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(12) (19) (CA) **Demande-Application**

(21) (A1) **2,246,258**
(22) 1998/08/31
(43) 2000/02/29

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(51) Int.Cl.^{6} G03H 1/04, G02B 5/32, G03H 1/12

(54) METHODE OPTIQUE NOVATRICE POUR L'IMAGERIE HOLOGRAPHIQUE D'ELEMENTS DIFFRACTEURS COMPLEXES DANS DES MATERIAUX

(54) NOVEL OPTICAL SCHEME FOR HOLOGRAPHIC IMAGING OF COMPLEX DEFRACTIVE ELEMENTS IN MATERIALS

$$(< \frac{\lambda}{50}$$

(57) The purpose of the invention is to take advantage of the high peak powers of short laser pulses to modify the bulk index of reaction of materials with minimal average power or least amount of heat deposition. Applications of high power femtosecond pulses are well known in this regard but generating the necessary intersecting beams to generate a complex structure requires the optical phases of the different beams remain constant or locked. Previously this phase locking of different beams requires an active feed back circuit to maintain equal beam lengths to a few 100 A's. This degree of precision can be achieved but it is sufficiently difficult that it can not be extended to multiple beams. We describe a simple optical system for holographic imaging of one-dimensional diffractive structures using ultrafast pulses. The invention can be simply adapted to image complex 3-d objects. In order to obtain spatiotemporal overlap of the laser pulses in the sample, tilted wavepackets are generated through the use of a diffractive optic beamsplitter. These wavepackets are imaged onto the sample with a spherical mirror with a 1:1 conjugate ratio to eliminate the effects of angular dispersion at the sample. This system will enable the use of ultrafast pulses in machining applications for writing periodic 1-D structures and more complex structures with a single laser slit and provides a method for fabricating strongly modulated, large-dimension periodic structures in non-UV- photosensitive materials. The extremely high phase stability (see formula above) drift for periods of hours to days) will also enable writing structures that require large accumulations of shots with a fixed pattern. Applications include rapid production of fibre optic wave guides and Bragg grating structures using undoped glass. As an example, this process would avoid the need of couplers from regular undoped fibre to doped WDM Bragg filters. The fibre could be a completely integrated system. Other important applications include the manufacture of any holographic volume diffractive element. Such optical components are typically produced using cromatized gelatin (eg. diffractive notch filters) and have finite storage times. Bulk fused silica diffractive optics would last essentially forever. Also critical the use of conventional glass avoids all the processing and ultra clean steps required for fixing gelatin storage media. Anyone could write diffractive elements in glass in single or multiple shot exposures using this approach. Basically any complex structure to full blown 3-d holograms could be permanently stored in robust glasses or even single crystals. As another example an important potential application would be eye surgery. A procedure can be carefully engineered into a diffractive optic and using this invention ensure the desired performance at every instance.

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NOVEL OPTICAL SCHEME FOR HOLOGRAPHIC IMAGING OF COMPLEX DEFRACTIVE ELEMENTS IN MATERIALS

Abstract

The purpose of the invention is to take advantage of the high peak powers of short laser pulses to modify the bulk index of refraction of materials with minimal average power or least amount of heat deposition. Applications of high power femtosecond pulses are well known in this regard but generating the necessary intersecting beams to generate a complex structure requires the optical phases of the different beams remain constant or locked. Previously this phase locking of different beams requires an active feed back circuit to maintain equal beam lengths to a few 100 Å's. This degree of precision can be achieved but it is sufficiently difficult that it can not be extended to multiple beams. We describe a simple optical system for holographic imaging of one-dimensional diffractive structures using ultrafast pulses. The invention can be simply adapted to image complex 3-d objects. In order to obtain spatiotemporal overlap of the laser pulses in the sample, tilted wavepackets are generated through the use of a diffractive optic beamsplitter. These

