Hybrid Integrated Circuits

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The Science Vision for the Hybrid Integration Project is to create novel materials and 3-D optical structures that enhance the capabilities of photonic integrated circuits for optical processing; quantum technology and mid-IR science

The concept behind our hybrid photonic chips is shown in Fig. 1. We create complex circuits with a range of distinctly different functions by vertical stacking of layers of different materials. These may include simple passive layers fabricated from silica glass or polymers that interface to optical fibers; amplifying layers made of erbium-doped tellurium dioxide or chalcogenide glasses; and nonlinear layers made of chalcogenide glass for optical signal processing. Vertical tapers couple light adiabatically from the low index lower layers to higher index upper layer. Splitters, couplers, filters, etc are fabricated in the passive layer. To implement this concept and create efficient, complex circuits we must develop new materials and processing techniques.

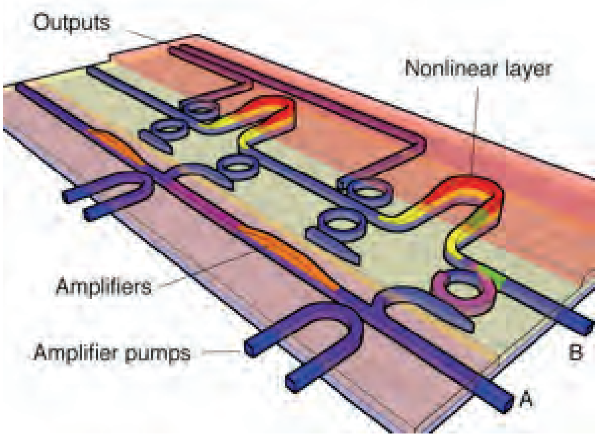

Fig. 1. The hybrid circuit concept being pursued by CUDOS involves vertically stacked layers of materials offering different functionalities coupled by vertical tapers. This example is creates a multi-channel all-optical demux.

The materials engineering and integrated platforms development integral to this project is conducted by the ANU and RMIT University CUDOS nodes. The project is focused on the creation of circuits and devices that support the objectives of all other flagship projects, so the team maintains strong ties to all of the nodes of CUDOS.

Progress

In 2011 the goals included the design and demonstration of low loss transitions between passive waveguides and tightly confined highly nonlinear waveguides, the development of new nonlinear glasses including those incorporating rare earth dopants for optical gain, and the demonstration of hybridized chalcogenide waveguides on an Er:TeO_2 amplifying layer that can compensate waveguide loss. Compensating the losses in nonlinear waveguides with gain will lead to an exponential improvement in performance of a nonlinear device.

We also aimed to demonstrate that second order nonlinear optical material can be deposited as thin films and formed using techniques that are compatible with inclusion into metamaterial nanostructures.

Vertical Taper Couplers

The key components for our approach to hybrid circuits are vertical taper couplers. Fig 2 (a) shows a taper coupling between high-NA optical fibre and a highly nonlinear waveguide. The red region is a polymer waveguide mode-matched to silica fibre, and the purple material is a highly nonlinear chalcogenide rib waveguide. The chalcogenide layer thickness is tapered to allow adiabatic transformation from the light between the polymer waveguide and the chalcogenide rib. Simulations indicate that the net losses should be well below 0.5dB per taper in realistic conditions.

We fabricated this tapered structure by introducing a shadow mask above the substrate during deposition of the chalcogenide layer. After processing of the chalcogenide, the SU8 layer was added and patterned using standard photolithography. The resulting structure is shown in Fig 2 (b). From measurements of the total losses of waveguides with different As_2S_3 length, we found that the total coupling loss at each end (due to both taper and mode overlap losses to the fiber) was 0.37dB – an excellent result. Because of the high loss of SU8 (≈1.5B/cm) the polymer waveguides need to be diced to be less than 1mm long to minimize the overall insertion loss. A dicing procedure is under development.

