Journal of Physics: Conference Series

**PAPER** • **OPEN ACCESS**

# Subwavelength population density gratings in resonant medium created by few-cycle pulses

To cite this article: R M Arkhipov *et al* 2017 *J. Phys.: Conf. Ser.* **917** 062005

IOP Conf. Series: Journal of Physics: Conf. Series **917** (2017) 062005 doi:10.1088/1742-6596/917/6/062005

# Subwavelength population density gratings in resonant medium created by few-cycle pulses

**R M Arkhipov[1,2], M V Arkhipov[1], A V Pakhomov[3,4], I Babushkin[5,6], A Demircan[5,7], U Morgner[5,7], N N Rosanov[2,8,9]**

[1] St. Petersburg State University, St. Petersburg, 199034, Russia
[2]ITMO University, 197101 St. Petersburg, Russia
[3]Department of Physics, Samara University, 443086 Samara, Russia
[4]Department of Theoretical Physics, Lebedev Physical Institute, 443011 Samara, Russia
[5]Institute of Quantum Optics, Leibniz University Hannover, 30167 Hannover, Germany
[6]Max Born Institute, 12489 Berlin, Germany
[7]Hannover Centre for Optical Technologies, 30167 Hannover, Germany
[8]Vavilov State Optical Institute, 199053 St. Petersburg, Russia
[9]Ioffe Physical Technical Institute, St. Petersburg 194021, Russia

E-mail: arkhipovrostislav@gmail.com

**Abstract.** We consider theoretically recently proposed a new possibility of creation, erasing and ultrafast control of population density grating. Such grating can be created in resonant medium when ultrashort pulses with duration smaller than relaxation times in the resonant medium (coherent light matter interactions) propagate without overlapping in this medium. Possible applications in the ultrafast optics such as optical switcher and laser beam deflector are discussed.

## 1. Introduction

Periodic spatial population density gratings are typically created in resonant medium via pattern produced by the interference of nearly long monochromatic light beams [1]. In this case, two beams overlaps in space and the spatial period of the grating is limited by the light wavelength. These gratings found a lot of applications in linear and nonlinear spectroscopy, Bragg diffraction, and nonlinear optics etc [2, 3].

To date, ultrashort pulses with few-cycle or even subcycle duration became available [4] and found huge amount of applications in ultrafast optics. It allows to observe and control previously inaccessible ultrafast processes in matter such as wave packet dynamics [5]. Furthermore, ultrashort pulses can coherently interact with a resonant medium when their duration is smaller than the medium relaxation times $T_1$ and $T_2$ [6].

In this paper, we revise recently proposed [7-11] novel method of creation and ultrafast control of spatial periodic gratings of polarization and inversion by few-cycle pulses coherently propagating in a resonant medium. This method allows achieving the subwavelength gratings by the pulses non-overlapping in space, which is contrast to well-known method, where overlapping of the pulses is needed [1-3]. Such grating are formed due to the interaction of incoming pulses with polarization wave created by the previous pulse. Possible applications of these gratings in ultrafast optics and attosecond science are discussed.

## 2. Theoretical model and subwavelength gratings created by unipolar sybcycle and bipolar few-cycle pulses

Our theoretical analysis is based on analytical and numerical solution of Maxwell-Bloch equations for the density matrix elements and electric field without use of slowly varying envelope and rotating wave approximations. Resonant medium is described as a two-level system. This system of equations is given by:

$$\frac{d\rho_{12}(z,t)}{dt} = -\frac{\rho_{12}(z,t)}{T_2} + i\omega_0\rho_{12}(z,t) - \frac{i}{\hbar}d_{12}E(z,t)n(z,t)\,, \tag{1}$$

$$\frac{dn(z,t)}{dt} = -\frac{n(z,t)-n_0(z)}{T_1} + \frac{4i}{\hbar}d_{12}E(z,t)\,\mathrm{Im}\,\rho_{12}(z,t)\,, \tag{2}$$

