Analysis of the spectral structure of the light modulated by means of transverse electrooptic modulator with two ADP crystals and a half-wave plate

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In this work we performed an analysis, in Jones matrix formalism, of the temporal evolution and the of harmonic structure of the light modulated by transverse electrooptic effect in a modulator with two ADP crystals and a half wave plate placed between them, for an arbitrary bias voltage applied to the ADP crystals. The most important cases for applications, no bias voltage and quarter-wave plate bias voltage applied to the ADP crystals, are particularized. The spectrum of the modulator output intensity is presented both theoretically and experimentally.

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1. Introduction

The ADP crystals are widely encountered in the structure of the both longitudinal electrooptic modulators and transvesverse electrooptic modulators. The ADP crystals in a longitudinal electrooptic effect configuration have a high half-wave voltage, of the order of kV. For decreaseing this half-wave voltage one should increase the number of crystals used, what involves the decrease of the output power. The ADP crystals with transverse electrooptic effect does not present this inconvenience, the half-wave voltage can be reduced by appropriate choice of the crystal size.

Because in transvese electrooptic effect the light does not propagate along the optical axis of the crystal, occurs, in addition to electrically induced birefringence, a natural birefringence. This depends on the crystal temperature. Natural birefringence can be compensated by means of a system with two crystals and a half-wave plate between them [1]. The half-wave plate transforms the ordinary ray (O) of the first crystal in extraordinary ray (E) for the second one, respectively, the extraordinary ray of first crystal in ordinary ray for second crystal, and thus natural birefringence is compensated, Fig. 1.

The interaction between the polarized light and the time-varying polarization devices can be analyzed in the Jones or Stokes matrix formalisms [2-6] or in a pure operatorial one [7].

This article presents an analysis, in the Jones matrix formalism, of the temporal modulation of the state of polarization (SOP) of the light by a transverse electrooptic modulator, that consists of two identical ADP crystals and an half-wave plate placed between them (the so-called "tandem arrangement"). It also presents graphically the evolution of the temporal and spectral structure of the modulated light intensity.

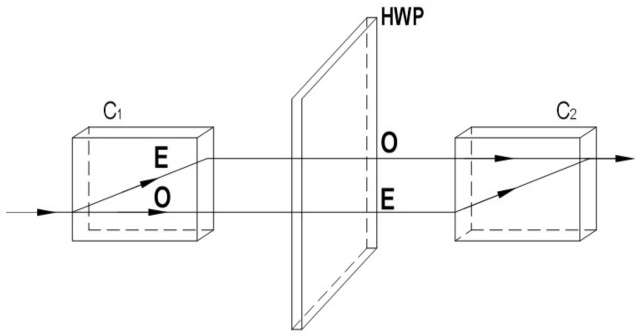

Fig. 1. Compensation of the natural birefringence of the ADP crystals in a tandem arrangement.

Such an analysis is important in conection with the transmision of information on laser beams and by optical fibers [8-9].

2. The matrix of the modulator

The ADP crystals are identical, with parallel electrodes, the modulating voltage is applied perpendicular on the direction of propagation of the light, thus the crystals exhibit transverse electrooptic effect. Between crystals is placed a half-wave plate for compensating the natural birefringence introduced by the ADP crystals. The scheme of the modulator is presented in Fig. 2.

The matrix analysis of the modulator is performed in the $OXYZ$ coordinate system. The neutral lines of the half-wave plate are parallel with the axes of the $OXYZ$ coordinate system (fast axis of the half-wave plate is parallel with OX axis). The light propagates along OZ axis, linearly polarized at 45° to the OX axis.

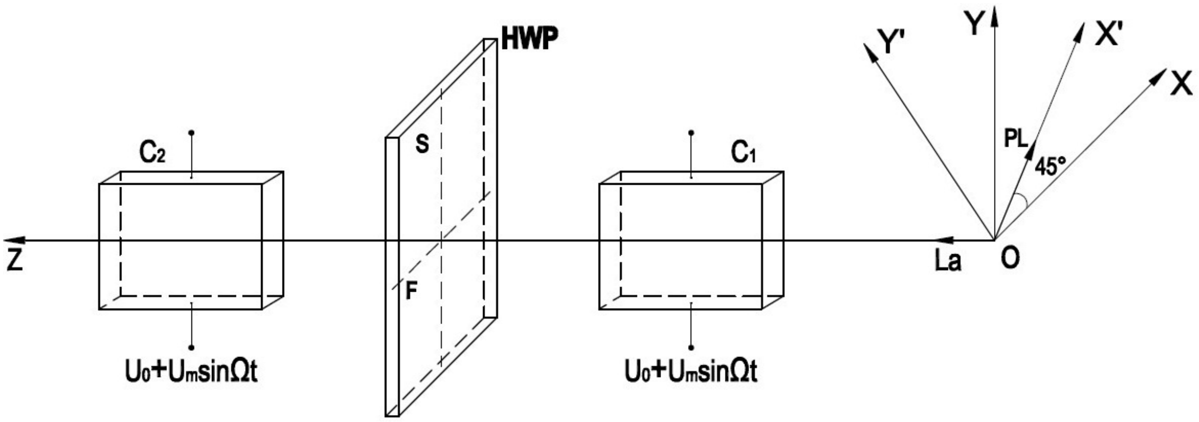

Fig. 2. Modulator with two ADP crystals and a half-wave plate between them.

If we apply to the crystals a modulating voltage with a d.c. component U_0, as well as a harmonically-varying one, $U_m \sin \Omega t$, they behave as phase shifters, whose phase shift between linearly polarized components along the OX and OY axes is [10-12]:

$$2\Phi = 2(\Phi_0 + \Gamma \sin \Omega t) \tag{1}$$

where:

$$2\Phi_0 = \pi \frac{U_0}{U_{\lambda/2}}, \; 2\Gamma = \pi \frac{U_m}{U_{\lambda/2}}, \tag{2}$$

and $U_{\lambda/2}$ is the half-wave voltage of the ADP crystals.

