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ILLUMINATION SYSTEM FOR A TIME-INTEGRATING CORRELATOR

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ILLUMINATION SYSTEM FOR A TIME-INTEGRATING CORRELATOR

by

N. Brousseau and J.W.A. Salt

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL NOTE 95-008

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September 1995
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Electronic Support Measures Section
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ABSTRACT

The purpose of this Technical Note is to present the design and performance of the illumination system for a tandem time-integrating correlator built at DREO. The requirements for the illumination system are analysed. The sub-systems of the illumination system (the beam attenuator, the beam expander and the beam splitter) are then described and experimental results on their performances are presented. The light budget of the illumination system is calculated.

RESUME

Cette note technique présente la mise en oeuvre et les performances du système d'illumination d'un corrélateur à intégration temporelle construit au CRDO. Les caractéristiques nécessaires au bon fonctionnement du système d'illumination sont analysées. Les composantes du système d'illumination (l'atténuateur, le collimateur et la séparatrice de faisceau) sont décrites ainsi que leur performances expérimentales. La quantité de lumière disponible au système est calculée.

EXECUTIVE SUMMARY

Time-Integrating Correlators (TIC) are analog optical computers designed to compare signals in applications such as DNA analysis, the processing of spread spectrum signals and searches in large unstructured data bases. One of the critical requirements for a TIC is the capability to produce correlation peaks of uniform height on the whole width of its aperture. This requirement generates important constraints on the illumination system. Another feature of the DREO TIC is its capability to operate with variable integration times. In order to avoid the saturation of the detector array, the intensity of the illumination has to be varied with the integration time and the signal strength. Finally, phase errors have to be kept under control to maintain the quality of the output signal.

The purpose of this Technical Note is to present the design and performance of the illumination system for a tandem TIC built at DREO. The requirements for the illumination system are analysed. The sub-systems of the illumination system (the beam attenuator, the beam expander and the beam splitter) are then described and experimental results on their performances are presented. The light budget of the illumination system is calculated.

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LIST OF ABBREVIATIONS

DREO	Defence Research Establishment Ottawa
RF:	Radio frequency
TIC:	Time-Integrating Correlator

1.0 INTRODUCTION

Time-Integrating Correlators (TIC) are analog optical computers designed to perform the correlation of two long duration, large bandwidth, data streams. TICs can be used to compare signals in applications such as DNA analysis [1], processing of spread spectrum signals [2-6] and searches in large unstructured data bases.

The purpose of this Technical Note is to present the design and performances of the illumination system for a tandem TIC built at DREO. Special attention will be given to the issues of light budget and quality of the beams required to operate the TIC.

2.0 ILLUMINATION REQUIREMENTS FOR TIME-INTEGRATING CORRELATORS

One of the critical requirements for a TIC is the capability to produce correlation peaks of uniform height on the whole width of its aperture. This requirement generates important constraints on the illumination system. Another desired feature of the DREO TIC is the capability to operate with integration times varying between 250 μs and 50 ms. Therefore, the illumination has to be kept at an optimal value by varying its intensity as a function of the integration time.

Finally, the control of the phase error at the output of the TIC is also an important issue. Phase error have multiple origins such as imperfect optical components, misalignment of otherwise perfect components, temperature changes[7] and atmospheric turbulence. The effect of phase error have been described in detail and a data collection method that tolerates a moderate amount of phase error has been proposed at DREO[8]. However, phase errors still have to be kept under control and optical components of a sufficient quality have to be used in the illumination system as in the other parts of the system, although diffraction limited performance is not required.

2.1 Approach to the Illumination System

The TIC for which the illumination system was built is described in Section 3. It includes a He-Ne laser producing a pencil beam of linearly polarized light with a Gaussian intensity profile and a diameter of .68 mm that passes through an attenuator. The attenuator consists of a polarizing cube beam splitter that is rotated to change the attenuation of the light. The Gaussian beam is then expanded by a beam-expander into a line of light with a uniform intensity. The line of light is finally separated into two identical beams propagating at an angle of 4.06 degrees. Each beam interacts with only one of the Bragg cells. The following sections contain details about the design, construction and performance of these components of the illumination system.

3.0 DESCRIPTION OF A TIME-INTEGRATING CORRELATOR

There are many ways to build optical TICs which are well documented in the literature [2-6]. We will consider here the tandem architecture [6] illustrated in Figure 1. This configuration has the advantage of producing a compact system that is rack mountable. Another advantage of this approach is that the two paths of the laser light are almost superposed thus making the TIC more resistant to vibration and atmospheric turbulence.

