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Coherently induced one-dimensional photonic band gap

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We show theoretially that a one-dimensional photonic band gap can be generated by coherent optical processes in *n*-doped semiconductor quantum wells using intersubband transitions. This is illustrated in a waveguide structure where an optical field that is nearly resonant with such transitions induces resonance enhancement of the refractive index with vanishing absorption. For a particular InGaAs/AlGaAs quantum well structure we show that a 3.2 μm beam with intensity $\sim$1.9 MW/cm^2 can generate an active photonic band gap centered at $\sim$4.55 μm with more than 10 nm width and no loss.

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Photonic band gap (PBG) structures are normally constructed from dielectrics with different nonresonant (background) refractive indices. The periodic nature of these passive structures inhibits propagation of light within a certain frequency range or band gap. Recently, however, there has been progress in generating active PBGs using nonlinear optical processes and coherent control of light-matter interactions. This includes utilization of laser-induced transparency (LIT) in an atomic ensemble in the presence of a standing optical wave[1] and application of the complex susceptibility of excitons in a periodic quantum well (QW) structure.[2] In the latter case, a one-dimensional (1D) PBG was dynamically modified using an optical pump field to generate an ac Stark effect. An electromagnetically induced PBG has also been proposed in a heterostructure formed by semiconductor layers doped periodically with different densities of atoms. Nonlinear optical excitation of these atoms creates a periodic refractive index contrast.[3]

Here we theoretically demonstrate optical generation and control of a 1D PBG using coherent control of the refractive index and absorption associated with intersubband transitions in *n*-doped QWs. With a particular structure, we show that one can use a control field to dynamically generate a stop band centered near 4.55 μm. Quantum interference between intersubband transitions in two adjacent wells and electron tunneling lead to enhancement of the refractive index and suppressed absorption.

The key idea for this coherent or laser-induced photonic band gap (LI PBG) can be qualitatively understood with the generic optical Λ system shown in Fig. 1. The 1-2 transition is monitored by a signal field while a control laser couples the upper transition level ($|2\rangle$) with the auxiliary level ($|a\rangle$). The lower transition level ($|1\rangle$) also incoherently pumps $|a\rangle$. In the absence of such a pumping process this system exhibits LIT, i.e., at frequencies close to that of the 1-2 transition system absorption becomes insignificant.[4] In the presence of the incoherent pumping process, however, the electron population in $|1\rangle$ and $|2\rangle$ combined with the direct 1-2 and indirect $1-2-a$ interfering transition paths allow resonant enhancement of the refractive index with vanishing absorption for the 1-2 transition. Such phenomena have been predicted[4,5] and experimentally tested in atomic systems.[6]

To achieve a dynamic LI PBG we apply the Λ system concept to the double QW structure shown in Fig. 2. This structure consists of 4 nm and 2.6 nm wide $\mathrm{In_{0.5}Ga_{0.5}As}$ wells separated by a 1 nm $\mathrm{Al_{0.4}Ga_{0.6}As}$ barrier. The left barrier is $\mathrm{Al_{0.4}Ga_{0.6}As}$ and the right barrier is $\mathrm{Al_{0.6}Ga_{0.4}As}$. The upper and lower transition levels of the Λ system are the second and third subbands and the populated ground subband acts as the auxiliary state. The control field couples the ground state with the third subbands while the incoherent pumping process occurs via tunneling of electrons from $|1\rangle$ to the ground subband. With strain- and energy-dependent electron effective mass effects included,[7] we obtain a large dipole moment for the 1-2 transition ($\langle z\rangle_{12}=1.35$ nm) at 4.2 μm. The $a-2$ transition occurs at ~ 3 μm with $\langle z\rangle_{a2}=0.77$ nm. An important feature of the system shown in Fig. 2 is that for a specific frequency and intensity of the control field the refractive index of the 1-2 transition increases dramatically while absorption is reduced to zero.[8]

To achieve a 1D LI PBG we consider a waveguide structure consisting of 50 periods of the QW structure shown in Fig. 2. Although this structure is highly strained, it can be grown on a GaAs substrate using a graded $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ buffer layer (Fig. 3). This layer allows accommodation of high strain and provides the optical confinement needed for the waveguide.[9] A possible growth recipe for this purpose invovles deposition of 1 μm or more of $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ over the GaAs substrate as x is linearly increased from 0 (AlAs) to 0.26 ($\mathrm{In_{0.26}Al_{0.74}As}$). The upper confinement layer is also taken to be $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ with an average refractive index of 3 in the vicinity of 4 μm, similar to that of the lower confinement layer.[10] At 4 μm the background refractive indices of the wells are 3.43, and those of the left and right barriers are 3.25 and 3.15, respectively.