The matrices of the ADP crystals in the OXY coordinate system are identical, their expressions being [13]:

$$M_1 = M_2 = \begin{pmatrix} e^{i\Phi} & 0 \\ 0 & e^{-i\Phi} \end{pmatrix} \tag{3}$$

The matrix of the half-wave plate is [14]:

$$M_{\lambda/2} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{4}$$

Consequently the Jones matrix of the whole modulator is given by the formula [9]:

$$M = M_2 M_{\lambda/2} M_1 \tag{5}$$

By substituting the expressions of the matrices M_1, M_2 and $M_{\lambda/2}$ in the equation (5), the Jones matrix of the modulator becomes:

$$M = \begin{pmatrix} e^{2i\Phi} & 0 \\ 0 & -e^{-2i\Phi} \end{pmatrix} = \begin{pmatrix} e^{i(2\Phi_0 + 2\Gamma \sin \Omega t)} & 0 \\ 0 & -e^{-i(2\Phi_0 + 2\Gamma \sin \Omega t)} \end{pmatrix} \tag{6}$$

The equation (6) shows that the modulator behaves as a wave plate whose phase shift between the linearly polarized components along the OX and OY axes is time-varying The modulator acts on the incident polarized light as a dynamic polarization optical device.

3. Spectral analysis of the Jones vector of the modulated light relative to the $OX'Y'Z'$ coordinate system

The Jones matrix of the modulator, M', in the $OX'Y'Z'$ coordinate system is determined according to the Jones matrix, M, in the coordinate system $OXYZ$, by the formula [15]:

$$M' = R(-\theta) M R(\theta) \tag{7}$$

where, $R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$, is Jones matrix of rotation, and θ the angle of rotation of the $OX'Y'Z'$ coordinate system relative to the $OXYZ$ coordinate system.

In the our case $\theta = 45^\circ$, thus we obtain for M' Jones matrix the following expression:

$$M' = \begin{pmatrix} i\sin 2\Phi & \cos 2\Phi \\ \cos 2\Phi & i\sin 2\Phi \end{pmatrix} = \begin{pmatrix} i\sin 2(\Phi_0 + \Gamma \sin \Omega t) & \cos 2(\Phi_0 + \Gamma \sin \Omega t) \\ \cos 2(\Phi_0 + \Gamma \sin \Omega t) & i\sin 2(\Phi_0 + \Gamma \sin \Omega t) \end{pmatrix} \tag{8}$$

By using the formulae [16]:

$$\cos\left(2\Gamma\sin\Omega t\right)=\sum_{n=-\infty}^{\infty}J_{2n}\left(2\Gamma\right)e^{i2n\Omega t}$$
$$\sin\left(2\Gamma\sin\Omega t\right)=-i\sum_{n=-\infty}^{\infty}J_{2n-1}\left(2\Gamma\right)e^{i(2n-1)\Omega t} \tag{9}$$

where $J\left(2\Gamma\right)$ are Bessel functions of the first kind, the M' Jones matrix may be developed in Fourier series as follows:

$$M'=\sum_{n=-\infty}^{\infty}J_{2n}\left(2\Gamma\right)\begin{pmatrix} i\sin 2\Phi_0 & \cos 2\Phi_0 \\ \cos 2\Phi_0 & i\sin 2\Phi_0 \end{pmatrix}\exp(i2n\Omega t)$$
$$+\sum_{n=-\infty}^{\infty}J_{2n+1}\left(2\Gamma\right)\begin{pmatrix} \cos 2\Phi_0 & i\sin 2\Phi_0 \\ i\sin 2\Phi_0 & \cos 2\Phi_0 \end{pmatrix}\exp\left[i(2n+1)\Omega t\right] \tag{10}$$

From the above equation we observe that elements of the matrices oscillate harmonically. The frequency of oscillation is an integer multiple of the modulating voltage's frequency. The amplitudes of various elements depend on the corresponding order Bessel functions of 2Γ, implicitly of the alternative voltage amplitude, U_m, and the value of the term Φ_0, and thereby, of value of the d.c. component U_0.

The equation (10) reveals that the modulator have only two reprezentative matrices:

$$M_{2n}'=\begin{pmatrix} i\sin 2\Phi_0 & \cos 2\Phi_0 \\ \cos 2\Phi_0 & i\sin 2\Phi_0 \end{pmatrix} \text{ and}$$
$$M_{2n+1}'=\begin{pmatrix} \cos 2\Phi_0 & i\sin 2\Phi_0 \\ i\sin 2\Phi_0 & \cos 2\Phi_0 \end{pmatrix}$$

These matrices are time invariant and determine a well-defined polarization state (SOP) in the light emerging from modulator. Each of them corresponds to a static alteration of the incident polarized light . Both correspond to a wave plate of a phase diference determined by the dc voltage applied to the crystals [4].

The incident light on modulator is characterized, in the $OX'Y'Z'$ coordinate system, by J'_{in} Jones vector. It has the formula [4, 9]:

$$J'_{in}=\begin{pmatrix} 1 \\ 0 \end{pmatrix}e^{i\omega_0 t} \tag{11}$$

Thus, the J'_M Jones vector of the modulated light, in the $OX'Y'Z'$ coordinate system, is [9]:

$$J'_M=M'J'_{in}=\begin{pmatrix} i\sin 2\Phi \\ \cos 2\Phi \end{pmatrix}=\begin{pmatrix} i\sin 2(\Phi_0+\Gamma\sin\Omega t) \\ \cos 2(\Phi_0+\Gamma\sin\Omega t) \end{pmatrix}=\begin{pmatrix} E_{X'}(t) \\ E_{Y'}(t) \end{pmatrix} \tag{12}$$

The J'_M vector is a periodically time-varying Jones vector, so it represents a periodically time-varying state of polarization. Thus, the state of polarization of the light emerging from modulator is temporally modulated. $E_{X'}(t)$ and $E_{Y'}(t)$ are the components of the electric field vector of the modulated light.