The first operation performed by a TIC is the transformation of the electrical signals a(t) and b(t) to be correlated into modulated light beams. The two input signals are applied to the piezoelectric transducers attached to the Bragg cells crystals and acoustic waves are generated. They propagate in the Bragg cells crystals thus forming a moving grating of changing indices of refraction. The two Bragg cells are then illuminated by expanded laser beams and the laser light interacts with the acoustic waves. For optimum illumination of the Bragg cells, the profile of the beams needs to be as uniform as possible. Some of the incident light is diffracted through the acousto-optic interaction thus transferring the information contained in the electrical signals to the diffracted laser beams. The signals propagating in the Bragg cells are imaged, with a lens, onto a linear array of light detectors in such a way as to be counterpropagating. The array of detecting elements performs a time integration of the coherent addition of the two images.

The correlation between the two signals a(t) and b(t) is mathematically described by:

$$f(t) = \int a(t)\, b(t-u)\, du \qquad \textbf{(1)}$$

If the variable z is the distance along the Bragg cells and their images, and if the origin z=0 is defined to be at the centre of the Bragg cells and, correspondingly at the centre of their images on the detector array, the optical signal diffracted by the Bragg cells are a(t+z/v) and b(t-z/v) where v is the velocity of propagation of the signal in the Bragg cells. The detected electrical signal, s(t,z) is proportional to the square of the light distribution:

$$s(t,z) \begin{array}{l} = |a(t+z/v) + b(t-z/v)|^2 \\ = a^2(t+z/v) + b^2(t-z/v) + 2a(t+z/v)\, b^* t-z/v) \end{array} \qquad \textbf{(2)}$$

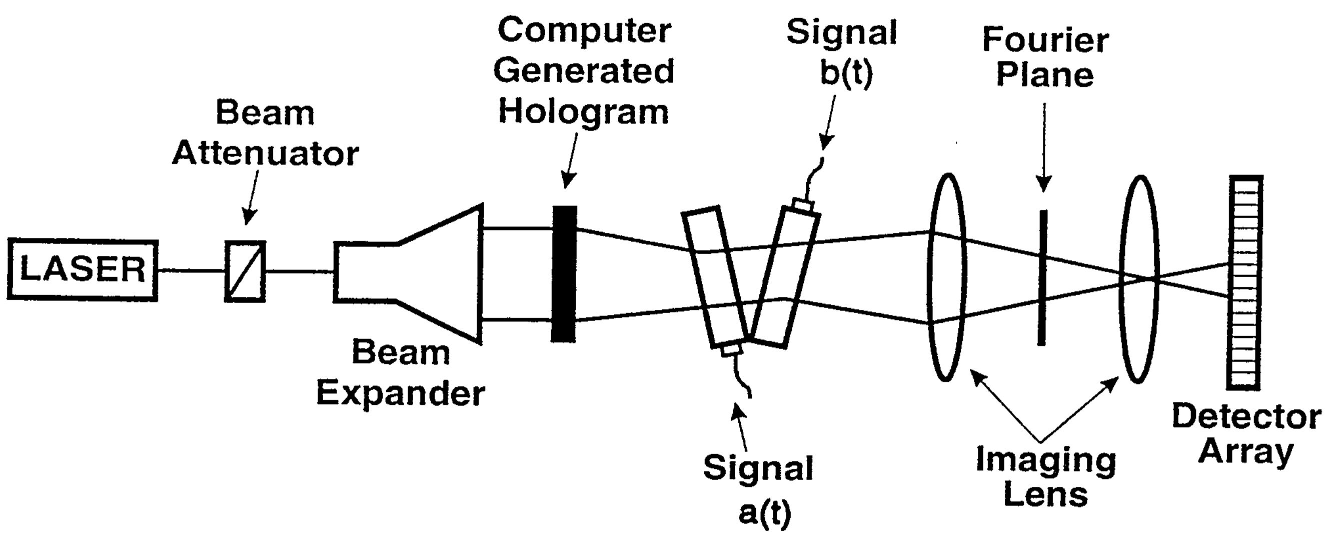

FIGURE 1: TIME-INTEGRATING CORRELATOR: TANDEM CONFIGURATION

This electrical signal is then time-integrated and the resulting signal S(T,z) is:

$$S(T,z) = \int [a^2(t+z/v) + b^2(t-z/v) + 2a(t+z/v)\, b*(t-z/v)]\, dt \quad \textbf{(3)}$$

The first two terms give a pedestal that has the shape of the illumination of the Bragg cells. The third term is the correlation, after an appropriate change of variable. A typical electrical signal S(T,z) produced by a detector array and an illumination with a Gaussian profile is illustrated on Figure 2.

