Femtosecond Pulse Characterization As Applied To One-Dimensional Photonic Band
Edge Structures

Final Report

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Introduction:

One-dimensional photonic band gap structures, also called photonic crystals, fabricated from layered semiconductors are an attractive candidate for constructing an optical delay line for use in agile beam steering or optical phased arrays. We report rapid and precise measurement of the group delay, group delay dispersion, and transmission of such structures over a 40 nm wide spectral range with time resolution of the order of 20 fsec. We also explore progress toward structures of this kind capable of providing adjustable control of the phase properties of the transmitted optical pulse. We demonstrate high quality data that spans multiple resonances of the photonic band edge structure and present that data in a particularly informative display.

The ability that we demonstrate for measuring the group delay, group delay dispersion, and transmission of a photonic band edge structure in a single simple measurement sequence is important in two respects. The method demonstrates a capacity to measure group delay, group delay dispersion, and transmission for an optically complex structure in a single measurement sequence in a short time. Our evidence indicates the possibility of obtaining real time displays of these optical properties by the relatively straightforward technique of increasing the repetition rate of the probe and reference pulses and the rate at which the delay of the reference pulse is scanned. This ability to rapidly measure phase distortion combined with the potential for adjustment of the phase distortion by voltage control of the photonic band edge structure provide means of both sensing and correcting phase distortion of optical signals over a broad spectral range. We expect this capability to be important to agile beam steering and optical phased arrays.

Task 1: *Contractor shall experimentally examine the adjustable group velocity and adjustable phase velocity in compact one-dimensional band edge structures.*

We probed the spectral variation of the group delay in a static one-dimensional band edge structure. Measurements were made on a 28 period GaAs/AlAs photonic crystal on a 670 μm GaAs substrate, with the long wavelength band edge resonance at 1038 nm. The structure was grown by molecular beam epitaxy at Wright Patterson Air Force Base. Characterization of the static device provided a calibration and confirmation of the experimental and data analysis procedures. We found that the measurement method gave accurate measure of the group delay and transmission over a 40 nm spectral range in one simple measurement sequence. The experimental setup used to measure the group velocity and transmission is shown in Fig. 1.
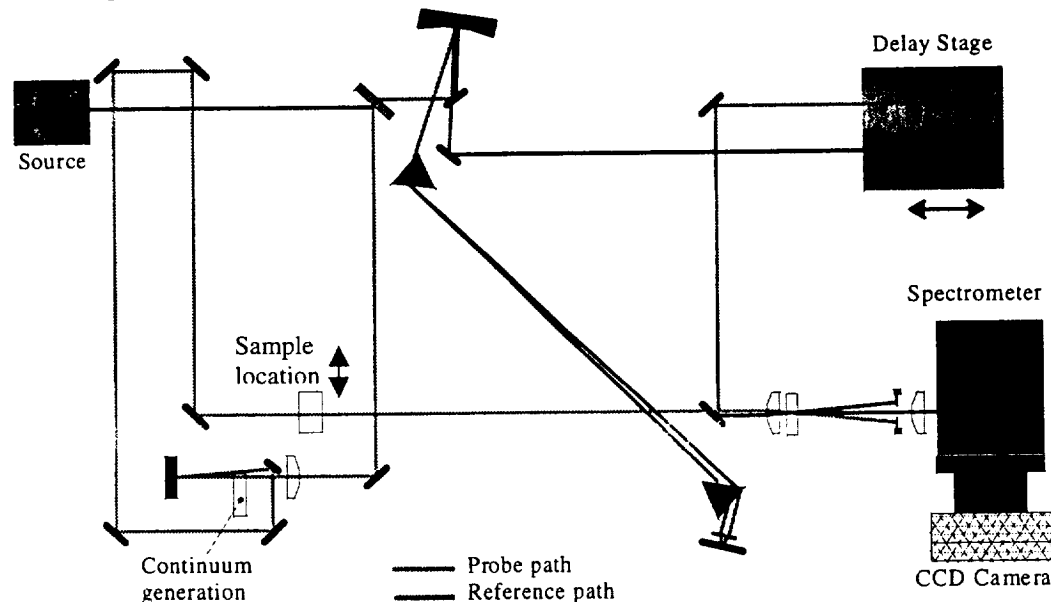

Fig. 1. Experimental setup.

