From 2005-2006 success was made in incorporating the nanocrystal into Polymethyl methacrylate (PMMA) matrix. The sensitivity of this composite to electron beams makes it attractive in the fabrication of photonic devices. From 2004-2005, numerical simulations were made for experimentally plausible system parameters for the network sending a single photon wavepacket and for entanglement between two nodes. The team continued optimizing the properties of the quantum dot composites and succeeded to make the nanocomposites in both PMMA and SU-8 hosts with high level of uniformity. A near field optical characterization tool for nanophotonic devices was developed. A study was started on excitation of ultrashort pulse surface plasmon polariton (SPP) fields as well as an investigation of ultrafast electrodynamics of the ultrashort SPP wavepackets. From 2003-2004 the team completed a theoretical study on nonlinear phase shift in the system with a quantum dot embedded in a two-sided cavity from the weak-coupling regime to the strong coupling regime. Additionally, the team developed an approach to manufacture photonic crystal-based on a two-step process consisting of holographic lithography patterning to define the photonic crystal lattice followed by optical direct-write of the functional elements.
March 23, 2007

Dear Dr. Pomrenke:

Please find enclosed the Final report for the grant FA9550-04-1-0245 entitled “Resonant Quantum Device Technologies,” by Y. Fainman, L. J. Sham, and C. W. Tu, at UCSD.

Should you have any questions about this report, please do not hesitate to contact me.

Sincerely,

Y. Fainman
Professor
Resonant Quantum Device Technologies

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2. Objectives/Statement of work

1. **Theoretical Analysis and Design of Resonant Quantum Devices:** The theoretical effort is focused on design and simulation of the optoelectronic devices for information processing of a mixture of quantum and classical information with special emphasis on nanophotonic devices.

2. **Fabrication of Quantum Devices:** The fabrication effort is focused on developing nanofabrication techniques for resonant quantum devices including growth of III-V based quantum dots and cavities for operation at the telecommunication wavelength, advanced holographic lithography to achieve large area photonic crystal lattice that can be used to define photonic device elements and circuits, and integration of colloidal quantum dots based on II-VI and IV-VI compound semiconductors into polymer that can be patterned to fabricate quantum devices. We also explore surface plasmon-polariton phenomena that holds great potential for confinement of optical fields which is essential to enhance linear and nonlinear interactions with quantum systems such as semiconductor quantum dots.

3. **Characterization of nanophotonic quantum devices:** The characterization of nanophotonic devices effort will focus on developing novel nonlinear optical characterization tools at cryogenic temperatures and near field optical microscope with the goal to operate it with nanoscale spatial and femtosecond scale temporal resolution. Additionally, for operation and control of quantum devices we need to devise ultra high resolution optical waveforms synthesis methods that can be optimized for coherent control of quantum systems that are being investigated and operated on time scales of 10-100 psec.

4. **Status of effort**

**Period 2003-2004:**

1. In order to assess the capability of a quantum dot (QD) cavity system as a compact replacement for the nonlinear Kerr medium for optical quantum information processing, we completed a theoretical study on nonlinear phase shift in the system with a QD embedded in a two-side cavity from the weak-coupling regime to the strong-coupling regime [1]. Fig.1 shows the phase shift for a coherent pulse light which contains one photon on average for an InAs dot as a function cavity Q factor and the exciton-cavity coupling g. The value of $g=0.1 \, \text{meV}$ is now achieved by our collaboration team [Scherer Nature article]. For equivalent phase shift, the length of the Kerr medium with the best nonlinearity would be of the order of one meter.

2. We have shown how a fundamental node (Fig. 2) can be built with a coupled system of a quantum dot,
cavity and wave guide, based on our theory of the quantum electrodynamics of the excited state (trion) of a spin qubit in the dot interacting with the cavity photon which is coupled to the photon wavepacket in the wave guide. The optical process involves laser control of the trion of the dot and the output or input of the wavepacket via the wave guide. The node and wave guide may be formed into a quantum net [3], or be used for distributed quantum computing [4], or used to enhance photon-photon interaction such as in a phase gate [2].

