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HOLOGRAPHIC MODULATOR ARRAYS

Georgia Institute of Technology

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The report contains an assessment of the performance of a spatial light modulator concept known as double phase conjugate mirrors using a barium titanate crystal as the conjugating medium. It was concluded that these crystals are inaccurate for this application because of their low efficiency and speed. More research is necessary on new materials such as non-linear optical polymers to provide materials with the necessary response times to be useful in this application. It also contains an assessment of a method to write complex microwave antenna information onto laser beams in analog format. It was concluded that the performance of spatial light modulators that are currently available makes them unacceptable for this application.

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I. INTRODUCTION

The objective of this contract was the development of Spatial Light Modulator (SLM) concepts for direct writing of microwave antenna information onto laser beams in analog format. The problem can be divided into two parts. First, what encoding scheme is best? Second, what SLM is best?

II. USE OF SPATIAL LIGHT MODULATOR FOR ANTENNA SIGNAL PROCESSING

2.1 Introduction

Large radar antenna arrays record vast amounts of information that require very powerful computers for processing. Since we essentially deal with information contained in an electromagnetic wavefront, an ideal procedure would be to use optical methods for real-time parallel processing. Some of the conceivable optical operations are weight calculation, multipath suppression, optical phase adjustment and automatic frequency analysis[1]. To facilitate such processing it is necessary to write the time varying complex amplitude of the incident microwave directly onto a coherent laser beam. We would then have direct access to an analog optical computer. Although we address here the specific case of microwaves, the same procedure may be employed for detector arrays involved in the detection of any other wave phenomena such as ultrasonic systems.

In the next section we propose procedures for converting the complex amplitude of a microwave wavefront detected by elements in an antenna array into an optical wavefront. The procedure employs an interferometric system to coherently superpose two plane waves each modulated by a spatial light modulator (SLM). These are addressed by the information signal in quadrature. The present approach is reminiscent of a proposal by

Rhodes[2] for bipolar incoherent proccessing, a totally different application. The operating principles are described in the next section while some of the technical problems and their solutions are discussed in section III.

2.2 Wavefront Conversion

We assume an electromagnetic field represented by its scalar analytic signal,

$$E(x,y,t) = A(x,y,t) \exp j[\omega_m t + \phi (x,y,t)] \qquad (1)$$

incident on a microwave antenna array laid out on plane $z = 0$. The real, information carrying functions, $A(x,y,t)$ and $\phi (x,y,t)$ vary slowly as compared to the microwave frequency ω_m. Our objective is to imprint these two information carrying functions onto an optical wavefront to make optical processing methods applicable.

The microwave antenna detector array samples the field and converts it into voltage signals. Denoting by (x,y) the position of each antenna element we may describe the voltages as a two-dimensional time varying voltage signal,

$$V(x,y,t) = A(x,y,t) \cos [\omega_m t + \phi (x,y,t)] \qquad (2)$$

This signal can now be mixed with a local oscillator signal,

$$V_o(t) = R \cos (\omega_o) \qquad (3)$$

to generate, after proper filtering of the voltage distribution,

$$V_c(x,y,t) = RA(x,y,t) \cos [\omega_i t + \phi (x,y,t)] \qquad (4)$$

where

$$\omega_i = \omega_m - \omega_o \tag{5}$$

is any convenient intermediate frequency that may be chosen from 0 to ω_m depending on the devices employed.

Simultaneously, in a second channel, the local oscillator signal may be shifted by 90^o to obtain the complementary signal,

$$V_s(x,y,t) = RA(x,y,t) \sin [\omega_i t + \phi (x,y,t)] \tag{6}$$

To reconstruct the complete complex amplitude of the incident microwave, the two signals, (3) and (6) can now be superposed coherently with a phase shift of 90^o using a Twyman-Green interferometric setup as shown in Fig. 1. Depending on the nature of the spatial light modulators (SLM) employed the reconstruction may be implemented either by using non-negative signals or bipolar signals.