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Applications include rapid production of fibre optic wave guides and Bragg grating structures using undoped glass. As an example, this process would avoid the need of couplers from regular undoped fibre to doped WDM Bragg filters. The fibre could be a completely integrated system. Other important applications include the manufacture of any holographic volume diffractive element. Such optical components are typically produced using cromatized gelatin (eg. diffractive notch filters) and have finite storage times. Bulk fused silica diffractive optics would last essentially forever. Also critical the use of conventional glass avoids all the processing and ultra clean steps required for fixing gelatin storage media. Anyone could write diffractive elements in glass in single or multiple shot exposures using this approach. Basically any complex structure to full blown 3-d holograms could be permanently stored in robust glasses or even single crystals. As another example an important potential application would be eye surgery. A procedure can be carefully engineered into a diffractive optic and using this invention ensure the desired performance at every instance.

I Background

A number of photonics devices are based on the ability to create permanent photorefractive changes in transparent materials, e.g., Bragg gratings in linear or planar waveguides. These devices are normally fabricated holographically by side-coupling a UV laser beam into the cladding or core of the material. An optical interference pattern is generated by overlapping replicas of the laser pulse at an angle in the material, either through the use of external beamsplitters and steering mirrors[1] or by placing a transparent phase mask just before the medium.[2,3] Index changes written in standard UV-photosensitive optical materials such as Ge-silicate glasses are normally limited to $\Delta n < 10^{-3}$.[4] A great deal of work has been devoted toward elucidating the mechanism for photorefractive index changes in glasses upon exposure to UV light, and progress has been made toward developing materials with enhanced photosensitivity, e.g., hydrogen-loaded or specially-doped silcate glasses[5] for waveguiding applications, or photorefractive gels for bulk diffractive elements.[6] However, these materials all suffer in one way or another from inferior optical or mechanical properties compared with normal optical glasses. Often a curing process is required following UV exposure, which can cause shrinkage and distortion of the optically written pattern. Photorefractive gels, in particular, are limited in their application due to the non-permanent nature of the index change, which decays on a timescale of a few years.[6]

An alternative mechanism which employs high-intensity ultrafast pulses for creating permanent photorefractive changes in glasses has recently been explored by several groups.[7,8] Index changes on the order of $\Delta n \sim 0.1$ have been written in fused silica using tightly focused pulses with peak intensities ~ 10^{13} W/cm^2.[8] The physical process that gives rise to this index change appears to be due to creation of free electrons through multiphoton ionization of bound charges, followed by avalanche ionization and localized dielectric breakdown as these free electrons are accelerated by the intense laser field.[9] Phenomenologically, this leads to a localized melting and compaction of the material, and a concurrent increase in the index of refraction.[10] Owing to the extremely high intensities required to activate this photorefractive mechanism, all work performed to date in this field has used pulses that are tightly focused to near-diffraction-limited spots. While this allows high-resolution spatial localization of the index change to a volume on the order of 1-10 μm^3,[8] it also requires that the laser focus be scanned point-by-point throughout three dimensions to build up a complete hologrammatic pattern in the material. This is a great disadvantage for writing diffractive structures that have extended dimensions, since $\lambda/100$ mechanical precision must be sustained across length scales up to centimeters. Over timescales of minutes, slight drifts in ambient temperature can lead to thermal expansions or contractions that often limit the accuracy of the fabrication process. Since raster scanning is an inherently slow procedure, this technique is not well-suited toward writing large diffractive structures.

