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Information Processing with Time-Holography*†

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INTRODUCTION

Holography is usually seen in terms of its spatial-imaging properties, and, indeed, these are the most spectacular aspects of the science. But holography, especially the well-worked-out case of a side-band Fresnel hologram, is a form of information encoding. Information from points on the object is encoded on the recording medium through the physical process of diffraction and the filtering properties of the intervening space.

One usually deals with transformations from a spatial distribution of information to a spatially extended recording medium, but this conception is not the sum of holography. One can apply a holographic transformation to information extended in time, transmit or record the time-hologram, receive or reproduce the time-hologram and reconstruct the original message. The gain in all this signal processing is redundancy and error correction, both being characteristic of communication codes and holograms. As is well known, scratches and gaps in photographic hologram plates decrease resolution, rather than destroy information at image points. Comparable "scratches" exist in communications and data storage media, especially magnetic tapes and drums. Holography of messages can be equivalent to continuous block coding, and may be more efficient in many cases.

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Since whole messages are typically very long compared to the coding delay one is willing to tolerate, one encodes only a finite portion of the message at a time, trading off error-correction ability against coding-system complexity.[1] In time-holography one takes a finite-sized segment of a time-domain message, transforms it into the spatial domain, makes a hologram of it, re-inserts it into the time domain, encoded. At the receiving or reproducing end one reverses the process, reconstructing the original message in time. There are two encoding delays, one for transformation and one for reconstruction.

REALIZATION: GENERAL

At the heart of this proposed technique lies an instrument well suited to converting a time message into a spatial amplitude distribution, the liquid delay-line light modulator. This device consists of a piezo-electric crystal, driven by the input signal, propagating an ultrasonic sound wave through a transparent medium.[2,3] The compressions and rarefactions of the medium are used to create variable phase delays for light passing through the cell at right angles to the direction of the ultrasound waves. Variations in frequency and amplitude of the driving signal are propagated throughout the length of the cell at a constant velocity (within limits). The cell forms a delay line for the signals, and also presents the signal over the entire delay period. Thus, using the cell is very like a scanning with a window of finite width through a tape or film of the message, except that the window stands still and the message moves.[3]

If one wished to make a hologram of this signal within one delay-time, one could use a conventional holographic setup, but the exposure would have to be in the nanosecond range so that fringe motion in the hologram plane would not smear out and destroy information.[4] Better, one might construct a moving hologram in the hologram plane and record it with a stationary photomultiplier/slit combination. Rather than scanning a stationary-line hologram with a moving slit, one holds the scanning slit stationary and moves the hologram. There is a phase shift in the outgoing light from the ultrasonic cell dependent on the velocity of sound propagation in the cell, as shown by Arm and King.[4] This term can also be interpreted as Doppler-shift in the light reflected from the moving sound wavefronts in the liquid. If one uses an uncompensated reference beam in construction of the hologram, the output signal as seen at the photomultiplier slit assembly will have an overall amplitude modulation. This problem is simply avoided by using another ultrasonic cell to generate a "moving" or frequency-shifted reference beam. The remaining modulation "problem" referred to by Arm and King,[4] working in the Fourier plane is, in fact, the essential information recorded with this technique.

The holographic setups now become the encoder and decoder. The delay-line character of the electro-optical cell gives the necessary coding delay, and the efficiency of the coding for error correction will be linear with delay time, as shown in communications theory.[1]

REALIZATION - DETAILED

The geometry of the apparatus determines the output bandwidth of the time-hologram and optimizes the redundancy of the holographic message. A setup with minimum bandwidth and maximum redundancy is here described. The time signal is a message in one dimension, and one considers the traveling string of data in the electro-optical cell to be a moving one-dimensional distribution of spatial phase information.

The velocity of the sound waves in the transducer is assumed to be a constant v. The length of the transducer is ℓ so time delay of the transducer is $\tau = \frac{\ell}{v}$. The time bandwidth of the transducer is from 0 - f_1, so the bandwidth and the highest frequency are f_1. Thus, the space bandwidth of the transducer and highest spatial frequency are $\nu_1 = \frac{f_1}{v}$. Small-angle approximations are used throughout, both for geometric factors and for the angular spectrum due to diffraction by spatial frequency distributions.

