Increasing the Memory Capacity of the Digital Light Deflector by "Color Coding"

By J. G. SKINNER

(Manuscript received December 23, 1965)

Considerations are given to the use of a multiwavelength light source in the digital light deflector for the purpose of increasing the memory capacity of the system. An increase of a factor of twenty or more is theoretically possible when potassium tantalate niobate (KTN) is used for the optical switches in the digital light deflector. Practical considerations may, however, limit the increase to about a factor of ten.

I. INTRODUCTION

This paper describes a scheme for increasing the memory capacity of an optical beam deflecting device, such as a digital light deflector, by utilizing the full wavelength bandwidth of the system. For convenience the scheme is referred to as "color coding".

The digital light deflector[1] is designed to deflect a monochromatic light beam to any one of an array of positions on a memory plane. The absence or presence of an obstruction at the memory plane produces a yes or no signal in a detector placed behind the memory plane. The capacity of the system is determined by the ratio of the maximum angular deflection of the beam to the smallest angular deflection that can be resolved by the system. Increasing the capacity by increasing the maximum beam deflection requires lenses that can operate over a larger angular field of view. On the other hand, increasing the capacity by reducing the minimum resolvable angle requires larger diameter components. Assuming the diameter of the components and the angular field of view of the lenses are at their maximum values, then other means of increasing the capacity must be investigated.

The capacity may be increased by paralleling information through the system so that each resolvable angular location in space becomes a word. This may be accomplished by splitting the deflected monochromatic light beam into M channels, each with its own detector. However, due to imperfections in certain components in the digital light deflector, a small portion of the incident light beam is deflected to several incorrect locations on the memory plane and also appears as a general background illumination on the memory. This extraneous light is undesirable because it reduces the signal-to-noise ratio of the correctly deflected spot of light. A method of reducing the unwanted light is to place a mirror behind the memory plane to reflect the light back through the deflector system to a detector located in a position conjugate to the light source. It can be shown[2] that this system reduces the extraneous light. In order to parallel information through this type of system it is necessary to code the word in the memory system, reunite the word for transmission back through the light deflector and then separate again for detection. This can be accomplished with a monochromatic light beam by coding a single pulse into a sequence of pulses by placing the different memory planes at different distances from the exit of the digital light deflector. This scheme,[2] however, requires large aperture, high-precision lenses which are expensive.

Another possibility is to transmit simultaneously several monochromatic beams of slightly different frequencies so that the beam can be reunited after coding and still be capable of yielding the coded word. The presence or absence of a reflector for a given frequency at a given location yields a yes or no bit of information. This is shown schematically in Fig. 1. The increase in capacity attainable with color coding is the ratio of the bandwidth allowed by the system to the bandwidth required per channel.

There are several ways of constructing a color-coding system. One scheme is to place a number of narrowband reflection filters at the memory plane as shown in Fig. 2(a). However, although narrowband

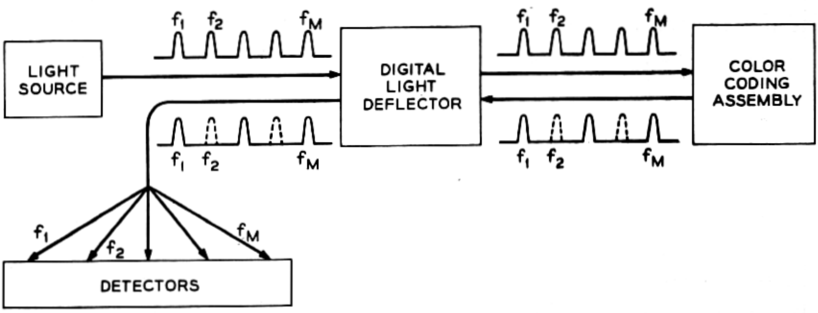

Fig. 1 — Schematic layout of the color-coding system.

