Modern Acousto-Optics: Physics and Applications

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Part 1: Acousto-optical technique for spectrum analysis of radio-wave and optical signals in astrophysics.

Part 2: Multi-wave coupled states in acousto-optics.
Part 1:
Acousto-optical technique for multi-channel spectrum analysis of ultra-high frequency radio-signals and optical signals over all the visible range; possible applications to the astrophysical needs.

In collaboration with: 1) Astrophysics Department of the INAOE,
2) Molecular Technology GmbH (Berlin, Germany),
3) Saint-Petersburg State Polytechnic University (St. Petersburg, Russia),
4) Institute for Applied Physics (Madrid, Spain).
Outline

- Introduction: Regimes of operation for the acousto-optic cells.
- The Bragg acousto-optical interaction in anisotropic medium.
- A one-phonon non-collinear acousto-optical interaction:
  The number of resolvable spots. Estimations for a tellurium dioxide crystal.
- A two-phonon non-collinear light scattering:
  The number of resolvable spots. Estimations for a tellurium dioxide crystal.
- Experimental data related to a multi-phonon light scattering in tellurium dioxide cell.
- General schematic arrangement for prototype of an advanced acousto-optical spectrometer.
- The first experimental data related to the spectrum analysis
  of analogous high-frequency radio-wave signals within a one-phonon light scattering.
- Collinear acousto-optical interaction and the opportunity of filtering analogous optical signals.
- Potential spectral resolution of a calcium molybdate crystal based collinear filter.
- Conclusive remarks.
Regimes of operating for the AO-cells

There are two limiting cases for light diffraction (scattering) regimes:

1. Raman-Nath regime (short $L$), in which the diffraction maxima are given by
   \[
   \sin \theta_p = \sin \theta_0 + p \lambda / n \Lambda ,
   \]
   where $Q = \lambda L / \Lambda^2 << 1$ and $\Lambda = V / f$.

2. Bragg regime (long $L$), in which the Bragg condition is given by
   \[
   \sin \theta_B = \lambda / 2n \Lambda ,
   \]
   where $Q = \lambda L / \Lambda^2 >> 1$.

Scattering light by a thin dynamic acoustic grating.

Scattering light by a thick dynamic acoustic grating.

The parameter $Q$ is the Klein–Cook factor characterizing the regime.
Plots for the light intensities in various orders of scattering

The Raman-Nath limit; $Q << 1$.

Conservation laws inherent in such interactions are

- $\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3$ or $\mathbf{p} = \hbar \mathbf{k}$
- $\omega_1 + \omega_2 = \omega_3$ or $E = \hbar \omega$

Since in conventional acousto-optics, $\omega_1, \omega_3 \approx 10^{14}$ Hz and $\omega_2 = \Omega \leq 10^9$ Hz, so that $\Omega / \omega \approx 10^{-5}$ and $E_{\text{photon}} \approx 10^{-5} E_{\text{phonon}}$.

Because $c = 3 \cdot 10^{10}$ cm/s and $V \approx 3 \cdot 10^5$ cm/s, we yield $V / c \approx 10^5$, $\omega_1 / c \approx \Omega / V$, and $k_{\text{photon}} \approx K_{\text{phonon}}$. 

The Bragg limit; $Q >> 1$. 

$S = \frac{1}{2} \sin^2(qz)$

$I_0 = \cos^2(qz)$
Realizing the parallel spectrum analysis by a TeO2 acousto-optical cell in the Bragg regime
A one-phonon light scattering

1. Normal scattering

\[ x = L \]
\[ \eta_0 L = 2\pi \]
\[ \delta \varphi = \frac{V}{(f_1 L)} \]

\[ \sin \theta = \frac{\lambda f_1}{2n V} \]
\[ \Delta f_1 = \frac{2n V^2}{\lambda L f_1} \]

2. Optimized anomalous scattering

\[ \Delta^2 = |n_0^2 - n_1^2| \]
\[ f_0 = \frac{V \Delta}{\lambda} \]
\[ x = L \]
\[ \eta_0 L = 2\pi \]
\[ \delta \varphi = \frac{V}{(f_0 L)} \]

\[ \sin \theta_{0,1} = \frac{\lambda f_1}{2n_{0,1} V} \left( 1 \pm \frac{\Delta^2 V^2}{\lambda^2 f_1^2} \right) \]
\[ \Delta f_0 = 2V \sqrt{\frac{2n_0}{\lambda L}} \]

The comparison for TeO_2-crystal shows that generally: \( \Delta f_1 < \Delta f_0 \).
A two-phonon acousto-optical interaction

Conservation laws: \( \omega_{m+1} = \omega_m + \Omega \) and \( \vec{k}_{m+1} = \vec{k}_m + \vec{K} \) (\( m = 0,1,2 \)).