Figure 1 shows the setup. θ_1 is the maxium angle of diffraction due to the highest spatial frequency in the transducer, $\theta_1 = \nu_1\lambda$. The distance D defined as the critical Fresnel distance, is set so that the highest-angle waves diffracted from the bottom of the transducer, neglecting for the time being convolution effects due to the edge of the aperture, reach the transducer and the lowest-angle or dc terms reach the transducer also. Thus,

$$D = \frac{\ell}{\theta_1} = \frac{\ell v}{f_1 \lambda} .$$

The inclusion of diffraction angles of only one sign makes this a single sideband system. The compensated reference beam should emanate from a source as close as to the end of the transducer as possible, to minimize the frequency offset of the hologram. If the reference beam is perfectly placed and comes from a point source, the frequency range of the moving hologram passing the slit will be exactly equal to the bandwidth of the information in the transducer.

GEOMETRY OF THE RECONSTRUCTION APPARATUS

The reconstruction apparatus is similar to the construction setup except for the absence of a reference beam. The distance D is the same, and in this case it is the focal length for the one-dimensional Fresnel zone plates in the transducer due to each point in the original message. The angular offset of the orignal reference beam separates the light due to the real and virtual foci at the detector. No phase-contrast techniques are necessary to extract the information, for a phase hologram will produce a perfect real reconstruction.

THE DETECTOR

The detector for the light intensity in this instrument is a fine slit of width approximately $\frac{1}{10\nu_h}$ where ν_h is the highest spatial frequency in the hologram, in front of a high-speed photomultiplier tube. One speaks of one-dimensional information strings and holograms, but in fact the transducer and lenses have finite thickness, so the scanning point will really be a line. There should be few problems with sensitivity, even with the number of light losses in this system, due to the great sensitivity of modern PM tubes, and certainly the signal frequencies anticipated for this system, up to 50 MHz, will be far from straining their frequency response.

THE LIGHT SOURCE

The most practical light source for this instrument is a continous-wave laser with a single-mode output. A helium-neon laser has been assumed in the calculations in this paper, but a higher frequency would give better signal/noise ratio in the detector and more effective geometrical aperature in the optics. Suitable lasers are available commercially, as well as the optics necessary to provide a wide, uniform illumination beam.

THE COMPENSATED REFERENCE BEAM

The diffraction of light from moving sound waves in the liquid medium of the electro-optical transducer causes a Doppler shift in the frequency of the light as seen at the hologram plane. If one used the same illumination source for object and reference beam, there would be an over-all amplitude modulation of the pattern at the hologram plane due to the Doppler shift. The simplest and most obvious way to eliminate this problem is to diffract the reference wave from a similar sound wave in a similar transducer cell before mixing it with the signal beam. The reference generator cell should be parallel with the signal-transducer cell, and the reference beam should see the same optical system as the signal beam until they are mixed so that the transverse velocity components of the two beams match. The system may be tuned for zero-beat Doppler frequency by tilting the reference generator cell. Since the system can be constructed very well with cylindrical optics, lens size and crowding will not be a problem.

REALIZATION OF OPTICAL SYSTEM

If one constructs the optical system as shown in the schematic Fig. 1, the critical distance D will be very large, due to small θ for practical bandwidths. Assuming the liquid in the cell is acetone, with $v = 10^5$ cm/sec., an input electronic bandwidth of 10 MHz, and $\lambda = 6.33 \times 10^{-5}$ cm, and cell length $\ell = 5$ cm, then D = 7.9 m. A lens placed immediately after the cell takes one into the Fourier plane in its focal length f,[5] and into the critical Fresnel plane here defined in a distance $D_1 = f - \frac{1}{D}$. Unfortunately, the spatial frequencies ν at the plane will be multiplied by a factor $\frac{D}{D_1}$, which for a 100-mm lens and the example above becomes approximately 800, and since $\nu = 10$ lines/mm, the spatial frequency at the detection plane is 800 lines/mm, making the required detector slit diameter impracticably small. Also, the distance between the Fourier plane and the critical plane would be so small as to make positioning impracticably difficult.

