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Dynamic response of a coupled-cavities one-dimensional photonic crystal in the femtosecond regime

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Temporal transmission properties of a 2.75 μm long coupled cavities one-dimensional photonic crystal were experimental investigated by using 70 fs pulses at 800 nm. The device has been designed and fabricated in order to guarantee distortion-free propagation of ultra-short pulses. Indeed coupling between multiple cavities produces a wide resonance within the gap which allows up to 70 fs delay without significant distortion of the pulse.

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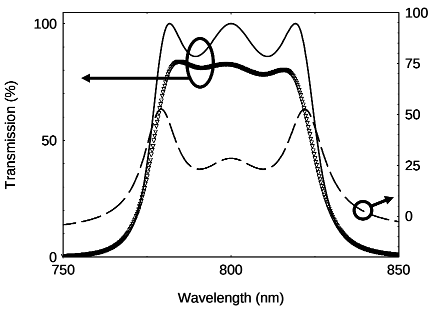
1. Introduction

Design and characterization of suitable temporal transmission properties of optical devices in the femtosecond and picosecond regime are useful issues in the telecommunication frame. In particular optical delay elements will be one of the key components for synchronization purposes in all-optical signal processors. For example demultiplexing and optical data buffering functionalities in optical computing need a strong local timing control of incoming signals in order to be performed. Future systems will require at the same time two main tasks on optical delay elements: they have to be compact and suitable for ultrashort (less than 100 femtosecond) pulses transmission [0]. Many efforts have been devoted in slowing light, both for basic physics studies and for telecommunications purpose. Electromagnetic induced transparency [2] and coherent population oscillations [3, 4 and references therein] are two of the physical processes that have been used in order to reach astonishing small group velocity (few m/s), though the small bandwidth (Hz-kHz) makes these systems more interesting for studying of basic properties of matter than in telecommunications. Stimulating Brillouin scattering [5] was usefully used in the range of 100MHz in order to delay ns pulses while, by using stimulated Raman scattering [6], 430 fs pulses (3 THz of bandwidth) were delayed up to 370 fs (i.e. 86% of original pulse). Photonic crystals (PCs), in which photons experience multiple reflections, are very promising candidates in terms of compactness and working speed [7,8]. Indeed a very small group velocity can be obtained at the band edge of PCs although extremely large group-velocity dispersion at the band edges would seriously distort ultrashort pulses. In order to solve this problem, the use of impurity bands formed by coupled defects as efficient delay lines for ultrashort pulses was recently proposed [9]. From the experimental point of view, a 20 μm long waveguide with hole defects was used to obtain a delay of 600 fs for 110 fs pulses [10-11].

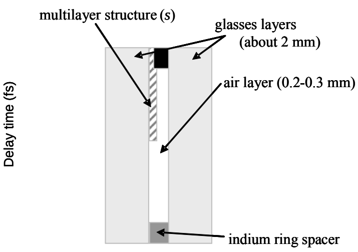
In this paper we report on the experimental characterization of temporal transmission properties of a one-dimensional (1-D) photonic crystal suitable as a delay line with pulses shorter than 100 fs (70 fs, corresponding to more than 14 THz of bandwidth) in the wavelength range of 800 nm. We have also compared the experimental results to our theoretical predictions.

2. Device design, fabrication and preliminary tests

The device was previously designed and used for distortion-free transmission properties studies of femtosecond pulses [12]. It comprises a coupled-cavity multilayer nanostructure made by alternating cryolite (Na_3AlF_6) (n_L=1.34 at λ_0=800 nm) and zinc sulphide (ZnS) layers (n_H=2.3 at λ_0=800 nm). Each layer, labeled as H (L) for high (low) index material, has a quarter-wave optical thickness with respect to λ_0 (i.e. 87 nm and 149 nm for H and L materials respectively). In terms of this notation, the structure can be illustrated as $HLH^4LHLHLH^4LHLHLH^4LH$, where H^4 indicates one-wave thick high refractive index layer (cavity) which is interposed every five quarter-wave layers [13]. Thus, the overall structure (2.75 μm long) exhibits three identical coupled cavities in resonance one to each other. As it happens with any coupled resonators [14], such configuration is responsible for the appearance of a wide pass band of more than 30 nm HWHM in the transmission spectrum. This is a necessary condition to be fulfilled in order to avoid distortions upon transmission of the 70 fs input pulses (see Fig. 1(a)). In our previous work [12] we studied the distortion properties of the PC and found, from calculation, that the structure could in principle also provide a delay of the order of pulse duration (Fig. 1(a), dashed line). This consideration stimulated us to investigate more deeply its temporal transmission properties looking in particular at the delay time felt by femtosecond pulses. The PC was grown by means of thermal vacuum evaporation on a BK7 glass substrate [15] and sealed on top with another BK7 glass substrate in order to avoid the deterioration of highly hygroscopic layers of ZnS. The deposition parameters can be found in ref.12. In order to measure the delay, we modified the sample by etching half of it from the substrate as shown in Fig. 1(b). In this way we could measure the delay introduced only by the PC by subtracting the substrate contribution.



(a)



(b)

Fig. 1. (a) Theoretical transmission spectrum of the PC structure (thin solid line) at normal incidence together with the experimental spectrum of the fabricated sample (open triangles). With the dashed line is represented the calculated group delay time. [the data are reproduced from the curves in ref.12] (b) Sketch of the test structure. The PC layers are growth only on half of the substrate in order to compare the delay due to the PC with respect to the air gap delay.