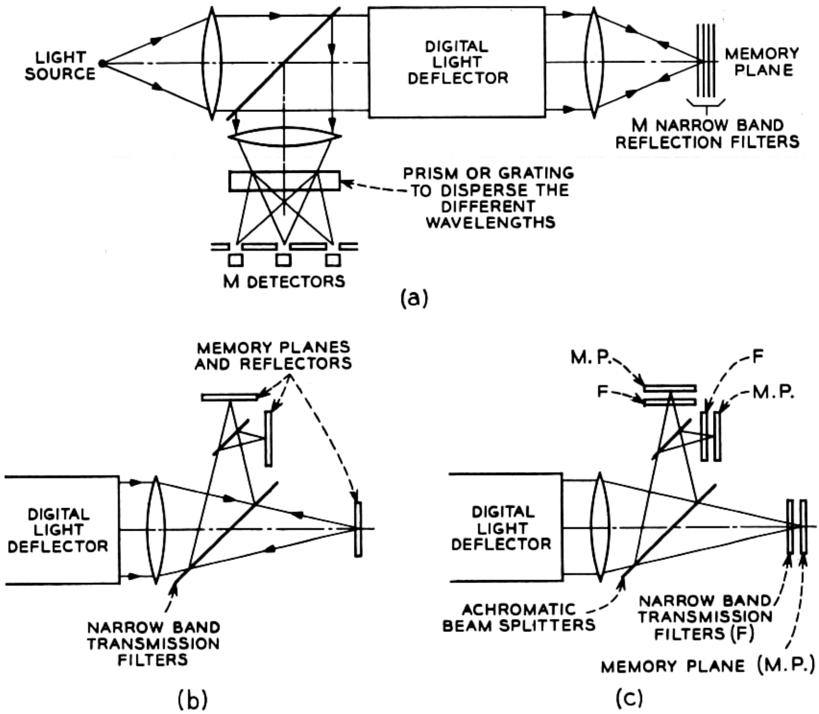

Fig. 2 — Different color-coding schemes.

reflection filters are theoretically possible, they are not presently available. Another scheme is to use narrow-band transmission filters which will transmit one channel and reflect the other channels to their appropriate locations. This is shown schematically in Fig. 2(b). This has the advantage that no energy is lost in the beam-splitting assembly but has the disadvantage that a filter requires a larger bandwidth for a given angular beam deflection when placed at an angle to the beam. In order to keep the bandwidth per channel to a minimum, it is necessary to use the filters normal to the beam. This arrangement requires an achromatic beam splitter to divide the beam into M channels. This is shown schematically in Fig. 2(c). The disadvantage of this scheme is that it reduces the beam intensity of each channel by a factor of M^2.

The calculations presented below are for narrow-band filters placed normal to the beam. If transmission filters were used, it would be necessary to tilt the filter at a small angle to avoid the unwanted light being reflected back to the detector. This small angular displacement of the filter has been ignored in these calculations. The calculations are based on the present design of the digital light deflector that employs potassium tantalate niobate (KTN) as the electro-optic material[3] for the light switches.[4]

II. BANDWIDTH OF THE DIGITAL LIGHT DEFLECTOR

The total bandwidth of the system is limited by the electro-optic elements that are used to rotate the plane of polarization of the light through an angle of 90°. Any error in this rotation allows light to leak through to the wrong locations in the memory plane. The light leakage is related to the phase difference $\Delta\Phi$ between the ordinary and the extraordinary rays at the exit face of the optical switch. Fig. 3 shows the parameters of the light beam relative to the optical switch. The value γ is the angle between the beam and the axis of the optical system, and α is the angle the intersection of the plane of incidence of the beam and the x,y plane makes relative to the x axis. The value of $\Delta\Phi$ to the second order in γ is given by[2,4]

$$\Delta\Phi = \left[1 + \frac{\left(\cos^2\alpha - \frac{1}{2}\right)\gamma^2}{n^2}\right]\frac{n^3}{\lambda}\pi l(g_{11} - g_{12})P^2 \tag{1}$$

where n is the ordinary index of refraction, λ is the free space wavelength, l is the length of the optical switch, g_{11} and g_{12} are the electro-optic coefficients, and P is the lattice polarization of the KTN crystal.

