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Resonant Photonic Bandgap Nanostructures: An Addendum to Quantum-Interference-Control and Transport of Spin-Polarized Currents in Semiconductors DAAD19-01-1-0556

ABSTRACT

Here we are expanding our existing program in which we are investigating the creation, control and transport of spin-polarized populations and currents. In addition to extending our previous switch operation to room temperature, this expansion is for the specific purpose of investigating spin-based switching in a new class of materials called resonant photonic bandgap (RPBG) nanostrucures. The proposed expansion will provide for (i) the growth of these nanostructures, (ii) switch development, (iii) the fundamental studies of promising switching processes, and (iv) the necessary theoretical support in the same package.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. "Light Pulse Deleay in Semiconductor Quantum Well Bragg Structures," N. H. Kwong, Z. S. Yang, D. T. Nguyen, R. Binder, and Arthur L. Smirl, in Advanced Optical and Quantum Memories III, edited by H. J. Coufal, Z. U. Hasan, A.E. Craig, Proc. of SPIE 6130, 61300A (2006).

2. "Light Pulse Delay in Semiconducting Quantum Well Bragg Structures," R. Binder, Z. S. Yang, N. H. Kwong, D. T. Nguyen, Arthur L. Smirl, Phys. Stat. Sol. (b) 243, 2379 (2006).

3. "Stopping, Storing and Releasing Light in Quantum Well Bragg Structures," Z. S. Yang, N. H. Kwong, R. Binder, and Arthur L. Smirl, J. Opt. Soc Am. B 22, 2144 (2005).

4. "Distortionless Light Pulse Delay in Quantum Well Bragg Structures," Z. S. Yang, N. H. Kwong, R. Binder, and Arthur L. Smirl, Opt. Lett. 30, 2790 (2005).

5. "A Near-Room-Temperature All-Optical Polarization Switch Based on the Excitation of Spin-Polarized "Virtual" Carriers in Quantum Wells," M. Yildirim, J. P. Prineas, Eric J. Gansen and Arthur L. Smirl, J. Appl. Phys. 98, 063506 (2005).

6. "All-Optical Spin-Dependent Polarization Switching in Bragg-Spaced Quantum Well Structures," W. J. Johnston, M. Yildirim, J. P. Prineas, Arthur L. Smirl, H. M. Gibbs, and G. Khitrova Appl. Phys. Lett. 87, 101113 (2005). Also selected to appear in the October 2005 issue Virtual Journal of Ultrafast Science.

7. "Ultrafast Polarization Modulation Induced by the 'virtual excitation' of Spin-Polarized Excitons in Quantum Wells: Application to All-Optical Switching," Eric J. Gansen and Arthur L. Smirl, J. Appl. Phys. 95, 3907 (2004).

8. "Many-Particle Theory of All-Optical Polarization Switching in Semiconductor Quantum Wells," I. Rumyantsev, N. H. Kwong, R. Binder, E. J. Gansen, and A. L. Smirl, Phys. Rev. B 69, 235329 (2004).

9. "Polarization State Dynamics Induced by the Virtual Excitation of Spin-Polarized Carriers in Semiconductor Quantum Wells," Eric J. Gansen and Arthur L. Smirl, Semiconductor Science and Technology 19, S372 (2004).

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1. "Theory of Ultrafast Optical Gain in the Nonlinear Reflectivity of Semiconductor Bragg Structures," D. T. Nguyen, N. H. Kwong, R. Binder, and Arthur L. Smirl, Quantum Electronics and Laser Science Conference (QELS 06), Long Beach, CA, 21-26 May 2006.

2. "Light Pulse Delay in Semiconductor Quantum Well Bragg Structures," R. Binder, Z. S. Yang, N. H. Kwong, D. T. Nguyen, Arthur L. Smirl, International conference on Nonlinear Optics and Excitation Kinetics in Semiconductors (NOEKS-8), Münster, Germany 20-24 February 2006.

3. Invited: "Light Pulse Delay in Semiconductor Quantum Well Bragg Structures," N. H. Kwong, Z. S. Yang, D. T. Nguyen, R. Binder, and Arthur L. Smirl, Photonics West SPIE Conference, San Jose, CA, 21-26 January 2006.

4. "Slow Light and Optical Transparency: Switching and Storage in Resonant Periodic Nanostructures," A. L. Smirl, J. P. Prineas, J. S. Aitchison, J. E. Sipe, H. M. van Driel, and R. Binder, DARPA Slow Light Phase II Workshop, Seattle, WA, 14-15 December 2005.

5. "Many-particle Effects in the Nonlinear Polarization Rotation in Semiconductore Quantum Well Bragg Structures," D. T. Nguyen, N. H. Kwong, Z. S. Yang, R. Binder, and Arthur L. Smirl, Optical Society of America Annual Meeting at Frontiers in Optics 2005, Tucson, AZ, 16-20 October (2005).

