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A universal scheme for the generation of ultrashort laser pulse trains by Kerr nonlinear photonic crystal ultrafast all-optical switching

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Abstract
We propose a universal way to generate ultrashort pulse trains in arbitrary frequency regimes by means of Kerr nonlinear photonic crystal ultrafast all-optical switching. When a continuous laser light passes through a nonlinear photonic crystal with its band gap edge matching the laser light wavelength and pumped by a high-intensity femtosecond pulse laser, the ultrafast optical switching can lead to ultrashort pulse trains of transmission light. Simulation results show that the duration of the generated seed pulses can be as short as 12, 25, 54 and 68 fs for incident laser wavelengths of 0.633, 1.55, 5.12, and 10.6 μm, respectively, and the signal-to-background ratio contrast is about 3×10^3, which is very suitable for the subsequent amplification of these seed pulses.

Keywords: photonic crystal, ultrafast nonlinear optics, pulse trains

1. Introduction

The generation of ultrashort laser pulses is a hotspot of modern optics and physics due to the increasing need for ultrafast and intense coherent emission for fundamental physical and chemical investigations [1, 2] and various applications [3–6]. As is known, the popular method of generating ultrashort pulses in the visible or near-infrared frequency range is the mode-lock optical resonator technique. However, the technology is hard to extend to some wavelengths directly, such as near-infrared wavelength ranges of 1.55 μm and mid-infrared wavelength ranges of 10.6 μm. Nowadays, there are two main kinds of methods to generate ultrashort pulses at these wavelengths. One is to fabricate an 'artificial gain medium'. Low-dimensional semiconductor heterostructures [7], such as 'quantum wells' and 'quantum dots', are used for this purpose. With these semiconductor quantum structures, ultrashort quantum cascade lasers [8, 9] can be realized in these wavelength ranges. Another popular way is the nonlinear frequency conversion method. The second-order nonlinear effect of difference frequency mixing (DFM) [10], the optical parametric oscillator (OPO) [11], the optical parametric amplifier (OPA) [12], and the third-order nonlinear effect of four-wave mixing (FWM) [13] are widely used to convert ultrashort pulses with central wavelength around 800 nm to the near-infrared and mid-infrared frequency ranges. In this paper, we propose another approach to generate ultrashort pulses based on ultrafast all-optical switching with nonlinear photonic crystal structures.

Photonic crystal all-optical switching with high-contrast, low-pump-power and ultrafast response time [14–16] has been demonstrated by combining a high-power pump pulse and a large third-order nonlinear susceptibility of organic–dielectric

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or organic–metal–dielectric composite materials. As organic materials such as polystyrene have extremely fast optical response down to several femtoseconds, optical switching with a response time down to 10 fs has been realized [16]. On the other hand, technologies towards the generation of continuous laser light have become very mature. Many gas, dye, and solid gain media have been explored to generate a continuous laser in the visible, near-infrared, and mid-infrared wavelength ranges. It is then interesting to see what happens when these two elements are brought together by sending a continuous laser light through ultrafast optical switching made from Kerr nonlinear photonic crystals. It turns out that the transmission light is in the form of ultrashort pulses with good temporal profile. The central wavelength of the pulse is the wavelength of the incident continuous laser light, while the duration of the pulse is close to the response time of the optical switching. In the following we will take several examples to show how this can happen and how the technique can be used in generating ultrashort pulses at arbitrary wavelengths.

2. Principle and model

The principle to generate ultrashort seed pulses with nonlinear photonic crystals is as follows. A continuous probe laser and a strong pump pulse laser which is available by a traditional mode-lock technique (such as the ultrashort Ti:sapphire laser) are both incident into the nonlinear photonic crystal. The pump pulse whose central frequency is located at the conductive band of the photonic crystal is used to excite the change of refractive index in the nonlinear composite material of the photonic crystal, which will make an ultrafast shift of the photonic band gap. The continuous probe laser is set to locate at the band gap edge of the photonic crystal. When the pump light power is high enough, the band gap shift is sufficiently large so that the incident light can witness the on-state (high transmission in the conductive band) when the pulse is exerted on the crystal and the off-state (low transmission within the band gap) when the pulse leaves the crystal. It turns out that such a dynamical change of the transmittance of the continuous laser light will lead to a series of pulse trains. The temporal width of each pulse is determined by the duration of the pump pulse provided that the nonlinear material has a much faster response time. The central wavelength of the pulse is still the wavelength of the incident continuous laser, and the modulation frequency of the probe laser is just equal to the repetition rate of the pump pulse.