3. We have developed an approach to manufacture photonic crystal-based devices based on a two-step process consisting of holographic lithography patterning to define the photonic crystal lattice followed by optical direct-write of the functional elements. First, the photonic crystal lattice is patterned in photoresist using holographic optical lithography with multiple exposures, producing a large-area (about 1 cm²) lithographic pattern quickly and easily (Fig. 2a). In the second step, the variations or defects in the lattice to implement the functional devices are created using optical direct-write with a strongly focused optical beam (see Fig. 2b). After the patterning processes, the mask is developed and a dry-etching process (with the CAIBE system) is used to transfer the desired pattern into a high dielectric constant GaAs substrate (Fig. 2c). With optimized dry-etching parameters, a vertical sidewall etched profile was achieved. The erosion rate of the resist and the etching rate of GaAs are 5 nm/min and 16 nm/min, respectively, such that the etching rate selectivity is approximately 3:1. Since the entire large-scale photonic crystal lattice is essentially created at once using interferometric patterning (Fig. 2a), the direct-write process is needed only to implement the functional elements (e.g., waveguides in Fig. 2b, cavities, etc.) instead of the entire lattice. The negative photoresist nature of SU-8 allows for further modification of the exposed photonic crystal lattice by selective point-by-point exposure of areas that have not yet been exposed. Such a process may be used to introduce point defects to create 2-D nanocavity, line defects to create a linear waveguide as well as any desired pattern in principle. To achieve high resolution for direct-write the line defect, we choose a reflective microscope objective lens 36X (0.52NA) with focal length of 10.4mm (from Thermo Oriel). We used vertical axis of
our optical table to achieve high precision alignment by aligning the axis of the interference pattern to the translation stage axis in the translation direction. Thus, this hybrid approach possesses an advantage in terms of fabrication time and cost as compared to E-beam lithography for the patterning of large-scale photonic crystal-based integrated systems. We have also started to make resonant ring cavities and coupled ring cavities (see Fig. 3) and will explore using this geometries for realization of quantum phase gates using colloidal quantum dots integrated into polymer or SU-8 nanocomposites.

![Fig. 3: Resonant ring cavities and coupled ring cavities](image)

We continued developing fabrication process of quantum dot composites and succeeded to make the nanocomposites in both PMMA and SU-8 hosts. The process uses commercially available colloidal II-VI and IV-VI quantum dots and mixes them into resist for patterning to create photonic devices and circuits. This method allows us to construct photonic devices. To avoid cluster aggregation within the bulk polymer matrix in contrast to previous approaches based on using ligand and other surfactants we suspended QDs in the MMA during polymerization step. When MMA polymerizes to PMMA, the large molecular weight PMMA with enveloped QDs sinks to the bottom of the container, whereas the non-polymerized MMA moves towards the top. Furthermore, due to the higher solubility of QDs in non-polymerized MMA, the non-enveloped QDs diffuse to the top MMA layer, leaving a gap in the middle region. We resolved this issue using pre-polymerization method: The MMA QDs solution was heated in a thermostatic water bath at about 90°C for 20 min to obtain the desired viscosity, or pre-polymerization, and then poured into molds, which were heated at 60°C for ~20h to achieve post-polymerization. We optimized synthesis of composite

![Fig. 4: Photoluminescence and absorption spectra of PbSe and CdSe quantum dots-PMMA nanocomposites](image)

![Fig. 5: Dependence of the PL spectrum on the temperature for quantum dot nanocomposites in PMMA](image)
semiconductor quantum dots into resist, varying the optical photoluminescence range, density of dots as well and structure of the pattern applied to these resists: different dots and at different concentrations. The nanocomposites have been characterized by measuring the PL for both PbSe and CdSe quantum dots nanocomposites in PMMA (see Fig. 4). Low temperature measurements show blue shift of the quantum dots in PMMA of about 16 nm (see Fig. 5).

5. We also initiated fabrication of nano- and microstructures using the nanocomposite quantum dots in PMMA and SU-8. For PMMA nanocomposite we used standard E-beam lithography method. An SEM of a periodic nanostructure with features of 200-300 nm made out of such a resist is shown in Fig. 6. We have also started to fabricate photonic resonant structures from SU-8 nanocomposites utilizing the uniqueness of negative resist that we need just to expose the regions of the desired devices. We fabricated coupled rings configurations as they are essential for realization of quantum phase gate as designed in 1 and 2 (see Fig. 7a). We also fabricated a spiral structure to achieve a compact package for a very long

![Fig. 6. SEM of a periodic structure in a quantum dot composite resist.](image)

This configuration may be possible to use for realization of a compact quantum dots based amplifier. UV illuminated structure is shown in Fig. 7b and enlarged portion in Fig. 7c.

