave motion i.e. the vibrations are at right angles to the direction of propagation. In terms of electromagnetic theory, it is customary to consider these vibrations as being those of the electric rather than the magnetic field.

The following definitions assume, unless otherwise stated, that the light is monochromatic and is travelling through a non-attenuating medium.

1.2. DESCRIPTION OF POLARIZED LIGHT

1.2.1 Linearly polarized light

Light in which the electric vector is at a fixed azimuth i.e. it is confined to a plane containing the direction of propagation of the light.

1.2.2 Direction of vibration

The direction of the electric vector (or E vector) of a light wave.

1.2.3 Plane of vibration

The plane containing the electric vector and the direction of propagation of the light.

1.2.4 Plane of polarization

Originally 'plane of polarization' was used to define the plane containing the direction of propagation of a light wave and the direction of the *magnetic* vector. More recently the term has been less employed and then usually refers to the plane containing the *electric* vector. Because of possible ambiguity it is strongly recommended that the term 'plane of polarization' is not used.

1.2.5 Circularly polarized light

Light in which the electric vector is of constant amplitude and rotates about the direction of propagation at a frequency equal to the radiation frequency.

1.2.6 Handedness

Circularly polarized light is right-handed (left-handed) if the rotation of the E vector is clockwise (anticlockwise) as viewed by an observer receiving the light.

1.2.7 Elliptically polarized light

Light in which the electric vector rotates at the radiation frequency but varies in amplitude; the terminal point of the electric vector describes an ellipse. The sense of rotation is that defined for circularly polarized light.

1.2.8 Relation between polarization states

Elliptically polarized light is the most general form of polarized light, and linear and circular polarization can be regarded as special cases of this more general form.

Circularly (elliptically) polarized light can be considered as being composed of two components with orthogonal states of linear polarization, the components being equal (unequal) in amplitude and differing in phase by $\pi/2$.

1.2.9 Ellipticity

If, in an elliptically polarized beam of light, a and b are the major and minor semi axes of the ellipse respectively (i.e. they are the maximum and minimum values of the electric vector), then the ratio b/a of the semi axes is called the ellipticity of the beam.

1.2.10 Eccentricity

Defined as $(a^2 - b^2)^{1/2}/a$, this term is less used than ellipticity.

1.2.11 Azimuth

The angle between the x axis of a cartesian coordinate system and a specific direction of a polarization type or polarization device, e.g. the direction of vibration of linearly polarized light, the major axis of an elliptical vibration, the transmission axis of a linear polarizer or the fast axis of a linear retarder.

1.2.12 Unpolarized light (often referred to as natural light)

Unpolarized light is not an elementary state of polarization and is therefore difficult to define satisfactorily. The following description should however prove useful in the analysis of polarization phenomena.

Unpolarized light exhibits no preferential directional property in a plane normal to the direction of propagation of the light, the directions and phases of the electric vectors being randomly distributed.

Unpolarized light can be regarded as elliptically polarized light in which the ellipticity and azimuth of the ellipse and its handedness are constantly changing at an unresolvable rate.

A beam of unpolarized light can be regarded as being composed of two components of equal amplitude but with orthogonal states of polarization, the two components being unrelated in phase.

It should be noted that strictly monochromatic light always exhibits polarization. Thus for light to be unpolarized, it must possess a finite bandwidth so that its coherence time is small compared with the measuring time of the detection system.

The descriptions above assume that the light beam has uniform properties over its cross sectional area. A beam that exhibits random and spatially unresolvable variations in polarization state over its aperture (or direction) will behave as though unpolarized to a detector (see Section 1.4.8, Depolarizer).

1.2.13 Orthogonal states of polarization

Two states of polarization are said to be orthogonal if their characteristic points on the Poincaré sphere lie at opposite ends of a diameter.

Thus two states of linear polarization are said to be orthogonal if they possess the same direction of propagation but their directions of vibration differ in azimuth by 90° .

Left and right-handed circular states of polarization are also said to be orthogonal.

Two elliptical states of polarization are said to be orthogonal if they possess identical ellipticities, opposite handedness and the azimuths of their major axes are at 90° to each other.

1.2.14 Partially polarized light

A beam of light, whether originating from a natural or artificial source, is rarely completely polarized or completely unpolarized. It usually possesses some degree of polarization and is then referred to as being partially polarized. A partially polarized beam can be regarded as being composed of two components, one polarized and the other unpolarized.