A two-phonon Bragg scattering of light occurs when

\[
\sin \theta_0 = (n_0)^{-1} \sqrt{n_0^2 - n_1^2}, \quad \Omega_2 = 2\pi f_2 = 2\pi \lambda^{-1} V \sqrt{n_0^2 - n_1^2}.
\]
General schematic arrangement of the advanced prototype of acousto-optical spectrometer for the Large Millimeter Telescope (GTM)
A multi-prism beam expander

The light beam passing through glass prisms.

\[
B_1 = \frac{d_1}{d_0} = \frac{\sqrt{(n^2 - \sin^2 \varphi) [1 - n^2 \sin(\alpha - \delta)]}}{n \cos \varphi \cos (\alpha - \delta)},
\]

\[
\delta = \arcsin \left( \frac{\sin \varphi}{n} \right). \quad B_m = (B_1)^m.
\]

\[
d_0 = 1 \text{ mm}; \quad D = 35 \text{ mm};
\]

\[
n = 1.5; \quad \alpha = 30^\circ.
\]
The flatness can be estimated by about 25% ;
The experimentally estimated average transmittance is about 70%.
Optical aperture of a cell: $D = 3.5$ cm; Length of interaction: $L = 1.0$ cm;
Slow shear elastic wave velocity: $V = 0.660 \times 10^5$ cm/s;
Operating light wavelength: $\lambda = 633$ nm; Refractive indices: $n_0 = 2.30$, $n_e = 2.46$;
Central acoustic frequency: $f_0 = 75$ MHz; Frequency bandwidth: $\Delta f = 45$ MHz;
Ideal theoretical frequency resolution: $\delta f = \frac{V}{D} = 18.8$ KHz;
The estimated maximum number of resolvable spots, i.e. the number of parallel frequency channels for spectrum analysis: $N = 2360$. 
Experimental light scattering efficiency of a TeO$_2$ - cell

This diagram represents the obtained degree of linearity in a dependence between the electric power and the irradiance of light.

The observed variations are potentially conditioned by the interplay between an electronic impedance of the matching circuits and an acoustic impedance of the crystalline piezo-electric transducer.

Intensity of the scattered light versus the applied electric power.
Experimental frequency bandwidth of a TeO$_2$ - cell

$\Delta f \approx 65$ MHz
The resulting resolution characterization

Thus, at the current step of our researches an advanced prototype of the acousto-optic spectrometer can be characterized by:

1. Total frequency bandwidth: $\Delta f = 65 \text{ MHz}$;
2. Frequency resolution: $\delta f = 42 \text{ KHz}$;
3. The number of resolvable spots or the number of parallel frequency channels for spectrum analysis: $N = 1550$. 

An advanced prototype of the acousto-optic spectrometer.
Scheme of the collinear acousto-optical interaction in a uniaxial crystal

The transmitted light

The incident light

The acoustic (elastic) wave beam

16
Collinear acousto-optical interaction in terms of the wave vectors

\[ \vec{p} = \hbar \vec{k}, \quad E = \hbar \omega, \quad \vec{k}_0 + \vec{K} = \vec{k}_1, \quad \omega_0 + \Omega = \omega_1 \]

Acoustic wave is slow \( v \ll c \), so that \( \Omega \ll \omega_0, \omega_1 \), but \( |\vec{k}_0| \approx |\vec{K}| \approx |\vec{k}_1| \)

In the special case of mismatched wave numbers, when detunings \( \Delta K \) and \( \Delta \Omega \) are connected with the slow wave and \( \Delta K \ll K, \Delta \Omega \ll \Omega \), we yield \( \Delta K \ll K \approx k_{0,1} \) and \( \Delta \Omega \ll \Omega \ll \omega_{0,1} \).