6. We continued construction of a unique all-fiber near-field optical microscope for measurement of the complex amplitude of the near field on the nanoscale at operating wavelengths around 1.55 µm, extending

![Figure 8. Set-up of the 1.55 µm coherent scanning near-field optical microscope working either with CW or ultra-short pulses.](image)
its design and operation with femtosecond laser pulses and in a broad spectral range for investigation of both linear and non-linear optical phenomena in the near field. The coherent NSOM is implemented with a combination of an NSOM and an interferometer (heterodyne in our case). We use an all fiber-based system design to achieve interferometric stability and operate the system at a telecommunication wavelength in the infrared range (~1.55 μm) to meet the need in building characterization tools for better understanding nanophotonic devices for telecommunication applications. Also, our interferometric detection system can work either with CW light or ultrashort pulses. For the pulsed system, an optical delay line is used for temporal pulse correlation with τ=2 fs resolution steps. A schematic diagram of the set-up is presented in Fig. 8. The 1.55 μm laser is split to create a reference with a frequency shifted using two acousto-optic modulators. The second beam is used for illumination in different configurations, according to the desired measurement (collection mode, illumination mode, waveguide injection collection mode). The polarization mode is adjusted using a fiber polarization controllers. A fiber tip is brought close to the surface using an atomic force microscope (AFM). The NSOM tip is mounted on a tuning fork and an electronic feedback controls the sample-tip distance within a few nanometers. The commercial AFM (Nanonics TS-2000) is composed of two flat piezoelectric scanners permitting either the tip or the sample to be moved. The light (propagating or evanescent) emerging from the structure is collected by the fiber tip. The signal and the reference beams are recombined into an InGaAs detector for post signal processing and analysis. For the functional characterization on nanophotonic devices we use a waveguide implemented in a photonic crystal lattice. The PC waveguide, consisting of a missing row of holes in a square-lattice PC structure, is shown in Fig. 9. The experimental measurements are performed using a heterodyne SNOM system designed to operate at wavelengths around 1.55 μm. A solid-state laser with a tunable range of 1520–1580 nm is used as the light source. The detected amplitude and phase for light of wavelength 1560 nm propagating in the PC waveguide are shown in Figs. 10a and 10b, respectively. The amplitude image clearly shows that the light is mostly confined to the waveguide channel. Looking also at the phase image, we observe that most of the guided light appears to be propagating in a single mode having even transverse symmetry. Furthermore, Fig. 10b shows a distinct phase pattern having transverse phase fronts in the region of the waveguide channel, with a period

![Fig. 9. SEM picture of the photonic crystal waveguide, consisting of a missing row of holes in a Silicon square-lattice photonic crystal membrane and a tapered ridge waveguide for light injection. The waveguide length in the membrane is 30 μm, and the lattice period is 496 nm.](image)

![Fig. 10. Observed (a) amplitude and (b) phase over a 14 μm square area for 1560nm light propagating in a square-lattice photonic crystal waveguide detected using heterodyne SNOM. The diamond symbols at the edges of the images indicate the approximate position of the](image)
significantly smaller than in the surrounding area as expected. In addition, we also investigate the spectral characteristics of light guided in this structure. The amplitude and phase images taken with the heterodyne SNOM for light at three different wavelengths are shown in Fig. 11. At a vacuum wavelength of 1541 nm (Figs. 11a and 11b) we observe a change in the mode. In this case, most of the light propagates in an odd mode having transverse maxima at the edges of the waveguide channel. This suggests that different modes are dominant at these two wavelengths. At a wavelength of 1533 nm (Figs. 11c and 11d), the light appears to still be guided, although significantly more scattering is observed. At a wavelength of 1521 nm (Figs. 11e and 11f), a significant amount of light escaping the waveguide channel can be seen. In summary, we have demonstrated the direct observation of the amplitude and phase of an optical field propagating inside a PC waveguide using heterodyne SNOM. In addition, we have observed a change in the propagating mode in the waveguide corresponding to changes in the optical wavelength, and found an agreement between near-field and far-field measurements. Further comparisons of experimental measurement results with theoretical predictions could provide further insight into the design and optimization of PC waveguides and other nanostructured devices. Finally, application of this technique to the study of other subwavelength-scale photonic devices could advance the understanding of light propagation phenomena in a variety of nanostructured devices and systems.

Fig. 11. Amplitude (a, c, e) and phase (b, d, f) images over a 7 μm square area taken with the heterodyne SNOM of light propagating in the PC waveguide at various wavelengths: (a,b) 1541 nm; (c,d) 1533 nm; (e,f) 1520 nm.
Period 2004-2005:

1. At the heart of this proposed solid state system for quantum network and distributed computation is a scheme of quantum control for arbitrary interchange between a stationary qubit and a flying qubit (carried by single photon wavepacket) at a quantum interface composed of a single quantum dot containing either two excitons or a spin coupled to a photon continuum through a resonant cavity. It can be used for generation or reception of an arbitrarily shaped single-photon wavepacket. The generation process can also be controlled to create entanglement between stationary qubit and flying qubit. The generation and reception operation can be combined to perform quantum network operations such as transfer, swap or entanglement creation of qubits between distant nodes. Numerical simulations were made for experimentally plausible system parameters for the network sending a single photon wavepacket and for entanglement between two nodes.