With respect to the angular orientation α, the maximum change in $\Delta\Phi$ occurs at $\alpha = 0°$. Under this condition (1) reduces to

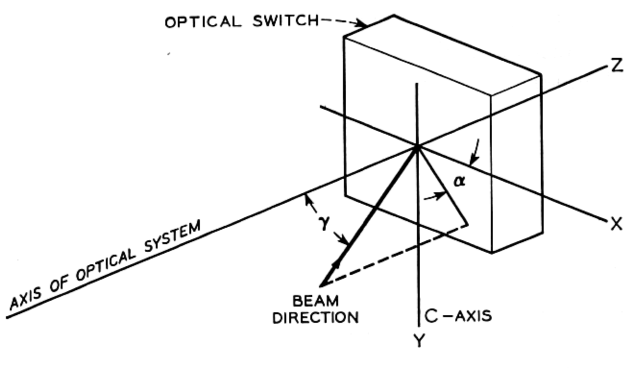

Fig. 3 — Coordinate axes showing the relation of the optical switch to the incident beam.

$$\Delta\Phi = \left[1 + \frac{\gamma^2}{2n^2}\right] \frac{\pi l n^3}{\lambda} (g_{11} - g_{12}) P^2. \tag{2}$$

We will assume that the optical switches are normally biased to $\Delta\Phi = N\pi$ and are switched to $\Delta\Phi_o = (N + 1)\pi$ for $\lambda = \lambda_0$ and $\gamma = 0°$. The error in $\Delta\Phi_o$, due to λ and γ being different from λ_0 and $0°$, respectively, is

$$\delta\Phi = \frac{\pi l n_0^3}{\lambda_0} (g_{11} - g_{12}) P^2 \left[1 - \frac{\lambda_0 n^3}{n_0^3 \lambda}\left(1 + \frac{\gamma^2}{2n^2}\right)\right] \tag{3}$$

$$\delta\Phi = (N + 1)\pi\left[1 - \frac{\lambda_0 n^3}{\lambda n_0^3}\left(1 + \frac{\gamma^2}{2n^2}\right)\right] \tag{4}$$

where n_0 and n are the refractive indices at wavelengths λ_0 and λ, respectively, and are given by the equation[4]

$$n^2 = 1 + \frac{3.7994}{1 - (\lambda_s/\lambda)^2} \tag{5}$$

where $\lambda_s = 0.2012\ \mu$. The light leakage δ, due to the error in $\Delta\Phi_o$, is given by

$$\delta = I/I_0 = \sin^2 (\delta\Phi/2). \tag{6}$$

Combining (4), (5), and (6) we can obtain a plot of the allowed bandwidth, $\Delta\lambda = \lambda - \lambda_0$, for a given dc bias of the optical switch, expressed by N, and an allowed light leakage δ. The bandwidth has been plotted in Fig. 4 as a function of N for values of $\delta = 0.1$, 0.01, and 0.001, and a beam angle γ of 0.07 radians (i.e., 4°). This value of γ is a typical value that may be used in the digital light deflector; however, the term $\gamma^2/2n^2$ is negligible except for $\lambda = \lambda_0$.

A typical bias point for KTN optical switches is $N = 20$ and an acceptable light leakage in the digital light deflector, due to color coding, is $\delta = 0.01$. From Fig. 4 we see that the available bandwidth under these conditions is only 20 Å. The maximum bandwidth is at zero bias (i.e., $N = 0$) and equals 436 Å for a light leakage value of $\delta = 0.01$.