I use an optical system which allows spatial-frequency filtering in the Fourier plane and also gives a moving hologram having reasonable spatial frequencies. Such an optical system is shown in Fig. 3, without a reference-beam generator.

The cell diameter is arbitary, the only significant dimensions being lens focal lengths and spacings. f_a has a focal length of 150 mm, this giving a spacing of 0.9 mm for the first orders at 10 lines/mm in the Fourier plane. f_b has 1/10 the focal length of f_1, and is spaced so that the Fourier plane is focused at infinity. Then, the critical distance from f_2 is 1/10 the original, but the spatial frequencies of the hologram are magnified by 10. Other optical systems could easily decrease the size of the system and magnify or demagnify the final spatial frequencies as desired.

One must restrict the maximum differential phase shift of the light in the transducer, as pointed out by Arm *et al.*,[2] to keep down intermodulation terms. This means that the dc term from the transducer will be too strong for good signal-to-noise ratio at the detector. This effect can be contralled by using a subcarrier scheme. The information to be encoded is impressed on a high-frequency subcarrier in a modulator prior to insertion into the electro-optical transducer (see Fig. 4.). The information may be modulated on the carrier by any modulation technique desired. The carrier frequency of the one sideband now becomes the dc term as in Fig. 4 and all else is as before, save for geometrical corrections. The subcarrier frequency shift will not appear in the hologram if the reference beam is brought in close to the highest-frequency information. Only the angle between the information beams and the reference beam determines this systematic baseband frequency shift, and this applies in the case without the subcarrier as shown in Fig. 3. One may, in fact, deliberately introduce a baseband shift by simply changing the angle of the reference beam. The subcarrier technique can also reduce velocity-dispersion effects in the cell, since relative bandwidth for a given signal can be reduced.

SOME LIMITATIONS

The basic limitations on this instrument are due to the finite size of the transducer and its finite delay characteristics. First, the detector slit cannot really be even with the edge of the transducer, as in Fig. 1, for the convolution of the edge of the transducer "window" is junk information, spurious modulation. One may smooth or apodise the edges of the transducer with a density mask so that the highest spatial frequency generated by the convolution of the mask with the information is some small fraction of the spatial bandwidth, say 5 percent. Then, 5 percent of the transducer aperture at either end is lost. There will be angular frequencies of the wrong sign coming in now, and these can be separated out by spatially filtering the output of the transducer in the Fourier plane. The edge effects will still cause distortion of the lower spatial frequencies, but this is an unavoidable effect due to the finite aperture.

The high-frequency sound wave in the transducer attenuates as it travels through the medium. This causes an exponential falloff in light-modulation index along the cell, and this can be eliminated. The effect of the modulation falloff is that the quantity of diffracted light from each point of the cell is different, and a density mask which is the inverse of the attenuated sound amplitude will equalize the diffracted light output. This density mask can also be the apodising mask mentioned above. As the diffraction efficiency falls off across the cell, the ratio of diffracted to undiffracted light will change also, and this is another reason to use the subcarrier scheme, in which one uses diffracted light only.

The data flow by the the fixed-length window of the transducer at a constant rate, and as the spacing between resolution elements or bits approaches the length of the cell, self-redundancy of the time-hologram begins to fall off. One should establish a bit rate, corresponding to perhaps 5 bits in the cell which is the lower-rate cutoff for effective operation. For the cell referred to before with a length of 5 cm, time-width would be 50 μsec and the lower-limit bit rate would be 10^5 bits/sec. The upper limit is set by the frequency response of the transducer cell and the geometric aperture of the optics used.