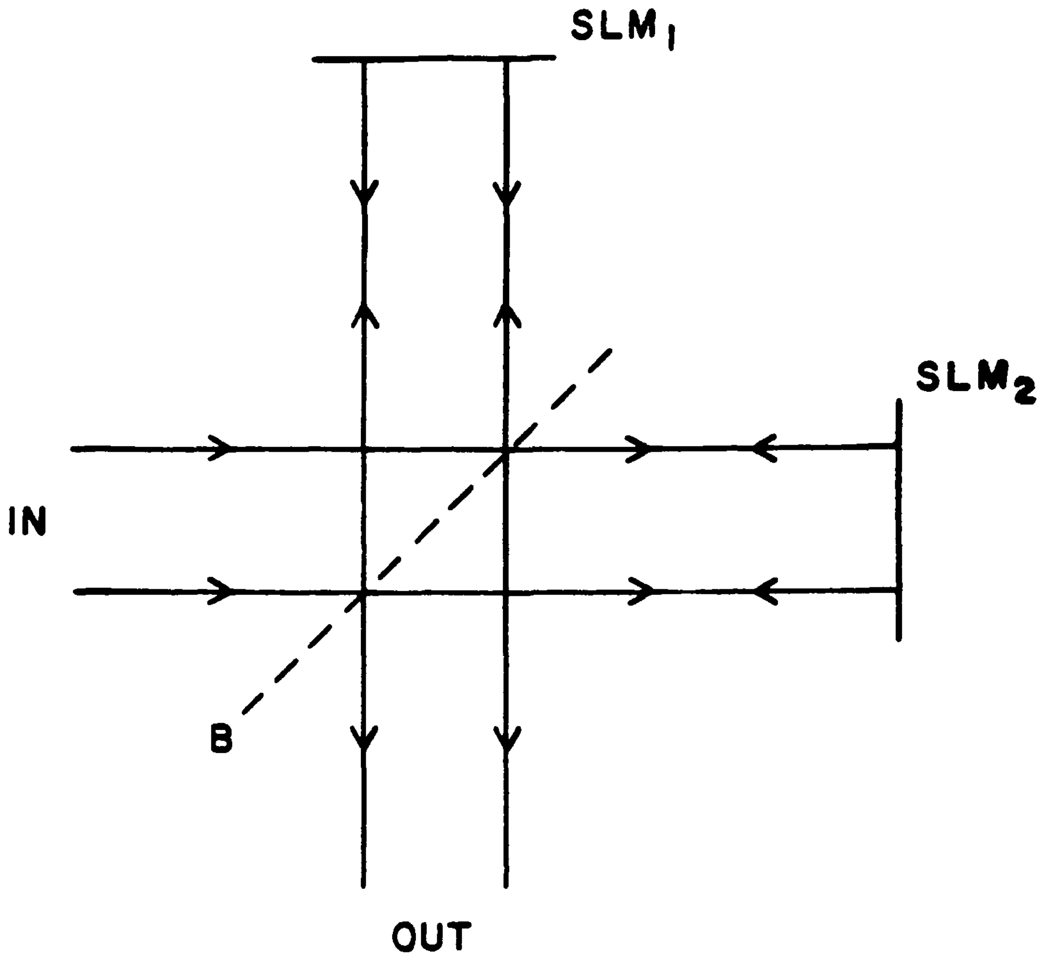

Fig. 1. Optical superposition system. Collimated laser beam from left is split by beam splitter, B to illuminate the two SLM's. A path difference is introduced to attain the 90^o phase shift. The reconstruccted wavefront emerges at the output port.

Non-negative signals. In conventional applications, spatial light modulators are used for modulating the amplitude of an incident coherent plane wave. For this kind of modulation one must use non-negative signals. The voltages of Eqs. (4) and (6) can be converted into non-negative signals by adding to the a.c. voltage of each pixel an appropriate d.c. term. One good choice for this term is the measured value,

$$2^{1/2} v_{rms} (x,y,t) \tag{7}$$

to yield the corresponding signals received by the SLM's,

$$V_1(x,y,t) = RA (x,y,t) \{1 + \cos [\omega_i t + \phi (x,y,t)]\} \tag{8}$$

and

$$V_2 (x,y,t) = RA (x,y,t) \{1 + \sin (\omega_i t + \phi (x,y,t)]\} \tag{9}$$

Illuminating the interferometer by a coherent plane wave and introducing an optical phase shift of 90^0 will produce the two visible wavefronts,

$$U_c = KA (x,y,t) \{1 + \cos [\omega_i + \phi (x,y,t)]\} \exp j\omega_v t \tag{10}$$

and

$$U_s = jKA (x,y,t)\{1 + \sin[\omega_i + \phi (x,y,t)]\} \exp j\omega_v t \tag{11}$$

where ω_v is the optical frequency and K is some proportionality factor.

At the output of the interferometer these two waves are coherently superposed to produce the reconstructed wave,

$$U (x,y,t) = KA (x,y,t)\{1 + j + \exp j[(\omega_i + \omega_v)t + \phi (x,y,t)]\} \tag{12}$$

The D.C. term can be removed by spatial filtering before further proccessing.