The output of a Coherent RegA 9000 regenerative amplifier (the center wavelength is 809 nm, and the spectral bandwidth is ~10 nm) is split into a probe and a reference path. As seen in Fig. 1, the probe field is

produced by focussing 30% of the laser output into a sapphire flat to generate a continuum [1]. and either allowing it to pass through the sample location. The sample was on a computer controlled translation stage so that data could be taken with the sample present in the probe bath and then remove the sample and take a data set with the sample absent. The reference pulse passes through a prism pair compressor/filter with a variable slit width to narrow the spectrum. This allows centering of the probe spectrum at a particular wavelength, as well as adjustment of its spectral bandwidth and compensation of group velocity dispersion [2,3]. A variable delay stage in the path of the reference pulse allows control over the relative delay between the probe and reference pulses. The two pulses are recombined and focussed into a BBO crystal for background free upconversion.

We made two sets of measurements, one with the sample in the probe beam path, and one without, to remove any group delay or amplitude imparted by the continuum generation process [1] that may obscure the effects of the photonic crystal. Once the two measurements are made, the spectral dependence of the group delay imparted by the sample can be obtained by subtracting the delay at which the upconverted signal is maximized for the continuum probe through the sample from that for just the continuum probe. The transmission can be obtained by dividing the maximum upconverted signal for the continuum probe through the sample by that for the continuum.

For each data set, the variable delay stage was scanned through the region of interest alternately with and without the sample in the probe path until two sets of measurements were made through the sample, and three were made with the sample absent. A reference pulse having a spectral width of 1.7 nm was used. All of the like data sets were averaged together, and then for every frequency, were fit to a Gaussian in time to determine the location and magnitude of its maximum.

The results are shown in figures 2-5. Figure 2 shows a single processed data set. The horizontal axis is
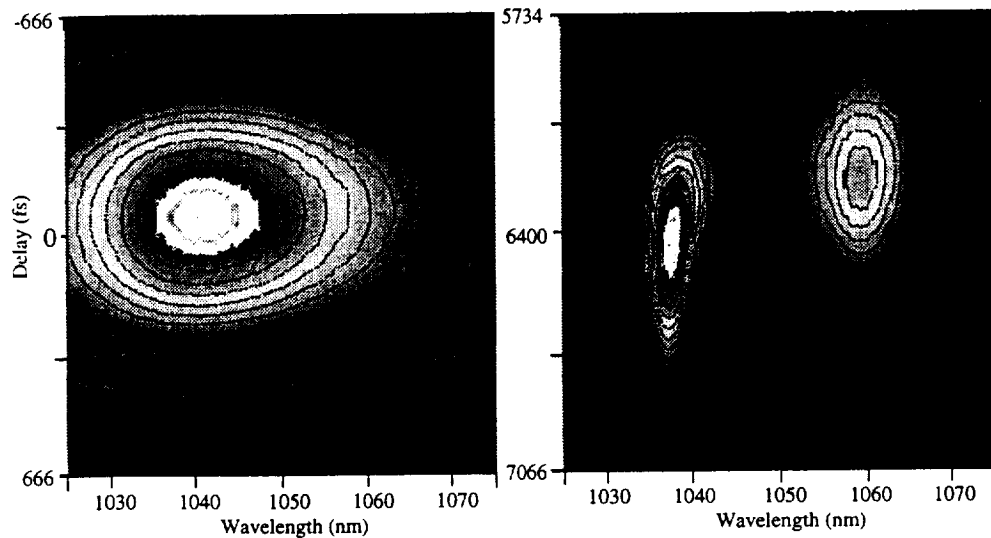

Fig. 2. The processed data sets. The leftmost data set represents the upconverted spectral region of the continuum, and the data set on the right is that of the continuum through the sample. For display purposes, here, zero delay has been arbitrarily set to coincide with the center of the continuum data set. The choice of where "zero" is located is not important as we are interested only in the difference between the delay of the two data sets.

