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Wide-band transmission of nondistorted slow waves in one-dimensional optical superlattices

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Few micron-thick one-dimensional optical superlattices were designed and grown, in which an optimized choice of external dielectric layers allows the formation of a wide and high transmission miniband of coupled cavity states. In such structures a reduction in light group velocity and minimal line shape distortion of propagating optical signal was observed. Group velocity reduction by a factor of 5, obtained both from phase (white-light interferometry) and from time-resolved measurements, is in reasonably good agreement with those calculated through a transfer matrix approach. Time-resolved experiments confirm the minimal line shape distortion for optical pulses of 1.8 THz bandwidth at $\lambda = 1.5$ μm wavelength. © *2006 American Institute of Physics*.
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Stopping and slowing down of electromagnetic waves in various physical systems, such as in ultracold atomic gases[1,2] and photonic crystals,[3,4] has triggered an intensive research, which is rapidly developing. Experimental demonstration of slow waves, propagating at a group velocity v_g that is two to three orders of magnitude smaller than the vacuum speed of light c, have been reported recently.[5–7] Various theoretical approaches have been suggested, which describe mechanisms of suppressing adiabatically the group velocity of light pulses down to zero.[4,8] Coupled resonator optical waveguides (CROW),[3,4] in which a resonant suppression of group velocity of optical pulses occurs, have been suggested as reliable photonic systems to slow down light propagation. From the point of view of device application, it is desirable to maintain the propagating signal line shape along with small group velocities. High-finesse one-dimensional (1D) Fabry-Perot cavities offer very low group velocities at the resonant frequencies, while they strongly distort optical pulses. It is possible to design a finite size coupled cavity system with optimized coupling to the environment,[9] which results in an almost flat v_g dispersion in the center of the wide and high transmission miniband of photonic states.

In this letter we report on fabrication and characterization of several micron thick 1D CROW structures, which can transmit without distortion short pulses of 1.8 THz bandwidth [full width at half maximum (FWHM) ~14 nm] in the third telecom window at a $v_g/c \simeq 0.2$ group velocity. Samples were grown using controlled electrochemical etch technology of (100)-oriented heavily doped p-type silicon wafers (a detailed description of multilayer growth technology can be found elsewhere[10]). An optical superlattice is built up by coupling identical half-wavelength cavities through dielectric Bragg mirrors. The structure sequence can be presented as $M_{\text{ext}}/C_1/M_{\text{int},1}/C_2/M_{\text{int},2}\cdots/C_n/M_{\text{ext}}$, where M_{ext} denotes the external mirrors and $M_{\text{int},n}$ and C_n stand for the internal mirrors and cavities, correspondingly. Three different types of self-standing optical superlattices have been designed and realized. Firstly, a four coupled cavity sample was grown with identical external and internal Bragg mirrors (sample S1). A second structure was grown (sample S2) with similar cavities and internal mirrors, while the external mirrors have been chosen such that a good coupling condition to the environment (impedance matching) was fulfilled. Finally, the third sample, composed of five cavities and optimized external mirrors was prepared (sample S3).

In Fig. 1(a) the light intensity distribution inside sample S1, calculated using a standard transfer-matrix (TM) approach,[11] is shown. Four distinct resonances appear in the

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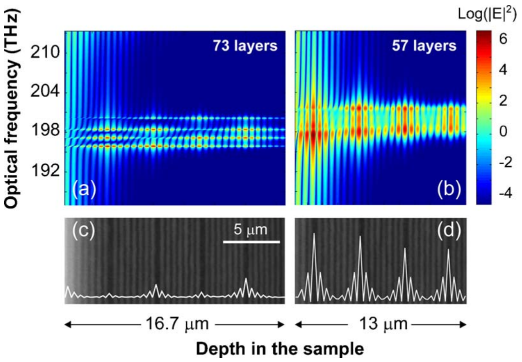

FIG. 1. (Color online) Light intensity distribution around the miniband regions (a) in a 1D CROW structure with identical internal and external Bragg mirrors (sample S1) and (b) in a thinner sample with optimized external mirrors (S2). (c) and (d) show the cross-sectional SEM micrographs of samples S1 and S2. The electric field distribution inside the photonic structures at the central frequencies of the minibands is also plotted, showing an enhancement and significant penetration inside the mirrors for sample S2.

photonic stop band due to a resonant mode repulsion. Narrow peaks, corresponding to these resonances appear in the transmission spectrum. An optimized choice of external mirrors in the case of sample S2 modifies strongly the light distribution inside the superlattice [Fig. 1(b)]. This results in a broadening of single peaks and a formation of a wide and high transmission miniband.[12] In Figs. 1(c) and 1(d) scanning electron micrographs (SEM) of both samples are shown. The electric field distributions at the center of the minibands are plotted in the same scale: the high and symmetric field profile with enhanced penetration into the mirrors throughout sample S2 is clearly visible.

