Abstract:

We demonstrate evanescent coupling between a strip waveguide and a periodically-patterned ring resonator in the slow light regime. Resonances with a group index > 22 are efficiently coupled with an extinction ratio of > 20 dB. This result opens up the possibility of new applications in compact device integration in wavelength-division multiplexing (WDM) systems while reducing the in-band four-wave mixing (FWM) crosstalk.

Summary of Research:

Periodic structures exhibit strong dispersion that enables dense optical device integration. Recently, photonic crystal based waveguides [1] and resonators [2] have been demonstrated as compact delay lines [3] and small-modal volume cavities [4]. Recently, we reported a novel microring resonator structure patterned with periodic circular air holes on a silicon-on-insulator (SOI) platform [5,6]. By taking advantage of the slow light effect near the Brillouin zone edge, the size of the ring resonator can be reduced while still preserving its capacity to support multiple optical channels in wavelength-division multiplexing technology. The non-zero dispersion reduces the in-band FWM crosstalk in a WDM system. However, the impedance mismatch between the highly dispersive resonance modes and the linear dispersive strip waveguide could result in insufficient coupling. We match the phase velocities by tuning the widths of strip waveguide in order to compensate for this effect.

Figure 1(a) shows the top-view scanning electron micrograph (SEM) of a fabricated device. The devices are fabricated on SOI wafers with a 3 µm buried oxide layer and a thin silicon layer 250 nm thick. Patterns are defined by electron beam lithography with negative-tone HSQ photoresist. The silicon layer is etched by an ICP-RIE etcher with chlorine gas. The periodicity of the air holes is a = 450 nm. There are 100 circular air holes on the ring with hole radius of 0.3a. The width of the ring is 1.00a. The periodically-patterned microring is coupled evanescently to a straight strip waveguide. We measure the transmission spectra by using a wavelength scanning technique. From the measured transmission spectra [6], we estimate the highest group index of ~ 20, and Q ~ 1,000. The slow-light modes are critically coupled with high extinction ratio of > 20 dB. The Q-factor is mainly limited by the scattering losses induced by the interface roughness and the disordering of the periodic structure.

References:

Figure 1: Scanning electron micrograph of a fabricated microring resonator with 100 periodic circular holes (top), and magnified micrograph of the evanescent coupling region with strip waveguide width $w$ (bottom).
Transformation Optics on a Silicon Platform

CNF Project # 980-01
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Abstract:

Transformation Optics (TO) is a tool for design of innovative devices. Nonetheless, its implementation in optical frequencies remains a challenge. The use of solely dielectric materials and non-resonant structures is desirable in the optical domain to guarantee operation in a broad range of wavelengths. In this report, we discuss our advances in fabrication methods employed to create TO devices using silicon-on-insulator (SOI) as our dielectric platform.

Summary of Research:

Transformation Optics shows that spatial geometry and the constitutive parameters of materials affect electromagnetic waves in the same manner [1,2], allowing the implementation of virtual geometries in real space, via gradient refractive index (GRIN) media.

The fabrication of GRIN media is common in fiber optics, where the amount of dopants in the glass can be well controlled, and, in turn, determines the refractive index of the glass. However, this allows no more than a few percent variation in refractive index, while requirements for TO devices can easily reach index contrasts of 2:1 and more. By using a silicon platform, we are able to work with higher refractive index contrasts (nSi = 3.5) and operate at wavelengths around 1550 nm.

We use SOI wafers to fabricate the structures, so that light is confined in a high index layer, surrounded by low index media. If the final devices are large enough to approximate adiabatic index variations, we can decouple the vertical confinement in the guiding layer and the wave propagation in the plane. In this case, the index we need to control is the effective index in the propagation direction only. Looking at the guiding structure, a layer of thickness t and index n surrounded by lower index media, we note that, if the surrounding media is kept constant, we can change either n or t to control the propagation constant.

The guiding layer index can be changed through effective medium theory. The result of mixing sub-wavelength regions of high and low indexes is an effective index that is proportional to the volumetric fraction of each component [3,4]. In our platform, mixing sub-wavelength silicon pillars with air-filled regions, allows us to reach index contrasts a little over 2:1. The fabrication of such structures can be achieved via high-resolution e-beam lithography and anisotropic etching. The downside of this technique is that the resulting structure presents high scattering losses. In our experiments, we were able to achieve silicon pillars with diameters down to 60 nm with precise positioning,
fundamental to control the local fractions of silicon and air. Figure 1 shows a scanning electron microscope (SEM) image of a device fabricated using electron-beam lithography and inductively coupled plasma, reactive ion etching on silicon: a Maxwell fish eye lens [5].

The other alternative, changing the thickness of the guiding layer, can be implemented by different methods. Using a calibrated focused ion beam (FIB), we can sculpt the design into the silicon layer in a one-step process. However, the FIB will implant ions in this layer, as well as break its crystalline structure to some extent, both of which will increase propagation losses. Surface roughness introduced by the FIB is not a major concern, since it can be held below 2 nm RMS.

Another possible method for controlling the thickness of the silicon slab is gray scale lithography [6], with its own advantages and disadvantages. We fabricated the Maxwell fish eye lens using the FIB method, and achieved minimal error with respect to the design in a very repeatable fashion. Figure 2 shows an atomic force microscope (AFM) scan of the lens, and Figure 3 compares a cross-section of this scan with the designed profile. We can see that the surface roughness is minimal, at the same time that the thickness control is very precise.

Using only dielectrics and non-resonant structures for TO devices guarantees a broad wavelength range of operation. This report briefly discusses our advances in the fabrication processes that will allow TO devices to fulfill their potential in fundamental areas such as invisibility, imaging, and solar power collection.

References:

Abstract:

We fabricate and characterize a CMOS-compatible, Mach-Zehnder-coupled, second-order-ring-resonator filter with doubled free spectral range and demonstrate non-blocking operation, while tuning it to a new wavelength.

Summary of Research:

Optical Networks-on-Chip (NoC) can overcome bandwidth limitations of a typical multi-core microprocessor system [1]. The characteristics that determine the bandwidth efficiency of a of NoC are: 1) the number of channels that can be allocated in the network, which is determined by the Free Spectral Range (FSR); and 2) the process of reconfiguration of the network, which depends on the dynamics of individual filters. The ability to efficiently increase the number of channels in a network has been demonstrated a variety of ways, as using small ring resonators [2], Vernier filters [3,4], or by merging a Mach-Zehnder interferometer (MZI) with a ring resonator (see Figure 1) [4-7].

The last approach presents the compelling features of doubling the FSR without high radiation losses, intrinsic to tight bends, and without the typical insertion loss for misaligned resonances, intrinsic to Vernier filters. Here, we demonstrate non-blocking [6] operation of a FSR-doubled filter, which prevents channel interference during reconfiguration.

We implemented the filters with large FSR by replacing the single point coupling between a waveguide and a ring resonator by a two-point coupling topology (Figure 1a). In this case, each ring resonator also comprises a MZI, as shown in Figure 1a, which suppress one of the ring resonances. In Figure 1b we show the overall transfer function of the second order filter of Figure 1a with one resonance suppressed. Unlike a typical Vernier filter [3,4], the resonance removed by this approach leaves behind a negligible spectral signature where the original resonance was present (around 1560 nm in Figure 1b).

We demonstrate non-blocking tuning of the filter described above. This is achieved by first changing the refractive index of one of the ring resonators, which modifies the transfer function from a box-like filter to an all-pass filter, and then changing the effective indices of the other ring resonator and of the MZ arms to be resonant at the new wavelength, without blocking any other channel in the process [8]. We use the thermo-optical effect to provide tunability for the filter. As shown in Figure 2a, doped silicon heaters were formed inside the rings and in the surroundings of the external arms of the MZI’s. The cross section of the heaters
is 215 nm high by 1000 nm wide, while the cross section of the crystalline silicon waveguides is 215 nm high by 450 nm wide. A thin 35 nm silicon slab is left underneath the structure to enhance heat transfer from the heaters to the waveguides. The overall structure is fabricated on an SOI wafer with a 3 µm SiO₂ buried oxide and is clad by a 1.2 µm thick SiO₂. Vias are etched for electrical contact, where a thin stack of TiSi and TiN is formed prior to the evaporation of Cu wiring and pads. The final structure is shown in Figure 2b.

The transfer function of the device fabricated is shown in Figure 3a, where a doubled FSR of 19.2 nm can be observed for the 10 µm radius fabricated rings, with its main resonance at 1594.6 nm. The residual power dropped at the suppressed resonance (at 1604.2 nm) is about 16 dB below the signal level. In Figures 3b and 3c, we demonstrate the non-blocking tuning of the fabricated filter. For the first step of the non-blocking tuning, we apply 28 mW to the heater inside the ring connected to the drop port, which changes the box-like transfer function (Figure 3a) to an all pass transfer function (Figure 3b), as expected. In Figure 3c we show the final step of the tuning, where a new central resonance wavelength, at 1603.1 nm, is observed under 115 mW of heat power applied for all heaters. This overall process demonstrates that non-blocking tuning can be achieved for a doubled FSR filter, which translates to a higher throughput for NoC’s.

References:


Optical Bistability in Etchless Silicon Ring Resonators

CNF Project # 980-01
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Abstract:
We demonstrate an atypical reverse optical bistability (blue shift of the resonance) in etchless silicon ring resonators by compensating the thermo-optic red shift with a strong free carrier dispersion blue shift.

Summary of Research:
The ability to tailor the spectral dependence of photonic devices on input intensity is critical. In resonators the spectral shift with input optical power leads to optical bistability and has been observed in silicon resonators, such as microdisk resonators, photonic crystal microresonators and ring resonators [1–4]. These resonators have shown a red shift of the resonance due to the dominant thermo-optic effect over the free carrier dispersion (FCD) in silicon. Here we demonstrate an atypical reverse optical bistability (blue shift of the resonance) by employing a stronger FCD and a weaker thermo-optic effect in a designed silicon ring resonator.

