Inside QPI - Nugent Overview

An introduction to the technology and applications of Quantitative Phase Imaging

Iatia Imaging Pty Ltd

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2 QPI technology

The QPI algorithm enables the extraction of phase information from incoherent, polychromatic radiation without requiring special optical components. The algorithm can recover phase information from just two conventional brightfield images taken at slightly different focal planes.

The algorithm has a number of key advantages, including:

- returns phase and intensity information independently
- provides quantitative, absolute phase (with DC offset)
- is a rapid, stable, non-iterative solution
- works with non-uniform and partially coherent illumination
- offers relaxed beam conditioning
- solves the twin image problem of holography
- has been experimentally applied to a number of radiations

Iatia's QPI algorithm was developed by Professor Keith Nugent, then head of the School of Physics at the University of Melbourne, and his team. For a simple introduction to the technology, please see Professor Nugent's overview.

3 An overview by Professor Keith Nugent FAA

The nursery rhyme 'Twinkle, Twinkle Little Star', the shimmer over a hot road and the network of bright lines at the bottom of a swimming pool on a sunny day all have their origins in phase. In fact, light is characterised by three main properties: colour, intensity and phase.

When light passes through a stained glass window its colour is changed. When light passes through a pair of sunglasses, its intensity (how bright it is) is changed. When it passes through a pair of prescription spectacles, the glass alters the phase of the light.

Many objects in nature are transparent. Obvious examples are air, glass and water, but think also of biological materials, eyes and, if you are 'seeing' with x-rays, even your aircraft carry-on luggage. Yet all transparent objects change the phase of the light - nothing is truly invisible to phase. It follows that any method that can 'see' phase can see things that are otherwise invisible.

Phase microscopy is a technique that has been around for a considerable time, with the first and most important development being due to the Dutch physicist, Frits Zernike, who received the Nobel Prize for this invention of phase-contrast imaging in 1953. Zernike's work was the first to allow a phase image to be seen. But the phase in the image could still not be measured.

I have spent much of my professional life trying to invent new ways of seeing things. For the most part, I have been looking at new developments in x-ray imaging and it was this work that led me to think about phase in a new way. With my colleagues and students, I set out to use my insights to develop new ways that would allow the phase in an image to be measured.

The obvious approaches to the problem turned out to be mathematically difficult and totally impractical. However, in 1998, with my student Dr David Paganin (now at Monash University) we developed an approach that seemed to have the promise of being simple, fast and very practical. With another student, Dr Anton Barty (now at the University of California), we showed that the methods could indeed be very effectively applied to optical, and then electron, microscopes. Their results were able to reveal - and measure - the phase in an image using clever calculations, but completely standard hardware. It was an extraordinarily flexible method.

The Paganin-Barty-Nugent technique has subsequently been used to also solve problems in x-ray, neutron and atom imaging. The international scientific interest in these new methods exploded and it rapidly became clear that the methods being developed by my team could be applied to a whole range of both practical and scientific problems.

We saw that this work had many commercial possibilities and so, with Drs Paganin and Barty, we took out a patent covering our new methods. This is the core patent licensed to Iatia Limited. Iatia has developed commercial packages for optical and electron microscopy. Iatia is now beginning to explore and develop the myriad other areas that can benefit from quantitative phase imaging methods.

3.1 Inside QPI

Our core algorithm, QPI (Quantitative Phase Imaging), provides a unique solution to the Transport of Intensity Equation.

The algorithm enables the extraction of phase information from incoherent, polychromatic radiation without requiring special optical components. The algorithm can recover phase information from just two conventional brightfield images taken at slightly different focal planes.

The algorithm has a number of key advantages, including:

- Returns phase and intensity information independently
- Provides quantitative, absolute phase (with DC offset)
- Is a rapid, stable, non-iterative solution
- Works with non-uniform and partially coherent illumination
- Offers relaxed beam conditioning
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3.2 Recovery of the phase information

The algorithm is able to recover the phase information from just two images taken at slightly different focal planes, though a third image taken at the point of best focus is generally used for normalisation.

Figure 1 below shows the recovery of the phase information for an optical fibre.