wavelength measured in nanometers. The vertical axis is calibrated in terms of relative delay measured in femtoseconds. Both data sets span a 1332 fs time interval and a 50 nm wavelength interval. Figures 3 and 4, respectively, show the transmission and delay recovered from the data shown in Fig. 2. The effect of the group velocity dispersion of the substrate can be clearly seen in the overall slope of the delay in Fig. 4. Figure 5 shows the delay corrected for the group delay and group delay dispersion of the substrate by calculating the delay for the substrate using the dispersion relation in reference [4] and mathematically removing it from both the theoretical and measured results. The measured delay, corrected for the effect of

the substrate, can be seen to vary from 200 fs at the peak of the band edge resonance to 27 fs in the first transmission valley.
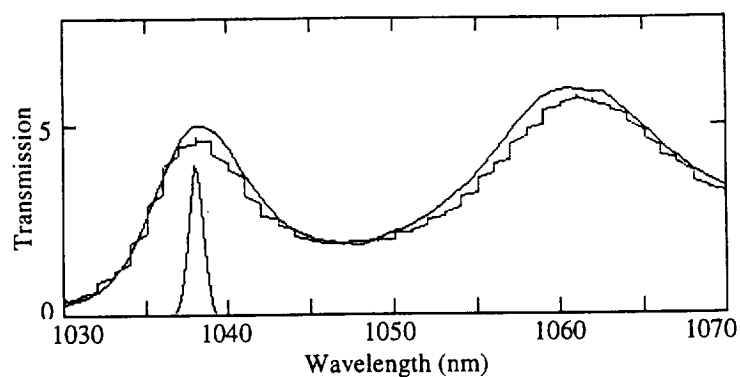

Fig. 3. Transmission recovered from data shown in Fig. 2 (red), and measured at WPAFB (blue). The spectral width of the reference pulse (black), actually centered at 809 nm, is shown here for comparison with the size of the features of the transmission spectrum.
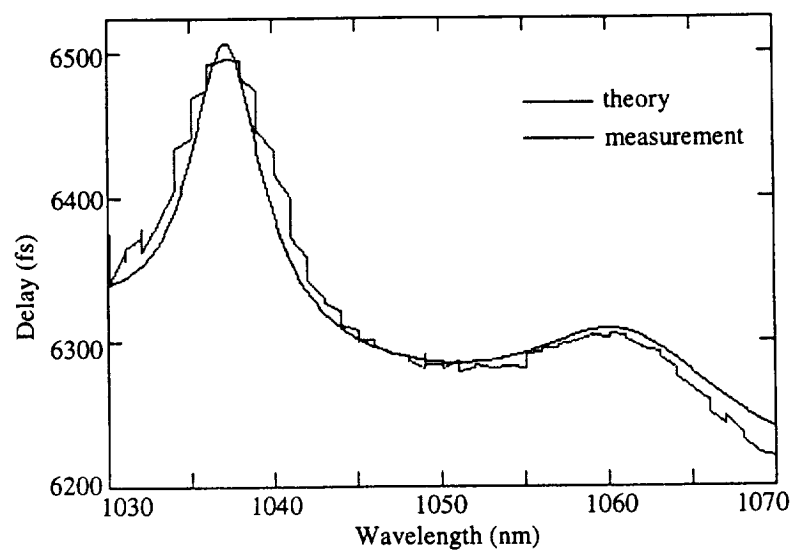

