Chapter 10

Summary and conclusions

A complete, scalar diffraction based, mathematical analysis has been presented for evaluating the signal generation process in the ordinary reflectance, single detector MO and differential detector MO, Type 1 and Type 2 (confocal), scanning optical microscopes. Expressions have been developed that describe the response of the scanning microscopes when imaging both one-dimensional and two-dimensional, reflectance and MO, samples.

A ‘transfer function’ representation has been presented that enables the response to be expressed in a form where the spatial frequency properties of the imaging system are distinct from the properties of the sample. In all the scanning microscope configurations investigated the generated signal can be expressed in the same functional form where the one-dimensional response can be easily generated using Fourier transform techniques. The spatial frequency properties of the imaging system are represented by the so called partially coherent transfer function (PCTF) and the properties of the sample are represented by the so called medium function. The PCTF is independent of the properties of the sample and is solely determined by the properties of the optical channel. For the Type 1 scanning microscope the PCTF is shown to be a function of the transmission properties of the objective and collector lenses and is generated by a convolution type operation involving the objective aperture pupil function, its complex conjugate and the square magnitude of the collector aperture pupil function. For the confocal scanning microscope the PCTF generation process is more complex and entails a convolution type process involving the objective and collector aperture pupil functions, their complex conjugates and the Fourier transform of the square magnitude of the confocal pinhole pupil function. The medium functions are shown to be independent of the properties of the optical channel and depend solely upon the type of detection strategy employed, i.e.

reflectance, single detector MO or differential detector MO. For the reflectance scanning microscope it is shown that the medium function depends upon the spectra of the reflectance properties of the sample. However, in the single detector and differential detector MO scanning microscopes the medium function depends upon the spectra of the reflectance and magneto-optic properties of the sample and the angle of the analyser and half wave-plate respectively.

Two computational procedures are presented for modelling the readout signal process in the scanning microscopes. These are the so called ‘direct calculation’ and ‘transfer function’ approaches. The modelling approaches have been applied for generating the responses to both one-dimensional and two-dimensional samples using the analysis and expressions developed. The computational procedures have been demonstrated using pseudocode and have been implemented using the C programming language.

The direct calculation approach involves the formulation of the optical field distribution as it propagates through the optical system, after interaction with the sample that is scanned beneath the focused spot. The direct calculation approach is shown to be relatively straight forward to implement, but computationally demanding. Hence, the direct calculation approach is limited in this thesis to imaging in Type 1 systems. The direct calculation approach is shown to be particularly beneficial for generating two dimensional images of samples. This technique is found to be especially useful for generating the response in optical storage systems and for investigating the effects of tracking error and cross-talk.

In the transfer function approach the signal from the scanning microscopes is generated using the transfer function representation presented. The signal from each configuration may be easily calculated using the same computational procedure, where the appropriate PCTF, depending upon whether the imaging system is Type 1 or confocal, and the appropriate medium function, depending upon whether the detection strategy is reflectance, single detector MO or differential detector MO, is included in the modelling process. The transfer function approach is shown to be principally useful for generating the response to one-dimensional objects and for the quantitative comparison of the spatial frequency response, and hence, the relative performance of different imaging configurations. A prime example is in the investigation of super-resolution and channel optimisation techniques.

The models have been utilised to investigate the response and characteristics of the various scanning microscope configurations. It has been demonstrated that in all the optical configurations investigated the two modelling approaches produce identical results when generating the response to one-dimensional samples. This gives great confidence in the accuracy and validity of the modelling methods.

In the Type 1 reflectance scanning microscope the effects on the step response due to the form of incident illumination have been investigated. It has been shown that for the case of uniform illumination the response is at its sharpest compared with the response due to untruncated Gaussian illumination. However, the extremes of the response under uniform illumination are degraded due to the sidelobes of the Airy disc focused spot. In both cases it is shown that the responses lag the edge by 0.05λ/NA. For the confocal configuration it is discussed that the size of the confocal pinhole effects the imaging properties of the confocal system and for an infinitesimally small pinhole it is demonstrated that the width of the impulse response is at its narrowest, compared with the Type 1 response, and leads to improved lateral resolution. For a pinhole diameter less than 0.4λ/NA the signal from the confocal system is comparable with that from the ideal confocal system, i.e. infinitesimally small pinhole, and for a pinhole diameter greater than 2 λ/NA it is found that the response is comparable with that of the Type 1 system. These results are shown to agree exactly with the results produced by other workers.

It was shown that for the analyser aligned to the extinction position the single detector MO scanning microscope is unable to distinguish the polarity of the Kerr rotation and in fact operates as a phase contrast system where a change in Kerr rotation is measured. A particularly interesting result is that the impulse response of the single detector MO system is identical to the reflectance impulse response for a MO sample of uniform ordinary reflectance and zero phase, with the analyser aligned to the extinction position. This is true in both the Type 1 and confocal configurations.

Hence, it can be deduced that the confocal single detector MO scanning microscope offers similar improved lateral resolution characteristics as evident in the reflectance system. It is shown that for a analyser alignment of 82° then the polarity of the Kerr rotation is observed in the output signal, a response that is observed experimentally.

