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Optical Storage Device

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Summary

A new holographic image storage device which uses four-wave mixing in two photorefractive crystals is described. Photorefractive crystals promise information storage densities on the order of 10^9 to 10^{12} bits per cubic centimeter at real-time rates. Several studies in recent years have investigated the use of photorefractive crystals for storing holographic image information. However, all of the previous studies have focused on techniques for storing information in a single crystal. The disadvantage of using a single crystal is that the read process is destructive. Researchers have developed techniques for fixing the information in a crystal so that it may be read many times. However, when fixed, the information cannot be readily erased and overwritten with new information. If two photorefractive crystals are used , holographic image information may be stored dynamically. That is, the stored image information may be read out more than once and, it may be easily erased and overwritten with new image information.

Introduction

In the mid 1960's, researchers discovered what has come to be known as the photorefractive effect. Certain types of crystals, when placed in the optical cavities of lasers, were found to suffer "optical damage" after a brief period of time (ref. 1). Later, it was determined that the crystals were in fact not damaged, but rather had the remarkable property that when exposed to light would undergo a change in refractive index. In the late 1960's, researchers realized that this property could be exploited and these crystals could be used to record holographic information (ref. 2). When exposed to multiple coherent interfering beams of light, these crystals will record (on a microscopic level) the interference patterns generated by the beams. These interference patterns (recorded as a change in the index of refraction) are phase holograms or holographic gratings.

The mechanism by which holograms are recorded in photorefractive crystals can be understood with a simple example. In figure 1 is a drawing showing two coherent plane wave beams of light with wave vectors κ_1 and κ_2 intersecting at some angle 2θ in a photorefractive crystal. The alternating dark and light bands within the region of intersection represent the light distribution resulting from interference of the two beams. The spacing of the bands is described by the spatial frequency $\mathfrak{k}$, where

$$\mathfrak{k} = 2\,|\kappa_1|\,\sin\,\theta$$

For very small angles of θ, the spacing of the bands of light will be very fine. On a microscopic level, the individual atoms of the crystal are exposed to alternating bands of light and dark. In the illumninated regions, light is absorbed, causing excitation of trapped charges within the crystalline structure. The excited charges migrate and become retrapped in regions of low light intensity (the dark bands). This results in charge separation within the crystal. This charge separation sets up a strong static electric field which in turn causes a change in the refractive index of the crystal due to the linear electro-optic effect (ref. 3). As shown in figure 2, the induced change in refractive index mimics the interference pattern except it is shifted in space $\pi/2$ out of phase with respect to the incident light intensity pattern. The microscopic spatial variation in the refractive index of the crystal produced by the interference of two coherent beams of light is a type of hologram known as a phase hologram.

Holograms of objects differ from photographs in that they are not a record of the light intensity distribution reflected from an object, but rather a record of the amplitude and phase distribution of light reflected from an object. When holograms are illuminated, the amplitude and phase of the wavefront of the light reflected from (or transmitted through) the original object are reconstructed. To an observer, this wavefront is indistinguishable from the wavefront reflected off the object itself and the observer therefore "sees" the original object in three dimensions. It is by illuminating the hologram that the information stored in the hologram is read out. Unlike a holographic grating recorded in film or other fixed media, when a holographic grating in a photorefractive crystal is illuminated, the charges in the crystal redistribute and the grating is erased. For this reason, the read process, if separated from the write process, is destructive.

The optical storage device described herein uses a four-wave mixing geometry to store holograms in two photorefractive crystals. In four-wave mixing, the read and write processes are combined. Three coherent beams of light are incident on a photorefractive crystal as shown schematically in figure 3. One beam, denoted as the object beam carries the information to be stored in the form of a complex phase and amplitude distribution. This beam is interferred with a plane wave reference, denoted as the write beam in figure 3, thereby generating a complicated interference pattern which is recorded in the crystal as described previously. A third beam, denoted as the read beam, is a plane wave reference beam counterpropagating with respect to the write beam. When the holographic grating is illuminated by the read beam, a portion of the read beam is diffracted by the grating and reconstructs the phase conjugate of the object beam. The phase conjugate is counterpropagating with respect to the object beam. It is a time-reversed replica of the object beam.

