Heavy photon dispersions in photonic crystal waveguides

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Heavy photon dispersion curves exhibiting group velocities suppressed by two orders of magnitude are measured directly for deeply etched AlGaAs waveguide structures by means of surface coupling techniques. It is shown that due to the wave vector-selective nature of surface coupling, such techniques permit the excitation of modes of specific, known dispersion in photonic crystal waveguides. Coupling to regions of very strong anomalous dispersion is demonstrated, with potential to be developed into a method for excitation of gap solitons. © *2000 American Institute of Physics.* [S0003-6951(00)04728-8]

There has been a great deal of interest recently in the properties of two-dimensional (2D) photonic crystals fabricated in the form of thin films, commonly termed photonic crystal waveguides (PCWs).[1–5] A feature of the design of PCWs in comparison with conventional grating waveguides[6] is the very deep patterning which leads to wide photonic band gaps (PBG) and strong dispersive effects over large ranges of energy.[7,8] Such structures show significant promise to solve the long-standing problem of light extraction from light emitting diodes (LEDs)[9] and to create PBG-defined microlasers.[10] These applications require detailed knowledge of the dispersions of the photonic bands of PCWs, which exhibit pronounced heavy photon properties in the vicinity of band edges.

Until very recently, the experimental investigation of photonic dispersions in PCWs was limited to measurement of in-plane transmission and reflection spectra.[1,5] We have now shown that surface coupling techniques allow direct measurement of photonic dispersion curves in PCWs.[11–13] In this method illumination at a particular angle of incidence selects a specific value of in-plane wave vector, with coupling to the photonic bands appearing as sharp resonances in reflectivity. By varying the geometry we are able to map out large parts of the photonic band structure. Similar information has also been obtained recently from angle-resolved emission measurements.[14]

In the present letter heavy photon dispersions with group velocities suppressed by two orders of magnitude relative to those in bulk semiconductors are clearly observed in one dimensionally (1D) patterned AlGaAs waveguides. For 2D honeycomb lattices of air cylinders we show that photonic dispersions with pronounced heavy photon properties at k vectors within the first Brillouin zone can be achieved due to anticrossing of photonic bands. In comparison with conventional fiber and waveguide coupling methods[15] such surface coupling techniques possess the important advantage of external angular control of the group velocity and group velocity dispersion of the modes excited. We demonstrate this control by coupling external light directly to regions with very strong anomalous dispersion, opening the prospect for observation of nonlinear effects connected with propagation of ultrashort pulses.[15,16]

1D lattices of air stripes [Figs. 1(a) and 1(b)] and 2D honeycomb lattices [Fig. 3(a)] of air cylinders of periods 360–740 nm were fabricated by deep etching (etch depth $h = 650$ nm), using electron beam lithography and reactive ion etching,[1] of $Al_xGa_{1-x}As$ waveguides having 400 nm thick $x = 0.12$ cores and 1.35 μm thick, $x = 0.35$ cladding. Reflectivity experiments were carried out using plane parallel white light illumination from a tungsten halogen lamp. The light reflected from the 100×100 μm^2 lattices was strongly magnified (~50 times) and imaged on to the slits of a spectrometer and detected with a charge coupled device camera.

We first present the calculations of the reflectivity properties for structures patterned at different depths. In contrast to the well known case of shallow gratings which can be understood by simplified perturbation theories,[6] for deeply etched structures the patterning is a strong perturbation and an accurate theoretical approach needs to be based on a rigorous solution of Maxwell equations. Such calculations were carried out using a scattering matrix (SM) treatment of Maxwell equations, as described elsewhere,[17] including all layers in the structure and coupling to the external fields. Spectra are presented [Figs. 1(c) and 1(d)] for a 1D lattice of period 740 nm, air fill factor 0.19, transverse electric (TE) incident polarization, and illumination perpendicular to the grooves.