2. We continued optimizing the properties of the quantum dot composites and succeeded to make the nanocomposites in both PMMA and SU-8 hosts with high level of uniformity. We also focused our effort to reduce the concentration of semiconductor quantum dots in PMMA and create ultrathin samples such that we can easily find single quantum dots using conventional microscopes. These samples are being used in spectroscopic measurements at few degrees K. Our preliminary experimental results show both biexitonic and oscillatory behaviour. We are in the process of analyzing and interpreting these experimental data and correlating it with theory.
3. The fabrication of resonant structures at a specific precisely defined resonance frequency that matches that of a quantum dot resonance has been a challenging task primarily due to the fabrication tolerances. We developed a new method that allows to overcome this issue. Our approach uses a fluidic cladding over the resonant structures where the refractive index of the fluid can be very accurately tuned to reach the desired resonance. Specifically we constructed a microfluidic mixer integrated with resonant ring microcavities shown in Fig. 12. The experimental characterization of our device shows extinction ratio of 37 dB. In comparison with currently reported performance of under 15 dB, our devices shows significant performance enhancement of over 20 dB.

4. We also continued developing our near field optical characterization tool for characterization of near field optical nanophotonic devices. Specifically we demonstrated for the first time the existence of two types of modes in a photonic crystal waveguide. A band diagram of our fabricated photonic crystal lattice waveguide is shown in Fig. 14. There are two waveguide modes e1 and e2 which are excited at different optical frequencies. e1 lies above the free space line and therefore is more lossy (leaky mode) whereas the e2 mode is propagating mode. Fig. 15 shows The redistribution of amplitude in the two modes. However, most important results of our measurement is
both amplitude and phase of the modal structures propagating in the photonic crystal waveguide. Using the complex amplitude of the detected field we performed a Fourier Transform in the propagation direction of the field and found the propagation constants $\beta$ for the 2 modes as evident from the Fig. 16.

![Complex Amplitude](image1)

![1D (z-direction) Fourier Transform](image2)

Fig. 16 Spectrum of the near field complex amplitude showing spatial frequency content of the excited mode structure as a function of the excitation frequency

5. We recently started a study on excitation of ultrashort pulse surface plasmon polariton (SPP) fields and investigated ultrafast electrodynamics of these ultrashort SPP wavepackets. For the excitation and visualization of propagation of ultrashort SPPs we fabricated a number in samples of nanohole arrays on a total area of 200x200 micrometers.

![Experimental apparatus for excitation and visualization of ultrashort SPPs](image3)
The samples were fabricated using such metals as gold, silver, and aluminum on various substrates such as glass, alumina, GaAs, and Si. We have excited SPP on a single side of Metal-Dielectric boundary as well as on both sides depending on the thickness of the metal which was varied from 20-100nm. The experimental apparatus is shown schematically in Fig. 17. We used image heterodyne detection method followed by signal processing that allows us to detect amplitude and phase of the ultrashort pulse SPP. Snap shots of ultrashort pulse SPP propagating and scattered from the nanohole array is shown in Fig. 18.

We also investigated transfer of optical phase onto the ultrashort pulse SPP wavefront in order to investigate SPP focusing properties. This results reveal that we can transfer optical phase onto the SPP phase and thereby manipulate plasmonic fields from the optical fields. The results of this study are summarized in Fig. 19.
6. For operation and control of quantum devices we need to devise ultra high resolution optical waveforms synthesis methods that can be optimized for coherent control of quantum systems that are being investigated and operated on time scales of 10-100 psec.

Our approach, shown schematically in Fig. 20 is based on longitudinal spectral decomposition. In contrast to existing approaches that use transverse spectral decomposition, our method allows to achieve time bandwidth product of 10,000-100,000, which is about 100 better than what can be achieved with compact pulse shapers implemented in free space using transverse spectral decomposition. Our implementation uses conjugate dispersive components (single mode fiber and dispersion compensated fiber as well as a matched pair of chirped fiber Bragg gratings) in combination with fast electro-optic modulators. The method has been used for experimental validation showing expected performance. For example when the modulator is used for single tone RF modulation with a bias to suppress the carrier, we observed 3 pulses in the autocorrelation trace as expected for such synthesized waveform (see Fig. 21).