In the optical storage device, holographic information is recorded in two photorefractive crystals. An object wave bearing the information to be stored is interferred with a plane wave reference or write beam, and the resulting interference pattern is stored in the first of two photorefractive crystals. A second plane wave reference or read beam is diffracted by this grating and reconstructs the phase conjugate of the original object wave. This phase conjugate is interfered with a third plane wave reference and the resulting interference pattern is stored in the second crystal. A fourth reference wave reconstructs the phase conjugate of the phase conjugate, which is just a reconstructed version of the original object wave. The reconstructed object wave is directed back to the first crystal to rerecord the original grating. The advantage in using two crystals over one is now obvious. The holographic information can be read out without being lost. Each crystal refreshs the information written in the other crystal. A diagram of the two-cystal memory is shown in figure 4. To read out the information, a beamsplitter is inserted in the cavity formed by the two crystals, as depicted in the figure.

The above discussion is a simple description of how the two-crystal optical storage device works. However, to fully appreciate how the device works, and some of the potential difficulties encountered in developing an implementable design, a more detailed discussion of the theory and some preliminary experimental results will be presented.

Theory of Operation

Because the photorefractive crystal generates a phase conjugate of the original object beam, it is referred to as a phase conjugate mirror or PCM. The reflectivity of the phase conjugate mirror is defined as the ratio of the intensity of the phase conjugate wave to the intensity of the incident object wave. Using a four-wave mixing geometry, it is possible with proper beam geometries to have reflectivities greater than 1.0 (ref. 4). As a result, it is possible to build optical resonators using phase conjugate mirrors in place of conventional mirrors. The optical storage device is a type of phase conjugate resonator. The image information, in the form of a complex wavefront, oscillates between two photorefractive crystals or phase conjugate mirrors. In the literature, the term double phase conjugate resonator is used to describe this type of oscillator.

Modelling the behavior of phase conjugate resonators has been the subject of intense research over the last ten years (refs. 5-7). Phase conjugate resonators differ from conventional resonators in some important ways. Two which are relevant to the optical storage device are; 1) the frequency of the light will shift or detune in a two-crystal oscillator to compensate for phase mismatches at the boundaries, and; 2) the structure of the light beam in the transverse direction, or the direction normal to propagation, is not subject to the same constraints as in the case of an optical resonator formed by two mirrors. First, the effect of frequency detuning on the design of the optical storage device will be addressed. According to theory and experiments, the frequency detuning is a function of the cavity length and can be changed by adjusting the length of the cavity (ref. 7). No frequency shift takes place provided that the cavity length is set so that the phase after one roundtrip is an integral multiple of 2π. However, maintaining this exact distance over time is difficult. In the optical storage device, a second feedback loop is provided to maintain the phase match if so desired. The total light output of the cavity is detected with a photodetector, the output of the photodetector is phase shifted, and the phase shifted signal is used to drive an acousto-optic modulator which amplitude modulates the write beam on the first crystal. By amplitude modulating the write beam, the phase of the phase conjugate wave can be varied and adjusted. In this way, the phase match at the boundaries can be maintained. The second difference stated above does not directly affect the design of the storage device, but is the fundamental reason why a phase conjugate resonator can be used to store holographic images. With conventional oscillators, where a beam of light oscillates between two mirrors (as in a laser cavity), only certain structures are allowed in the transverse direction. That is, because of the boundary conditions, and the conditions required for oscillation, the structure of the beam, or intensity profile, can take on only one of a set of distinct patterns. These patterns correspond to what are known as the transverse modes of the resonator (ref.8). When the mirrors of the conventional resonator are replaced with phase conjugate mirrors, the boundary conditions change. Theory predicts that the transverse modes are no longer restricted in form. Therefore, a very complex form or structure, or multiple transverse modes (of the form predicted for a conventional resonator) may be supported simultaneously within the cavity (ref. 6).

The structure, or lack of structure, in the transverse direction predicted for the phase conjugate resonator means that a wavefront of arbitrary phase and amplitude profile can be maintained in the resonator cavity. Therefore, theoretically, holographic image information can be stored as a complex wavefront in the cavity formed by two phase conjugate mirrors. This is the theory behind the operation of the optical storage device.

Experimental Results

Experiments have been carried out to study the image information storage capability of a two crystal oscillator (ref. 9). In figure 5 is a picture of the optical setup. The smaller photograph,, a picture of the Airforce Resolution chart, is the image output from the cavity of the two PCM resonator. For this particular setup, the gain of the cavity was slightly less than one. As a result, the image could not be retained for an indefinite period of time. Rather, the image was stored for approximately a minute. This represents more than a factor of 100 increase over the length of time the image could be stored in one crystal for the geometries and power levels which were used.

