Effect of implementation of a Bragg reflector in the photonic band structure of the Suzuki-phase photonic crystal lattice

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Abstract: We investigate the change of the photonic band structure of the Suzuki-phase photonic crystal lattice when the horizontal mirror symmetry is broken by an underlying Bragg reflector. The structure consists of an InP photonic crystal slab including four InAsP quantum wells, a SiO_2 bonding layer, and a bottom high index contrast Si/SiO_2 Bragg mirror deposited on a Si wafer. Angle- and polarization-resolved photoluminescence spectroscopy has been used for measuring the photonic band structure and for investigating the coupling to a polarized plane wave in the far field. A drastic change in the k-space photonic dispersion between the structure with and without Bragg reflector is measured. An important enhancement on the photoluminescence emission up to seven times has been obtained for a nearly flat photonic band, which is characteristic of the Suzuki-phase lattice.

OCIS codes: (250.0250) Optoelectronics; (250.5300) Photonic integrated circuits; (250.5230) Photoluminescence

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1. Introduction

Since the discovery that certain periodic structures can confine the light, photonic crystals (PC) [1, 2] have been deeply studied due to the possibility of accurate control of the light at the wavelength scale [3, 4]. Particular interest has been devoted to the use of two-dimensional photonic crystal slabs (2D-PCs) for the development of such building blocks of the future integrated photonic circuits [5] as photonic crystal lasers [6, 7, 8] and photonic crystal waveguides [9, 10]. A way for improving the properties of 2D-PCs is to combine them with one-dimensional Bragg reflectors. Some devices combining a 2D-PC and a one-dimensional Bragg reflector have been already done [11, 12, 13, 14]. The combination of a Bragg reflector with an active 2D-PC slab can enhance the quality factor of the resonant mode giving rise to a decreasing of the lasing threshold [11, 12]. In this way, we study the actual effect of the Bragg mirror on the photonic bands. For this purpose, we have fabricated the Suzuki-phase (SP) 2D-PC [15] in samples with and without bottom Bragg reflectors. The Suzuki lattice belongs to a set of 2D structures, like also the graphite and the Archimedean lattices [16, 17], which possess a basis made of several rods per unit cell. All these lattices seem to support several low-dispersive photonic bands, similar to coupled cavity arrays [18]. The SP lattice presents two features that are very useful for this study: On one side, it has a complex photonic band structure in two dimensions, which allows to probe several bands in the region of wavelengths of interest (around 1500 nm). On the other side, the SP pattern presents a flat band along the direction $\Gamma X1$, well isolated from other bands and which shape remains almost unchanged when we calculate the band structure in the "symmetric" and in the "nonsymmetric" or full band approach [15]. The fabricated structures were characterized by polarization-resolved angle-resolved photoluminescense (PR-ARP) in order to obtain the photonic band structure and its polarization. A drastic difference in the photonic band structure was measured between the samples with and without Bragg mirror. Moreover, an important enhancement of the intensity of the photoluminescense (PL) emission between four and seven times for one particular photonic band was measured.

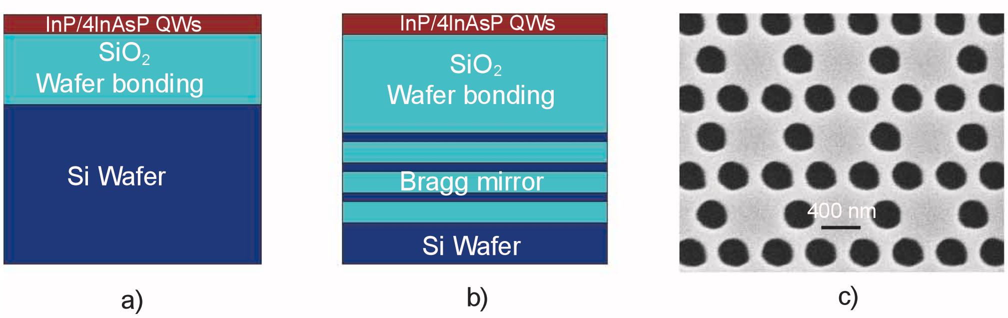

Fig. 1. Layout of the transversal section of the fabricated structures. (a) InP/InAsP layer epitaxy bonded to a Si wafer. (b) InP/InAsP layer epitaxy bonded to a Bragg reflector on top of the Si wafer. (c) Scanning electron microscopy (SEM) image of the fabricated structure with Bragg mirror.

