Mid-infrared Photonics

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Mid-infrared (MIR) photonics is a growing field whose primary concern is the creation, manipulation and detection of light at wavelengths longer than 1.5 μm. At CUDOS, we aim to move spectroscopy and sensing onto a chip-scale platform that will operate at wavelengths beyond those used for telecommunications. This is an ambitious project. The materials, waveguides and photonic devices must be designed and fabricated from the ground up, with many fundamental issues to be overcome before reliable and practical devices are realized.

Many chemical and biological materials have their fundamental absorption features in the MIR; hence light at these wavelengths is supersensitive to the presence of these materials. Thus, chip-scale mid-infrared sensors are compact, sensitive detectors. In astronomy, cooler objects such as planets, comets and asteroids come into view in the mid infrared allowing information about our solar system and beyond to be increased. The mid-infrared is an exciting area in science and at CUDOS we aim to access the possibilities that this region of the electromagnetic spectrum offers.

In 2011 we focused on the construction of MIR pump and probe sources for the integrated optics components. We also fabricated and tested chalcogenide and silicon-on-sapphire waveguides that will be the platforms for MIR integrated optical circuits. With our Partner Investigators, we studied photonic crystals in silicon that resonate in the MIR. These devices allow light to pass through the analyte many times, increasing the sensitivity.

Working in the MIR is significantly different to and much harder than working in the well established 1550 nm telecommunications window. Completely different infrastructure is required, so we established during 2011 a range of test facilities with unique capabilities for both passive and ultrafast nonlinear devices. We successfully fabricated MIR fibre and planar devices, although we encountered challenges achieving good guidance in fibres and low absorption losses. The project is in a strong position to attain a range of world first demonstrations in 2012 built on the achievements of 2011.

Progress

MIR chalcogenide device fabrication was based on two approaches: one, using an all-chalcogenide "low" index contrast buried channel waveguide platform for passive devices such as astrophotonic spectrometers and the other, a dispersion-optimised nonlinear platform based on chalcogenide on tellurite aimed at MIR supercontiuum generation (see Fig. 1). Devices of both types were successfully fabricated. We observed light guidance at 1550nm with reasonable losses, but not at 3.4 μm. There are several possible explanations. The design of the all-chalcogenide device depends on the glass dispersion for the core and cladding materials for which there is little available data in the MIR. A program to rectify this is now underway using MIR-capable scanning ellipsometers to obtain the required optical data. For the nonlinear platform, there appears to be OH contamination during the tellurite fabrication process which introduces significant absorption at 3.3 μm. Work is underway to eliminate this contamination. We expect to see successful implementations of both device types in 2012.