III. REQUIRED BANDWIDTH PER CHANNEL

The bandwidth required per channel depends on the type of filter used to separate the channels. We will consider a system using the Fabry-Perot type of narrow-band transmission filter[5] that consists of two reflecting surfaces separated by a suitable dielectric material. The

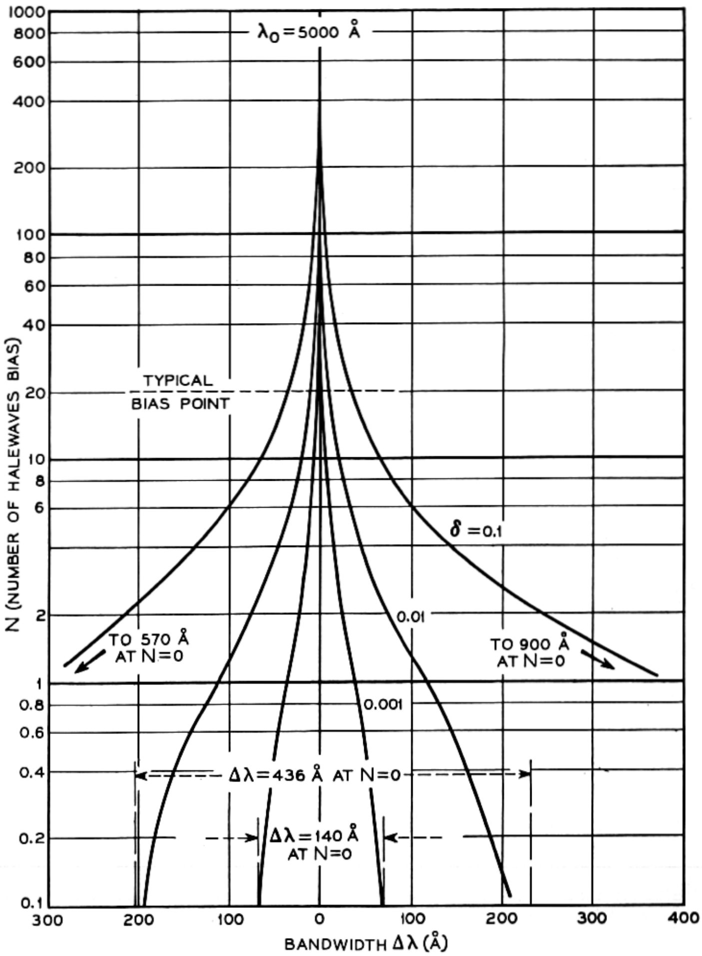

Fig. 4 — Frequency bandwidth of the KTN optical switches.

per cent transmission through such a filter depends on the wavelength and the angle of incidence of the beam. Since the beam will be deflected through a range of angles it is necessary to specify the minimum permissible transmission T, relative to the peak transmission, for each channel. It is also necessary to specify the maximum transmission T' of adjacent channels. The light reaching the detector from the memory plane passes through the filter twice, so that the single pass transmission values will be the square root of T and T'. The various parameters of the transmission curve are shown in Fig. 5; the values marked with a prime are parameters of the adjacent channel.

The peaks of the transmission for a Fabry-Perot filter occur at

$$\Omega = \frac{4\pi\mu h \cos\theta}{\lambda} = 2m\pi \qquad (m = 1,2,3, \cdots), \tag{7}$$

where μ is the refractive index of the dielectric between the two reflectors, h is the thickness of the dielectric, θ is the angle the beam travels through the dielectric relative to the normal of the surfaces of the filter, and λ is the free space wavelength of the beam.

The shape of the transmission curve is given by

$$\frac{I}{I_0} = \frac{1}{1 + F \sin^2 (\Omega/2)}$$

where $F = 4R/(1 - R)^2$ and R is the power reflection coefficient of the reflecting surfaces. If F is sufficiently large (i.e., high-reflectivity mirrors), then $\sqrt{F} = 4/\varepsilon$, where ε is the half bandwidth of the transmission curve.