6. "Light Delay in Quantum Well Bragg Structures," Z. S. Yang, N. H. Kwong, R. Binder, Arthur L. Smirl, APS Division of Laser Science Meeting (Laser Science XXI) at Frontiers in Optics 2005, Tucson, AZ, 16-20 October (2005).

7. Invited: "A Tale of Two Systems: Resonator Structures and Coupled Quantum Wells," J. E. Sipe, H. M. van Driel, J.S. Aitchison, R. Binder, J. P. Prineas, and A. L. Smirl, APS Division of Laser Science Meeting (Laser Science XXI) at Frontiers in Optics 2005, Tucson, AZ, 16-20 October (2005).

8. "Stopping, Storing and Releasing Light in Quantum Well Bragg Structures," Z. S. Yang, N. H. Kwong, R. Binder, and Arthur L. Smirl, Quantum Electronics and Laser Science Conference (QELS 05), Baltimore, MD, 22-27 May (2005).

9. A Room Temperature All-Optical Polarization Switch Based on the Excitation of Spin-Polarized "Virtual" Carriers in Quantum Wells," M. Yildirim, J. P. Prineas, E. J. Gansen and Arthur L. Smirl, Conference on Lasers and Electro-Optics (CLEO 05), Baltimore, MD, 22-27 May (2005).

10. "Ultrafast All-Optical Polarization Spin Switching in Resonant Photonic Bandgap Structures," W. J. Johnson, M. Yildirim, J. P. Prineas, and A. L. Smirl, Conference on Lasers and Electro-Optics (CLEO 05), Baltimore, MD, 22-27 May (2005).

11. Invited: "Stopping, Trapping and Releasing Light in Doubly-Resonant Nanostructures," Arthur L. Smirl, Z. S. Yang, N. H. Kwong, R. Binder, Philip Chak, and J. E. Sipe, Physics of Quantum Electronics (PQE XXXV), Snowbird, Utah, 3-6 January 2005.

12. "Slow Light and Optical Transparency: Switching and Storage in Resonant Periodic Nanostructures," A. L. Smirl, J. P. Prineas, J. S. Aitchison, J. E. Sipe, H. M. van Driel, and R. Binder, DARPA Slow Light Kickoff Meeting, Washington, D. C., 24-25 August 2004.

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(d) Manuscripts

1. "Ultrafast all-optical polarization switching in Bragg spaced quantum wells at 80K, W. J. Johnston, J. P. Prineas, Arthur L. Smirl, H. M. Gibbs, and G. Khitrova, submitted to J. Appl. Phys. (2006).

2. "Spin-Dependent Ultrafast Optical Nonlinearities in Bragg-Spaced Quantum Wells," W. J. Johnston, J. P. Prineas, Arthur L. Smirl, H. M. Gibbs, and G. Khitrova, submitted to J. Appl. Phys. (2006).

3. "Tunable Slow Light in Bragg-Spaced Quantum Wells," J. P. Prineas, W. J. Johnston, M. Yildirim, J. Zhao, and Arthur L. Smirl, submitted to Appl. Phys. Lett. (2006).

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U.S. ARMY RESEARCH OFFICE FINAL TECHNICAL REPORT
for the period 1 September 2004 to 31 May 2006
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for the period 1 September 2005 to 31 May 2006

TITLE of PROJECT: Resonant Photonic Bandgap Nanostructures**:** An Addendum to Quantum-Interference-Control and Transport of Spin-Polarized Currents in Semiconductors DAAD19-01-1-0556

GRANT NUMBER: W911NF-04-1-0225

INSTITUTIONS: The University of Iowa

PRINCIPAL INVESTIGATOR: Arthur L. Smirl

INTRODUCTION & PROBLEM STATEMENT:

This grant was an expansion to our existing program (which also ends this year) in which we were investigating the creation, control and transport of spin-polarized populations and currents. This expansion was for the specific purpose of seeding initial investigations of spin-based switching in a new class of materials called resonant photonic bandgap (RPBG) nanostrucures and to optimize and to extend the operation of our present spin-based switches, which utilize the optical Stark effect. The expansion provided for (i) the growth of these nanostructures, (ii) the demonstration of switch prototypes, (iii) the fundamental studies of promising switching processes, and (iv) the necessary theoretical support in the same package. To put the current progress into a broader context, the reader should also consult reports and publications associated with the parent program.

Here, we are developing a new generation of optically-addressed polarization switches and modulators that take advantage of spin and that are based on the coherent response of semiconductors. We expect these devices to provide orders of magnitude improvement over existing polarization switches in terms of contrast ratio, throughput, switching speed, and repetition rate (i.e. bandwidth) in thin semiconductor nanostructures that are compatible with current integrated circuit technology. Already, we have demonstrated an optically-addressed coherent polarization switch that is based on the near-resonant excitation of a spin-polarized population of “virtual excitons” in MQWs. By taking advantage of the optical Stark effect, our near-resonant device exhibits a pulse-width-limited femtosecond response and produces large contrast ratios in thin MQW samples. By producing a spin-polarized virtual carrier population, the device produces a rotation of the signal polarization. Our investigations show that the switching action is dominated by the third-order coherent emission induced by the control pulse. That is, the switch operation depends upon the coherent manipulation of the spin-dependent excitonic wavefunctions. We emphasize that this device is already 1000 times faster than the corresponding resonant “spin switches”.