In order to control the degree of spectral tuning with optical power, we design the structure to present strong FCD with opposite spectral dependence on input power to the traditionally dominant thermal effect. The FCD is maximized here by designing a structure with long free carrier lifetime through surface passivation of the device. We fabricate a 50 µm-radius silicon ring resonator using an etchless fabrication technique. The details of the fabrication were described in our previous work [5].

To give critical coupling at 1550 nm, the dimensions of the ring resonator are designed to be 800 nm wide by 60 nm tall with a coupling gap of 930 nm (see Figure 1).

This silicon layer is never exposed to any etching plasma throughout the fabrication process, therefore preventing damage from the ion bombardment and chemical reactions. This fabrication technique results in an ultra-smooth Si/SiO$_2$ interface comparable to that between the silicon and buried oxide. This 50 µm-radius ring resonator has a loaded quality factor of 350,000 with a ring loss of 0.8 dB/cm.

We measure the effective carrier lifetime of the ring resonator using a pump-probe optical setup (see Figure 2). We couple a 500 fs Er-fiber pulse laser with a 25 MHz repetition rate and a spectral width of 6 nm at center wavelength $\lambda_{\text{pump}} = 1543$ nm into the ring resonator. The pump pulses are absorbed by the silicon ring resonator via two-photon absorption (TPA) to generate free carriers and cause a blue shift in the resonance due to FCD.

Concurrently, a quasi-TE polarized continuous-wave probe laser at $\lambda_{\text{probe}} = 1489.484$ nm is coupled into the ring resonator with a resonance at $\lambda_0 = 1489.487$ nm. We measure the effective carrier lifetime to be 10 ns (see Figure 3). The effective carrier lifetime of this silicon structure is more than one order of magnitude longer than the 450 ps carrier lifetime of an etched 450 nm by
250 nm channel waveguide [6]. The surface passivation of the silicon through the thermally grown silicon dioxide reduces the recombination rates of the carriers, and therefore results in a longer carrier lifetime.

We demonstrate a reverse optical bistability in the high-\(Q\) etchless silicon ring resonator for input power as low as 60 \(\mu\)W. Due to the long resonant photon lifetime, the stored cavity energy is large at this low input power. When light propagates in the ring resonator, it can be absorbed via TPA and generates free carriers, causing a blue shift in resonance due to FCD. These generated carriers also lead to free carrier absorption (FCA). The TPA and FCA nonlinear processes, together with the linear surface absorption at the Si/SiO\(_2\) interface, result in the heating of the ring resonator and hence a red shift in the resonance. With increasing input power coupled into the ring resonator, we observe a reverse optical bistability in the ring resonator (see Figure 4). An effective blue shift in the resonance occurs due to the long carrier lifetime of 10 ns and low confinement factor of 0.32.

To conclude, we demonstrated a reverse optical bistability in etchless silicon ring resonators by employing a long carrier lifetime of 10 ns to give stronger free carrier dispersion (FCD) and a low confinement factor of 0.32 to give weaker thermo-optic effect. This engineering of optical bistability has potential applications in making input optical power-insensitive photonic devices.

References:


Optical Frequency Conversion in Silicon Waveguides at Mid-Infrared Wavelengths

CNF Project # 980-01  
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Abstract:
We demonstrate for the first time parametric wavelength conversion of continuous wave signals inside a silicon waveguide at mid-infrared frequencies. Using four-wave mixing, we show wavelength conversion over 748 nm.

Summary of Research:
Low power [1] and broadband [2,3] four-wave mixing (FWM) wavelength conversion has been demonstrated in silicon nanowaveguides pumped with lasers emitting in the C-band. However, the maximum conversion efficiency achievable with pumps lasing in the telecommunication bands is limited by two-photon absorption and free-carrier absorption. The impact of these two impairments can be mitigated by pumping with a source emitting beyond 1.7 µm [4]. It can even be completely avoided if the pump wavelength is larger than 2.2 µm, which corresponds to half of the band-gap energy of silicon. Moreover, using a pump working close to 2 µm enables the conversion of signals into the mid-infrared, which is useful for free-space and spectroscopy applications.

Four-wave mixing in silicon waveguides with a 2 µm pump has been demonstrated previously with pulsed sources [5,6]. Here, we present the first demonstration of broadband FWM with a continuous wave (CW) 2 µm pump in silicon nanowaveguides. We show continuously tunable wavelength conversion over 320 nm, which was limited only by the availability of signal sources. Furthermore, we observe wavelength conversion over 748 nm and we generate an idler at 2384 nm [7].

To optimize the conversion bandwidth, the waveguide is designed to have zero group-velocity dispersion (GVD) between 1940 nm and 1970 nm, which is the tuning range of our pump CW thulium fiber laser. Figure 1 shows simulated dispersion curves of the fundamental TE mode for a waveguide with a fixed core height of 280 nm and widths varying between 940 nm and 970 nm. The waveguide used in this demonstration have a height of 280 nm and a width of 940 nm. Inverted tapers narrowing down to 250 nm were defined at the input and output of the waveguides to maximize coupling. Arrays of nanowaveguides were fabricated using silicon-on-insulator wafers having a 500 nm silicon slab over a 3 µm buried oxide layer. The silicon slab was thinned down to 280 nm by wet oxidation. The oxide layer created during this process was removed by wet etching in hydrofluoric acid. The waveguide pattern was then written by electron beam lithography in ma-N 2403 resist before being transferred in the silicon slab by
reactive ion etching. Lastly, the samples were clad with 3 µm of silicon dioxide by plasma-enhanced chemical vapor deposition.

To measure the conversion bandwidth and optimize the pump wavelength, a second CW thulium fiber laser continuously tunable between 1790 nm and 1930 nm is used as the source signal. The TE polarization of the pump and signal lasers is selected with a polarization beamsplitter cube and a polarization controller, respectively. Both signals are combined and then coupled into the nanowaveguide with a microscope objective. The output light is collected with a single mode tapered-lensed fiber and measured with an optical spectrum analyzer. Figure 2 shows the measured spectra with a pump wavelength of 1940 nm and the signal wavelength tuned from 1792 nm to 1928 nm. We observe continuous wavelength conversion over 324 nm, which is limited by the tuning range of our signal laser. The 3-dB theoretical conversion bandwidth is over 946 nm.

To confirm that we used a Fabry-Perot laser emitting at 1636 nm as the signal source and we were able to generate an idler at 2348 nm with a -38.6 dB conversion efficiency. Figure 3 shows the conversion efficiency as a function of signal-idler detuning for waveguides of varying widths and a pump fixed at 1950 nm. We estimate the pump power inside the nanowaveguides to be around 25 mW, which resulted in a peak conversion efficiency of approximately -30 dB. Further increase of the pump power to 160 mW results in a peak conversion efficiency of -17.8 dB. The maximum input power that could be coupled to the waveguides was limited by the damage threshold of the input tapers.

This demonstration shows that silicon photonics is a practical platform to develop compact all-optical processing devices for applications in the mid-infrared. Moreover, we expect that operating at pump wavelengths beyond 2.2 µm will result in additional improvement in conversion efficiency.

References:


Figure 2: Four-wave mixing spectra.

Figure 3: Theoretical (curves) and measured (dots) conversion efficiencies as functions of idler wavelength for waveguides of varying widths.
Waveguide-Integrated Telecom-Wavelength Photodiode in Deposited Silicon

CNF Project # 980-01  
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Abstract:
We demonstrate photodiodes in deposited polycrystalline silicon at 1550 nm wavelength with 0.15 A/W responsivity, 40 nA dark current, and gigahertz (GHz) time response [1]. Sub-band absorption is mediated by defects that are naturally present in the polycrystalline material structure. The material exhibits a moderate absorption coefficient of 6 dB/cm which allows the same microring resonator device to act as both a high-Q demultiplexing filter and a photodetector. The device offers an alternative to standard germanium-based photodetectors in the silicon photonic platform.

Summary of Research:

The crystalline silicon-on-insulator (SOI) platform enables modulation and low-loss waveguiding in the telecommunication wavelength bands centered at $\lambda = 1.3 \mu$m and 1.55 $\mu$m. These functions can be implemented due to the 1.12 eV bandgap of bulk crystalline Si which only produces significant linear absorption for $\lambda < 1.1 \mu$m. To add infrared photodetection to silicon photonic circuits, germanium can be integrated as an absorbing material in CMOS processing environments [2]. However, epitaxial growth of Ge on Si requires complex processing steps to manage the 4% lattice mismatch between the two crystals as well as a crystalline starting material.

It is known that silicon can generate photocarriers via sub-band absorption of light with $\lambda > 1.1 \mu$m when defects are present that contribute energy states within the bandgap [3]. For integrated SOI devices, surface state absorption can produce a relatively low responsivity $R = 0.036$ A/W in thin waveguides [4]. Jessop, Knights, et al. showed that the absorption can be further enhanced by distributing defects throughout the waveguide by ion implantation [5]. Other groups have shown improved responsivity and bandwidth, but all demonstrations to date have required single-crystalline SOI as a starting material.

Here we show photodiodes in polycrystalline silicon (polysilicon), a standard deposited material that can be integrated in the CMOS material stack. We have previously used polysilicon to build integrated optical filters and electro-optic modulators [6] for monolithic integration of optical functionality onto a microelectronic chip. The results presented here demonstrate that at least 12% of the propagation loss in these submicron polysilicon waveguides is due to sub-band absorption that generates useful photocarriers. Polysilicon can therefore be used for both the modulator and photodetector at the start and end of an optical link on a CMOS chip.