Fig. 4. The delay obtained from the data sets shown in Fig. 2. The group delay dispersion imparted by the substrate on which the structure was grown can be seen in the overall downward slope of the delay.
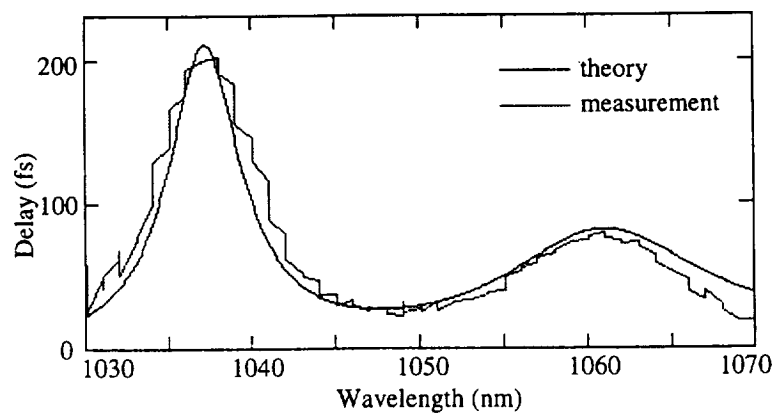

Fig. 5. The theoretical and measured delay corrected for the effect of the substrate.

We have demonstrated a measurement technique that provides an easily understood display of the influence of a structure having complex optical properties on a short optical pulse. We have applied this technique to the simultaneous measurement of the group delay and spectrally dependent transmission of a one-dimensional photonic crystal. We find strong agreement between theory and experiment over spectral and temporal ranges that span the pulse duration and multiple photonic resonances. We expect this method to be valuable in studying the spectral and temporal influence of complex optical structures on short optical pulses. These results show that we are able to probe the group velocity with precision of tens of femtoseconds over a broad spectral region (up to 50 nm).

Task #2: *Contractor shall evaluate use of femtosecond white light continuum pulses to measure and characterize elements.*

The use of femtosecond white light continuum pulses to characterize the spectral variation of a photonic crystal has a great advantage over other techniques [5-7] because it allows us to achieve temporal resolution in the region of tens of femtoseconds over a broad spectral range (30-50 nm) in one single measurement sequence. The key aspect of this method is that the probe pulse is broad band, while the reference pulse has a narrow spectral bandwidth. This combination of temporally short, spectrally broad probe with the temporally stretched, spectrally narrowed reference allows us to gain spectral resolution without losing temporal resolution. An additional, no less important advantage is speed and simplicity due to the fact that all of the required data is contained in a single data set taken over a single delay scan sequence. Previous measurements of photonic crystal group delay have employed the use of spectrally narrow probe pulses [5-7]. This method requires that the probe beam be tuned to a different frequency for each data point. A separate delay scan cycle must then be performed for each data point, which can be very time consuming.

Task #3: *Contractor shall evaluate the degree of adjustment in group velocity and phase velocity that can be realized by electronic means.*

The means by which the group delay and phase are electronically adjusted is by applying a bias to, in effect, shift the transmission spectrum of the structure in frequency relative to the incident pulse frequency. Because of the difficulty of causing the transmission spectrum to shift over a large spectral with a reasonable applied bias, the group and phase velocity of the structure must vary significantly with frequency so that a small shift will result in an appreciable change in group or phase velocity. According to simulations [8] the maximum possible total phase adjustment in a single resonance peak is π radians. The undesirable complication is that across the single resonance peak, the transmission varies greatly, as much as 80% for a sharp peak. This behavior is exhibited in figure 6, which shows the theoretical variation
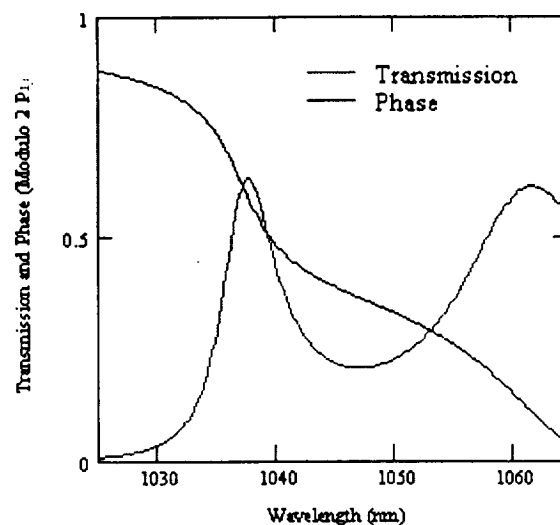

Fig. 6. Theoretical variation of the phase across the BER of a 28 period GaAs/AlAs structure.

of the phase across the band edge resonance in the 28-period GaAs/AlAs photonic crystal discussed in task #1.