On this expansion, we have introduced resonant photonic bandgap (RPBG) nanostructures in the spin-dependent polarization-rotation switch described in the following paragraph, instead of using simple MQWs. RPBG's are a new class of materials that should allow the switch to retain femtosecond switching speeds and high repetition rates, while actually improving the on/off ratios and the throughput by two orders of magnitude. In addition, RPBG's exhibit other intriguing properties that should be useful for modulation, switching, routing, and perhaps, buffering applications.

ALL-OPTICAL HIGH-SPEED SPIN SWITCHES: A-C Stark Effect at 100K

All-optical polarization switches based on the *resonant* excitation of *spin-polarized* electrons have been demonstrated, and they are part of the growing interest in technologies that take advantage of the spin degree of freedom. To date, the turn-off times for these resonant spin switches have been determined either by the spin relaxation time or by the Γ-X interlayer scattering in type II MQWs, and in all cases, the complete device recoveries have been limited by carrier recombination or sweep-out.

Our objective on this task is to demonstrate and to construct a new generation of much faster polarization modulators and switches that (like previous "spin switches") take advantage of the spin-dependent phase space filling and Coulomb contributions to the excitonic saturation. However, in contrast to previous "spin switches", the turn off times will not be determined by the spin relaxation times, and the full recovery (and thus, the repetition rate or bandwidth) will not be determined by carrier recombination or carrier sweep out.

The first approach involves tuning the optical wavelength well-below the heavy-hole (hh) exciton in an ordinary (not Bragg spaced) multiple quantum well. Under these conditions, no carriers will be resonantly excited; however, there will be a blue shift and saturation of the exciton associated with the a-c Stark effect. This Stark shift can be crudely viewed as *virtual* phase space filling. Consequently, if we excite on the hh with right circularly polarized light, we will create virtual carriers with a specific spin. If we probe with linearly polarized light (which contains equal amounts of right and left circular polarizations), the probe polarization will be rotated because the right circular component will "see" the filled states, but the left circular component will not. Since the "carrier creation," is virtual, this switch will turn on and off *instantaneously*, that is, the response will follow the pulse temporal profile. By operating near (but below) resonance, such spin switches are able to exhibit fs switching times and to produce high contrast ratios. That is, these near-resonant devices exhibit speeds that are characteristic of non-resonant excitation, but nonlinearities that approach those typically associated with resonant excitation, yet these devices are able to avoid the restrictions that accompany carrier generation. The dominant switching mechanism in these devices is the optical Stark effect.

During a previous reporting period, we demonstrated an optically-addressed coherent polarization switch that is based on the near-resonant excitation of a spin-polarized population of "virtual excitons" in MQWs. By taking advantage of the optical Stark effect, our near-resonant device exhibits a pulse-width-limited response (~400 fs FWHM) and produces large contrast ratios (194:1) in thin (40 well) MQW samples. By producing a spin-polarized virtual carrier population, the device produces a rotation of the signal polarization. We emphasize that this device is already 1000 times faster than the corresponding resonant "spin switches".

To verify that the description given above is accurate and to optimize the switch performance, we subsequently performed an exhaustive set of spectrally-integrated and spectrally-resolved differential transmission (DT) measurements as a function of fluence and time delay. These DT measurements (i) exhibit definite signatures of the Optical Stark effect, (ii) demonstrate that we are creating a virtual spin-polarized carrier population that adiabatically follows the switching field, and (iv) verifies that there is no significant carrier accumulation due to one or two-photon absorption.

We also have performed systematic (and tedious) measurements of the time-integrated, spectrally-integrated, time-resolved and spectrally-resolved polarization state of the switch emission/transmission as a function of time delay. These studies reveal that the switching action is primarily due to the third-order coherent emission induced by the control pulse and that the polarization state of this coherent emission varies dramatically in time during the emission.

During this grant period, in collaborating with Rolf Binder and his group at the University of Arizona, we have also completed a theoretical analysis of the switching described above and of the accompanying experiments. We have shown that our theoretical results are overall in good agreement with a wide variety of experimental data, ranging from time-resolved complete vectorial polarization-state dynamics of the signal polarization to the time-integrated contrast ratio of the complete switch. Furthermore, we have performed a general analysis of the microscopic processes involved in the switching action. We have considered contributions due to phase-space filling, Hartree-Fock mean field effects, and two-exciton correlation contributions. Amongst other things, we found that at large detunings of the control pulse, the dominating contribution is the Hartree-Fock (HF) mean field effect. We have also used the resulting parametric dependence of the switching action as a basis for proposing further optimization of the device.