1.2.15 Degree of polarization

Let a partially polarized beam of light be considered as being composed of a component of intensity I_a that is completely polarized and one of intensity I_b that is unpolarized and has no coherence with the other component.

Then the degree of polarization P is defined by

$$P = \frac{I_a}{I_a + I_b}$$

Alternatively, let the beam be considered as being composed of the two orthogonally polarized components possessing the maximum difference of intensity. If the corresponding intensities are $I_{\max}$ and $I_{\min}$, then

$$P = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

1.3. MATHEMATICAL DESCRIPTION OF POLARIZED LIGHT

1.3.1 Poincaré sphere

The representation on the surface of a sphere of all states of perfectly polarized light. Points on the equator indicate linear polarization, with the upper and lower poles representing left and right-handed circularly polarized light respectively. Other points represent elliptical polarization. Points at the opposite ends of a diameter correspond to orthogonal states of polarization.

The Poincaré sphere is particularly useful for determining the effect of retarders on the state of polarization of a light beam.

1.3.2 Jones vector

A two element column vector describing the complex amplitudes of the x and y components of a perfectly polarized beam of light travelling along the z -axis. The Jones vector is used in conjunction with 2×2 matrices, representing various polarization devices, e.g. polarizers and retarders. The matrix elements are, in general, complex. The Jones calculus can deal only with the description of perfectly polarized beams.

1.3.3 Stokes vector

A four element column vector with scalar parameters that describe the intensity and polarization of a beam of light. Each parameter corresponds to a time averaged intensity. The first parameter is proportional to the intensity of the wave, with the other three relating to the azimuth and ellipticity of the polarized component. The Stokes vector is used in conjunction with 4×4 matrices which describe polarization devices and contain only real elements. The Stokes vector and associated Mueller calculus can be applied to the description of completely, partially or unpolarized light.

1.4. POLARIZERS AND DEPOLARIZERS

1.4.1 Polarizer (perfect)

An optical device that produces a light beam with a unique state of polarization irrespective of the polarization of the incident light. The polarizer is called a linear, circular or elliptical polarizer depending on the state of polarization produced.

In the literature the unqualified term "polarizer" is frequently used to describe a linear polarizer.

1.4.2 Polarizer (imperfect)

A polarizer that in addition to transmitting a unique state of polarization does not completely exclude all other polarization states.

1.4.3 Transmission axis

The transmission axis of a perfect linear polarizer is defined as the direction of vibration of the emergent linearly polarized beam. For an imperfect polarizer, it is the direction of vibration of an incident linearly polarized beam for which the transmittance of the device is a maximum.

1.4.4 Principal transmittances

If the direction of vibration of an incident linearly polarized beam is oriented so that the transmittance of a polarizer is a maximum (i.e. the vibration direction is parallel to the transmission axis of the polarizer), then the ratio of transmitted to incident intensities is defined as the major principal transmittance, k_1 . The ratio obtained when the transmittance is a minimum is defined as the minor principal transmittance, k_2 .

1.4.5 Principal transmittance ratio

The principal transmittance ratio of a linear polarizer is defined as k_1/k_2 .

1.4.6 Extinction ratio

The extinction ratio of a linear polarizer is the inverse of the principal transmittance ratio, i.e. it is equal to k_2/k_1 . For unpolarized light incident in succession on a pair of polarizers of identical performance, the ratio of minimum (crossed polarizers) to maximum (parallel polarizers) intensities will equal

$$\frac{2k_1k_2}{k_1^2 + k_2^2} \quad \text{or } 2k_2/k_1 \quad \text{where } k_1 \gg k_2$$

1.4.7 Polarizance

The polarizance of a polarizer is the degree of linear polarization it produces when the incident light is unpolarized. In terms of principal transmittances, the polarizance is equal to $(k_1 - k_2)/(k_1 + k_2)$. If the incident beam of light is partially polarized, the degree of polarization produced by the polarizer will not be equal to its polarizance.

1.4.8 Depolarizer

An optical device that produces a beam of unpolarized light irrespective of the state of polarization of the incident light.

No simple and completely satisfactory way of depolarizing a light beam is known. Methods employed usually produce a large variety of polarization states with respect to time or wavelength or aperture of the light beam. Devices functioning on this principle are usually referred to as 'pseudodepolarizers'.