# The new ultra high-speed all-optical coherent streak-camera

**R.M.Arkhipov[1,2], M.V.Arkhipov[1], V.S.Egorov[1], I.A.Chekhonin[1], M.A.Chekhonin[1], S.N.Bagayev[3]**

[1]St.Petersburg State University, St.Petersburg, Russia
[2]Weierstrass Institute for Applied Analysis and Stochastics, Leibniz Institute in Forschungsverbund Berlin e.V, Berlin, Germany
[3]Institute of Laser Physics, Novosibirsk, Russia

E-mail: arkhipovrostislav@gmail.com

**Abstract.** In the present paper a new type of ultra high-speed all-optical coherent streak-camera was developed. It was shown that a thin resonant film (quantum dots or molecules) could radiate the angular sequence of delayed ultra-short pulses if a transverse spatial periodic distribution of the laser pump field amplitude has a triangle shape.

## 1. Introduction

For solving various problems of data transfer and processing, it is necessary to change at high speed the direction of propagation of laser radiation in space. The problem of rapid angular laser beam deflection is one of the most difficult problems of controlling the parameters of laser radiation. Nowadays mirror galvanometers and acousto-optic deflectors are widely used. The ratio between the angle of deviation $\alpha$ and setting time $\tau$ for mirror galvanometers and acousto-optic deflectors has order of magnitude $90^{o}/10^{-4}$ sec and $2^{o}/10^{-6}$ sec, respectively.

In this paper we address the following question: how to increase angular deflection rate? In the present work, we consider all-optical angular deflectors of laser radiation. To date it has been suggested several types of deflectors with different principles of action. In Refs. [1-8] the optical deflector using the effects of light-induced transverse gradient index of refraction $n(x)$ of the medium, leading to a deflection of the laser beam propagating through an optically inhomogeneous medium was studied. In Refs. [9,10] an effect of optically steering phase matching in the multiwave parametric excitation in photonic crystals has been analyzed. Effect of all-optical steering of light was considered for gazes of three-level and four-level atoms. This effect is based on the phenomenon of electromagnetically induced transparency (EIT) under inhomogeneous optical pumping of the medium leading to the changes of the index of refraction [11-13].

In [14] we have proposed for the first time a new principle of the ultra high-speed all-optical coherent streak-camera and deflectors, which uses the effect of self-diffraction of ultrashort coherent pulse on the grating of polarization $P(t,x)$ of resonant two-level medium with an optically controlled grating pitch. In [15], this principle was generalized for the pump-probe method using the diffraction effect of the probe pulse on the grating of the population difference $N(t,x)$ induced by the pump pulse in the resonant medium.

The using of the resonant media seems to be promising. One can use resonant media based on atoms, molecules, excitons and quantum dots. Coherent laser radiation can rapidly change the polarization of the medium $P(t,x)$ and the level populations $N(t,x)$ in these media. The ratio of the deflection angle $\alpha$ to the setting time $\tau$ can reach the value $10^{o}/10^{-11}$ sec, which is much greater than angular deflection rate of mirror galvanometer and acousto-optic deflectors.

## 2. All-optical coherent streak-camera: a new principle of operation

The principle of operation of a coherent deflector is based on the sequence in time of the excitation of nonlinear spatial harmonics of the polarization $P(t,x)$ and the population difference $N(t,x)$ in a thin layer of resonant medium. A diffraction of the incident pulse on the grating leads to the appearance of the sequence of $n$ pulses separated in time and each of them is emitted at angle $\alpha_n$.

In the first case, laser pumping pulse is divided into the series of pulses with variable direction of the propagation in space due to self-diffraction, see Fig. 1. In the second case, illustrated in Fig.2 pumping pulse creates in the resonant layer periodic grating of population $N(t,x)$ which is used for the diffraction of the probe pulse.
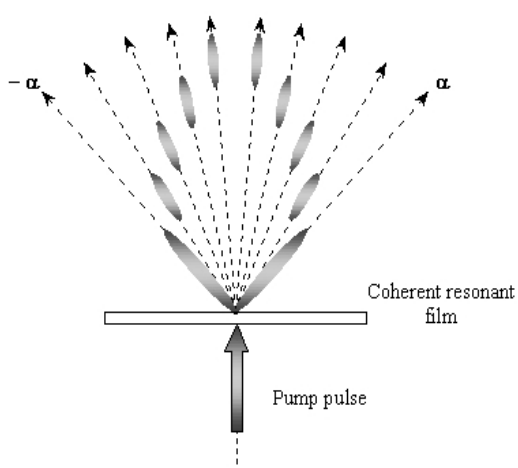