We design photodetectors with an integrated PIN diode to sweep out generated carriers and a ring resonator geometry to reduce the footprint. The fabrication is similar to [6] with a summary as follows. We use 3 $\mu$m oxide as a lower cladding, deposit 270 nm of high quality amorphous silicon by low pressure chemical vapor deposition (LPCVD), and crystallize the material into polysilicon by a furnace anneal in $N_2$ at 1100°C to maximize the grain size. We perform moderate $n$-type phosphorus doping to an average concentration of $2 \times 10^{17}$ cm$^{-3}$.

Many of the dopant ions and donor electrons are trapped at the material grain boundaries. We pattern waveguides and resonators using e-beam lithography, etch the devices to leave a 40 nm slab for electrical access, and dope p+ and n+ contact regions. We clad the devices in silicon dioxide by plasma enhanced chemical vapor deposition (PECVD) and make electrical contact with nickel silicide and aluminum.
The device is shown in Figures 1 and 2.

Input light is trapped in the device by constructive interference when an integer number of wavelengths fits inside the optical path length of the microring. When the light is on resonance, it travels multiple round trips around the resonator until some percent of it is absorbed to generate photocurrent and the rest is scattered away. This ratio of absorption loss to total loss gives the efficiency of carrier generation inside the device.

We determine the internal responsivity of the photodiode to be as high as 0.15 A/W. Figure 3 shows the transmission and measured current when we sweep the laser wavelength with a DC reverse bias on the device. Figure 4 shows the resonant photocurrent at -13 V. The optical power coupled into the resonator is 6.65 µW. We find a quality factor $Q = 10,500$ and a maximum photocurrent $I = 0.975$ µA corresponding to internal responsivity $R = 0.15$ A/W, or internal quantum efficiency of 12%. The microring device acts as a wavelength-selective photodetector which can both demultiplex and detect one wavelength of a WDM signal. This combined functionality is not possible in strongly absorbing materials where high loss would prevent the formation of a high-$Q$ resonance. Based on the optical loss and the quantum efficiency we determine that at least 6 dB/cm of the device propagation loss is due to useful absorption. Finally using an external modulator, we have shown operation of the device at data rates up to 2.5 Gbps.

References:


Figure 1: Microscope image of device and input waveguide.

Figure 2: Cross-section schematic.

Figure 3: Transmission (top) and photocurrent (bottom).

Figure 4: Photocurrent vs. wavelength.
Abstract:
Integration of photonics with electronics, although common in academic research, still fails to be commercialized due to the incompatibility of materials and processes of simple photonics. Utilizing CMOS-compatible materials and processes, we develop a multi-layered backend process to integrate silicon photonics using low temperatures on a pre-existing electronics stack. We achieve losses of ~ 1 dB/cm in the L-band, -0.04 dB waveguide crossings and 24 dB extinction frequency filters.

Summary of Research:
Advances in silicon and silicon-compatible photonics have spurred intense research in the area of optical interconnects, where it could potentially be used to increase the bandwidth and lower the power of computing systems such as multi- and many-core processors [1,2]. Unfortunately, densely integrated silicon photonics with microelectronics has yet to emerge commercially. While there may be clear advantages over electronic communication, the integration of photonic interconnects with on-chip electronics requires a costly change to well-established complimentary metal-oxide-semiconductor (CMOS) processes.

Multilayer photonics can go beyond simple integration, providing interesting advantages to the system as a whole. Single layer interconnect photonics is typically criticized as not providing enough performance gain in terms of bandwidth and power, to justify the integration challenges. Losses from waveguide crossings for example, a necessary limitation of single layer optical networks, are often cited as one of the biggest obstacles in these systems [3]. A multilayered system could reduce or eliminate these restrictions altogether by avoiding physical crossings. We would also give architects a new dimension to explore, perhaps leading to denser as well as more complex networks with radically higher cross-sectional bandwidth and reduced communication power consumption.

Along with using group IV compatible materials, the most important detail in backend photonics is using processes around or below 400°C to avoid distressing the metallization and changing the dopant diffusion. Our fabrication uses plasma enhanced chemical vapor deposition (PECVD) of all layers, planarization to allow for vertical stacking, and proper patterning and spacing of structures to allow for coupling and insulation. We work with Si₃N₄ as a guiding medium for its good optical characteristics. Si₃N₄ is readily found in CMOS for passivation, masking and dielectric layers and provides lower optical losses than c-Si in the NIR [4] when using SiO₂ cladding, also a CMOS dielectric.

We demonstrated the waveguide loss to be just over 1 dB/cm for most of the L-band in our 400 nm × 1 μm geometry Si₃N₄. The loss increases steadily into the C-band due to Si-H and N-H bonds in the film [5]. These losses are comparable to those shown in the literature for silicon nitride and are still better than most comparable silicon single-mode waveguides [4]. We measure losses for the waveguide crossings to be -0.04 ± 0.002 dB/cross for waveguides separated vertically by 800 nm. Lastly we test the optical path through the vertically-coupled filter and measure a channel bandwidth of 25 GHz and an extinction ratio of -24 dB. Figure 2 shows both the drop port and through port normalized by the input power to the device. We also measure an insertion loss of -0.6 dB from the drop port response, and we calculate the loaded quality factor of the resonator from the linewidth to be $Q_L = 7.5 \times 10^3$ and estimate an ideal intrinsic value of $Q_{i-sim} = 1.7 \times 10^5$. 

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**3D Backend CMOS Optics Integration Using Compatible Materials and Processes**

**CNF Project # 980-01**  
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References:


Figure 1: Fabricated device; (a) microscope image of bus waveguides and microring resonator, (b) vertically coupled structure with TE mode and geometry parameters, (c) false color SEM image of ring cross section, and (d) close-up SEM of silicon nitride waveguide cross section.

Figure 2: Results of fabrication; (a) propagation losses of PECVD Si$_3$N$_4$ waveguides (400 nm × 1000 nm) over wavelength of interest, (b) averaged loss per vertical crossing (800 nm separation), and (c) microring resonator (30 µm radius) through and drop port responses from both layers.
Fabrication of Nanofluidic Channels on Fused Silica Wafers

CNF Project # 1096-02
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Abstract:

This current project has been dedicated to fabricating 500 nm wide and 400 nm deep channels on fused silica wafers. The channels are fabricated on a bottom wafer using photolithography, and reservoirs connecting the ends of the channel are made on a top wafer. The two wafers are then bonded together by wafer-bonding.

Summary of Research:

The fabrication procedure has been developed for repeatable and reliable fabrication of the nanometer sized channels, sealed between two fused silica wafers.

Each wafer assembly consists of two fused silica wafers bonded to each other and it contains 82 individual flow-cells fabricated on it. Each flow-cell consists of two reservoirs 3 mm away from each other, and a 1 mm wide and 400 nm deep channel connects these reservoirs. Halfway from the reservoirs, the channel is divided by a 15 µm wide and 400 nm high ridge, in which 500 nm wide channels are made.

In the past years, the nanochannels were used in the project of developing a new method for nanoparticle recognition [1,2]. Nanoparticles are recognized by measuring the optical force acting on nanoparticles in a strongly focused laser beam [3]. Currently, the nano-channels are used in the project for interferometric recognition and classification of single nanoparticles such as viruses in real-time, using light scattering [4,5,6].

Fabrication Procedure:

A fused silica glass wafer (Mark Optics, USA) was precleaned in a nanostrip bath for 30 minutes. The wafer was vapor primed in the YES oven. The wafer was spin-coated with i-line photo-resist (OIR 620-7i) at 3000 RPM for 30 seconds with three seconds ramping speed. The nano-sized parts of the flow-cell were patterned using the GCA Autostep 200 DSW i-line wafer stepper, and the micro-sized features were patterned using EV620 contact aligner (Electronic Visions, Phoenix, AZ). The channels were etched using reactive ion etching technique in the Oxford 81 etcher. The remaining resist was then removed using acetone and in the hot resist stripper. Second glass wafer was used to seal the channels. Holes for liquid delivery were made in the second glass wafer using sand-blasting tool. Both wafers are cleaned in acetone, powder detergent solution, isopropanol, methanol, nanostrip and also in the MOS clean area. They are then bonded together using wafer-bonding and dried overnight and also in a 90° convection oven for two hours. Finally, the bonded wafers are annealed in the N2 anneal furnace.

References:

Figure 1: Optical micrograph of the fabricated glass nanochannels.

Figure 2: AFM topography of a nanochannel.
Porous Polymer Waveguides and Ring Resonators

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Abstract:

Label-free optical biosensors are particularly interesting because of their ability to tightly confine light while avoiding complications often associated with label dependent detection. However, many traditional optical biosensors often store the majority of their optical energy in the waveguide core, leaving only the evanescent field to interact with biomolecules. In this work we develop nanoporous polymer waveguides and ring resonators which allow increased interactions between core energy and biomolecules. Initial results indicate a 20% increase in device sensitivity between control and porous devices.

Summary of Research:

Significant research efforts have been made at developing advanced biosensing technology over the last few decades yet the amount of commercialized technology hasn’t increased significantly. Devices have been developed based on optical, mechanical, and electrical methods of signal transduction, and have been optimized on the nanoscale [1-4]. Optical devices are of particular interest because of their ability to detect minute quantities, as far down as ten attograms [3]. Many of these current devices rely on fabrication techniques and materials developed in the semiconductor industry, and face difficulties associated with widespread fabrication and the cost of devices. Recently, others have investigated the feasibility of using non-traditional nanofabrication techniques and materials to reduce costs and make devices that are easier to mass produce [2].

However, many of these cheaper polymer devices aren’t capable of matching the sensitivity of their Si counterparts. In this work we investigate how the sensitivity of polymer optical biosensors can be increased to match that of silicon devices and how polymers can provide other advantages in optical biosensing, including robustness and flexibility. Specifically, we use nanoimprint lithography as an alternative to traditional techniques and create porous polymer waveguides and ring resonators where biomolecules can interact directly with the core waveguide energy. Because the energy in the waveguide core is many...
times higher than in the evanescent field, we expect porous devices to be more sensitive to changes in the cladding solution than typical ring resonators.