![Fig. 20 Longitudinal ultra-high resolution waveform synthesizer for coherent control of quantum devices and systems](image)

![Fig. 21. An autocorrelation trace of a synthesized ultrafast waveform for various settings of the RF signal applied to the electro-optic modulator in the waveform synthesized based on longitudinal spectral decomposition.](image)
Period 2005-2006:

1. We continued the study of semiconductor quantum dots (QDs) formed in colloidal solution, called nanocrystal (NC), via chemical synthesis. In colloidal solutions, however, NC's are suspended in a solvent, making them less practical for fabrication and integration of photonic and optoelectronic devices. The introduction of such NC's into a solid-state matrix, therefore, is of great interest for numerous applications. We have succeeded in incorporating the NCs into Polymethyl methacrylate (PMMA) matrix (as described above). The sensitivity of this composite to electron beams makes it attractive in the fabrication of photonic devices. We particularly studied the spectra of single NC in PMMA. It's useful for the future application of single NC in PMMA photonics device. Our study is primarily focused on the quantum information applications.

We conducted a series of experiment on spectroscopy of NC in PMMA at cryogenic temperatures in order to better understand their quantum coherence properties and effects. Specifically, we found and investigated several quantum dots switching between two states. Spectra from a typical switching NC, recorded at six different excitation powers, are shown in
Fig. 22 (a)-(f). These spectra are recorded continuously with an integration time of 2 s each. The greyscale plot represents intensity, while the horizontal axis is time, and the vertical axis is the emission energy. Fig. 22(g) shows the typical spectrum for the two states. The red line (bold line) is for the lower energy state, which we will call state 2, while the blue line (thin line) is for the higher energy state which we call state 1. The energy difference between the two states is 5.6 meV. Fig. 22(h) is a plot of intensity vs. time for data taken from Fig. 22(a)-(f). Fig. 22(i) is the plot of the characteristic frequency vs excitation power. From Fig. 22(g) and 22(h) we see that there is no sizable change in the integrated PL intensity for the two states. The excitation power density is of the order of 10 kW/cm$^2$. Figure 22 shows that state 1 dominates at low excitation powers while state 2 is more pronounced at high excitation powers. In addition, the switching frequency increases with increasing excitation power density. Since the widths of both state plateaus decrease with increasing excitation power, we can conclude that the transitions from the two states are light induced.

Figure 23 (a-c) shows that in some NC's, higher laser intensity not only increases the switching frequency, but also makes the states moving randomly. In addition, the figures show that there is an additional peak in lower energy side with the energy difference 22.7 meV. The energy shifts of the lines are shifting in step. Therefore, we infer that these lines come from a single NC. The right side of Figure 24(a-c) shows the normalized spectrum respectively. We attribute the side peaks to phonon replicas since the ratio of its intensity to the exciton intensity remains constant when the pump intensity changes.

In order to observe more spectral lines, we integrated over 30 second for each frame in Figure 24. We record 200 measurements continuously with constant temperature and excitation power. Again the energy shifts of the lines are correlated, and therefore, we conclude that these lines come from a single NC. The energy difference between the main line and the satellite lines are 22.7 meV and 25.8 meV, respectively. Also we can see more lines on the lower energy side. The energy
differences with the main line are 45.4 meV and 48.5 meV respectively. We identified them as
the lines from surface optical (SO) phonons, longitudinal optical (LO) phonons, two SO phonons,
and one SO plus one LO phonons.

In summary, we have investigated random switching between two states in the PL from
CdSe/ZnS colloidal nanocrystal in PMMA. The commonly observed blinking behavior was
suppressed. The spectrum switching behaviors are dominant and some of them are similar to
what has been observed in III-V quantum dots. To explain these observations new models going
beyond those established in the literature need to be developed. We also found the random
energy shift which follows approximately a Lorentzian distribution. Identical jitter patterns allow
the unambiguous identification of the emission spectra of single NC’s. By means of excitation
density dependent spectroscopy the lines are identified as phonon replica of the exciton transition
involving local SO-phonon and LO-phonon modes of the NC. Huang-Rhys factors of $S$ of about
0.2 are observed.