**Figure 1.** Dynamics of the angular distribution of the film radiation under the self-diffraction of the pumping pulse
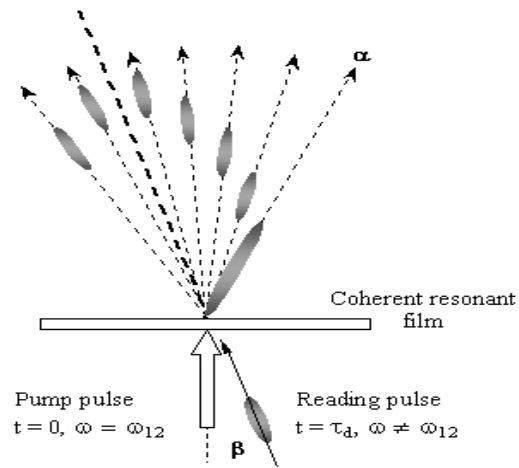


**Figure 2.** Dynamics of the angular distribution of the film radiation under the diffraction of the probe pulse

The angular deflection can be achieved by laser excitation of a resonant layer with a periodic "sawtooth" transverse spatial profile of the field, $E(t,x) = \varepsilon(t)saw(x)$ with a period $\Delta$. Graphic of the unit function $saw(x)$ $(|saw(x)| \leq 1)$ is illustrated in Fig.3.
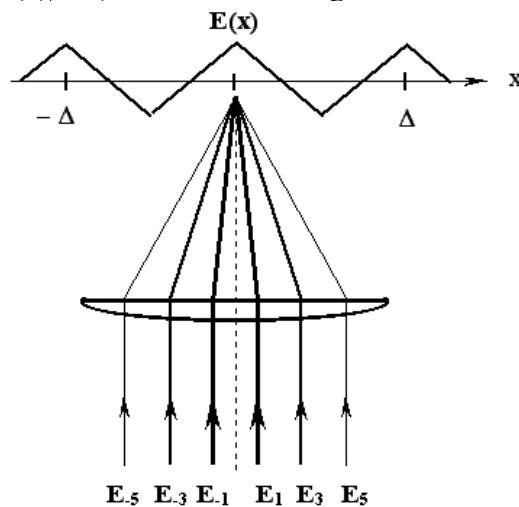


**Figure 3.** Fourier synthesis of the spatial distribution of the electric field $E(t,x) = \varepsilon(t)saw(x)$
The ratio of the wave amplitudes - $E_{\pm 1}: E_{\pm 3}: E_{\pm 5}: E_{\pm 7}\ldots = 0.8106: 0.0901: 0.0324: 0.0165\ldots$

The pumping field for obtaining "sawtooth" distribution $E(t,x) = \varepsilon(t)saw(x)$ can be simply realized as illustrated in Fig.3. Due to the interference of the wave pairs electric field profile $E(t,x)$ formed in the focal plane of the lens can be described by the Fourier series (1):

$$saw(x) = \sum_{m=1}^{\infty} a_m \cdot \cos(Q \cdot x \cdot m) \tag{1}$$

$$a_m = 2 \cdot \mathrm{sinc}\left(\pi \cdot \frac{m}{2}\right)^2 , \tag{2}$$

where $Q=2\pi/\Delta$ и $sinc(Z)=sin(Z)/Z$. This Fourier synthesis is effective due to the fast decreasing of the Fourier series components (2) - $a_1:a_3:a_5:a_7 \ldots = 0.8106: 0.0901: 0.0324: 0.0165 \ldots$

