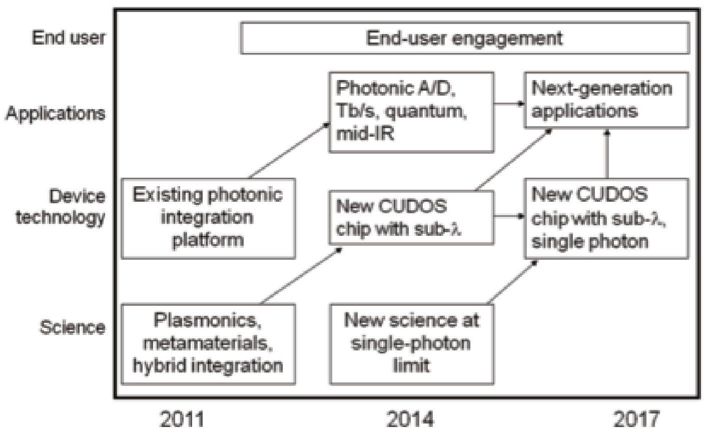
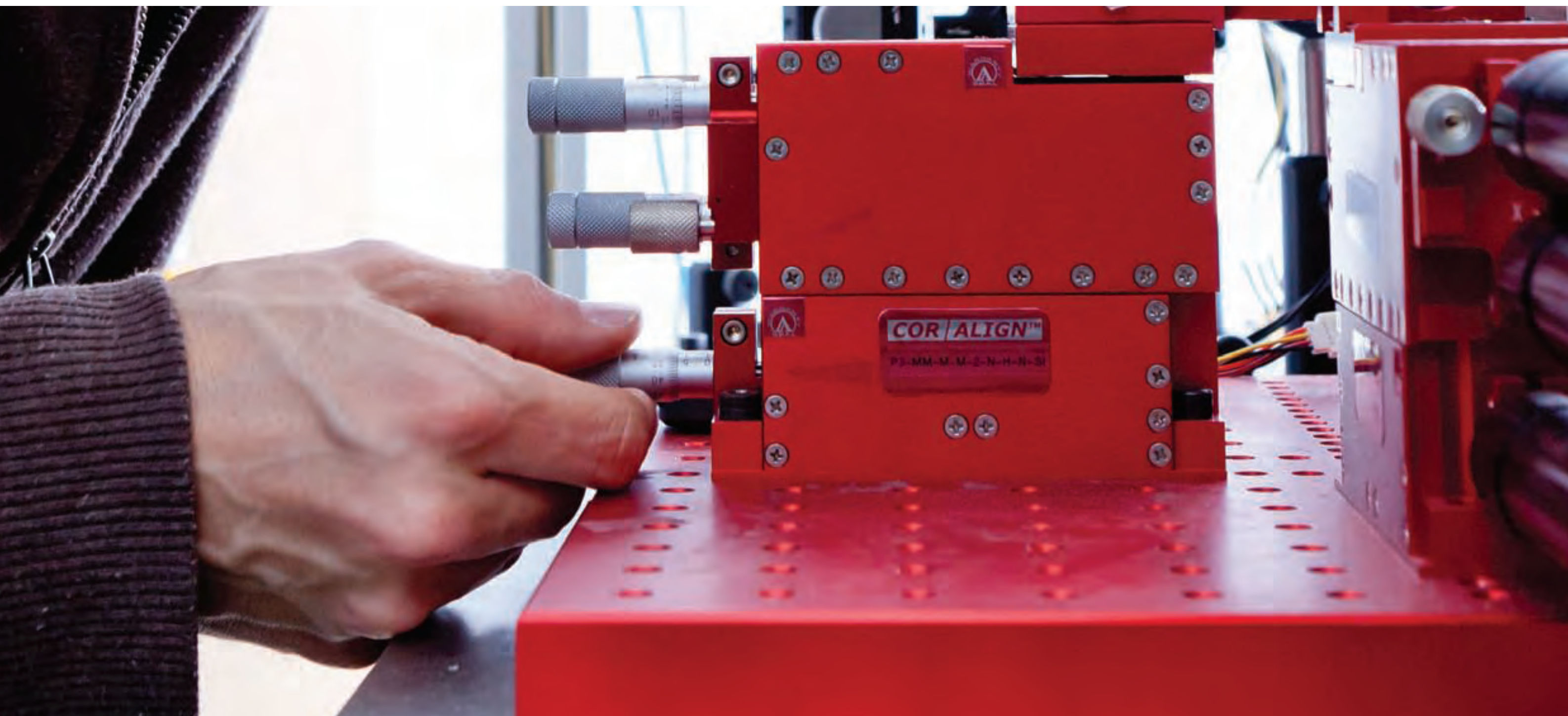
Research Overview