Bipolar signals. The progress in the development of spatial light modulators makes it feasible to add a binary phase modulation to the amplitude modulation. Using bipolar SLM's can reduce the step leading to Eqs. (8) and (9) by using the signals of Eqs. (4) and (6) directly in the interferometric system. The output will be similar to Eq. (12) but without the D.C. term.

2.3 Practical Considerations

The present state of art in various devices may present some difficulties in the implementation of the procedures proposed in the previous section but they can be overcome by proper design. The first obvious difficulty is the parallel addressing of all the pixels in the two input planes. Although the SLM's can be addressed directly by electronic signals, it seems more practical (for parallelism) to drive an LED with each antenna element, i.e., the spatially sampled signals of Eqs.(4) will be,

$$u_c(x,y,t) = KA^2(x,y,t)\cos^2[\omega_i t + \phi\ (x,y,t)]\ \exp j\omega_v t$$
$$= 0.5\ \{KA^2(x,y,t)\ \{1 + \cos 2[\omega_i t + \phi(x,y,t)]\}\exp j\omega_v t\} \qquad (13)$$

that is similar to Eq. (10) but the amplitude information is squared and the phase is doubled. The squaring of the amplitude usually has no disturbing effects while the phase doubling may cause appreciable distortions. In several cases (i.e., when the phase is approximately linear and the amplitude does not carry much information) these distortions induced by the squaring of the signal are unacceptable, one may use an electronic preprocessing on each signal element.

To generate the shifted signal for the second SLM, here only a phase shift of 45^0 is required to obtain the sine signal after squaring:

$$u_s(x,y,t) = KA^2(x,y,t)\cos^2[\omega_i t + \phi(x,yt) + \pi/4] \exp j\omega_v t$$
$$= 0.5\,(KA^2(x,y,t)(1 + \sin 2[\omega_i t + \phi(x,y,t)]) \exp j\omega_v t) \quad (14)$$

As before, the optical phase shift is introduced by a quarter wave path difference in the interferometric setup. To maintain this path difference constant one can use a few pixels in each SLM as reference and control the phase shift through a feedback loop.[3]

To complete this section one should point out that the performance of presently available SLM's is far from satisfactory for perfect wavefront reconstruction. Actually most performance characteristics are to be improved, including speed of response, dynamic range, linearity and resolution. Regarding resolution, one does not need more than that available on the antenna array. Linerarity can be produced artificially by electronic preprocessing to take into account known nonlinearities in the response of the SLM. The other imperfections will induce distortions the accceptance of which depends on the specific application.

2.4 Conclusions

A procedure was proposed to write the amplitude and phase information received by an antenna array onto a coherent laser beam. This procedure enables one to employ the highly parallel processing capabilities of optical system for processing any spatially sampled electronic signal.

Addressing technical problems we indicated that the implementation of the process with the performance limitations of presently available SLM's would require various degrees of electronic preprocessing of the signal elements.

III. WHAT SLM IS BEST?

Existing SLMs lack both speed and resolution. We believed that Double Phase Conjugate Mirror (DPCM) operation could be frustrated by an external incoherent beam thus writing the incoherent image onto both DPCM beams in negative form. Laboratory tests, however, showed that, while the expected result was obtained, the $BaTiO_3$ crystal used was far too slow (seconds) and far too insensitive in frustration (~ 1 mw/mm^2) to be useful. Some organic materials hold promise if they can be made to work. To determine this we performed a detailed theoretical and experimental analysis spatio-temporal modulation in DPCM

3.1 Introduction

In a recent work[4,5] we demonstrated that an appreciable fraction of a temporally modulated light beam may be deflected and directed into the source of a second, mutually incoherent beam, by using a photorefractive crystal. Simultaneously, a fraction of a second beam is deflected towards the source of the first one. Each deflected beam is spatially modulated with the complex conjugate of the transverse complex amplitude distribution of the other one. The physical process can be clarified with the help of Figure 2. The two beams 2 and 4 that may be derived from two independent lasers are incident on the photorefractive crystal, PR. The two generated beams 1 and 3 carry the respective temporal modulation of 2 and 4 and the respective phase conjugate of the transverse distributions of beams 4 and 2. (This peculiar numbering system is adopted for historical reasons only). The phase conjugation effects were studied earlier[6] only with c.w. illumination. In Ref. 7 it was shown that the quality of the phase conjugation is adequate for coupling beam 1 into a single mode optical fiber that carried the temporally modulated beam 2 from a remote laser. These results[5] indicate that temporal modulation has no appreciable influence on the double phase conjugation effects.