Two different techniques have been employed to study the light propagation peculiarities through the different CROW structures. Firstly, white-light interferometry was performed to measure the phase delay of the light transmitted through samples using a Mach-Zehnder interferometer coupled to a Fourier-transform spectrometer.[13,14] The phase spectra were then corrected for the delay (in vacuum) corresponding to the sample thickness, which was measured independently by a micrometric comparator. Both transmittance and phase spectra were recorded. In general, in a $\lambda/2$-thick cavity the phase shift suffers a π jump. This can be well appreciated in sample S1, as shown in the inset of Fig. 2(a), where corresponding jumps in the phase appear through each of four transmission resonances. On the contrary, as predicted, for sample S2 [Fig. 2(a)], the phase suffers a smooth increase through the wide and high transmission miniband, summing up to a total shift of 4π. In Fig. 2(b) a similar phase behavior is shown for sample S3, where the phase shift sums up to exactly 5π. Numerical calculations for the phase (solid lines) are in rather good correspondence with the measured ones.

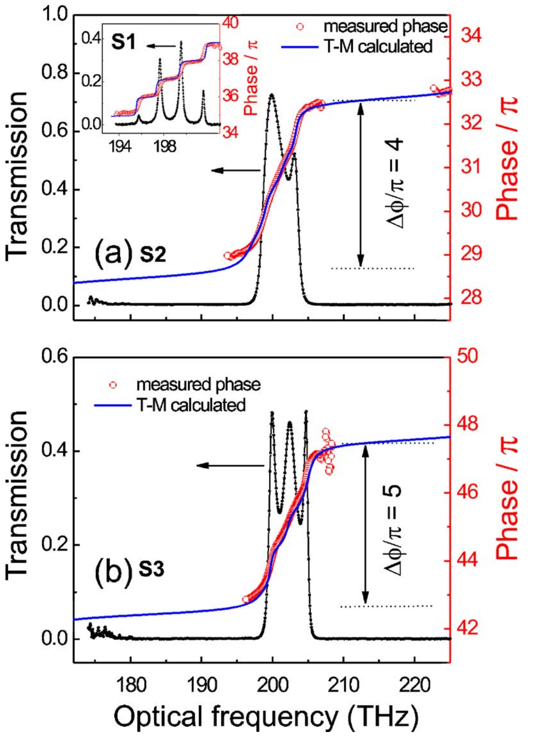

FIG. 2. (Color online) Static transmission spectra and the measured phase obtained through white-light interferometry method: (a) four (sample S2) and (b) five (sample S3) coupled cavity structures with optimized external mirrors. Numerically calculated phase is plotted as a solid line in both graphs for comparison. The inset shows the transmission and the phase around the miniband region of sample (S1) with nonoptimized external mirrors.

In order to study the temporal evolution of light pulses, propagating through the CROW structures, we employed an optical gating technique to detect ultrafast (160 fs) tunable pulses between 1400 and 1600 nm transmitted from the samples (details can be found in, e.g., Ref. 15). We report in Fig. 3 several signals (scatter) transmitted through sample S2 together with the reference signal (without sample). The origin of the time scale corresponds to the peak position of the reference Gaussian pulse. One can see that the transmitted signals are delayed with respect to the reference pulse. In addition, the signals present different line shapes depending on the probe frequency of the input pulses. When the narrow state at the band edge (204 THz) is excited, the transmitted pulse is strongly distorted, showing a long exponential tail for long times. The pulse centered at the dip in the transmission spectrum (201 THz) [see Fig. 2(a)] excites both maxima of the miniband. This results in characteristic beatings, which appear as oscillations in the temporal spectrum. Finally, when the ultrashort pulse at 199 THz is fitting perfectly in the broad part of the miniband, it is similarly delayed, while the input Gaussian line shape remains almost undisturbed.