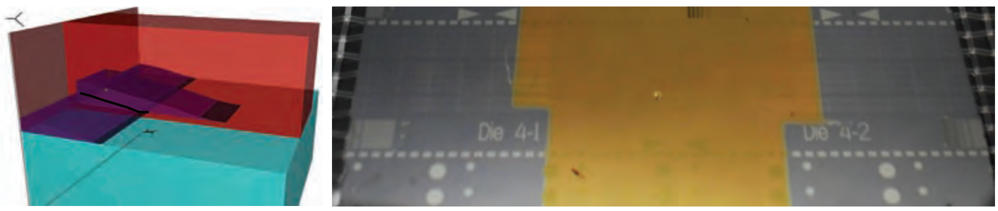

Fig 2. LHS, a schematic of a taper coupler used to convert a mode from a polymer waveguide matched to UHNA-3 fibre to a highly nonlinear As_2S_3 rib waveguide; RHS a photograph of the fabricated device showing the tapered chalcogenide layer (yellow) connected to SU8 input waveguides.

Co-thermal evaporation for deposition of novel thin films

One of our major objectives is to develop chalcogenide glasses with optimized compositions for nonlinear applications and which are doped with rare earths so that laser gain can be used to compensate waveguide loss. It is notoriously difficult to deposit rare earth doped chalcogenide films using conventional thermal evaporation, so the ANU-LP node of CUDOS has installed a new co-thermal evaporator containing five individually controlled furnaces, three sputter sources and one thermal source to deposit films directly by evaporating elements rather than bulk glasses. We successfully deposited Er-doped GeGaSe films, but found deficiencies in film morphology. We are now changing the furnace geometry.

Hybridized Chalcogenide and Erbium Doped Tellurite Waveguides

Another approach to achieving nonlinear chalcogenide waveguides with gain is to deposit a standard chalcogenide layer onto a slab waveguide amplifier. The light is guided by a chalcogenide rib, but part of the guided light extends into the amplifying layer. We explored this option by depositing an As_2S_3 chalcogenide nonlinear layer onto $Er:TeO_2$ film and then forming waveguides via lithography and etching. These composite waveguides were tested by co-propagating both a signal and pump beam through the composite structure. The first results showed that over a narrow range of wavelengths, zero net loss was observed which is very encouraging. For 2012, these waveguides will be optimized for net gain over a relatively broad range of wavelengths.

Hybrid Integrated Circuits Continued

Demonstration of Single Domain Strontium Barium Niobate (SBN) thin films

We are also interested in hybrid waveguides formed from materials with second order nonlinearity for parametric processes including second harmonic generation. One of the most popular second order materials is strontium barium niobate (SBN). SBN is usually in bulk form but in 2011 we demonstrated some of the world's first SBN thin films.

By definition, second order nonlinear materials exhibit a strong in built electric field that points in a particular direction. When such materials are first formed the material will typically exhibit randomly distributed domains where the in-built field points in opposite directions and thus must be 'poled' using a strong external field. We examined the domain structure of our 'as grown' films using piezoresponse force microscopy (PFM) (Fig 3a). This shows films of uniform, single domain without poling.

It should be possible to re-orient the domains in our thin film by probing the surface with the sharp, conducting top of the PFM tool and applying a sufficient voltage. By translating the tip and applying the voltage selectively, we created a structured domain pattern. Fig 3b) shows a PFM map of our thin film in which domains have been formed with sub-micron dimensions.

If these thin films can be formed into waveguides, then strong nonlinear behavior should be observed. These waveguides may even enable efficient generation of distinguishable, entangled photon pairs which would be valuable for on-chip experiments supporting the CUDOS Quantum Optics flagship program. Our work on these thin films so far has been published in CrystEngComm 14(2) 356-361 (2012); the demonstration of these films as waveguides is a 2012 milestone for the Hybrid Integration flagship project.

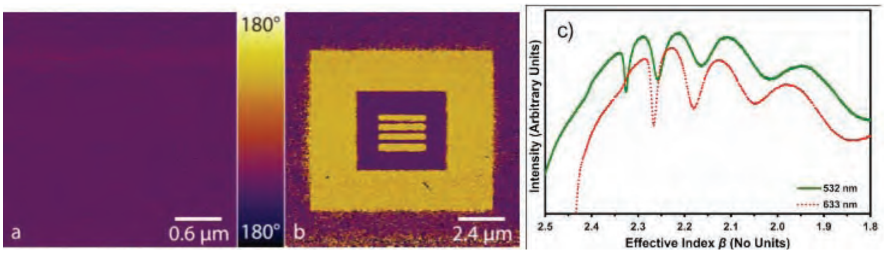

Fig. 3: Analysis of SBN thin from a) PFM showing as grown film is single domain; b) PFM after poling with an AFM tip showing nano-scale patterning of domains is possible; c) prism coupling results enabling measurement of thickness and refractive index.

