Nanophotonics for optical delay engineering

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The goal of this multidisciplinary project is to investigate nanoscale and sub-wavelength optical dielectric and semiconductor materials, nanoscale devices and monolithically integrated sub-systems with special focus on Nanophotonics for Optical Delay Engineering (NODE). Our approach is focused on the design, fabrication and characterization of geometrical (e.g. ring resonators, Fabri-Perot, etc.) and material (e.g. resonant transitions in quantum dots, novel metalo-dielectrics and novel nanomaterials) resonances for slow light applications. The media can be either linear, or nonlinear (e.g. Kerr effect). Our ultimate goal is to demonstrate chip-scale realization of a multistage optical delay architectures using nanoscale photonic materials and devices, taking advantage of the polarization degree of freedom.

Optical delay is important for various optoelectronic system applications including optical buffering for large optical data routing systems, true time delay phased arrays, and general digital optical signal processing architectures. On-chip integration of optical delay structures relies on our ability to construct and integrate nanophotonic components and devices realizing various functionalities such as coupling light from an optical fiber into the nanophotonic chip, on-chip control of polarization, modulation of the refractive index for tunability, and wavelength filtering. It should be noted that near field interactions between the various components on the nanophotonic chip need careful consideration and tools that can characterize near field optical amplitude and phase are essential. Hereby, we summarize some of the major achievements obtained during the first year of the project.

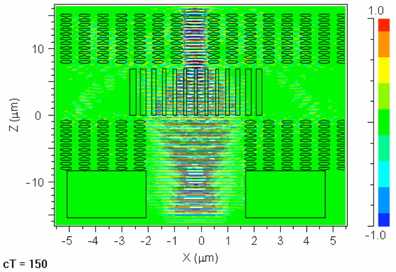
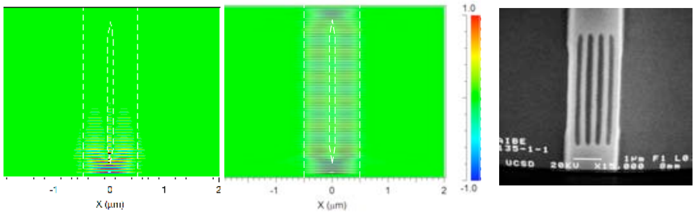


Fig. 1: Nanostructured lens for efficient coupling from a W5 PhC waveguide to a W1 PhC waveguide.



(a) (b) (c)

Fig. 2: Field distributions of the incidence waves with (a) TE_{00} and (b) TM_{00} polarizations, (c) SEM image of a nanoslot array waveguide in GaAs on AlAs.

For efficient coupling of light into the nanophotonic chip and between various on-chip components we investigated the implementation of novel graded index slab lenses made of nanostructures [1]. The slab lens is realized by etching a nanostructure into a slab waveguide made of high index material (e.g., Si, GaAs, etc.). The duty cycle of the nanostructures varies along the horizontal axis to control the local effective refractive index. Vertical confinement is provided by the high refractive index of the slab layer, similar to that of a two dimensional photonic crystal slab. With this configuration, large interaction length is achieved by propagating light along the nanostructure stripes. Fig. 1 shows simulation result of a slab lens that couples light from a W5 photonic crystal (PhC) waveguide (here W5 stands for PhC waveguide with 5 missing rows) to a W1 PhC waveguide. The minimal air gap features are set to <50 nm for optimization of phase matching. The simulation predicts coupling efficiency >90% with a device length of only ~7 µm. Coupling efficiency can be further increased by optimization of the nanostructure feature size and profile. We are currently working on the experimental demonstration of this device.

Most of the nanophotonic components are designed to operate with a specific state of polarization. To eliminate the orthogonal state of polarization, an integrated waveguide polarizer can be employed. A good polarizer is characterized by low insertion loss and high extinction ratio. We designed a novel TM-pass waveguide polarizer based on geometry-induced birefringence, by introducing a slot into the waveguide. With proper design, only TM-like mode is supported. For a slot waveguide with GaAs (n=3.37) core on top of AlAs cladding (n=2.95) the cut-off of the TE-like mode occurs for slot width larger than 20 nm. Increasing the slot width to about 100 nm is beneficial in terms of extinction ratio, since the TE-like mode leaks "faster" into the substrate making the device smaller. Fig. 2 shows TE-like and TM-like field distributions calculated for the optimized geometry of a waveguide polarizer with Y-branch of 3μm and slot width of 100 nm in a 20 μm slot length. As expected, TE-like mode is not supported by the waveguide providing extinction ratio better than 20 dB with minimal loss for TM-like mode. The approach can be extended by etching nanoslot array into the waveguide, allowing independent control over the propagation parameters for the two orthogonal polarization states (see SEM in Fig. 2).

Typically, characterization of nanophotonic devices is carried out in the far field, by measuring the transmission spectrum of light that is emitted from the structure. This approach does not allow investigating the near field interactions and evanescent coupling between various components on the chip. To overcome this limitation, we designed and built a heterodyne near field scanning optical microscope (NSOM), measuring the optical fields propagating inside the device with nanoscale resolution and with amplitude and phase information. This tool, working in the telecommunication frequency band, provides significant and detailed information about the optical properties of the nanoscale optical devices, interaction between their near fields, and greatly facilitates both fundamental understanding of their operation in the near field and improving their performance. Furthermore, as manufacturing technology advances and photonic systems achieve higher degrees of integration, localized in-situ characterization of optical fields will become increasingly useful and necessary.