Due to the fact that the *theoretical* limit on the phase variation across the resonance is only π, which is half of what is needed for efficient beam steering, and due to this unwanted transmitted amplitude variation that accompanies the phase variation, these particular devices are not good candidates for use in a beam steering device. We instead focus our efforts on the adjustable group delay.

Due to fabrication issues, none of the adjustable samples from WPAFB showed significant variation in delay. Figure 7 shows the results of measurement of an adjustable device. It looks promising if we note the following two concerns:

1) This device was made from a piece from the edge of the wafer, and the growth process causes the thickness of the individual layers to increase as the measurement point is moved from center to edge. Because of this, the long band-edge resonance has been pushed all the way out to 1073 nm. The device
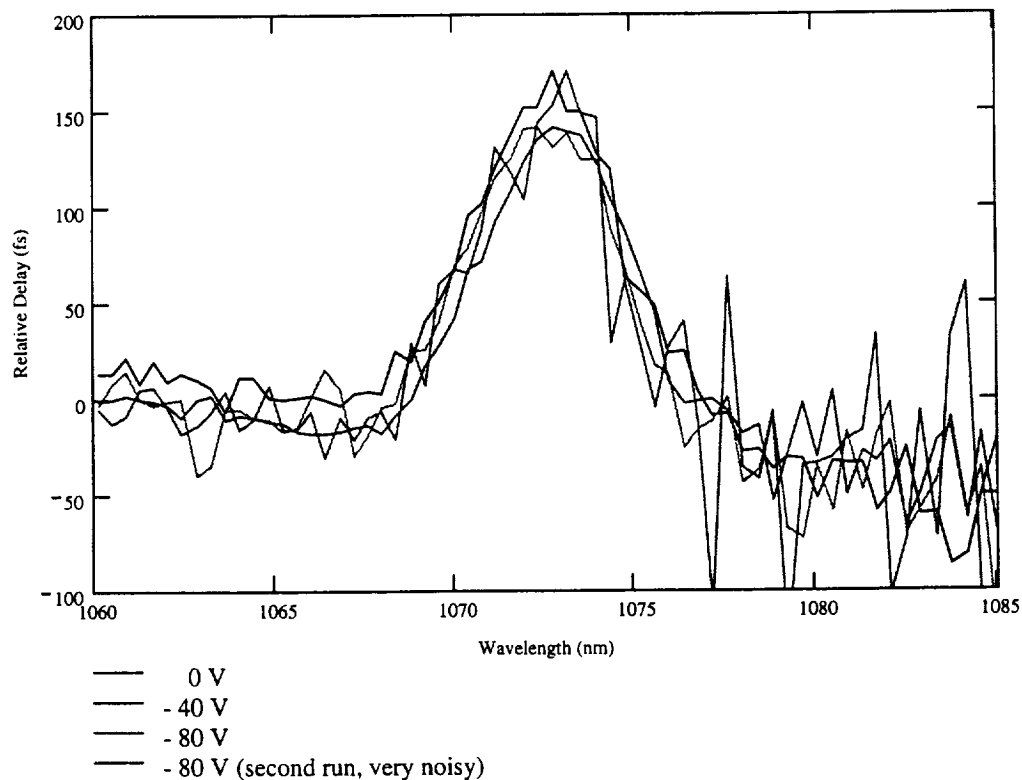

Figure 7. The measured relative delay for several applied biases on an adjustable photonic band gap structure.

was designed for the band edge resonance to occur near 1060 nm. Given that the exciton peak of the quantum wells is designed to be effective near 1060 nm, we do not expect to see appreciable variation in the delay in this particular device.

2) We are able spectrally resolve the variation in group delay in the band edge resonance. This implies that were there a definite variation in the delay in this particular device, we would detect and measure it. We expect to receive new sample devices from WPAFB in the beginning of November 1999 which will exhibit electronically controllable group delay in the band edge resonance.