Nanostructures for ferroelectric metamaterials

As a medium term goal we aim to fabricate metamaterial structures with integrated ferroelectric materials, to give tailored second order nonlinear behaviour and electro-optic tunability. We produced metamaterial structures using so called 'lift-off' lithography, which is compatible with the growth of ferro-electric thin films. A fishnet metamaterial structure was designed by researchers at ANU and generated in photoresist using a modified electron beam lithography technique developed at RMIT suitable for high-aspect ratio patterns. After patterning, a sequence of gold, magnesium fluoride and another layer of gold was deposited over the pattern and then the photoresist was removed, 'lifting off' the portions of the layers that were deposited over the top of the resist. The results are presented in Fig 4.

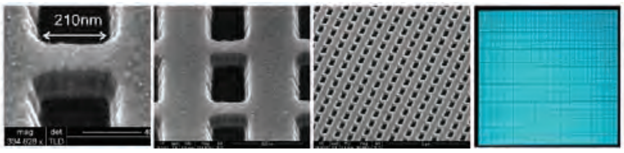

Fig. 4: Fishnet metamaterials fabricated using lift-off process – the dielectric (MgF) is clearly visible between the upper and lower gold layers. The fishnets cover a 4x4mm square which was fabricated overnight using the e-beam lithography tool at RMIT.

The multi-layer structure of the fishnet is clearly visible. A sequence of scanning electron microscope (SEM) images with reducing magnification is shown. The final image is an optical microscope image showing the entire array which covers 4x4mm. Such large area coverage will be important for the extraction of effective material parameters.

Other Activities

- The Hybrid Integration project was a new endeavour at the start of 2011. There were 9 journal publications produced that related to this project. Two were in journals with impact factor higher than six, a collaborative publication between RMIT and ANU utilising lithium niobate waveguide arrays to study the nonlinear behaviour of broad beams which appeared in Physical Review Letters, and particularly a review of Chalcogenide Photonics which appeared in Nature Photonics.
- Dr. Duk-Yong Choi, ANU-LP was awarded the Future Fellowship by the Australian Research Council. He will be working on silicon compatible light sources.
- Dr. Zhiyong Yang, ANU-LP was awarded the Discovery Early Career Research Award (DECRA) fellowship by the Australian Research Council, he will be studying integrated microcavity sensors operating at mid-infrared wavelengths.

Future Directions

In 2012, the Hybrid Integration project will aim to both refine results from 2011 and will also embark on several new investigations. The taper waveguides will be further refined while improved waveguides with these taper interfaces will be deployed to other flagship projects in CUDOS, particularly the Tb/s project. We will also explore whether similar tapers can be achieved in silica waveguides. With modifications to the co-thermal evaporator we aim to achieve improved film morphology and new films with Er or Ho doping. Fundamental studies on the properties of chalcogenide glasses will also continue leading to improved materials for waveguides in the mid-infrared. We will produce hybrid chalcogenide waveguides on Er:TeO_2 substrates with net gain over a wide range of optical wavelengths for nonlinear optics experiments in lossless nonlinear waveguides.

We will produce domain-engineered second order nonlinear devices with the SBN thin films being used to form waveguides. We will also investigate UV direct write methods for sub-micron domain engineering of lithium niobate waveguides. We will commence collaboration with our partner investigators at The University of Ghent to integrate our electro-optic thin films with their silicon photonic waveguides. We will also explore new concepts for hybrid integration of metamaterial structures with traditional waveguides.

We will also unify the approaches used across CUDOS for the design and simulation of waveguide devices. We will assess the available tools within CUDOS and compare these with tools used by our partner investigators and propose a unified approach.

Project Leader

Arnan Mitchell received the Ph.D. degree in Engineering from RMIT University, in 1999. From 1999 until 2004, he worked with the Australian Photonics CRC and the Defence Science Technology Organisation (DSTO) developing high speed modulator technology which was certified to military specifications and licensed to industry. He joined RMIT University as a Professor in 2004 and leads the micro-platforms research group comprising over 50 research staff and students. He is the recipient of the prestigious 2003 Victoria Fellowship. His activities span many fields of microtechnology with particular emphasis on the concept, simulation, materials engineering and realisation of novel waveguide structures in silicon, polymer and lithium niobate, providing unique platforms enabling experimentation in fundamental physics and branches of optical science and also applications in sensing platforms.

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