Nanoimprint masters are fabricated on silicon wafers, by depositing a 2 µm film of silicon dioxide, spinning SPR 955 - 0.9 (MicroChem Corporation, Newton, MA, USA) positive photoresist on top, exposing on an i-line autostepper, and developing the resist. The resulting pattern is then etched into the silicon dioxide using fluorine gas based chemistry, and the remaining photoresist stripped off. Waveguides are then fabricated by depositing a 2-3 µm silicon dioxide cladding onto a silicon wafer, spinning a blend of polystyrene and polymethylmethacrylate on top, and imprinting using the master. Later, dimethylsulfoxide can be used to dissolve PMMA from the composite structure, leaving a porous polystyrene waveguide behind. Figure 1 shows characteristic scanning electron micrographs of an example porous ring resonator. Light is coupled into waveguides using a 1550 nm tunable laser, a lensed fiber, and a set of translational stages, and is coupled out using a lens to collect light leaving the waveguide. Microfluidic channels fabricated using traditional photolithography and PDMS-casting are used to deliver fluids directly to the resonators.

By varying the refractive index of the cladding solution and plotting the resonant wavelength of each ring it’s possible to determine the sensitivity of each device (Figure 2). Further, by comparing initial sensitivity results between both pure and porous polystyrene devices it’s possible to measure an approximately 20% increase in the sensitivity of the device, as shown in Figure 3.

We expect that an even larger change in the sensitivity of polymer ring resonators will be observed as we optimize the generation of pores in our devices. Further, we’ve recently fabricated resonators which we expect to have a higher Q-factor, allowing us to introduce more pores without reducing the rings’ ability to confine light significantly.

References:

Microring-Based Optical Pulse Train Generator

CNF Project # 1708-08
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Abstract:

Recently, we developed the concept of a new optical pulse train generator, based on microring resonators and the circuit technique of time interleaving. Here we report the experimental demonstration of a four-tap prototype fabricated on silicon-on-insulator (SOI) substrate.

Recently, we proposed a new microring-based optical pulse-train generator (M-OPTG) [1], as shown in Figure 1. Multiple microrings are coupled to the input trigger waveguide in series, and are used as compact couplers to divide the input pulse into multiple pulses. Meandering waveguides are inserted between stages as optical delay lines to introduce large stage delays, which determines the timing of the output pulses. The amplitude of the output pulses is controlled by the coupling coefficient of the microrings in each stage. Finally, the stage outputs are symmetrically combined to form a pulse train in the output waveguide. A four-tap, first order prototype is designed and fabricated on SOI substrate. We use rectangular ring resonators to control the stage coupling by changing the coupling lengths \( l_1 \) as shown in the inset of Figure 1. A test circuit without output combiner is also fabricated to measure each stage output separately.

To fabricate the device, we start with the SOI wafer, which has 250 nm thick top silicon and 3 mm thick buried oxide. Electron beam lithography is used to pattern all the structures due to the submicron waveguide cross section. The circuit patterns are then transferred to the top silicon layer by chlorine reactive ion etching (RIE). Thermal oxidation is then applied to further smooth the sidewalls. Finally, oxide cladding is deposited using plasma enhanced chemical vapor deposition (PECVD). The circuit is checked under scanning electron microscopy (SEM) after Si etching. As we can see from Figure 2, ring resonators with larger coupling length \( l_1 \) are used in the latter stages for a larger stage coupling. A close-up SEM image of the ring resonator in the first stage is also shown in the inset.

Summary of Research:

Microrings have become one of the critical building blocks in silicon photonics due to their ultracompact size, which enables large-scale electronic photonic integrated circuits (EPICs) to be foreseen in the near future. To overcome the fundamental challenge of the large potential bandwidth of photonics but the significantly lower speed of electronics in EPICs, we would like to explore microring-based EPICs more in their time domain properties and applications instead of many other wavelength-division multiplexing (WDM) approaches.
Figure 3 shows the results of initial time-domain measurement of the test circuit with separate stage outputs. Due to the limited 20 GHz optical bandwidth of our oscilloscope, the measured pulse width is broadened from about 20 ps to about 40 ps. However, the stage delay, which is measured as the timing between the output pulse peaks, is quite uniform for all the stages as shown in the inset of Figure 3. The stage delay is designed to be 25 ps and measured as 30 ps. The output pulses from the latter stage are smaller than the former ones, especially for the fourth stage. This is caused by the waveguide propagation loss as well as the shift of the resonant frequency of the microrings. Therefore, post-fabrication thermo-optic (TO) or electro-optic (EO) tuning capabilities are needed to improve the circuit performance.

To conclude, we demonstrate the prototype implementation of a four-tap, first order M-OPTG. Test circuit with uncombined outputs shows correct timings of the four output pulses with stage delay of 30 ps.

References:

Reconfigurable Photonic Systems from Optofluidic Waveguides

CNF Project # 1764-09
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Abstract:

The developments of two liquid-core / liquid-cladding waveguide based photonic elements — an optical switch and a signal attenuator—are presented for use in reconfigurable photonic systems. In this work, we were able to demonstrate the ability to couple light between conventional multimode optical fibers through interconnecting them with the liquid waveguide. Small scale flow control enabled the reconfigurable shape and position of the liquid waveguide yielding an attenuation range of 3.1-10.7 dB and a 1 × 2 sub-second switching system with a maximum coupling efficiency of 3.87 dB.

Summary of Research:

A reconfigurable system is one that can dynamically adapt its properties or function in response to an externally issued command or autonomously in response to changes in operational conditions. In electronics, the Field Programmable Gate Array (FPGA) [1] is the ubiquitous example of such a system in that it can provide “on-the-fly” reconfigurability. Despite the advantages, there are very few other microsystem based fields which have demonstrated technologies that exhibit anywhere near the level of reconfiguration possible through FPGAs. Recent developments in optofluidics [2,3] have demonstrated how incorporating microfluidic elements into photonic systems can yield much higher reconfigurability in their reflective indices. In this report, we demonstrate the use of high performance liquid-core/liquid-cladding waveguides to achieve optical attenuation and 1 × 2 switching in a fiber-in and fiber-out system.

The operating principle of both these devices is shown schematically in Figure 1(a). Briefly, in

Figure 1: Schematic views of (a) the optofluidic switch (upper) and the tunable modulator (lower) (b) experimental setup. (c) Output power as a function of the waveguide width for different channel lengths. (d) Fluorescence intensity from the liquid waveguide as a function of downstream distance. All figure images are regenerated from the paper “Optofluidic waveguides for reconfigurable photonic systems”, Optics Express, 19 (9), 8602-8609 (2011) © OSA.
both cases light is first coupled from the input optical fiber to the adaptable liquid-core/liquid-cladding waveguide. In the case of the switch the liquid waveguide is then directed to one of the two output fibers by changing the input pressure of one of the cladding flows. For the attenuator we modulate the power transferred from the input to the output optical fiber by adjusting the width of the liquid-core waveguide. This is done by increasing or decreasing the pressure of both cladding flows equally. Based on the power output for the 1.25 mm waveguide length shown here, the observed attenuation power range was between 3.1 to 10.7 dB. Figure 1(c) shows results for four different channel lengths: 1.25, 2.25, 3.25 and 4.25 mm. Regardless of the length of the liquid waveguide a linear response of the output power was observed as a function of the core width.

To characterize the loss in the liquid waveguide itself, we performed an experiment where the liquid waveguide was doped with a fluorescent dye and the change in emitted intensity was measured as a function of the downstream distance. Figure 1(d) shows the intensity profile for a 120 µm wide waveguide for two centimeters of propagation distance. With these results, we calculate the waveguide loss is 0.451 dB/mm. Figure 2(a) shows the optofluidic chip and optofluidic switching between the two states of a 1 × 2 switch is shown in Figure 2(b). Figure 2(c) shows the relationship between the measured output power and the switching period. The two output channels are represented by blue and red lines. As expected, when the switching period is decreased, the maximum output power is also decreased. The maximum coupled power for all switching periods is plotted in the inset of Figure 2(d). As can be seen, the quality of the switching also decreased for quicker switching periods placing an upper limit on the rate at which this technique could be used to reconfigure a photonic system.

References:
Advancements in Microfluidically Reconfigurable Photonics

CNF Project # 1764-09
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Abstract:
In this paper we describe two major advancements in the area of microfluidically reconfigurable photonics: the demonstration of a highly efficient fiber-in, fiber-out microfluidic switch and the use of fluid recirculation to enable indefinitely long operation without the need for fluid replenishment.

Introduction:
Although liquid-core/liquid-cladding waveguides (LWGs) have fundamental advantages over solid state components, such as reconfigurable structure, chemical adaptability, and thermal stabilization [1], they have not penetrated the commercial device market due to a number of significant hindrances; first, diffusion of liquids yields relatively high losses, and second, the systems require a continuous supply of liquids during operation. Here we suggest methods for solving these problems and experimentally demonstrate them.

Discussion:
To address the first of these problems, we have developed a liquid core fluid optic device that allows switching and controlled attenuation between an input and two output optical fibers. Our previous numerical results [2] showed that the coupling efficiency can be as high as 80%. Figure 1(a) illustrates the numerical result of the concentration and the electrical field profiles within the LWG and SWGs. Guided light in the LWG is coupled into the SWG starting at the middle of the micro-fluidic channel. We also experimentally demonstrated the end-fire coupling using an optical fiber similar to the numerical setup. As shown in Figure 1(b), we inserted the optical fiber into a micro-fluidic channel and coupled the light from the LWG made of CaCl$_2$ (n = 1.44) and DI water (1.33). We achieved the maximum coupling efficiency of 47% from the inserted optical fiber and less than 20 db cross talk.