For more information on our work on this subject see (and references therein):

[1] “Femtosecond All-Optical Polarization Switching Based on the Virtual Excitation of Spin-Polarized Excitons in Quantum Wells,” E. J. Gansen, K. Jarasiunas, and Arthur L. Smirl, *Appl. Phys. Lett.* **80**, 971-973 (2002).

[2] “Polarization State Dynamics Induced by the Virtual Excitation of Spin-Polarized Carriers in Semiconductor Quantum Wells,” Eric J. Gansen and Arthur L. Smirl, *Semiconductor Science and Technology* **19**, S372 (2004).

[3] “Many-Particle Theory of All-Optical Polarization Switching in Semiconductor Quantum Wells,” I. Rumyantsev, N. H. Kwong, R. Binder, E. J. Gansen, and A. L. Smirl, *Phys. Rev. B* **69**, 235329 (2004).

[4] “Ultrafast Polarization Modulation Induced by the ‘Virtual Excitation’ of Spin-Polarized Excitons in Quantum Wells: Application to All-Optical Switching,” Eric J. Gansen and Arthur L. Smirl, *J. Appl. Phys.* **95**, 3907 (2004).

ALL-OPTICAL HIGH-SPEED SPIN SWITCHES: A-C Stark Effect Near Room Temperature

It should be noted that the proof-of-principal spin-switch experiments described in the previous section were performed using a pulse shaper and at a temperature of 100 K in order to study the underlying physics. Neither is desirable (or necessary) for actual switching applications. Consequently, during this reporting period, we have investigated the near-room-temperature operation of an optically addressed polarization switch based on the virtual excitation of spin-polarized carriers. We have demonstrated that the device turns on and off in a time dictated by the control pulse width (~540 fs for the pulses used here), exhibits a contrast ratio of >18 DB, and an optical bandwidth of ~3 THz at a switching fluence of ~80 $\mu J/cm^2$. We also found, however, that there is a price to pay for operating the switch near room temperature, in that the device exhibits increased carrier accumulation and decreased contrast and throughput in comparison to our original low temperature (~100 K) measurements. The residual carriers produced by the control pulse lose their spin-polarization in ~70 ps and recombine on ns time scales. The circular dichroism associated with the residual carriers, however, does not contribute substantially to the switch signal, and additional suppression of these carriers is expected by increasing the control detuning. Moreover, we want to emphasize that this is still an unoptimized device and that, in addition to reduced carrier accumulation, significant improvements to the contrast ratio and throughput of the switch should be possible by using more wells and by optimizing the control detuning and the spectral content of the signal pulses.

For more information on our work on this subject see (and references therein):

“A Near-Room-Temperature All-Optical Polarization Switch Based on the Excitation of Spin-Polarized “Virtual” Carriers in Quantum Wells,” M. Yildirim, J. P. Prineas, Eric J. Gansen and Arthur L. Smirl, J. Appl. Phys. 98, 063506 (2005).

ALL-OPTICAL SPIN-DEPENDENT POLARIZATION SWITCHING in BRAGG-SPACED QUANTUM WELL (BSQW) STRUCTURES at 10 K

In the previous two sections, we have described spin switches in which spin-polarized populations of *virtual* carriers are *non-resonantly* excited by tuning the circularly polarized control below the hh exciton. Under these excitation conditions, the virtual carrier population follows the control pulse envelope. Consequently, the switching time (i.e. the time required to turn the switch on and off) is determined by the control pulse width, and carrier accumulation is negligible. As described above, at 80K, these switches exhibit a high contrast ratio of >300:1 (~25 dB) with an extremely fast switching time of ~350 fs and a large optical bandwidth >1 THz (~5 meV); however, the switching energy was ~150 $\mu J/cm^2$, and the insertion loss was ~21 dB [corresponding to a throughput (i.e., transmission in the *on*-state) of <1%]. This low throughput is typical of polarization switches.

During this grant period, we have demonstrated a polarization switch that exhibits a dramatically improved throughput (> 40 %), an increased contrast ratio (>10,000:1, or >40 dB), a reduced switching energy (~14 $\mu J/cm^2$), and a large optical bandwidths (~0.6 THz), while maintaining ~1 ps switching time and exhibiting no apparent carrier accumulation. This switch takes advantage of the properties of a Bragg-spaced quantum well (BSQW) structure that is grown such that its fundamental Bragg frequency ω_B is approximately equal to the (lowest) hh exciton frequency ω_x of the quantum wells. When $\omega_B = \omega_x$, the photonic bandstructure consists of a forbidden gap with both resonance frequencies located within the gap. Such BSQWs have been shown to exhibit large optical nonlinearities and sub-ps recovery times when a spectrally narrow control pulse is tuned within the forbidden gap. Here we have used these properties to construct a polarization switch that is based on the polarization dependence of the *spin-dependent selection rules for the BSQW photonic bandgap*.