Task #4: *Contractor shall improve laser pulse techniques to yield measurement precision of a femtosecond or better.*

Substantial improvement in the measurement technique was achieved by use of a prism pair compressor/spectral filter in the reference arm of the experimental set-up. As the PBG structures exhibit spectrally sharp features, it is imperative to have good spectral resolution in order to be able to temporally resolve the sharp spectral features. The spectral resolution in a background free upconversion optical gating experiment like the one that we have employed can be seen to improve with the narrowing of the reference pulse. For illustrative purposes, we present a simple mathematical treatment of the experiment.

It has been shown that the second harmonic generated signal due to two non-collinear plane waves intersecting in a non-linear crystal can be expressed as [9]:

$$E_{Signal}(\omega) = f_{Xtal}(\omega) \int_{-\infty}^{\infty} E_{Probe}(\omega_1) e^{-i\tau\omega_1} E_{Reference}(\omega - \omega_1) d\omega_1 \qquad (0)$$

This is simply the convolution between the reference pulse and the probe pulse times the phase function that contains τ, the relative time difference between the two, where $E_{Reference}$ is the reference field, E_{Probe} is the probe field, and $f_{Xtal}(\omega)$ is a function describing the phase matching conditions in the crystal. This function depends on the thickness of the crystal, the angle between the two beams, the angle of the crystal axis, and the frequencies of the two beams.

We assume that the spectrum of the reference pulse is Gaussian, centered on the frequency ω_r, with a small width, $\Delta\omega_r$. Letting $\omega_p = \omega - \omega_r$, and assuming that $\Delta\omega_r$ is small so that we can evaluate the magnitude of E_{probe} at ω_p and keep only the first term in the Taylor series expansion of the phase of E_{Probe} about ω_p,

$$E_{Probe}(\omega_1) \approx \left| E_{Probe}(\omega_p) \right| e^{i[\phi_{Probe}(\omega_p) + (\omega_1 - \omega_p)\phi'_{Probe}(\omega_p)]} \qquad (2)$$

where ϕ' is the first derivative of the phase with respect to ω. Using eq. (2) to evaluate the integral in eq. (1), it can be further shown that for a given ω_p, the τ dependence of the measured intensity is:

$$I(\omega_p, \tau) = \left| E_{Signal}(\omega_p, \tau) \right|^2 \propto e^{-\frac{[\tau - \phi'_p(\omega_p)]^2}{2\Delta\omega_r^{-2}}} \qquad (3)$$

Which will obtain its maximum value at $\tau = \phi'(\omega_p)$. By curve fitting the measured intensity to a Gaussian in time for each frequency, its peak, $\tau^{max}(\omega)$, will correspond to the first derivative of the phase of the probe beam, and consequently, the group velocity and delay.

The validity of equation (3) depends strongly upon the spectral width of the reference pulse. The above analysis assumes an un-chirped reference pulse, or equivalently a pulse spectrally narrow enough so that any residual chirp will be negligible. The accuracy improves as the spectral width of the reference pulse decreases, but the signal also decreases, so a compromise must be found, with an acceptable signal to noise ratio, and an acceptable spectral resolution. To further increase the accuracy, the repetition rate of the pulses could be increased to increase the average signal , allowing further decrease of the spectral width of the reference pulse.

Conclusions:

1. We conclude that femtosecond pulses can be used to provide detailed information regarding the group delay, group delay dispersion, and transmission of one-dimensional photonic band edge structures in a single measurement sequence.

2.We found that on the structures designed to show a variation in delay with applied voltage the group delay did not exhibit an adjustable variation; however, this was the first sample so investigated and there was a reasonable explanation for the lack of an observed variation. We conclude that the negative result was due to sample fabrication problems.

3. We also concluded that an important component of the measuring system is an adjustable frequency filter that can be used to precisely set the spectral bandwidth and the center frequency of the reference

signal. We constructed such a system using two prisms and a slit that was variable in both position and width. We also concluded that the phase variation of the signal is of interest from a fundamental point of view.

4. We concluded that it was not feasible to measure the phase change of the probe light on transmission or reflection with the resources and time available. We expect to measure the phase change in future experiments. Part of the next stage of work will be to design technology for measuring the phase variation.