The active PBG proposed here is not related to periodic semiconductor layers with different background refractive indices, but rather due to coherent processes associated with the Λ system. To allow the control field to induce periodic change in the refractive index one can periodically modify the thickness of the wider wells by about two or three monolayers. The change of the background refractive index via such a thickness modification is insignificant. Alternatively, one can etch the QWs with a specific duty cycle and subsequently refill them epitaxially with a semiconductor with the

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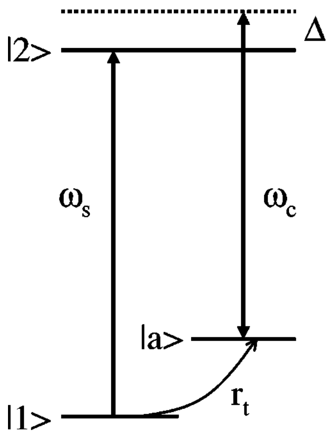

FIG. 1. Schematic diagram of a generic Λ system. $|1\rangle$ and $|2\rangle$ are, respectively, the lower and upper transition levels and $|a\rangle$ refers to the auxiliary state. The one- and two-sided arrows refer to the signal and control fields, respectively.

same effective refractive index as that of the regions containing QWs in the absence of the control field (Fig. 3). Since it is more conventional, in this paper we consider the second method and assume that the 50 periods of the QWs are etched with a rectangular grating with a 50% duty cycle and then refilled with $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$. Note that both control and signal fields propagate in the plane in the waveguide and are polarized along the growth direction (see Fig. 3).

The theoretical development of the 1D LI PBG is performed by solving the equations of motion for the density matrix of the system, given as

$$\frac{\partial \rho^{\mathbf{k}}}{\partial t} = -\frac{i}{\hbar}[H_0+H_1,\rho^{\mathbf{k}}] + \left.\frac{\partial \rho^{\mathbf{k}}}{\partial t}\right|^{\text{e-e}}_{\text{incoh}} + \left.\frac{\partial \rho^{\mathbf{k}}}{\partial t}\right|^{\text{e-p}}_{\text{incoh}} . \tag{1}$$

Here H_0 is the QW Hamiltonian in the absence of any optical field and H_1 is the interaction term between the system and the control and signal fields. $(\partial\rho^{\mathbf{k}}/\partial t)|^{\text{e-e}}_{\text{incoh}}$ and $(\partial\rho^{\mathbf{k}}/\partial t)|^{\text{e-p}}_{\text{incoh}}$ refer to the incoherent contributions of electron-electron and electron-phonon scattering processes. After solving Eq. (1) under steady state conditions, we solve the coupled-mode equations using the frequency-dependent complex dielectric function of the waveguide structure.

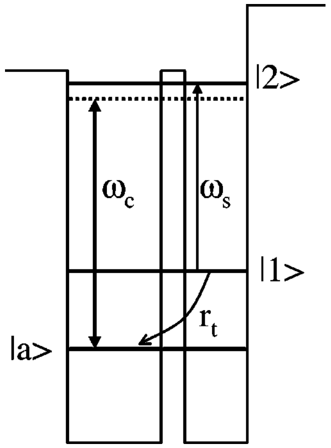

FIG. 2. Schematic diagram of a Λ system in an asymmetric n-doped InGaAs/AlGaAs QW structure. $|a\rangle$ is the ground state of the QW, and $|1\rangle$ and $|2\rangle$ are its lower and upper transition subbands, respectively.

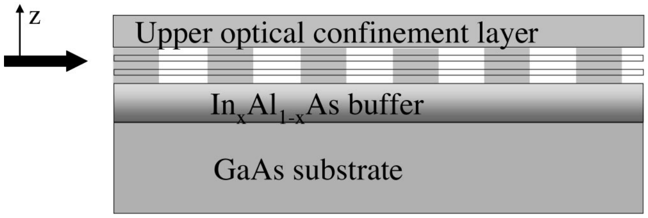

FIG. 3. Schematic representation of the 1D LI PBG waveguide structure. The parallel lines between the buffer and upper confinement layers refer to the QW structure. Here the darker regions refer to the etched QWs filled with $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$. The thick arrow indicates the propagation direction for the control and signal fields and the thin arrow is their polarization axis.