The sample that we used for these initial proof-of-principle demonstrations consists of 200 periods of 8.5 nm-wide $In_{.04}Ga_{.96}As$ quantum wells separated by GaAs barriers such that the period, *d*, is equal to half the excitonic wavelength in the material ($d = \pi c/(\omega_x n_b)$, where n_b is the background index of GaAs at ω_x). The switch is constructed by placing the sample between crossed polarizers in a reflection geometry. A 14 $\mu J/cm^2$, 1-ps circularly polarized control pulse and a linearly polarized 650-fs signal pulse (spectral widths 1.3 meV and 2.5 meV, respectively, full-width at half maximum (FWHM)) were both generated by external shaping of 80-fs pulses from a mode-locked Ti:Sapphire laser and were tuned near the low-energy edge of the reflectivity stop band of the BSQW. The sample was mounted in a cryostat that was cooled to 10 K.

The basic switch operation can be understood in terms of a circular dichroism and birefringence that is induced in the BSQW sample by the circularly polarized control pulse. The origin of this circular dichroism and birefringence in the reflectivity of the stop band can be understood heuristically in terms of the circular selection rules for the 1s hh excitonic transition in III-V semiconductor quantum wells: namely, that right (left) circularly polarized light σ^+ (σ^-) couples to the “spin-down” (“spin-up”) transition (respectively). When the frequency spectrum is restricted sufficiently close to the hh resonance, transitions to other excited states can be ignored, and the photonic band structure (and, therefore, the reflectivity stop band) can be attributed to the periodically spaced hh excitonic resonance. Thus, the band structures for the two circular polarization components ($\sigma^\pm$) are effectively decoupled (in the limit where only Pauli Blocking and first order Coulomb correlation are included), and in this regime, the σ^+-polarized control pulse would be expected to couple to (and to distort) the “spin-down” stop band, but not the “spin-up” band. This simplified description seems to work well for excitation frequencies below the hh resonance; however, for the frequencies above ω_x and in the nonlinear regime, the data show a coupling between the two bands and suggest the importance of including higher lying resonances and higher-order Coulomb correlations.

The most obvious and serious shortcoming is the low temperature (10 K) operation demonstrated here. While higher temperature operation has been subsequently demonstrated by us (see below), the value of this demonstration is that it points the way to similar performance at room temperature in formally equivalent systems, once fabrications issues are resolved.

For more information on our work on this subject see (and references therein):

“All-Optical Spin-Dependent Polarization Switching in Bragg-Spaced Quantum Well Structures,” W. J. Johnston, M. Yildirim, J. P. Prineas, Arthur L. Smirl, H. M. Gibbs, and G. Khitrova, Appl. Phys. Lett. 87, 101113 (2005).

SPIN-DEPENDENT ULTRAFAST OPTICAL NONLINEARITIES in BRAGG-SPACED QUANTUM WELLS

Under support from this grant, we have also studied the spin-dependent ultrafast optical nonlinearities responsible for the switching action in BSQW's by performing systematic spectrally-resolved and temporally-resolved differential reflection measurements using right (σ^+) and left (σ^-) circularly polarized pump and probe pulses. Among other features, we have observed: (i) two reflection stop bands, a spin-down and a spin-up band that can be independently excited with the appropriate circular pump polarization, and with full recovery of the sample after passage of the pump; (ii) a spin-dependent blue shift of the photonic bandgap (caused by the ac Stark effect); (iii) a significant transient gain in the reflected probe ; (iv) the opening of a spectral transmission window in the photonic bandgap (associated with a shift of ω_x away from ω_B induced by the dynamic Stark shift); and finally (v) we have shown that the nonlinear response of the reflectivity is dominated by Pauli blocking and Hartree Fock correlations and that bound and unbound biexcitonic effects play only a weak role.

For more information on our work on this subject see (and references therein):

"Spin-Dependent Ultrafast Optical Nonlinearities in Bragg-Spaced Quantum Wells," W. J. Johnston, J. P. Prineas, Arthur L. Smirl, H. M. Gibbs, and G. Khitrova, submitted to J. Appl. Phys. (2006).

ALL-OPTICAL SPIN-DEPENDENT POLARIZATION SWITCHING in BRAGG-SPACED QUANTUM WELL (BSQW) STRUCTURES at 80 K

Above, we have described our demonstration of an all-optical polarization switch in a BSQW at 10 K exhibiting dramatically improved throughput (~ 40%), contrast ratio (> 40dB), and a control-pulse-width-limited recovery time (time required to turn the switch on and off), while showing no evidence of carrier accumulation. Here, we have extended the switch operation to the more technologically relevant temperature of 80K. We have shown that contrast ratio and throughput, while reduced, are still large at 80K and that control pulse width limited recovery is still possible, but requires larger control detunings with respect to the photonic band edge. In brief, the polarization switch at 80K exhibits a contrast ratio greater than 30 dB, a throughput of ~5%, a switching fluence of 8 μJ/cm^2, and a pulse-width-limited picosecond response time.