In this disclosure, we present a method for holographic fabrication of one-dimensional periodic structures using femtosecond pulses that is inherently single-shot, i.e., the desired pattern is encoded upon exposure to a single laser pulse. *In the case of repeated exposure, the desired pattern is also unconditionally guaranteed by this invention.* In this regard, our method resembles the standard phase-masking techniques for fabrication of photorefractive elements using UV light.[2-4] however, there are additional constraints imposed by the use of high-intensity ultrafast pulses that disqualify standard phase-masking methods. Close-coupling a phase mask to create an interference pattern in the sample is not feasible, since the mask will experience optical damage owing to the high peak intensity required at the sample position. Therefore, the mask must be located remotely and the diffracted light imaged onto a small spot at the sample. Since a phase mask introduces angular dispersion in the diffracted beams owing to the broad spectral content of ultrashort pulses, simply redirecting each individual diffracted beam so that they are overlapped in the sample, as was done in Ref 4 for example, will result in greatly reduced peak intensity as the spectral content of the pulse is distributed over a relatively large area. Thus, it is necessary to design an imaging system that can overlap replicas of the short pulse without significant spatial or spectral aberrations, and without any element experiencing peak intensities within two orders of magnitude of those at the sample.

There is one additional consideration for generating large-dimension interference patterns with ultrafast pulses that is not present for long pulse sources. To create an interference pattern, two phase-coherent replicas of the laser pulse must be overlapped in the sample with their wavefronts tilted with respect to one another as shown in Fig. 1(a). At any point in time, an ultrashort pulse can be viewed as a spatially localized wavepacket of light, whose transverse dimensions are those of the laser beam and whose longitudinal dimension is $c\Delta t$, where c is the speed of light and Δt the temporal pulsewidth. If two replicas of the short pulse are crossed at an angle, the region in which they are spatially overlapped will be limited to a transverse dimension of $\sim 2c\Delta t/\tan(\theta)$, where θ is the crossing angle between beams. For devices operating at optical or near-IR wavelengths, grating periods on the order of $\Lambda \sim 1$ μm are of greatest interest, which implies $\theta \sim 1$

radian for 800 nm excitation wavelengths. The maximum spatial dimension that can be written in this case will then be limited to ~ 40 μm. Generally, device lengths will not be able to exceed dimensions of a few tens of grating periods along the direction of the grating wavevector owing to this problem.

Despite the limitations of the phase-masking technique, this method does eliminate the short-pulse overlap problem. As an illustrative example of how this works, consider the simple situation depicted in Fig. 1(b), in which an incident short pulse is diffracted into two orders. Since the pulse envelope is not changed upon diffraction, immediately following the phase mask there is still perfect spatial overlap between the two pulse replicas. Thus, the use of a phase mask extends the overlap regions for single-shot writing of diffractive structures using ultrafast pulses to dimensions on the order of the input beam diameter (~1 mm). In addition, the spatial period of the interference pattern between different diffractive orders will be independent of the source wavelength,[2] since each spectral component will be diffracted by the mask into a slightly different direction.

The optical system shown in Fig. 2 preserves these desired features of the phase mask approach while allowing high intensities at the sample and eliminating the detrimental effects of angular dispersion arising from the mask. For simplicity only two separate beams are shown following the mask, although this system can in general image any one-dimensional mask pattern or even more complex patterns onto the sample. An ultrafast laser pulse in a 1 mm diameter collimated beam is incident on the phase mask, which generates pulse replicas with tilted wavepackets. A 300 mm radius f/1 spherical mirror (SM) placed so that the mask is located at its center of curvature retroreflects the diffracted light from the phase mask, regardless of the diffraction angle or the optical wavelength. The SM is tilted slightly off-axis to separate the incoming beams from the outgoing beams, which are picked off by a folding mirror and sent toward the sample. At the sample position the various diffractive orders overlap and produce an interference pattern that is the inverted image of the phase mask. At high enough intensities, a hologrammatic replica of the phase mask will be created in the sample via the photorefractive mechanism discussed above. To achieve these intensities, the input beams are concentrated in one spatial dimension by a 10 mm focal-length cylindrical lens, resulting in approximately 100x greater intensity at the sample than at the input mask. While tight focusing unavoidably distorts the image in the focused dimension, this is of no consequence for writing one-dimensional periodic structures.