## 3. Dynamics of radiation emitted by a grating of resonant medium polarization

To calculate the dynamics of the medium polarization $P(t,x) = d_{12}N_0(u(t,x)+iv(t,x))$ and population difference of the layer interacting with the field $E(t,x) = \varepsilon(t)saw(x)$ we used a numerical solution of the system of optical Bloch equations [16]:

$$\frac{d}{dt}u(t,x) = -\Delta\omega \cdot v(t,x) - \frac{1}{T_2} \cdot u(t,x) \tag{3}$$

$$\frac{d}{dt}v(t,x) = \Delta\omega \cdot u(t,x) - \frac{1}{T_2} \cdot v(t,x) + \Omega_R(t,x) \cdot w(t,x) \tag{4}$$

$$\frac{d}{dt}w(t,x) = -\frac{1}{T_1} \cdot (w+1) - \Omega_R(t,x) \cdot v(t,x). \tag{5}$$

Here $N_0$ - particle density in the layer, $u(t,x)$, $v(t,x)$ - components of the medium polarization, $w(t,x)$ - population difference per unit atom, $\Delta\omega$ - frequency detuning of the field frequency from transition frequency $\omega_{12}$ of the two-level particles $d_{12}$ - transition dipole moment, $T_1$ - population difference relaxation time, $T_2$ - polarization relaxation time, $\Omega_R(t,x) = d_{12}E(t,x)/\hbar$ – Rabi frequency of the pumping pulse.

In particular case when detuning $\Delta\omega = 0$ one can neglect medium relaxation times, $T_1 = T_2 = \infty$, the system of optical Bloch equations (3)–(5) can be solved analytically using local "area" of the pumping pulse $\Theta(t,x)$ [17, 18]:

$$\Theta(t,x) \equiv \frac{d_{12}}{\hbar} \cdot \int_{-\infty}^{t} E(t',x)dt'. \tag{6}$$

The analytical solution of (3)-(5) allows one to obtain the following expressions for the medium polarization $P(t,x)$ and population difference $N(t,x)$ in the form [17, 18]:

$$P(t,x) = d_{12}N_0 \sin(\Theta(t,x)) = d_{12}N_0 \sin(\Theta(t)saw(x)) \tag{7}$$

$$N(t,x) = N_0 \cos(\Theta(t,x)) = N_0 \cos(\Theta(t)saw(x)). \tag{8}$$

From (7)-(8) one can immediately see that current pulse area $\Theta(t)$ has a significancy of current spatial frequency of the polarization grating and population difference grating $N(t,x)$. Spatial period of

the both grating depends on time. Therefore, one can expect an occurrence of the radiation of different diffraction orders emitted by polarization $P(t,x)$ grating with a time delay, see Fig.1.

Spatial Fourier spectrum of the resonant polarization $P(t,x)$ contains only odd harmonics of grating wave vector $Q = 2\pi/\Delta$: $Q_n = (2n+1)Q$, $n = 0,1,2\ldots$ - integer number. The basic idea of the streak camera (or deflector) can be described in the following way. Each of the spatial harmonics of the polarization $P_n(t)$ radiates in series in the far-field zone a short pulses, propagating at the angle which is satisfying to the Vavilov-Cherenkov condition, $\alpha_n = arcsin(Q_n/k)$, where $k = 2\pi/\lambda$ - is the wave number.

Therefore, self-diffraction of the pumping pulse looks as the separation of it on the series of $n$ short pulses each of them is propagating at his own angle $\alpha_n$ (Fig. 1).

Fig.4 illustrates an evolution of the spatial Fourier spectrum of the polarization $P(t,x)$ for the unipolar pumping pulse having Gaussian shape $\varepsilon(t) = \varepsilon_o \, exp(-(t/\tau_p)^2)$ with duration $\tau_p = 25$ psec and total pulse area $\Theta_\infty = 19.5\,\pi$. It is clearly seen the appearance of the harmonics of the polarization $P_n(t)$ successive in time with wave vectors $Q_n = (2n+1)Q$.