Thus, the total detuning can be described via only a mismatch related to just the wave vectors.
Schematic arrangement for the experiments with filtering optical signals by just collinear AO-cell.
Physical parameters of the collinear acousto-optical cell used currently in experiments for filtering analogue optical signals:

Tetragonal single crystal CaMoO$_4$ (along the x-axis):

$L = 4.5 \text{ cm}$, $T = 15 \mu\text{s}$, $V = 2.95 \times 10^5 \text{ cm/s}$, $\Delta \lambda = 0.4 - 4.0 \mu\text{m}$,
$M_2 = 6.16 \times 10^{-16} \text{ s}^3/\text{kg}$, and $f_0 = 61.3 \text{ MHz}$ for $\lambda_0 = 532 \text{ nm}$.

In this particular case of the CaMoO$_4$-crystal, one can expect the following tuning dependence and spectral resolution:

$$\lambda = \frac{\Delta n \cdot V}{f} , \quad \delta \lambda_0 = \frac{\lambda_0 \cdot V}{f_0 \cdot L} \approx 0.569 \text{ nm} \approx 5.7 \text{ Å} .$$

This cell is successfully exploited during our experiments in the INAOE.
Conclusive remarks

The current situation looks like:

- **1a.** At the moment, an advanced prototype of an acousto-optic spectrometer has been created in INAOE using a TeO$_2$-crystal cell, which operates in the frequency range of 60 MHz with the frequency bandwidth of 65 MHz and frequency resolution of 42 KHz.

- **1b.** Nevertheless, this prototype of an acousto-optic spectrometer is under construction and testing in INAOE. This prototype is mainly oriented on applying multi-phonon regimes of light scattering to improve the frequency resolution (CONACyT project # 61237).

- **2.** The second step can be done with involving a LiNbO$_3$-crystal cell operating in the frequency range of 1.0 - 1.5 GHz with the frequency resolution of ~ 200 KHz (under consideration).

- **3.** The third step can be developed in the frequency range of 3 - 4 GHz with the frequency resolution of ~ 1.0 MHz (for the needs of cosmology; currently exists as a proposal).

In parallel, one can say:

- **a.** At the moment, the other prototype of an acousto-optic spectrometer is under construction and testing in INAOE. This prototype is based on the specifically designed a TeO$_2$-crystal cell and is mainly oriented on applying multi-phonon regimes of light scattering to improve the frequency resolution.

- **b.** Finally, the researches directed on creating a prototype of an optical filter based on a CaMoO$_4$-crystal collinear acousto-optic cell, which is potentially capable of overlapping both visible and near infrared optical ranges, have been already initiated in the INAOE.
Part 2: Solitary multi-wave coupled states in acousto-optics

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Outlines

- Abstract and general survey.
- Physical background and formulation of theory.
- Analytical model and its simplifications.
- Effect of the phase mismatches.
- A one-phonon light scattering.
- A two-phonon light scattering.
- A three-phonon light scattering.
- Revealing and observing five-wave multi-component non-collinear acousto-optical coupled states.
- Revealing and observing three-wave dissipative collinear acousto-optical coupled states.
- Conclusion.
Abstract

The physical principles of realizing the Bragg regime of one-, two- and three-fold scattering of light by acoustic phonons in optically anisotropic crystals in specially elaborated case are considered.

The exact and closed analytical models with slightly mismatched wave numbers for describing such regimes are developed. Both the analysis and the computer simulations are oriented to revealing the specific acousto-optical solitary waves in the form of multi-component coupled states, which can appear within a multi-phonon Bragg light scattering in optically birefringent media.

These solitary waves have been observed and identified in the core of various experiments with a multi-phonon Bragg light scattering in uniaxial crystals.
Vector diagrams for the wave vectors of light and acoustic wave in a TeO$_2$ – single crystal

When these cross-points are lying equidistantly, the two- or three-fold scattering of light can be provided by only one harmonic acoustic wave, as shown here for a tellurium dioxide crystal. By this is meant that under certain conditions, i.e. at a set of the angles of light incidence on selected crystal cut and at the fixed frequency of the acoustic wave, one can observe the Bragg scattering of light caused by sequential participation of one, two or even three identical phonons in a crystal.
The conservation laws and angles of scattering

\[ \omega_{p+1} = \omega_p + \Omega_m , \quad \vec{k}_{p+1} = \vec{k}_p + \vec{K}_m , \quad p = 0, 1, 2, \text{and } 3 . \]

A two-phonon light scattering:

\[ \Omega_2 = 2\pi f_2 = 2 \pi \lambda^{-1} V \sqrt{n_0^2 - n_1^2} ; \]

A three-phonon light scattering:

\[ \Omega_3 = 2\pi f_3 = \pi \lambda^{-1} V \sqrt{2} \left| n_0^2 - n_1^2 \right| ; \]
Dielectric permittivity and boundary conditions

Under action of the elastic wave, the dielectric permittivity takes the form

\[ \varepsilon(y, t) = \varepsilon_0 + \varepsilon_1 \sin(K_m y - \Omega_m t + \Phi). \]

Generally, in crystalline materials, both \( \varepsilon_0 \) and \( \varepsilon_1 \) are tensors.