By using the formulae (9), the Jones vector J'_M may be developed into Fourier series as follows:

$$J'_M=\sum_{n=-\infty}^{\infty}J_{2n}\left(2\Gamma\right)e^{i(\omega_0+2n\Omega)t}\begin{pmatrix} i\sin 2\Phi_0 \\ \cos 2\Phi_0 \end{pmatrix}+\sum_{n=-\infty}^{\infty}J_{2n-1}\left(2\Gamma\right)e^{i[\omega_0+(2n-1)\Omega]t}\begin{pmatrix} \cos 2\Phi_0 \\ i\sin 2\Phi_0 \end{pmatrix} \tag{13}$$

The spectral structure of the modulated light contains the optical carrier ω_0 and sidebands at multiples of the modulation frequency Ω.

Some general features of the state of polarization (SOP) of the modulated light arise from the equation (13):

- The SOP of each spectral component of the modulated light is fully described by representative Jones vectors:

$$J'_{even}=\begin{pmatrix} i\sin 2\Phi_0 \\ \cos 2\Phi_0 \end{pmatrix} \text{ and } J'_{odd}=\begin{pmatrix} \cos 2\Phi_0 \\ i\sin 2\Phi_0 \end{pmatrix}$$

- The SOP remains unchanged for each spectral component, only their amplitudes, depend on the maximum alternative voltage applied to the crystals, oscillate with a pulsation $\omega_0+k\Omega$, k -integer.
- The SOP of all even-ordered spectral components of the emergent light is the same, generally elliptical. The SOP of all odd-ordered spectral components is, also, the same, generally elliptical. The axes of the SOP ellipses are oriented along OX' and OY' axes. The SOP depends on the value of dc bias applied to the ADP crystals.
- The states of polarization of the spectral components by even order and odd order are orthogonal:

$$J'_{even}\cdot J'_{odd}=\left(-i\sin 2\Phi_0 \quad \cos 2\Phi_0\right)\begin{pmatrix} \cos 2\Phi_0 \\ i\sin 2\Phi_0 \end{pmatrix}=0$$

- The SOP of the spectral components by even order and, respectively, by odd order are symmetrical with respect to the axes of the $OXYZ$ coordinate system.

If $S = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ is Jones symmetry matrix then:

$$SJ'_{even} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} i\sin 2\Phi_0 \\ \cos 2\Phi_0 \end{pmatrix} = \begin{pmatrix} \cos 2\Phi_0 \\ i\sin 2\Phi_0 \end{pmatrix} = J'_{odd}$$

and, respectively, $SJ'_{odd} = J'_{even}$.

The features of the SOP for arbitrary dc voltage, U_0, applied to the ADP crystals, can be analyzed and by means of the graphical representation from figure 3, where we have considered only optical carrier and first six spectral components from development (13).

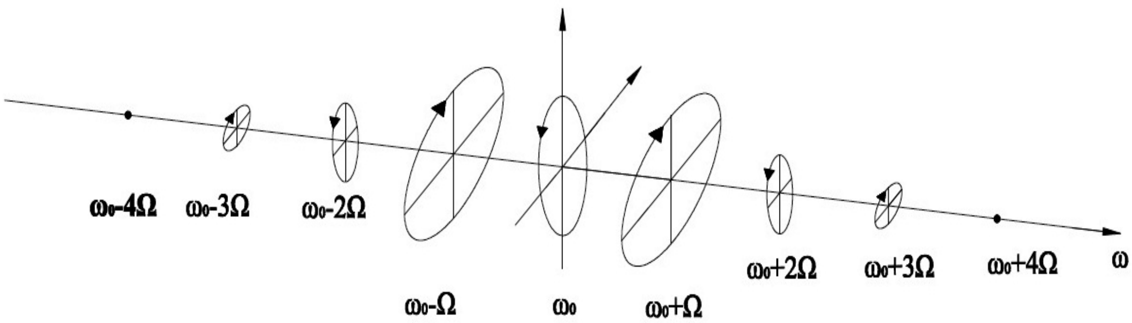

Fig. 3. The graphical reprezentation of the SOP for an arbitrary dc voltage.

In function by dc voltage, U_0, the applied to the ADP crystals, the harmonics of even order or odd order from equation (13) can be suppressed in block:

a) For no dc voltage applied to the ADP crystals: $U_0 = 0$, $\Phi_0 = 0^\circ$. By using the formula (13) the Jones vector of the modulated light has the expression:

$$J'_M = \sum_{n=-\infty}^{\infty} J_{2n}(2\Gamma) e^{i(\omega_0 + 2n\Omega)t} \begin{pmatrix} 0 \\ 1 \end{pmatrix} + \sum_{n=-\infty}^{\infty} J_{2n-1}(2\Gamma) e^{i[\omega_0 + (2n-1)\Omega]t} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \tag{14}$$

The even-ordered components are linearly polarized along the OY' axis, the transverse to the polarization direction of the incident light on modulator. Thus, the modulator acts on these components in the same way as a half-wave plate, although no dc voltage is applied to the ADP crystals.

The odd-ordered components have the same SOP as the incident light on modulator, so, these are linearly polarized along OX' axis. The modulator acts on odd-ordered components of the modulated light as a zero wave plate.

The SOP of each spectral component from equation (14) is represented in Fig. 4.