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2. Fabrication and Optical characterization

2.1. Fabrication

The SP PC lattice was fabricated in two kinds of semiconductor slabs. The first one (Fig. 1(a)) consists of an InP slab incorporating four $In_{0.65}As_{0.35}P/InP$ quantum wells grown on an InP substrate by molecular beam epitaxy. The layer has a thickness $d =$ 237 nm. The epitaxy is transferred onto a silicon-on-silica substrate by wafer bonding (SiO_2 thickness $=0.9\pm0.1\mu$m) [19]. The second one (Fig. 1(b)) consists of an InP slab containing the same quantum well structure as before. The thickness is $d = 250$ nm. A three pair quarter-wavelength Si/SiO_2 is deposited in the top of a Si wafer by low pressure chemical vapor deposition. The thickness of the Si and SiO_2 $\lambda/4$ layers are 110 nm and 255 nm, respectively. A reflectance spectra of the Bragg mirror is shown in Ref.[11]. The epitaxial structure is transferred on the top of the Bragg mirror by SiO_2 wafer bonding. The thickness of the SiO_2 bonding layer is $d_{SiO_2} = 790$ nm [11]. Both structures present a strong PL around 1.5μm.

A 90 nm-thick SiO_2 layer was deposited by plasma assisted sputtering on top of both samples as mask layer for the etching process. Electron-beam lithography and reactive ion-etching were used for the patterning [20]. For the structure without Bragg mirror the lattice parameter a is 455 nm ($d/a = 0.514$) while for the structure with Bragg mirror $a = 484$ nm ($d/a = 0.516$). It is important to have the same d/a value for both samples because the photonic bands change with the thickness of the slab [21, 22, 23], which may prevent easy comparison of the emission properties between structures. The same value of the radius of the holes was $r = 0.33a$ for both structures. The size of the fabricated structures was $25\mu m \times 25\mu m$ for the sample without Bragg and $30\mu m \times 30\mu m$ for the sample with Bragg.

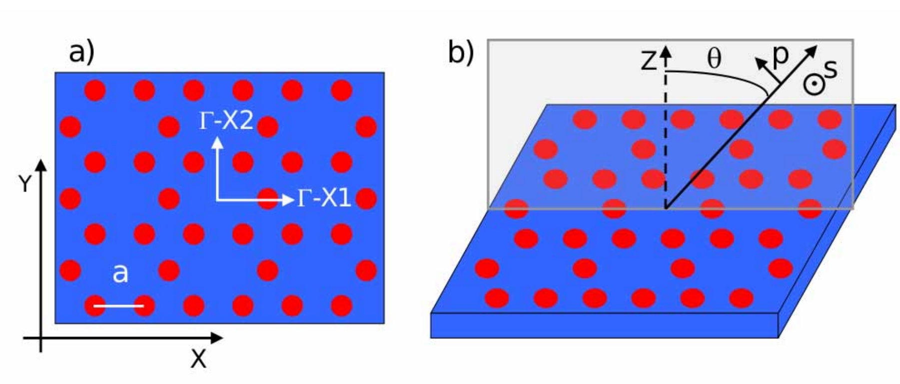

Fig. 2. (a) Suzuki lattice with the axes in the XY plane. (b) Schematic drawing of the experimental geometry, for the specific case of Γ-$X1$ orientation, with the polarization directions of the electric field with respect to the plane of observation. Under specular reflection $\hat{\sigma}_{kz}$ with respect to a vertical mirror plane including the wavevector, transverse magnetic or p-modes are even ($\sigma_{kz} = +1$) while transverse electric or s-modes are odd ($\sigma_{kz} = -1$).