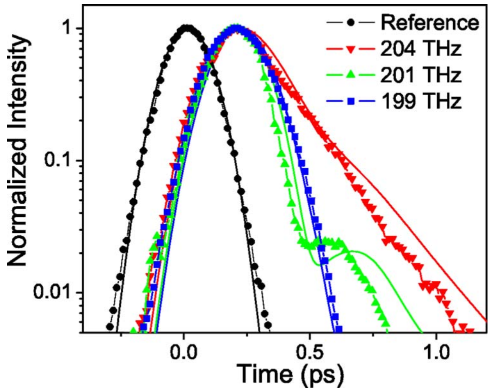

FIG. 3. (Color online) Measured (scatter) and calculated (solid lines) time-resolved ultrashort pulse propagation through sample S2. The reference Gaussian pulse is transmitted with negligible distortion (199 THz) when it fits the wide transmission miniband. Long exponential decays or oscillatory behavior is observed when the input pulse excites the edge states (204 THz) or two maxima (201 THz) of the miniband.

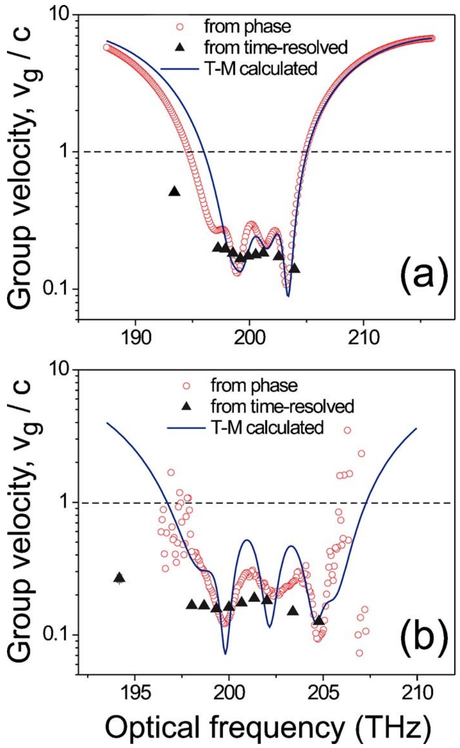

FIG. 4. (Color online) The group velocity obtained from phase (open circles) and from time-resolved measurements (full triangles). (a) Four cavity (S2) and (b) five cavity sample (S3) cases. Transfer matrix calculations are plotted in both graphs as solid lines. A group velocity reduction by a factor of 5 is observed in both samples. The group velocity has been extracted within a 4% error in the case of time-resolved data.

The transmitted pulse suffers a slight homogeneous broadening due to the fact that it travels through the dielectric medium, while the reference pulse propagates in air. We note that the highest absolute transmission value is measured (not shown) for the nondistorted signal. In Fig. 3 corresponding calculated spectra (solid lines) are shown for comparison, which confirm that the general behavior is reproduced quite well.

We have analyzed further the phase and time-resolved measurements in order to obtain the group velocity behavior in the miniband regions of samples S2 and S3. In particular, the group velocity has been obtained from the measured phase using the relation[14]

$$v_g^{-1} = \frac{1}{L}\frac{d\phi}{d\omega}, \tag{1}$$

where L is the physical extension of the sample and ω is the angular frequency. In the case of time-resolved measurements, v_g has been derived from the measured delay time of the transmitted signal at different frequencies (the delay of the center of the mass of the signals) corrected for the sample physical thickness. The obtained results are plotted in Fig. 4 together with the one calculated by a transfer matrix method. Quite good correspondence is found between the data derived from two different measuring techniques and the numerical results. Apart from the small variations, the group velocity is found to be around $v_g/c \simeq 0.2$.

In conclusion we have reported on the realization and characterization of few micrometers long 1D optical superlattices that can transmit nondistorted optical pulses of 1.8 THz frequency bandwidth at group velocities of $v_g/c \simeq 0.2$, centered at $\lambda = 1.5\ \mu$m. The results have interesting implications for the slowing down of light wave packets at telecom wavelengths and are amenable to further improvement by an optimized design of the coupled microcavity structures.

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