In the differential detector MO scanning microscope it is found that the step response due to uniform and Gaussian illumination are very similar to those obtained for the reflectance system, for a MO sample of uniform ordinary reflectance and zero phase and with an optimally aligned half wave plate, 22.5°. However, unlike the reflectance system no lag in the response to an edge is observed. Furthermore, the signal generation process using the transfer function approach is subtly different from the other cases investigated. In the differential detector case the response is generated solely by the properties of the PCTF along the n_x=0 and n_x'=0 axes and not the properties of the PCTF over all $\{n_x, n_x'\}$ space. An interesting and unexpected result is that the impulse response of the Type 1 and confocal configurations are identical to the impulse response of the incoherent optical system. As a result the confocal configuration offers no improved lateral resolution over the Type 1 configuration. In fact, it is observed that the response can be slightly degraded by employing a confocal pinhole and the FWHM of the impulse response is at its maximum width when the pinhole radius is 0.7λ/NA.

The applications of the computational models to predicting the readout signal in optical storage systems has been presented. It is valid to apply the computational models to predict the response of optical storage systems since the optical channels of the optical storage systems discussed are analogous to the scanning microscope configurations investigated. The readout channels of the CD-ROM and phase change systems are analogous to that of the Type 1 reflectance scanning microscope and the readout channel of the magneto-optic system is analogous to that of the Type 1 differential detector MO scanning microscope. The response from a commercial PD drive to an arbitrary data pattern and the predicted theoretical response, generated using the reflectance model, have been compared and indicate that the predicted result agrees extremely well with the real data, thus confirming that the models produce valid and accurate responses. A interesting example of the use of the direct calculation approach is for predicting the response of future optical storage technologies, such as DVD systems. The model is demonstrated to produce simulated pulse responses to the minimum and maximum bit lengths which can be used to asses the performance of the storage system.

The transfer function approach has been utilised for investigating the effects due to optical filtering techniques, i.e. apodisation, on the response of the scanning microscopes. In particular, the effects due to the form of the incident illumination and common forms of obscurations, such as shading bands and annular apertures, is described. In the case of the form of incident illumination it is found that as it is changed from uniform to Gaussian the effective cut-off spatial frequency of the PCTF reduces. This is an expected result since the Gaussian focused spot is broader than the Airy disc which results in a loss in resolution. The application of shading bands in the collector arm of the imaging system has been studied in detail. For a clear shading band of varying width it is found that for a narrow shading band the effective cut-off spatial frequency of the imaging system is reduced. For an obscured shading band of varying width it is discovered that for a wide shading band the magnitude of the PCTF over the central region is relatively constant, although this is at the expense of SNR due to the reduction in the amount of light reaching the photo-detector. For the case of an annular aperture with an outer radius equal to the radius of the collector pupil, it is demonstrated that as the inner radius of the annulus is increased then the high spatial frequency response of the optical channel is improved with respect to the low frequency response, although again at the expense of SNR. It is illustrated that by the judicious combination of incident illumination characteristics and optical filtering, then the form of the spatial frequency response of the optical channel can be optimised to suit a desired characteristic. A novel example demonstrated is in the modification of the spatial frequency response of the optical channel to match that of the class 1 partial response channel for a particular bit period T. The example illustrates that the response of such an optically equalised channel to a pulse of period T matches exactly with the desired response of the PR channel. Thus, demonstrating that such an approach is feasible.

The effects of common forms of aberrations found in optical disc systems is discussed and presented. It is illustrated how aberrations may be included as a complex phase factor into the objective and collector aperture pupil functions during the modelling process. The effects due to defocus, spherical aberration and astigmatism on the spatial frequency response of the Type 1 optical system have been presented. It is shown that defocus and spherical aberrations introduce similar degradation into the response. The result is a broadening of the focused spot, that leads to a reduction in the effective cut-off spatial frequency of the optical system. In the case of defocus a large amount of contrast reversal is introduced, where bright areas on the sample appear dark in the image and vice versa. In the case of astigmatism, it is discussed how astigmatism may be used, as a first approximation, to model the effects on the response of optical storage systems due to substrate birefringence. It is observed that astigmatism introduces a broadening of the focused spot along a particular axis, and has different effects depending upon the direction of the astigmatism, i.e. along track or cross track. The understanding of the effects due to aberrations is of particular importance in the development of future optical storage technologies where greater storage densities are predicted using higher NA objectives and short wavelength laser sources. A high NA and short wavelength optical system is inherently sensitive to aberrations and can introduce focus problems due to the relationship between the depth of focus and NA^2/λ.

Finally, experimental studies have been presented that have been generated using an existing scanning laser microscope. In particular, the response of the reflectance and differential detector MO scanning microscopes were investigated by generating the step response of both a reflectance and magnetic edge. Initial comparisons indicate that the theoretical predictions generated using the optical models agree extremely well with experimental results and that indeed the confocal differential detector MO scanning microscope offers no improved lateral resolution properties over the Type 1 configuration. However, it is suggested that to verify the results of the model it would be advantageous to generate images of better quality samples.

This thesis has demonstrated the usefulness of a mathematical model for generating the response of the scanning microscope configurations investigated. Results have been generated that have helped to understand the imaging performance and limitations of the optical imaging systems. Such an extensive model has proven advantages in the design of future optical storage systems where a clear understanding of the resulting imaging process is required. Comparisons with experimental results have demonstrated that the models produce reliable results that accurately predict the response of the scanning optical microscope.