$$\frac{\partial^2 E(z,t)}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E(z,t)}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 P(z,t)}{\partial t^2}\,, \tag{3}$$

$$P(z,t) = 2N_0 d_{12}\,\mathrm{Re}(\rho_{12}). \tag{4}$$

Equations (1)-(2) describe the evolution of nondiagonal element of density matrix $\rho_{12}$ and population difference $n$ (inversion) between ground and excited states. Propagation of the electric field $E$ is governed by the wave equation (3). Medium polarization is given by Eq. (4). Other parameters: $\omega_0$ – resonance transition frequency ($\lambda_0 = 2\pi c/\omega_0$ - corresponding wave length), $d_{12}$– transition dipole moment, $n_0$ – inversion in the absence of the electric field ($n_0 = 1$ for absorbing medium), $N_0$ – concentration of two-level atoms, $c$ – speed of light, $\hbar$ – Planck constant.

We investigated the grating dynamics created by the train of bipolar pump pulses (see Refs. [7,8,11]) given by

$$E_p(t) = \sum_{i=1}^{N} E_0 \exp\left(-\frac{[t-\tau_i]^2}{\tau_p{}^2}\right)\sin(\omega_0[(t-\tau_i)]), \tag{5}$$

and the train of unipolar subcycle pulses without carrier frequency given by (see Refs [9,10])

$$E_p(t) = \sum_{i=1}^{N} E_0 \exp\left(-\frac{[t-\tau_i]^2}{\tau_p{}^2}\right). \tag{6}$$

Here, $\tau_p$ is the pulse duration, $\tau_i$ is delay between the 1st pulse and the $i$th pulse, $N$ is the number of pulses. Using of unipolar subcycle pulses (6) seems to have more advantages with respect of bipolar ones (6) seems to have more advantages due to their smaller duration and unipolar character.

Numerical simulations revealed that with proper selection of the delay between the incident bipolar few-cycle bipolar pulses (5) of subcycle pulses (6) and their propagation directions it is possible to create, erase and even multiplicate the spatial period of polarization and inversion gratings, see

IOP Conf. Series: Journal of Physics: Conf. Series **917** (2017) 062005 doi:10.1088/1742-6596/917/6/062005

figure 1. For more details see Refs. [7-10]. Figure 1 illustrates the typical dynamics of inversion $n$ under the action of single-cycle bipolar pulse train (5). In figure 2 the dynamics of polarization is plotted. These results were obtain from the numerical solutions of Maxwell-Bloch equations (1)-(4). The pulses were launched from left to right and from right to left and are not overlapped in the medium.