Spectra calculated for different etch depths $h \ll d$, $h = d$ and $h > d$ (where d is the thickness of the waveguide core) at the same angle of incidence $\theta = 60°$, are shown in Fig. 1(c). For very shallow patterning ($h \ll d$, 50 nm), two very sharp peaks at ~1.33 and ~1.54 eV are observed due to resonant

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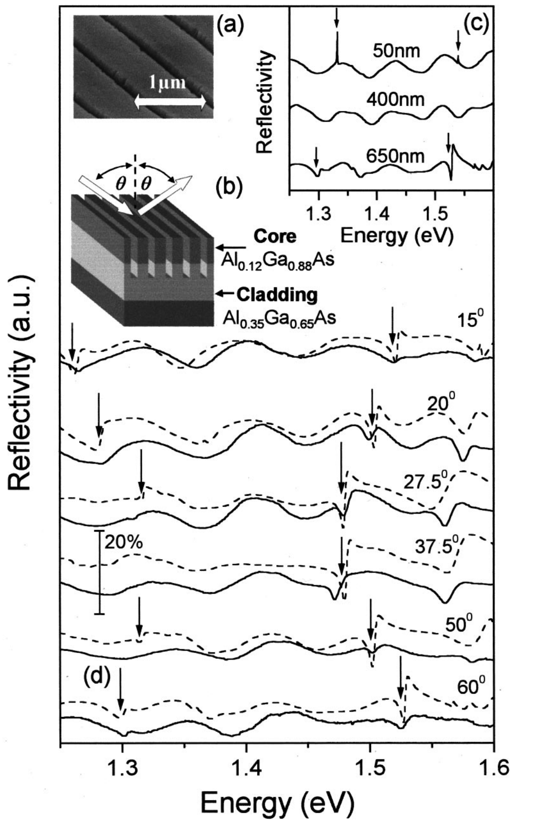

FIG. 1. (a) Scanning electron micrograph of typical 1D photonic crystal waveguide (with 630 nm period). (b) Schematic diagram of structure and the experimental geometry. (c) Calculated TE reflectivity spectra at $\theta=60°$ as a function of etch depth. (d) Experimental (full) and theoretical (dashed) reflectivity spectra for 740 nm period 1D structure, as a function of θ, for TE incident polarization. The edge of the folded BZ boundary is reached at ~30°, where it is seen that the energies of the sharp features indicated by arrows exhibit either minima (at 1.47 eV) or maxima (at 1.33 eV).

coupling to the folded band structure of very weakly perturbed guided modes.[6] For $h=d$, resonance features are not observed due to the loss of waveguide confinement as a result of the reduction of the average index of the core, which leads to strong scattering and leakage into the cladding. However, most importantly, loss into the cladding is strongly suppressed when h significantly exceeds d due to recovery of the effective index guiding, as shown by the reappearance of sharp resonance features in the simulated reflectivity spectra for $h>d$. Even though such deeply etched structures scatter light much more strongly than their shallow grating counterparts, the calculations show that coupling features can nevertheless be observed with high finesse in the range 10^2-10^3, as in Fig. 1(c).

This conclusion is confirmed by comparison of calculated spectra with experiments performed on the 740 nm period 1D lattice for TE polarization and a range of angles θ from 15° to 60°, shown in Fig. 1(d). Sharp resonant features, indicated by arrows, which shift strongly in energy with θ, superimposed on broad oscillations, are observed. The spectra are reproduced by the calculations very well, in both energy position and lineshape, for all θ.