2.2. Optical characterization

PR-ARP spectroscopy was used for optical characterization. The samples were optically pumped with a 635nm laser diode through a 10× (NA=0.26) objective placed at an

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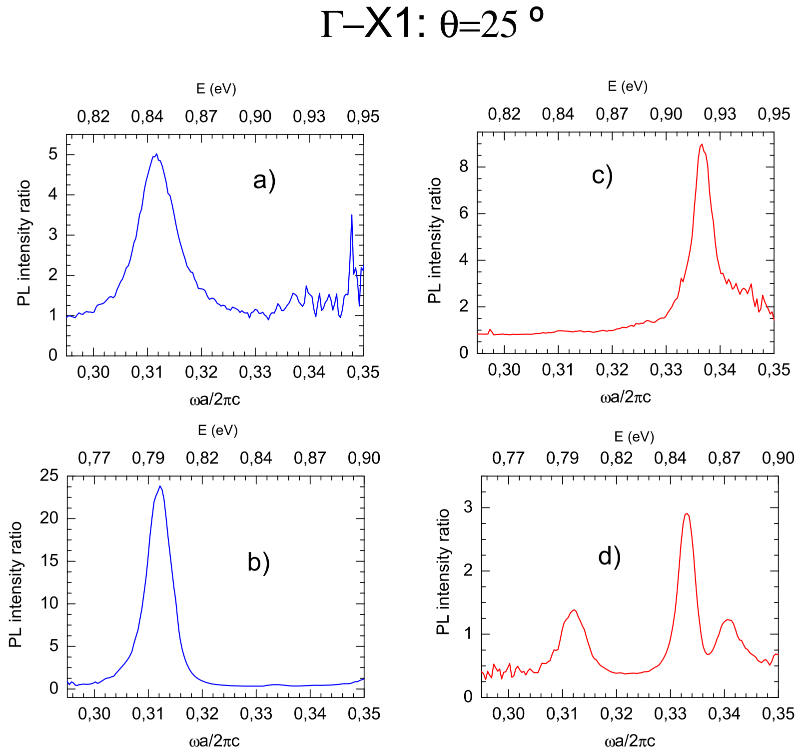

Fig. 3. Normalized PL spectra along the direction Γ-$X1$, for the sample without Bragg (a,c) and for the sample with Bragg reflector (b,d) at angle $\theta = 25°$. Blue line for even ($\sigma_{kz} = +1$) or p-polarization, red line for odd ($\sigma_{kz} = -1$) or s-polarization with respect to a vertical mirror plane.

angle of 45° with respect to normal incidence. The angle-resolved PL emission was collected by a fiber coupled to a Fourier-transform spectrometer (Bruker IFS66/s). An InGaAs p-i-n photodiode was used as detector. The PL at room temperature can be collected with an angular resolution of ±1°. The PL was collected at different angles from 0° to 30° at intervals of 5° along the directions $\Gamma - X1$ and $\Gamma - X2$ with a linear polarizer in the collection arm. The measured PL spectra were used to determine the photonic band dispersion through conservation of the wavevector parallel to the sample surface [24, 25, 26, 27, 28], and their polarization.

The axes of polarization and the experimental geometry are defined according to Fig. 2. For incidence in a plane along the Γ-X1 direction, since the xz plane is a mirror plane of the Suzuki-phase lattice, the electromagnetic field can be even or odd under the mirror reflection operation $\hat{\sigma}_{kz} = \hat{\sigma}_{xz}$: the former states are denoted as $\sigma_{kz} = +1$, while the latter are denoted as $\sigma_{kz} = -1$. For incidence in a plane along the Γ-X2 direction, since the yz plane is again a mirror plane of the Suzuki lattice, the eigenstates of the electromagnetic field can be even ($\sigma_{kz} = +1$) or odd ($\sigma_{kz} = -1$) under the mirror reflection operation $\hat{\sigma}_{kz} = \hat{\sigma}_{yz}$. We notice that $\sigma_{kz} = +1$ states are coupled to transverse-magnetic or p-polarized

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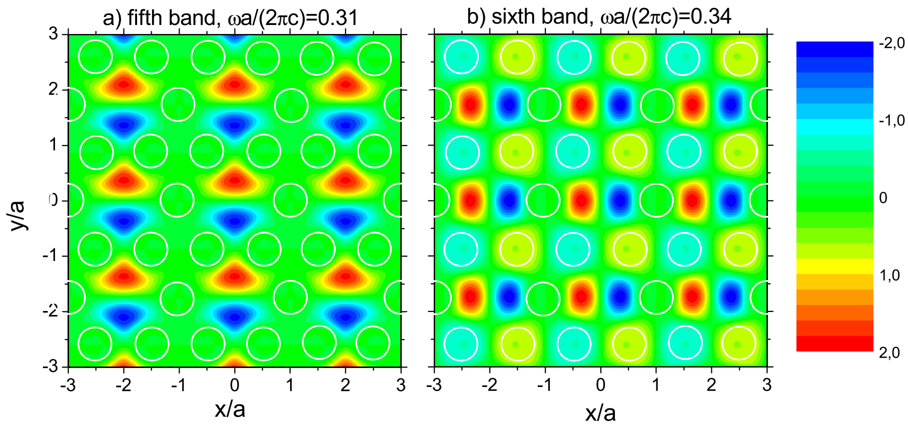