The presence of a peak (see Figure 2) indicates that the two input signals a(t) and b(t) are identical and conversely the absence of the correlation peak indicates that the two inputs are different. Inspection of eq.3 shows that the height of the peak above the pedestal cannot exceed the height of the pedestal. As the maximum height of the peak above the pedestal is set by the height of the pedestal, the pedestal has to have a uniform amplitude over the width of the TIC aperture to ensure the formation of peaks with uniform height over the whole aperture of the TIC.

4.0 ATTENUATION OF THE LIGHT

The TIC is expected to operate with the integration time of the detector array varying between 250 μs and 50 ms and the light attenuator has to provide the capability to adjust, for optimal response, the illumination level from 50% to 85% of the saturation level of the detector for each integration time. The attenuator selected for the DREO TIC consists of a polarizing beam-splitter cube set on a rotation stage. A 45° rotation of the cube changes the intensity of the transmitted beam from 0.4% to 99.0% of the incident beam as illustrated in Figure 3. As the cube rotates, the polarization of the transmitted beams also rotates. The resulting polarization changes of the transmitted beam have little effect on the performance of the TIC because of the small angle between the beams diffracted by the Bragg cells. The range of attenuation provided by the attenuator is sufficient to allow the operation within the range of specified integration times as indicated in Figure 3. The rotation of the cube is motorized and controlled to one degree increments by a remote control.

5.0 BEAM-EXPANDER

The purpose of the beam-expander is to produce a uniform line of light for the Bragg cells with minimum phase error and minimum loss of light. To achieve a high efficiency expansion of the beam, the shape of the illumination pattern has to match, as closely as possible, the shape of the active area (1 mm x 35 mm) of the Bragg cells.