2. We also continued the development of the heterodyne SNOM (H-NSOM) and applied it for
study of various fundamental phenomena in nanophotonic resonant structures and devices. Our
first example is on Negative refraction in the photonic crystal lattice. Using a
heterodyne scanning near field microscope, we analyzed the
phase and amplitude of the electric field of an optical
wave across the boundary of a positive to negative refraction
media. The photonic crystal acts as an extremely
anisotropic material with a negative curvature of its
dispersion surface whose shape is clearly resolved
experimentally. This extreme anisotropy results in the beam having two peculiar phase
properties that do not occur in isotropic media. The first is that the converging wave has
diverging wavefronts and after the internal focus, the now diverging wave has converging
wavefronts. For this study we prepared a sample shown in Figure 25, where the photonic crystal
sample consists of three stages. First, light propagates through a 2μm wide incident ridge
waveguide, then it propagates in a 15μm long region of unpatterned silicon-on-insulator (SOI)
substrate and finally refracts into a 20μm long PC region. The PC is a square array of holes
whose front interface is cut along the <11> direction, as shown in Figure 25A. The sample is
excited with TE polarization and has a fundamental mode size of 1.5μm in the ridge waveguide.
The beam then diffracts through the homogenous silicon slab region and expands to a size of
6.6μm where it sees the silicon/PC interface. The Bloch mode excited in the PC then negatively
refracts and forms an internal focus 3μm behind the interface, which has a transverse size of
2.6μm. Behind the internal focus the beam continues to expand through the PC, as seen in
Figure 25B. The second phase anomaly results from the first and is that the negatively refracting

Figure 25. A) shows a scanning electron micrograph of the positive to negative refraction interface. The positive index material consists of an unpatterned region of silicon, which has a thickness of 300nm. The negative refraction material is a square array of holes with a lattice constant of 410nm and a hole diameter of 295nm. B) Shows the field amplitude as measured by a heterodyne SNOM with a low resolution scan. The sample is illuminated with 1560nm light in the TE polarization.
wave has a negative Gouy phase shift. By measuring the full complex values of the guided field, we are able to observe both anomalous phase features of the Bloch wave as well as its dispersion surface.

In another example we study an integrated total internal reflection prism that generates a transversely localized evanescent wave along the boundary between a photonic crystal and an etched out trench. The reflection has previously been described by the symmetry of the Bloch wave field distribution. In this project we show that a tangential momentum matching condition can also describe the reflection. In addition, the Bloch mode propagates through the photonic crystal in a negative refraction regime, which manages diffraction through the prism. A device with three input channels has been fabricated and tested that illuminates different regions of the reflection interface (see Fig. 26). The reflected wave is then sampled by a photonic wire array, where the individual channels are resolved. Heterodyne near field microscopy is used to characterize the spatial phase variation of the evanescent wave and its decay constant. We measured the amplitude and phase of the guided wave at the reflection interface. Figure 27A and its inset show that the amplitude image of the detected field has a peak at the interface and then decays into the air trench, while staying at a roughly constant value in the PC. The wavelength of illumination is 1552 nm, which does not give the tightest field confinement at the interface, but gives a strong signal showing a bright evanescent field. The phase of the field in Fig. 27B shows that along the reflection interface, the phase varies only in the tangential direction. An evanescent field’s momentum vector is only real parallel to the interface, so the phase should not progress in any other direction. The inset shows a cross-section of the phase 260 nm behind the interface, which has a period of 1.42 μm, which is below the free space wavelength, indicating that the wave is evanescent. The decay constant of the evanescent field is measured to be 1.20 μm/s, defined as the e−1 location of the field amplitude. The inset is obtained by summing a 10 μm wide field along the boundary, and plotting the summation as a function of vertical distance. The summation averages field values over several unit cells of the PC and results in a smooth curve. Field values in the HNSOM image are sampled at an interval of 260 nm, so there are 4-5 measurements in the e−1 decay region. A near-field object is convolved with the collection tip, in this case 200 nm. This convolution blurs sharp features by approximately this amount, which increases the measured decay distance. Along the interface, the amplitude is modulated by the surface periodicity of the PC, √3a, but this does not describe the phase progression, as we will see by looking at the tangential phase profile.

The phase image in Fig. 6 shows a coherent wave incident into the boundary from the PC and along the interface. The tangential momentum of these two waves is equal according to the boundary condition. By taking a cross-section of the phase image just beyond the interface in
the gap, the spatial period of the wave is observed to be 1.42 μm, which gives $k_{ev} = 1.09k_{air}$. The decay constant of an evanescent wave can be predicted from its momentum by the expression $D = \frac{1}{\sqrt{k_{ev}^2 - k_{air}^2}}$. Using $k_{ev} = 1.09k_{air}$, the decay constant is expected to be 570 nm, which is larger than the measured value of 1.2 μm. Because the field is spatially confined, there is a spectrum of transverse momentum values at the boundary. Lower spatial frequencies decay slower into the air region, so they have greater influence at large distances from the interface. In order to better understand the spectrum of the evanescent wave, we can Fourier analyze the measured complex field. This method also gives insight into the reason for measuring a larger $D$.