A simple one-dimensional photonic crystal structure can suffice for the above role because only a directional band gap is requested. As schematically depicted in figure 1, the structure is arranged alternatively with linear (air in our case) and Kerr nonlinear material (polystyrene) with a total period number of 18. Every layer has the same thickness ($d_1 = d_2$), and the refractive indices are $n_1 = 1.0$ and $n_2 = 1.59$, respectively. The third-order nonlinearity susceptibility of the polystyrene nonlinear material is 1.14×10^{-12} cm^2 W^{-1}, and the response of the nonlinear material is assumed to be instantaneous, as the response time (several femtoseconds) is much shorter than the pump pulse duration.

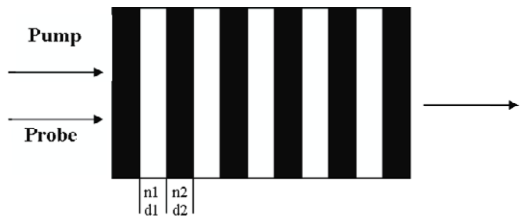

Figure 1. Schematic arrangement of a one-dimensional nonlinear photonic crystal. The refractive indices of the alternative materials are $n_1 = 1.0$ (air), and $n_2 = 1.59$ (polystyrene), respectively.

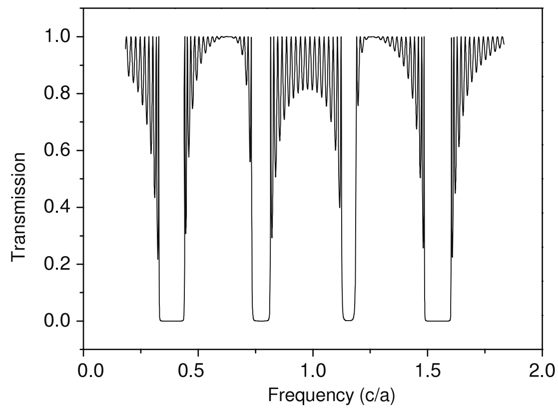

Figure 2. Calculated linear transmission spectrum of the one-dimensional photonic crystal. The frequency is normalized to c/a, where c is the speed of light in vacuum, and a is the lattice constant of the photonic crystal.

3. Calculation results and discussion

Let us first take a close look at the linear properties of one-dimensional photonic crystal structure as shown in figure 1. The linear transmission spectrum of this photonic crystal calculated by the finite-difference time-domain (FDTD) method is shown in figure 2. The high-frequency edge of the first band gap appears at the normalized frequency of $0.435(c/a)$, where c is the speed of light in vacuum, and a is the lattice constant of the photonic crystal. By changing the lattice constant of the photonic crystal, the first band gap will be located at different wavelength ranges. In the simulation below, the lattice constants are selected to be 272 nm, 668 nm, 2.2 μm, and 4.6 μm, so that the high-frequency edges of the first band gap are located at 625.3 nm, 1.53 μm, 5.06 μm, and 10.57 μm, respectively. In order to obtain higher signal-to-background ratio contrast, the frequency of the probe laser is selected at the forbidden band but very near to the high-frequency band edge of the first gap, with the normalized frequency around $0.43(c/a)$ and the linear transmittance about 3.5×10^{-3}. The corresponding wavelengths of the probe laser are 632.8 nm, 1.55 μm, 5.12 μm, and 10.6 μm, respectively.

Then we consider the nonlinear interaction processes. The ultrafast pump laser has a Gaussian temporal line shape with central wavelengths of 1064, 1064, 850 and 820 nm, respectively, which are located in the conductive band of the photonic crystal in each case, and their durations are 20 fs, 40 fs, 100 fs, and 100 fs, respectively. The nonlinear FDTD