Another issue with current LWGs is that liquids are consumed and have to be continuously supplied during the operation. Figure 2(a) shows the general LWG setup which consists of a micro-fluidic chip and liquid bottles that we have to fill and empty while running experiments.

Figure 1: (a) Left: concentration profile, Right: electric field profile. (b) The LWG on the top and the inserted optical fiber at the bottom. (c) Read an output through the inserted fiber.

Figure 2: (a) General setup of liquid waveguide. (b) Separation of water and oil in the reservoir. (c) Pump system that consists of external pumps.
Here we integrate a recirculation system into our chip in order to address this problem using immiscible liquids, water as a core liquid \((n = 1.33, \rho = 1000 \text{ kg/m}^3)\) and fluorinert® FC-72 oil as a cladding liquid \((n = 1.25, \rho = 1680 \text{ kg/m}^3)\). They are separated in a reservoir on a vertically placed chip as we can see in Figure 2(b) and recirculated by external pumps shown in Figure 2(c).

We also developed a single step fabrication using soft lithography to integrate all optical and fluidic components such as SWGs, micro-fluidic channels, and the reservoir on the chip. SU-8 photoresist is patterned on a SiO\(_2\) substrate to form the structures as represented in dark grey color in Figure 3(a) and (b). The SU-8 pattern is covered by a PDMS sheet to make micro-fluidic channels and the reservoir. Separated liquids in the reservoir are pumped by external pumps into micro-fluidic channels to make the LWG, and used liquids are collected and separated in the reservoir again and the cycle repeats. Meanwhile the light launched onto the input SWG is transferred to the LWG and finally coupled into the output SWG. The path of the light can be dynamically switched with a flow rate change. As a preliminary experiment we demonstrated that the LWG made of immiscible liquids can guide and switch lights as shown in Figure 3(c).

**Conclusion:**

We experimentally demonstrated the end-fire coupling between the LWG and SWGs. More importantly, we showed a recirculation system that can integrate all liquid components in a chip which can solve the most significant issue in the liquid wave guiding system.

**References:**


Measurement of Wavefront Aberrations of a Hard X-Ray Kinoform Lens

CNF Project # 1776-09
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Abstract:
We demonstrate that aberrations from a hard x-ray optic can be accurately measured at hard x-ray wavelengths, using phase retrieval with a moveable structure in the beam path. We induce aberrations on a hard x-ray kinoform lens through deliberate misalignment and show that the reconstructed wavefronts are in good agreement with numerical simulations. Reconstructions from independent data, with the structure at different longitudinal positions and significantly separated from the beam focus, all agreed within a root mean squared error of 0.006 waves. We additionally find that the kinoform lens under test satisfied the Marechal criterion for diffraction limited performance.

Summary of Research:
Existing and proposed new high-brightness x-ray sources need high-quality hard x-ray optics in order to focus x-ray-beams and thus create small x-ray spots. The nanosized x-ray spots can then be used to make spatially resolved measurements of samples in order to better understand the unique properties of materials at the nanoscale. Developing such high quality hard x-ray optics is an active research area. Imperfections or aberrations in the phase profile due to lens imperfections will prevent the user from obtaining the smallest spots possible.

Measuring the wavefront (a surface of points having the same phase) is a common method at optical wavelengths for testing the quality of surfaces and evaluating the overall performance and alignment of complicated imaging systems. If accurately measured, the deviation of the wavefront from an ideal sphere provides a quantitative map of the aberrations induced by manufacturing errors and/or misalignment of the optic.

Existing methods for measurements of aberrations at optical wavelengths are impractical or difficult at x-ray wavelengths, and as desired spot sizes become smaller, the aberrations need to be made correspondingly smaller. Clearly, the ability to accurately measure these aberrations is critical to realizing the full potential of bright x-ray sources to investigate materials at the nanoscale.

Currently, the most widely used method of x-ray-optics performance characterization is a series of knife-edge scans at different distances from the optic. From such measurements, one can extract the best focal spot size and distance. This method, however, does not contain direct information on the aberrations and is slow.

A phase retrieval method called “transverse translational diversity” or TTD was applied to measure wavefront aberrations. In TTD, the x-ray field of the focusing optic is perturbed with a known object placed at a diversity of transverse positions. At each position, the corresponding far
field diffraction intensity pattern is measured. The resulting data allows for a more robust resolution of the ambiguities typically present in phase retrieval data, with the ambiguities being especially severe for the one-dimensional case of conventional phase retrieval. The measured data is quickly processed using a computer algorithm to obtain the x-ray wavefront aberrations. This, in turn, can be used to optimize the alignment of the existing optic on-line or to improve the manufacture of future optics.

To test this new method, an aberration was deliberately introduced into the focusing set-up by rotating a one-dimensional-focusing kinoform x-ray optic away from its optimal position. Since the aberrations created by the rotation can be accurately predicted, the accuracy of their wavefront measurement method could be deduced. The new method is found to be rapid, accurate, and robust: independent measurements agreed within a root mean square of 0.006 waves. Additionally, the kinoform optic under test which was fabricated at CNF was shown to satisfy the Marechal criteria for mean squared deviation from perfect profile required for diffraction limited performance. Consequently, the lens errors are small enough that the spot size is not broadened by the errors, but just a reduction in the flux in the spot, and hence a reduced signal to noise ratio.

Acknowledgements:

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References:

Abstract:

In this report, we describe the fabrication and testing of three x-ray optics: a silicon nitride Transmission Mirror (TM), a Spoked Channel Array (SCA) and a von Hamos x-ray energy analyzer. Transmission mirrors together with traditional x-ray reflection mirrors form a tunable broadband optic which is useful in selecting appropriate x-ray energies for Laue diffraction experiments by acting as a bandwidth filter. The SCA optic is a fan-shaped arrangement of deep reactive ion etched channels in silicon made using the Oerlikon tool at the CNF. The channel width determines the linear size or collection resolution of x-ray fluorescence from the sample being probed. These measurements determine elemental composition vs. depth of the sample.

Summary of Research:

Transmission Mirror (TM). The objective of this project is to develop TM optics that are robust and have very long lifetimes. The critical parameters that determine the optical properties must satisfy the conditions of being thin, flat, smooth, and uniformly thick. In previous attempts, the TM lifetime was not long enough in the x-ray beam; lasting from a couple of hours with soap-bubble films to a day or two with Mylar films [1,2]. Si₃N₄ serves as the appropriate material because it has low atomic number and is a radiation-hard material. Low stress silicon nitride (LS-SiN) is deposited on a double-side polished silicon wafer. The window pattern is exposed and etched on the bottom side of the wafer using CF₄ gas at a power of 150 Watts at 30 sccm. The topside of the wafer is also patterned and etched with CF₄ to open the front ends of the window after which the whole wafer is etched in 25% TMAH at 80°C. After etching all the way through the wafer, it is bonded to a handle wafer via a 120°C heat cure of spin-on Cylotene BCB. The front ends are then broken off to release the mirrors.
Spoked Channel Arrays (SCAs). The technique of using x-ray fluorescence in obtaining elemental vs. compositional information from heterogeneous samples is the focus of this project. We build on our prior work in fabricating SCAs from silicon for confocal-XRF (CXRF) as an alternative to the glass polycapillary [4-7], which is used to efficiently collect x-ray fluorescence from a point source. Using deep reactive ion etching (DRIE), the channels are fabricated in silicon as seen in Figure 2. Our optic design consisted of three variations with the channel widths: 1, 2 and 5 µm wide channels. We also included a 1 µm thick sacrificial etch-wall at the entrance and exit of the channel to protect the integrity of the channels. The principle of operation as shown in the inset of Figure 3 shows the fan-shaped arrangement of the etched channels which collects a slice of the hard x-ray fluorescence from a point source. The point source is formed by focusing the x-ray beam using a single-bounce monocapillary. By translating the sample through the 3D active volume, a composition vs. depth information can be extracted from the sample as also shown in Figure 3.

von Hamos Analyzer. A von Hamos analyzer is used to collect, energy resolve, and spatially disperse x-ray fluorescence so a detailed line shape is recorded. This optic is being realized by cylindrical bending of a silicon-on-insulator (SOI) wafer. The scheme as seen in Figure 4 [3] is achieved by processing a slotted bar pattern on the handle side of the wafer by use of DRIE. The handle, used to diffract x-rays, is about 400 µm thick. It is etched down to the oxide stop layer using photoresist as an etch mask. The 40 µm device layer can then be bent to a radius as small as 100 mm to focus more intensity with no sacrifice to the energy resolution.

References:

Thermal Characterization of an Opto-Fluidic Photonic Crystal

**CNF Project # 1857-10**  
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**Abstract:**

We fabricated 1D photonic crystal resonators, which we expect to be able to trap down to 7 nm polystyrene spheres. We studied theoretically and experimentally the temperature rise of the optofluidic photonic crystal resonator and its consequences on particle transport and flow properties. We observe effects such as thermophoresis that affect trapping and sensing with such devices.

**Summary of Research:**

Photonic crystal resonators offer the possibility to confine and amplify light fields to sub wavelength geometries. These fields allow for trapping of nanoscale beads through the gradient force [1].

Building up on this technique [2] in order to achieve trapping even smaller objects, we numerically predicted the possibility of extremely high trapping stiffness and stability using 1D photonic crystal resonators [2]. We improved the design by inserting a cavity within the cavity in which the field gradient was particularly high and in which the particle is able to interact with the full field rather than only the evanescent tail. This method allows us to expect trapping stiffness as high as 69 pN nm⁻¹ W⁻¹ and a potential depth of 170,000 k_BT which represents an order of magnitude improvement on the literature. We find that the device can trap 7 nm polystyrene beads with very high stability and only 10 mW power consumption.