The complication in raising the temperature of the structure from 10 K (used in previous studies[7]) to 80 K (used here) is that the increased dephasing (associated with the phonons) rounds and broadens the photonic bandgap and increases the absorption near its edges. This absorption will increase carrier generation and, hence, lengthen the sample recovery time (time until switching can be performed again).

For more information on our work on this subject see (and references therein):

"Ultrafast all-optical polarization switching in Bragg spaced quantum wells at 80K, W. J.

Johnston, J. P. Prineas, Arthur L. Smirl, H. M. Gibbs, and G. Khitrova, submitted to J. Appl. Phys. (2006).

SLOWING, STOPPING, STORING and RELEASING LIGHT in BRAGG SPACED QUANTUM WELLS

Materials that can be engineered to have large, tunable group velocities ($v_g = d\omega/dk = c/n_{group}$, $n_{group} = n + \omega_0 dn/d\omega$) are attractive for applications that require pulses or pulse packets to be spatially compressed and stored for a continuously variable time (e.g., optical buffers). On this task, we have demonstrated that InGaAs/GaAs Bragg-spaced quantum wells (BSQW) can be used to produce tunable slow light delays and that anti-reflection coatings are necessary for improving the coupling of light into such structures. BSQWs are attractive for slow light applications because they can be fabricated from technologically important semiconductor materials, making them compact and potentially integrable with optoelectronic systems.

The potential of BSQWs for slow light applications arises from the presence of an intermediate band in their photonic bandstructure. As we have discussed above, BSQW structures are characterized by two frequencies: (i) the 1s-heavy-hole quantum well excitonic resonance (ω_X) and (ii) the fundamental Bragg frequency ($\omega_B=\pi c/n_b a$, where n_b is the background index and a is the periodic spacing of the quantum wells). The presence of two characteristic frequencies breaks the photonic bandstructure into three bands: In addition to the two usual propagation bands (i.e., the “valence” and “conduction” bands separated by a forbidden gap), an intermediate propagation band opens between ω_B and ω_X of width $\Delta\omega_{IB}=|\omega_B-\omega_X|$. The width of the intermediate band (IB), $\Delta\omega_{IB}$, and the v_g associated with it are each proportional to the relative detuning $|\omega_B-\omega_X|$. Thus, the speed of light in a BSQW can be varied and controlled either by engineering the photonic bandstructure (e.g., controlling the well width or spacing during growth) to produce a given $|\omega_B-\omega_X|$ or by shifting ω_B and/or ω_X externally following growth.

One of the things that we have done on this contract is to derive expressions for $\Delta\omega_{IB}$ and v_g. These show, for example, that the group velocity can be made arbitrarily small by narrowing the IB. In fact, when $\Delta\omega_{IB}=0$, the IB is flat, $v_g=0$ and no propagation is allowed. However, as the intermediate band is narrowed and the group velocity reduced, the bandwidth of any transmitted pulse will be narrowed. In fact, we have shown analytically that the time delay τ_{delay} in units of the pulse width τ_{pulse} (i.e., the bit delay) that is possible without spectrally narrowing the input pulse depends only on the excitonic oscillator strength and number of wells. [Note: this is equivalent to saying that the time delay-bandwidth product is a constant for a given structure.]

Experimentally, we have measured the slowing and broadening by group velocity dispersion of picosecond pulses propagating in the IB of two InGaAs/GaAs BSQWs: one non-AR coated and the other AR coated. The group velocity of light was continuously varied in the intermediate band of a Bragg spaced quantum well structure by tuning the pulse frequency. Delays of 0 to 0.4 bits, without significant pulse distortion, were measured. Unoptimized AR coatings were shown to improve the coupling of light into the structure. AR coatings fabricated from GaAs and AlGaAs were also found to be sensitive to small errors (1.5%) in the AR coating layer thicknesses.

We have also suggested and anaylzed light propagation schemes aimed at evaluating the feasibility of controlled stopping, storing, and releasing of light pulses by parametric manipulation of the BSQW's bandstructure. The basic stopping, storing, and releasing of light is achieved by opening and closing the transmission window in the IB through a parametric manipulation of ω_x. Initially, $\omega_x \neq \omega_B$; the IB has a small (but nonzero) width and the group velocity is low (but nonzero). Therefore the transmission window is open, and the incident pulse is allowed to enter the sample. While the pulse is located within the sample, the exciton frequency is parametrically shifted (e.g., with a control pulse through the ac Stark effect) to coincide with the Bragg frequency $\omega_x = \omega_B$. This parametric shift of ω_x causes the dispersion relation of the IB to flatten completely (adiabatically), which closes the transmission window (i.e., the group velocity is zero) and traps the pulse. After the desired delay, ω_x is allowed to return to its original value, the dispersion relation of the IB is adiabatically restored to its original shape, the group velocity is again nonzero, and the pulse is released. In the ideal case of a long structure, the spectral and phase information in the pulse is preserved through the stopping and restarting process if the pulse does not suffer excessive loss (for example, owing to absorption in the quantum wells). We found that sufficiently long MQW Bragg structures with small absorption losses allow for multibit light-pulse delays.