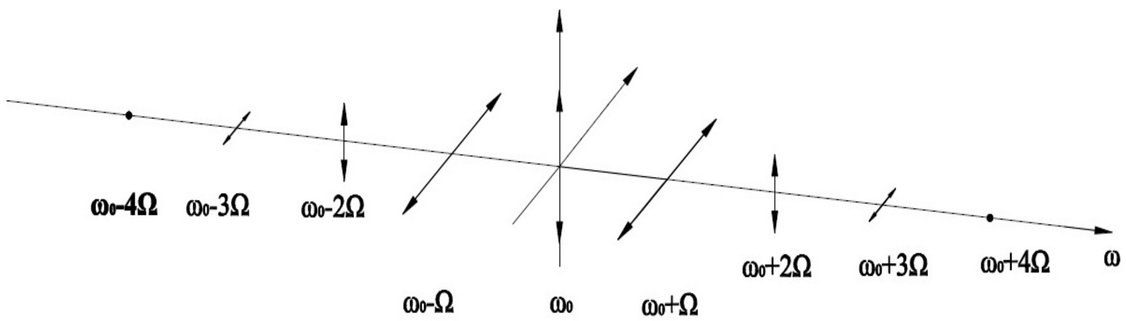

Fig. 4. The graphical reprezentation of the SOP for dc voltage $U_0 = 0$.

b) Quater-wave plate dc voltage applied to the ADP crystals: $U_0 = U_{\lambda/4}$, $2\Phi_0 = \frac{\pi}{2}$. From equation (13) we obtain for the Jones vector of the modulated light the expression:

$$J'_M = i\left\{\sum_{n=-\infty}^{\infty} J_{2n}\left(2\Gamma\right)e^{i(\omega_0+2n\Omega)t}\begin{pmatrix}1\\0\end{pmatrix}+\sum_{n=-\infty}^{\infty} J_{2n-1}\left(2\Gamma\right)e^{i[\omega_0+(2n-1)\Omega]t}\begin{pmatrix}0\\1\end{pmatrix}\right\} \tag{15}$$

In this case, the even-ordered components emerge from the modulator with the same SOP as the incident light on modulator. The spectral polarization action of the modulator on these components is that of a zero wave plate. The SOP of the odd-ordered spectral components are symmetrical (with respect to the OX and OY axes) and orthogonal relative to that of the incident polarized light. For these components the modulator acts as a half-wave plate. The spectral structure of the SOP is represented in Fig. 5.

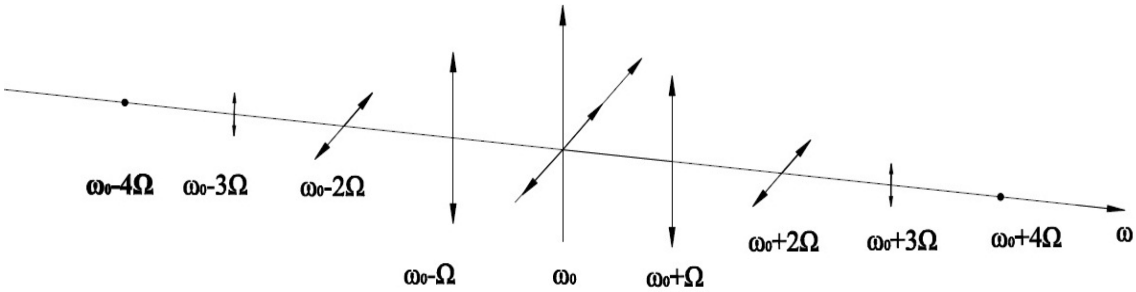

Fig. 5. The graphical reprezentation of the SOP for dc voltage $U_0 = U_{\lambda/4}$.

4. The spectrum of the modulated light intensity

Most direct information in regard to modulated light in terms of measurable quantities are given by light intensity [6]. Polarized light along the OX' and OY' axes , after crossing the modulator, undergoes a temporal modulation of the state of polarization. If after the modulator is placed an *A* polarizer then the light emerging from modulator is modulated in intensity. The light intensity can be determined by using a *Ph* photodetector.

When transmission axis of the A polarizer is parallel to the polarization direction of the incident light is determined the component of the light intensity on OX' axis ($I_{X'}$). If transmission axis of the polarizer is orthogonal to the polarization direction of the incident light then is determined the component of the light intensity on OY' axis ($I_{Y'}$).

The intensity of the linearly polarized light along the OX' and OY' axes is proportional to the square of the Jones vector components, $E_{X'}(t)$ and $E_{Y'}(t)$, of the modulated light emerging from modulator-analyzer system [3, 9, 13]. From the expression (12) we obtain modulated light intensities emerging from A analyzer, in the $OX'Y'Z'$ coordinate system:

$$I_{X'} = \frac{1}{2}\left|E_{X'}\right|^2 = \frac{1}{2}\sin^2 2\Phi = \frac{1}{4}(1-\cos 4\Phi) = \frac{1}{4}[1-\cos 4(\Phi_0+\Gamma\sin\Omega t)]$$
$$I_{Y'} = \frac{1}{2}\left|E_{Y'}\right|^2 = \frac{1}{2}\cos^2 2\Phi = \frac{1}{4}(1+\cos 4\Phi) = \frac{1}{4}[1+\cos 4(\Phi_0+\Gamma\sin\Omega t)] \tag{16}$$

By applying the formulae [16]:

$$\cos\left(4\Gamma\sin\Omega t\right) = J_0(4\Gamma)+2\sum_{n=1}^{\infty} J_{2n}\left(4\Gamma\right)\cos\left(2n\Omega t\right)$$
$$\sin\left(4\Gamma\sin\Omega t\right) = 2\sum_{n=1}^{\infty} J_{2n-1}\left(4\Gamma\right)\sin\left[\left(2n-1\right)\Omega t\right] \tag{17}$$

the intensity components have the following spectral development:

$$I_{X',Y'} = \frac{1}{4}\left\{1\mp\cos 4\Phi_0\left[J_0(4\Gamma)+2\sum_{n=1}^{\infty} J_{2n}(4\Gamma)\cos(2n\Omega t)\right]\pm\sin 4\Phi_0\left[2\sum_{n=1}^{\infty} J_{2n-1}(4\Gamma)\sin(2n-1)\Omega t\right]\right\} \tag{18}$$