The photonic crystal resonator was fabricated on a 250 nm silicon-on-insulator wafer with 3 µm of buried oxide. The waveguides and resonators were patterned with electron beam lithography using the JEOL 9300 and an oxide resist (XR-1541), and the silicon was etched with a chlorine recipe in the Plasma Therm 770 (left chamber). Last, a 1 µm silicon oxide layer was sputtered (lift-off process) on the non-optofluidic components of the chip to protect the chip and reduce transmission losses.

Further investigating the behavior of an optofluidic photonic crystal resonator, we are interested in the thermal effects of the resonant silicon device on the particle transport. Water, in the microwave wavelength, has a high absorption coefficient that causes it to warm up under the influence of a silicon resonator. In particular, when one is to increase the interaction between molecules and electromagnetic field, the heat generation is also increased. The power lost to heat can be estimated by electromagnetic simulations. Given the volumetric heat generation coefficient, its impact on temperature and fluid flow can be solved numerically solving coupled Laplace and Navier-Stokes equations.

We compute the temperature increase in several of the devices we fabricated and verified experimentally our predictions. For the microcavity, we find a temperature increase of nearly 60K per Watt in the feeding laser as can be seen in Figure 1. We verified this temperature increase numerically and experimentally.

![Figure 1: Numerical temperature profile near an optofluidic photonic crystal resonator. The temperature is the highest in the central cavity where it can be increased by up to 57K. The numerical simulation was performed with COMSOL, a commercial Finite Elements Method. Bar: 500 nm.](image)
increase experimentally with a rhodamine B fluorescent measurement. The quantum yield of rhodamine B is temperature dependent so we can link fluorescent signal change to temperature increase. Numerical predictions and experimental measurements were in good agreement. The temperature increase is proportional to the absorption coefficient of the medium. We envision overcoming the temperature rise by changing the medium or the wavelength of operation.

The temperature increase changes the fluid flow, the particle transport properties and consequently the trapping or sensing capabilities. Numerically, we observe that the buoyancy force induces a negative pressure at the optical hotspot which in turn pinches the flow at the resonator. Experimentally, we do not observe this behavior when using lambda-DNA as flow tracer. We explain the difference by the thermophoretic coefficient and show that our corrected simulations match the observed flow very well. The agreement between the model and the experimental measurements is quantified in terms of concentration profiles around the resonator. We present in Figure 2 the results of the numerical prediction for the concentration profile of DNA near the cavity.

References:


Figure 2: Numerical concentration profile near an optofluidic photonic crystal resonator. The convective flow counterbalances the thermophoretic flow and leads to a depletion at the resonator and an accumulation in front of it. The maximum concentration is 3 times the bulk concentration whereas the concentration at the resonator is a billion times diluted. Simulation were run in COMSOL. Bar: 25 μm.
Highly Sensitive Spectroscopic Interferometers Using Photonic Crystal Structures

CNF Project # 1862-10
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Abstract:

We propose using slow light to greatly enhance the spectral performance of on-chip interferometers. We propose a calzone photonic crystal line-defect waveguide geometry, which can have large group index over a certain wavelength range. The geometric parameters of such a calzone photonic crystal waveguide can be optimized to meet specific demand in terms of group index and bandwidth. We fabricated the proposed waveguide structure on silicon-on-insulator platform using e-beam lithography and induction coupled plasma (ICP) etching.

Summary of Research:

Interferometric spectrometers are used for a wide range of applications in research and industry. The capability of an interferometric spectrometer to resolve closely spaced spectral components can be extremely important for applications such as analytic chemistry and biology. Meanwhile, planar integrated photonic devices are becoming more and more important because of their small footprint and easy integration of various functional modules to form various types of systems-on-a-chip. Thus, a miniaturized spectrometer with unprecedented spectral performance becomes desirable and can lead to a molecular and biological substance recognition system on a chip.

Slow- and fast-light technology [1] has recently attracted a great deal of interest, both in terms of fundamental and practical aspects [2-4]. It has recently been shown that slow light can be used to enhance the performance of various types of spectroscopic interferometers [5-10]. It has also been recently shown that by changing the width of a channel waveguide, one can enhance the group index by a factor of approximately 30%, which can be used for integrated dispersive elements such as arrayed waveguide gratings [11].

Figure 1: (a) SEM micrograph of a slab photonic crystal calzone line-defect waveguide with lattice constant a, hole radius r, and waveguide width w. (b) dispersion relations of the fundamental guided Bloch modes of a flat-band calzone line-defect waveguide with a = 403 nm, r = 0.3, and w = 488.6 nm; and (c) the corresponding reduced group index $n'_g$ as a function of wavelength for such a waveguide structure.
Regardless of specific geometries, we have recently shown [12] that the minimum spectral resolution $\delta \nu_{\text{min}}$ of a slow-light interferometer is determined by the quantity:

$$\delta \nu_{\text{c}} \equiv \left| c \alpha / (2 \pi n' g) \right|$$

Here, $\alpha$ and $n' g = n g - n$ are the loss coefficient and the reduced group index of the slow-light medium, where $n$ is the refractive index and $n' g = n + \omega dn/d\omega$ is the group index. To achieve a high spectral resolution, one would need a medium with large group index as well as small loss coefficient. Furthermore, the working finesse $F_w$ shows how many spectral lines a slow-light spectroscopic interferometer can resolve, and it is primarily limited by the uniformity of the group index and the loss coefficient near the center operating wavelength. Photonic crystal line-defect waveguides [13-17] are quite promising on-chip slow-light mechanisms, and have been widely used for various on-chip functionalities, such as delay lines, nonlinear optical interaction, sensing, and so on.

Here, we study a flat-band, slow-light calzone photonic crystal line-defect waveguide. Our geometry is based on a hexagonal lattice W1 line defect waveguide, in which one row of holes is removed to serve as the core of the waveguide. Besides that, the first rows on each side of the defect line are truncated into semicircles. Due to the shape of the first rows, we name our proposed structure “a calzone line-defect waveguide” following [18]. A schematic diagram of the waveguide structure is plotted in Figure 1(a). The design parameters include the width of the line defect $w$, the radius of the holes $r$, and the lattice constant $a$, and one can optimize these parameters such that group index has a plateau over a certain wavelength region, and therefore meet the needs for a desirable slow-light mechanism for specific spectroscopic applications.

For example, when $a = 403$ nm, $r = 0.3$, and $w = 0.7 \times \sqrt{3}a = 488.6$ nm, the calculated dispersion relation over the wavelength range near 1550 nm is shown in Figure 1(b). The corresponding reduced group index $n' g$, as a function of wavelength, is plotted in Figure 1(c).

One sees that for this design, there is a plateau near $\lambda = 1551$ nm over which the group index is approximately 60.

If one defines the working bandwidth by requiring that the group index does not change by more than 10% within the bandwidth, this example calzone waveguide structure has a working bandwidth of 3.2 nm.

References:

Nanoscale Photonic Biosensors from Biological Building Blocks

CNF Project # 1872-10
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User(s): Aadhar Jain

Affiliation(s): Mechanical and Aerospace Engineering, Cornell University
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Abstract:

In order to exploit the strong core field of an optical waveguide, we demonstrate a fully functional optical waveguide structure fabricated out of agarose hydrogel. We also show the capability of incorporating live cells within these optical waveguides and thus a new regime for optical biosensing and bio manipulation on the micro/nano scale.

Summary of Research:

In this project, we are looking to develop optical devices for biological applications using non traditional materials for fabrication. Specifically, the motivation is to use the strong optical field present in the core of an optical waveguide instead of the weak evanescent field available in traditional optical devices constructed out of semiconductor devices like silicon or glass. In order to achieve this, we use a biocompatible hydrogel, specifically agarose hydrogel, to fabricate the optical hydrogels.

Though there are other approaches to fabricating optical structures from hydrogels, they involve harsh methods like femtosecond lasers [1], which don’t allow for biological entities to be embedded inside the structure (which is necessary for exploiting the core field of the waveguides). On the other hand, fabrication process with agarose hydrogel is completely compatible for incorporating bio specimens [2].

Briefly, we use SU-8 masters fabricated in the Cornell NanoScale Facility (CNF) to mold PDMS stamps which are subsequently used to mold a molten solution of agarose (2% w/v) on an agarose hydrogel substrate (1.5% w/v), to obtain the required optical structure.

The final structure, shown in Figure 1, consists of a 1.5% w/v agarose hydrogel (index of refraction, n = 1.3342) as the substrate, a 2% w/v agarose hydrogel (n = 1.3357) as the core, and air (n = 1). A He-NE laser (633 nm, red) was subsequently used to couple to the hydrogel waveguides through an optical fibre to demonstrate a working optical waveguide, and can be seen in Figure 2. As a proof of concept experiment, cells (MDA-MB231 cancer cells) were incorporated inside the agarose waveguides, and were found to be viable using a Calcein AM live cell stain (Figure 3). In other experiments (results not shown), we also demonstrated the capability of embedding DNA inside the waveguides. We are now looking to explore the capabilities of the new platform and fabricate novel optical biosensing and bio manipulation tools which are cheap, implantable and more sensitive than other available devices.

References:


Figure 1: Agarose hydrogel waveguides with 1.5% Agarose Gel as substrate and 2% Agarose Gel as core.

Figure 2: Demonstration of a working hydrogel waveguide. A He Ne laser (red, 633 nm) was coupled into the waveguides using a multimoded fibre (from bottom right).

Figure 3: Cells inside optical waveguides: a) MDA–MB231 Cells (circled in red) stained with Calcein AM (live cell stain) embedded inside the optical waveguides. b) A cell (circled in red) interacting with a laser (488 nm) coupled into the gel waveguide.
Three-Dimensional Metallo-Dielectric Photonic Crystal Thermal Emission through Electrical Bias

CNF Project # 1880-10
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Abstract:

A five-layer three-dimensional metallo-dielectric photonic crystal is realized with cavity modes inside photonic bandgap. With electric bias at the voltage of 15 V, the narrow thermal emission exhibits at $\lambda \sim 2.83 \, \mu m$ with a full width at half-maximum of $\Delta \lambda = 150 \, nm$. The enhancement of thermal emission is about six times, compared to the blackbody radiation at temperature of $540 \, K$. This amazing result is made possible by a complete metallic photonic band gap in the infrared ($\lambda > 1.5 \, \mu m$) and intra-structure resonances.