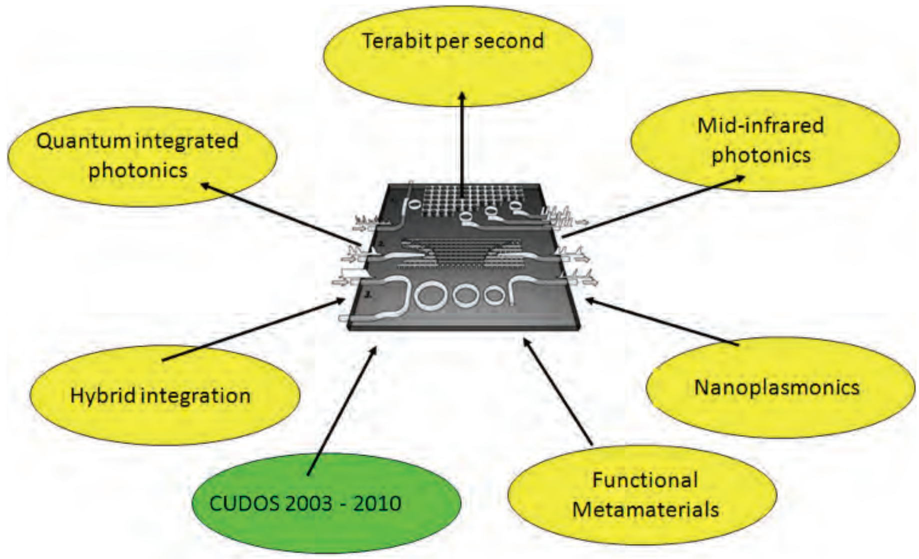
Our 2011 research program takes our photonic integration platform and science base in nonlinear photonics into new areas of opportunity: quantum integrated photonics, mid infrared photonics, and novel encoding and optical transport technologies for ultrahigh speed photonic signal processing. Concurrently with this, we are initiating new programs of fundamental research on novel, optically-engineered synthetic materials called *metamaterials*, on sub-micrometre optical elements based on *nanoplasmonic* structures, and on techniques for the *hybrid integration* of different materials (each with optical properties specific to an optical function) into one monolithic photonic platform.



This strategy is demonstrated in the schematic. It shows two parallel evolutionary paths for our research: in one, our existing photonic platform will progress via focused projects in areas of end user interest towards eventual implementation; in the second, a new program of fundamental research will be initiated, leading over time to a new generation of photonic circuits operating at single photon levels and with behaviour determined by sub-wavelength structuring of the optical material.

In this section we introduce each of the flagship project areas in the new Centre. Our three new applications-oriented projects (quantum integrated photonics, mid infrared photonics, and terabit per second communications) derive their strength from an advanced photonic integration platform built on skills, knowledge, and facilities built up during the first eight years of the Centre ("CUDOS I") and new research in hybrid integration, metamaterials and nanoplasmonics. The outcomes of our programs at the conclusion of our first year of operation are presented in the subsequent sections of this Annual Report.





Functional Metamaterials and Nanoplasmonics

Metamaterials are artificial optical materials engineered at sub-wavelength scales through which light propagates in ways starkly different from those found in nature. Nanoplasmonic structures are similarly engineered at the sub-wavelength scale, and contain metallic constituents that serve to concentrate the field and provide a response to the magnetic as well as the electric field of the optical wave.

Metamaterials can be designed to have negative refractive index, leading to such phenomena as a perfect lens and to cloaking (à la Harry Potter). This extraordinary behaviour occurs because the optical wave does not interact just with the bulk material or materials from which the metamaterial is made, but with periodic structures within the metamaterial whose dimension is of order the optical wavelength or less.

Our interests in this field lie in the ability to first develop metamaterials to pre-determined dispersion characteristics, rather to accept what nature gives us. This *functionalisation* would be an enormously powerful enhancement to our photonic integration platform. Second, we aim to establish international leadership in the entirely new field of nonlinear metamaterials. Finally, we aim to exploit the special properties of metals, in particular their extremely high refractive index and their magnetic response to the electromagnetic field.