This imaging system bears some analogy with the typical "4f" imaging system shown in Fig 3, used in Fourier optics for image processing and pulse shaping.[11,12] Like the 4f system, the setup used here has a delta-function impulse response function, which means that the image at the input plane is perfectly reconstructed at the sample. An immediate consequence of this property is that the setup of Fig. 2 corrects for the angular dispersion of the pulse spectrum that arises owing to diffraction from the phase mask. This system was chosen over a 4f system to avoid the need for large (and expensive) aspheric mirrors, which would be required in the 4f setup to eliminate geometric aberrations due to the infinite conjugate ratio at the mirrors. As shown in Fig. 3, if the 4f system were used with SM's, these geometric aberrations would result in very large chromatic aberrations due to the spatially dispersed spectral components at the mirrors. These will both distort the final interference pattern and reduce the peak intensity to unacceptable levels. The SM in our setup, on the other hand, acts at a conjugate ratio of 1:1 where there is no geometric aberration.

The crucial feature of this invention is that this optical system exhibits a high degree of interferometric stability between the various diffracted beams.[13] *This is necessary in order to preserve a constant phase relationship between the beams at the sample, so that the interference pattern on the substrate does not shift appreciably over the timescale of exposure.*[14] *The origin of this stability lies in the fact that all beams interact with the same set of optical elements, so that small mechanical fluctuations of any of the elements in the beam paths affect each beam approximately the same and thus do not appreciably perturb their relative pathlengths. All other schemes for generating the interfering beams to write the desired structure in bulk materials suffer from incorrelated mechanical motions of the constituent mounts and optical components.*

Note: path length stabilities of a few 100 Å over total pathlengths of approximately 1 meter are required (1 part of 10^{10} *position stability). This position stability is not physically possible for extended periods of time. At room temperature thermal fluctuations even under constant temperature exceed this value. Some kind of active feedback with an interferometric reference is required. Moreover, one would want the path length to remain constant for the entire time a particular operation is to be conducted. Even with active feedback, drift and changes day to day make this impossible. Any active feedback employs a* ***relative reference*** *(a two beam interference). The diffractive optic serves as an* ***absolute reference*** *point such that the same optical operation can be conducted with adequate phase stability for unconditional time periods*

It is this advance and combination with intense laser field, which also makes the advent of multiple beam interactions for writing diffractive elements even possible.

The potential applications of this holographic system are numerous. Amplified Ti:sapphire laser systems are capable of emitting 100 fs pulses with 1 mJ of energy at kilohertz repetition rates. This high pulse rate naturally leads one to consider scanning the location of the interference pattern on the sample to produce larger structures. By taking advantage of existing precision optical alignment methods used in fabricating fiber Bragg gratings, photowritten gratings can be laid sequentially end-to-end with excellent control over the relative grating phase, resulting in periodic structures with dimensions far greater than those which can be fabricated on a single-shot basis. In addition, structures with large transverse dimensions can easily be made as well simply by scanning the beam in the dimension perpendicular to the grating wavevector. Since the high-intensity photorefractive mechanism appears to be present in virtually all common optical materials,[8] strongly modulated structures can be made in undoped glasses which are not UV-photosensitive. Finally, the 800 nm excitation wavelength is only very weakly absorbed in most materials, which will naturally enable the formation of deep structures, limited only by nonlinear pulse breakup effects[13] that will eventually reduce the peak intensity after ~millimeter propagation distances. Thus, the method presented here should enable fabrication of large volume (>1 mm^3), bulk diffractive elements in virtually any optical material. There are also numerous applications in laser based medical treatments. One can imagine wanting to write structures in the cornea or achieve very precise beam alignments to execute an operation. This invention assures constant reproduction under harsh environments (factory or operating room).