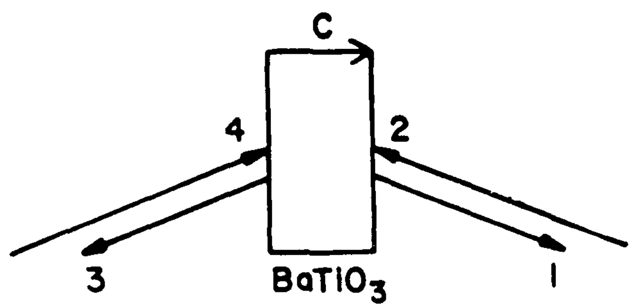

Fig. 2. Basic beam arrangement in the photorefractive medium.

Additional experiments described in the next section while a theoretical explanation is given in section 3.3 deriving the potential bandwidth of a communication system. An exact theoretical treatment would require a complete three-dimensional solution of the wave equations in a medium which is not yet completely understood. The semi-quantitative theory developed here is an extension of the approach followed in Ref. 7. The resulting mathematical description accounts for the high quality reconstruction of the transverse information and is adequate to estimate the allowable modulation bandwidth.

3.2 Modulation Experiments

The essential parts of the experimental system are shown in Fig. 3. Experiments were performed with beams 4 and 2, sometimes from a single He-Ne laser and also from two independent lasers. The various phenomena reported here were not dependent on the specific sources used except for issues involving absolute power that could be scaled accordingly. For convenience, the experiments described here were performed uniformly with a single Argon laser using path differences exceeding the coherence length. The photorefractive material was a poled $BaTiO_3$ single crystal. Temporal modulation was detected by the two detectors, D_1 and D_2, and the wavefront reconstructions could be observed on the screens, S_1 and S_2. For low frequency modulation we used mechanical choppers while high frequency measurements were made with acoustooptic modulators.

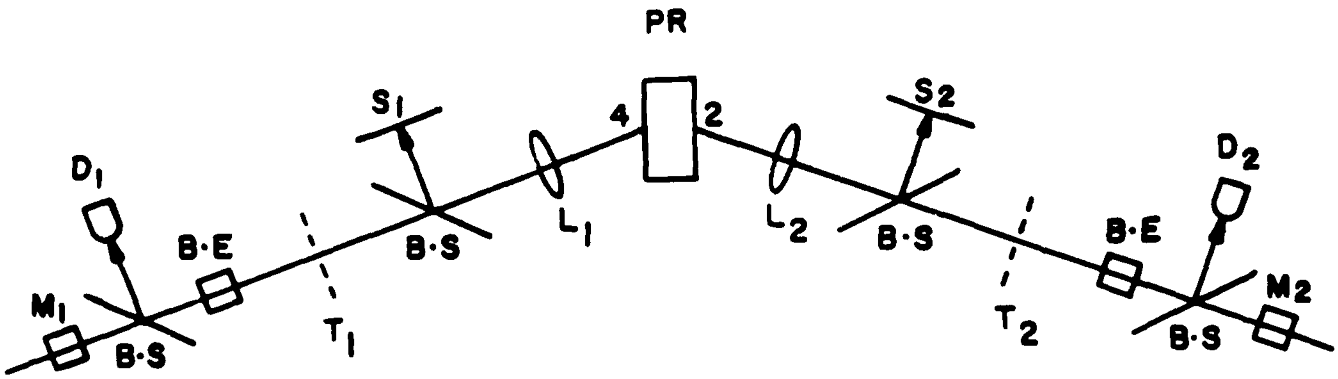

Fig. 3. Relevant part of experimental system: M - modulator, B.S. - beam splitter, B.E. - beam expander, T - transparency, S - observation screen, L - lens, D - detector, PR - photorefractive material.

When the two modulators were operated at different frequencies the modulated signals were observed by the two detectors with no detectable trace of coupling between them. The present high frequency limits of our equipment (square pulses of one microsec.), indicated no distortion. (The apparent distortions visible in Fig. 4 are due to the detection system). Therefore, the upper frequency bound could be estimated only theoretically to be above 3 GHz, as shown in the next section. The lower bound, however, is much easier to access experimentally.