We aim to develop the tools and capabilities to fabricate metamaterials and nanoplasmonic structures whose properties are engineered for the near infrared, around 1.5 μm. This is no mean task; the wavelength of light inside the high index materials we use to fabricate the metamaterials is typically around 500 nm for dielectric materials and down to less than 100 nm for metals and the dimensions of the structures we need to fabricate are smaller than this. Electron beam lithography is one approach; an exciting new alternative based on Stimulated Emission Depletion (STED) microscopy is under development within the Centre. STED is an outgrowth of confocal microscopy, an area in which Centre researchers have substantial expertise and facilities.

Hybrid Integration

A true photonic integrated circuit will combine many different functions, some linear (photon transport, dispersion management) and some nonlinear (amplification, wavelength shifting, optical switching). There is no one material that can support all these and so any monolithic photonic device must integrate the different materials that are capable of supporting the range of functions required. In a quasi-planar geometry one might envisage different sections of the substrate being composed of different materials, and researchers have demonstrated some simple integration of materials using this approach.

This problem has been solved elegantly in microelectronics, where lithography and thin film deposition technology combine to create multi-layered structures with electrical connections between them to transport electrons between different layers of material. We plan to use this approach to create three dimensional photonic circuits using deposition of different layers of material. The different layers will give us the range of functions we require. To couple light between layers we will fabricate vertically tapered couplers using area-selective deposition.

At the same time we need to broaden the range of optical materials at our disposal. Using a range of approaches we will create, optimize and hybridize new amorphous materials for linear, active and nonlinear waveguides. The properties of these materials will be superior to those currently available and match the requirements for effective practical integrated circuits.

Research Overview Continued

Quantum Integrated Photonics

Photons are natural candidates for qubits (bits of quantum information as opposed to binary bits) because they interact weakly with their surroundings and so carry quantum state information over long distances. This strength forms a formidable barrier to actually using such qubits, since ultimately they need to be combined and the resultant states measured to retrieve the information. Furthermore, most optical sources produce many photons using stochastic processes, whereas qubits are produced deterministically in numbers that are sufficiently small that they can be interrogated and processed one at a time.

CUDOS has commenced a program to address these both challenges. We will use nonlinear photonics to produce correlated pairs of single photons by four wave mixing at very low powers in our nonlinear optical waveguides. One of each of these photon pairs can be used as a trigger for the interrogation of the second, single photon. To process this, we will build on the achievements of our laser writing group in CUDOS I to produce planar circuits with the combination of splitters and beam recombiners needed to form an integrated quantum logic circuit.

Mid-infrared Photonics

The CUDOS integrated photonic circuits have been developed mainly for use at the telecommunications wavelength band around 1.5 µm. In principle this technology should be adaptable to longer wavelengths provided the materials used in the circuits still transmit light. Our two principal research materials, silicon and chalcogenide glass transmit well into the mid infrared. Chalcogenide glass (depending on the composition) transmits light of wavelengths up to 10 µm and beyond.