When the power levels and beam ratios were set such as to achieve a gain in the cavity in excess of 1.0, the transverse structure of the beam was corrupted for some of the experimental runs. A particular (repeatable) pattern emerged. This was not anticipated. According to theory, as described above, the transverse modes of a PCM resonator are degenerate, meaning that the energy of all transverse modes is the same. This being true, no one mode or combination of modes should dominate. Further experiments and analyses are required to explain the observed phenomenon.

The feedback described above for amplitude modulating the write beam was tested experimentally. The optical setup is shown in the diagram of figure 6. It was found that the ability to control the phase of the phase conjugate wave was limited by the amplifier which was used to phase shift the light signal. It was possible to affect the phase of the phase conjugate, but it was not possible to stabilize the oscillation with the setup that was used. Further experiments are planned along these lines.

Conclusions

A design has been proposed for an optical storage device which can store holographic information in two photorefractive crystals. The advantages of using photorefractive crystals is that these crystals provide the capability of recording holographic image information at near real-time rates and promise high storage densities. Potential applications for optical storage devices such as the one described in this paper include storage of holographic image information for distributed sensing and processing. A conceptual design of a distributed sensor and processor for large flexible space structures is described in reference 10. All of the techniques which have been developed for holographic sensing of structures using fixed media can now, with the development of a dynamic holographic recording media, be used to develop sensors which can measure the motion of structures.

The image resolution which can ultimately be achieved using photorefractive crystals is unknown. The resolution is a function of the size of the crystal. Techniques are currently being studied which will allow crystals of larger sizes to be grown. Presently, the crystals are limited in size to approximately 5 mm cubes ($BaTiO_3$). The growth of photorefractive thin films is also being explored. Thin films are much easier to grow, can be fabricated in much larger sizes, and require less time to grow than bulk crystals.

Using $BaTiO_3$ crystals, experiments have been carried to evaluate the operation of the two-crystal optical storage device. Thus far, good results have been obtained in the laboratory. An increase in image storage time on the order of 100 has been achieved using two phase conjugate crystals rather than a single phase conjugate crystal. Further studies are needed to refine the model and design for the two-crystal oscillator.

References

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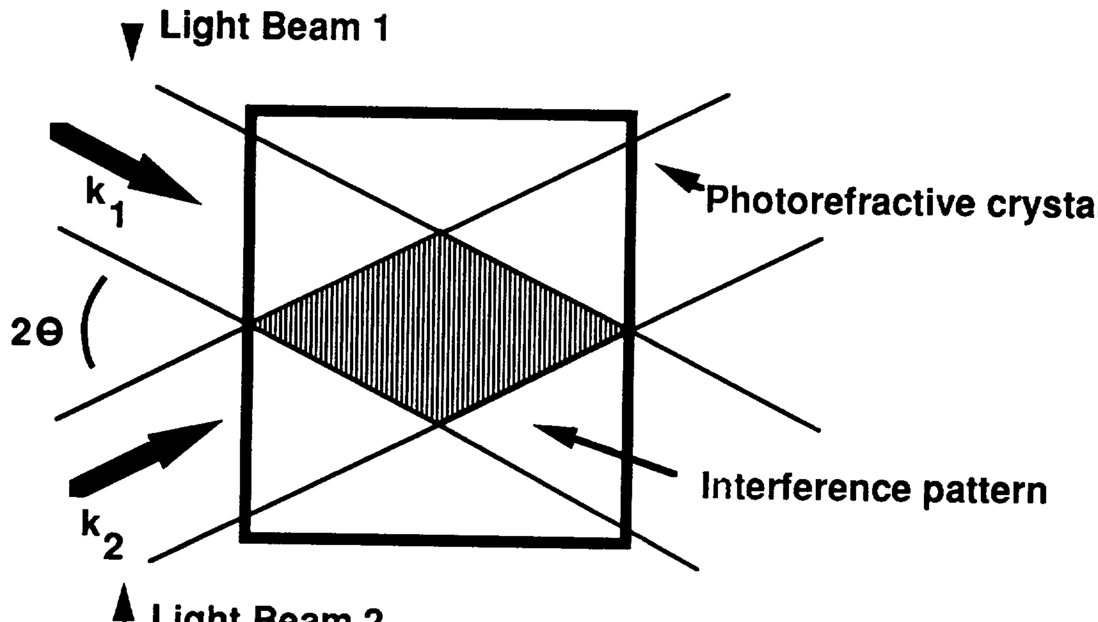
Figures

Figure 1.