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Claims

1. A method of writing a spatial modulated index pattern in a light transmissive material comprising the steps of:

providing a high power laser light source having a power of at least 10 kw/cm^2;
providing a diffractive optic element having predetermined characteristics;
irradiating the diffractive optic element with the high power light for a period of time suitable to generate a beam pattern in the light transmissive material;
focusing diffracted light received from the diffractive optic element onto the light transmissive material to effect a permanent refractive index change within the light transmissive material that corresponds to the spatial modulated index pattern.

2. A method as defined in claim 1 wherein the high power laser light is in the form of a plurality of pulses.

3. A method as defined in claim 2 wherein the plurality of pulses are femtosecond pulses.

4. A method as defined in claim 1 further comprising the step of passing the light diffracted from the diffractive optic element through a spatial filter to filter predetermined orders of light.

5. A method as defined in claim 1 comprising the step of
using spatial filtering focusing the light and irradiating a light transmissive material.

6. A method as defined in claim 1 wherein the focusing step comprises focusing the light to a desired power prior to irradiating the light transmissive material.

7. A method as defined in claim 1 wherein a plurality of beam are utilized.

8. A method as defined in claim 1 wherein multiple beams are utilized.

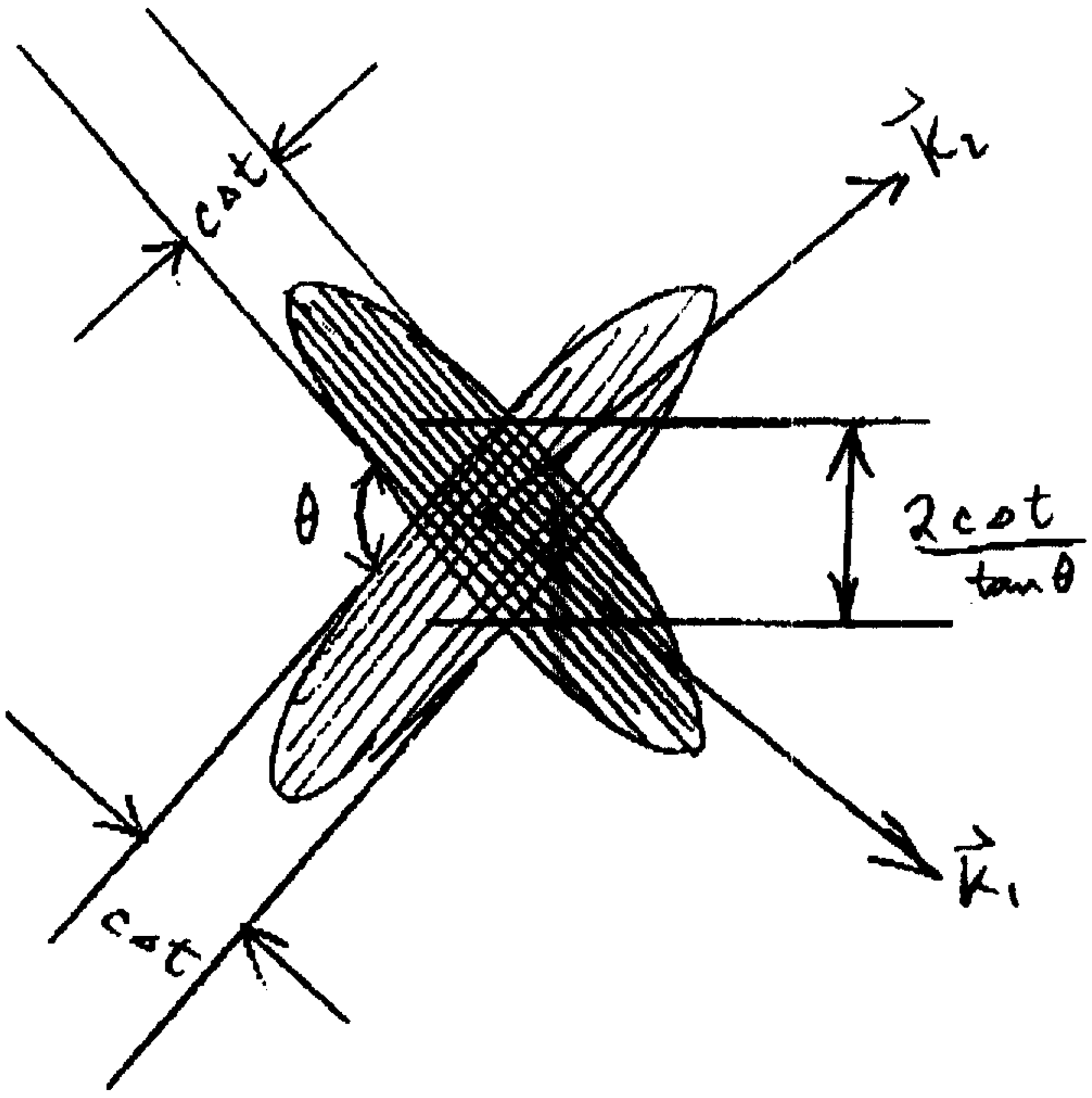
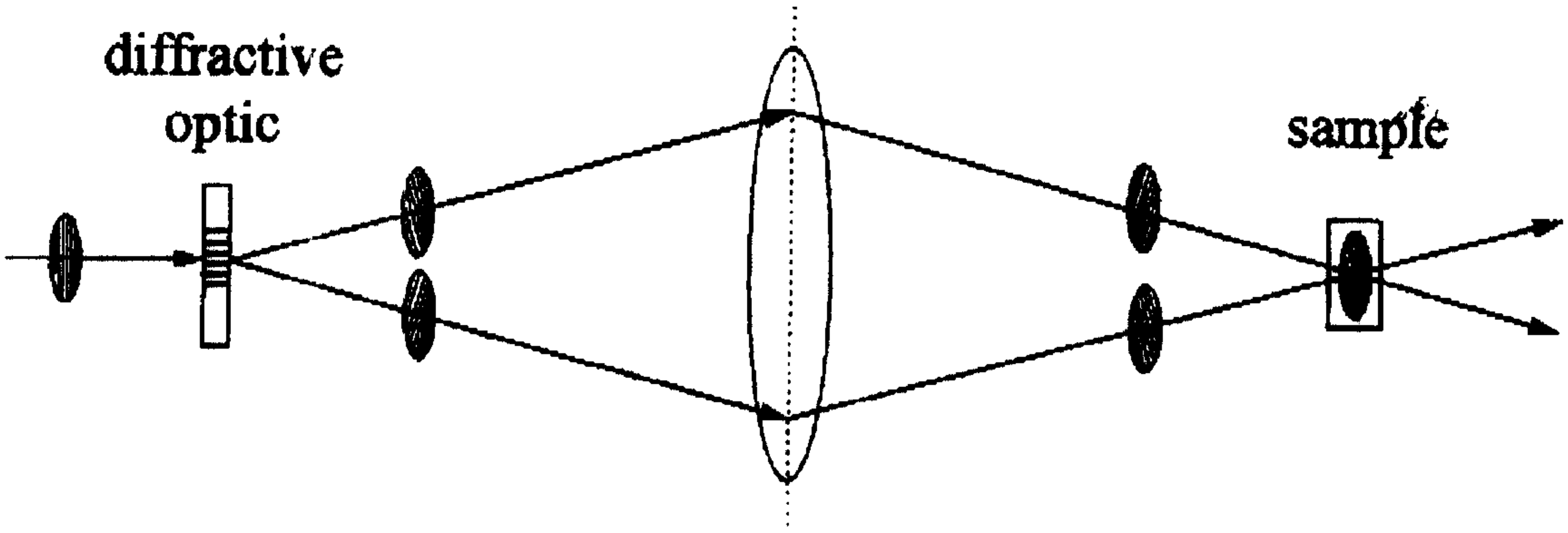