Fig. 4. Real part of magnetic field component H_z at the Γ point for the photonic modes corresponding to the resonant structures in Fig. 3(a) at $\omega a/(2\pi c) = 0.31$ (fifth band) and in Fig. 3(c) at $\omega a/(2\pi c) = 0.337$ (sixth band).

light with respect to the observation plane shown in Fig. 2(b), while $\sigma_{kz} = -1$ states are coupled to transverse electric or s-polarized light: these denominations, however, relate only to vertical mirror symmetry $\hat{\sigma}_{kz}$ and have nothing to do with specular reflection $\hat{\sigma}_{xy}$ with respect to the xy plane, which is not a symmetry operation of the structure with Bragg.

Figure 3 shows four typical normalized PL spectra along the $\Gamma - X1$ direction, for one particular angle ($\theta = 25°$), for the samples with and without Bragg reflector. The PL spectra were normalized dividing the PL intensity from the patterned area over the PL intensity of a close unpatterned area. Similar spectra were obtained for the rest of the angles of measurement. A clear change in the intensity (Fig. 3(a,b)) and number of peaks (Fig. 3(c-d)) for each polarization ($\sigma_{kz} = +1$, $\sigma_{kz} = -1$ respectively) is observed between the samples with and without Bragg reflector. For each angle (θ), the observed peaks were fitted to gaussian functions. The center of the fit function was extracted and plotted versus the parallel component of the wavevector.

Figure 4 shows the real part of the magnetic field component H_z at the Γ point for the photonic modes corresponding to the resonant structures in Fig. 3(a) around $\omega a/(2\pi c) = 0.31$ and in Fig. 3(c) around $\omega a/(2\pi c) = 0.337$. These modes correspond to the fifth and the sixth band, respectively, of the sample without Bragg. Considering that the magnetic field $\mathbf{H}$ is a pseudo (or axial) vector, we notice that the fifth band is even along the $\Gamma - X1$ direction ($\sigma_{xz} = +1$) and odd along the $\Gamma - X2$ direction ($\sigma_{yz} = -1$). Thus, we expect the fifth band to couple to p-polarized light along the $\Gamma - X1$ direction and to s-polarized light along the $\Gamma - X2$ direction. The sixth band, instead, is odd along the $\Gamma - X1$ direction ($\sigma_{xz} = -1$) and even along the $\Gamma - X2$ direction ($\sigma_{yz} = +1$), thus it couples to s-polarized light along $\Gamma - X1$ and to p-polarized light along $\Gamma - X2$. These results are in agreement with those shown in Fig. 3(a,c) and show that polarization-resolved PL is a powerful tool to identify photonic bands through their symmetry properties.