$k=k_1-k_2$

Figure 1.

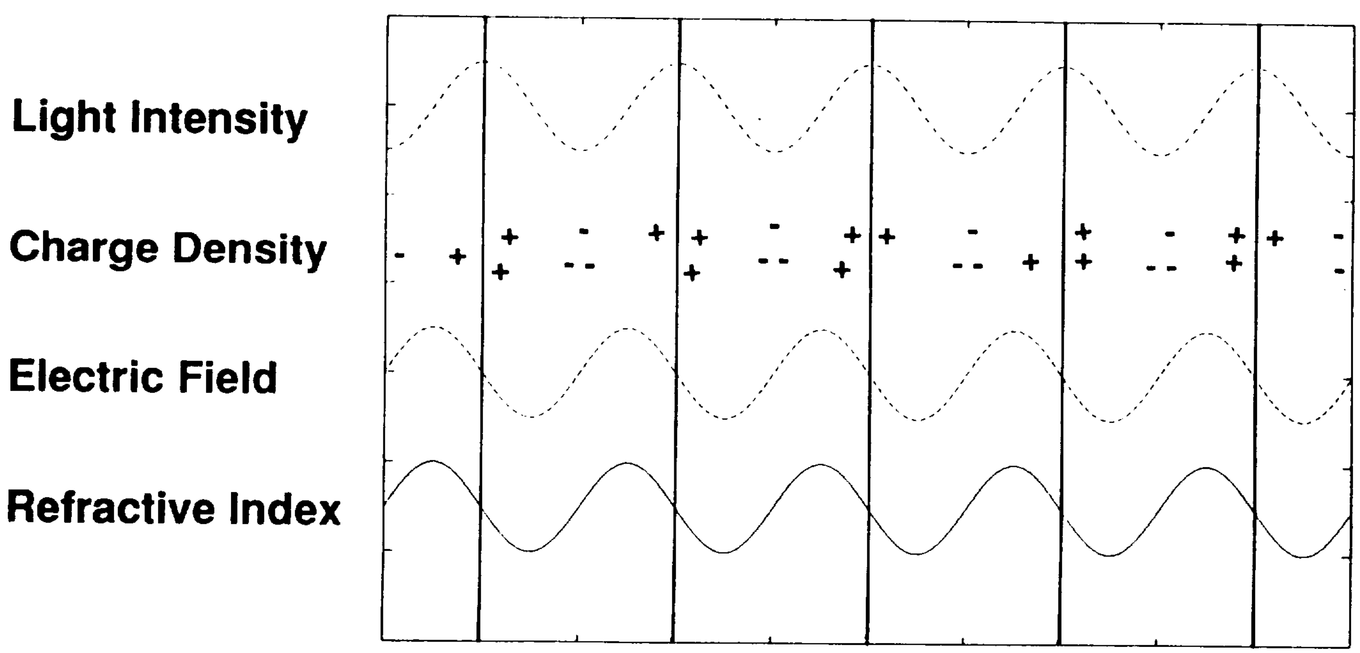


Figure 2.