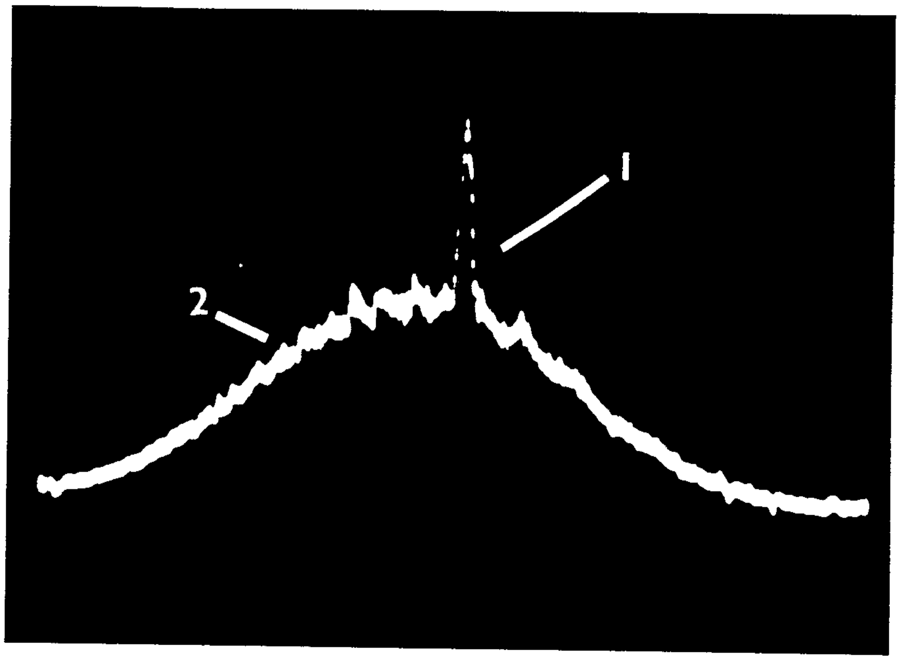

FIGURE 2: CORRELATION PEAK OVER A GAUSSIAN PEDESTAL:
1) PEAK
2) PEDESTAL

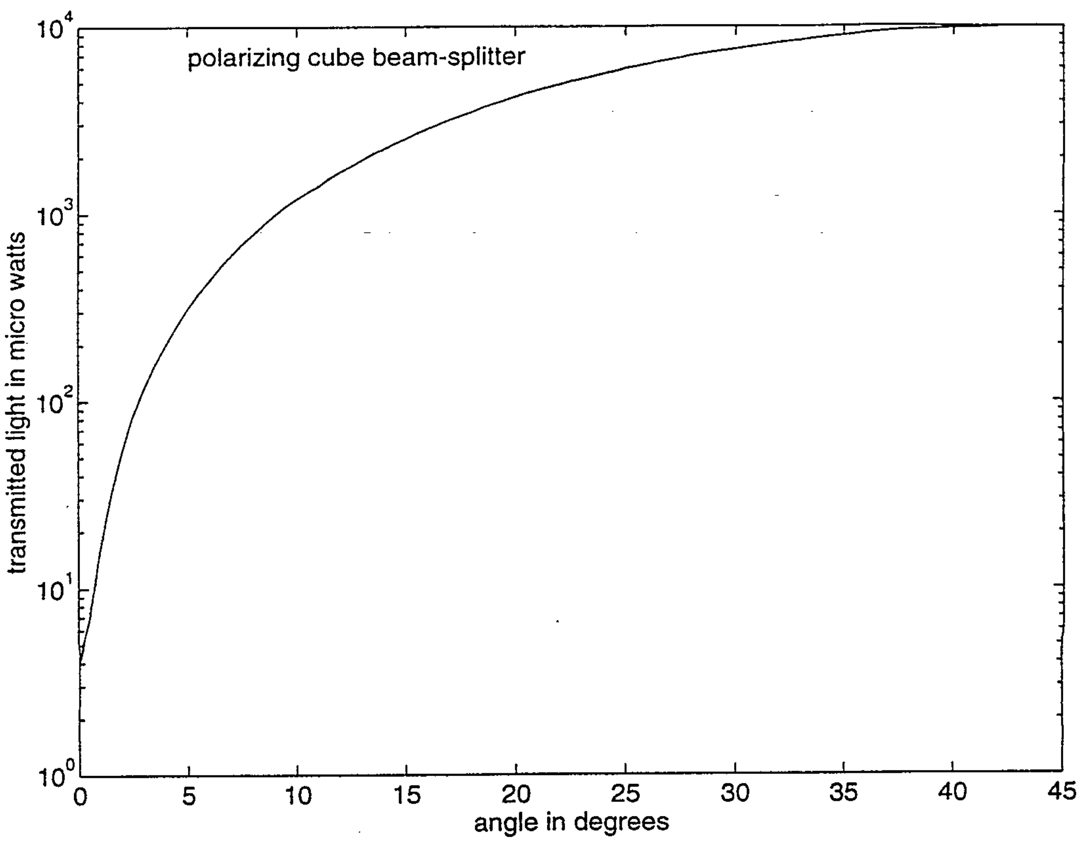

FIGURE 3: ATTENUATION OF THE POLARIZING BEAM-SPLITTER

5.1 Description

The beam-expander designed and constructed at DREO is illustrated in Figure 4. The Gaussian beam from the laser is expanded on the horizontal axis only, into a diverging line of light of uniform intensity by a special anamorphic lens. The diverging fan beam is then collimated by a lens of appropriate focal length.

5.1.1 The Powell lens.

The anamorphic lens used to perform the beam expansion was designed at NRC by Dr. I. Powell[9] for the purpose of transforming a parallel laser beam with a circular section and a Gaussian intensity distribution, into a diverging uniform line of light. The Powell lens has to be matched to the diameter and divergence of the Gaussian beam to be expanded. The lenses are available at low cost ($100) in a selection of diverging angles. The Powell lens has power only on one axis and leaves the light distribution from the laser unchanged on the other axis.

5.1.2 The collimating lens

The purpose of the collimating lens is to transform the diverging line of light produced by the Powell lens into a parallel one. The focal length of the collimating lens and the divergence of the Powell lens have to be matched in order to produce a line of light of the desired length. It is also required to keep the length of the beam expander to a minimum to facilite the construction of a compact TIC. A spherical lens, with a focal length of 250 mm, designed to collimate a spherical beam, was selected rather than a cylindrical lens of the same quality and focal length because of its lower cost and availability. They both would achieved the same results on the horizontal axis. However, the spherical lens adds some focal power to the vertical axis of the light distribution but that effect is not detrimental to the operation of the TIC.

5.2 Performances

The uniformity of the light distribution and the quality of the phase distribution produced by the beam expander described in section 5.1 were measured. The results are illustrated in Figure 5 and 6. Figure 5 illustrates the light distribution produced by the beam expander as detected by a 35 mm long, 5000-element detector array. The horizontal axis is in terms of pixels (px) or elements of the detector array. Each pixel is 7 μm x 7 μm. 80% of the light of the laser beam is sampled through the middle section (1mm by 35 mm) of the line of light that is used to illuminate the Bragg cells.