Fig 1a

Figure 1b



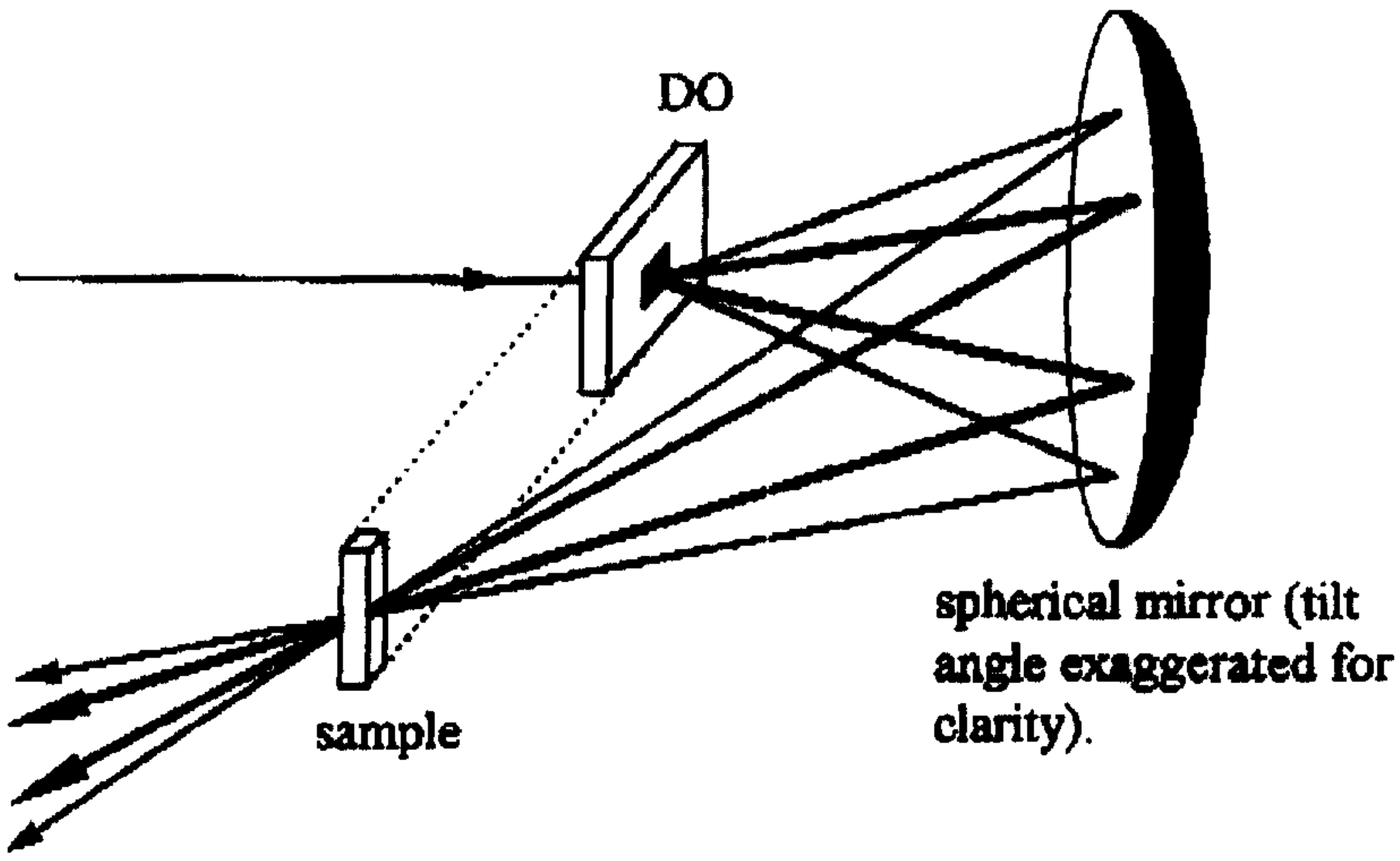


Fig. 2. Imaging setup for writing diffractive elements using a diffractive optic phase mask. Two different wavelength beams are shown: short wavelength = thick rays; longer wavelength = thin rays. Since the different colors are diffracted into different directions, the period of the structure written is independent of the source wavelength. This property is usually only obtained for near-field coupling of a phase mask into a sample.