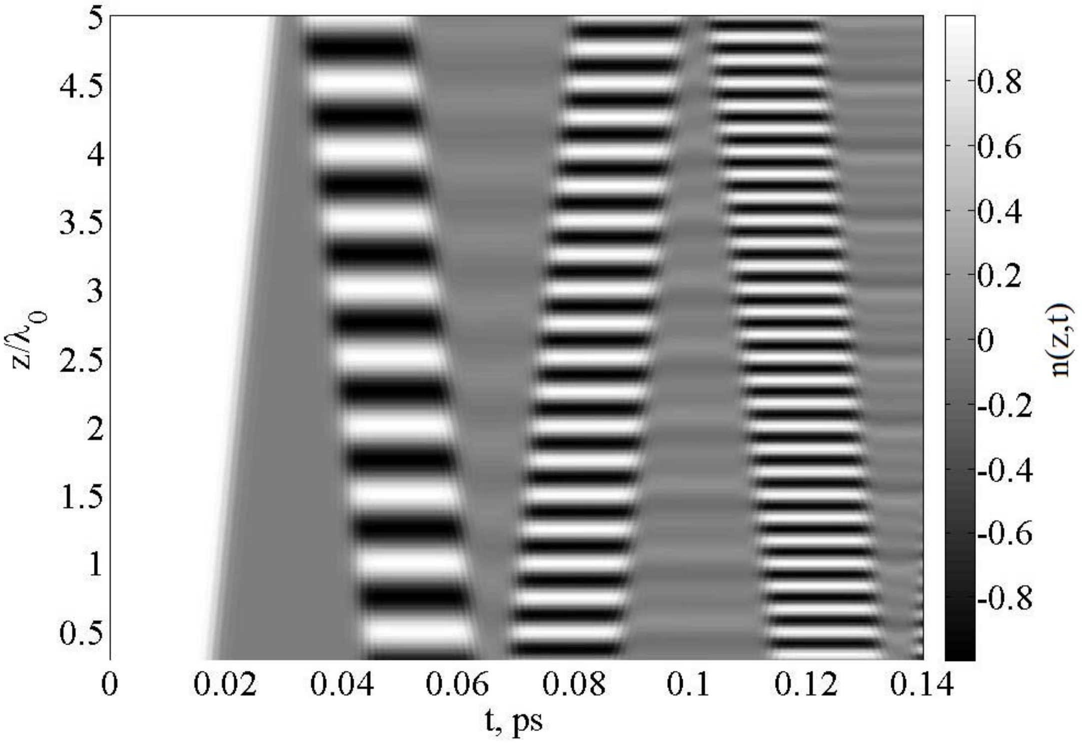


**Figure 1.** Typical behaviour of spatial and temporal dependence of the population inversion $n$ in a resonant medium demonstrating creation, erasing of periodic gratings and multiplication of its wave vector. Train of few-cycle pulses is launched in the system. Parameters: $\lambda_0 = 700$ nm, $d_{12} = 5$ D, $T_1 = 1$ ns, $T_2 = 2$ ps, $\tau_p = 2$ fs, $N_0 = 10^{17}$ cm$^{-3}$.

Pulse amplitude was set in a way that pulse acted as $\pi/2$ pulse. From figure 1 and figure 2 it is easy to see the possibility of grating creation, erasing and their spatial frequency multiplication. More detailed description of these grating dynamics can be found in Refs. [7-11]. We remark that this method allows to create the inversion gratings with the spatial frequencies $2mk_0$ ($k_0 = 2\pi/\lambda_0$ is the wave number), $m = 1,2,3...$ and polarization gratings with the frequencies $(2m+1)k_0$, $m = 0,1,2,3...$, see Ref. [8] and figures 1, 2. This method is valid for the pulses with durations smaller than medium relaxation times and can be realized even when the pulse duration approaches subcycle duration [9,10].