We assume that area of propagation for the elastic wave is bounded by two planes \( x = 0 \) and \( x = L \), and that a triplet or a quartet of the plane electromagnetic waves with various states of polarization

\[ E_{in} = \sum_{p=0}^{2 \text{ or } 3} A_p \exp\left[ i \left( k_p x \cos \theta_p + k_p y \sin \theta_p - \omega_p t + \varphi_p \right) \right] \]

strike the plane \( x = 0 \) at the angles \( \theta_p \) (\( p = 0, 1, 2, 3 \)) to the \( x \)-axis.

Here:

\[ \omega_p = \omega_0 + p \Omega, \quad k_p = |\vec{k}_p| = \omega_p \varepsilon_0^{1/2} c^{-1}. \]
A one-fold or one-phonon regime of light scattering in an acousto-optical modulator

The other regime of light diffraction occurs with a large $L$. In this case, the dynamic acoustic grating is rather thick, so during the analysis of diffraction one has to take account of the phase relations between waves in different orders. Such a regime can be realized only when the angle $\theta_B$ of light incidence on a thick acoustic grating meets the Bragg angular condition $\sin\theta_B = \lambda/2n\Lambda$ and $Q = \lambda L/\Lambda^2 >> 1$. Usually, the Bragg regime includes the incident and scattered light modes and the acoustic mode.
A one-phonon light scattering

With \( p = (0, 1) \), the set of Eqs. (8) gives

\[
\frac{dC_0(x)}{dx} = -q_1 C_1(x) \exp \left( -2i \eta_0 x \right), \quad \frac{dC_1(x)}{dx} = q_0 C_0(x) \exp \left( 2i \eta_0 x \right).
\]

Using the boundary conditions \( C_0 (x = 0) = 1, \ C_1 (x = 0) = 0 \) and the notation \( q^2 = q_0 q_1 \), one can find

\[
|C_1|^2 = \frac{q^2}{q^2 + \eta_0^2} \sin^2 \left( x \sqrt{q^2 + \eta_0^2} \right)
\]

\[
\Delta f_1 = \frac{2n V^2}{\lambda L f_1}
\]
A two-fold or two-phonon light scattering

With \( p = (0, 1, 2) \), equations can be rewritten as

\[
\frac{dC_0(x)}{dx} = -q C_1(x) \exp(-2i \eta_0 x),
\]

\[
\frac{dC_1(x)}{dx} = q C_0(x) \exp(2i \eta_0 x) - q C_2(x) \exp(-2i \eta_1 x).
\]

\[
\frac{dC_2(x)}{dx} = q C_1(x) \exp(2i \eta_1 x),
\]

There are two different frequency mismatches \( \eta_0 \) and \( \eta_1 \). We assume precise angular alignment and extend \( \eta_0 \) and \( \eta_1 \) into a series in powers of only the frequency detuning \( f - f_2 \) for the current frequency \( f \) relative to the central frequency \( f_2 \) for a two-phonon light scattering.

In the first order approximation, we obtain from the vector diagram:

\[ \eta_0 \approx 0. \]
A two-phonon light scattering; the frequency bandwidth

The frequency detuning is
\[(f - f_2) \approx n_0 V^2 \left( 2\pi \lambda f_2 \right)^{-1}.\]

The first unity-level maximum for $|C_2|^2$ can be reached at $q x = \pm \pi / \sqrt{2}$.

One can estimate the bandwidth of a two-phonon light scattering as:

\[\Delta f_2 = \frac{1}{4} \Delta f_1.\]
A three-phonon light scattering

With \( p = (0, 1, 2, 3) \), equations can be rewritten as

\[
\frac{dC_0}{dx} = -q_a C_1 \exp\left(-2i\eta_0 x\right),
\]

\[
\frac{dC_1}{dx} = q_a C_0 \exp\left(2i\eta_0 x\right) - q_n C_2 \exp\left(-2i\eta_1 x\right),
\]

\[
\frac{dC_2}{dx} = q_n C_1 \exp\left(2i\eta_1 x\right) - q_a C_3 \exp\left(-2i\eta_2 x\right),
\]

\[
\frac{dC_3}{dx} = q_a C_2 \exp\left(2i\eta_2 x\right).
\]