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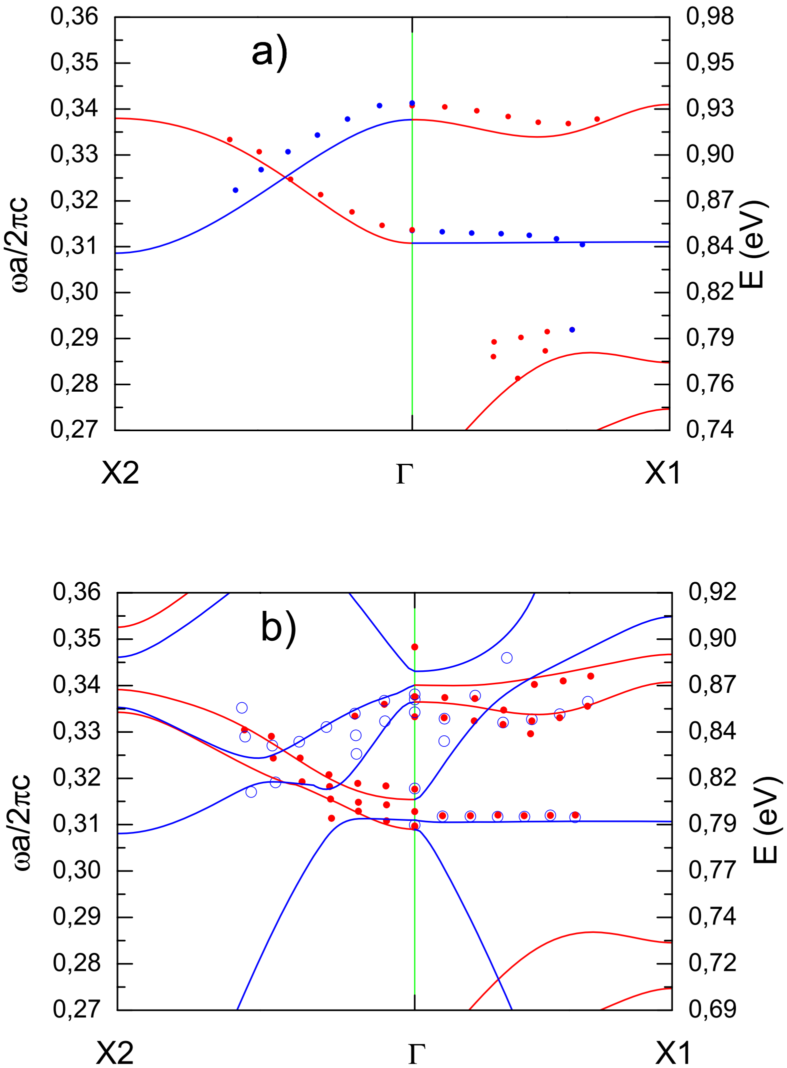

Fig. 5. Photonic band structure of the Suzuki-phase lattice. Blue color for bands with $\sigma_{kz} = +1$ polarization. Red color for bands mainly $\sigma_{kz} = -1$ polarized. (a) Sample without Bragg: Solid lines show the bands calculated by guided-mode expansion in the "symmetric" approximation with the parameters $d/a = 0.514$ and $r/a = 0.33$. Only $\sigma_{xy} = +1$ or TE-like modes are shown. Circles: measured points. (b) Sample with Bragg reflector: Solid lines show the full band structure calculated by guided-mode expansion with the parameters $d/a = 0.514$ and $r/a = 0.33$. Filled points for $\sigma_{kz} = -1$ polarization. Blue open circles for $\sigma_{kz} = +1$ polarization.

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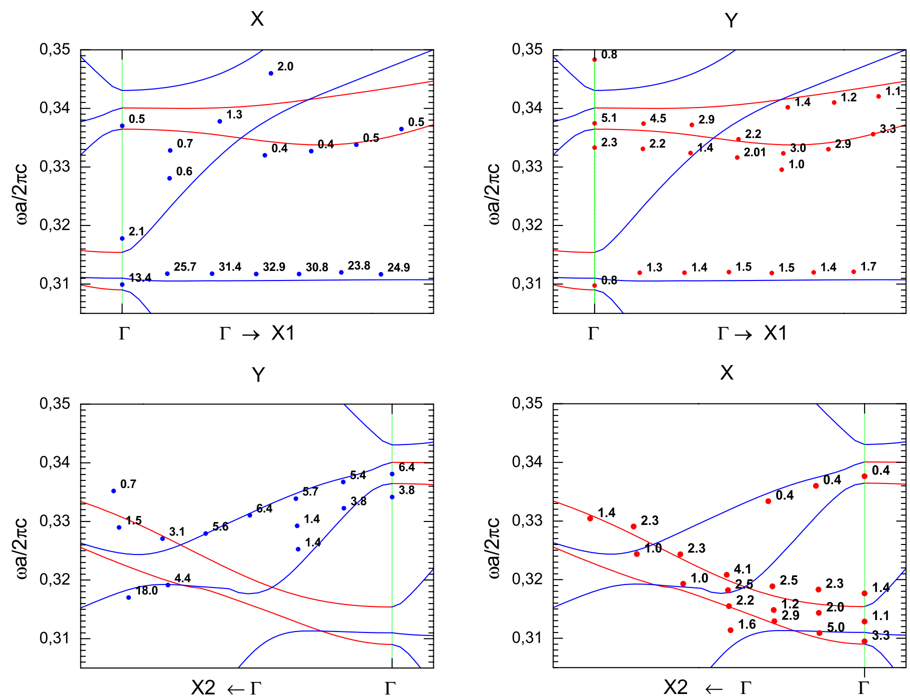