Since the electron density in the QW structure is assumed to be $1.4\times10^{12}\ \mathrm{cm}^{-2}$, the contribution of polarization scattering to the dephasing rate and the countering energy renormalization terms caused by the exchange and exciton effects can be ignored.[11,12] In addition, since the carrier density in the conduction band is not changed by the control field, depolarization shifts are not important. The effects of electron-electron scattering processes in the $a-1$ and $a-2$ transition dephasing rates ($\gamma_{ij}^{\text{e-e}}$) are included phenomenologically with $\gamma_{a1}^{\text{e-e}}=\gamma_{a2}^{\text{e-e}}=1.5\ \mathrm{ps}^{-1}$. Since for any intensity of the control field most of the electrons remain in the ground subband, the effects of such processes in other transitions can be ignored. The LO-phonon–electron scattering processes, however, are the dominant energy and polarization relaxation mechanisms for the electrons in $|1\rangle$ and $|2\rangle$ and their corresponding transitions. We consider the decay rates of electrons from $|2\rangle$ to $|1\rangle$ and $|2\rangle$ to $|a\rangle$, respectively, to be 0.66 and 1 ps^{-1}.[13,14] The tunneling rate of electrons from $|1\rangle$ to $|a\rangle$ is taken to be 2 ps^{-1}.

To understand the basis of the dynamic PBG proposed here, we consider resonant enhancement of the refractive index with vanishing absorption in the structure shown in Fig. 2. We assume that the control field is detuned by about -20 meV from the $a-2$ transition, having 384 meV photon energy ($\sim$ 3.2 μm). As the intensity of the control field, I_c, increases, the 1-2 transition develops absorption and gain regions [Fig. 4(a)] while its refractive index is enhanced [Fig. 4(b)]. When I_c reaches 1.9MW/cm^2, however, the absorption region nearly disappears. The 1-2 transition shows an overall gain, except at the signal field wavelengths near 4.55 μm where the absorption coefficient is insignificant or zero. At these wavelengths the refractive index is enhanced dramatically.

The resonant enhancement of refractive index with zero absorption occurring near $\sim$4.55 μm is the main mechanism for the generation of a LI PBG. To illustrate this we assume that the grating period of the waveguide structure shown in Fig. 3 is 726 nm and its length is 900 μm. When $I_c=0$ the signal field does not experience a periodic structure and passes through the waveguide unchanged. However, as I_c

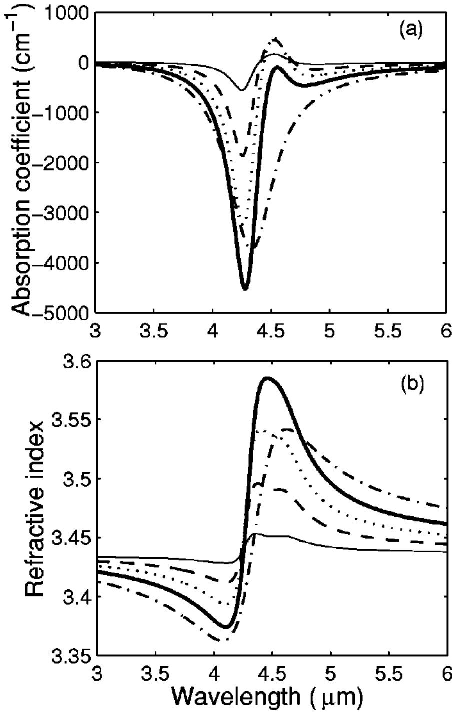

FIG. 4. The absorption coefficient (a) and refractive index (b) of the 1-2 transition. The thin solid, dashed, dotted, thick solid, and dash-dotted lines refer, respectively, to the simulation results obtained assuming $I_c = 0.1$, 0.4, 0.9, 1.9, and 8.1 MW/cm^2.

increases the reflectivity becomes larger and shifted toward longer wavelengths and meanwhile becomes broadened [Figs. 5(a)–5(c)]. As Fig. 5(d) shows, when the large enhancement of refractive index is accompanied by zero absorption at $I_c = 1.9$ MW/cm^2, a fully developed stop band with more than 10 nm width develops.