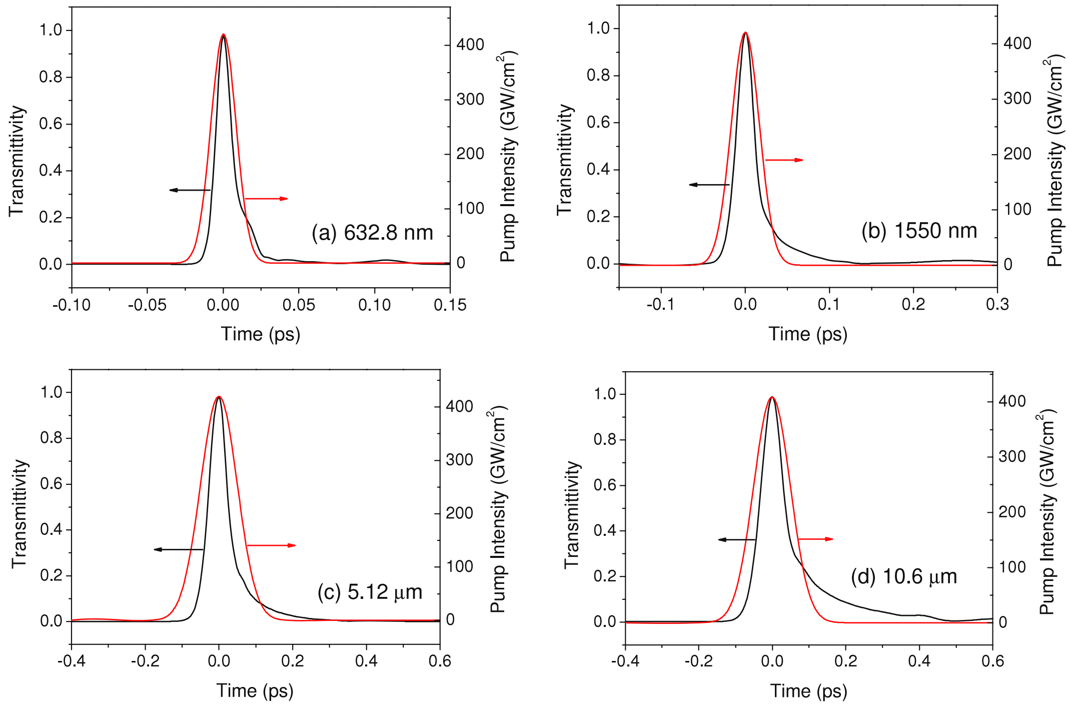

Figure 3. Calculated temporal profile of the transmission light (black lines) through nonlinear photonic crystal switching ignited by external Gaussian pump pulses (red lines). Four laser lights at 633 nm, 1550 nm, 5.12 μm, and 10.6 μm are considered. Under the pump pulses with durations of 20, 40, 100, and 100 fs, the output light is also ultrafast pulses with durations of 12, 20, 54, and 68 fs, respectively.

(This figure is in colour only in the electronic version)

method [17, 18] is used to examine the temporal evolution of the probe light when it passes through the nonlinear photonic crystal under external pump pulses. The simulation results for the transmission light temporal profile are shown in figures 3(a)–(d). The incident pump pulses in each case are also shown in figure 3 by the red lines. Here, we only consider the generation of an ultrashort seed pulse controlled by one period of the pump pulse, and the pulse train can be obtained with the repetition of the pump pulse.

According to the electromagnetic variational theorem [19], for the photonic band structure of photonic crystals, the low-frequency modes concentrate their energy in the high dielectric constant regions (called the 'dielectric band'), and the high-frequency modes concentrate their energy in the low dielectric constant regions (called the 'air band'), which ensure that the system stays at the minimized energy state. The band structures will shift with the changes of dielectric constant contrast of the photonic crystals. If the dielectric constant contrast slightly increases, the band structure will shift to lower frequency to maintain the lowest energy state of the system. So, for our system, due to the positive third-order nonlinear susceptibility of polystyrene, its dielectric constant increases with the incidence of strong pump pulses. As a result, the dielectric constant contrast of the photonic crystal will increase and the frequency of the photonic band gap edge mode will shift to lower frequency (red shift). That is to say, the transmittance of the probe laser increases at first, and then decreases when the pump pulse passes through. If the pump pulse is strong enough, the transmittance will change from very small (here of the order of 10^{-3}) to 1.0. There are two main parameters for characterizing the ultrashort seed pulses, the temporal width and the signal-to-background ratio contrast. The full-widths at half-maximum (FWHMs) of these seed pulses are about 12, 25, 54 and 68 fs, respectively, which are shorter than the duration of the pump pulse. The reason is that the frequency of the probe laser is located in the forbidden gap of the photonic crystal, and the transmittance will begin to change obviously only when the pump power reaches some value, such as $1/e$ of the maximum pump power. On the other hand, the signal-to-background ratio contrast is about 3×10^3, which is suitable for the subsequent amplification process for the seed pulses. We should notice that the signal-to-background ratio contrast of the seed pulse is related with the sharp extent of the photonic band gap edge. In addition, we have also calculated the situation when the pump pulses have a duration of 100 fs and central wavelengths of 850, 850 and 830 nm, and the probe laser is located at 2.56, 7.67, and 15.14 μm, respectively. We have observed generation of ultrashort seed pulses with durations of 53 fs (for 2.56 μm), 65 fs (for 7.67 μm) and 86 fs (for 15.14 μm).