We require that $I(T)/I_0 = \sqrt{T}$ at $\Omega = 2m\pi \pm \zeta$; therefore,

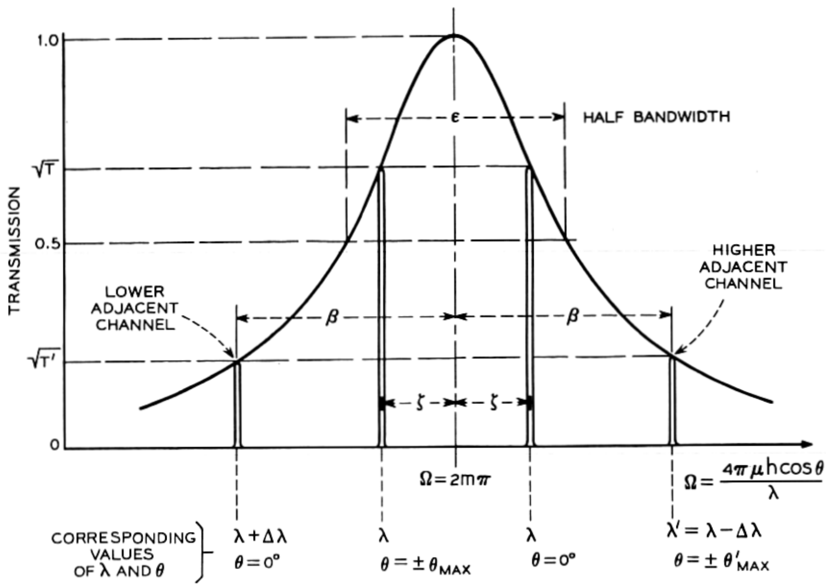

Fig. 5 — Transmission curve showing the various parameters involved.

$$\frac{I(T)}{I_0} = \sqrt{T} = \frac{1}{1 + F \sin^2\left(\frac{2m\pi + \zeta}{2}\right)} = \frac{1}{1 + F\sin^2(\zeta/2)}. \quad (9)$$

Approximating $\sin(\zeta/2)$ with $(\zeta/2)$ for small values of ζ, we obtain

$$2\zeta = \frac{4}{\sqrt{F}} \sqrt{\frac{1}{\sqrt{T}} - 1} = \varepsilon t \quad (10)$$

where

$$t = \sqrt{\frac{1}{\sqrt{T}} - 1}.$$

Similarly, the requirement that $I(T')/I_0 = \sqrt{T}$ at $\Omega = 2m\pi \pm \beta$ yields

$$2\beta = \varepsilon t' = 2\zeta t'/t \quad (11)$$

where

$$t' = \sqrt{\frac{1}{\sqrt{T'}} - 1}.$$

From (7) and Fig. 5,

$$2m\pi - \zeta = 4\pi\mu h \cos \theta_{\max}/\lambda \quad (12)$$

$$2m\pi + \beta = 4\pi\mu h \cos \theta_{\max}'/\lambda' \quad (13)$$

$$2m\pi + \zeta = 4\pi\mu h/\lambda. \quad (14)$$

From (12) and (14),

$$2\zeta = (2m\pi - \zeta)(1 - \cos \theta_{\max})/\cos \theta_{\max}. \quad (15)$$

From (12) and (13), and noting that $\theta_{\max} = \theta_{\max}'$,

$$\zeta + \beta = (2m\pi - \zeta)\, \lambda \left(\frac{1}{\lambda'} - \frac{1}{\lambda}\right). \quad (16)$$

Combining (11), (15), and (16), and expressing the bandwidth required between channels as $(\Delta\lambda) = \lambda - \lambda'$, we obtain

$$(\Delta\lambda) = \lambda(1 - \cos \theta_{\max})(t + t')/2t \cos \theta_{\max}. \quad (17)$$

For small angles of $\theta_{\max}$, (17) may be written as

$$(\Delta\lambda) = \lambda\theta_{\max}^2(t + t')/4t. \quad (18)$$

This equation shows that the required bandwidth per channel increases rapidly as the maximum beam deflection angle is increased.