A supreme value of the deflection angle $\alpha_{max}$ for the unipolar pumping pulse is determined only by the total pulse area, $\Theta_\infty = \Theta\,(t=\infty)$: $\alpha_{max} = arcsin(2\Theta_\infty Q/\pi k)$. Similar situation for the bipolar pumping pulse (breather) with total pulse area $\Theta_\infty = 9.75\,\pi$ is illustrated in Fig. 5.
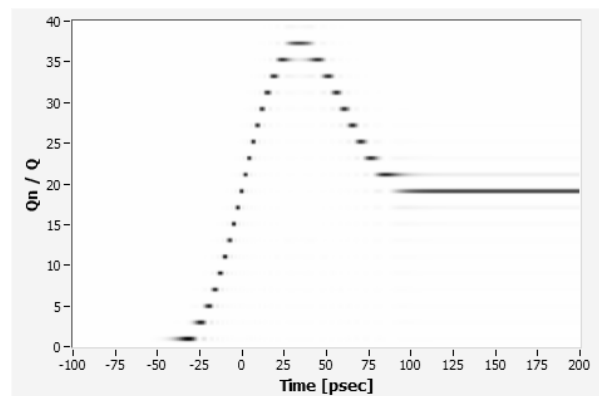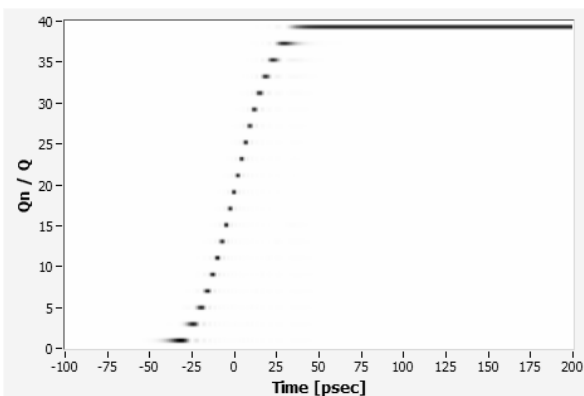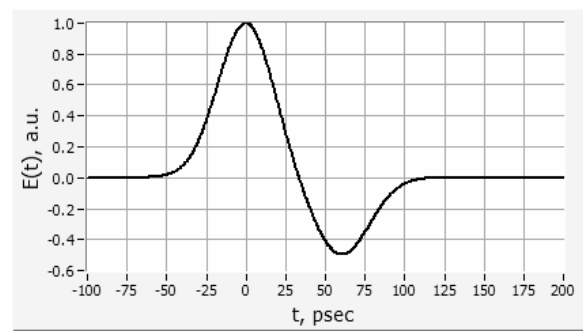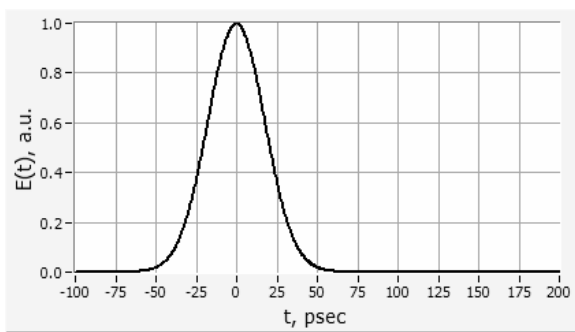


**Figure 4.** Dynamics of the Fourier spectrum of the polarization $P(t,x)$ (low figure) under pumping by unipolar pulse (upper panel) $E(t,x) = \varepsilon(t)saw(x)$, $\Delta\omega = 0$, $T_1 = T_2 = \infty$, $\Theta_\infty = 19.5\,\pi$

**Figure 5.** Dynamics of the Fourier spectrum of the polarization $P(t,x)$ (low figure) under pumping by bipolar pulse (upper panel) . $E(t,x) = \varepsilon(t)saw(x)$, $\Delta\omega = 0$, $T_1 = T_2 = \infty$, $\Theta_\infty = 9.75\,\pi$

## 4. Dynamics of the radiation emitted by resonant polarization grating under realistic conditions

It should be noted that sawtooth profile of the pumping field $E(t,x) = \varepsilon(t)saw(x)$ is not practical because of the using of the infinite numbers of interfering harmonics in Fourier series (1). However, as it was mentioned above, the components of the series (2) rapidly decrease with the

increase of the index $m$. Therefore, to create the sawtooth profile of the pump field one can take a finite number of interfering waves.

Fig.6 illustrates the dynamics of the resonant polarization radiation in the case when three pairs of the waves are used - $E_{\pm 1}$, $E_{\pm 3}$ and $E_{\pm 5}$. It is clear that dynamics of emission from resonant layer is almost ideal for the sawtooth pumping $E(t,x) = \varepsilon(t)saw(x)$.