The analysis of equation (18) reveals the following features of the modulated light intensity components:

- Have the same harmonic structure, except that, between any two harmonics of the same order there is a phase difference of π rad.
- Contains a steady term.
- Appear all multiples of the modulating frequency.
- The amplitudes of various harmonics are depend on constant voltage U_0 by means of sine or cosine trigonometric functions of $4\Phi_0$ argument and of the amplitude of the harmonic voltage U_m, by means of Bessel functions of the first kind of argument 4Γ.
- The number of spectral components increases with the modulation index, Γ.
- All spectral components of odd or even order can be canceled for certain values of d.c. voltage U_0.

In the following, we present the spectral structure of the modulated light intensity in the same two important cases: for no and quarter wave dc voltage applied to the ADP crystals.

a) For no dc voltage applied to the ADP crystals: $U_0 = 0$, $\Phi_0 = 0^\circ$. From (18) it is obtained:

$$I_{X',Y'} = \frac{1}{4}\left[1 \mp J_0(4\Gamma) \mp 2\sum_{n=1}^{\infty} J_{2n}(4\Gamma)\cos(2n\Omega t)\right] \quad (19)$$

The intensity components contain only even order harmonics of the modulating frequency. The spectrum of the intensity is that of the beat frequency pattern between the harmonic components of the electric field vector.

b) Quater-wave plate dc voltage applied to the ADP crystals: $U_0 = U_{\lambda/4}$, $2\Phi_0 = \frac{\pi}{2}$. In this case equation (18) gives:

$$I_{X',Y'} = \frac{1}{4}\left[1 \pm J_0(4\Gamma) \pm 2\sum_{n=1}^{\infty} J_{2n}(4\Gamma)\cos(2n\Omega t)\right] \quad (20)$$

We obtain the same harmonics as in the previous case, but harmonics of a certain order differ from those in the case a) with a phase difference of π rad.

The scheme of the experimental setup for the study of the modulated light intensity is represented in the Fig. 6.

The light source, the He-Ne laser ($\lambda = 632,8nm$) *La,* emits unpolarized light. The linear polarizer *P* transforms incident light in linearly polarized light. The modulator *M* modulates light by transverse electrooptic effect. The linear polarizer *A,* with the role of an analyzer, selects one of the orthogonal components of the modulated light intensity. The photodetector *Ph* provides an electrical signal proportional to the intensity of incident light. Through the MatLab program can be plotted the temporal evolution and spectral structure of the orthogonal components of the modulated light intensity, $I_{X'}$ şi $I_{Y'}$, for various values of the dc voltage U_0 and of the amplitude of the alternative voltage U_m applied to the modulator.

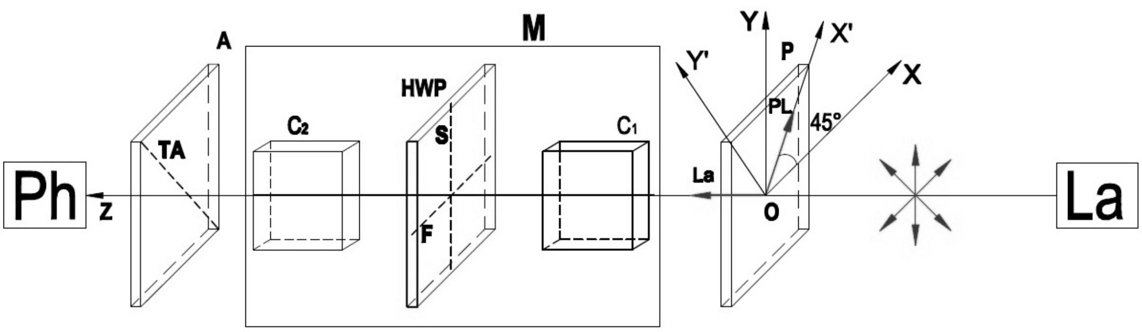

Fig. 6. Experimental setup. La: He-Ne laser, P: Linear polarizer, M: Transverse electrooptic modulator, A: Linear analyzer, Ph: Photodetector.

In the following figures are represented the temporal evolution and spectral structure of the components of the modulated light intensity, $I_{X'}$ şi $I_{Y'}$, for four pairs of values of the d.c. voltage U_0 and the amplitude of the alternative voltage U_m applied to the modulator: ($U_0 = 0V$, $U_m = 50V$), ($U_0 = 0V$, $U_m = 400V$), ($U_0 = U_{\lambda/4}$, $U_m = 50V$), ($U_0 = U_{\lambda/4}$, $U_m = 400V$).

The half-wave voltage of the ADP crystals is $U_{\lambda/2} = 200V$, and modulating frequency is $\nu = 2250Hz$.