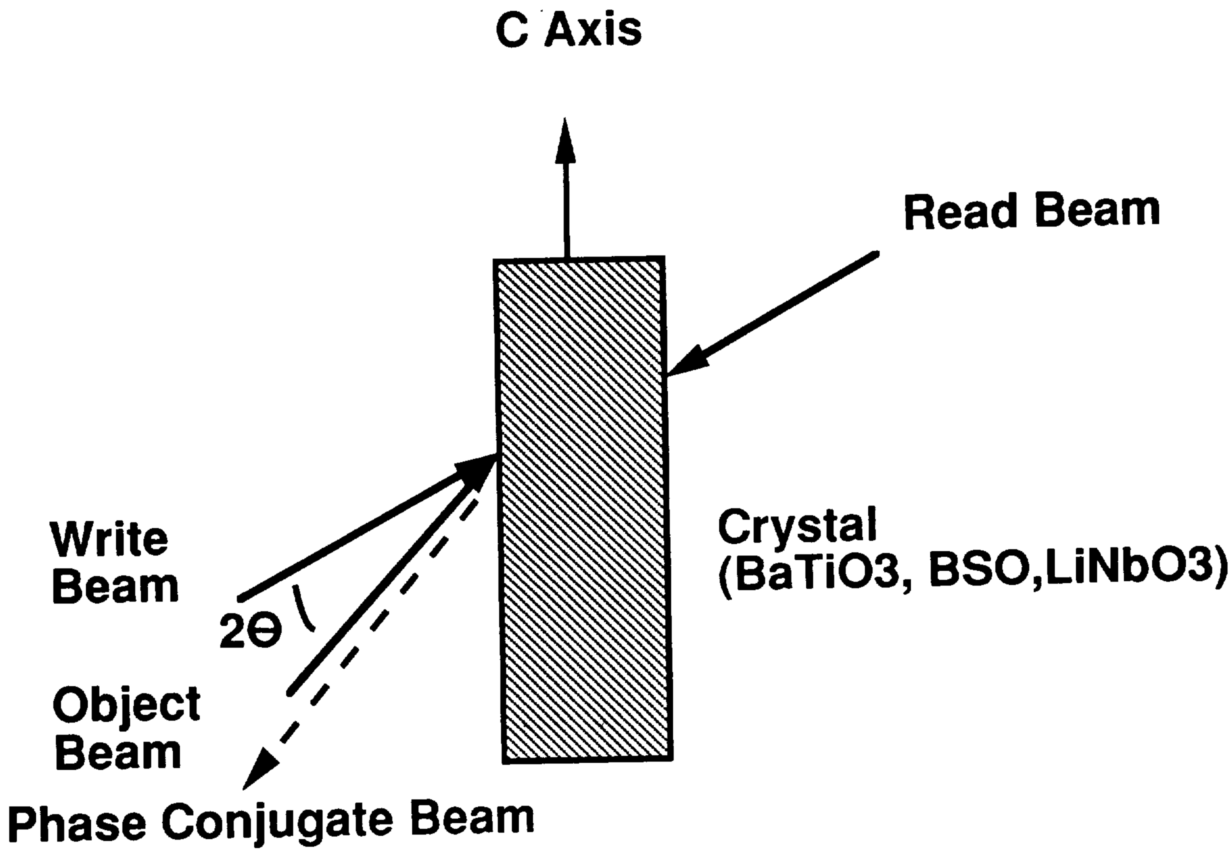


Figure 3.

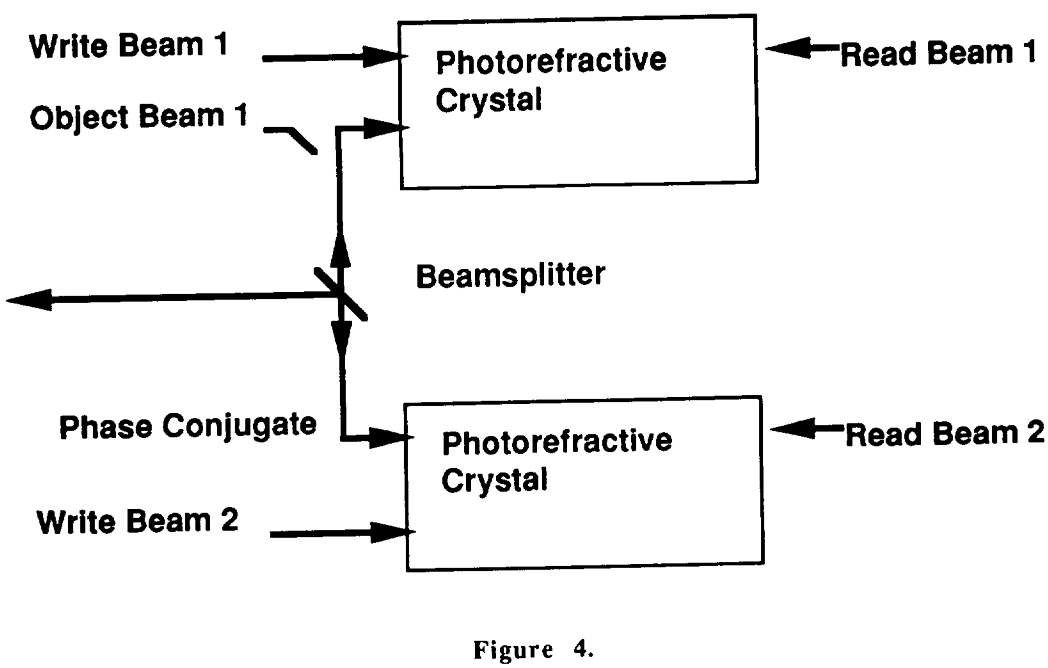


Figure 4.