Figure 28 is the numerical Fourier transform of the measured complex field from a 15 x 15 μm scanning area centered at the reflection edge. The brightest feature in the spectrum is the incident Bloch wave, $k_{i,PC}$, and is located in the upper left region indicating that its phase progresses in that direction. By measuring the magnitude of $k_{i,PC}$, the effective index of the primary momentum distribution is estimated to be 2.2. As long as this value is larger than 2.0, the Bloch wave will TIR at the boundary when the incident angle is 30°. This value agrees with the numerical prediction from FDTD of 2.35 and further illustrates the close momentum match between the slab mode and the PC mode, which has an index of 2.54. It is also evident that the momentum distribution is flat indicating that the wave is in a slow diffraction regime. This region of the spectrum is labeled A.

At the same tangential momentum, but along the $k_{t}$-axis, is the second brightest region labeled B. The spectrum of the evanescent wave is expected to be in region B because the only real component of its momentum is along the tangent of the interface. From the figure, the evanescent wave is expected to be in region B because the only real component of its momentum is along the tangent of the interface. From the figure, the evanescent wave is expected to be in region B because the only real component of its momentum is along the tangent of the interface.
spectrum lies just beyond the air light line and has energy from 1.0-1.3k_{air}. The momentum components only slightly larger than k_{air} will decay very slowly and are responsible for the larger than expected measured value of D. The higher end of the k_{ev} spectrum compares well with the value expected by numerical simulation. Region C contains the reflected wave spectrum, which is surprising weak considering the large efficiency observed in far-field measurements.

Each region can be windowed and inverse Fourier transformed back to the spatial domain to view where that piece of the spectrum is located. The inset labeled A shows that this region is in fact the incident PC mode, which starts at the PC input facet and ends at the reflection interface. Region C, though weaker, shows the reflected PC wave starting at the reflection interface and ending at the PC output facet. Region B, which is the evanescent wave, is confined to the reflection edge. The windowed spatial field distribution has less resolution, but makes it possible to isolate different components of the detected field. The near-field microscope efficiently collects the PC prism’s evanescent field as can be seen by the low noise floor in inset B compared to the other insets. In summary, a PC TIR prism has been demonstrated that acts as an efficient evanescent wave source that is integrated onto a silicon platform. Different resolvable regions along the PC to air boundary can be illuminated due to diffraction management and the presence of input and output waveguide arrays. These channels spatially overlap in the prism so consequently perform a function that is difficult to obtain in conventional integrated optics. The device can in the future be scaled up, where the number of resolvable channels will be dictated by the aperture of the prism divided by the beam size, which can be on the order of 1-2 \lambda. In addition, the near-field performance of this device has been characterized. We have directly measured the phase and amplitude distributions of the generated evanescent wave. Although previously the PC’s inability to couple across an air boundary has been described by mode symmetry, we have shown here that transverse momentum conservation can also describe the reflection. These arguments have been made using the Fourier spectrum of both numerical and experimental data. The strong presence of the detected evanescent field imply that the PC TIR prism might allow efficient and flexible evanescent wave coupling, imaging, and sensing functionalities. The device presents a means to generate an evanescent wave with high efficiency and a localized extent into a parallel system on an integrated platform.

3. We also started a new direction in Si Nanophotonics that we call “free space optics on a chip”. Besides a number of new near field optical phenomena that we investigated numerically and are in the process of fabrication and testing, we have demonstrated a new “Inhomogeneous Metamaterial with Space-variant Polarizability” which is extremely useful for mode matching on a Si chip. The design was performed using both rigorous coupled wave (plane wave spectral) analysis and an approximate effective index theory developed by Rytov (with proper modifications). The

![Fig. 29: Scanning electron micrograph showing the fabricated device: (a) a top view of the entire structure. (b) a magnified slanted view showing part of the slab lens and the output waveguide.](image)
designed nanostructure was fabricated using our e-beam lithography and reactive ion beam etching (see Fig. 29). The fabricated devices were characterized with the H-NSOM tool. The experimental results shown in Fig. 30 confirm our design and fabrication process, demonstrating a slight discrepancy due to lithographic proximity effects during fabrication of features less than 100nm. This study clearly demonstrated the value of closing the loop between design, fabrication and testing-nanophotonics process pioneered in our group.

![Fig. 30: Experimental results obtained with the Heterodyne Near field Scanning Optical Microscope (H-NSOM). (a) The amplitude and (b) the phase of the optical field in the region that includes the input waveguide, the non-patterned slab ("S") and large portion of the slab lens section ("L"). The dashed vertical white lines mark the boundaries between the various sections. Light is propagating from left to right. (c) Cross sections showing phase profile at several planes along the device. The planes are marked in Fig. 5b.](image)

4. We further enhanced Si Nanophotonics research by exploiting a single lithographic step in creating geometries on the sub-100 nm scale that realize complex nanophotonic structures, devices and circuits. A simple example we used for the first validation of our ideas is a one dimensional photonic crystal waveguide with a single mode defect that implements a resonant filter. We implement vertical side wall modulation in a silicon waveguide implemented with standard SOI. Transmission resonant filters in a waveguide with vertical gratings have been realized in silicon on insulator (SOI) wafers (see Fig. 31a).