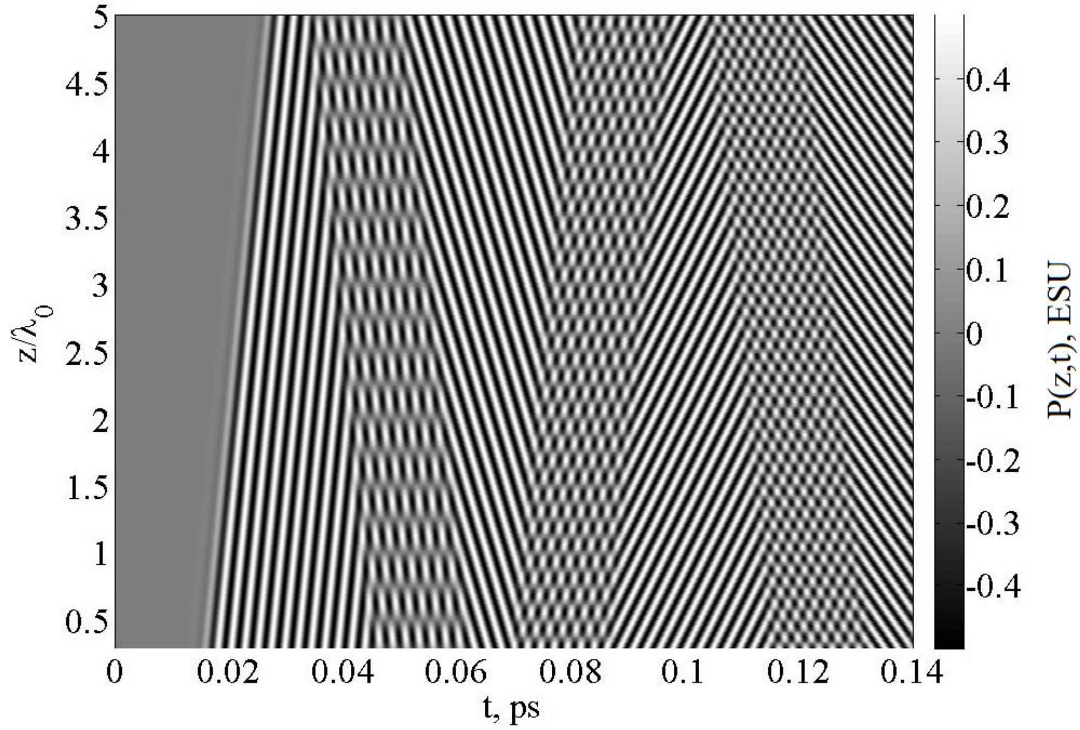


**Figure 2.** Typical behaviour of spatial and temporal dependence of the polarization $P$ for the parameters of figure 1 in resonant medium demonstrating creation, erasing of periodic gratings and multiplication of its wave vector.

## 3. Conclusions

To conclude, we briefly described recently proposed mechanism of the ultrafast control of the polarization and inversion gratings in resonant medium by train of few-cycle and subcycle pulses coherently interacting with resonant medium. It allows grating creation, erasing and spatial frequency multiplication. Proposed method is extremely fast, which opens novel opportunities in ultrafast optics. It can be realised in various media where coherent light-matter interactions were observed experimentally – gases, semiconductor bulks, quantum dots. Investigated phenomena, for instance, can find their applications, for laser beam deflectors, ultrafast control of medium properties, attosecond science, spectroscopy, and optical signal processing. A detailed analysis of the grating dynamics can be found in Refs. [7-12].

## Acknowledgments

This work was supported by Russian Science Foundation (17-19-01097).

## References

[1] Eichler H J, Günter E, Pohl D W, *Laser-Induced Dynamic Gratings* (Springer-Verlag, Berlin, Heidelberg, 1986)
[2] Dao L V, Lowe M, Hannaford P, Makino H, Takai T, Yao T 2002 *Appl. Phys. Lett*. **81** 1806
[3] Scholes G D, Kim J, Wong C Y 2006 *Phys. Rev. B* **73** 195325

[4] Krausz F, Ivanov M, 2009 *Rev. Mod. Phys.* **81** 163
[5] Gallmann L, Cirelli C, Keller U 2012 *Ann. Rev. Phys. Chem*. **63** 447
[6] Allen L, Eberly J H, *Optical resonance and two-level atoms* (Wiley, New York, 1975)
[7] Arkhipov R M, Arkhipov M V, Babushkin I V, Rosanov N N 2016 *Opt. and Spectr.* **121** 758
[8] Arkhipov R M, Arkhipov M V, Babushkin I, Demircan A, Morgner U, Rosanov N N 2016 *Opt. Lett.* **41** 4983
[9] Arkhipov R M, Arkhipov M V, Babushkin I, Pakhomov A V, Rosanov N N, 2017 *Quantum Electron*ics **47** 589
[10] Arkhipov R M, Arkhipov M V, Babushkin I, Pakhomov A V, Rosanov N N, 2017 *Laser Physics Letters* , in press
[11] Arkhipov R M, Pakhomov A V, Arkhipov M V, Babushkin I, Demircan A, Morgner U, Rosanov N N, in preparation
[12] Bagaev S N, Egorov V S, Nikolaev V G, Chekhonin I A, Chekhonin M A 2015 *Russian Journal of Physical Chemistry B* **9(4)** 582