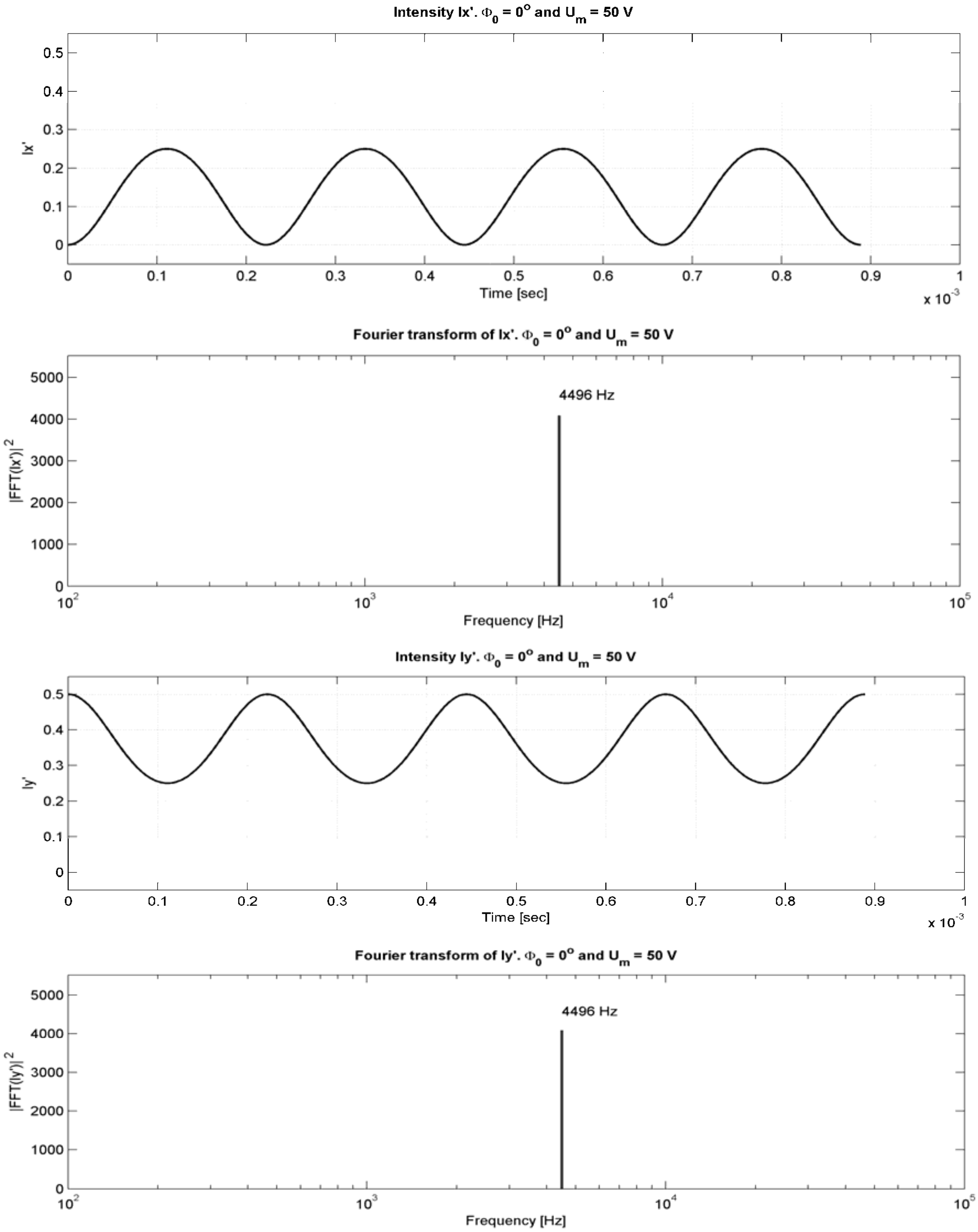

Fig. 7. The temporal evolution and spectral structure of the components of the modulated light intensity for $U_0 = 0V$ *and* $U_m = 50V$.