Figure 5.

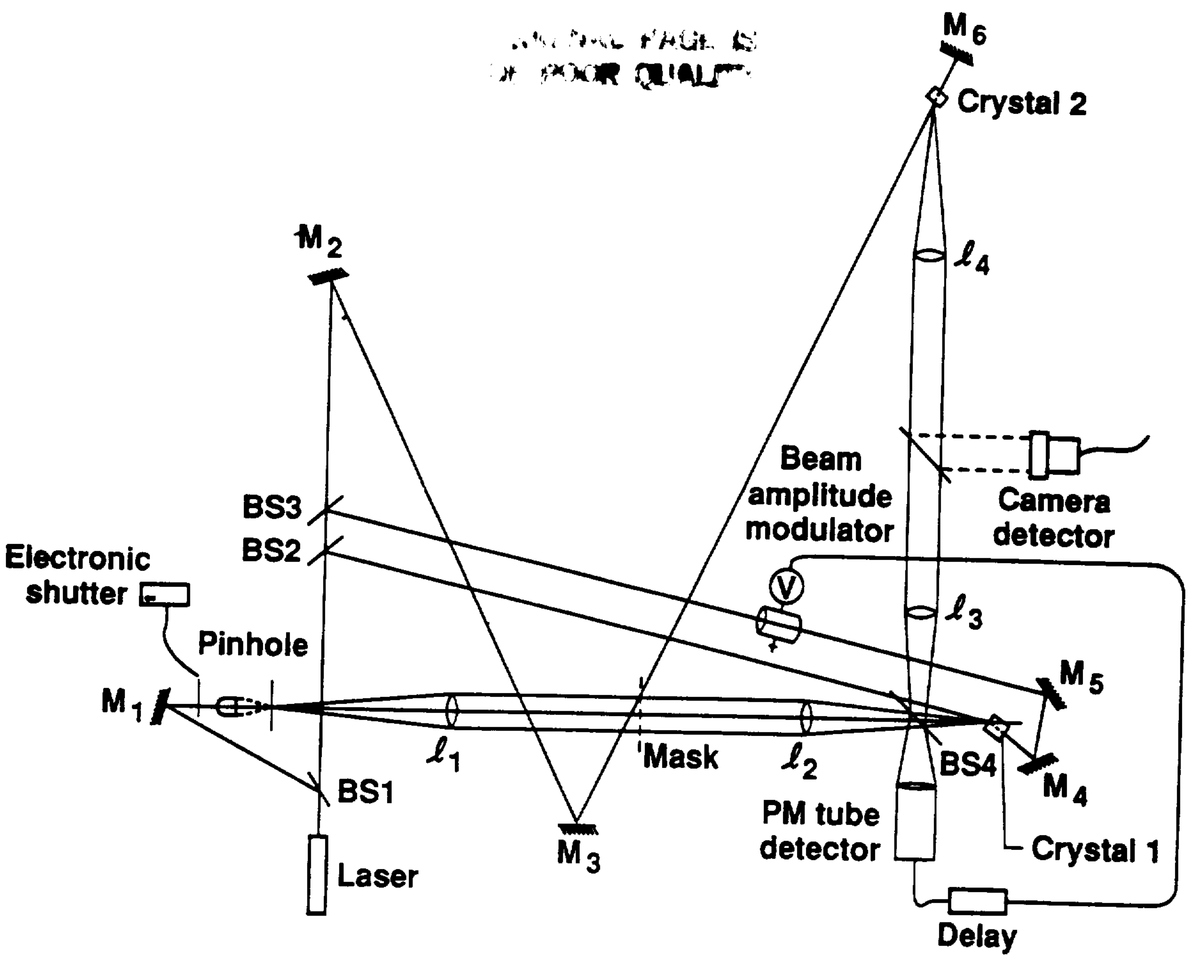


Figure 6.