Note, that in the case of pumping by one pair of waves $E_{\pm 1}$ the distribution of the pumping field has a form $E(t,x) = \varepsilon(t)\cos(Qx)$ and angular deflection does not occur. In this case, we have a huge amount of diffraction orders emitted by the polarization grating. It was observed experimentally with sodium vapors [19].
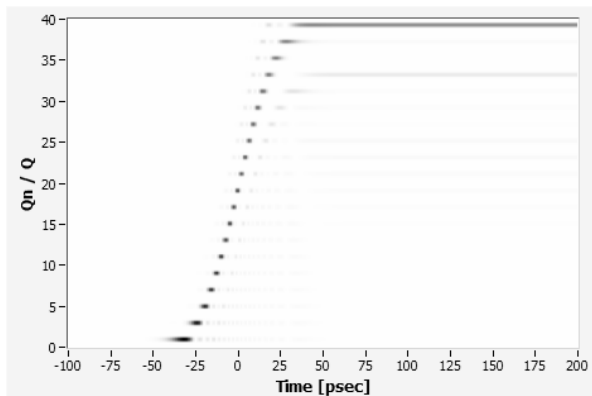
**Figure 6.** Dynamics of Fourier spectrum of polarization $P(t,x)$. $\Delta\omega = 0$, $T_1 = T_2 = \infty$, $\Theta_\infty = 19.5\ \pi$, $E_{\pm 1}$: $E_{\pm 3}$: $E_{\pm 5}$ = 0.8106: 0.0901: 0.0324
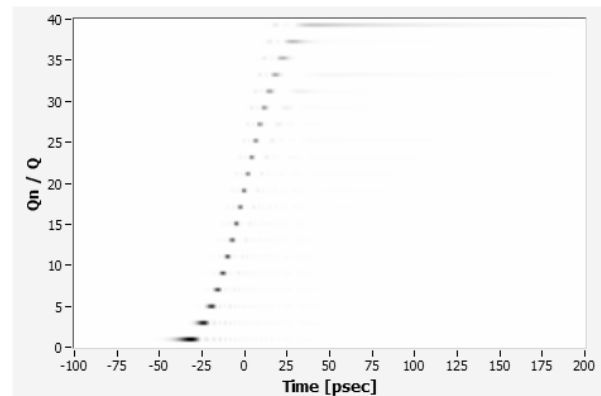
**Figure 7.** Dynamics of Fourier spectrum of polarization $P(t,x)$. $E(t,x) = \varepsilon(t)saw(x)$, $\Delta\omega = 0$, $T_1 = 1$ nsec, $T_2 = 100$ psec, $\Theta_\infty = 19.5\ \pi$

Effect of coherent angular deflection was also investigated in the general case when relaxation times $T_1$ and $T_2$ have finite values, see Fig.7. It is seen from this figure that relaxation leads only to monotonic decrease of the amplitude of high orders of diffraction and effect of angular deflection is preserved.

We have found that greatest negative impact on the decrease of the emission field amplitude with deflection angle $\alpha_{max}$ provides the frequency detuning $\Delta\omega$, see Fig. 8. In this case it is necessary to use pump-probe method [15] (Fig. 2). Linear and nonlinear diffraction of a probe pulse on the resonant harmonic grating of population difference $N(x)$ was considered in detail in [20].
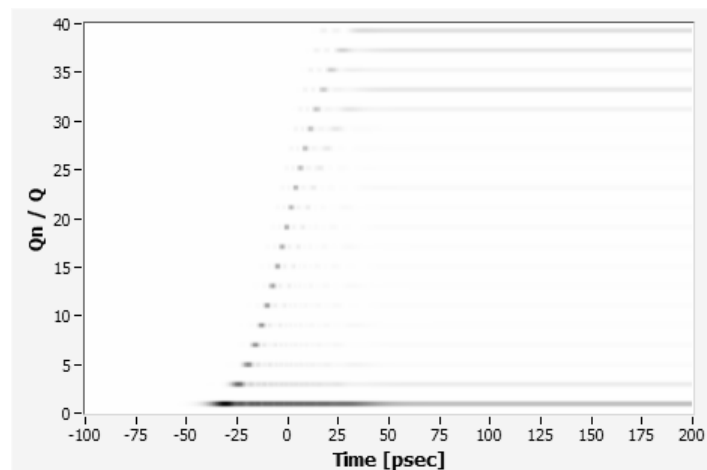
**Figure 8.** Dynamics of Fourier spectrum of polarization $P(t,x)$. $E(t,x) = \varepsilon(t)saw(x)$, $\Delta\omega = 0.05\ \Omega_R$, $T_1 = T_2 = \infty$, $\Theta_\infty = 19.5\ \pi$