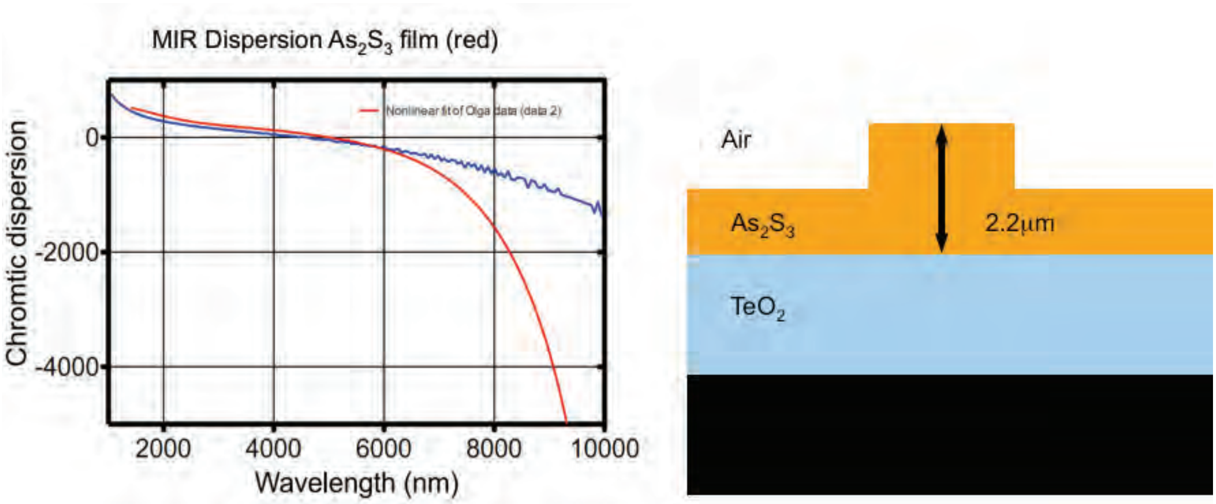
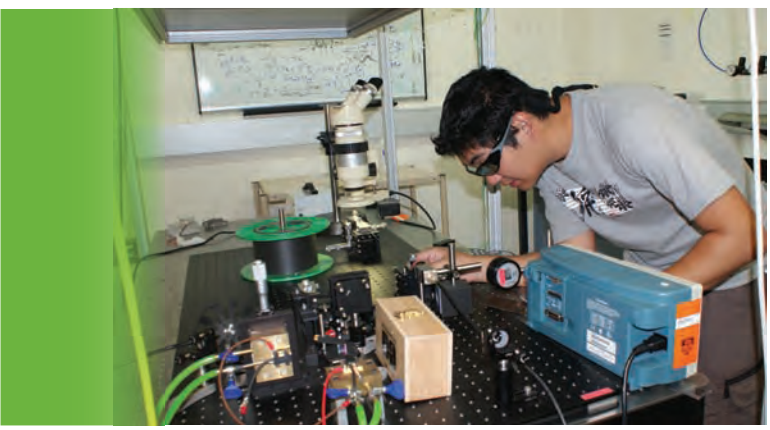


Figure 1 (a) Calculated dispersion of As_2S_3 waveguides in the mid-infared and (b) schematic of a As_2S_3 waveguide that employs a TeO_2 substrate.

Silicon-on-Sapphire (SOS) represents a significant opportunity as a platform for integrated photonic chips from 2 µm to 6 µm, since silicon and sapphire are both transparent in this wavelength range. We initiated a project to develop photonic chips in SOS for the mid-infrared with our industrial partner Silanna. We demonstrated low loss waveguides using comparatively thin (280 nm) silicon nanowires designed for the near and short-wavelength infrared regions (1.5 to 2 µm), where our measurement capabilities are well established. These results were achieved using stepper mask aligner lithography and were published in Optics Express. We fabricated thicker nanowires (500nm) that are more appropriate for mid-infrared wavelength propagation; these are currently under test. In parallel with this we designed and created photo-mask layouts for echelle grating spectrometers and Arrayed Waveguide Grating spectrometers in collaboration with overseas partners. These chips with their advanced structures will be fabricated during 2012 and should be the first integrated spectrometers based on SOS reported worldwide for the MIR wavelength range.



PhD student Tomonori Hu in the Mid-infrared Lab.