The half bandwidth of a filter is usually measured with the beam normal to the filter (i.e., $\theta = 0°$). Therefore, the half bandwidth $(\Delta\lambda)_\varepsilon$, in angstroms, is given by

$$(\Delta\lambda)_\varepsilon = \frac{\varepsilon}{\beta + \zeta} (\Delta\lambda) = \frac{\lambda \theta_{max}^2}{2t} . \tag{19}$$

IV. NUMBER OF CHANNELS AVAILABLE FOR COLOR CODING

Three values T, T', and θ_{max} must be specified before the number of channels available for color coding can be determined. T and T' are determined by the required signal-to-noise ratio of the over-all system which has not yet been specified. However, typical requirements of the color coding system may be that the intensity of each channel may vary by no more than a factor of two in any beam position and that the crosstalk between each channel be no more than 10 db. This requires that $T = 0.5$ and $T' = 0.05$.

The angle of incidence θ of the beam at the filter is related to the bit capacity N^2 of the digital light deflector. The number of resolvable bits in one direction is given by[2]

$$N = K\theta D/\lambda \tag{20}$$

where θ is the maximum deflection angle of the beam in one plane, D is the effective aperture of the digital light deflector, λ is the wavelength of the light beam, and K is a constant. The value of K is determined by the transverse mode of propagation of the light beam and the ratio of the linear bit separation in the memory plane compared to the theoretical limit; its value is about 0.2. Practical values are $N = 512$ for $\theta = 4°$ with an aperture diameter of about 2 cms. Present considerations of the digital light deflector have the arbitrary requirement that the center ray of the reflected beam from the memory plane can just be accepted by the aperture of the optical system when the beam deflection is a maximum along the x or y axis. This is shown schematically in Fig. 6. Therefore, the maximum angle of incidence of the light at the filter is the angle Ψ as determined by the extreme rays of the light cone when the beam is focused in the center of the memory plane. To a close approximation, Ψ equals 2θ. The angle of the beam inside the filter is reduced due to refraction at the surface of the dielectric layer in the filter and for small angles $\theta_{max} = 2\theta/\mu$. The total number of channels M available for color coding is, therefore,

$$M = \frac{B}{(\Delta\lambda)} = \frac{B\mu^2 t}{\lambda\theta^2(t' + t)} \tag{21}$$

where B is the bandwidth of the modulator.

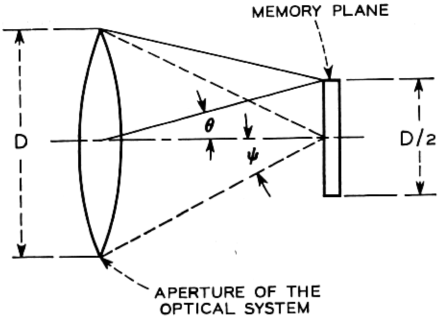

Fig. 6 — Schematic showing the maximal angle of incidence of the beam at the memory plane.

The total capacity C of the digital light deflector and the color coding system is

$$C = N^2M = (K^2B)\frac{D^2\mu^2}{\lambda^3}\frac{t}{(t' + t)}. \tag{22}$$

This relation shows that the total capacity of the system is independent of the maximum beam deflection angle but strongly dependent upon the wavelength of the beam.

The maximum capacity of the color coding system for a beam deflection angle of $\theta = 4°$, also $T = 0.5$, $T' = 0.05$, $D = 2$ cm, $\lambda = 5000$ Å, $\mu = 2.45$ (which is the refractive index for TiO_2 that is frequently used in Fabry-Perot filters), and an optical switch bandwidth of $B = 436$ Å (which is the maximum value for a zero biased KTN switch and a light leakage of $\delta = 0.01$) is 27 channels. This means that the capacity of the digital light deflector that has $N = 512$ resolvable spots in each direction could be increased from 2.6×10^5 to 7.1×10^6 bits. The half bandwidth of the filters for the above values is given by (19) as 12.6 Å, which is well within the capabilities of present day technology.