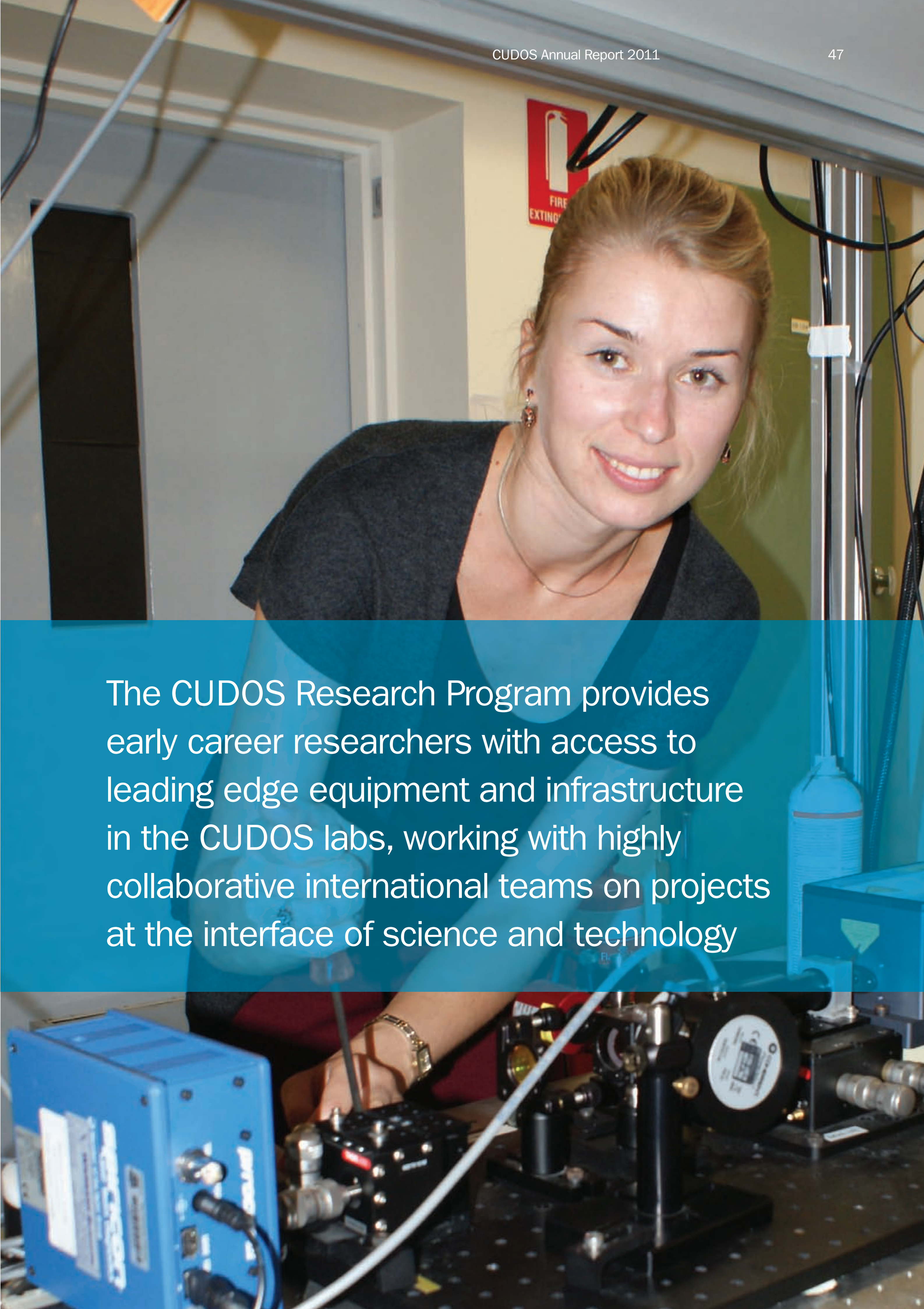
Optics at mid infrared wavelengths is difficult. Light beams are invisible, making alignment of complex circuits difficult to impossible. Sources are inefficient or unavailable: broad band thermal sources have low emissivity in the mid IR and the coverage of this part of the spectrum by laser sources is quite patchy. Our aims therefore are twofold. We aim to demonstrate mid IR photonic circuits, which will have the advantages of compactness, pre-alignment and potential for mass production. We also aim to demonstrate high-brightness mid IR optical sources based on either novel fibre lasers or on the generation of a mid IR supercontinuum in a dispersion-engineered fibre pumped by an infrared laser source.

Terabit Per Second

The aims of this project are encapsulated in the title. The project builds very much on the expertise, facilities and research outcomes of CUDOS I to establish bold new activities in areas of current and future interest for the optical communications industry, which is faced with the continuing challenge of rapid increases in data transfer capabilities to match the rapid growth of the internet.

Communications researchers are pursuing ways in which polarisation, phase, and amplitude can be used to modulate an optical carrier with information. By doing this, more information can be packed onto an optical carrier with little increase in the modulation rate. There are a range of such advanced approaches and CUDOS is investigating one of these, *optical frequency domain multiplexing.*

Packing more information requires higher power carrier power, which in turn produces nonlinear effects in the fibre that compromise the integrity of the data transmission and prevent the limits to data transmission per channel first derived by Shannon to be reached. Concurrently with our research into high spectral density transmission of information we are investigating novel approaches to circumventing this so-called *nonlinear Shannon limit.*



The CUDOS Research Program provides early career researchers with access to leading edge equipment and infrastructure in the CUDOS labs, working with highly collaborative international teams on projects at the interface of science and technology