Mid-infrared Photonics Continued

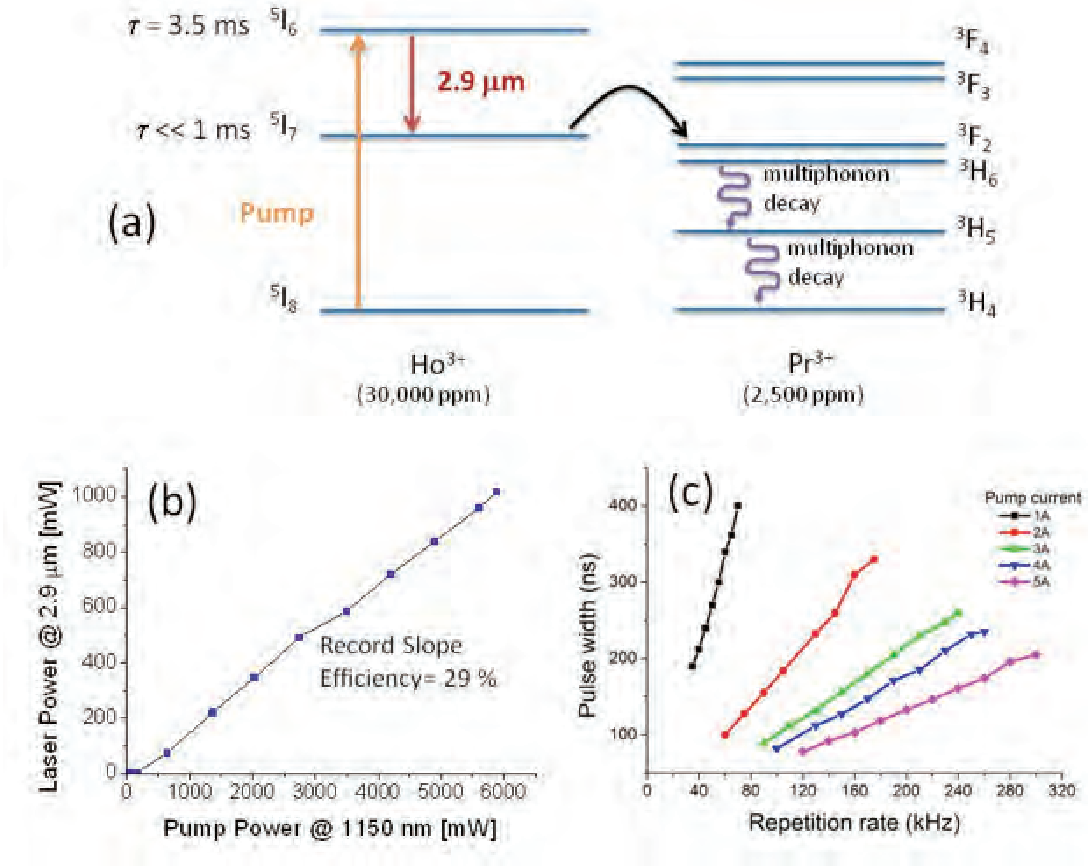


Figure 2 (a) Schematic diagram of the Ho^{3+}, Pr^{3+}-co-doped systems showing the pump, laser and energy transfer processes, (b) Output power vs input pump power of the tunable Ho^{3+}, Pr^{3+}-co-doped fibre laser at tuning range centre and (c) pulsewidths from a Q-switched Ho^{3+}, Pr^{3+}-co-doped fibre laser as a function of repetition rate of the acousto-optic modulator.

The creation and development of laser sources operating in the mid-infrared is critical. Traditional sources in this range rely on parametric processes including difference frequency generation. We took an alternative approach that promises to yield much higher and more robust performance using rare-earth doped fluoride glass fibres. Our studies in 2011 focused on fibre lasers based on holmium and praseodymium rare-earth ions, see Fig. 2(a). Using a co-doped holmium/praseodymium fibre, we achieved record slope efficiency for a tuneable 3 μm laser (Fig. 2(b)). This system incorporated wavelength dependent feedback (via a diffraction grating) for tuning over a large bandwidth (> 70 nm), had a narrow linewidth (< 1nm), and operated at high power (> 1 W average power). This system promises to be a useful tool in 2012 and beyond for testing our waveguide devices.

To produce peak powers sufficiently high to explore nonlinear optics in the mid-infrared, the holmium/praseodymium fibre laser system was Q-switched to produce bursts of mid-infrared light less than 70 ns in duration, a record for Q-switched systems at 3 μm, see Fig. 2(c). The output was coupled into dispersion-engineered selenide glass tapers that we designed and fabricated specifically for the excitation of nonlinear phenomena. We were unable to reach the threshold for nonlinear effects because of poor guidance in the fibre. We will repeat this experiment in 2012 with photonic crystal fibre whose numerical aperture will ensure much better guidance in the mid-infrared.

Our St. Andrews University partners created high Q cavities in 2-D photonic crystals (PhCs) structures in the mid-infrared using standard electron-beam lithography with chemically assisted ion beam etching on a silicon-on-insulator (SOI) platform. Cavity defects in two-dimensional planar PhCs can provide excellent spatial and temporal light confinement, enabling nonlinear optical effects to be excited at low power. A series of L3 cavities with shifted end holes of variable size were designed and produced along with more exotic cavities with engineered far-field radiation patterns for optimised vertical out-coupling efficiency.