In reflectivity measurements, the in-plane photon wave vector is related to θ by $k=(\omega/c)\sin\theta$. Thus, angular dependent reflectivity spectra can be used to map out PCW dispersion curves as shown in Figs. 2(a), 2(b), and 2(c) where the

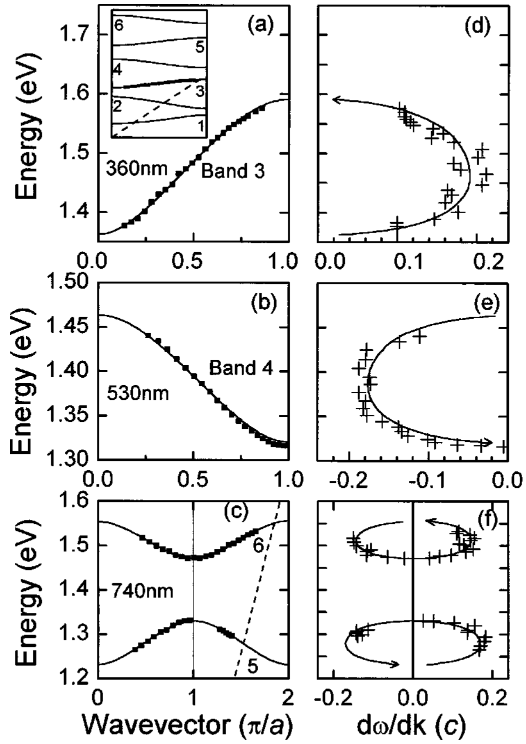

FIG. 2. (a), (b), and (c)—measured photonic dispersions for 360, 530, and 740 nm 1D lattices indicated by squares, and calculated (full lines). The inset to Fig. 2(a) shows the calculated band structure for the 360 nm lattice, with bands labeled (1)–(6). The diagonal dashed lines on 3(a) and 3(c) indicate the boundary of the light cone. 3(d), 3(e), and 3(f)—group velocities, in units of the velocity of light in vacuum (c), obtained by differentiation of the results of Figs. 3(a), 3(b), and 3(c), crosses experimental, full lines theory; arrows show the direction of increasing k.

measured energies (squares) of the sharp features are plotted versus k for 360, 530, and 740 nm periods, respectively. The energies of the features are seen to increase with k for 360 nm, to decrease with k for 530 nm and to exhibit turning points in the $E-k$ diagram of Fig. 2(c). In Figs. 2(d), 2(e) and 2(f) the variation of the photon group velocity (v_g) with k, obtained from the derivative $d\omega/dk$ of the dispersion curves of Figs. 2(a), 2(b), and 2(c) is presented. Regions of positive, negative and very small $v_g\sim10^{-2}c$, where c is the light velocity in vacuum, are found. The regions of very small of v_g represent regimes with pronounced heavy photon properties, and correspond to suppressions by factors of 10–100 relative to v_g in AlGaAs.

The $E-k$ results can be understood by comparison with band structure calculations, where the 1D structure is modeled as a periodically modulated layer with perfectly reflecting surfaces. The band structure was calculated using standard plane wave techniques,[18] with inclusion of a perpendicular wave vector ($q=\pi/d^*$, where d^* is the effective thickness of the guide) to allow for the vertical confinement. The results of the calculations are shown by the full lines on Figs. 2(a), 2(b), and 2(c) and are seen to be in very good agreement with experiment for all three periods, with the only adjustable parameter $d^*=550\,\text{nm}$.

From inspection of Figs. 2(a), 2(b), 2(c) and the Fig. 2(a) inset, it is clear that as a result of the approximate energy scaling of the band structure with inverse lattice period ($1/a$) we are able to realize coupling to different photonic bands by varying the period (the scaling is approximate since the en-