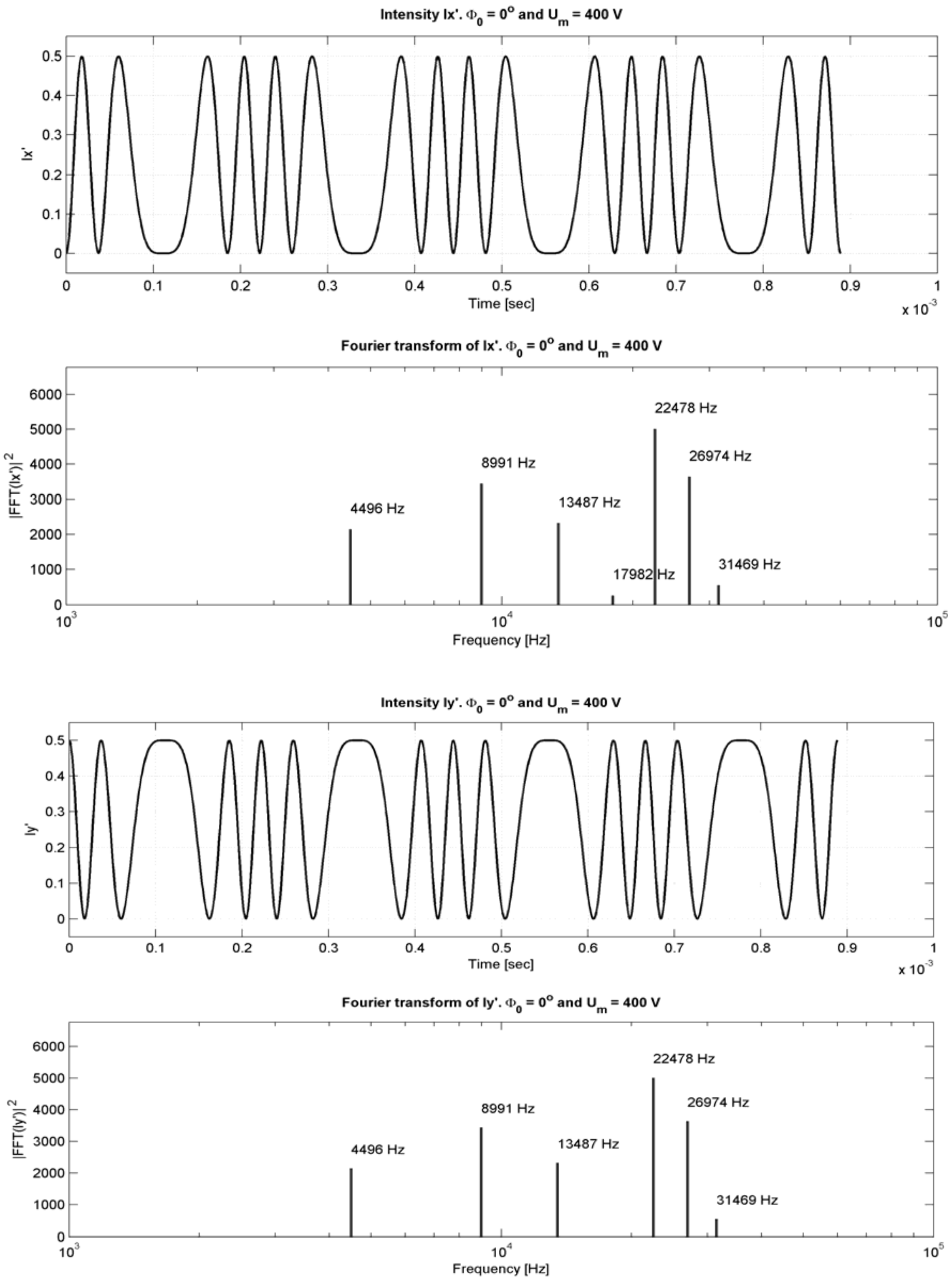

Fig. 8. The temporal evolution and spectral structure of the components of the modulated light intensity for $U_0 = 0V$ and $U_m = 400V$.

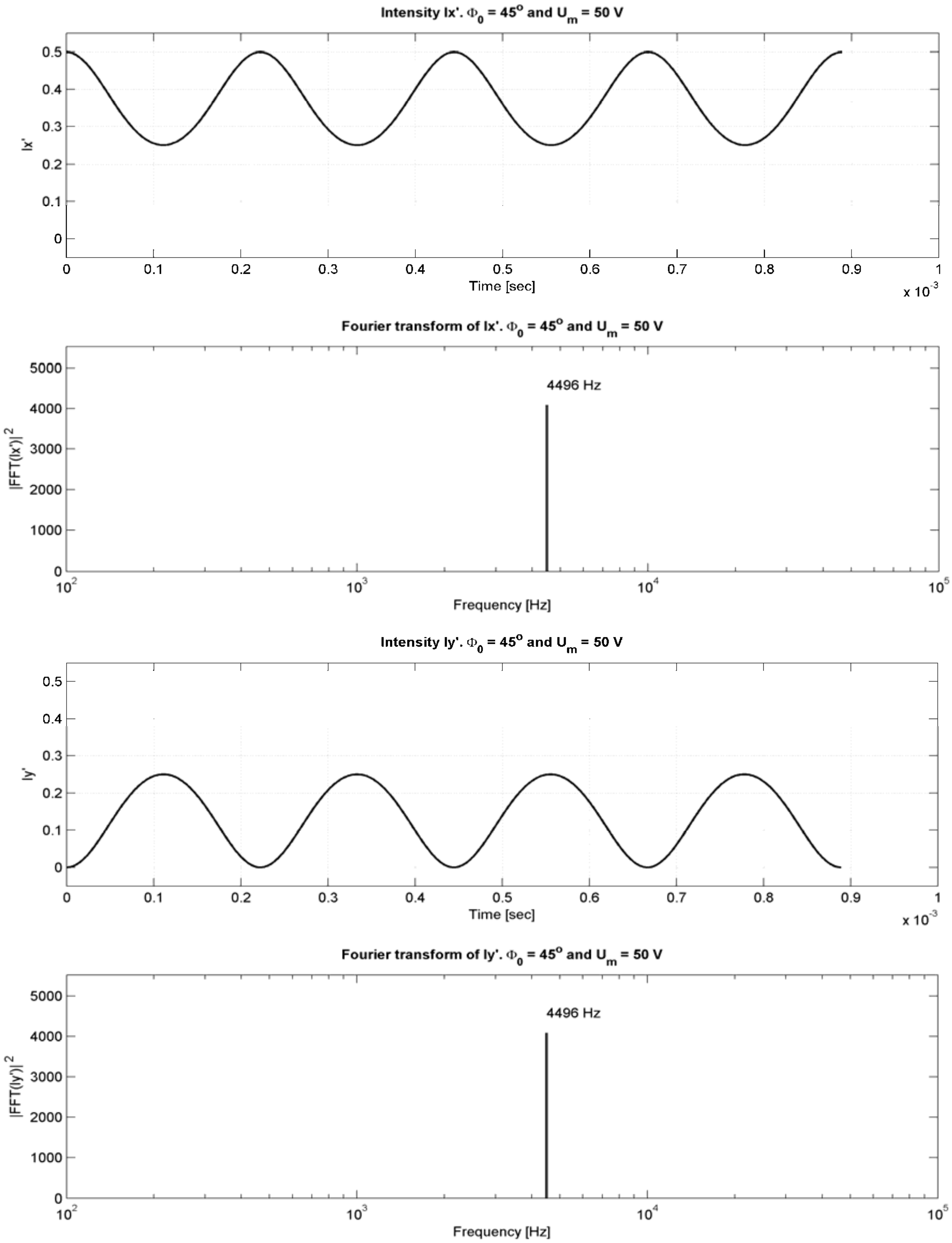

Fig. 9. The temporal evolution and spectral structure of the components of the modulated light intensity for $U_0 = U_{\lambda/4}$ *and* $U_m = 50V$.