We established a comprehensive MIR characterisation facility to probe these PhC cavities. We built a free-space vertical coupling setup based on resonant scattering method and an evanescent coupling setup using tapered chalcogenide optical fibres. In the resonant scattering method, the fundamental resonance of cavities is probed from vertical incidence using cross-polarised reflectivity, exhibiting Fano spectral response. In the evanescent coupling setup, the broadband light launched into a tapered fibre propagates along the fibre core, and couples evanescently to the cavity modes at the resonant wavelength.

We converted energy from near-infrared wavelengths to mid-infrared wavelengths using the nonlinear Soliton Self-Frequency Shift (SSFS) in a silica photonic crystal fibre (PCF), which had been carefully engineered to have an anomalous dispersion between 800 nm and 1900 nm. We used a specially annealed, low-OH loss fibre provided by Bath University to achieve a continuous shift of the input pulse (800 nm transform-limited 100 fs) over the entire anomalous dispersion range, well beyond the 1400 nm limit due to hydroxyl absorption seen in previous experiments. A dispersive wave feature was observed in the normal dispersion regime at 2040 nm. Up to 22% of the photons incident at the input facet of the PCF were shifted to the final soliton (at 1708 nm), containing 52% of the energy incident in the PCF.

Chalcogenide fibres (As_2S_3, As_2Se_3) are a superb platform for mid-infrared photonics due to their transparency from the visible to MIR wavelengths. Chalcogenides are also photosensitive: their refractive index changes after exposure to visible light. We have exploited this property of As_2S_3 glass fibre to create functional passive filters operating at mid-infrared wavelengths. In particular, we are interested in photo-inscription of short period Bragg gratings in As_2S_3 fibres that reflect light in the range 3 µm to 5 µm. These long spatial period gratings are expected to be more stable and less sensitive to fibre non-uniformity or fabrication defects than gratings fabricated for operation at shorter wavelengths. We illuminated the As_2S_3 fibre core with red light and observed a refractive index change on the order of 0.001. This index change is sufficient to fabricate reflection filters with extinction ratios of over 3 dB.

Highlights

1. We achieved the lowest reported loss at 1.5 µm and low loss guidance at 5 µm in silicon-on-sapphire waveguides.
2. We reported the most efficient 3 µm tunable fibre laser.
3. We generated an octave of radiation in the infrared from a record low pump power.
4. We produced the first high power fibre laser operating at wavelengths >3 µm.
5. We demonstrated a record soliton self-frequency shift.

Future Directions

In 2012 we will taper chalcogenide PCF and pump the tapers with a picosecond mid-infrared source to excite nonlinear phenomena in the MIR. We will create shorter, picosecond pulses in the mid-infrared using active mode-locking of holmium, praseodymium co-doped fluoride fibre. We will design and manufacture a mid-infrared resonant cavity defect with a high-Q factor and couple light efficiently into the resonant cavity defect to achieve excitation of cavity nonlinearities at low pump power. We will fabricate and characterise cavity structures optimised for higher vertical out-coupling efficiency in the far-field radiation pattern by modifying the size of the holes. Far-field optimised cavities allow larger collection of higher order harmonics generated from the mid-infrared light source.

Project Leader

Stuart Jackson received the BSc and the BSc(Hons) degrees in 1989 and 1990 respectively from the University of Newcastle (Australia). In 1990, he joined the Centre for Lasers and Applications at Macquarie University to undertake research toward the PhD degree, which he received in 1996. In 1995, he joined the Laser Photonics Group at the University of Manchester and initiated the research at the group into high power fibre lasers. In 1999 he joined the Optical Fibre Technology Centre at The University of Sydney where he became a Senior Research Fellow and Technical Manager of silica fibre fabrication. In 2009 he joined the School of Physics at The University of Sydney as a Queen Elizabeth II Fellow. His interests include diode-pumped solid-state lasers, spectroscopy, nonlinear optics and integrated optics.