EQUIVALENCE TO OTHER SYSTEMS

The time spectrum of the input signal is filtered by the diffraction and the distance D so that in the time-hologram apparatus each frequency component f_i is time-shifted by $\tau_f = \tau \frac{f_i}{f_1}$, a fraction of the total time delay linearly proportional to frequency. This is equivalent to the action of a linear dispersive delay line, and the transformations on the signal are essentially identical. These delay lines are used in "chirp" radar, in which the transmitter sends out a linearly FM'd signal which is actually a one-half time-Fresnel zone plate. The optical system, I believe, has a higher time-bandwidth product and better linearity than any other such delay line in existence.

APPLICATION

The major advantage to be gained with this technique is rapid, simple, self-redundant coding of signals. A disturbance in the time-hologram at a single point in time is spread over the entire decoding time delay T. If the time-bandwidth product of the transducer were such that 1000 bits were in the transducer at one time, say 100 μsec, a disturbance of 10 μsec long, which would normally eradicate 100 bits, would be spread over 110 μsec and would reduce the resolution of the data in those 110 μsec, but no bits would be eradicated unless one were operating too close to the signal/noise ratio edge. This disturbance could be many things, an example being an imperfection or series of imperfections in an instrumentation tape. Valuable high-speed analog data could be safeguarded by time-holography before recording.

The instrument described is analog and continuous, and if it were to be used in a digital data transmission or recording process, the digital data would have to be filtered and treated before time-holography and redigitized afterward. Analog data would be holographically encoded first, then digitized. The signal conditioning and digitization required would still be, I believe, simpler than elaborate high-speed digital error-correcting coding.

FINAL THOUGHTS

The continuous holographic transform performed by this proposed instrument could be performed by digital equipment, just as digital holograms are calculated but, at present, at nowhere near the information capacity for the same cost. Although most of the ideas expressed in this paper are in an empirical "hardware" form, I have had no opportunity to investigate them experimentally.

ACKNOWLEDGMENTS

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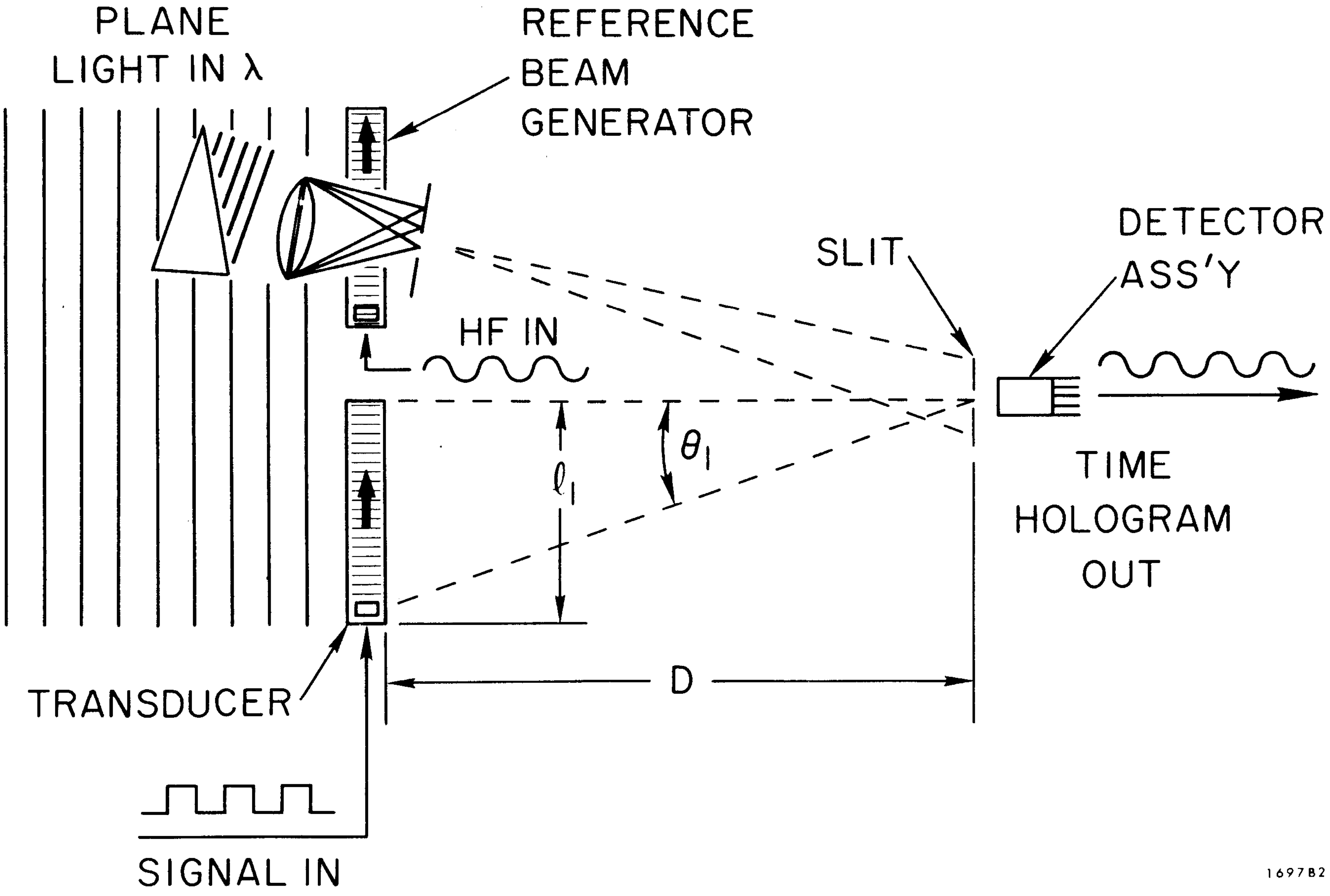