There are three different frequency mismatches \( \eta_0, \eta_1, \) and \( \eta_2 \). We assume a precise angular alignment and extend these mismatches into a series in powers of only the frequency detuning \( f - f_3 \) for the current frequency \( f \) relative to the central frequency \( f_3 \) for a three-phonon light scattering. In the first approximation, we find from vector diagram that

\[
2\eta_0 \approx \pi \lambda n_0^{-1} V^{-2} f_3 (f - f_3)
\]
A three-phonon light scattering; simulations and estimations of the frequency bandwidth

The frequency detuning is \( (f - f_3) \approx 2 \eta_0 n_0 V^2 (\pi \lambda f_3)^{-1} \).

The first unity-level maximum for \(|C_3|^2\) can be reached at \( q_n x = \pi \).

Taking \( 2\eta_0 L = \pi / 6 \) from the figure at \( x = L \), one can estimate the bandwidth of a two-phonon light scattering as:

\[
\Delta f_3 = \frac{1}{6} \Delta f_1.
\]
Originating five-wave Bragg non-collinear weakly-coupled acousto-optical states.

The solutions to the equations governing the three-phonon interaction:

\[ C_0(q_n x) = \frac{I}{2\sqrt{1+4q^2}} \left[ \left( -2q^2 + P^2 \right) \cos \left( \frac{S q_n x}{\sqrt{2}} \right) + \left( 2q^2 - S^2 \right) \cos \left( \frac{P q_n x}{\sqrt{2}} \right) \right], \]

\[ C_1(q_n x) = \frac{I}{2q\sqrt{2(1+4q^2)}} \left[ P \left( 2q^2 - S^2 \right) \sin \left( \frac{S q_n x}{\sqrt{2}} \right) + S \left( 2q^2 + P^2 \right) \sin \left( \frac{P q_n x}{\sqrt{2}} \right) \right], \]

\[ C_2(q_n x) = \frac{qI}{\sqrt{1+4q^2}} \left[ \cos \left( \frac{S q_n x}{\sqrt{2}} \right) - \cos \left( \frac{P q_n x}{\sqrt{2}} \right) \right], \]

\[ C_3(q_n x) = \frac{I}{\sqrt{2(1+4q^2)}} \left[ P \sin \left( \frac{S q_n x}{\sqrt{2}} \right) - S \sin \left( \frac{P q_n x}{\sqrt{2}} \right) \right]. \]
The localization conditions

Having two sets of the localization conditions, which are given by

1) \[ q_n L = 2 \sqrt{2} \pi k / S = 2 \sqrt{2} \pi m / P , \]

where \( k \) and \( m \) are the whole numbers; \( m > k \), because \( P > S \).

Putting, \( k \neq 0 \) and using the parameters \( P \) and \( S \), one may obtain

\[ m \sqrt{1 + 2q^2} - \sqrt{1 + 4q^2} = k \sqrt{1 + 2q^2 + \sqrt{1 + 4q^2}} , \]

correlating \( k \) and \( m \) and the parameter \( q \).

Graphical interpretation of the 1-st set of localization conditions.
The localization conditions

2) \( q_n L = \sqrt{2(\pi + 2\pi k)/S} = \sqrt{2(\pi + 2\pi m)/P} \),

In this case, the inequality \( m > k \) as valid, but now \( k = 0 \) is acceptable, and the interrelation between \( k \) and \( m \) and the parameter \( q \) is given by:

\[
(1 + 2m)\sqrt{1 + 2q^2} - \sqrt{1 + 4q^2} = (1 + 2k)\sqrt{1 + 2q^2} + \sqrt{1 + 4q^2}.
\] (20)

Graphical interpretation of the 2-nd set of localization conditions.

The last two figures show various interplays between the whole number \( m \) and the parameter \( q \) for a set of the whole numbers \( k \).
Spatial-frequency distributions for a quartet of optical components in a multi-pulse five-wave weakly coupled state with $q = 4.5$ and $q_n L \leq 2\pi$.