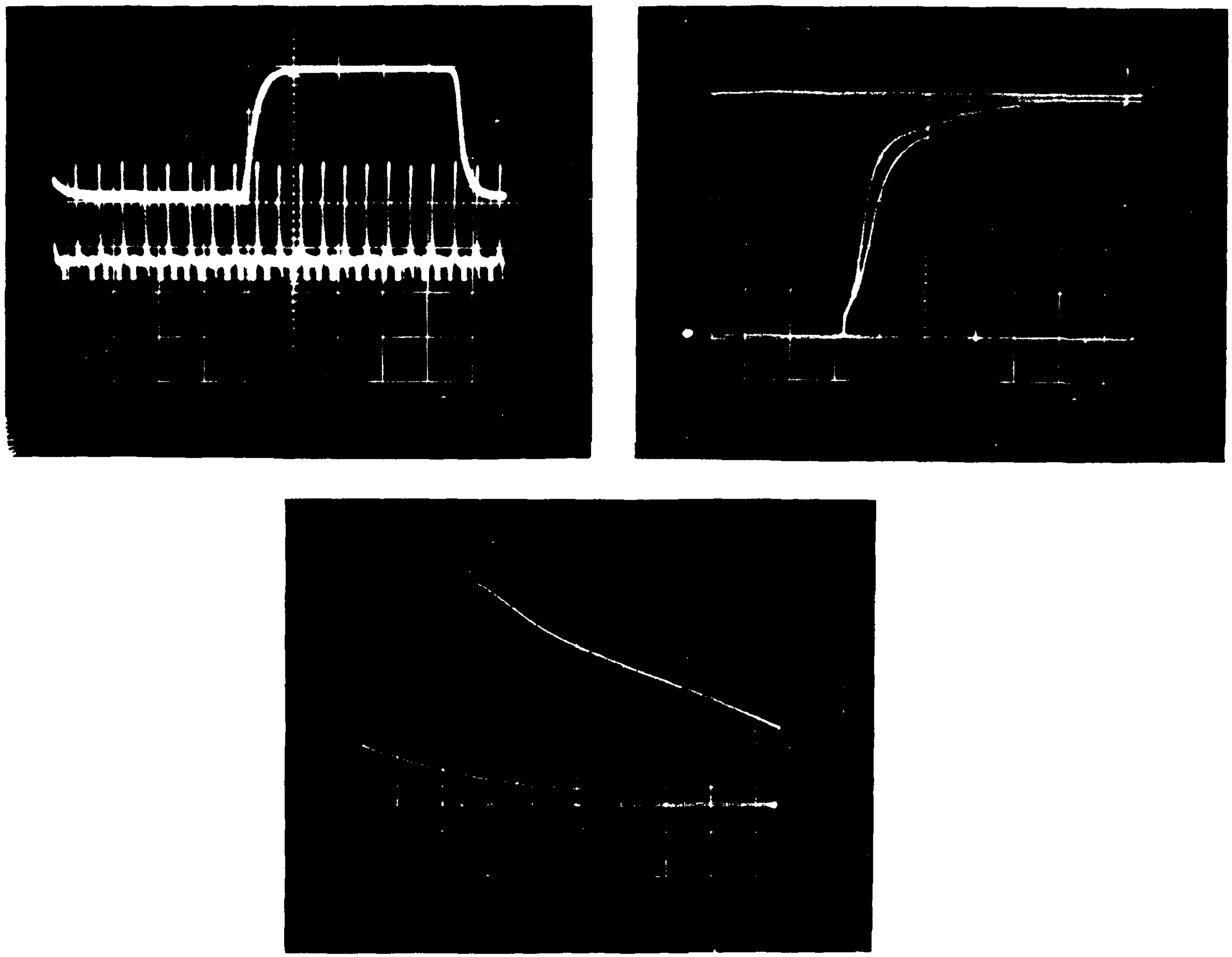

Fig. 4. Simultaneous detection of the two modulated and phase conjugated beams. (Time scale is 0.2 msec/div.)

Most of the phenomena observed with photorefractive materials depend roughly on some time integral of the power until a steady state is obtained. This is not the case regarding the efficiency of the beam coupling in the present configuration. Defining a coupling efficiency as the ratio between the intensity of beam 1 and the intensity of beam 4 (and likewise, the intensity ratio between beams 3 and 2), the highest efficiency is obtained when the intensities of 2 and 4 are approximately equal[6]. It turns out that this is the case also for temporal squarewave periodically modulated beams with the intensities measured around their maximal values. The reason is that the diffraction efficiency of the photorefractive gratings is determined by maximum interference fringe contrast as long as the slow decay is ineffective. Nevertheless, the grating buildup time depends on the total integrated power as indicated in Fig. 5a. The lower horizontal line in the figure represents the zero intensity level at the detector of beam 1 in Fig. 2. As a shutter on beam 2 is opened there is a small jump due to scattered noise and then beam 1 is generated until it reaches the saturation level--the upper horizontal time. The rise-time is much faster for c.w. illumination (upper curve) than when beam 2 is chopped with a duty cycle of 50% (lower curve) but the same saturation level is finaliy reached.