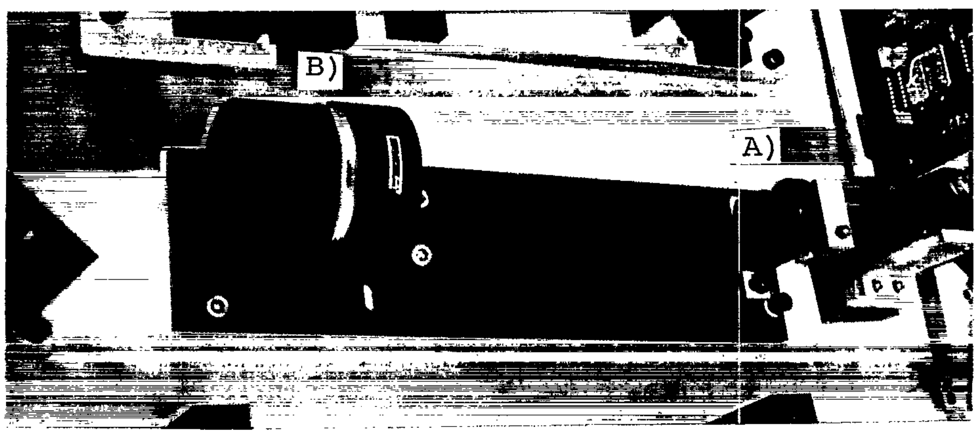

FIGURE 4: BEAM-EXPANDER
A) POWELL LENS
B) COLLIMATING LENS

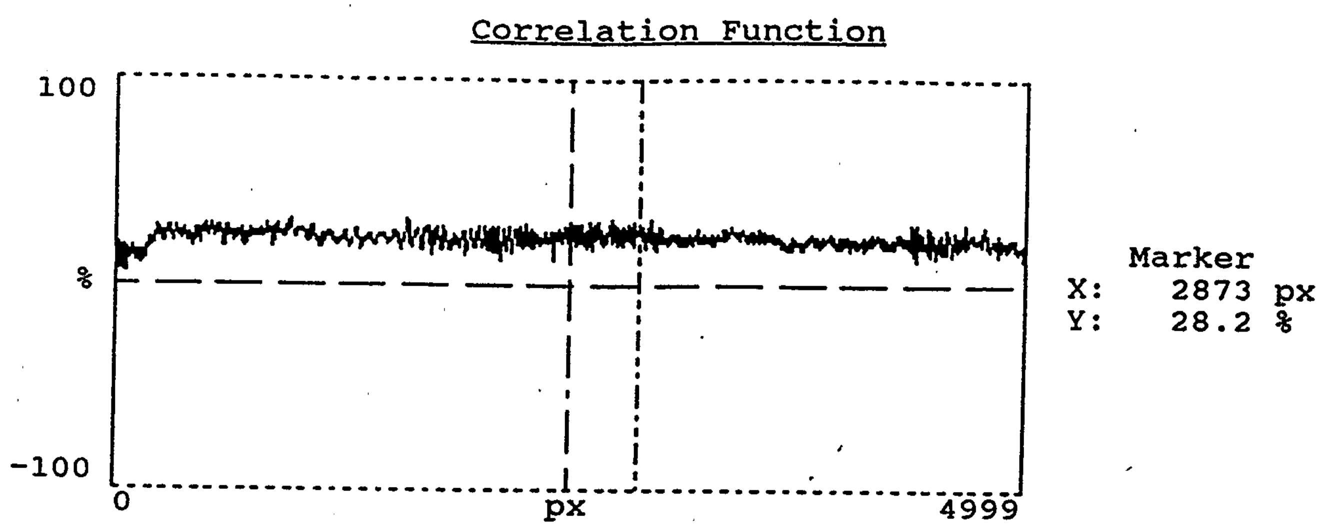

FIGURE 5: PROFILE OF THE LIGHT DISTRIBUTION PRODUCED BY THE BEAM-EXPANDER

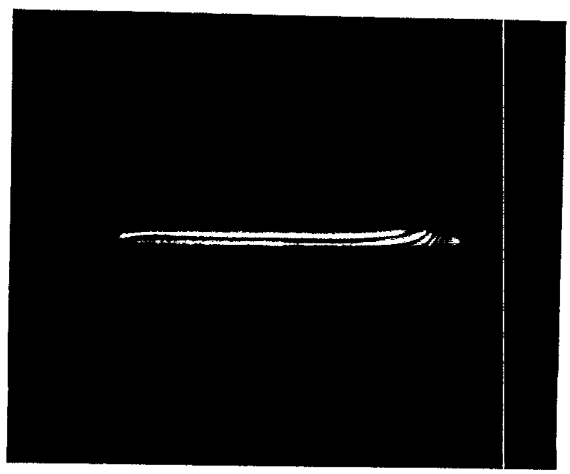

FIGURE 6: BEAM-SHEARING INTERFEROGRAM OF THE LIGHT DISTRIBUTION PRODUCED BY THE BEAM EXPANDER (ACTUAL SIZE)

The phase error was evaluated using a beam-shearing interferometer and the resulting 42 mm long interferogram is illustrated on Figure 6 (actual size). There is little phase error on the horizontal axis as evidenced by the fringes that are almost horizontal on that axis. The phase distribution exhibits some error at both end, indicated by the fringes curving upward at the right and downward at the left, but the middle 30 mm is error free. The fringe pattern on the vertical axis is caused by the focal power introduced on that axis by the spherical collimating lens of the beam expander. This is not detrimental to the detection of the correlation function because the elements of the detector array are only 7 μm high.

These results compare very favorably with the conventional expansion of a Gaussian beam performed by a commercial beam expander using spherical lenses and pinhole filter. In this case the expanded beam still has a Gaussian profile and only a small part of the middle section can be used if a uniform (within certain criteria) beam is desired. The performance of such system was measured for comparison purposes. The laser beam was expanded into a 50 mm diameter circular beam. An aperture of 1 mm x 35 mm located in the middle of the expanded beam was transmitting only 1% of the available laser power. The intensity variations from each edge to the middle 35 mm segment of the beam was 18 % (see Figure 7). Expansion of the beam with cylindrical lenses was not considered because of the cost of high quality cylindrical lenses, their difficult availability and because the expanded beam still retains its original Gaussian profile.

6.0 THE BEAM-SPLITTER

The function of the beam-splitter is to separate the line of light into two similar beams propagating at 4.06° from each other. This angle was calculated to illuminate the Bragg cells in such a way as to produce the fringe system required for the optimal detection techniques described in[8]. Ideally, the beam-splitter should produce only the two desired beams, each containing 50% of the incident light. However, in practice, many low intensity diffraction orders are generated.

6.1 Performances.

The beam-splitter used in the DREO TIC is a Dammann grating designed and constructed with diffractive optics technology [10]. The particular Dammann grating considered here is computer generated with a periodic binary phase modulation implemented in a photo resist layer.