From figure 3, we can find that the temporal line shapes of these seed pulses of the probe light are Gaussian-like with little tails at the dropping edge. As is shown above, the pump pulses have Gaussian temporal line shapes, which determine the main line shapes of the generated probe pulses. The tail at the dropping edge of the seed pulses originates from the complicated nonlinear interaction processes. Due to the strong nonlinear interaction between the ultrashort pump pulses and the photonic crystals, the transmission seed pulses can be treated as two parts: zero-order main pulse and the scattered

Table 1. The summarized calculation parameters and results of figure 3.

Wavelength of probe light	Durations of pump pulses	Lengths of photonic crystals (μm)	Duration of generalized seed pulses (fs)	Number of optical cycles of seed pulses
632.8 nm	20 fs (6 μm)	4.896	12	5.69
1550 nm	40 fs (12 μm)	12.024	20	3.87
5.12 μm	100 fs (30 μm)	39.6	54	3.16
10.6 μm	100 fs (30 μm)	82.8	68	1.94

pulse. When the length of the photonic crystal is long enough or the duration of the pump pulse is wide enough, the two parts of the probe light are not separated, and a relatively good temporal line shape will be obtained. In our simulations, we expect to obtain seed pulse trains with the duration as short as possible and the temporal shape as good as possible. Here we summarize the calculation parameters and results of figures 3(a)–(d) in table 1. In all cases, the photonic crystals possess the same periodical numbers ($N = 18$) but different lattice constants. For the probe wavelength of 632.8 nm, the length of the photonic crystal is short (less than 5 μm). If the duration of the pump pulse is narrow enough, i.e. less than 15 fs, the scattered pulse will be separated away from the zero-order main pulse and affect the line shape of the seed pulse seriously. For this reason, to obtain a relatively good temporal shape of the seed pulse, we select the duration of the pump pulse as 20 fs. The same considerations are made with other probe wavelengths. With a longer probe wavelength, the length of the photonic crystal also increases in order to have a sufficiently developed band gap. In this case, the duration of the pump pulse should be wider in order to avoid the separation between the zero-order main pulse and the scattered pulse. From table 1, we can also find that because of the complicated nonlinear interactions between the ultrashort pump pulses and photonic crystal structures, the number of optical cycles of the generated seed pulses decreases as the probe wavelength becomes longer.

In the above simulations, we have assumed high power of the pump pulse. For the switching contrast of 3×10^3, the average powers of single pump pulses are about 200 GW cm^{-2}, 120 GW cm^{-2}, 100 GW cm^{-2}, and 80 GW cm^{-2} for the 632.8 nm, 1.55 μm, 5.12 μm, and 10.6 μm situations, respectively. The pump power can be significantly reduced when the request for the signal-to-background ratio contrast is relaxed. For a 10^2 contrast, the average pump power is lowered down to 70, 50, 45, and 40 GW cm^{-2}, respectively. At the same time, the pulse duration of the probe light does not change. In this condition, the maximum changes of dielectric constant in the nonlinear layers are about 6.3% (from 2.5281 to 2.6877), 4.5% (from 2.5281 to 2.6421), 4% (from 2.5281 to 2.6307) and 3.6% (from 2.5281 to 2. 6193). Assuming that the diameter of the focal point of the pump pulse is 10 μm and that the repetition rate is 80 MHz, the average powers of the incident pump pulse are 88, 126, 285 and 250 mW, which are available in practical applications. On the other hand, the contrast can be improved by adopting a nonlinear photonic crystal sample with more period numbers and a steeper band gap edge. This is another efficient way to reduce the pump power.

The above scheme of photonic crystal ultrafast optical switching can yield ultrashort pulse trains for any continuous or long pulse laser light of arbitrary frequency. Although the peak intensity of each pulse is close to the incident laser light, the overall energy of each pulse is low due to very short duration of the pulse. This might greatly limit the practical applications. A way out of this weakness is to inject the low-power, ultrashort seed pulse with good signal-to-background ratio contrast into a series of amplifiers [20]. Ultrashort laser pulses with arbitrary central frequency (in particular the mid-infrared regime) and sufficiently high power will be very beneficial to a wide variety of fundamental and technological applications.

4. Conclusions

In summary, we have shown that it is promising to generate ultrashort seed pulses in arbitrary wavelength regimes by passing continuous or long pulse laser light through Kerr nonlinear photonic crystal all-optical switching that is ignited and controlled by external ultrafast pump pulses. The duration of the pulse can be as low as 12, 25, 54, and 68 fs for center wavelengths of 632.8 nm, 1550 nm, 5.12 μm, and 10.6 μm, respectively. At the same time, sufficiently high signal-to-background ratio contrast can be achieved. The approach is universal and flexible because suitable nonlinear photonic crystal structures can be conveniently designed and adjusted to match with arbitrary seed continuous lasers and pump pulse lasers.