Fig. 1

Time-hologram construction schematic set-up.

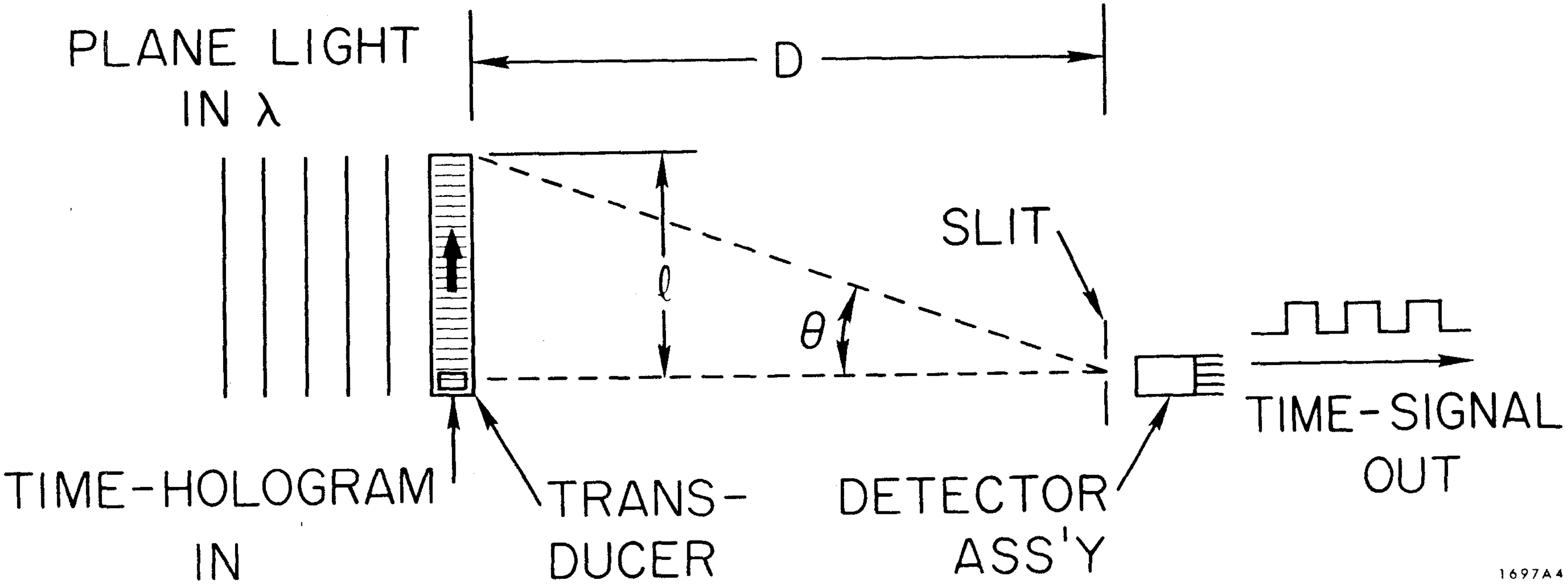

Fig. 2

Reconstruction schematic set-up.