![Fig.31 (a) SEM micrographs of the whole device and its inset showing resonant filter device. Dotted rectangle shows the area defined at × 1000 magnification and (b) Measured transmission spectra from the fabricated devices](image)

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Experimental studies of fabricated devices show a broad stopband of ~19 nm with a narrow transmission band of ~0.6 nm (see Fig 31b). The developed fabrication procedures show very good surface quality which is also indicated by the measured value of the single mode cavity Q of about 3,000. These resonant cavities are useful for laser cavities, switches, modulators, detectors, and tunable filters.

5. We also continued our studies of the surface plasmon polaritons in the 2-D nanohole arrays. Specifically we continued the studies of various modes excitation, interaction, and detection with special emphasis on integrating plasmonics with optofluidics and gain medium. These studies are currently being investigated in conjunction with the sensing applications.
4. Personnel Supported

Y. Fainman, PI, Professor (UCSD)
Lu Sham, co-PI, Professor (UCSD)
Charles W. Tu, co-PI, Professor (UCSD)
Kevin Tetz, Research Assistant (UCSD)
Maxim Abashin, Research Assistant (UCSD)
Yaoming Shen, Research Assistant (UCSD)
Vladimir Odnoblyudov, Research Assistant (UCSD)
Lin Pang, Postdoctoral Researcher (UCSD)
Hiroshi Ajiki, Postdoctoral Researcher (UCSD)
Wang Yao, Graduate Research Assistant (UCSD)
Robbie Saperstein, Graduate Research Assistant (UCSD)
Kaz Ikeda, Graduate Research Assistant (UCSD)
5. Publications


7. A. Nishikawa, Y.G. Hong, and C.W. Tu, "Temperature dependence of optical properties of Ga$_{0.3}$In$_{0.7}$N$_x$As$_{1-x}$ quantum dots grown on GaAs (001)", J. Vac. Sci. Technol. B, vol.22, no.3, pp.1515-17, May 2004.


9. Y.G. Hong, A. Nishikawa, and C.W. Tu, "Similarities between Ga$_{0.48}$In$_{0.52}$N$_x$P$_{1-x}$ and Ga$_{0.92}$In$_{0.08}$N$_x$As$_{1-x}$ grown on GaAs (001) substrates", J. Vac. Sci. Technol. B, vol.22, no.3, pp.1495-8, May 2004.


11. A. Nishikawa, Y.G. Hong, and C.W. Tu, “Effects of thermal annealing on Ga$_{0.3}$In$_{0.7}$N$_x$As$_{1-x}$ QDs grown on GaAs (001)”, 2003 Int’l Symp. Comp. Semicon., pp.55-60, 2004.


**During Period 2004-2005:**


**During Period 2005-2006:**


6. Interactions/transitions

   a. Meetings, Conferences, Seminars, Proceedings


2. Y. Fainman, "Ultrafast Information Processing with Optical Nonlinearities," CLEO/QELS, June 1-6, 2003, Baltimore, Maryland, (Tutorial)


**During Period 2004-2005:**


31. Tortora, M. Abashin, W. Nakagawa Investigation of the spectral characteristics of photonic crystal waveguides with heterodyne scanning near-field optical microscopy NPIS 2005 Conf. Proc. NThC2


During Period 2005-2006


59. Y. Fainman, “ Nanophotonics for information systems integration, OSA Topical Meeting, April 26-28, Mohegan Sun, CT, 2006 (Invited)
61. Y. Fainman “Information Processing with Ultrashort Laser Pulses, 5-th Intl. Workshop on Information Optics, Toledo, Spain, June 5-7, 2006 (Invited)

b. Consultative and advisory functions

During Period 2004-2005:

2. Y. Fainman, General Chair and Program co-Chair of the first OSA Topical Meeting on Nanophotonics for Optical Information Systems Integration,” San Diego, April 14-16, 2005


During Period 2005-2006:


11. Y. Fainman “ Optofluidics for adaptive optics and sensing”, DARPA Center on Optofluidics Integration, Retreat, Harvard University, April 2006.


15. Y. Fainman “Optical feedback with gain processing,” DARPA P3A Workshop, August 22, 2006, DC

7. New discoveries: None

8. Honors/Awards: None

C.W. Tu was elected Fellow of the AVS, 2004
Y. Fainman was elected Fellow of the SPIE, 2004.