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Homogeneous polarized light by non-quadrature amplitude modulation

Cruz Meneses-Fabian*, Gildardo-Pablo Lemus-Alonso, Rosaura Kantun-Montiel, Uriel Rivera-Ortega

Facultad de Ciencias Físico-Matemáticas, Benemérita Universidad Autónoma de Puebla, Apartado Postal 165, Puebla, Pue. 72000, México

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A method to create homogenous polarized light based on non-quadrature amplitude modulation is proposed. This method consists of the addition of two optical fields out of phase, different from $m\pi$ and in the variation of their amplitudes, only for obtaining a resulting field modulated in both phase and amplitude. This principle is used to modulate the vertical components in both phase and amplitude, while the horizontal component is varied in amplitude but with a constant phase. Thus, any amplitude relation and phase difference between components can be created, and therefore any polarization state could be obtained. A theoretical model is shown and supported with numerical simulations of several polarization examples.

1. Introduction

The creation of homogeneously or inhomogeneously polarized optical fields has been an important task in polarimetry [1–4]. This is due to its great capacity and variety of application in several fields of science and technology such as biology, physics, chemistry, and so on [5,6]. In particular it has been useful in microscopy, characterization of materials, and string measurements [7,8]. For this reason polarization is one of the most important characteristics of an optical field. A homogeneously polarized beam has the same polarized state in the field's cross-section, also known as a scalar field, and an inhomogeneously polarized one has a different polarization state, also known as a vector field [1]. Recently, this last feature has received particular attention because of the optical angular momentum and to the formation of an axial component when it is focused [2]. On the other hand, it is very well known that to create a scalar or vector field a phase difference and an amplitude relation between the components have to be carried out. Typically, these two conditions are generated by dichroism [3], reflection [4], birefringence [9], and scattering [10]. In practice, any polarization state is created by means of different optical elements such as polarizers, retarder wave plates or rotators [3] or by spatial light modulators [11], among others [12]. Recently we have introduced a novel method for creating scalar fields, which was based on quadrature amplitude modulation (QAM) in phase and amplitude modulation (PAM) mode [13]. In that paper we proposed modulating the vertical component in both amplitude and phase by QAM, which consists of adding two auxiliary fields out of phase by $\pi/2$ and modulating their amplitudes only in order to obtain an amplitude relation and phase difference between components, and thus to obtain a desirable elliptical polarization state. However, in an experimental situation the phase difference of $\pi/2$ could not be easily obtained since it could vary because of mechanical vibrations or atmospheric turbulence or fabrication defects of the optical elements used.

For this reason and to give a generalization of this method, in this paper we report a study in which the auxiliary fields are not in quadrature, that is when their phase difference is different of $\pi/2$ or in general when it is within the range $(0, 2\pi)$. It is important to say that this method is carried out without using any typical optical method as reported before [3,4,9–12] to generate the two conditions mentioned above. This proposal consists of a theoretical description only by focusing on creating scalar fields; its extension for vector field could be immediate. Specifically, the present method is based on a non-quadrature amplitude modulation (NQAM) in PAM mode in order to modulate in amplitude and phase the vertical component of the field; this idea has been recently introduced for the case of quadrature amplitude modulation (QAM) to create polarized light [13] and in the phase-shifting interferometry [14–16] for the cases QAM and NQAM in the modality of phase modulation only.

The principal characteristic of this method deals with the modulation of each amplitude of two fields that are superposed

* Corresponding author. Tel.: +52 2224558902; fax: +52 2222295636.
E-mail address: cmeneses@fcfm.buap.mx (C. Meneses-Fabian).

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while their phase difference is kept constant within the range $(0, 2\pi)$. In this paper the vertical component is modulated in amplitude and phase by using this technique while the horizontal component is only modulated in amplitude. Thus a relation of amplitude and phase between components and a polarization state could be created, which can be graphically represented by using the well-known Poincaré sphere. For higher states of polarization of vector vortex beams that include radial and azimuthal polarized cylindrical vector beams, whose graphical representation can be done by the higher order Poincaré sphere as studied in [17].

2. Basic theory

In general, a homogeneous and monochromatic optical field, traveling in the z-direction as a plane wave and elliptically polarized can be described in complex form by

$$\mathbf{E}(z,t) = \mathbf{i}E_x(z,t) + \mathbf{j}E_y(z,t) = \mathbf{i}A_x e^{i(kz-\omega t+\alpha_x)} + \mathbf{j}A_y e^{i(kz-\omega t+\alpha_y)} = \mathbf{A}e^{i(kz-\omega t)}, \tag{1}$$

where E_x and E_y are the field components on x- and y-direction, as they are indicated with blue and orange lines in Fig. 1(a), while the resulting vector $\mathbf{E}$ is indicated with cyan line, whose amplitude complex vector is denoted by $\mathbf{A}$, in which all information of the polarization field is contained, that is

$$\mathbf{A} = \mathbf{i}A_x e^{i\alpha_x} + \mathbf{j}A_y e^{i\alpha_y} = \begin{pmatrix} A_x e^{i\alpha_x} \\ A_y e^{i\alpha_y} \end{pmatrix} = Ae^{i\alpha_x}\begin{pmatrix} \cos\sigma \\ e^{i\alpha}\sin\sigma \end{pmatrix}, \tag{2}$$

where the bold letter means the vector characteristic of the field A_x and A_y are the nonnegative real amplitudes, α_x and α_y are the initial phases of the wave components, $\mathbf{i}$ and $\mathbf{j}$ are the unitary vectors on x- and y-direction, $A = |\mathbf{A}|$ is the amplitude of the wave, $\alpha = \alpha_y - \alpha_x$ is the phase difference between the field components, σ is an auxiliary angle, related by means of $A_x = A\cos\sigma$, $A_y = A\sin\sigma$, and $\tan\sigma = A_y/A_x$, and i is the imaginary unit. Then, the polarization ellipse is written as,

$$\frac{E_x^2}{A_x^2} + \frac{E_y^2}{A_y^2} - 2\frac{E_x E_y}{A_x A_y}\cos\alpha = \sin^2\alpha \tag{3}$$