In our initial work, we considered releasing the light in only the forward direction (transmission geometry). In this geometry, the light pulses suffer considerable temporal distortion due to group velocity dispersion. Consequently, we subsequently suggested a scheme in which the light traveled in the backward (or reflected) direction. As with the transmission scheme, the reflection scheme starts with $\omega_x = \omega_B$. Hence, the IB again has a small (but finite) width, the group velocity is low (but also finite). The transmission window is open and the incident pulse is allowed to propagate into the sample. The group velocity dispersion and higher derivatives of the polariton dispersion curve can lead to significant pulse distortion. The pulse is subsequently trapped by parametrically shifting the exciton frequency from its original value to coincide with the Bragg frequency, while the pulse is located within the sample. The shift of ω_x causes the dispersion relation of the IB to completely flatten, which closes the transmission window (i.e., the group velocity is zero) and traps the pulse located within the sample at the time of the shift. (Note: to this point the scheme is the same as the transmission scheme described in the previous paragraph.) However, in contrast to the transmission scheme (in which ω_x is returned to its original value), now ω_x is shifted above ω_B by the same amount as it was originally below ω_B. This shift exactly reverses the original curvature of the IB dispersion relation, and therefore the group velocity as well as all higher derivatives of the polariton dispersion changes signs. Thus, the pulse propagates backward, and the distortion caused by the group velocity dispersion during its forward propagation into the sample is completely reversed as it exits.

By comparing the distortions associated with this reflection geometry with those incurred in a transmission geometry, we have demonstrated that the reflection geometry automatically compensates for group velocity dispersion. In addition, we have provided an estimate of the minimum length required for Bragg-spaced MQW structures and provide approximate expressions for the bandwidth–time delay product for both transmission and reflection geometries.

For more information on our work on this subject see (and references therein):

[1] “Tunable Slow Light in Bragg-Spaced Quantum Wells,” J. P. Prineas, W. J. Johnston, M. Yildirim, J. Zhao, and Arthur L. Smirl, submitted to *Appl. Phys. Lett*. (2006).

[2] “Light Pulse Deleay in Semiconductor Quantum Well Bragg Structures,” N. H. Kwong, Z. S. Yang, D. T. Nguyen, R. Binder, and Arthur L. Smirl, in *Advanced Optical and Quantum Memories III*, edited by H. J. Coufal, Z. U. Hasan, A.E. Craig, *Proc. of SPIE* **6130**, 61300A (2006).

[3] “Light Pulse Delay in Semiconducting Quantum Well Bragg Structures,” R. Binder, Z. S. Yang, N. H. Kwong, D. T. Nguyen, Arthur L. Smirl, *Phys. Stat. Sol. (b)* **243**, 2379 (2006).

[4] ”Stopping, Storing and Releasing Light in Quantum Well Bragg Structures,” Z. S. Yang, N. H. Kwong, R. Binder, and Arthur L. Smirl, *J. Opt. Soc Am. B* **22**, 2144 (2005).

[5] “Distortionless Light Pulse Delay in Quantum Well Bragg Structures,” Z. S. Yang, N. H. Kwong, R. Binder, and Arthur L. Smirl, *Opt. Lett.* **30**, 2790 (2005).

PUBLICATIONS and PRESENTATIONS

(a) Papers published in peer reviewed journals

1. “Ultrafast all-optical polarization switching in Bragg spaced quantum wells at 80K, W. J. Johnston, J. P. Prineas, Arthur L. Smirl, H. M. Gibbs, and G. Khitrova, submitted to J. Appl. Phys. (2006).

2. “Spin-Dependent Ultrafast Optical Nonlinearities in Bragg-Spaced Quantum Wells,” W. J. Johnston, J. P. Prineas, Arthur L. Smirl, H. M. Gibbs, and G. Khitrova, submitted to J. Appl. Phys. (2006).

3. “Tunable Slow Light in Bragg-Spaced Quantum Wells,” J. P. Prineas, W. J. Johnston, M. Yildirim, J. Zhao, and Arthur L. Smirl, submitted to *Appl. Phys. Lett*. (2006).

4. “Light Pulse Deleay in Semiconductor Quantum Well Bragg Structures,” N. H. Kwong, Z. S. Yang, D. T. Nguyen, R. Binder, and Arthur L. Smirl, in *Advanced Optical and Quantum Memories III*, edited by H. J. Coufal, Z. U. Hasan, A.E. Craig, *Proc. of SPIE* **6130**, 61300A (2006).

5. “Light Pulse Delay in Semiconducting Quantum Well Bragg Structures,” R. Binder, Z. S. Yang, N. H. Kwong, D. T. Nguyen, Arthur L. Smirl, *Phys. Stat. Sol. (b)* **243**, 2379 (2006).