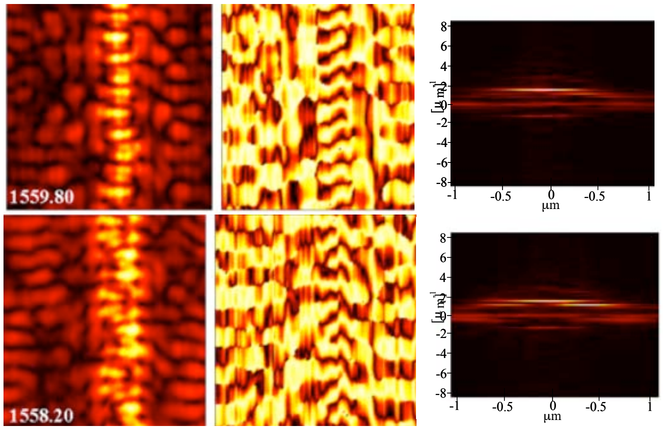


Fig. 3: Amplitude (left), phase (center) and 1-D Fourier transform (right) of the optical field propagating through the W1 PhC waveguide. Top raw was measured at λ=1559.8 nm and bottom at λ=1558.2 nm.

Using our NSOM tool we measured, for the first time, both amplitude and phase of optical modes propagating in a W1 PhC waveguide. The PhC lattice can be used as a platform for integration of optical delay circuits made with nanocavities. Also, the high field localization can give rise to enhanced optical nonlinear effects, allowing to overcome the delay-bandwidth product limits. Fig. 3 shows the propagation of an optical field in a W1 PhC waveguide, fabricated in a silicon membrane with lattice period of 496 nm, air holes of radius 190 nm, and a membrane thickness of 290 nm. The waveguide was created by removing a single row of air holes, thus realizing a W1 PhC waveguide. The guided modes amplitude and phase at different optical wavelengths have been detected (see Fig. 3). In the top raw of Fig 3 we observe a dominant even mode excited at the wavelength of 1559.8 nm while at the bottom raw we observe a mixture of even and odd modes excited at the wavelength of 1558.2 nm. This conclusion is substantiated by the availability of the phase information allowing to perform a 1-D Fourier transformation of the measured complex amplitude of the optical field along the propagation direction. The resulting spectrum shown in Fig. 3 (right) reveals experimentally measured propagation constants for the two dominant modes and their relative strength.

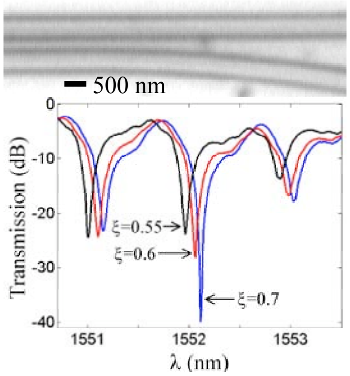


Fig. 4: Top-magnified image of the coupling region between the ring resonator and the bus waveguide. Bottom-Transmission vs wavelength. ξ stands for relative refractive index change in the cladding.

Ring resonator filters can be used for implementation of geometric-resonance based optical delay [4]. Since the sensitivity of such geometric resonance structures to fabrication tolerances is crucial for these applications we explore post-fabrication adaptive tuning the nanoscale coupling region and the cladding of the device. We designed, fabricated and characterized a tunable optical filter based on a bus waveguide coupled to a ring waveguide resonator located inside a microchannel of a microfluidic chip (see the SEM of the coupling region in Fig. 4). Liquid flowing in the microchannel constitutes the upper cladding of the waveguides and the refractive index of the liquid controls the resonance wavelengths and strength of coupling between the bus waveguide and the resonator. The refractive index is varied by on-chip mixing of two source liquids with different refractive indices. Fig. 4 (bottom) shows the optical measurements of the transmission through the bus waveguide. By fine-tuning of the refractive index of the fluid we demonstrate adjustment of the resonance by 2 nm and tuning to an extinction ratio of 37 dB on resonance. The delay can be tuned by controlling the coupling between the bus waveguide and the resonator which affects the Q of the cavity.

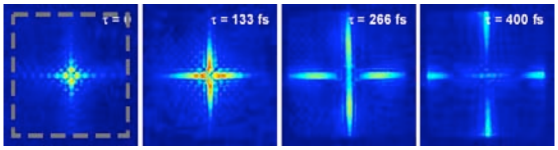


Fig. 5: Time confined 200 fsec SPP images as they propagate in the nanohole array in Al on GaAs

Optical delay can be also achieved by creating surface waves that reduce the group velocity, such as surface plasmon polariton (SPP) fields. We investigate modes in metal-dielectric nanostructures made of nanohole arrays in metal films of different thickness (20-100 nm) and nanohole diameter (50-300 nm) for various substrates (glass, Si, GaAs) [5]. We fabricated and used such structures to excite and image femtosecond SPP fields using a spatial heterodyne imaging method. The femtosecond pulses were used to excite the SPP fields in the middle of a 200x200 μm sample of 2D nanohole array in Al film on GaAs substrate. Fig. 5 shows snap shots of the femtosecond SPP as it propagates from the center towards the edges of the nanohole array, revealing the ultrafast electrodynamics of the SPP fields [6].

References

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