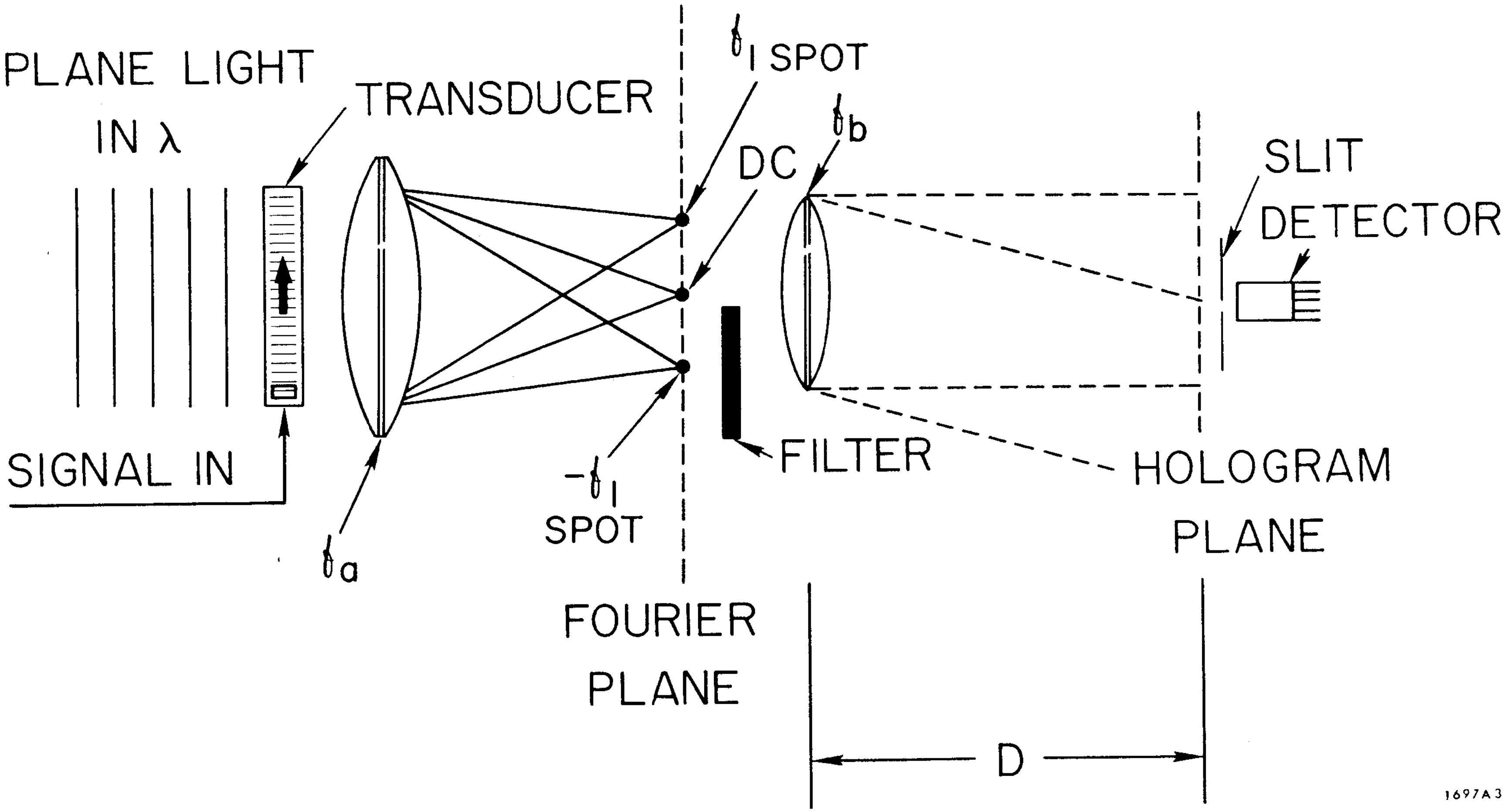

Fig. 3

Practical optical system.