6. ”Stopping, Storing and Releasing Light in Quantum Well Bragg Structures,” Z. S. Yang, N. H. Kwong, R. Binder, and Arthur L. Smirl, *J. Opt. Soc Am. B* **22**, 2144 (2005).

7. “Distortionless Light Pulse Delay in Quantum Well Bragg Structures,” Z. S. Yang, N. H. Kwong, R. Binder, and Arthur L. Smirl, *Opt. Lett.* **30**, 2790 (2005).

8. “A Near-Room-Temperature All-Optical Polarization Switch Based on the Excitation of Spin-Polarized “Virtual” Carriers in Quantum Wells,” M. Yildirim, J. P. Prineas, Eric J. Gansen and Arthur L. Smirl, *J. Appl. Phys.* **98**, 063506 (2005).

9. “All-Optical Spin-Dependent Polarization Switching in Bragg-Spaced Quantum Well Structures,” W. J. Johnston, M. Yildirim, J. P. Prineas, Arthur L. Smirl, H. M. Gibbs, and G. Khitrova *Appl. Phys. Lett*. **87**, 101113 (2005). Also selected to appear in the October 2005 issue *Virtual Journal of Ultrafast Science*.

10. “Ultrafast Polarization Modulation Induced by the ‘virtual excitation’ of Spin-Polarized Excitons in Quantum Wells: Application to All-Optical Switching,” Eric J. Gansen and Arthur L. Smirl, *J. Appl. Phys.* **95**, 3907 (2004).

11. “Many-Particle Theory of All-Optical Polarization Switching in Semiconductor Quantum Wells,” I. Rumyantsev, N. H. Kwong, R. Binder, E. J. Gansen, and A. L. Smirl, *Phys. Rev. B* **69**, 235329 (2004).

12. “Polarization State Dynamics Induced by the Virtual Excitation of Spin-Polarized Carriers in Semiconductor Quantum Wells,” Eric J. Gansen and Arthur L. Smirl, *Semiconductor Science and Technology* **19**, S372 (2004).

(b) Papers published in non-per-reviewed journals

(c) Papers presented at meetings, but not published in conference proceedings

1. “Theory of Ultrafast Optical Gain in the Nonlinear Reflectivity of Semiconductor Bragg Structures,” D. T. Nguyen, N. H. Kwong, R. Binder, and Arthur L. Smirl, *Quantum Electronics and Laser Science* Conference (QELS 06), Long Beach, CA, 21-26 May 2006.

2. “Light Pulse Delay in Semiconductor Quantum Well Bragg Structures,” R. Binder, Z. S. Yang, N. H. Kwong, D. T. Nguyen, Arthur L. Smirl, International conference on *Nonlinear Optics and Excitation Kinetics in Semiconductors* (NOEKS-8), Münster, Germany 20-24 February 2006.

3. **Invited:** “Light Pulse Delay in Semiconductor Quantum Well Bragg Structures,” N. H. Kwong, Z. S. Yang, D. T. Nguyen, R. Binder, and Arthur L. Smirl, *Photonics West SPIE Conference*, San Jose, CA, 21-26 January 2006.

4. “Slow Light and Optical Transparency: Switching and Storage in Resonant Periodic Nanostructures,” A. L. Smirl, J. P. Prineas, J. S. Aitchison, J. E. Sipe, H. M. van Driel, and R. Binder, DARPA Slow Light Phase II Workshop, Seattle, WA, 14-15 December 2005.

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7. **Invited:** “A Tale of Two Systems: Resonator Structures and Coupled Quantum Wells,” J. E. Sipe, H. M. van Driel, J.S. Aitchison, R. Binder, J. P. Prineas, and A. L. Smirl, APS Division of Laser Science Meeting (Laser Science XXI) at *Frontiers in Optics 2005*, Tucson, AZ, 16-20 October (2005).

8. “Stopping, Storing and Releasing Light in Quantum Well Bragg Structures,” Z. S. Yang, N. H. Kwong, R. Binder, and Arthur L. Smirl, *Quantum Electronics and Laser Science Conference* (QELS 05), Baltimore, MD, 22-27 May (2005).

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11. **Invited:** “Stopping, Trapping and Releasing Light in Doubly-Resonant Nanostructures,” Arthur L. Smirl, Z. S. Yang, N. H. Kwong, R. Binder, Philip Chak, and J. E. Sipe, *Physics of Quantum Electronics* (PQE XXXV), Snowbird, Utah, 3-6 January 2005.

12. “Slow Light and Optical Transparency: Switching and Storage in Resonant Periodic Nanostructures,” A. L. Smirl, J. P. Prineas, J. S. Aitchison, J. E. Sipe, H. M. van Driel, and R. Binder, DARPA Slow Light Kickoff Meeting, Washington, D. C., 24-25 August 2004.