Focus Issue: Coherent X-Ray Optics

Introduction

The ready availability of copious quantities of coherent visible light, through the development of the laser, has spawned a huge surge of activity in optical science and technology. Coherent visible optics, in its many guises, now plays an enormous role throughout modern science and technology.

The electron synchrotron was developed for the exploration of nuclear and particle physics. In the last thirty years the uses for the loss of energy though synchrotron radiation – a nuisance to the particle physicist – has had an impact on almost all of the rest of science (contradicting, in a sense, the physicist's maxim: "Today's signal is tomorrow's noise"). The first generation of the modern x-ray synchrotron were those that permitted the use of the radiation in a "parasitic" mode. The particle physicists retained control. The second generation synchrotrons were purpose built for the x-ray scientist, and the third-generation machines incorporate insertion devices – complex magnetic structures designed to optimise x-ray generation – in purpose-built straight sections of the accelerator. The net result of this development is that the available coherent output is increasing exponentially. This rate is set to continue through the development of x-ray free-electron lasers.

It is therefore timely to produce an *Optics Express* Focus Issue concerned with coherent x-ray optics. This idea issue follows two meetings this year: the *Second International Workshop on Non-Crystallographic Phase Retrieval* held in Cairns, Australia; and *X-ray Science with Coherent Radiation,* a satellite workshop to the Synchrotron Radiation Instrumentation Conference recently held in San Francisco, USA. This issue has very much the flavour of these meetings.

The first five papers discuss techniques that are analogous to coherent optical methods, but are adapted to the x-ray regime. Speckle is a very familiar feature to any user of optical lasers but is relatively new to the x-ray scientist. Speckle can carry much useful information about the dynamics of complex materials. In the first paper, Sutton *et al.* explore the use of X-ray Intensity Fluctuation Spectroscopy to make high resolution studies of, among other things, non-equilibrium colloids. This explicit use of coherent properties is destined to play an important role in the application of coherent x-ray optical methods.

Another example of adaptation from the optical community is given in the paper by Di Fabrizio *et al*. This paper develops the idea that custom built diffractive optical elements can be used to perform x-ray wavefront engineering. This is a very powerful idea that will ultimately find many applications. The authors concentrate on the development and demonstration of an x-ray version of a central technique from optical microscopy: differential interference contrast (DIC) microscopy.

The fact that there is now strong motivation to develop x-ray phase contrast methods is a reflection of another recent development in coherent x-ray optics, which is the realisation that phase can be an important information channel. Until the development of third-generation sources, refraction of x-rays was generally considered to be negligible. Mayo *et al.* explore the use of refraction in the development of phase contrast microscopy and tomography. Interestingly, this work was motivated by an observation using third-generation synchrotrons but is being applied to experiments on laboratory sources – it is now recognised that refractive effects have been seen but not understood for many years in small-scale laboratory experiments.

The phase-contrast theme is further developed by A. Momose who looks at the problem of performing quantitative x-ray phase-contrast imaging using interferometry. This is a complex method that has a range of potential applications in materials science and elsewhere and this paper explores some of the advantages of using interferometry in the measurement of phase.

A. G. Peele and K. A. Nugent complete the papers with direct visible light analogues. Singular optics is a new field in the visible region in which it is recognised that phase almost always contains discontinuities, or singularities. An x-ray vortex – a singular phase structure carrying orbital angular momentum – has recently been observed. The paper here explores some of the features of phase singularities that are likely to be unique to x-ray optics.

The final four papers concern coherent optical issues and applications that are particular to the x-ray regime.

An underlying issue in coherent x-ray optics is the problem of designing an experimental system that is able to fully utilise the coherence of the x-ray source. The problem of "decoherence" is one that has been discussed for some time. Although it is well established that coherence must be conserved, the experimental observation is that the coherence is degraded by the optics. The next paper in the issue, by Nugent *et al*., explores the transport of coherence down a beamline and suggests that the apparent lack of coherence arises due to unresolved coherent speckle.

The remaining papers explore the application of coherent x-rays to very high resolution imaging. As x-ray free electron lasers become available it will be possible to illuminate very small samples with very large numbers of coherent x-ray photons. Will it be possible to reconstruct the structure of these samples from the diffracted x-rays? If so, then very high resolution lensless x-ray imaging will be possible. There has been a considerable amount of very promising work in this direction. Robinson *et al.* look at the diffraction from nanocrystals and explore the consequences of using x-ray optics to focus the x-rays onto the sample. They report that, while the diffraction patterns do acquire a different structure, there is every likelihood that shape information will be able to be recovered.

The shape information recovered in the paper by Robinson et al is obtained using iterative phase recovery methods that assume some knowledge of the two-dimensional extent of the sample. Weierstall *et al.* explore related ideas but use knowledge of the depth extent of a monolayer as information to be used in recovering the phase. Their discussion is couched in terms of electron microscopy experiments, but these ideas have important applications in the development of high resolution coherent x-ray imaging.

Fittingly, the final paper, by Marchesini *et al*., is a critical evaluation of the potential for very high resolution diffractive imaging – what the authors term "Coherent X-ray Diffractive Imaging" – both as a high resolution method for third-generation synchrotron sources and for the imaging of single molecules using x-ray free electron laser pulses. The authors indicate that there are great challenges ahead, but that the promise for the further development and expansion of the field of coherent x-ray optics is very exciting.

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