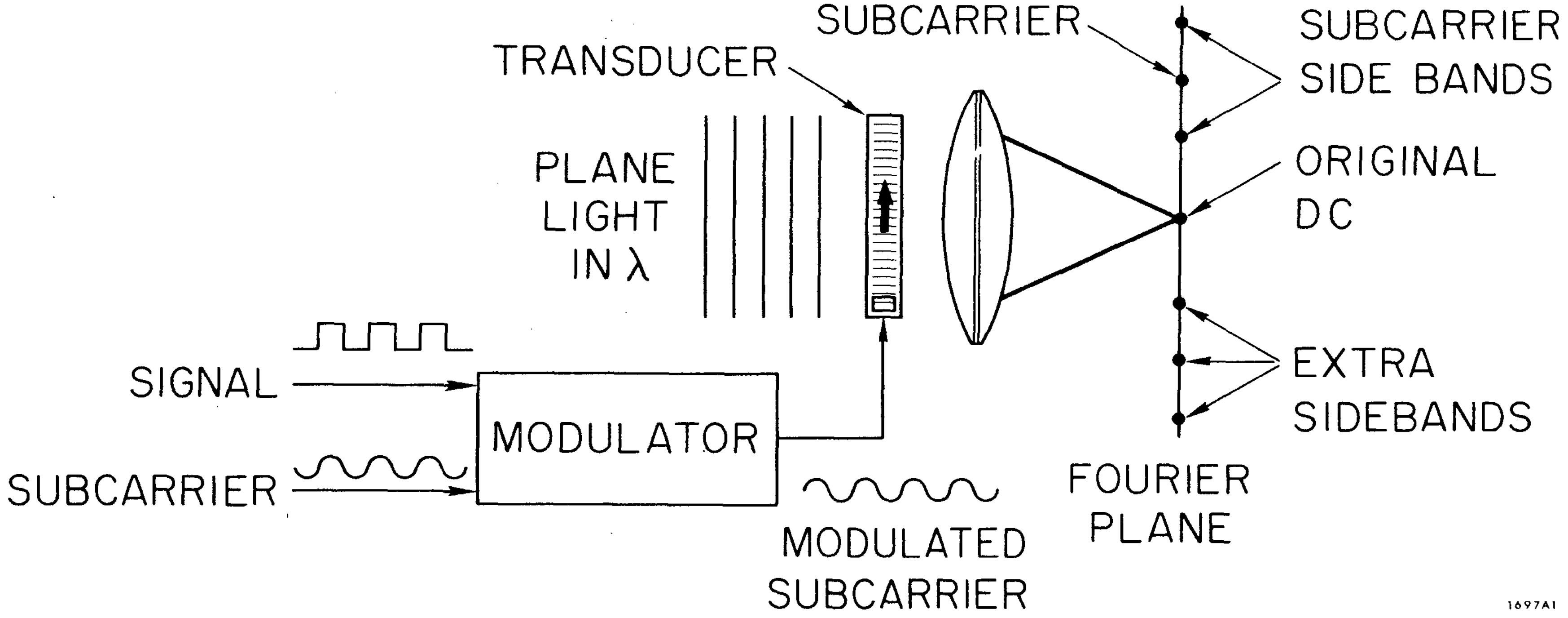

Fig. 4

Subcarrier scheme.