Fig 29 · IT imaging pulse shaper

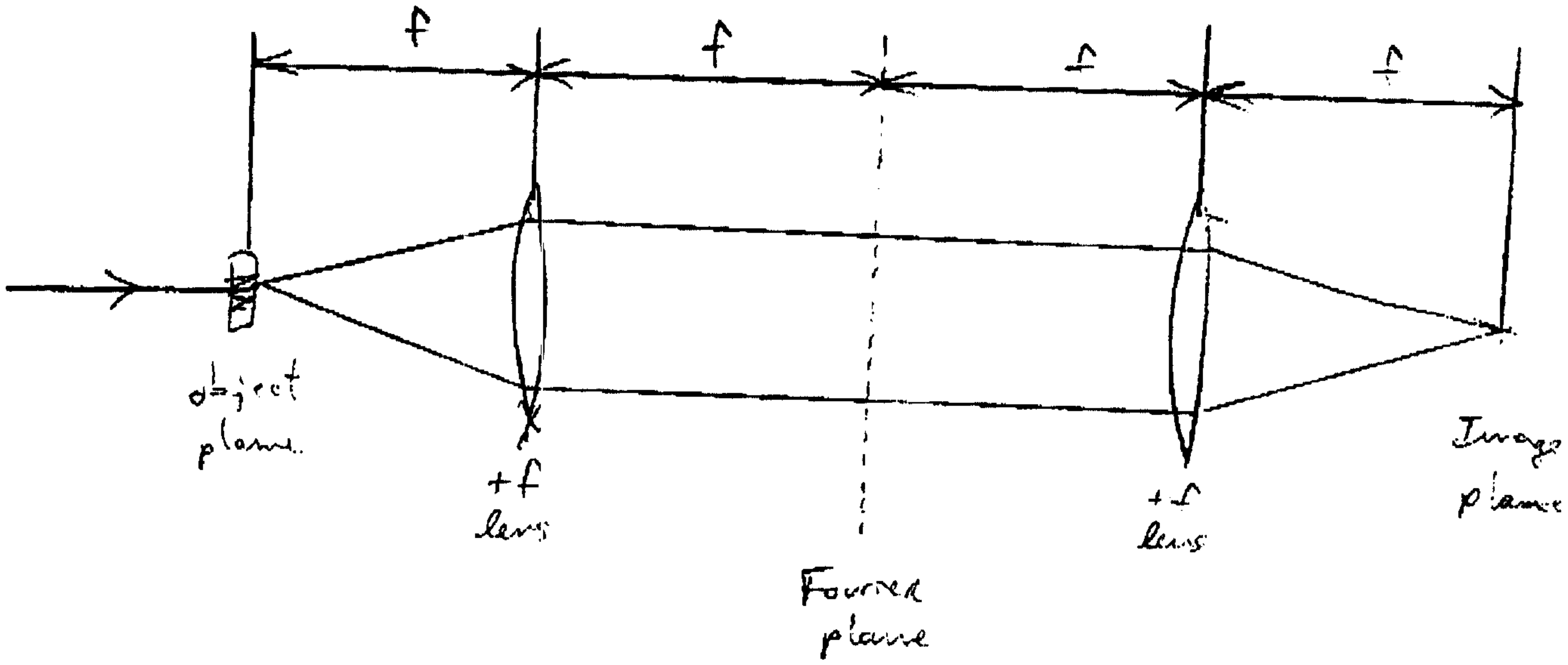


Fig 3b Effect of spherical aberration on [illegible] imaging system