Note that in conventional passive PBG structures the alternating materials are usually used far from any resonances and the refractive indices are essentially frequency independent. Therefore, absorption in these materials at the frequency range where the stop bands occur is usually insignificant. This differs from the situation for the dynamic LI PBG structures considered here. To see this, in Fig. 6 we show the transmission of our example structure under the same conditions as those of Fig. 5. As the intensity of the control field increases the waveguide becomes increasingly lossy [Figs. 6(a)–6(c)]. For $I_c = 1.9$ MW/cm^2, however, the loss becomes insignificant and the 1D LI PBG acts like a conventional PBG where the sum of reflection and transmission is nearly unity. For $I_c > 1.9$ MW/cm^2, the QW structure exhibits increasing gain. This can even lead to laser action and the waveguide structure acts as a strongly gain-coupled distributed-feedback laser.[15,16]

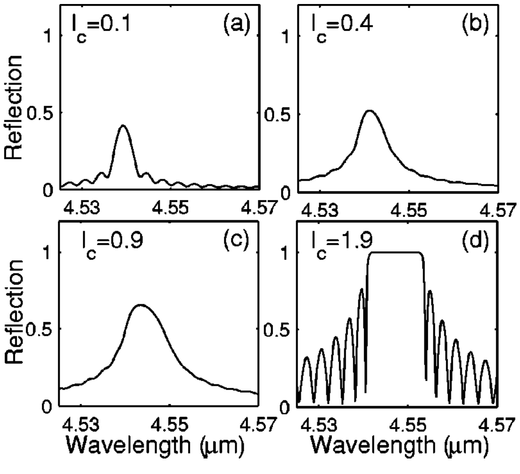

FIG. 5. Reflection of the 1D LI PBG for different values of the control laser intensity, I_c (in MW/cm^2).

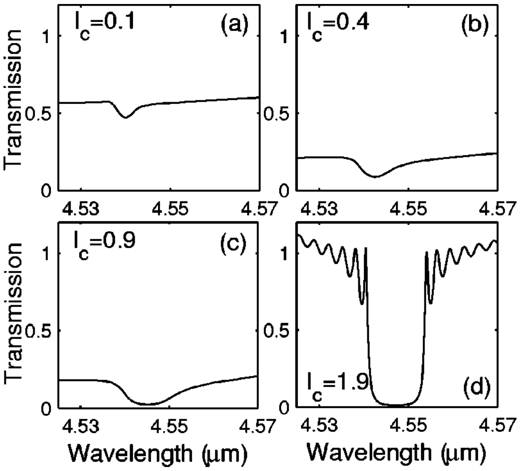

FIG. 6. Transmission of the 1D LI PBG for different values of the control laser intensity, I_c (in MW/cm^2).

The recent developments in QW materials and growth techniques have already shown that the intersubband transition wavelengths can reach wavelengths near 1.5 μm.[17,18] Although in this paper we chose an InGaAs/AlGaAs QW structure to illustrate a dynamic 1D PBG using well-established QW parameters, one can apply the scheme presented here to other materials to reach shorter wavelengths. For example, application of $In_{0.5}Ga_{0.5}As$/AlAs QW structures studied in Ref. 19 can lead to ~2.1 and ~2.7 μm for the wavelengths of the control and signal fields, respectively. However, the reduction of dipole moments and the increase of inhomogeneous broadening could lead to a reduced enhancement of the refractive index, requiring a more intense control field. The use of triple QWs, however, might also allow one to reach shorter wavelengths and larger dipole moments.

The results of this paper can provide avenues for the design of optical ultrafast switching processes based on PBGs, since the dephasing times associated with the intersubband transitions are short. In addition, the waveguide geometry of the active PBG proposed is quite compatible with monolithic and hybrid integrations of optical components in photonic circuits. Moreover, for efficient coupling of light with the structure shown in Fig. 3, one can consider a ridge-waveguide structure, similar to those in edge emitting lasers or semiconductor optical amplifiers. Such a structure allows one to use standard light coupling techniques to inject the signal and control fields into the QW structure and efficiently collect the transmitted or reflected lights.

In conclusions, we propose the use of resonant enhancement of the refractive index with vanishing absorption in the conduction intersubband transitions of *n*-doped quantum wells to dynamically generate one-dimensional photonic band gap materials. We illustrate this with a waveguide structure containing InGaAs/AlGaAs double quantum wells interacting with an IR laser field. Our simulations show that when the intensity and wavelength of this field are ~ 1.9 MW/cm^2 and 3.2 μm, a band gap centered around 4.55 μm is coherently generated. We also point out that shorter wavelengths for the band gap could be achievable using different semiconductor materials and/or triple QW systems.

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