The distributions are completely locked with $\eta_0 = 0$. 

an eight-pulse component in the zero order of scattering

a nine-pulse component in the first order of scattering

a nine-pulse component in the second order of scattering

an eight-pulse component in the third order of scattering
Experimental results: the tellurium dioxide acousto-optical cell

1. A TeO₂-crystal has rather dispersive refractive index: n₀ = 2.26 at λ = 633 nm, n₀ = 2.33 at λ = 488 nm, and n₀ = 2.35 at λ = 442 nm. The ultrasound velocity equals v = 0.6 10⁵ cm/s for the slow shear acoustic mode running exactly along the [110]-axis with the displacement vector directed along [110]-axis. The figure of acousto-optical merit for this shear mode wave in a TeO₂-crystal is M₂ = 1.2 10⁻¹⁵ s³/g, which is the highest one for solid-state acousto-optical materials in the visible range known up to now.

2. At first, one has to check the realization of just Bragg regime for light scattering in the chosen cell. In such a regime, the Klein-Cook parameter Q should exceed unity. Operating at the light-blue optical wavelength λ = 488 nm and at the lowest expected acoustic wave frequency 40 MHz with L = 1 cm one can calculate Q = 10, which confirms the Bragg character of light scattering in the regime selected within the visible range of light spectrum.
Scheme of the collinear acousto-optical interaction in a uniaxial crystal

The incident light

The acoustic (elastic) wave

The transmitted light

n_e

n_0

The transmitted light
Co-directional collinear acousto-optical interaction in the presence of linear acoustic losses.

A triplet of nonlinear differential equations describing the regime of a weak coupling with linear acoustic losses is given by

\[
\frac{\partial U}{\partial x} + \frac{1}{V} \frac{\partial U}{\partial t} = -\alpha U, \quad \frac{\partial C_0}{\partial x} + \frac{1}{c} \frac{\partial C_0}{\partial t} = -q_1 C_1 U^* \exp(2i\eta x),
\]

\[
\frac{\partial C_1}{\partial x} + \frac{1}{c} \frac{\partial C_1}{\partial t} = q_0 C_0 U \exp(-2i\eta x),
\]

where \(\alpha\) describes losses of the non-optical wave.

The exact solutions to this equations in the case of a weak coupling are given by

\[
|C_0(x)|^2 = \frac{\eta^2}{\sigma^2 + \eta^2} + \frac{\sigma^2}{\sigma^2 + \eta^2} \cos^2[G(x) - G(0)];
\]

\[
|C_1(x)|^2 = \frac{q_0}{q_1} \frac{\sigma^2}{\sigma^2 + \eta^2} \sin^2[G(x) - G(0)]; \quad \sigma^2 = q_0 q_1 |U|^2.
\]
The localization conditions

The localization condition can be written as

\[ G(x) - G(0) = \pi N, \quad \text{where: } N = 1, 2, \ldots \]

If the spatial length \( x_0 \) of the non-optical pulse is much shorter than \( L \), i.e. when

\[ T_0 = x_0 / V << T = L / V \]

the localization process may have 3 stages:

1) The localizing non-optical pulse is incoming through the facet \( x = 0 \);
2) The pulse is passing along the crystal;
3) The pulse is issuing through the output facet \( x = L \).

Such a process can be illustrated for the scattered light waves under conditions:

\[ G(x) - G(0), \quad 0 \leq \tau \leq T; \]

\[ G(x) - G(x - x_0), \quad T \leq \tau \leq x(c-V)/(cV); \]

\[ G(L) - G(x - x_0), \quad x(c-V)/(cV) \leq \tau \leq T + x(c-V)/(cV); \]

\[ 0, \quad \tau < 0 \text{ or } \tau > T + x(c-V)/(cV). \]
Intensity of the scattered light components vs. $\tau$ and $L$ with $\sigma = 2$ and $\alpha = 0.05$. 

a) $\eta = 1.5$, the beginning of one-pulse dissipative coupled state; b) $\eta = 2.4$, a one-pulse dissipative coupled state; c) $\eta = 3.5$, an intermediate stage; and d) $\eta = 6.0$, a two-pulse dissipative coupled state.

An example: Numerical simulations of the light wave $|C_1|^2$
Schematic arrangement for the experiments with the collinear AO-cell
We have developed a special approach to Bragg scattering of light in optically uniaxial crystals marked by the inclusion of multi-fold processes. In particular, the configurations related to one-, two-, and three-phonon scattering processes have been analyzed in details to highlight both the angular-frequency conditions peculiar for their realization and the characteristics that can be optimized from the viewpoint of potential applications.

The analysis performed has given us the opportunities for revealing and observing various multi-wave collinear and non-collinear multi-component acousto-optical coupled states.

Thank you