Unfortunately, when a KTN optical switch is operated with zero electrical bias, the required voltage and power dissipation are greater than can be accepted. The problem is the increase in the light leakage through the switch caused by the change in the operating temperature due to this increase in the dissipated power. A compromise may be possible, however, by using less than 27 color coding channels, hence reducing the required bandwidth, and increasing the allowed light leakage due to color coding. As an example, if the system has 10 color coding channels and the light leakage δ is increased to 0.035, then the optical switches can be biased to $N = 4$; this reduces the dissipated power in the KTN crystal by about a factor of four compared with the unbiased case.

V. CONCLUSIONS

The calculations show that the capacity of the digital light deflector can be increased by a factor of twenty or more by the addition of a color coding scheme. The device could be constructed with present technology by making the optical switches of the digital light deflector from KTN crystals and by using narrow-band transmission filters for the channel selection, but it would have several practical problems. One problem is the necessity to operate the KTN optical switches at zero, or a very low, electrical bias. This would require higher operating voltages and greater power dissipation in the KTN crystals than is anticipated in the present design of the digital light deflector. Other electro-optic materials have been considered for use as the optical switch, but either the angular aperture of the material is too small, the power requirement is too large, or the material is not presently available in large enough pieces. An alternative is to use a stressed optical plate in which the birefringence necessary to produce the 90° rotation of the plane of polarization is induced by applying a mechanical stress. The wavelength bandwidth of a fused quartz stressed plate is approximately 600 Å when operated with a light beam with a wavelength at 5000 Å. This bandwidth can accommodate 37 color coding channels. The disadvantage of the stressed plate optical switch is that it is limited to switching times of the order of milliseconds compared to microseconds for a KTN optical switch.

A disadvantage of using narrow-band transmission filters for channel selection is the large attenuation in the reflected beam due to the achromatic beam divider. This can be overcome by the use of narrow-band reflection filters.

One other item that the color coding system requires is a multiple frequency light source. The light beam should have high intensity, be highly directional, and have a frequency spread between each line equal to the channel separation. One possibility is to use a laser that oscillates at many frequencies simultaneously, such as the argon laser. Another possibility is to use a stimulated Raman source in which several frequencies are produced by down shifting the incident laser beam by Raman scattering from a suitable medium.

VI. ACKNOWLEDGMENTS

It is a pleasure to acknowledge the discussions with J. E. Geusic, who was jointly responsible with the author for initiating this device consideration.

REFERENCES

1. Schmidt, U. J., *Optical Processing of Information*, Spartan Books, Inc., Baltimore, 1963, p. 98.
   Nelson, T. J., B.S.T.J. *43*, May 1964, p. 821–845.
   Tabor, W. J., B.S.T.J. *43*, May 1964, p. 1153–1154.
   Kulcke, W., Harris, T. J., Kosanke, K., and Max, E., IBM J. Res. and Dev. *8* 1964, p. 64–67.
   Soref, R. A. and McMahon, D. H., Appl. Opt. *5*, March 1966, p. 425–434.
2. Tabor, W. J., A High-Capacity Digital Light Deflector Using Wollaston Prisms, To be published in B.S.T.J.
3. Geusic, J. E., Kurtz, S. K., Nelson, T. J., and Wemple, S. H., Appl. Phys. Letters, *2*, 1963, p. 185.
4. Chen, F. S., Geusic, J. E., Kurtz, S. K., Skinner, J. G., and Wemple, S. H., to be published in Appl. Phys., January, 1966.
5. Born, M. and Wolf, W., *Principles of Optics*, Pergamon Press, 1959.