Acknowledgments

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References

[1] Woutersen S and Bakker H J 1999 Resonant intermolecular transfer of vibrational energy in liquid water *Nature* **402** 507–9
[2] Baltuska A *et al* 2003 Attosecond control of electronic processes by intense light fields *Nature* **421** 611
[3] Tidrow M Z and Dyer W R 2001 Infrared sensors for ballistic missile defense infrared *Phys. Technol.* **42** 333–6
[4] Fecko C J, Eaves J D, Loparo J J, Tokmakoff A and Geissler P L 2003 Ultrafast hydrogen-bond dynamics in the infrared spectroscopy of water *Science* **301** 1698–702
[5] Miranda R S, Tom H W K, Johnson A M, Bridges T J and Aumiller G D 1991 Use of time-resolved IR reflection and transmission as a probe of carrier dynamics in semiconductors *Opt. Lett.* **16** 1859–61
[6] Wolf M, Ferrar M and Quaresima V 2007 Progress of near-infrared spectroscopy and topography for brain and muscle clinical applications *J. Biomed. Opt.* **12** 062104
[7] Kukushkin V A 2007 Efficient amplification of mid-to far-infrared pulses due to optical pulse conversion in waveguiding quantum-well heterostructures *Phys. Rev.* A **76** 023817

[8] Paiella R, Capasso F, Gmachl C, Sivco D L, Baillargeon J N, Hutchinson A L, Cho A Y and Liu H C 2000 Self-mode-locking of quantum cascade lasers with giant ultrafast optical nonlinearities *Science* **290** 1739–42

[9] Soibel A *et al* 2004 Active mode locking of broadband quantum cascade lasers *IEEE J. Quantum Electron.* **40** 844–51

[10] Koller F O, Haiser K, Huber M, Schrader T E, Regner N, Schreier W J and Zinth W 2007 Generation of narrowband subpicosecond mid-infrared pulses via difference frequency mixing of chirped near-infrared pulses *Opt. Lett.* **32** 3339–41

[11] Kennedy G T, Reid D T, Miller A, Ebrahimzadeh M, Karlsson H, Arvidsson G and Laurell F 1998 Near- to mid-infrared picosecond optical parametric oscillator based on periodically poled $RbTiOAsO_4$ *Opt. Lett.* **23** 503–5

[12] Petrov V, Badikov V, Panyutin V, Shevyrdyaeva G, Sheina S and Rotermund F 2004 Mid-IR optical parametric amplification with femtosecond pumping near 800 nm using $Cd_xHg_{1-x}Ga_2S_4$ *Opt. Commun.* **235** 219–26

[13] Fuji T and Suzuki T 2007 Generation of sub-two-cycle mid-infrared pulses by four-wave mixing through filamentation in air *Opt. Lett.* **32** 3330–2

[14] Hu X Y, Jiang P, Ding C Y, Yang H and Gong Q H 2008 Picosecond and low-power all-optical switching based on an organic photonic-bandgap microcavity *Nat. Photon.* **2** 185–9

[15] Liu Y H, Zhang D Z, Tian J, Feng S, Zhang D X and Cheng B Y 2006 All-optical switching with 20 fs response *Proc. SPIE* **6353** 635307

[16] Liu Y, Qin F, Wei Z Y, Meng Q B, Zhang D Z and Li Z Y 2009 10 fs ultrafast all-optical switching in polystyrene nonlinear photonic crystals *Appl. Phys. Lett.* **95** 131116

[17] Tran P 1995 Photonic-band-structure calculation of material possessing Kerr nonlinearity *Phys. Rev.* B **52** 10673–6

[18] Liu Y, Zhou F, Zhang D Z and Li Z Y 2009 Energy squeeze of ultrashort light pulse by Kerr nonlinear photonic crystals *Chin. Phys. Lett.* **26** 014208

[19] Joannopoulos J D, Meade R D and Winn J N 1995 *Photonic Crystals: Molding the Flow of Light* (Princeton, NJ: Princeton University Press) chapters 2 and 4

[20] Filip C V, Narang R, Tochitsky S Y, Clayton C E and Joshi C 2002 Optical Kerr switching technique for the production of a picosecond, multiwavelength CO_2 laser pulse *Appl. Opt.* **41** 3743–7