Summary of Research:

It has been suggested that a photonic bandgap (PBG) structure may be utilized to modify a thermal emission spectrum. Lin et al. has experimentally demonstrated that the thermal emission of a three-dimensional (3D) tungsten photonic crystal was suppressed in the PBG and enhanced by 3 times near the band edge [1]. To have efficient thermal photovoltaic power generation, it is desirable to have a narrow-band spectrum with its radiation energy slightly above the electric band gap.

In this report, a five-layer 3D metallo-dielectric photonic crystal is experimentally realized with a complete PBG at wavelength $\lambda > 1.5 \, \mu m$. At a bias of 15 V, the photonic-crystal emission exhibits a peak at $\lambda \sim 2.83 \, \mu m$ and a narrow spectrum width of $\Delta \lambda = 150 \, nm$.

The 3D metallo-dielectric photonic crystal is composed of a five-layer gold modified-woodpile structure immersed in a dielectric material known as hydrogen silsesquioxane (HSQ). The sample is fabricated layer-by-layer using electron-beam (e-beam) lithography, metal deposition, lift-off process, and planarization. Figure 1 shows a top-view scanning electron microscopy (SEM) image of the five-layer 3D metallo-dielectric photonic crystal. The pitch is

Figure 1: A top-view SEM image of the five-layer 3D gold metallo-dielectric photonic crystal.

Figure 2: Measured reflectance, transmittance, and absorptance of a 3D metallo-dielectric photonic crystal.
600 nm, rod width is 200 nm, rod thickness is 160 nm, HSQ spacer is 300 nm.

Figure 2 shows the measured reflectance, transmittance, and absorptance of this 3D metallo-dielectric photonic crystal measured by Fourier transform infrared (FTIR) spectroscopy. The results show a narrow reflectance band well within the high-reflectance PBG with dip reflectance of 64% at a wavelength of $\lambda = 2.58 \, \mu m$ and a secondary peak of 53% at $\lambda = 2.81 \, \mu m$. Both dips represent intra-structure resonances. This physical origin of the propagating modes has been investigated in a metallo-dielectric photonic crystal by means of finite-difference time-domain (FDTD) modeling [2]. In Figure 2, the measured thermal emission spectrum at 15 V is shown. The thermal emission measurement is also performed using FTIR from 1-25 $\mu m$. The measured spectrum consists of a broad emission at $\lambda \sim 3-18 \, \mu m$ and a sharp peak at $\lambda \sim 2.83 \, \mu m$. The broad peak position thus behaves like a gray-body radiation. The sharp peak agrees with that of the resonance absorption. This agreement indicates that the peak is due to intra-structure resonances. The measured thermal emission spectrum of the 3D metallo-dielectric photonic crystal is compared with the computed blackbody spectrum at 540 K. The thermal emission at $\lambda \sim 2.83 \, \mu m$ is enhanced by six times.

In summary, a 3D metallo-dielectric photonic crystal is electrically excited and exhibits a narrow thermal emission peak with a full width at half-maximum of $\Delta \lambda = 150 \, nm$ at $\lambda \sim 2.83 \, \mu m$. The enhancement factor is six times, compared to blackbody spectrum at 540 K. This finding is attributed to a complete metallic photonic band gap in the infrared ($\lambda > 1.5 \, \mu m$) and intra-structure resonances.

References:

Abstract:

Silicon is the primary material used for the fabrication of solar cells and it is responsible for about 40% of the cost [1]. Metamaterials show promise in enhancing the performance of silicon solar cells thus, improving the efficiency. Here we report on the fabrication of a broadband, antireflective, conductive metamaterial capable of channeling light into a solar cell. As a precursor to making the metamaterial, standard p-n junctions were fabricated. Conventional phosphorus oxychloride furnace diffusion was used to create the p-n junction. The metamaterial, consisting of periodic apertures, capable of channeling light, was placed atop the p-n junction and characterized.

Summary of Research:

For solar cells, the advantage of using conductive metamaterials, in addition to producing antireflective properties, is that they provide sufficient geometric cross section for high electrical conduction. Metamaterials are also capable of trapping light within a solar cell for increased photocurrent generation.

To evaluate the performance of our metamaterial, standard p-n junction cells with typical metal grid contacts were fabricated, in order to compare the electrical and optical properties of the standard grid contact solar cells with that of our metamaterial's. Upon completion of p-n junction process either metal grid contact or the metamaterial was placed atop the silicon substrate. For the grid contact option, aluminum and platinum were deposited using an e-beam evaporator. Lastly, the grid contacts were annealed and the cells were tested. Current-voltage probe data was taken both prior to annealing the grid contacts and after annealing the grid contacts. From the measurement taken prior to annealing and with zero illumination, the p-n junction exhibited exponentially increasing current with respect to linear increasing forward biased voltage and rectifying diode behavior was noted for reverse bias. This is the expected characteristic operation for the cell.

The annealing process performed on the fabricated device wafers improved the ohmic contact between the metal and the semiconductor material. When the metal was annealed above the re-crystallization temperature and cooled, the metal’s ductility and strength are increased. The annealing process was carried out in nitrogen and forming gas. It was observed that there was no significant increase in the photocurrent of cells that were annealed below or at 350°C, irrespective of anneal time or gas employed. Cells annealed at temperatures greater than 450°C demonstrated an electrical shorting of the p-n junction. The best anneal conditions were found to be at 400°C for 60 minutes with forming gas and at 450°C for 30 minutes with nitrogen gas.

In the case of the metamaterial, it was first designed and modeled using the Ansys, Inc., 3D High Frequency
Structure Simulator. The structure of the metamaterial shown in Figure 1, comprises an aluminum film, 172 nm thick with a periodic array of two apertures with radii of 192 nm and 383 nm filled with silicon oxy-nitride. Two apertures are used because they result in a wider wavelength of high transmission and serve as wavelength filters. Light-channeling waveguide modes of different energies are excited within the broadband and polarization-independent apertures thereby transmitting different parts of the solar spectrum into the substrate. Silicon oxy-nitride was chosen to be the dielectric material within the apertures due to its low optical loss and the ability to dial in its index of refraction by choosing the appropriate oxygen and nitrogen compositions. Silicon oxy-nitride was deposited using low-pressure chemical vapor deposition. The metamaterial, patterned using optical lithography, was placed atop a p-n junction cell and tested. Preliminary experimental characterization showed low reflection (less than 10%) and low diffuse backscatter of light into air. Low reflection observed between 700 nm and 1200 nm highlights very good agreement between the simulation and experiment as shown in Figure 2. In conclusion, we have developed a fabrication process for p-n junctions using a monocrystalline silicon substrate and a metamaterial electrode. From tests results, when forward biased, the measured current grew exponentially with applied voltage, and when reversed biased, a rectifying behavior was observed. From the annealing study, it was noted that annealing improves the ohmic properties of the metal contacts and increasing the thickness of the frontside metal improved the series resistance. Recent efforts have been focused on optimizing and characterizing the metamaterial’s optical properties.

Acknowledgments:
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References:
Nanomanipulation using Silicon Nitride Photonic Crystal Resonators

CNF Project # 1928-10
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Abstract:
Silicon nitride photonic crystal resonators are designed and fabricated for manipulating nanomaterials in aqueous solution. The electric fields are strongly confined by the photonic crystal resonators to provide high trapping stiffness. To minimize thermal heating in the cavity, which is usually a major problem in nanomanipulation using near-field nanophotonic devices, we use silicon nitride instead of silicon to fabricate the device and choose 1064 nm as the operating wavelength. Our preliminary results show that our device can trap nanomaterials that are very difficult to be trapped by other optical trapping techniques.

Summary of Research:
We designed and fabricated silicon nitride photonic crystal resonators for trapping nanomaterials in solution. Trapping and manipulating micro- and nano-objects becomes increasingly difficult when the objects are smaller. The fact that the spot size of a focused laser beam is limited by diffraction limits the trapping stiffness of conventional optical tweezers. Therefore, the useful range of optical tweezers has been limited to dielectric targets with sizes larger than about 100 nm. To overcome this limitation, various kinds of near-field nanophotonic devices [1-3] have been developed to provide trapping stiffness that is higher than that of conventional optical tweezers. The problem of many of these near-field optical trapping devices is that significant thermal heating is generated at the trap point [3]. Thermal heating is an important issue when we want to trap and manipulate biomolecules in aqueous solution because biological targets can be damaged even at moderate temperature increases. In addition, our earlier trapping experiments conducted with silicon photonic crystal resonators show that thermal effects caused by the highly localized electric fields can prevent nanoparticles from coming to the cavity and thus made trapping difficult [2].

To provide high trapping forces while minimizing thermal heating, we have developed a near-field optical trapping device based on photonic crystal resonators that operate at 1064 nm. Although almost all silicon-based photonic crystal resonators demonstrated so far were designed to operate at a wavelength of ~ 1550 nm, we chose 1064 nm as the operating wavelength of our device to reduce heat absorption in water (Figure 1). In addition, we used silicon nitride instead of silicon to fabricate photonic crystal resonators and waveguides because of the consideration of energy loss at 1064 nm. The reduced thermal heating not only makes trapping of nanomaterials more feasible, but also reduces the possibility of damaging biological targets in a biological experiment.