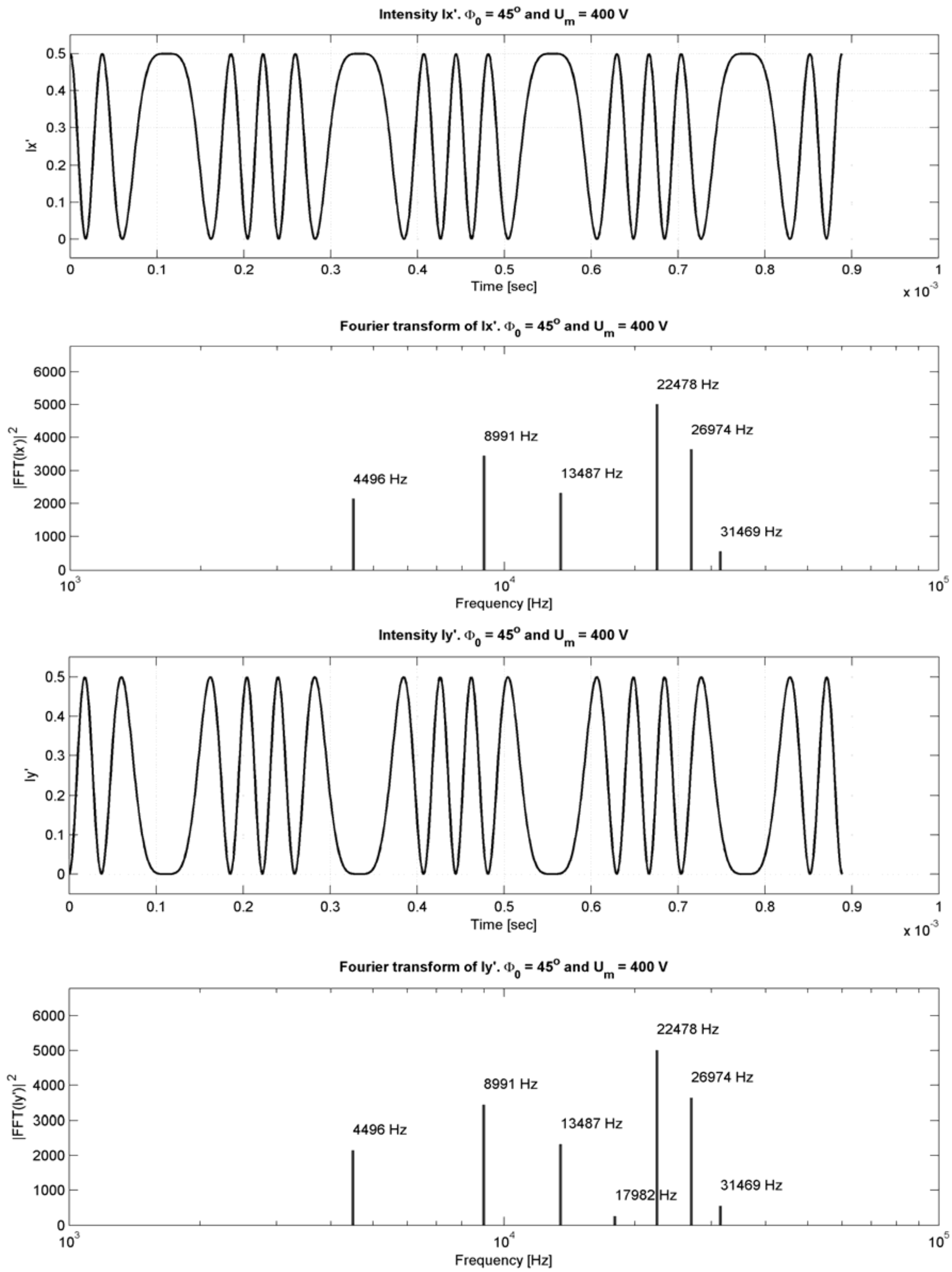

Fig. 10. The temporal evolution and spectral structure of the components of the modulated light intensity for $U_0 = U_{\lambda/4}$ *and* $U_m = 400V$.

5. Conclusions

This modulator, with two ADP crystals and a half-wave plate placed between them, acts on the incident light as a dynamic polarization optical device that transforms a stationary optical Jones vector in a time-varying one, thus it temporally modulates the state of polarization of the incident light.

The spectral structure of the Jones matrix of the modulator reveals that the action of the modulator represents a superposition of elementary spectral polarization actions, each of them occurring at an integer multiple of the modulating frequency. All even-ordered components have the same reprezentative matrix, all odd-ordered components have the same reprezentative matrix, too. Both reprezentative matrices are time invariant and determine a well-defined polarization state in the light emerging from modulator. They correspond to a wave plate of a phase diference determined by the dc voltage applied to the crystals.

The SOP of the modulated light has been also described in terms of the spectral structure of the corresponding time varying Jones vector. The SOP of all even-ordered spectral components of the modulated light is the same, generally elliptical. The SOP of all odd-ordered spectral components is the same, generally elliptical, too. The SOP depends on the value of dc bias applied to the ADP crystals. The modulating voltages determine only the amplitudes of the sidebands. For each spectral component the SOP remains unchanged, only its amplitude depend on the maximum alternative voltage applied to the crystals oscillate with a pulsation $\omega_0 + k\Omega$, k -integer. The SOPs of the spectral components of even order and those of odd order are orthogonal and symmetrical with respect to the axes of the $OXYZ$ coordinate system.

The modulated light intensity components have the same harmonic content, except that, any two harmonics of the same order oscillate in phase opposition. These contain a steady term and all multiples of the modulating frequency. The amplitudes of various harmonics depend upon the Bessel function of four times modulation index Γ, implicitly of the amplitude of the harmonic voltage applied to the ADP crystals. The number of spectral components increases with the modulation index. For certain values of d.c. voltage applied to the ADP crystals all the even order spectral components or all the odd order spectral components can be canceled.

We mention that similar matrix analyses may be performed in the spatial modulation polarization state largely used in biological application [17, 18] and metrology [19].

We have to underline that the problem of light modulation by dynamical electrooptic devices integrates to the very general problem of dynamics of two-state systems [20].

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