Recommendations:

1. This measurement technique should be pursued as a resource for rapidly characterizing optical elements such as one-dimensional photonic band edge structures. There remain substantial opportunities for improving the measurement technique as by increasing the repetition rate of the pulses and hence the rate at which data can be acquired.

2. New samples should be fabricated with attention to the spectral position of the band edge resonance and hence the exciton position. The shift in refractive index, and hence the ability to produce an observable change in group delay, depends sensitively on exciton position. These new samples should be examined and the differences measured as compared with existing samples.

3. The adjustable frequency filter that also provided dispersion compensation was an important part of the experimental resources. We recommend that this adjustable frequency filter or one like it be included in future systems.

4. Means for measuring the phase should be added to the experimental capability. This is both possible and important, but not trivial of execution. There is a fundamental difference in measuring phase as compared to group delay in that the measurement usually cannot be made by simply introducing or removing the sample. A successful demonstration of the voltage controlled phase shift would resolve this problem by providing a means of varying the phase shift while the sample remains in the beam path.

References Cited:

1. R. L. Fork, C. V. Shank, C. Hirlimann, R. Yen, W. J. Tomlinson, "Femtosecond white-light continuum pulses," Opt. Let. **8**, 1-3 (1983)
2. R. L. Fork "Optical frequency filter for ultrashort pulses," Opt. Let. **11**, 629-631 (1986)
3. K. L. Schehrer, R. L. Fork, H. Avramopoulos, E. S. Fry "Derivation and measurement of the reversible temporal lengthening of femtosecond pulses for the case of a four-prism sequence," Opt. Let. **15**, 550-552 (1990)
4. E. D. Palik, "Gallium Arsenide (GaAs)" in *Handbook of Optical Constants of Solids*, E. D. Palik, ed. (Academic Press, 1998)
5. M. Scalora, R. J. Flynn, S. B. Reinhardt, R. L. Fork, M. J. Bloemer, M. D. Tocci, C. M. Bowden, H. S. Ledbetter, J. M. Bendickson, R. P. Leavitt, "Ultrashort pulse propagation at the photonic band edge: Large tunable group delay with minimal distortion and loss," Phys. Rev. E **54**, R1078-R1081 (1996)
6. Y. A. Vlasov, S. Petit, G. Klein, B. Honerlange, C. Hirlimann, "Femtosecond measurements of the time of flight of photons in a three-dimensional photonic crystal," Phys. Rev. E **60**, 1030-1035 (1999)
7. S. Wang, H. Erlig, H. R. Fetterman, E. Yablonovitch, V. Grubsky, D. S. Starodubov, J. Feinberg, "Measurement of the temporal delay of a light pulse through a one-dimensional photonic crystal," Micro. Opt. Technol. Let. **20**, 17-21 (1999)
8. Andrew S. Keys, Richard L. Fork, Thomas R. Nelson, and John P. Loehr, "Resonant Transmissive Modulator Construction for use in Beam Steering Array," SPIE Proc. **3787**, 115-125, (1999)
9. J. P. Foing, J. P. Likforman, M. Joffre, A. Migus, "Femtosecond pulse phase measurement by spectrally resolved up-conversion: Application to continuum compression," IEEE J. Quantum Electron **28**, 2285-2290 (1992)

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13. ABSTRACT *(Maximum 200 words)*

The ability to control the group velocity and phase of an optical pulse is important to many current active areas of research. Electronically addressable one-dimensional photonic crystals are an attractive candidate to achieve this control. This report details work done toward the characterization of photonic crystals and improvement of the characterization technique. As part of the work, the spectral dependence of the group delay imparted by a GaAs/AlAs photonic crystal was characterized. Also, a first generation an electrically addressable photonic crystal was tested for the ability to electronically control the group delay. The measurement technique, using 100 femtosecond continuum pulses was improved to yield high spectral resolution (1.7 nanometers) and concurrently with high temporal resolution (tens of femtoseconds). Conclusions and recommendations based upon the work done are also presented

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