Situations considered above are valid for optically thin layer of resonant medium and the propagation of the pumping pulse in the layer was not taken into account. In general case it is necessary to include a finite length of the medium and diffraction of the optical field during its propagation in the extended medium. Numerical simulations for this case were performed by us using general system of Maxwell-Bloch equations in the slowly varying envelope approximation of the electric field, polarization and population difference in a two-level extended resonant medium. Numerical simulations showed that the including of the diffraction leads to the spreading of spatially periodic structures of polarization and population difference. Therefore, it is necessary to use thin optical layers with large values of relaxation times.

## 5. Acknowledgements

## References

[1]   C.H.Sarantos, J.E.Heebner 2010 Opt. Lett. **35** (9) 1389-1391.
[2]   Y.Li, D.Y.Chen, L.Yang, R.R.Alfano 1991 Opt. Lett. **16** (6) 438-440.
[3]   J.Hubner, H.M. van Driel, J.S.Aitchison 2005 Opt. Lett. **30** (23) 3168-3170.
[4]   S.Shwartz, M.Segev, U.El-Hanany 2004 Opt. Lett. 2004 **29**, (7) 760-762.
[5]   G.A.Swartzlander, Jr., H.Yin, A.E.Kaplan J. Opt. Soc. Am. B. 1989 **6** (7) 1317-1325.
[6]   H.-S.Albrecht, P.Heist, J.Kleinschmidt,  D.V.Lap Appl. Phys. B 1993 **57**, 193-197.
[7]   S.Blair, K.Wagner Appl. Opt. 1999 **38** (32) 6749- 6772.
[8]   A.Dreischuh, E.Eugenieva, S.Dinev IEEE Journal of Quant. Electron. 1994 **30** (7) 1656-1661.
[9]   T.Ellenbogen, A.Ganany-Padowicz, A.Arie Opt. Express 2008 **16** (5) 3077-3082.
[10]   S.M.Saltiel, Y.S.Kivshar Opt. Lett. 2002 **27** (11) 921-923.
[11]   C.Hang, V.V.Konotop Phys. Rev. A 2010 **81** 053849.
[12]   O.N.Verma, T.N.Dey Phys. Rev. A 2015 **91** 013820.
[13]   Q.Sun, Y.V.Rostovtsev, M.S.Zubairy Phys. Rev. A 2006 **74** 033819.
[14]   R.M.Arkhipov, S.N.Bagayev, V.S.Egorov, I.A.Chekhonin, M.A.Chekhonin.
Proceedings of the VI Intern. conf. HOLOEXPO-2009 81-86 Kiev Ukraine 01-02 July 2009.
[15]   R.M.Arkhipov, M.V.Arkhipov, S.N.Bagayev, V.S.Egorov, I.A.Chekhonin, M.A.Chekhonin
Scientific notes of the Physics Department of Moscow State University 2013 **5** 135034 (1-4).
[16]   L.Allen*, J.H.Eberly* Optical Resonance and Two-Level Atoms*. John Wiley*, New York, 1975.
[17]   V.S.Egorov, I.A.Chekhonin Zh. Tech. Phys. 1986 **56** (3) 572-574.  [Sov. Phys.-Tech. Phys. 1986 **31** 344].
[18]   V.S.Egorov, I.A.Chekhonin, N.N.Shubin Opt. Spektrosk**.** 1987 **62** (4) 853-859. [Opt. Spectr. 1987 **62** (4) 509-513].
[19]   N.Tan-no, K.Ohkawara, H.Inaba Phys. Rev. Lett.. 1981 **46** (19) 1282-1285.
[20]   R.M.Arkhipov, I.Babushkin, M.K.Lebedev, Yu.A.Tolmachev, M.V.Arkhipov Phys. Rev. A. 2014 **89** 043811.