Fig. 1(b) shows this ellipse where as it is well known, its tilt angle ψ and its ellipticity angle ε are related in terms of the field parameters, in trigonometric terms [6]

$$\tan(2\psi) = \tan(2\sigma)\cos\alpha, \quad \sin(2\varepsilon) = \sin(2\sigma)\sin\alpha, \tag{4}$$

from Eqs. (6) to (8a) and (8b), the inverse relations can be deduced,

$$\tan\alpha = \tan(2\varepsilon)\csc(2\psi), \quad \cos(2\sigma) = \cos(2\varepsilon)\cos(2\psi), \tag{5}$$

with the angles limited by

$$\varepsilon \in \left[-\frac{\pi}{4}, +\frac{\pi}{4}\right], \ \psi \in \left[-\frac{\pi}{2}, +\frac{\pi}{2}\right], \quad \text{and} \quad \sigma \in \left[0, \frac{\pi}{2}\right], \tag{6}$$

where the positive or negative sign of ε distinguishes the right-handed or left-handed rotation of the polarization ellipse. So, when a polarization ellipse with a certain tilt angle, an ellipticity angle and a rotation sense is desired, they must be substituted in Eq. (5) to obtain a appropriated value of σ and α. Note that this treatment is developed by omitting the coordinates (x, y), which has been done because of the polarization in this study is considered homogenous, that is, the polarization state is the same in the field cross-section.

3. Space NQAM in optics

First, let us consider the horizontal component in which the amplitude A_x will be homogeneously varied and its phase α_x will be considered constant. In second place, the vertical component will be obtained by the NQAM method presented here in the modality PAM. This method considers two waves, with the same characteristics as those described in Eq. (1), but lineally polarized on the y-axis and out of phase by an arbitrary value different of $m\pi$, such as,

$$E_{1y} = A_{1y}e^{i(kz-\omega t+\alpha_{1y})} \quad \text{and} \quad E_{2y} = A_{2y}e^{i(kz-\omega t+\alpha_{2y})}, \tag{7}$$

where A_{1y} and A_{2y} are the spatially constants amplitudes, α_{1y} and α_{2y} are the initial phases of the fields whose difference must comply $\alpha_{2y} - \alpha_{1y} = \Delta\alpha_y \neq m\pi$ with m integer. The superposition of these waves could be written by,

$$E_y = E_{1y} + E_{2y} = (A_{1y}e^{i\alpha_{1y}} + A_{2y}e^{i\alpha_{2y}})e^{i(kz-\omega t)} = A_y e^{i\alpha_y} e^{i(kz-\omega t)}, \tag{8a}$$

consequently

$$A_{1y}e^{i\alpha_{1y}} + A_{2y}e^{i\alpha_{2y}} = A_y e^{i\alpha_y}, \tag{8b}$$

where the amplitude A_y and the phase α_y are related by

$$A_y^2(A_{1y}, A_{2y}) = A_{1y}^2 + A_{2y}^2 + 2A_{1y}A_{2y}\cos\Delta\alpha_y, \tag{9a}$$

$$\tan\alpha_y(A_{1y}, A_{2y}) = \frac{A_{1y}\sin\alpha_{1y} + A_{2y}\sin\alpha_{2y}}{A_{1y}\cos\alpha_{1y} + A_{2y}\cos\alpha_{2y}}, \tag{9b}$$

so the amplitude and phase of the vertical component of field in Eqs. (8a) and (8b) will be modulated by the amplitude-only of the two initial waves given in Eq. (7). The minimum amplitude of A_y is zero and its maximum amplitude depends on the maximum amplitudes of A_{1y} and A_{2y}. If the amplitudes take positive and negative values, the range corresponding to α_y could be $[0, 2\pi]$, which can be met if a suitable phase change of π in the waves is done.

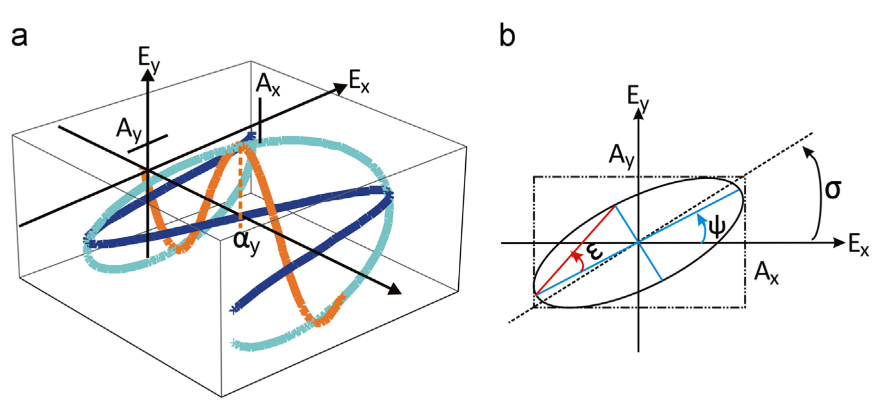

Fig. 1. The amplitude relation and relative phase difference between the field components giving any polarization state: (a) the field components and (b) the polarization ellipse. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)