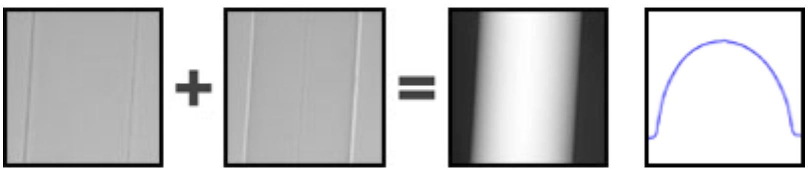

Figure 1: generating a phase image of an optical fibre

In the image above we can see the two brightfield images which were acquired with a conventional digital camera attached to a standard microscope. The images were taken at focal points approximately 5 microns either side of the point of best focus.

By applying the QPI algorithm to these images the phase image shown above can be calculated. The time required to generate the phase image from the 0.41 megapixel source data is approximately 1.5 seconds on a 2.4GHz Pentium IV.

Because the phase data provided by the QPI algorithm is quantitative is it now possible to make absolute measurements of the object's properties, including its thickness, refractive index, and so on.

A plot through the phase image shows the projected thickness of the circular cross section.

3.3 Behind the algorithm

The problem with a wave's phase is that it is lost when we can only measure the irradiance of the wave.

If we consider a wave propagating in the +z direction that has an amplitude $u_o(x,y)$ and phase $\Phi(x,y)$ such that

$$u(\vec{r}) = u_o(x,y)e^{i(kz+\phi(x,y))}$$

experimentally we only measure the irradiance

$$I = |u(\vec{r})|^2 = |u_o(x,y)|^2$$

thus we lose the phase information.

In order to recover the phase various optical techniques have been developed including interferometry, Zernike & Schlieren phase contrast, perfect crystal analysis, and various iterative propagation-based phase contrast methods. These techniques all require additional optical components, and traditionally are limited to measurements modulo 2π or computer-intensive iterative methods. This is not the case with our algorithm.

Iatia's QPI algorithm makes use of the paraxial approximation of the propagation of intensity distribution as described by the Transport of Intensity Equation (Teague, 1983)

$$k\partial_z I(\vec{r}) = \nabla_\perp \bullet \left[I(\vec{r})\nabla_\perp \phi(\vec{r})\right]$$

Given an intensity with no zeroes, and its longitudinal derivative, we can solve uniquely for the phase, up to an additive constant (the phase can't be known absolutely).

Solving for phase in the Transport of Intensity equation we get

$$\phi = -\bar{k}\nabla_\perp^{-2}\left\{\nabla_\perp \bullet \left[\frac{1}{\bar{I}}\nabla_\perp \nabla_\perp^{-2}\partial_z \bar{I}\right]\right\}$$

In formulating this solution we have used a generalised notion of phase where we regard the energy flow vector of a wave as the important quantity, not the amplitude or phase. This formulation is applicable even for polychromatic radiation where the notion of phase is not well defined.

The solution for the TIE phase may be coded using Fast Fourier Transforms. This coding is the QPI algorithm, a flowchart is provided later in this document.

3.4 Derivation of the transport of intensity equation

The Transport of Intensity equation is derived from the hydrodynamic continuity equation. Parallels between the hydrodynamic formulation of non-relativistic quantum mechanics and classical scalar wave optics are shown below.

	non-relativistic quantum mechanics (Schrödinger)	**monochromatic scalar electromagnetic waves (Helmholtz)**
wave function	$\Psi(\vec{r}) = \sqrt{\rho(\vec{r})}e^{iS(\vec{r})/\hbar}$	$u(\vec{r}) = \sqrt{I(\vec{r})}e^{i\phi(\vec{r})}$
wave equation	$\left(\nabla^2 + 2m(E-V)/\hbar^2\right)\Psi(\vec{r}) = 0$	$\left(\nabla^2 + k^2\right)u(\vec{r}) = 0$
momentum density	$\vec{j} = \rho\nabla S / m$	$\vec{S} = I\omega\nabla\phi / 4\pi$
continuity equation	$\nabla \bullet [\rho\nabla S] = 0$	$\nabla \bullet [I\nabla\phi] = 0$
paraxial approximation/TIE	$k\partial_z\rho(\vec{r}_\perp) = \nabla_\perp \bullet [\rho(\vec{r}_\perp)\nabla_\perp S(\vec{r}_\perp)]$	$k\partial_z I(\vec{r}_\perp) = \nabla_\perp \bullet [I(\vec{r}_\perp)\nabla_\perp \phi(\vec{r}_\perp)]$