In Fig. 1(a) we compare the theoretical transmission spectrum (thin solid line) with the experimental spectrum obtained for the realized sample by using p-polarized light with a standard spectrophotometric technique (open triangles). In the same figure we show also the expected group delay time (dashed line) that a pulse undergoes when passing through the sample, calculated from the theoretical transmission function [16]. The delay was calculated by using the phase time [17] defined by:

$$\tau_\varphi(\omega) = \frac{\partial \varphi_t}{\partial \omega} - \frac{L}{c} = \frac{\mathrm{Re}\,t\,\frac{\partial}{\partial\omega}\mathrm{Im}\,t - \mathrm{Im}\,t\,\frac{\partial}{\partial\omega}\mathrm{Re}\,t}{|t|^2} - \frac{L}{c} \quad ,(1)$$

where L is the geometric length of the multilayer, E is the electric field inside the PC, E_0 is the electric field at the input of the structure, r and t are the reflection and transmission coefficients respectively.

3. Exprimental set-up and measurements

Our experiment was performed by using 70 fs pulses at 795 nm wavelength provided by a Fourier-transform limited Ti:Sapphire mode-locked oscillator.

The effect of the PC on the pulse delay was measured by using a cross-correlation set-up based on non-collinear second harmonic generation (SHG), as shown in Fig. 2. The laser pulse is split by 50% beam splitter (BS) onto two arms of an interferometer. M1-MMT is a retro-reflector mirror mounted on a manual micrometric translation stage to roughly adjust the paths (they have to be equal within 30 μm) and M2-AT is a second retro-reflector mirror mounted on a motorised translation stage with sub-micrometer sensitivity. The two pulses pass through the sample, one in the region where the PC is present and the other in the bare substrate. They were then recombined and focused on a nonlinear crystal designed for non-collinear SHG. The intensity of the SHG signal as a function of the pulses' path difference yielded the cross-correlation and then information about their time delay.

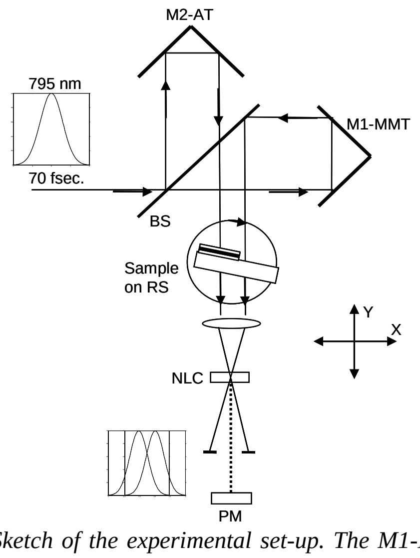


Fig. 2. Sketch of the experimental set-up. The M1-MMT mirrors are mounted on a manual micrometric translation stage with a 10 μm sensitivity. The M2-AT mirrors are mounted on an automatic motorized translation stage with sub-micrometric sensitivity.

The test sample is mounted on a rotation stage (RS) in order to explore different delay regions: by changing the incidence angle it is tuned in this way the central wavelength of our source at different position of the PC transmission spectrum. Indeed, increasing the input angle, the spectrum and consequently the group delay curve, shift towards the blue spectral region [12, 18]. Fig. 3 shows the experimental results. At 0 deg the measured delay is 25±1 fs with a 81% of transmission, while the maximum delay of 70±9 fs can be obtained at an angle of 31 deg. In the latter case the central laser wavelength is tuned close to the band edge and the transmission is lower (43%), which leads to a higher noise value. A better compromise between delay value (51±1 fs) and transmission (60%) can be obtained at 27 deg. In any case (0 deg – 30 deg interval) we are in a weak distortion condition as shown in our previous work [12].

Experimental results were then compared with numerical calculations (continuous line in Fig. 3) using a theoretical model detailed in ref. 19. Linear pulse propagation trough the layered structure was numerically simulated by calculating the complex transfer function $\tilde{t}(\omega)$ of our device in frequency domain. The input pulse $f_{input}(t)$ is Fourier transformed, then the transfer function is applied to the spectral components of the field and finally the inverse Fourier transform gives the output field profile according to the formula:

$$f_{output}(t) = FT^{-1}\left(\tilde{t}(\omega) FT(f_{input}(t))\right) \qquad (2)$$

We note that theoretical results are in very good agreement with the experimental data. The effective index of refraction $n_{eff} \approx 7.5$ is in the same range of previous presented geometry suitable for femtosecond pulses (see ref. 6 for example).

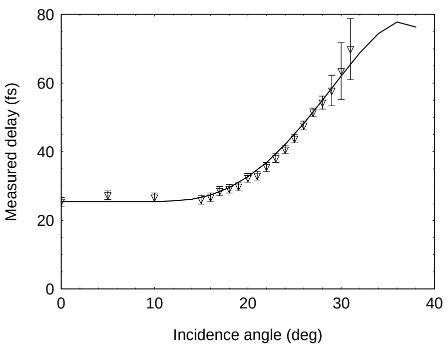


Fig. 3. Measured delay time felt by the incoming pulses as a function of the incidence angle. The experimental data are compared with the numerical calculation of the delay time (solid line).

4. Conclusions

In conclusion, our PC structure can produce up to 70 fs delay of 70 fs pulses (100% of the pulse duration) without any significant distortion. Moreover the coupled cavity geometry allows to use series of similar structures (i.e. by using more than three cavities) in order to achieve the desired delay without changing the spectral properties of the incoming pulse.

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