Fig. 6. Polarization resolved photonic band structure measured for the sample with Bragg mirror. Point label indicates the normalized intensity of emission. Solid curves are calculated with guided-mode expansion: blue bands for bands with $\sigma_{kz} = +1$ or p-polarization, red color for bands with $\sigma_{kz} = -1$ or s-polarization. Arrow indicates the direction of the k-vector. Labels above the graphs indicate the direction of the axis of the polarizer in relation to the axes defined in Fig. 2.

3. Results

Figure 5 shows the photonic bands and their polarization measured for both samples with and without Bragg reflector. Figure 5(a) shows the photonic bands measured for the sample without Bragg and the calculated band structure in the "symmetric" approach [15, 23] where mirror symmetry $\hat{\sigma}_{xy}$ with respect to a horizontal plane through the InP slab is enforced and only the even modes $\sigma_{xy} = +1$ (sometimes called TE-like) are shown. The parameters of the fitting are $a = 455$ nm, $r = 0.33a$ and $d/a = 0.514$. It is remarkable that the fifth band ($\omega = 0.31$ in Γ) and the sixth band ($\omega = 0.34$ in Γ) have well defined polarization (p or s) for all k-vectors. The fifth band has $\sigma_{kz} = +1$ or p-polarization along the direction $\Gamma - X1$ and $\sigma_{kz} = -1$ or s-polarization along $\Gamma - X2$. The sixth band shows the complementary behavior, i.e, it shows s-polarization along the $\Gamma - X1$ direction and p-polarization along $\Gamma - X2$. This is in good agreement with the expected field patterns calculated by guided-mode expansion for several k-vectors along both directions $\Gamma - X1$ and $\Gamma - X2$, as exemplified in Fig. 4 at the Γ point, and is also analogous to previous results found in reflectance spectra of macroporous Silicon [25].

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The bands are dipole-active (i.e., coupled to polarized light in the far field) with the following orientation: For the fifth band the axis of the dipole is parallel to the $\Gamma - X1$ direction. For the sixth band, the axis of the dipole is parallel to the $\Gamma - X2$ direction. The same measurements were performed in samples with Bragg reflector. Figure 5(b) shows the photonic bands measured for the sample with the Bragg reflector and the calculated full band structure [15, 23]. The parameters of the fitting are $a = 484$ nm, $r = 0.33a$ and $d/a = 0.514$. In this case a drastic change in the photonic band structure is observed with respect to the sample without Bragg mirror. The experimental data are best fitted by the full band structure, showing that more photonic bands arise in the sample with Bragg mirror. Those bands are due to the breaking of the horizontal mirror symmetry $\hat{\sigma}_{xy}$ of the structure caused by the introduction of the Bragg mirror, which couples TE-like to TM-like modes of the structure without Bragg.