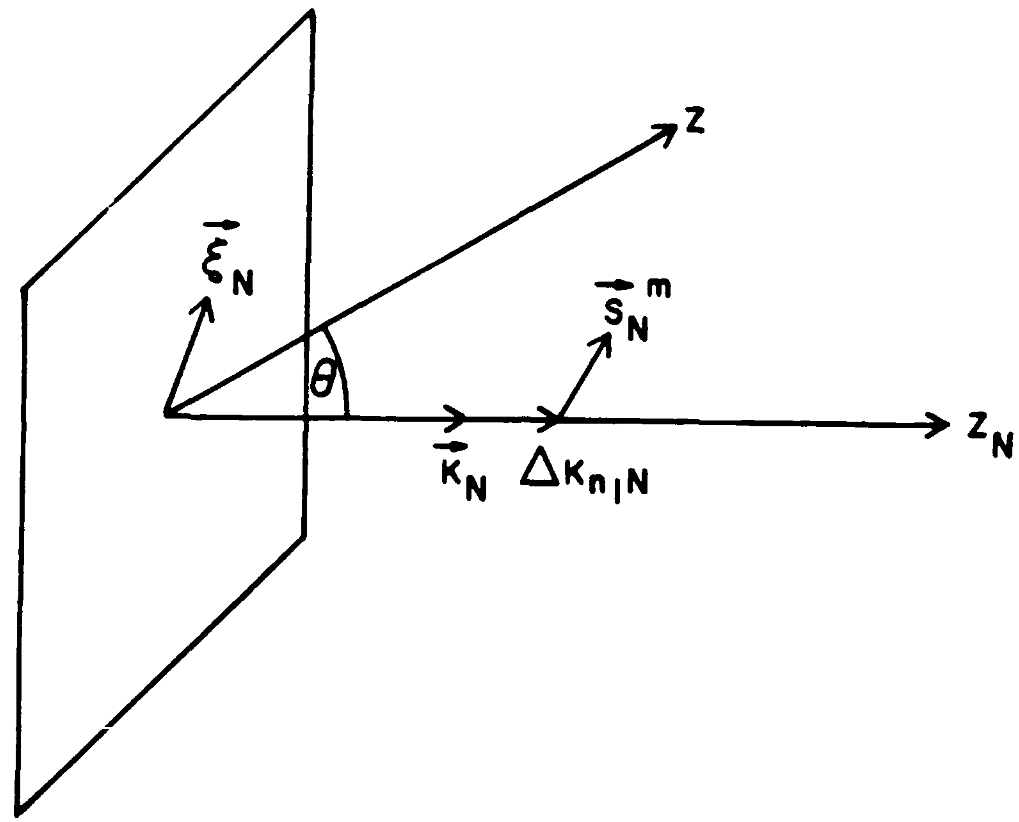

Fig. 5. (a) Signal recovery: Upper line with c.w. illumination, lower line with chopped illumination.
(b) Signal degeneration--lower lines are continuation of upper line. (Time scale is 1 sec/div.)

The line in Fig. 5b shows the intensity of beam 1 as beam 2 is blocked. This line represents the decay of the holographic grating in the crystal while the "read beam", 4, simultaneously reads and erases the hologram. The decay time depends strongly on the beam power and environment (temperature, ambient light etc.). In practice, this decay time puts a lower bound on the modulation frequency. As long a the modulation period is appreciably shorter than the decay time, the diffraction efficiency will stay constant. However, if the modulation frequency drops below some limit, a cross-modulation occurs between the two incident signals. Since the limiting frequency is below 1Hz, as indicated by the results for most currently available materials and power ranges, this effect may be ignored for all communication purposes.

Similar to the results reported in Refs. 6 and 7, any transverse spatial modulation was phase conjugated by the proper beams and there was no coupling between the spatial information contents on the two sides of the crystal. Temporal modulation had no detectable effect on these spatial phase conjugation phenomena.