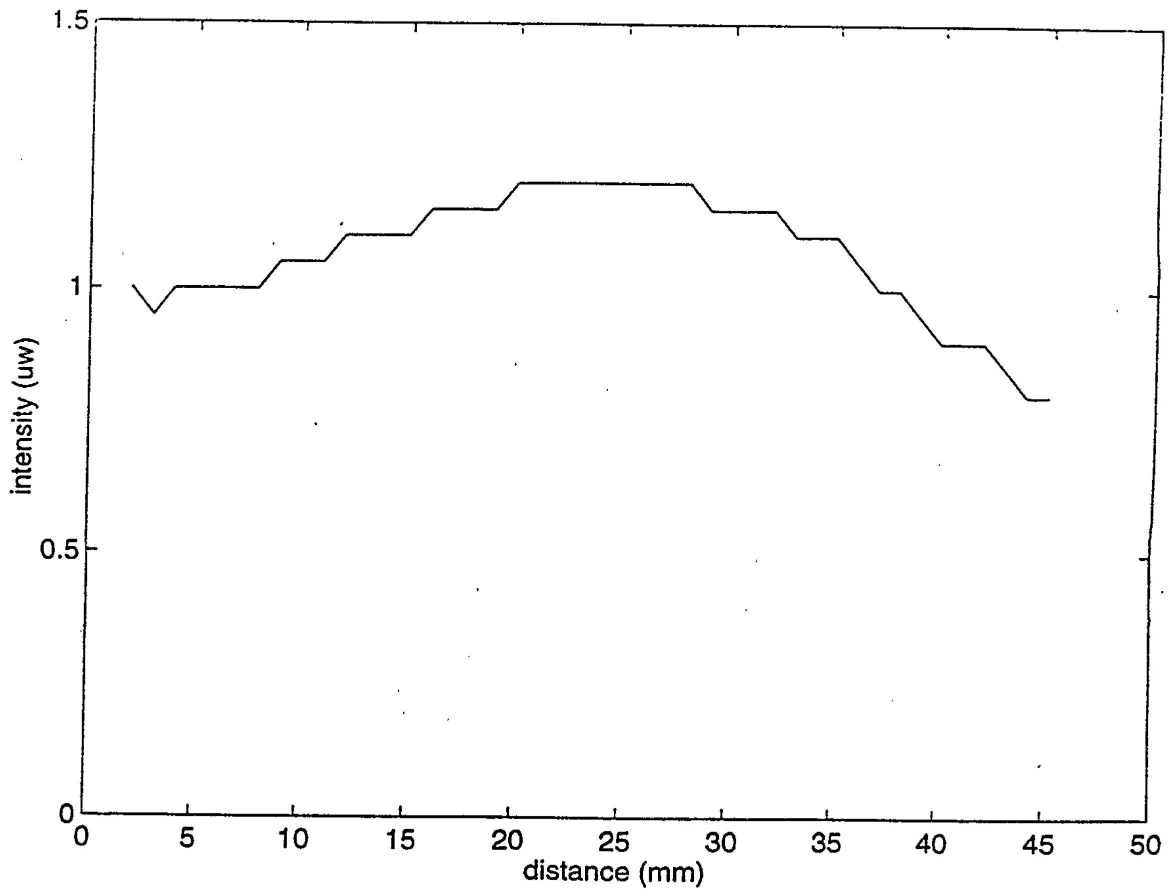

FIGURE 7: PROFILE OF THE LIGHT DISTRIBUTION PRODUCED BY A BEAM EXPANDER MADE OF SPHERICAL LENSES

6.1.1 Efficiency

The diffraction efficiency in the various orders of the beam-splitter was measured and is listed in Table 1. 5% of the light is reflected and 43.9% and 43.4% is diffracted respectively in the order +1 and -1 that are used to illuminate the Bragg cells. Some undiffracted light is directly transmitted (.17%) and can be removed by filtering in the Fourier plane with a small wire of appropriate size inserted in the imaging system. The diffraction efficiency was measured at many points on the 35mm by 35 mm Dammann grating and was found not to vary more than 1%.

TABLE 1: INTENSITY OF THE DIFFRACTION ORDERS OF THE DAMMANN GRATING BEAM SPLITTER

diffraction order %	diffraction efficiency
+4	0.18%
+3	4.6%
+2	0.1%
+1	43.9%
0	0.17%
-1	43.4%
-2	0.1%
-3	4.6%
-4	0.1%
reflected light	5.0%

6.1.2 Phase error.

The quality of the phase distribution produced by the Dammann grating beam-splitter was evaluated with a beam shearing interferometer. The interferogram of the incident illumination is shown as a reference in Figure 8a (actual size). The beam shearing interferograms of the +1 and -1 order are illustrated in Figure 8b (actual size) and 8c (actual size) respectively. It is possible to interpret these interferograms by remembering that a perfect, aberration free wavefront would give perfectly parallel and straight fringes. The distance between two fringes corresponds to one wavelength. The slight curvature observed in the three interferograms indicate the presence of a very small amount of aberration. It can also be noted that the Dammann grating add very little aberration to the illuminating beam. The aberration added by the Dammann onto an area of the size of the aperture of the Bragg cells (1mm x 30mm) is negligible.