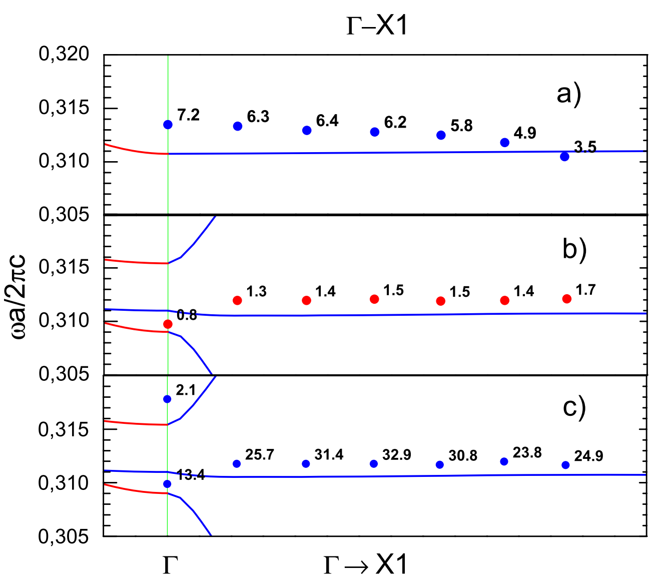

Fig. 7. Fifth band along the direction $\Gamma - X1$. The numeric labels indicate the normalized intensity. (a) Sample without Bragg: Blue color for bands with $\sigma_{kz} = +1$ or p-polarization. Red color for bands mainly $\sigma_{kz} = -1$ or s-polarization. Blue dots for measured points detecting p-polarized light. (b) Sample with Bragg: $\sigma_{kz} = -1$ or s-polarization. Red dots for experimental points detecting s-polarized light. (c) Sample with Bragg: $\sigma_{kz} = +1$ or p-polarization. Blue dots for measured points detecting p-polarized light.

Figure 6 shows the normalized intensities measured for the $\Gamma - X1$ and $\Gamma - X2$ directions of the sample with the Bragg mirror. The data show that the photonic bands that should correspond to “TM-like” modes (electric field along z) can be measured, despite the emission of the quantum wells is mainly “TE-like” polarized (electric field in xy plane). This is naturally explained by the breaking of horizontal mirror symmetry $\hat{\sigma}_{xy}$ in the sample with Bragg. On the other hand, vertical mirror symmetry $\hat{\sigma}_{kz}$ along the $\Gamma - X1$ and $\Gamma - X2$ orientation is preserved even in the sample with Bragg and pure $\sigma_{kz} = +1$ (p) or $\sigma_{kz} = -1$ (s) modes are expected. However, mixing of p/s polarizations

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is also observed in some bands and for some k-vectors with different intensities for each polarization. In general the degree of polarization defined as $\rho = \left|\frac{(I_x - I_y)}{(I_x + I_y)}\right|$ corresponds to the mixing induced by any symmetry-breaking effect present in the sample. It is remarkable that the fifth band which has p-polarization along the direction $\Gamma - X1$ shows also s-component which was not observed in the sample without Bragg mirror. This band has a degree of polarization (ρ) between 86% and 91%. The polarization mixing effect is attributed to the presence of disorder (variation of hole size, position, micro-roughness of hole sidewalls, mainly) which breaks mirror symmetry and whose effect may be enhanced in the sample with Bragg.

Figure 7 shows the fifth band for both samples and the calculated photonic band structure. According to the calculations, the fifth band is nearly flat along the $\Gamma - X1$ direction, well isolated in frequency and remains almost unchanged in the "symmetric" and full band approach. This makes the fifth band very suitable for the comparison of the intensity of emission between both samples with and without Bragg mirror. For this band the quality factors (Qs) are slightly higher (below two times) for the sample with Bragg mirror. The intensity of the emission for p-polarization is between 4 and 7 times higher for the sample with Bragg mirror in the whole wavevector (corresponding to angular) range, except for the Γ point, where the enhancement is 1.9. The enhancement of PL signal towards the vertical direction arises from multiple reflections by the Bragg mirrors in the SiO_2 wafer bonding layer, as previously analyzed in Ref.[11]. Notice that even at the X1 point, the internal angle in the SiO_2 layer is calculated to be around 20 degrees, which is well within the angular acceptance of a Si/SiO_2 Bragg reflector. This results in an almost k-independent enhancement, which is interesting for prospective applications of the Suzuki lattice to low-threshold lasing.

4. Summary

We have fabricated and measured the SP lattice on two kinds of InP semiconductor slabs with InAsP/InP quantum wells as active layer with and without underlying Bragg mirror. PR-ARP spectroscopy was used for the optical characterization. For the structure without Bragg reflector the experimental data are well fit by a "symmetric" calculation. For the sample with Bragg mirror are best fit by a full band calculation (i.e., TE-like and TM-like modes are coupled). A mixing of p/s polarizations defined with respect to a vertical mirror plane is observed for the structure with Bragg, whereas the polarization is well defined for the non-Bragg sample. An enhancement on the photoluminescence emission up to seven times has been obtained for a flat photonic band along the $\Gamma - X1$ direction, which is the main distinctive feature of the Suzuki-phase photonic lattice.

Acknowledgments

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