3.3 Theory

The illumination of a photorefractive medium generates several scattered beams that produce gratings due to interference[8]. In our case we assume two independent "write" beams (2 and 4 in Fig. 2) and consider two of the generated beams, 1 and 3. The respective fields of these four beams can be written in the form,

$$E_N(\vec{x},t) = e_N(\vec{x},t)\ \exp\ [i(\vec{k}_N\cdot\vec{x}-\omega_N t)] \quad ; N = 1,2,3,4 \tag{15}$$

The slowly varying amplitudes, $e_N(\vec{x},t)$, carry the spatial and temporal modulations. In most cases of interest the temporal modulations are independent of the spatial modulations. Therefore, one may expand the temporal contibution into a Fourier series:

$$e_N(x,t) = \sum_n A_{n,N}(x)\ \exp\ [i\Delta k_{n,N}Z_N - \Delta\omega_{n,N}t)] \tag{16}$$

For convenience, in each of these four relations (one for each N), we defined a separate coordinate system with its z coordinate along the general direction of propagation, k_N (Fig. 6) and its origin, z=0, at the photorefractive crystal entrance surface. The temporal modulation components, $\Delta\omega_{n,N}$ are constants Maxwell's equations require the dispersion relation,

$$c \left| \vec{k}_N + \Delta\vec{k}_{n,N} \right| = \omega_N + \Delta\omega_{n,N} \tag{17}$$

where c is the velocity of light.

Fig. 6. Notations in the local coordinate system.

We proceed by expanding the coefficients n Eq. (16) in a spatial Fourier series.

$$A_{n,N}(x) = \sum A_{mn,N} \exp\left(i\vec{s}_{m,N} \cdot \vec{\xi}_N\right) \tag{18}$$

where $s_{m,N}$ are the components of the wave-vector modulation and ξ_N is the transverse position vector in the local coordinate system. Substitution into Eq. (16) leads to

$$e_N(x,t) = \sum_{n,m} A_{mn,N} \exp\left[i\left(\Delta k_{mn,N} Z_N + \vec{s}_{m,N} \cdot \vec{\xi}_N - \Delta\omega_{n,N} t\right)\right] \tag{19}$$

when the wave-vector $\Delta k_{n,N}$ is modified to satisfy the dispersion relation,

$$c \left| \vec{k}_N + \Delta\vec{k}_{mn,N} + \vec{s}_{m,N} \right| = \omega_N + \Delta\omega_{n,N} \tag{20}$$

applicable for all the possible terms in (8). We should emphasize that in the undepleted beam approximation, $\Delta\omega_{n,N}$, and $\vec{s}_{m,N}$, (N = 2,4) are determined by the initial conditions from which we obtain $\Delta k_{m,n,N}$ according to Eq. (20). The values of $\Delta\omega_{n,N}$ and $\vec{s}_{m,N}$ for N = 1,3 will be discussed later.

As the various beams propagate through the photorefractive crystal, the coefficients in Eq. (19) vary with position and time. Neglecting absorption and scattering losses these variations are solely given by diffraction by the photorefractive gratings. Since the two write beams are mutually incoherent those grating can be generated only by beams 4 with 1 and 2 with 3 that must be pairwise mutually coherent. We are also interested in the transmitted beams that involves transmission grating thus the whole coupling process of interest here may be described by the equations[7,8],

$$\cos\theta_1 \frac{\partial e_1}{\partial z} = -\frac{\gamma}{I_0}\left(|e_4|^2 e_1 + e_2^* e_4 e_3\right) \tag{21}$$

$$\cos\theta_3 \frac{\partial e_3}{\partial z} = \frac{\gamma}{I_0}\left(|e_2|^2 e_3 + e_2 e_4^* e_1\right) \tag{22}$$

where we returned to a common coordinate system (Fig. 6) employing the relation,

$$Z_N = Z \cos\theta_N \tag{23}$$

and, γ is a coupling constant of the photorefractive material and I_0 is the total light intensity involved.

Recalling the slow response of the photorefractive material we may substitute relation (19) into (21) and (23) and, for a stationary solution, reject all time varying terms. Using the orthogonality of the Fourier expansion terms we may finally write equations (21) and (22) in the term by term form:

$$\cos\theta_1 \frac{\partial A_{m_1,n_1,1}}{\partial z} = -\frac{\gamma}{I_0} [(\sum | A_{mn,4} |^2) A_{m_1,n_1,1}$$

$$+ \int d\vec{\xi}_1 \sum \sum \sum A^*_{m_2,n_2,2} A_{m_3,n_3,3} A_{m_4,n_4,4} S] \qquad (24)$$

and

$$\cos\theta_3 \frac{\partial A_{m_3,n_3,3}}{\partial z} = \frac{\gamma}{I_0} [(\sum | A_{mn,2} |^2) A_{m_3,n_3,3} \qquad (25)$$

$$+ \int d\vec{\xi}_3 \sum \sum \sum A_{m_2,n_2,2} A^*_{m_4,n_4,4} A_{m_1,n_1,1} S']$$

where S is given be the relation,

$$S = \exp i[(-\Delta k_{m_2,n_2,2} Z_2 + \Delta k_{m_3,n_3,3} Z_3 + \Delta k_{m_4,n_4,4} Z_4 - \Delta k_{m_1,n_1,1} Z_1$$

$$- \vec{s}_{m_2,2} \cdot \vec{\xi}_2 + \vec{s}_{m_3,3} \cdot \vec{\xi}_3 + \vec{s}_{m_4,4} \cdot \vec{\xi}_4 - \vec{s}_{m_1,1} \cdot \vec{\xi}_1)] \qquad (26)$$