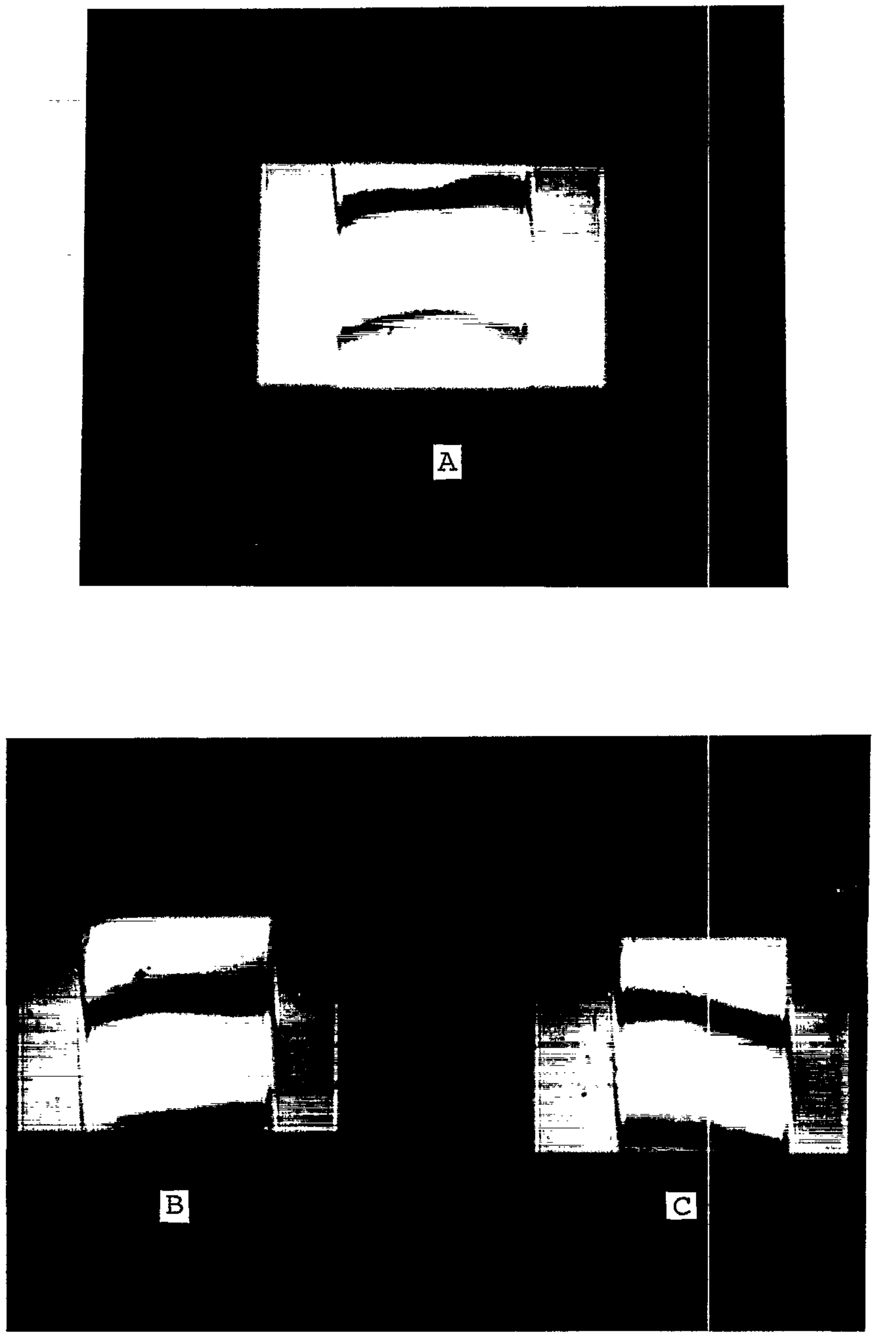

FIGURE 8: BEAM-SHEARING INTERFEROGRAM OF THE LIGHT DIFFRACTED BY THE DAMMANN GRATING (ACTUAL SIZE):
A) INCIDENT BEAM
B) ORDER +1
C) ORDER −1

7.0 EFFICIENCY OF THE ILLUMINATION SYSTEM

The energy efficiency of the illumination system of a TIC is defined as the percentage of light emitted by the laser that reaches the Bragg cells at the Bragg angle. In the case considered here the efficiency of the illumination system is the product of the efficiency of the three sub-systems used to build the illumination system. The attenuator, at maximum transmission, transmits 99% of the light it receives. The beam-expander produces a line of light that contains 80% of the incident light and the Dammann grating beam splitter diffracts 87% of the incident light into the +1 and -1 order to illuminate the Bragg cells. The efficiency of the illumination system is thus 69%. A 20 mw HeNe laser operating at a wavelength of 632.8 nm is currently used to illuminate the TIC. Improved efficiency allows use of lower power lasers that are cheaper, easier to package, with reduced heat generation and power consumption.

8.0 CONCLUSION

The requirements for the illumination system for a TIC have been analysed in term of the formation of correlation peaks of equal quality over the whole field of operation. The three subsystems (the beam attenuator, the beam expander and the beam splitter) have been described and their performances were measured. The beam attenuator can conveniently be adjusted between 0.4% and 99% of the incident laser light. The beam expander produces a line of light with uniform intensity and phase whose central 35 mm segment contains 80% of the light incident on the beam expander. The beam splitter produces two illumination beams that contain 87% of the light incident on it. The total efficiency of the illumination system is of 69% and the illumination produced has the intensity and phase uniformity required for the formation of correlation peaks over the whole field of operation of the TIC.

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