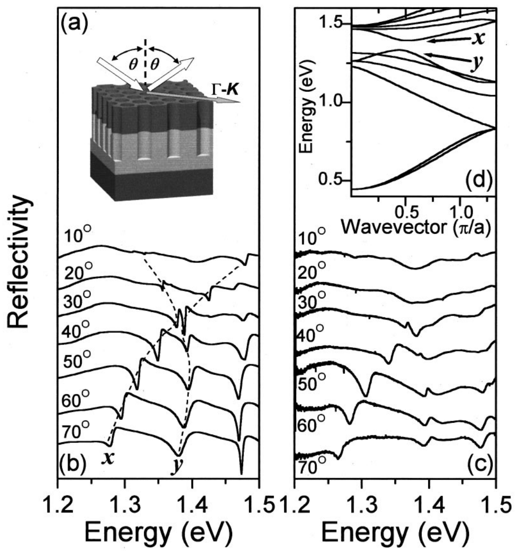

FIG. 3. (a) Schematic diagram of 2D photonic crystal waveguide. (b) Theoretical, (c) experimental reflectivity spectra for 360 nm 2D lattices, measured along the $\Gamma-K$ symmetry direction. Features x and y exhibit anticrossing at $\sim30°$. The dashed lines on Fig. 3(b) are a guide to the eye. (d) Calculated band structure for waveguide clad by perfectly confining mirrors. The region with anticrossing splitting between bands x and y of ~70 meV is visible at ~1.35 eV.

ergies of the bands are also affected by the vertical confinement). Coupling to the third TE band is observed for 360 nm [Fig. 2(a)], with the fourth band for 530 nm [Fig. 2(b)] and with the fifth and sixth bands for 740 nm [Fig. 2(c)]. For the 530 nm period the wave vector coverage of the light cone reaches the edge of the first Brillouin zone (BZ), and for the 740 nm period extends across the BZ boundary into the second zone [dashed diagonal line on Fig. 2(c)], thus allowing the coupling of incident light directly to heavy photon states in the regions of BZ boundaries.

We now show that 2D patterned PCWs may also exhibit heavy photon properties not only at BZ boundaries, but also in regions of k space far from any boundary. In this case the regions of $d\omega/dk=0$ arise from polarization mixing[7,12,13] which occurs in the presence of both 2D patterning and vertical waveguide confinement. Mixing between nominally TE and transverse magnetic bands leads to anticrossing, finite k regions of near zero v_g.

This behavior is illustrated by SM calculated [Fig. 3(a)] TE spectra for the 360 nm 2D structure as a function of θ along the $\Gamma-K$ direction. Pronounced reflectivity features (x and y) approach one another with an anticrossing splitting of about 10 meV at $\theta=30°$. The experimental spectra in Fig. 3(b) are very similar to those in Fig. 3(a), although in this case the linewidths are of the order of the splitting. However, calculations predict that the splitting can be significantly increased in the structures with stronger vertical confinement. This is illustrated by the band structure calculated for a 360 nm, 2D PCW clad by perfectly reflecting mirrors, shown in Fig. 3(d). A large anticrossing gap of ~70 meV then occurs between bands x and y leading to strong bending of photonic dispersions and pronounced heavy photon properties.

We have thus shown for both 1D and 2D structures that as a result of the wave vector selectivity of surface coupling techniques, we are able to achieve coupling to specific points of dispersion curves by variation of θ. This permits control not only of the group velocity [Figs. 2(d), 2(e), and 2(f)] as discussed earlier, but also of the group velocity dispersion parameter $\beta_2=d^2k/d\omega^2$ a key factor in determining the propagation of ultrashort pulses.[16,19,20] The energy dependence of β_2 diverges at band edges, with branches of both normal and anomalous ($\beta_2<0$) dispersion. By selecting θ, we can access each branch separately and realize very high values of $|\beta_2|$ up to $10^3\ \mathrm{ps}^2/\mathrm{m}$, three orders of magnitude larger than that for ordinary glass, opening up a very straightforward way to access nonlinear effects[19] of gap soliton propagation. Furthermore by comparison with e.g., shallow grating waveguides[21] and fiber gratings, the regions of large dispersion extend over very wide energy ranges of order 100 meV, due to the large photonic band gaps in PCWs.

To conclude, we have demonstrated that very strong dispersive effects can be accessed directly by the use of surface coupling techniques in photonic crystal waveguides. The direct characterization of the heavy photon dispersions reported earlier is of considerable significance is designing photonic structures to achieve efficient extraction of light in LEDs.[14] We have also showed that photonic crystal waveguides and associated surface coupling techniques may find important application in the study and realization of gap soliton effects.

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