A similar relation applies for S' but with indices 4 and 2 interchanged as well as 1 and 3. Note that S and S' are independent of time due to the coherence requirements as discussed earlier, i.e.,

$$\Delta\omega_{n,3} = \Delta\omega_{n,2} \qquad \Delta\omega_{n,1} = \Delta\omega_{n,4} \qquad (27)$$

which makes it possible to cancel the time dependent factors. This shows that the requirement for a stationary solution implies the transfer of the temporal modulations from beam 4 to beam 1 and from beam 2 to beam 3.

These coupled equations (24, 25) have the same form as those solved in Ref. 7. Thus, following the same reasoning one may conclude that the scattered noise will be amplified to generate beams 1 and 3 if the phase matching condition,

$$S = S' = 1 \tag{28}$$

is satisfied. If we assume no temporal modulation, i.e., all $\Delta\omega_{n,N} = 0$ and assume the two write beams to have essentially the same frequency, S and S' will depend only on the spatial modulation components, $s_{m,N}$. To eliminate this dependence one should require,

$$S_{m_1,1} = -S_{m_2,2} \; ; \; S_{m_3,3} = -S_{m_4,4} \tag{29}$$

and

$$\vec{\xi}_1 = \vec{\xi}_2 \quad ; \quad \vec{\xi}_3 = \vec{\xi}_4 \tag{30}$$

that is the transverse phase conjugation condition. With temporal modulation equations (29) and (30) also induce the cancellation of the $s_{m,N}$ - dependence the $\Delta k_{m,n,N}$ in S except for a residual phase factor, i.e.,

$$S = \exp\left[i\frac{z}{c}\left(\Delta\omega_{n,4} - \Delta\omega_{n,2}\right)\left(\cos\theta_1 - \cos\theta_3\right)\right] \tag{31}$$

and S' is the complex conjugate.

The above phase factor may be used for estimating the modulation bandwidth possible with our procedure as follows: Ideally, one is tempted to require absolute phase matching. However, if the wavelength of the beat frequency (i.e., one period of the phase mismatch) is much larger that the thickness of the crystal, oscillation and amplification may still occur. Observing the parameters involved we may immediately conclude that the bandwidth is inversely proportional to the crystal thickness. Assuming, for good coupling, a requirement that the crystal thickness does not exceed 1/10 of a beat-wavelength, a crystal 1cm thick leads to a bandwidth of 3GHz before taking into account the magnitude of the cosine factor. In all experimental configurations this factor is rather small since the two angles involved differ only slightly.

In summary, the conditions given by relations (27) and (28) determine the values of $\Delta\omega_{n,N}$ and $s_{m,N}$ for N = 1,3 to generate phase conjugation and transfer of temporal information as observed in the experimental investigation.

3.4 Conclusions

Mutually incoherent beam mixing in photorefractive crystals was investigated theoretically and experimentally with emphasis on temporal modulation effects. Transmission of independent, temporally modulated beams was demonstrated besides the earlier reported phase configuration effects. The results of this work may find applications in wide band optical communication through distorting media, but do not encourage the use of DPCM as a fast Spatial Light Modulator (SLM). The only real hope for a DPCM appears to lie in the organic photorefractive materials currently being tested at Celanese and other large chemical companies. In principle, they can be large, fast, sensitive, and inexpensive. For the moment, we have a device which is useless for practical SLMs. If the organic materials fulfill their promise, this should be the best SLM. Materials are the key.

IV. CONCLUSIONS

4.1 Use of Spatial Light Modulators

The use of Spatial Light Modulators (SLMs) to encode the complex antenna signal onto a laser beam has been shown to be possible. The requirements on the SLM are simple:

- enough spatial resolution to represent the suitably-scaled pattern,
- enough speed to follow the changes in signal (which can be very fast if the platform is moving), and
- enough dynamic range and accuracy to represent the signal with sufficient accuracy (since phase is far more important than amplitude, this restriction is not severe).

4.2 Special SLM

An SLM based on Double Phase Conjugate Mirrors was shown to be

- feasible,
- simple,
- much too slow for these purposes, and
- much too insensitive for practical use,

Only new materials can save this scheme. Certain organic crystals may be practical. We should know within a few years.

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