Figure 1: Absorption spectrum of water.
To achieve high confinement and amplification of the optical fields, our silicon nitride photonic crystal resonator has 53 holes of different sizes on either side of the cavity to form a pair of modulated Bragg mirrors. The sizes of the holes were designed by following the deterministic design method proposed by Quan et al. [4]. In addition, a small hole is added to the center of the cavity to enhance the field gradient [5]. According to the results of finite-difference time-domain simulation, the quality factor of our resonator is about 5000, and the mode volume is about $4.4 (\lambda/n)^3$. As shown in Figure 2, the field intensity is significantly enhanced within the center hole, which leads to high trapping force.

To experimentally verify our designs, we fabricated the silicon nitride photonic crystal resonators and the waveguides that couple light to and from the resonators (Figure 3). Stoichiometric silicon nitride is deposited using the low pressure chemical vapor deposition process on silicon wafers that have 3.5 µm of thermal silicon dioxide on the top. MaN-2403 electron beam resist is spun on the wafer and then patterned with an electron beam system. The silicon nitride structures are defined by inductively coupled reactive ion etching with the electron beam resist as the mask. A sputtering system is then used to deposit an oxide layer of 3 µm on most of the wafer except for the regions where the resonators are. This oxide layer, which is patterned using the lift-off process, functions as the cladding layer of the waveguides. Since we want the fields in the cavity to interact with particles to be trapped, we do not cover the resonator with a silicon dioxide layer.

Our preliminary results show that we can use our silicon nitride photonic crystal resonator to trap 22 nm polymer spheres, Lambda deoxyribonucleic acid (DNA), and quantum dots, which are very difficult to be trapped by other optical trapping techniques because of their small size. Figure 4 shows that 22 nm fluorescent polymer spheres are trapped by the resonator when they are in close proximity to the resonator. The spheres can be released from the resonator when the laser is switched off.

References:

Creation of Magnetic Janus Particles

CNF Project # 1947-10
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Abstract:
The goal of this project was to create magnetic Janus particles compatible with optical trapping by depositing a thin film of cobalt onto partially masked microspheres. A monolayer of the microspheres (ranging in diameter from 110 µm) was assembled onto a silicon substrate and pressed against another silicon substrate coated with S-1813 photoresist. The top silicon substrate was removed from the ‘sandwich’ to expose a monolayer of particles with approximately 20% of their surface area exposed while the remainder was encapsulated by the resist. The samples were then placed inside the e-beam evaporator. A 5 nm chromium adhesion layer followed by a 20 nm cobalt layer was evaporated onto the sample. The photoresist contained in the sample was removed with MF319 developer and gentle sonication to release the metal capped Janus particles.

Summary of Research:
With this research we hope to develop a new class of optically and magnetically controllable micro particles that can be used to apply prescribed torques and forces for force spectroscopy. Previous research produced 10 µm polystyrene particles, which functioned well in an optomagnetic trapping system [1]. However, because this diameter is on the fringes of the Mie regime, smaller diameter particles are necessary to improve behavior and system dynamics. We created a monolayer of 3 µm silica microspheres on a silicon substrate and then pressed the monolayer against another silicon substrate coated with S-1813 photoresist. The top silicon substrate was removed from the ‘sandwich’ to expose a monolayer of particles with approximately 20% of their surface area exposed while the remainder was encapsulated by the resist. As before both a 5 nm chromium adhesion layer and a 20 nm cobalt layer were deposited onto the sample. The photoresist contained in the sample was removed with MF319 developer and gentle sonication released the 3 µm metal capped Janus particles. The scanning electron micrograph in Figure 1 clearly shows the cobalt cap on the particle.

We are currently testing the 3 µm capped Janus particles in our optomagnetic system to access both compatibility and control. In addition we are working to improve the methods and throughput of the particle synthesis scheme. Continuing and future characterization will lead to an optimized particle which may be used for high resolution force spectroscopy.

Figure 1: Scanning electron micrograph of a Janus 3 µm silica particle. The circular surface deposit is composed of cobalt and covers an area of less than 20% of the particle’s surface area.

References:
Improvements of the Sensitivity of the High-Field Electron Paramagnetic Resonance Spectrometer Using Nanofabricated Mesh

CNF Project # 1973-10
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Abstract:

Sensitivity of 1 mm electron paramagnetic resonance spectrometer depends on critical coupling reached at the entrance of the resonator for different samples. An invented asymmetric mesh [1] was made using laser cutting and it worked perfectly at 95 GHz and 170 GHz electron paramagnetic resonance frequencies. However, at 240 GHz the wavelength is small enough that the imperfections of the manufacturing (see Figure 1) do not allow to use it for the samples with different losses using the same principle as the meshes in [1].

Summary of Research:

Using nanofacilities at Cornell University, a similar mesh was made using lift off procedures from silver put on the fused silica substrate (this material has no electron paramagnetic resonance signal).

Usage of the mesh outlined allowed to use the same tuning procedures as for 170 GHz and 95 GHz, where laser cutting of the mesh out of nonmagnetic stainless steel was proved to be a successful solution (probably because the accuracy of laser cutting is enough for wavelength of 2 mm, which corresponds to 170 GHz and 3 mm, which corresponds to 95 GHz).

In addition to this expected advantage, the signal to noise ratio was found to increase 2-3 times. During the previous work with stainless steel mesh, this ratio was already risen perceptibly and no increase was expected, that is why this increase is associated probably with higher quality of the resonator. (See Figures 3 and 4 for comparison.)

From the comparison of Figure 3 and Figure 4, it is possible to see the influence of the quality of the mesh (the mesh serves as the lower mirror in the resonator) to the quality of the spectrum. This improvement would be obvious for optical spectroscopy where the accuracy is comparable to wavelength, but for the case of microwave it may be explained as the consequence of the lesser amount of higher order harmonic excitation in the resonator, which ultimately leads to better profile of the fundamental mode of Gaussian beam.

References:

Figure 2: Photo of the mesh made with nano accuracy.

Figure 3: Electron paramagnetic resonance spectrum of biological sample recorded with old stainless steel mesh.

Figure 4: Electron paramagnetic resonance-spectrum of the same sample recorded with nanofabricated mesh.
Demonstration of an \textit{n-i-p-i} Photovoltaic Device

\textbf{CNF Project # 1989-11}  
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\textbf{Abstract:}

The fabrication of multi-period GaAs \textit{nipi} doping superlattice solar cells has been demonstrated. A fundamental benefit of the doping superlattice is the modification of the band structure, resulting in the absorption of sub-bandgap photons. Multiple fabrication steps required in the fabrication of the unique design have been characterized. A device has been fabricated and tested, where quantum confinement has been demonstrated within the doping superlattice structure.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Schematic depicting \textit{n-type} and \textit{p-type} contacts grown in the v-groove's that are etched into the \textit{nipi} epitaxial layers, and the lateral majority carrier transport that results in charge separation. Right side of the figure provides a band diagram depicting the sinusoidal type energy levels in the active region.}
\end{figure}

\section*{Summary of Research:}

An \textit{n-i-p-i} device consists of repeating \textit{n-type} / intrinsic / \textit{p-type} / intrinsic doped (\textit{nipi}) epitaxial GaAs layers, that are stacked vertically to form a parallel connected multi-period solar cell. The layers form a sinusoidal-like band alignment due to the alternating \textit{n-} and \textit{p-type} dopants \cite{1} as shown in Figure 1. This design results in a high carrier extraction efficiency due to the predominantly drift field dependent minority carrier collection in the growth direction \cite{2}. Higher extraction efficiency is resultant from the band alignment, which quickly sweeps carriers through the junction prior to recombination as long as the designed spacing between each junction is less than the minority carrier diffusion length \cite{3}. The benefits of increased extraction efficiency can be further boosted by modifying the bandgap of the device through quantum confinement. Confinement will occur as the doping layers become increasingly thin, resulting in band formation above the conduction band of the \textit{n-type} material, which is confined between the two \textit{p-type} layers. Similarly, confinement also occurs below the valence band of the \textit{p-type} material. The effective bandgap that is formed as a result of confinement has a large degree of tunability, depending on device design parameters, such as layer thickness and doping \cite{4}.

The process used to complete the fabrication of the device requires multiple steps, and a novel method for contacting. Following epitaxial growth of the \textit{nipi} stack, it is required that contacts are formed to promote charge separation laterally in the device as shown in Figure 1. Given the lateral majority carrier flow in this device, it is necessary to contact the sides of the device with a method that is selectively ohmic and highly rectifying to the opposing sides of each doped layer. The approach utilized requires epitaxial regrowth to grow \textit{n-} and \textit{p-type} GaAs in etched trenches that naturally forms ohmic and rectifying barriers to the doped layers. It has been shown that the regrowth methodology is the preferred method for contacting the device \cite{2}, and has been investigated more thoroughly.

Devices with a \textit{nipi} epitaxial doping superlattice have been grown and fabricated. The design was chosen to demonstrate quantum confinement in thin \textit{nipi} periods. The device designed with thin \textit{nipi} layers has 12 repeats of a \textit{nipi}
stack with 50 nm thick doped and intrinsic layers, as shown in the SEM of Figure 2. Thin superlattice layers result in quantum confinement, in the troughs of the energy level diagram, while increasing the thickness of the layers would result in the device operating more like a traditional solar cell.

Spectral response was measured for the nipi device, as well as for a baseline pin solar cell and is shown in Figure 3, where the results were normalized to the peak response value. Spectral response results do show a significant boost in the overall response of the device. Integrating under the curve of the bulk response and the sub-band response shows that the percent increase due to quantum confinement in the integrated spectral response is 6.81%, which results in a 4.03% increase in the calculated $J_{sc}$ under AM1.5 conditions.

Device characterization demonstrates an absorption peak at 922 nm through spectral response, and photoluminescence. The photoluminescence data as seen in Figure 4 shows multiple additional peaks at lower energy levels, where states are formed in the superlattice. Due to the increased sub-band collection, the potential for the nipi device to provide a performance boost through a tailored bandgap has been demonstrated.

References:


