THEORY

How Holography Works

TINY METRICS

1 METER
m

1 mm = .001 m
1,000 mm = 1 m

1 MILLIMETER
mm

1,000 µm = 1 mm
1,000,000 µm = 1 m
1 µm = .001 mm = .000001 m

1 micron
µm

1 nanometer
nm

1 nm = .001 µm = .000001 mm = .000000001 m
1,000 nm = 1 µm 1,000,000 nm = 1 mm 1,000,000,000 nm = 1 m

METRIC TIME

There are three different ways of stating lengths of time less than one second. There is fractional, which includes **camera** time; decimal, or sports time; and metric, or scientific, time. This table relates all of them.

FRACTIONAL (**Camera**)	DECIMAL (Sports)	METRIC (Scientific)
1	1.000	1000 ms
1/2	.500	500 ms
1/3	.333	333 ms
1/4	.250	250 ms
1/5	.200	200 ms
1/6	.167	167 ms
1/7	.143	143 ms
1/8	.125	125 ms
1/9	.111	111 ms
1/10	.100	100 ms
1/15	.067	67 ms
1/30	.033	33 ms
1/60	.017	17 ms
1/100	.010	10 ms
1/125	.008	8 ms
1/250	.004	4 ms
1/500	.002	2 ms
1/1000	.001	1 ms

One millisecond (ms) is to one full second as one second is to 1000 seconds or 16 minutes and 40 seconds. Light travels about 300 km or 186 miles in 1 ms.

1/2000	.0005	500 μs
1/4000	.00025	250 μs
1/5000	.0002	200 μs
1/10,000	.0001	100 μs
1/100,000	.00001	10 μs
1/1,000,000	.000001	1 μs

One microsecond (μs) is to one full second as one second is to 1,000,000 seconds or 11 days, 13 hours, 46 minutes, and 40 seconds. Light travels about 300 m or the length of a football field in 1 μs.

1/10,000,000	.0000001	100 ns
1/100,000,000	.00000001	10 ns
1/1,000,000,000	.000000001	1 ns

One nanosecond (ns) is to one full second as one second is to 1,000,000,000 seconds or 31 years, 259 days, 4 hours, 26 seconds. Light travels about 30 cm or one foot in 1 ns.

1/1,000,000,000,000, .000000000001 1 ps

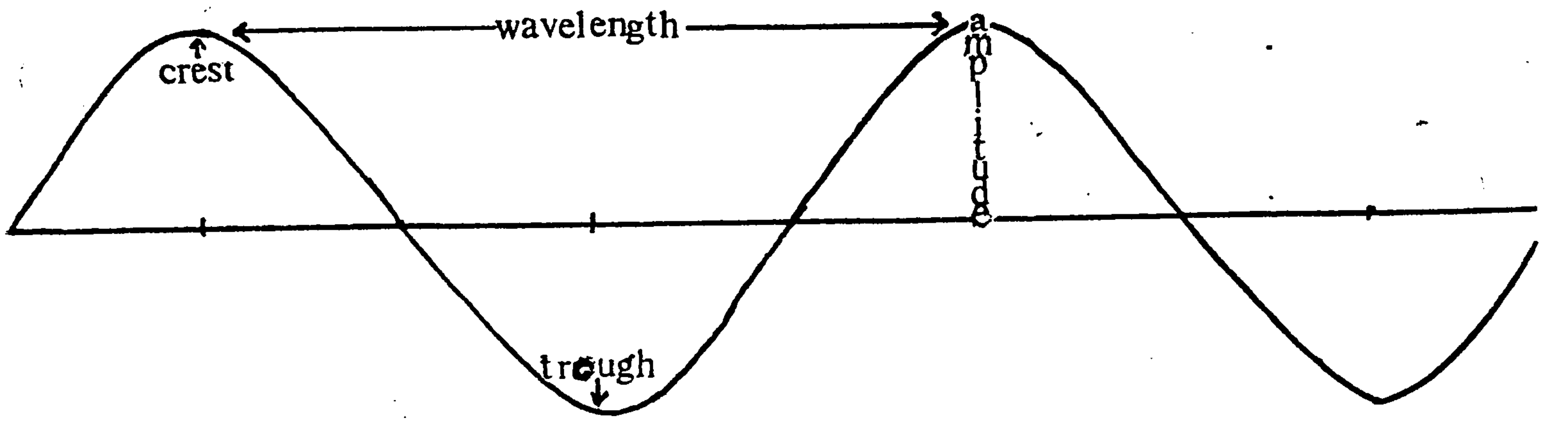
One picosecond is to one full second as one second is to 1,000,000,000,000 seconds or 31 millennia, 7 centuries, 9 years, 289 days, 1 hour, 55 minutes, 12 seconds. Light travels about 300 microns or about 1/100 of an inch in one picosecond.

1/1,000,000,000,000,000

.000000000000001 1 fs

One femtosecond (fs) is to one full second as one second is to 1,000,000,000,000,000 seconds which is 31,709,792 years. Light would travel 300 nm in 1 fs but that is shorter than anything in the visible! One oscillation of light of Helium-Cadmium laser wavelength of 441.6 nm takes 1.472 fs.

PARTS OF A WAVE



SINE WAVE-- Light's magnetic and electric vectors oscillate across space as a sine wave. A sine wave is the graph of the trigonometric function y=rsin O, derived from the relationships of sides and angles in a right triangle.

CREST-- The highest point or maximum of a wave.

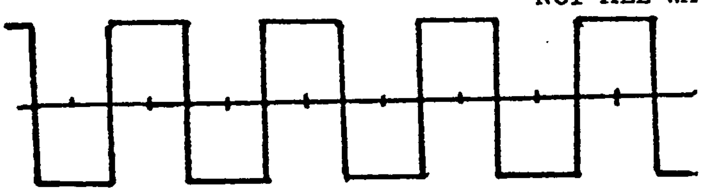
TROUGH--The lowest point or minimum of a wave.

AMPLITUDE--is one-half the distance from crest to trough. It is used to measure intensity.

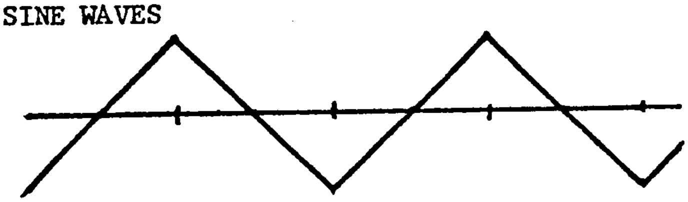
WAVELENGTH--represented by the Greek letter λ, is the distance between two consecutive crests. For visible light the wavelengths are between 400 and 700 nm.

FREQUENCY--tells how often a wave goes through a complete cycle from crest to crest in a unit of time. The unit commonly used to denote frequency is a Hertz, (Hz), one cycle per second, and the range of frequencies for light starts at 430 trillion Hz for red light and goes to about 750 trillion Hz for blue.

NOT ALL WAVES ARE SINE WAVES



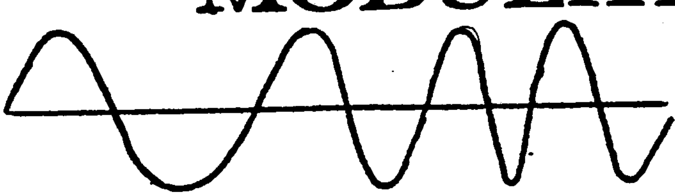
SQUARE WAVE



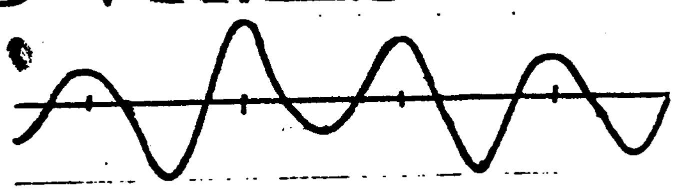
DELTA OR TRIANGULAR WAVE

The above terms are applicable to these waves.

MODULATED WAVES

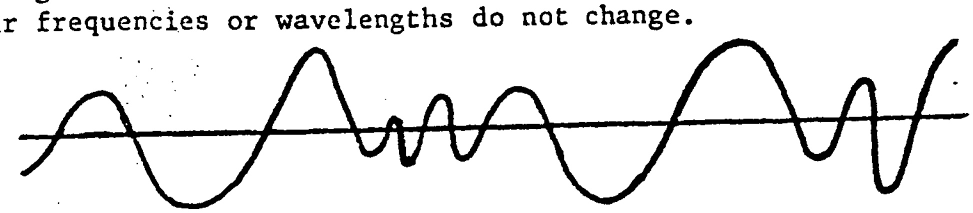


Wave of constant amplitude but varying frequency (Frequency Modulated)



Wave of constant frequency but varying amplitude (Amplitude Modulated)

The waves of light which are used for making holograms must be temporally coherent; that is, their frequencies or wavelengths do not change.

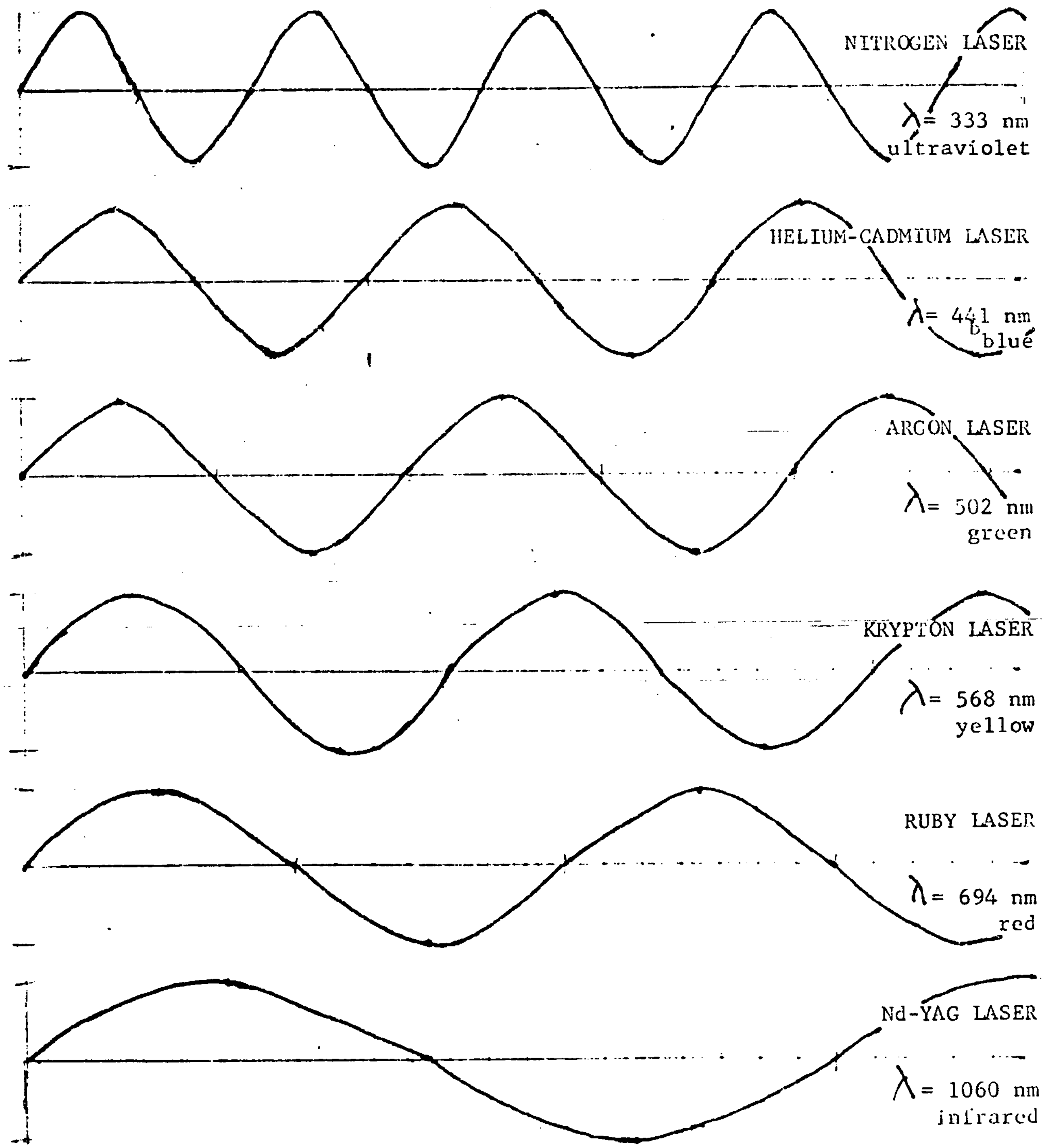


Wave of varying amplitude and frequency

WAVELENGTH AND COLOR

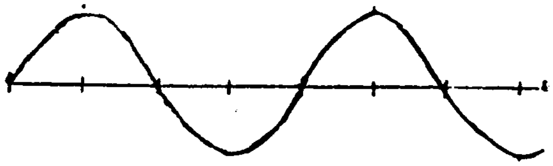
The visual effect of light which the brain interprets as color is directly related to the wavelength of the light. The visible spectrum starts with the reds which are the longer wavelengths and as the wavelengths get shorter (and the frequency gets larger) the colors transform into the familiar hues of the rainbow: orange, yellow, green, blue, indigo, and violet. Ultraviolet has a shorter than violet but it is a color to which the eyes do not respond. Infrared is of a longer wavelength than red, again invisible to the eye.

Lasers emit monochromatic light--light of only one wavelength, or just one line of the rainbow's many colors. Here are some typical laser lines and their wave patterns drawn to scale. ├──┤ = one nanometer

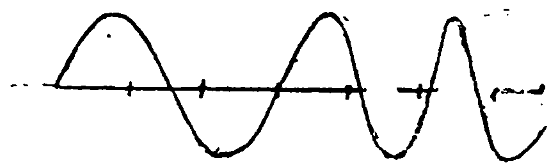


COHERENCE

Light coming out of a laser is both spatially and temporally coherent. Temporal coherence means that all the waves coming out of the laser have the same wavelength-the spacing between crests does not change with time.

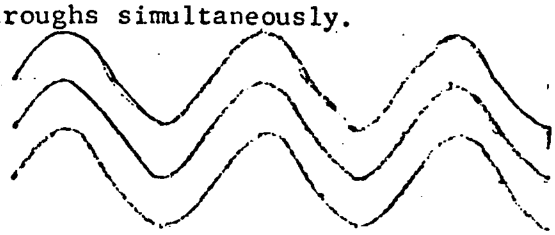


TEMPORALLY COHERENT WAVE

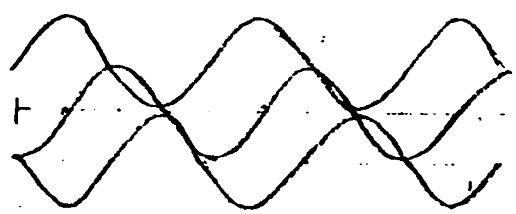


NOT A TEMPORALLY COHERENT WAVE

There is more than one wave of light coming out of the laser and these waves are all in step as they exit the port. They can be thought of as originating at the totally reflective mirror opposite the exit mirror, even though they make many round trips between the mirrors in the resonating cavity before leaving it. This is spatial coherence; all the waves make their crests and troughs simultaneously.

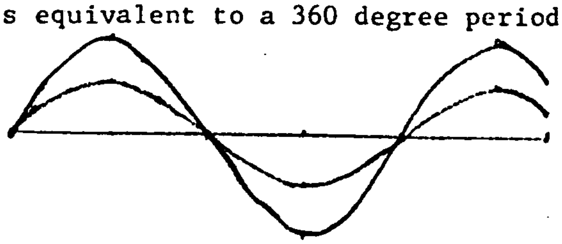


TEMPORALLY AND SPATIALLY COHERENT

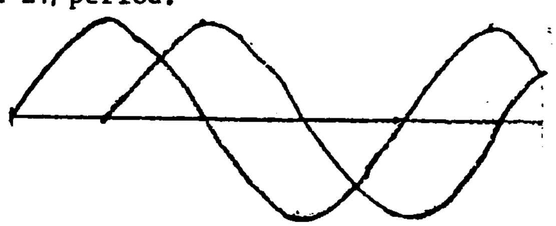


TEMPORALLY BUT NOT SPATIALLY COHERENT

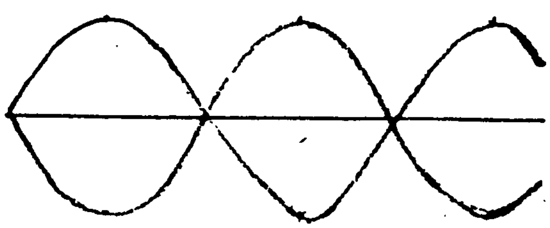
When temporally coherent waves are not spatially coherent, they are "out of phase" with each other. Crests do not match up, troughs don't match up, and neither do points in between. One way to indicate the amount that two waves are out of phase with each other would be to use fractions of a wavelength. Since these wave forms are based on the trigonometric sine curve we can also use degree measure or radian measure, assuming that every wavelength is equivalent to a 360 degree period or a 2π period.



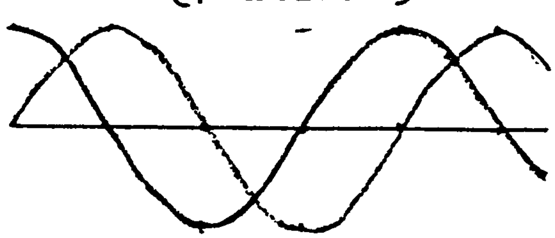
WAVES ARE IN PHASE



WAVES ARE {1/4 WAVELENGTH / 90 DEGREES / $\pi/2$ RADIANS} OUT OF PHASE



WAVES ARE {1/2 WAVELENGTH / 180 DEGREES / π RADIANS} OUT OF PHASE



WAVES ARE {3/4 WAVELENGTH / 270 DEGREES / $3\pi/2$ RADIANS} OUT OF PHASE

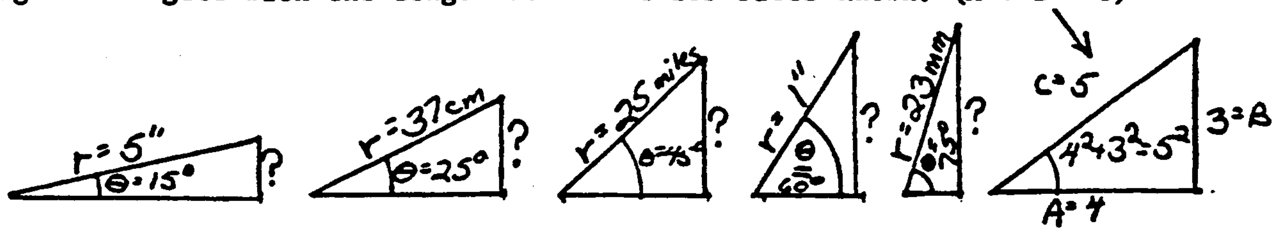
It's absolutely essential that the waves used to form a hologram be spatially and temporally coherent to form the constructive and destructive interference fringes.[1] If the wavelength of the interfering beams vary (lack of temporal coherence) the interference will not become a standing wave pattern and will be constantly changing its shape, leaving nothing but a blur on the holographic plate. The reference beam must have all its waves cresting and troughing at the same time to provide a non-random base of reference. The light reflected off the object loses its spatial conerence, but this modulation of the object beam is exactly the information we would like to record.

A phase hologram is recorded on a transparent medium that introduces phase differences in the reconstructing beam by optical path variations. For instance, in a bleached silver halide emulsion, light travels through gelatin, then through transparent silver halide whidh has a different index of refraction from the gelatin, so the light gets slowed down and bent, introducing a phase difference, then through several more gelatin and silver interfaces until when it finally exits it has reconstructed tne phase differences between reference and object beams recorded in the hologram. Phase holograms have been recorded on dichromated gelatin, photo-resest, thermoplastics, and photopolymer. Bleached silver halide emulsions are the most popular type of phase hologram because the materials are readily available from commercial manufacturers and relatively easier to handle. Phase holograms are much brighter than absorption holograms since they pass much more light

I. Holograms can be made with any type of wave sound, radio, maybe x-rays, and of course, light.

TRIGONOMETRIC FOOTNOTE

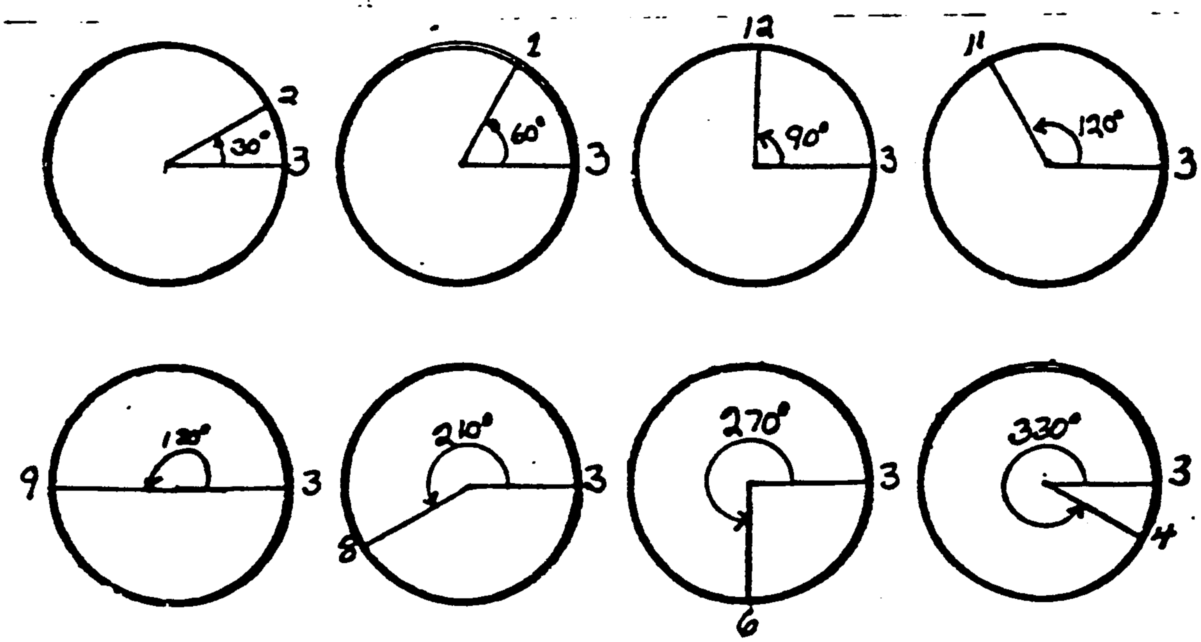
The sine function was devised to answer the question, "If I know one of the angles in a right triangle, and the length of the hypotenuse (the long side), what is the length of the side opposite the angle?" The Pythagorean Theorem falls short here, since it applies only to right triangles with the length of two of its sides known. $(A^2 + B^2 = C)$



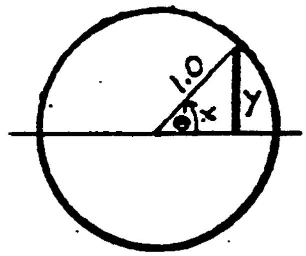
Notice what happens to the side opposite the angle we are examining as the angle gets bigger.

The solution to these problems is found by plugging the given values into the formula $y = r \sin \theta$, and conjuring up the sine function on a pocket calculator. But there are other uses of this function and its cousin, the cosine function, especially in holography. These functions pop up in the spatial frequency formula $f = \sin \theta / \lambda$, the reference beam is attenuated by the coefficient $\cos \theta$, the diffraction equation is chock full of trigonometric terms, and of course, light oscillates in a sine wave pattern.

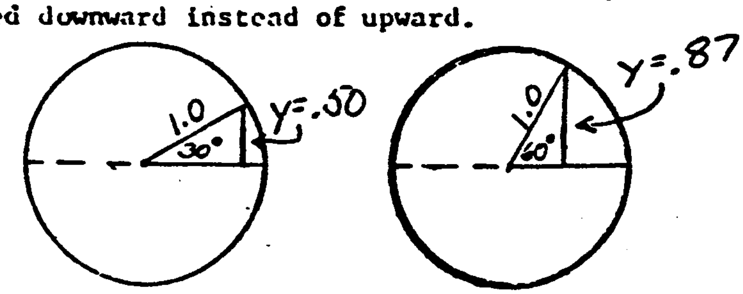
To understand what a sine curve is and why it has the shape that it has, imagine a clock whose hour hand always points at 3, and whose minute hand moves backwards. Suppose that we first look at the clock when the minute hand points in the same direction as the hour hand. As the minute hand moves counterclock-wise, the angle that it makes with hour hand becomes larger. Some angles made during one revolution are on the facing page. In each revolution the two hands form angles varying in measure from 0 to 360. When the hands point in the same direction, it is convenient to think of them as forming a 0° angle,



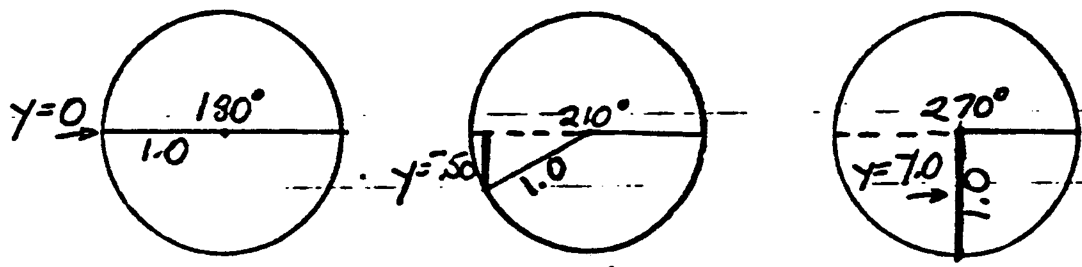
Now suppose that the minute hand of the clock is one unit long and that the clock is divided in half by a horizontal line through its center. If we let x represent the measure of the angle θ formed by the clock's hands at any moment, then the vertical distance, y, from this horizontal line to the tip of the minute hand is called the "sine" of the angle x. See picture below.



Diagrams of approximate sines of different angles are given below. In the last two, the sines are negative numbers; this is because the distances from the horizontal line to the tip of the minute hand are measured downward instead of upward.



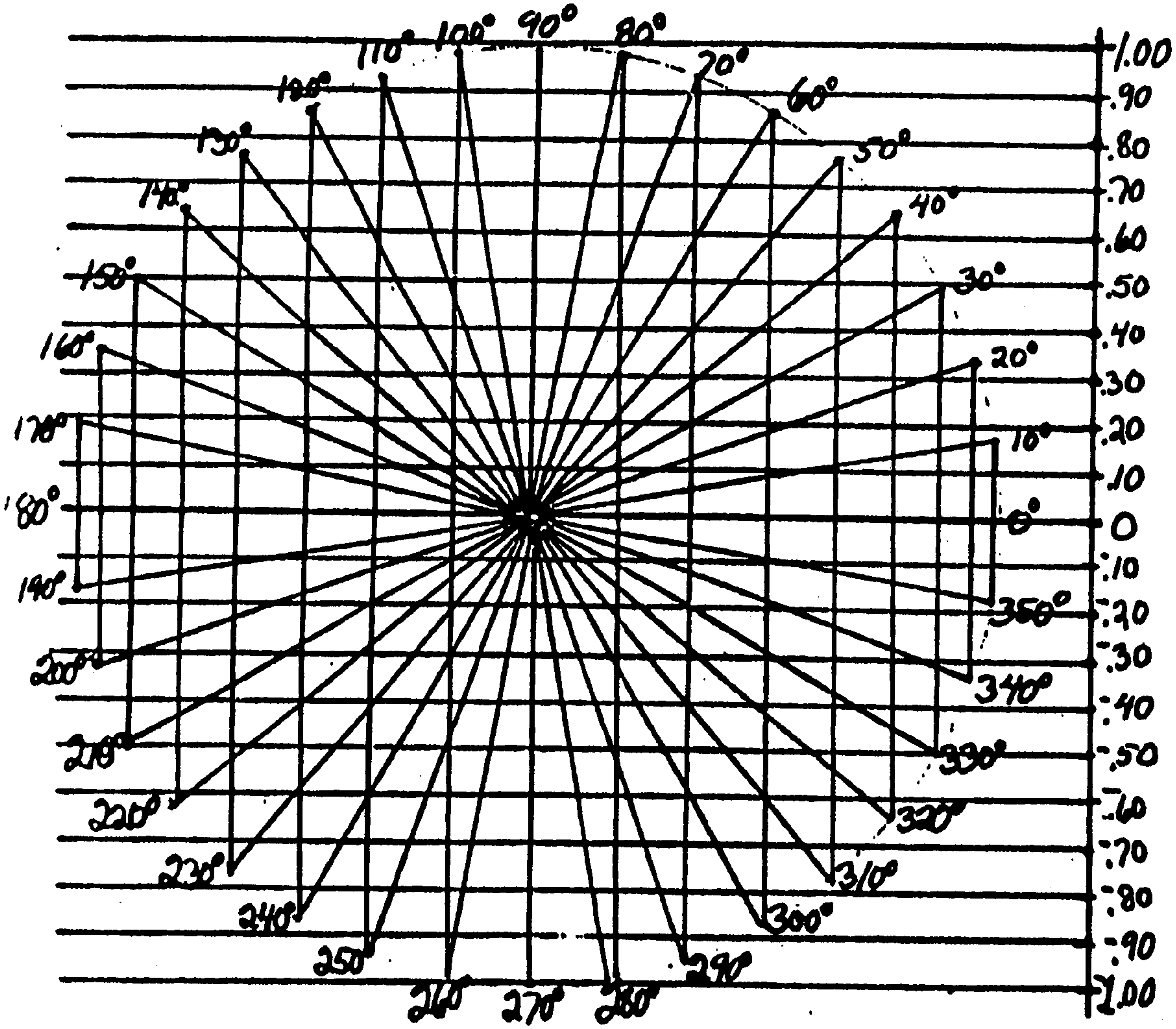
sine of 30° is .50 sine of 60° is .87 sine of 90° is 1.0



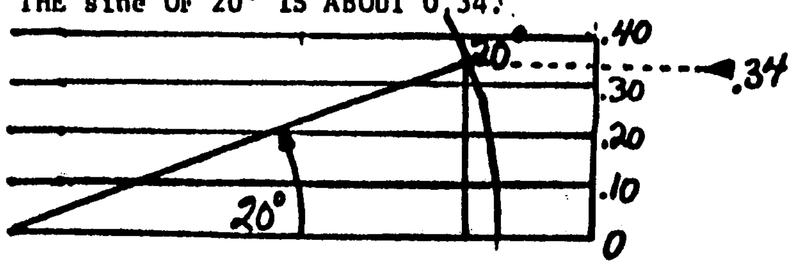
sine of 180° is 0 sine of 210° is -.50 sine of 270° is -1.0

Experience is the best teacher. Try drawing your own sine curve by following the directions on the next two pages, and you will gain some insight on what type of creature a sine wave is and then see its application in holographic technology.

HERE IS A LARGE DIAGRAM FROM WHICH YOU CAN ESTIMATE THE SINES OF SOME ANGLES TO THE NEAREST HUNDREDTH.



FOR EXAMPLE, THE sine OF 20° IS ABOUT 0.34.



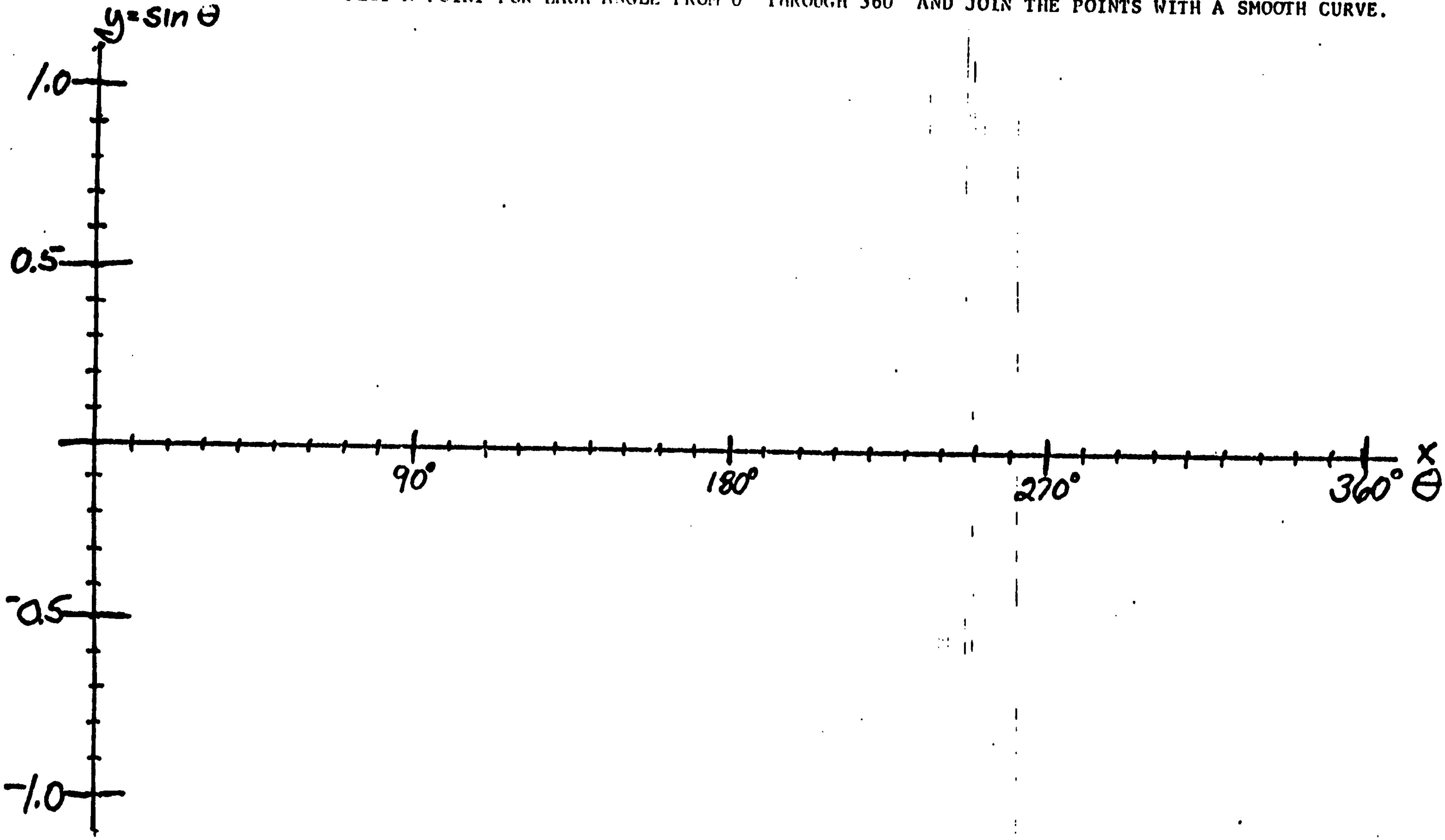
COMPLETE THIS TABLE, USING THE DIAGRAM AT THE LEFT.

ANGLE θ	y = sin θ
0°	0
10°	.17
20°	.34
30°	
40°	
50°	
60°	
70°	
80°	
90°	
100°	.98
110°	
120°	
130°	
140°	
150°	
160°	
170°	

ANGLE θ	y = sin θ
180°	
190°	-.17
200°	
210°	
220°	
230°	
240°	
250°	
260°	
270°	
280°	
290°	
300°	
310°	
320°	
330°	
340°	
350°	
360°	

CHECK YOUR APPROXIMATIONS WITH A POCKET CALCULATOR. THEN GRAPH YOUR TABLE ON THE NEXT SHEET.

THE MEASURE OF EACH ANGLE θ IS REPRESENTED ON THE HORIZONTAL AXIS AND THE sine OF EACH OF THESE ANGLES IS REPRESENTED ON THE VERTICAL AXIS. LET 1 UNIT ON THE X-AXIS REPRESENT 10° AND 1 UNIT ON THE Y-AXIS REPRESENT 0.1. USE YOUR TABLE TO PLOT A POINT FOR EACH ANGLE FROM 0° THROUGH 360° AND JOIN THE POINTS WITH A SMOOTH CURVE.



NOTES AND OBSERVATIONS INTERFERENCE LECTURE

The recording and reconstruction stages of holography are synonymous with interference and diffraction. These two concepts need to be understood to comprehend holography.

INTERFERENCE LECTURE NOTES

What happens when a razor blade cuts a laser beam?
Diffraction over edge of obstacle suggests wavelike nature.
Huygens principle explains diffraction in water.
Young shows two-source interference in ripple tank and two-slits of light.
Two razor blades = two bobbers or slits.
Michelson's interferometer demonstrates spatial frequency variation and stability requirements.
Moire patterns give excellent fringes.
Sixty year old handout graphs out secrets of multiple point interference patterns.
Diffraction gratings disperse light sources into wonderful spectra.
Reflections from coatings a fraction of a wavelength of light thick enhance or destroy colors.
Standing waves illustrate laser resonator cavities and the Lippmann photographic process.
Laser speckle is an indication of coherent light.
Interference effects generate holographic images.
Light in Flight holographic recording reveals the wave-like nature of light.

WHAT IS LIGHT A WAVE OF?
OUTLINE OF ELECTROMAGNETIC RADIATION SUB-LECTURE

I. The discovery of Magnetism.
  A. The test for Magnetism.
II. The discovery that moving electrons generate magnetism.
  A. Coiling the wires amplifies the magnetic field.
  B. Invention of Galvanometers to detect and measure electricity.
  C. Electric motors.
III. The discovery that moving magnets generate electricity.
  A. Induction coils.
  B. Electrical dynamos, generators, and alternators.
  C. Microphones.
IV. The oscilloscope.
  A. Electron gun and phosphorescent screen.
  B. The Time Base and directional coils.
  C. Voltage measuring channels.
  D. Storage Capability.
V. Electrical Waves.
  A. Sine, Square, and Delta.
  B. Wavelength, Period and Frequency.

METRIC MEASUREMENT

I. 10,000,000 meters from the North Pole to the Equator through Paris

II. One meter =
10 decimeters =
100 centimeters =
1000 millimeters =
1,000,000 microns =
1,000,000,000 nanometers

RECORDING A HOLOGRAM OF A CONVEX MIRROR

I. Scale of one micron = one foot
- A. Gelatin coating seven feet tall on top of Sears Tower glass.
- B. 35 nanometer silver bromide grains are the size of walnuts.

II. Twenty interference fringe planes in layer.

III. Processing chemicals action.
- A. Developer
- B. Fixer
- C. Rehalogenating Bleach
- D. Solvent Bleach
- E. Rehalogenation without Fixation
- F. Blood Bath
- G. Photo-Flo

<u>EYEWITNESS DEMONSTRATIONS: Recall what you saw.</u>
What does happen when a laser beam is cut in half?
Ripple tank demonstration: Review of wavelength and frequency; diffraction around edge; reflection from plane and curved surfaces; two source interference.
Thin film interference effects: Anti-reflection coatings, soap bubble colors, oil on water, and Newton's rings.
Young's fringes with razor blades and slits.
How does the fringe spacing relate to the angle between the two interfering beams?
Was the red or blue end of the spectrum nearer to the white light when you looked at it through the diffraction grating?
What were all the things mentioned that had diffraction grating properties?
What was the shape of the beam path in a Michelson interferometer?
What happens when you look through a smaller and smaller aperture at a laser illuminted target?
How does this explain resolution in a lens or hologram?

SCAVENGER HUNT: Enjoy these optical phenomena outside of class.
oil on water * soap bubbles * Newton's rings * diffraction gratings on windshields, window screens, CD's etc. * iridescent colors on animals *

OPTICAL SCIENTISTS AND INVENTORS: Remember the endeavours of these gentlemen which make them relevant to this lecture.
Sir Isaac Newton * Christian Huygens * Thomas Young * Sir Wiliam Bragg * Albert Michelson * Gabriel Lippmann * Nils Abramson *

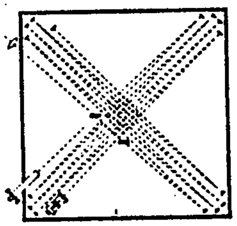
IMPORTANT WORDS: Know what they mean!
* coherent * interfere * constructive and destructive interference * in and out of phase * pathlength difference, epsilon * interference fringes * Young's double-slit experiment * diffraction grating * iridescent * thin film coatings * multiple layer thick stacks * Michelson's interferometer * standing wave generator * nodes and antinodes * Lippmann plate * interference filters * dichroic filters * Huygen's principle * diffraction * Fraunhofer diffraction * spatial frequency * resolving power * Light in Flight holographic recording *

BIBLIOGRAPHY: Outside reading for the truly faithful.
Optics Guide 5, pages 1-25 through 1-29, 4-5 through 4-38.
Sir William Bragg, The Universe of Light, Dover Reprint, pages 1-15, 125-145.

chelson/Morley

e Great Experiment Plain Terms

A Layman's Guide through Luminiferous Ether)



was the end of 19th century, the lassical Age" of ence. Physicists re secure in their derstanding of the ture of the world. e interrelation-ips of matter and nt, space, and ne were known, if not fully understood measured.

Scientific dogma at the time held that nt consisted of waves, and these ves moved through a medium called niniferous (or light-carrying) ether. The ture of ether had been a persistent oblem for scientists since the early 00s. Since it couldn't be seen or mea-red with instruments of the day, ether ust be an ultra-fine gas. But observa-ns on the properties of light indicated at the waves moved in a manner that uld be accommodated only by a very nse solid ether. Explanatory theories ere worked out, but each only raised ill more problems.

Albert A. Michelson, professor at the ase School of Applied Science, and dward W. Morley, professor of chemis-y at neighboring Western Reserve University, were the latest scientists to tackle the mystery of the ether. Michelson was interested in the effect of the movement of the earth on the speed of light. The ether was assumed to be motionless, and the earth, in its passage through it, would face a "wind." It was plausible, then, to theorize that light waves moving "with" the ether "wind" would have a different speed than light traveling "against" the path of the ether.

To detect the effect the earth's motion had on the speed of light, Michelson constructed a device called an "interfer-ometer." The interferometer split a beam of light in two. (One beam would be traveling with the ether current, the other across it.) Each beam was reflected at right angles to each other and then the beams were reunited. The hypothesis reasoned that the beam "halves" traveling at different speeds would "interfere" with each other. This interference would show up as bands of light and dark when the beams were combined. Measurement of the bands (or interference fringes, as they were called) as the interferometer was rotated, would enable Michelson and Morley to calculate the degree to which the earth's motion affected the speed of light.

The interferometer was mounted on a two-ton stone slab which, in turn, floated in a pool of mercury—this was Morley's idea to combat vibrations which would hinder the workings of the ultra-sensitive interferometer. The apparatus was set up in a building on the site of what is now the Millis Science Center.

Despite repeated tries, Michelson and Morley couldn't detect any change in the interference fringes when their instrument was rotated. There appeared to be no variation in the velocity of light under any circumstances. The scientific community was baffled by the results of the Michelson-Morley Experiment, but the ether theory eventually had to be abandoned.

Albert A. Michelson

Albert A. Michelson was the first American scientist to win a Nobel prize. He was born in 1852 in German-occupied Poland and came to the United States as a young child. A graduate of the U.S. Naval Academy, Michelson was named the first professor of physics at Case School of Applied Science, later to be known as Case Institute of Technology.

Michelson's scientific reputation extends beyond his collaboration with Morley. He was a pioneer in the measurement of the speed of light and proposed standardizing the length of the meter in terms of light. The interferometer, made famous in the Michelson-Morley experiment, was also put to practical use in 1920, when Michelson used the first stellar interferometer to measure the diameter of the star Betelgeuse.

He received numerous honorary doctorates and awards, but perhaps the highest honor came from Albert Einstein, who said, "It was you who led physicists in new paths and through your marvelous experimental work paved the way for the development of the theory of relativity."

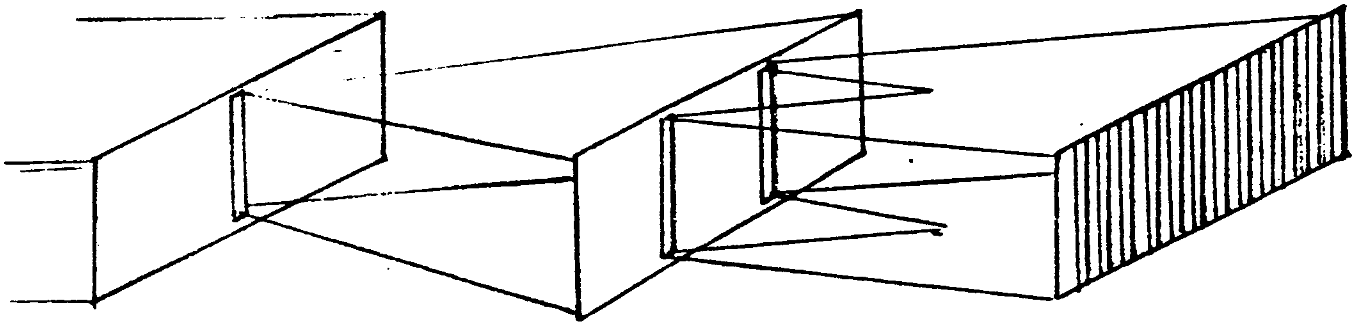
Edward W. Morley

Edward Williams Morley was among the best of the scholar-scientists found on college campuses during the turn of the century. Essentially a self-taught scientist, he became one of the greatest chemists of his era. His most important contribution to the field was his determination of the atomic weight of oxygen, along with the proportions of hydrogen and oxygen that make up water. His work set a new standard of accuracy and reliability among chemists of the era.

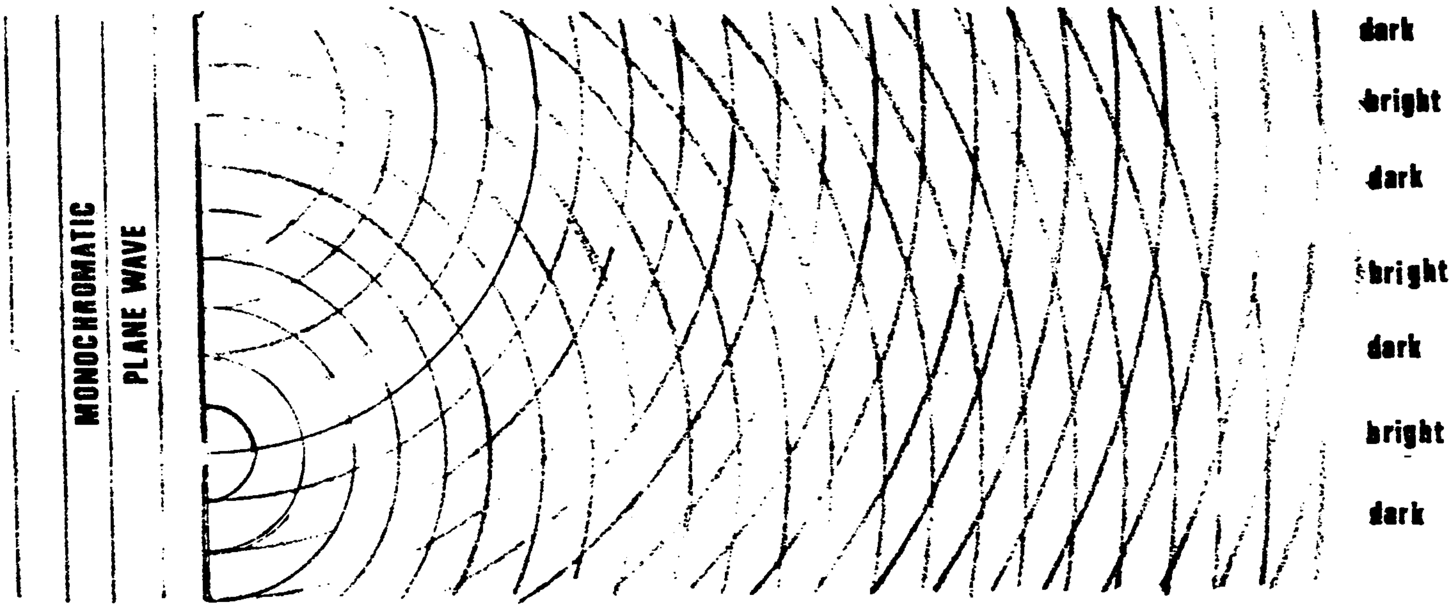
Morley was born in New Jersey, the son of a Congregational minister. He followed his father into the clergy, accepting a pulpit in Twinsburg, Ohio. Almost immediately, he joined the faculty of Western Reserve College, then located in nearby Hudson. In addition to his scientific work, he was devoted to the study of Greek, Latin, Hebrew, French, and German, as well as Chaldean and Russian. Morley received seven honorary degrees and three gold medal awards in the sciences.

DIFFRACTION

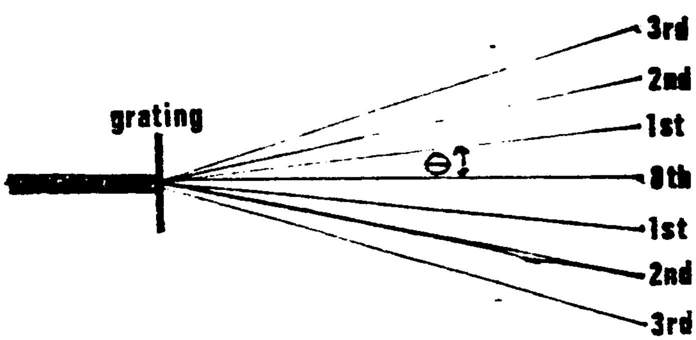
Thomas Young in the early 1800's explained interference in light waves by likening them to waves in water. The experimental setup shown below proved his hypothesis. This experiment illustrates the property of light called diffraction.



This is schematic representation of the experiment viewed from above.



Each overlapping set of crests produces the light bands by constructive interference, and the troughs' superposition produce the dark bands. The bright fringes are called the orders of diffraction, with the zeroeth order corresponding to the path light falling on the grating would have taken if the grating weren't there. The symmetric pair of fringes on either side of the zeroeth order are called the first order, the next pair the second order, etc. A hologram bends light by diffraction to reconstruct the wavefront that had come from the original object and this information is carried on one of the first orders.



The location of the orders of diffraction can be predicted by this equation:

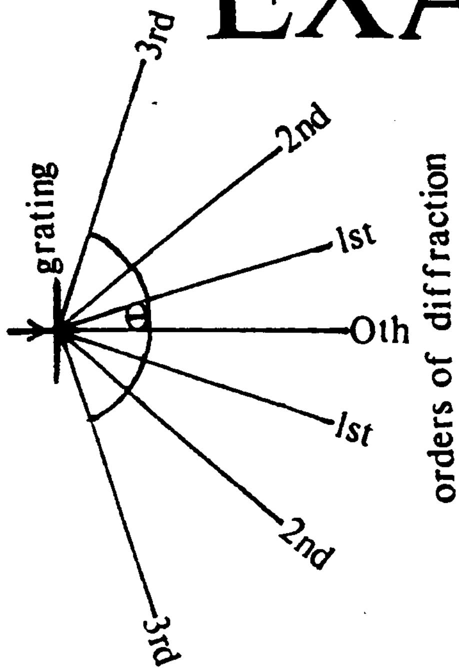
$$m\lambda = d\sin\theta$$

where d= distance between slits,
λ= wavelength of light,
m= order of diffraction,
and θ= angle between the diffracted light and the normal to the grating.

Notice that for a given d and m, different wavelengths of light will give different sin θ and therefore bend at different angles, producing a spectrum.

7/21/80

DIFFRACTION EXAMPLES

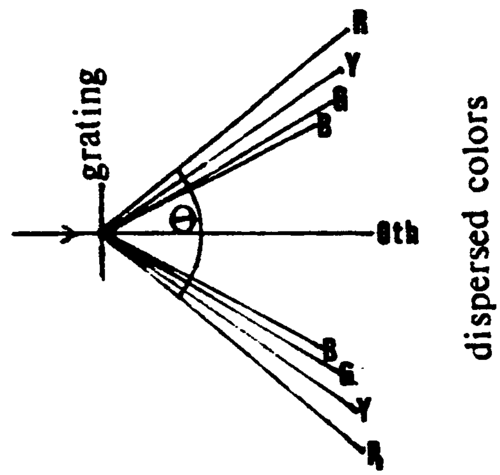


Light from a He-Ne laser with wavelength of 633 nm encounters a diffraction grating with a spatial frequency of 500 lines/mm. To what angles does the light get diffracted? Spatial frequency of 500 lines/mm = fringe spacing of 1/500 mm = .002 mm = 2 μm = 2000 nm. The diffraction equation is $m\lambda = d \sin\theta$, which changes to $m\lambda/d = \sin\theta$.
For the first order, m = 1, λ = 633 nm, d = 2000 nm
Sinθ = 1 x 633 nm / 2000 nm = .3165
Sinθ = .3165, θ = 18.5°.
For the second order of diffraction everything is the same except that now m = 2, so
sinθ = 2 x 633 nm / 2000 nm = .633
sinθ = .633, θ = 39.3°.
For the third order, m = 3, so
sinθ = 3 x 633 nm / 2000 nm = .9495
sinθ = .9495, θ = 71.7°.
Fourth order, m = 4,
sinθ = 4 x 633 nm / 2000 nm = 1.266. There is no angle with sine greater than 1, so there is no fourth order of diffraction for this grating at this wavelength.

If the fringe spacing, d, were smaller, like 1000 nm, then first order diffraction would have an angle of 39.3°. Second order of diffraction ends up with a sine greater than one, so there is no second order in this instance. Generally for a given wavelength the higher the spatial frequency, which means a smaller fringe spacing, the larger the angle of diffraction.

One method of separating the colors from a multi-line laser is to pass the undifferentiated beam through a diffraction grating. For a Krypton ion laser tuned to these four colors, the dispersion can be predicted by solving the grating equation four times.

Let d = 1000 nm
First order diffraction m = 1
BLUE: λ = 457 nm
sinθ = 1 x 457 nm / 1000 nm = .457
sinθ = .457, θ = 27.2°.
GREEN: λ = 514 nm
sin0 = 1 x 514 nm / 1000 nm = .514
sin0 = .514, 0 = 30.9°.
YELLOW: λ = 568 nm
sin 0 = 1 x 568 nm / 1000 nm = .568
sin 0 = .568, 0 = 34.6°.
RED: λ = 647 nm
sin 0 = 1 x 647 nm / 1000 nm = .647
sin 0 = .647, 0 = 40.3°.



The angle of diffraction is dependent not only on the grating spacing, but on the color or wavelength of the light incident on the grating. Short wavelengths, the blues, are bent less than the longer wavelengths, from green to yellow to red. This is called dispersion through a diffraction grating. White light can be broken up into all its components through a grating producing a continuous spectrum.

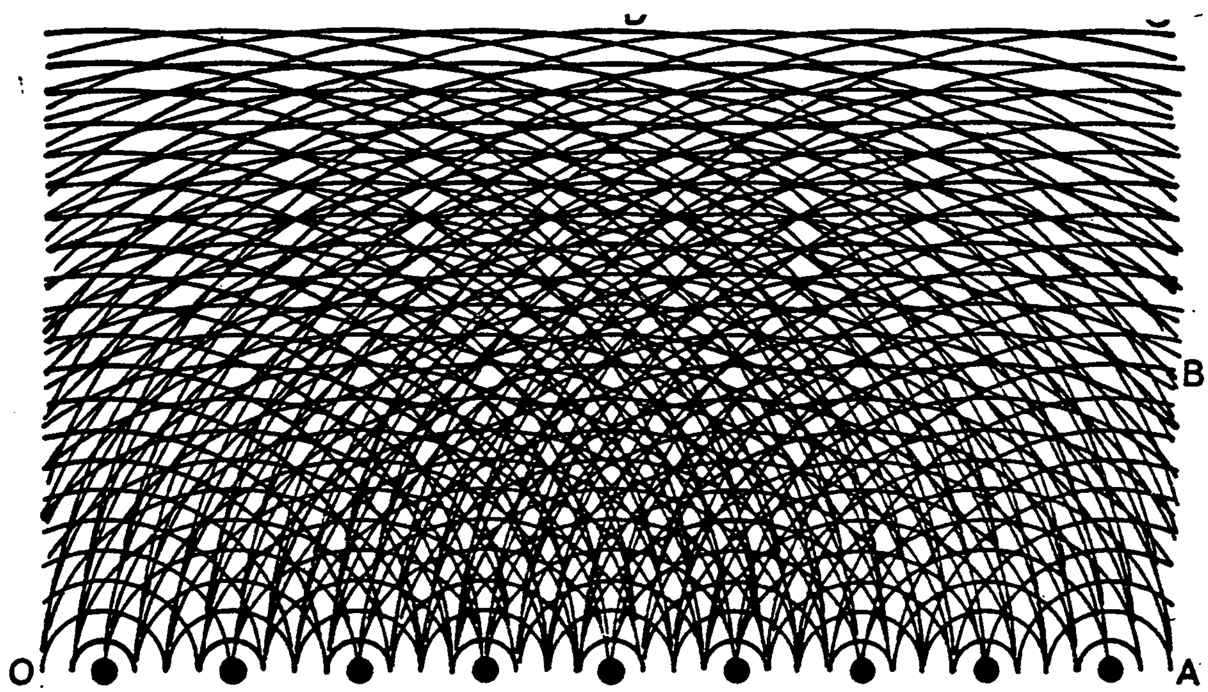


Fig. 66. The black dots here may represent a set of regularly spaced openings in the barrier of the ripple tank, or they may represent a set of particles, evenly spaced, which scatter the incident light in the form of circular ripples (or spherical if we extend the treatment to the three-dimensional case). The waves are advancing from below, and their front is parallel to O A. The wave-front D C is formed as already explained Fig. 65. Here other wave-fronts are formed also. To see them look along the diagram obliquely in the directions O A, O B, O C, and O D in turn. There are no other wave-fronts but these. (Diagram by W. T. Astbury.)

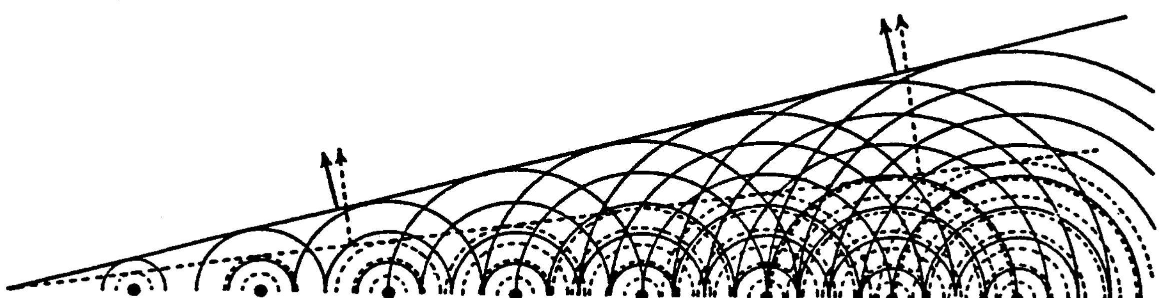


Fig. 67. This diagram is an extract from the last, showing the formation of the diffracted waves of the first order. It also shows how the direction of diffraction depends upon the length of the wave. The shorter waves are related to the longer in approximately the same way as the blue waves to the red.

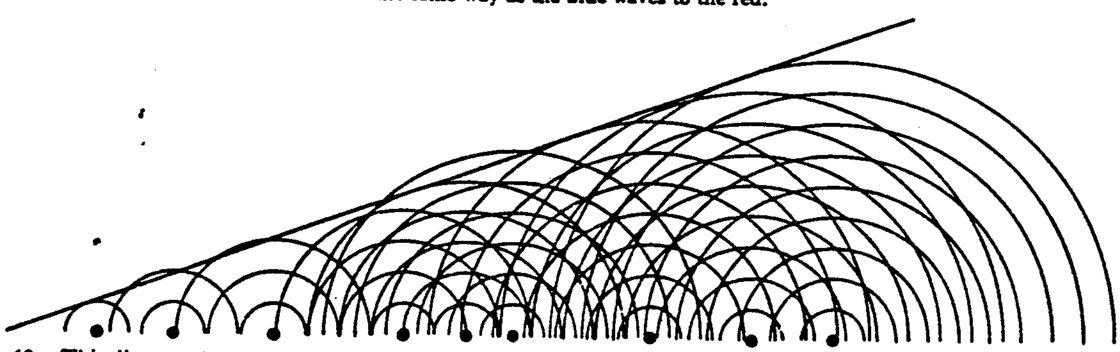
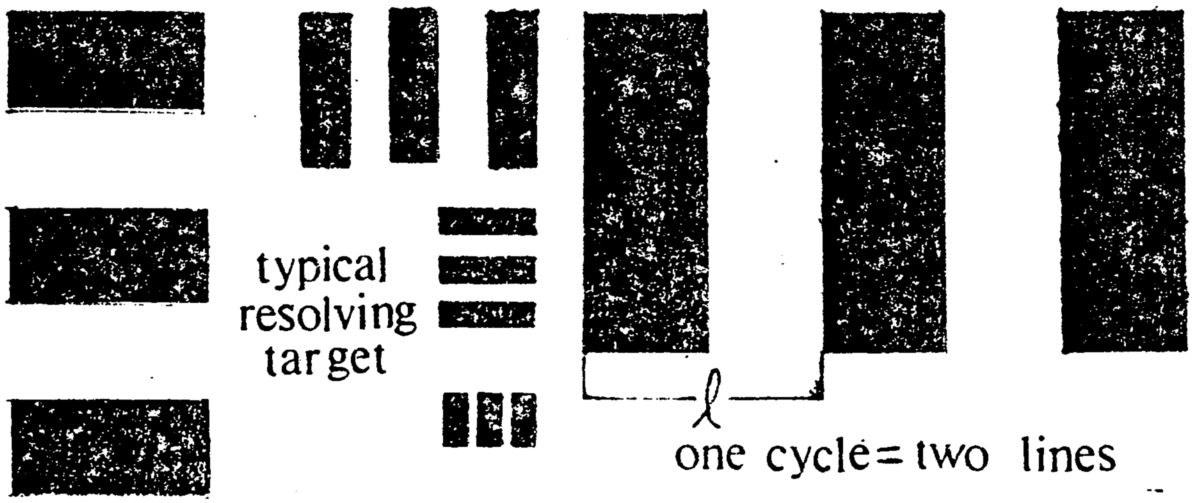


Fig. 68. This diagram shows that a diffracted set of waves is not formed unless the centres (black dots) are spaced evenly. If a straight line is drawn, as in the figure, to touch some of the wave crests which the circles represent, it goes between others. Thus some of the ripples would cause a crest on the front and some a hollow, and in the aggregate there is mutual destruction. The 'interference' between the separate sets of ripples is more fully discussed in what follows.

RESOLVING POWER



How fine a detail a photosensitive emulsion can discern is quantified in its resolving power. A test target is photographed through a lens of known resolving power, and the emulsion is developed under stringently controlled conditions. This target is composed of cycles of alternating light and dark bands. When a film reaches the limit of its resolution, then the light and dark bands are not differentiated but blend into a blob. If ℓ is the smallest distance between a cycle of a light and a dark band, then the resolving power, r is given by:

$$r = 1/\ell \text{ lines per mm}$$

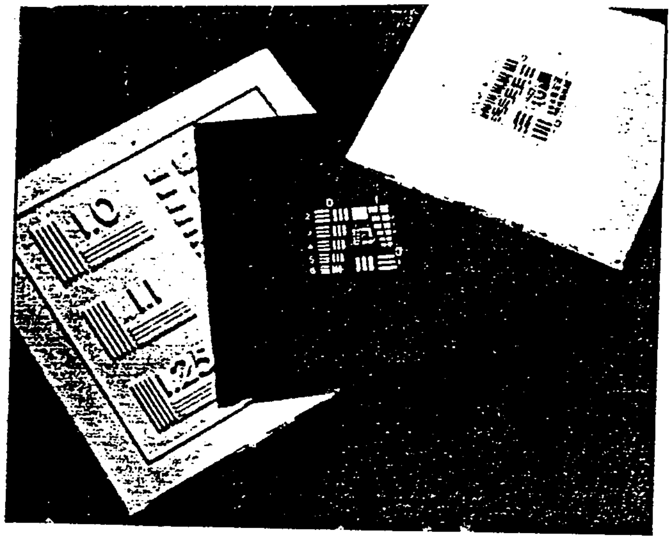
For instance, if the smallest spacing observed in the emulsion under a microscope was .02 mm, its resolving power is 1 / .02 = 50 cycles per mm. Since one cycle = 2 lines if the dark and light spaces are equal in size, then the resolving power would be 100 in the more familiar lines per mm. Notice that resolving power is an application of spatial frequency.

What we are capturing on the holographic film are patterns of bright and dark fringes. The range of resolving powers necessary to make holograms start at less than 100 line/mm for diffraction made with red laser light with a small angular separation to over 4000 lines/mm for a reflection hologram made with blue light. Typical camera films resolve at best 200 lines/mm for a fine grain emulsion like Kodak Panatomic-X. Holography films belong to the family of micro-fine grained emulsions.

The classical test for resolving power fails at the high spatial frequencies necessary for holographic recording. Manufacturers of these films will publish statements of estimated resolving powers or will say the film is capable of making reflection holograms with certain colors of laser light.

See the FILM SPEED sheet for a listing of comparative resolving powers for typical holographic emulsions.

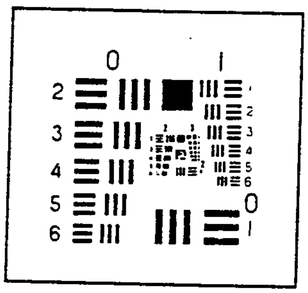
9/20/82
EW



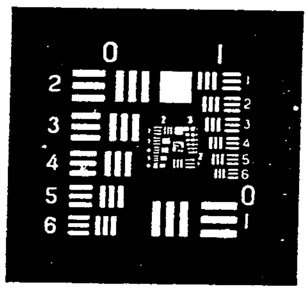
TEST TARGETS

The need to assign numerical tolerances to the performance of optical systems and photographic processes has resulted in the general acceptance of the USAF 1951 resolution test target. In this target the number of line pairs per millimeter doubles with every seventh target element (a "line pair" being a dark bar plus an equally spaced clear bar). An element consists of two target patterns of three lines each, at right angles to each other. These six elements are known as a group.

USAF TEST TARGET



Positive



Negative

Our chromium test targets cover the range from group 0 to group 7, while the emulsion targets cover 0 to 6. USAF test targets, of either chromium or emulsion type, are available in either positive or negative form. The corresponding numbers of line pairs per millimeter appear in the following table.

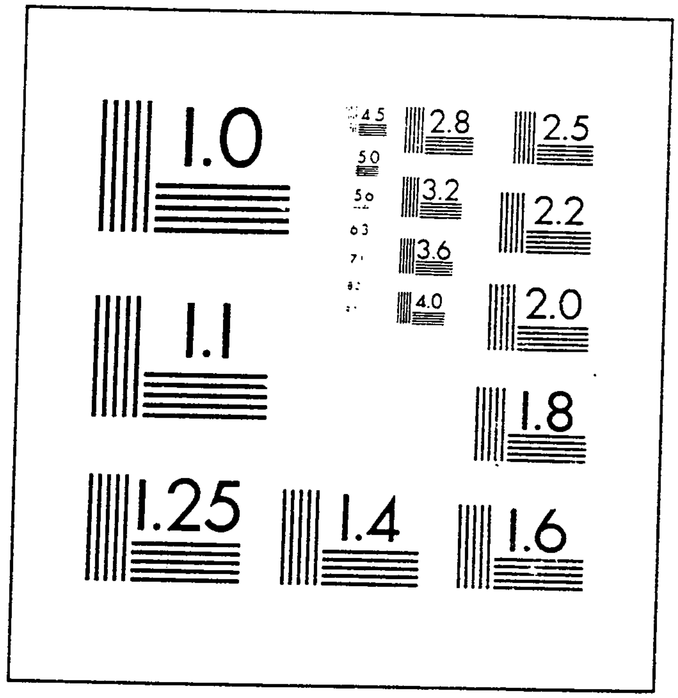
Line Pairs Per Millimeter

Element Number	Group Number 0	1	2	3	4	5	6	7*
1	1.00	2.00	4.00	8.00	16.0	32.0	64.0	128
2	1.12	2.24	4.49	8.98	17.95	36.0	71.8	144
3	1.26	2.52	5.04	10.1	20.16	40.3	80.6	161
4	1.41	2.83	5.66	11.3	22.62	45.3	90.5	181
5	1.59	3.17	6.35	12.7	25.39	50.8	102	203
6	1.78	3.56	7.13	14.3	28.51	57.0	114	228

*Chromium only.

Also in widespread use is the NBS 1963A test target. In appearance it is self-explanatory, the number nearest each pattern element being the number of line pairs per millimeter for that element. NBS test targets are chromium positive only.

NBS TEST TARGET



SPECIFICATIONS: TEST TARGETS

Substrate: 50 x 50 x 1.5mm for USAF pattern
63.5 x 63.5 x 1.5mm for NBS pattern
Type: Evaporated chromium or photographic emulsion
Pattern: USAF 1951 or NBS 1963A

Range:		
	USAF chromium type	1-228 lp/mm
	USAF emulsion type	1-114 lp/mm
	NBS chromium type	1-18 lp/mm

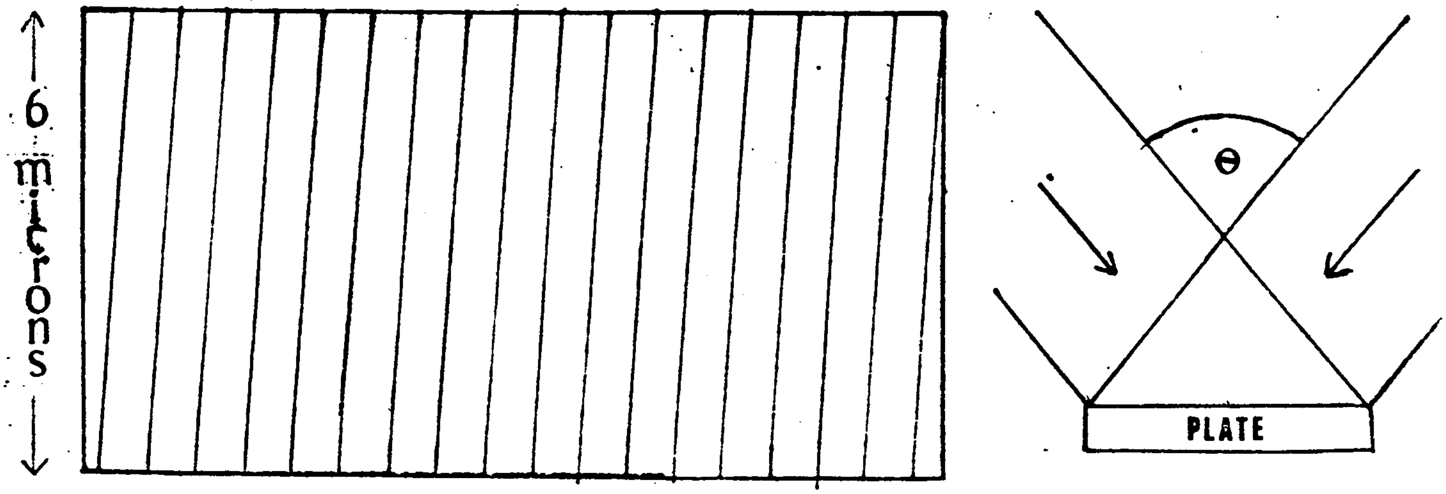
Test Targets

Description	PRODUCT NUMBER
USAF 1951 emulsion positive	04 TRP 001
USAF 1951 chromium positive	04 TRP 003
USAF 1951 emulsion negative	04 TRN 001
ISAF 1951 chromium negative	04 TRN 003
NBS 1963A chromium positive	04 TRP 005

FRINGE ARRANGEMENTS

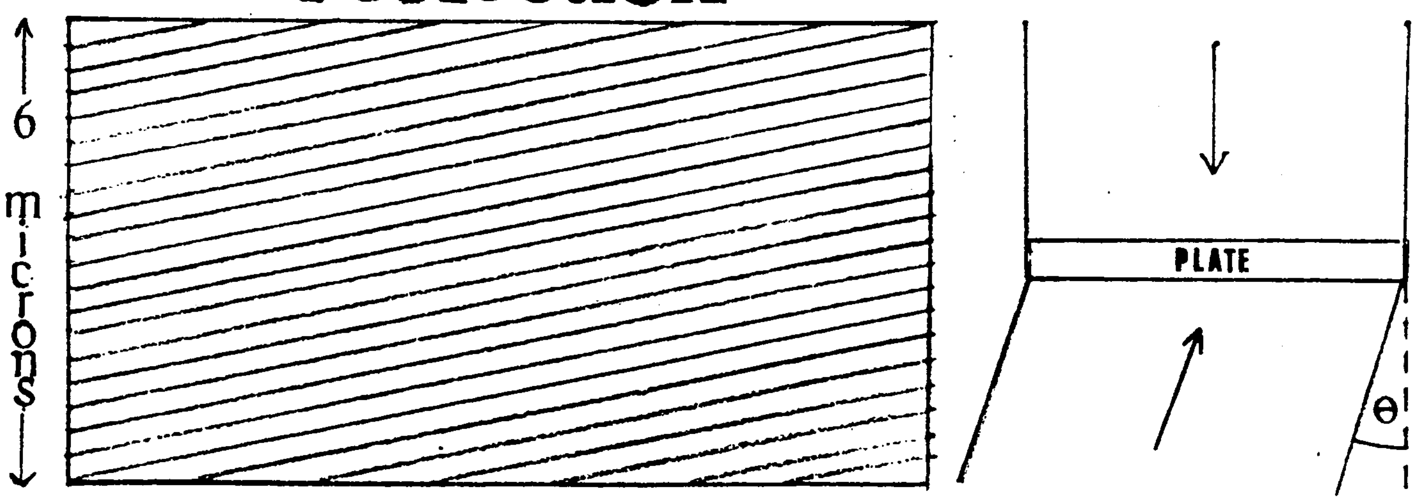
SCALE: 1 centimeter = 1 micron

transmission



d = λ/sinθ λ= 632.8 nm, θ = 80°
d = .642 micron

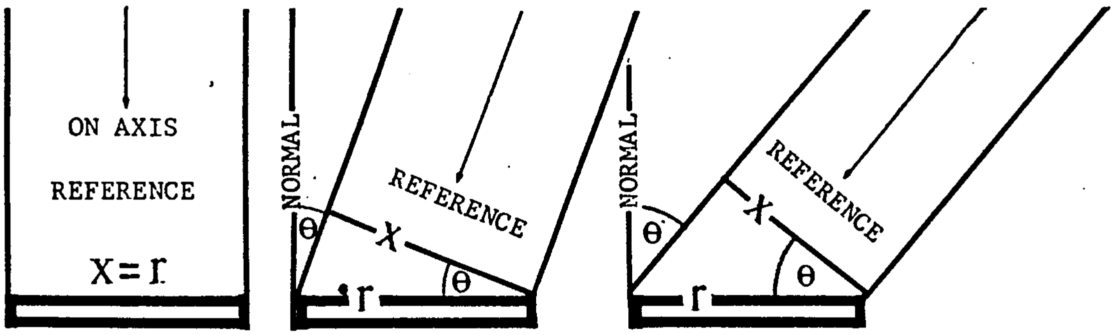
reflection



d = λ/2cos(θ/2) λ= 632.8 nm, θ = 20°, d = .3 micron

These scale drawings depict the fringe arrangements that would be found in a holographic diffraction grating using the set up geometries at the right. A typical holographic emulsion is about 6 microns thick; the support material is not shown because at this scale the film the emulsion is on would be one and a half meters long and the glass plates on which the emulsion is also available would be 14 meters long! Notice in these cross-sectional views the differences in the spacing and the position of the fringes in the two types of hologram.

the COSINE factor



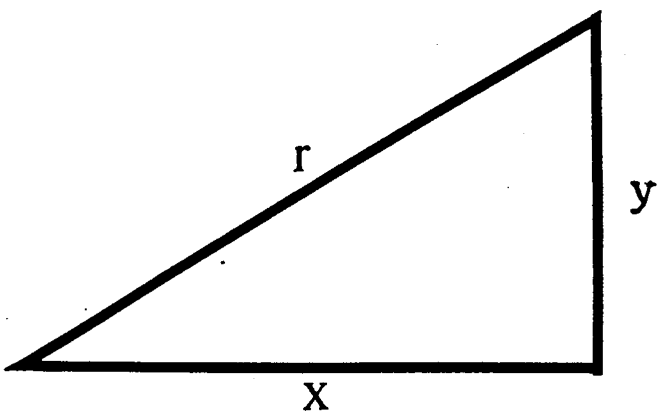
$\theta = 0^\circ$	$\theta = 20^\circ$	$\theta = 40^\circ$
$\cos\theta = 1$	$\cos 20^\circ = .94$	$\cos 40^\circ = .77$

X= width of beam   r = projection of X onto the film or plate

θ= angle of beam to the normal Both θ's are equal because they are complementary to the same angle.

Because r is the projection of X onto the plate, it is longer, spreading X's light out, so it has a lower density or flux. The exposure is cut down by the ratio of the beam's width to its projection, or $\frac{X}{r}$, which is the definition of cosine θ.

REMEMBER:



$$\sin\theta = \frac{X}{r}$$

$$\cos\theta = \frac{y}{r}$$

12/2/80

図４　ホログラフィーの原理
Principles of holography.

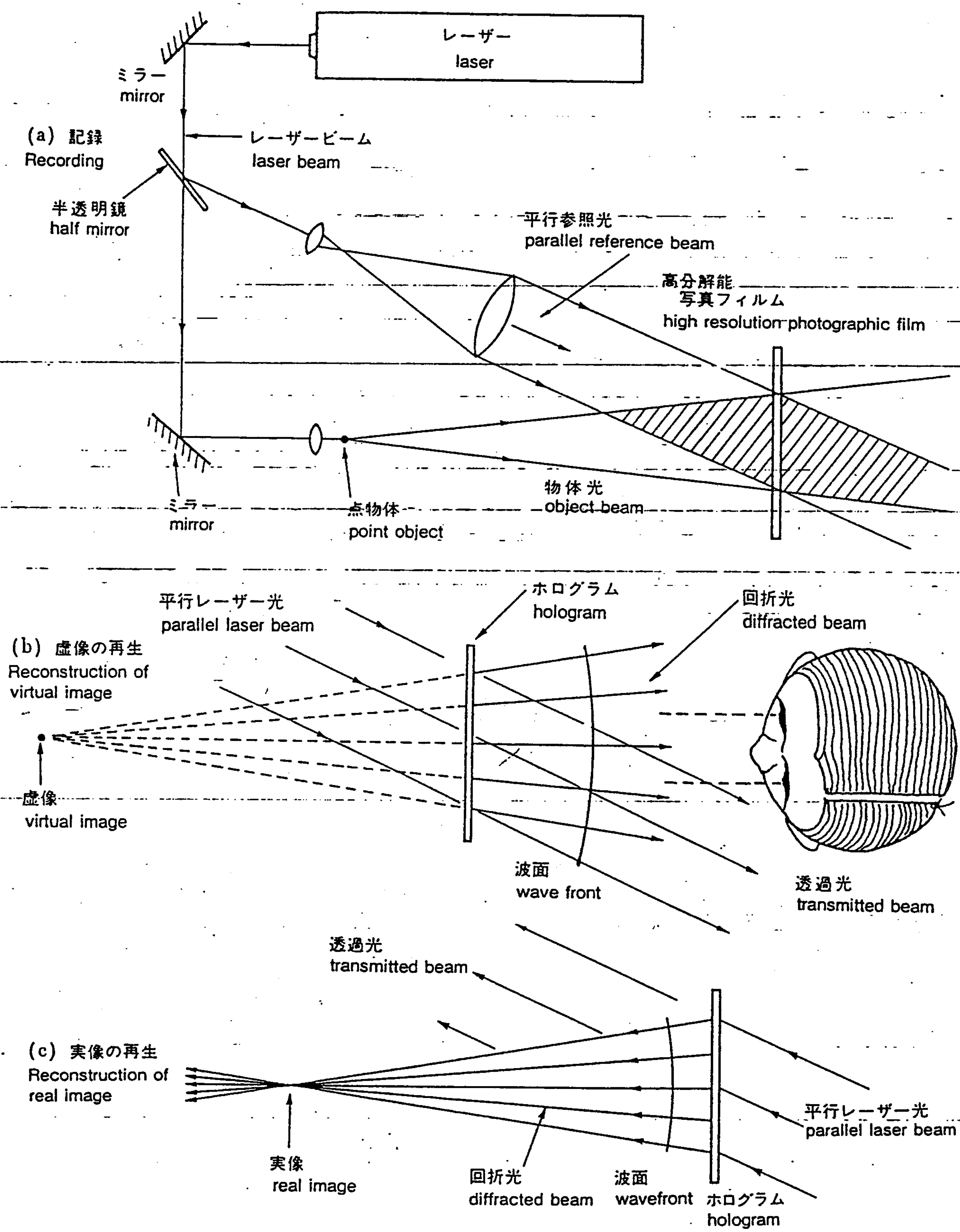


図 6　ワンステップ・レインボウ・ホログラム
One step raimbow hologram

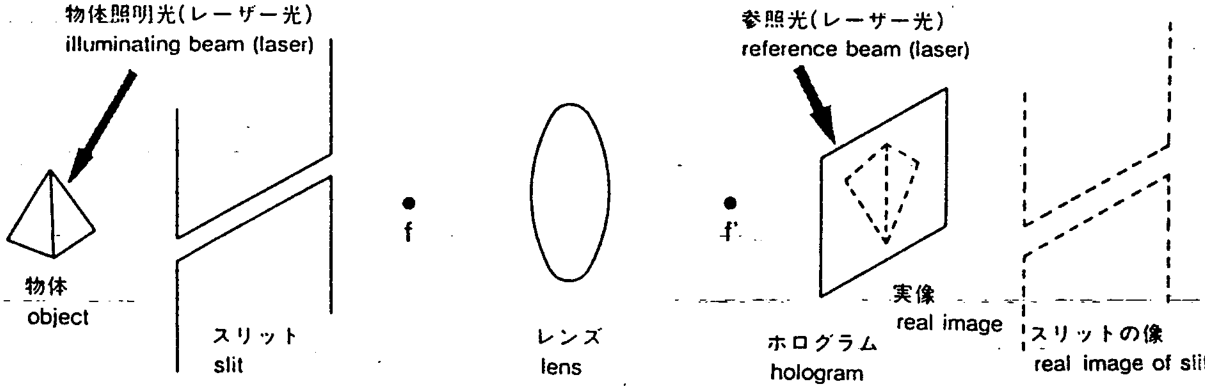


図 7　レインボウ・ホログラム
Rainbow hologram.

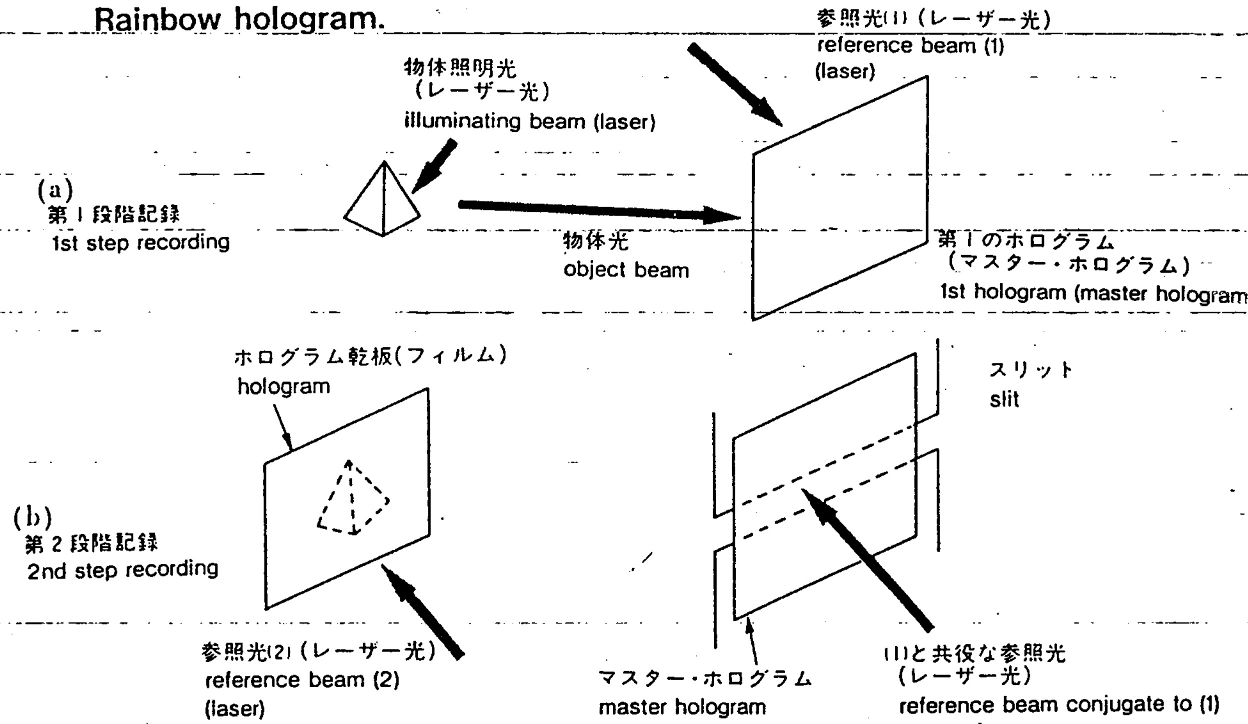


図 8　レインボウ・ホログラムの再生
Reconstruction of rainbow hologram.

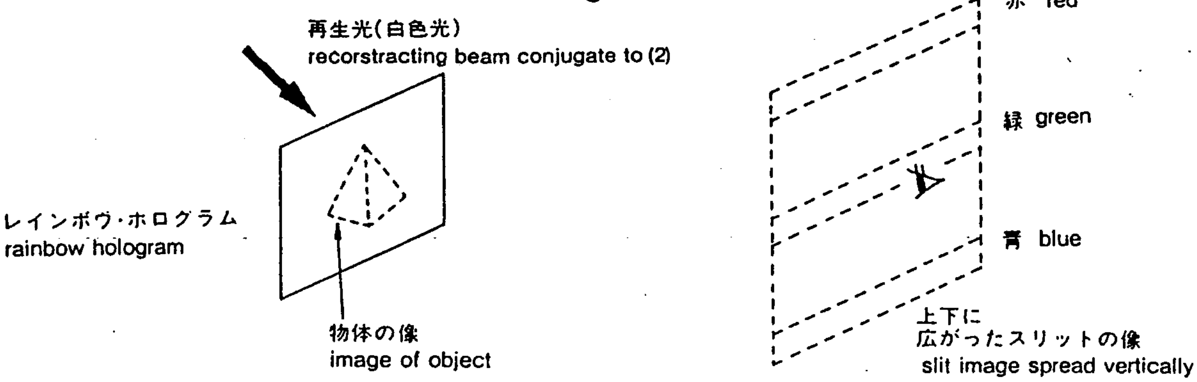


図12　マルチプレックス・ホログラムの原画撮影
Taking original film of multiplex hologram.

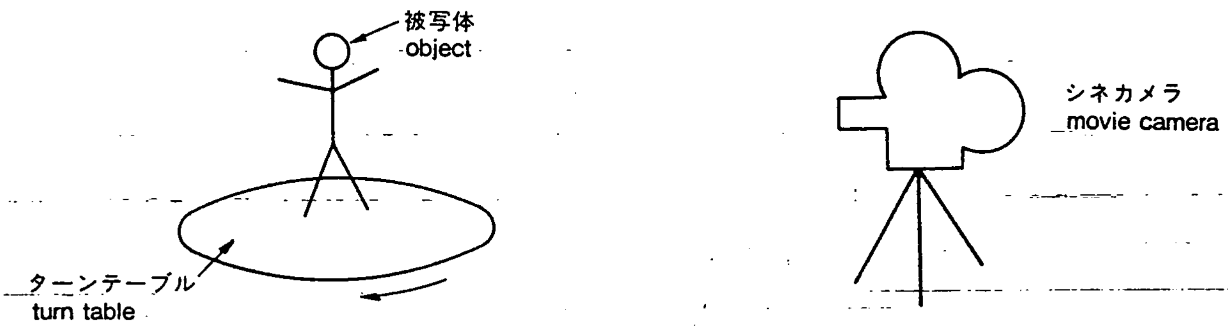


図13　マルチプレックス・ホログラムの合成
Synthesis of multiplex hologram.

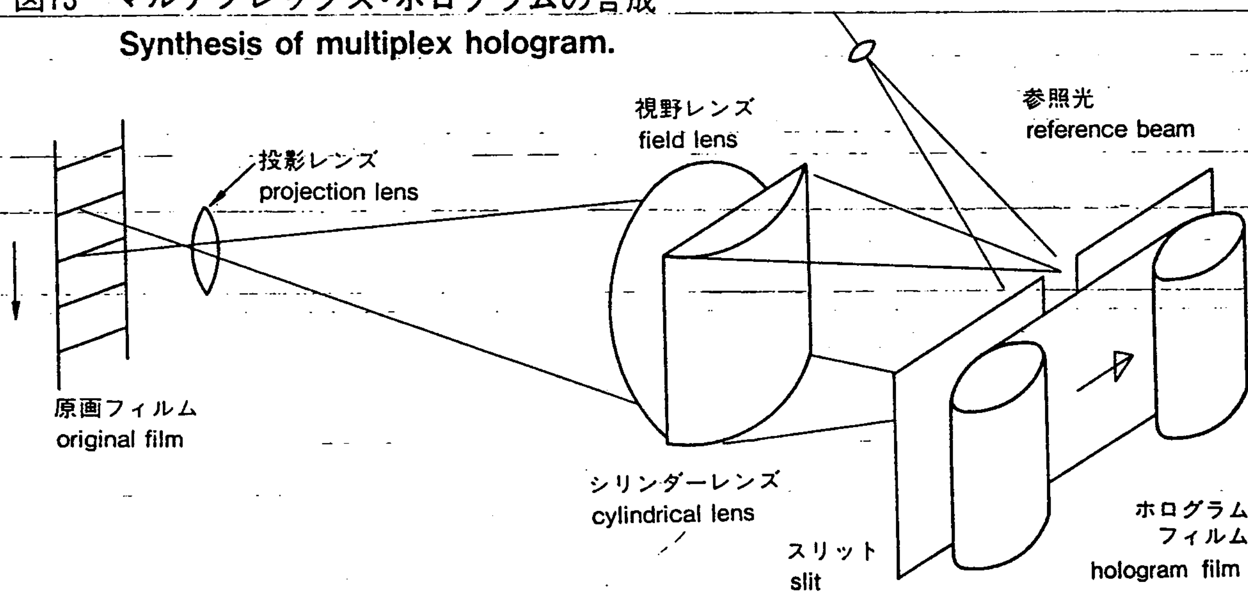
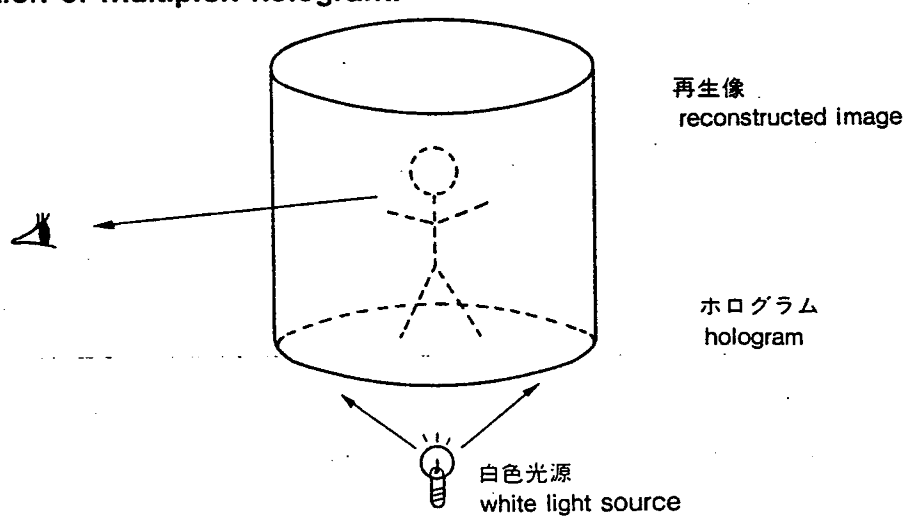


図14　マルチプレックス・ホログラムの再生
Reconstruction of multiplex hologram.



HOLOGRAPHIC RECORDING PARAMETERS

There are four parameters to check before making a holographic exposure. They are PATH LENGTH MATCHING, POLARIZATION VECTOR ALIGNMENT, BEAM BALANCE RATIO, and EXPOSURE DETERMINATION, in that order.

PATH LENGTH MATCHING should be done while setting up. The distance from beamsplitter to holographic plate in the reference beam path should equal the distance from the beamsplitter to the object to the holographic plate. All optics, like beam path folding mirrors should be included in the measurement. String is the best measuring tool, as the distance need not have a numerical value. One path should not be longer than the other by an amount longer than the coherence length of the laser. (For Melles Griot LHP-171, this is about 16 inches; for Spectra-Physics 124B, it's about 12 inches; for Spectra-Physics 127, it's about 8 inches.)

POLARIZATION VECTOR ALIGNMENT should be done next, as different amounts of light will be reflected from glass surfaces depending on their polarization state and the beam balance ratio will then change. If using a glass disc reflected/transmitted beamsplitter, a single half wave plate before it will suffice, as then both the reference beam and object beam will have the same polariztion state. If using the polarizing beamsplitting cube, half wave plates on one or the other or both outputs may be necessary.

Manipulate the half wave plate to ensure that the reference beam has maximum penetration of the holographic plate by observing the reflection from a piece of glass put in the plate holder. Minimum reflection means maximum transmission. Observe that the object beam has the same polarization. See the Handout, **ALIGNING POLARIZATION VECTORS**.

BEAM BALANCE RATIO should be set after all the pinholes are in place so that "bullseyes" do not affect the light measurements. Unfortunately, spatial filters may get detuned while ratio adjustments are being made, so check components downbeam of the splitter before making more measurements if you touch anything.

Measurements of the reference and object beams are taken individually, with the light meter probe parallel to the holographic plate. The ratio will vary depending on the application.

BEAM BALANCE RATIO SUGGESTIONS

TYPE OF HOLOGRAM	RATIO (Reference:Object)
Laser Transmission	4:1
White Light Transmission[1]	2:1

---

[1]. Reference Beam Intensity as compared to brightest spot on

One Step Rainbow Shadowgram	4:1
Two Beam Reflection	2:1
Single Beam Reflection	Determined by object
Diffraction Grating	1:1

(For the theorectical background see the Handout, **THE ROLE OF THE BEAM BALANCE RATIO IN HOLOGRAPHY**.)

TROUBLESHOOTING BEAM BALANCE RATIO

If the shadow aren't very black, or worse, a cloud of haze surrounds the object in a classical laser transmission hologram, then there is too much object light. Raise the ratio.

If there is a photographic negative image that overpowers the holographic one in an image plane hologram, then there is too much light in the real image from the master hologram. Cut back on the replay beam for the master.

If the object is lost in a Spectral Haze in the One Step Rainbow Shadowgram, add more reference beam.

If the shadows aren't very black and\or there is a milky haze on the surface of the split beam reflection hologram, add more reference.

For all types of holograms: If the image is not very bright, and stability and coherence length don't seem to be a problem, and exposure tests have been run up to the saturation point, then more object light is needed. If the beamsplitter is set for the maximum object light, spread the reference beam more to weaken its intensity.

DETERMINATION of the EXPOSURE TIME can be made using the S & M Meter. Place the probe up against a piece of glass in the plateholder. Read both beams simultaneously. Refer to the chart on the wall or on the S & M Instruction sheet. (See the handout, **MANUAL FOR SCIENCE & MECHANICS' SUPERSENSITIVE PHOTO METER-DARKROOM MODEL A-3 BY WILFRED M. BROWN)**

You may wish to expose a small test strip at this recommendation and develop it before a large hologram is attempted, (a trade-off between time and expense!) or to make a series of exposures on one test hologram centered around the recommended one. (See the Handout, **THEORY AND PRACTICE OF TEST STRIPS**.) Without a meter, a first best guess can be attempted, or a test series bracketing around this guess could be implemented. CAUTION! Film and Plates are not interchangeable sensitometrically! Tests should be made on the same material, preferably from the same package, as the final product. Always note the development times of your tests so that it can be duplicated on the next shot.

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real image on film plane.

THE REFERENCE BEAM SPECIFICATIONS

Gabor called the reference beam "the coherent background" which would interfere with the object, producing the holographic pattern. This reference beam should be easily reproducible, so that the hologram could be viewed without too much effort. (Not so easily reproducible reference beams, or coded ones, have security applications.)

The parameters of the reference beam which need to be specified are its Direction, its Angle of Incidence to the hologram, and its Distance from the hologram. The reference beam can come from either the same side as the viewer (reflection hologram) or the side opposite the viewer (transmission hologram), but it still has the same attributes.

The earliest holograms of both Gabor and Denisyuk had the reference beam incident normal to the plate. In the transmission hologram case of Gabor, this meant that the viewer would see the reference spot along with the object, creating an unpleasant viewing experience. For Denisyuk's earliest attempts, this meant that the replay beam would have to originate from between the viewer's eyes, an inconvenient situation. The off-axis reference geometry of Leith and Upatnieks first solved the blinding problem in the transmission case, then it was applied to reflection holograms.

THE DIRECTION of the reference beam can be from the left, right, top or bottom. Most display holograms are referenced from the top, as most display environments have lights directed down from the ceiling. But sometimes it is more convenient if the holographer is setting up the space to have the lights on the floor, and light the holos from below, as then there is no need to be up on ladders, attaching things to ceilings.

Many laser lit holograms of the Classical era were side-lit (although left or right were never standardized) because having a laser attached to the ceiling would be difficult. Having the laser on a table or tripod would be a much more stable mount, however people could walk behind the hologram, blocking the beam, plus there always is the danger of someone looking back into the reference spot and complaining of eye damage.

ANGLE OF INCIDENCE can really be any angle, but it's so much easier to assign 45 degrees as the angle since it's easiest for viewers to understand. The problem is that angles are measured from the normal in optics and holography, a concept that hasn't really caught on with the viewing public (or many holographers). It's harder to explain to people that 60 degrees from the normal is very steep, whereas if it were measured from the hologram plane it would be a shallow incidence.

For both reflection and transmission holograms, a shallower (lower) reference beam angle means that the light will have to be further from the hologram along the ceiling than a steeper one. But a steeper angle of incidence means greater loss of light due to reflection at the air-glass interface (both in recording and reconstruction), unless polarized light is used.

REFERENCE BEAM DISTANCE is measured along the angular direction. It is important for proper image reconstruction, without aberrations. (See the Handout, **HOLOGRAPHIC ABERRATIONS**.) This dimension is extremely important when viewing technical holograms when measurements need to be taken. Since many two-step image plane holograms are made with quasi-collimated beams the further away the better.

Intermodulation Noise

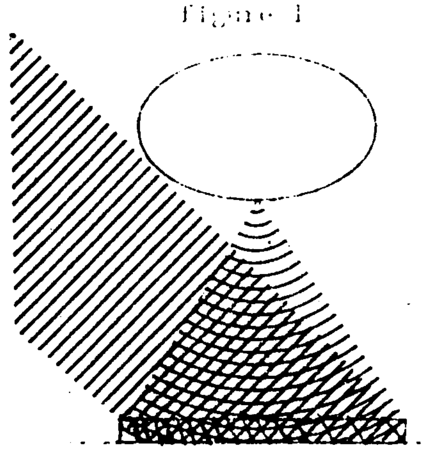
A noticeable speckle pattern can be seen on an object illuminated by laser light. This is caused by the constructive and destructive interference between light reflected from every pair of points all over the object. The holographic recording material is sensitive not only to the reference-object interference pattern but also to the self-interference of the object.

This speckle pattern may get in the way of viewing the image clearly. Anything that manifests itself as unnecessary information in a communication process is called noise. In holography, our signal is information about the object; it is encoded on the carrier which is the reference beam, and in reconstruction it is carried to our eyes.

This particular noise in holography is called <u>intermodulation noise</u>; <u>inter</u> because it is formed between object points, and <u>modulation</u> because it changes the reference beam. In some ways it is analogous to static in radio. Other noises in a hologram are recording medium noise and optical noise. All these effects may be minimized. In fact, reflection holograms are free from the intermodulation noise. Let's examine the causes of this noise and the ways to minimize it. It would be helpful to have the sheets on diffraction and spatial frequency handy for reference.

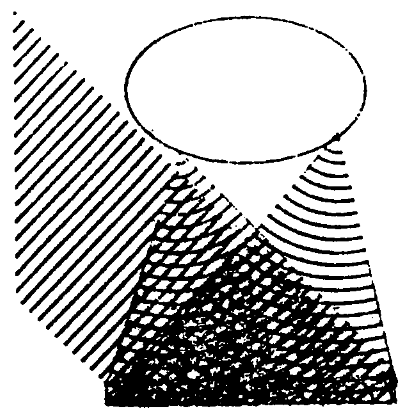
For a particular object, light from every point on it inter-

figure 1



one object point-reference beam interference pattern

figure 2

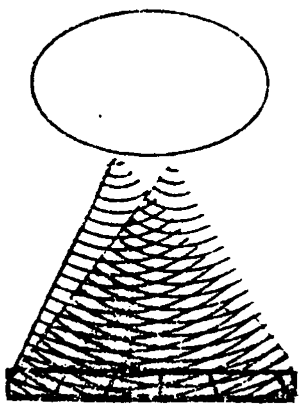


holographic information plus intermodulation noise

feres with the reference beam, producing a pattern on the hologram. (See figure 1.) Looking at the pattern produced by light from two object points and a reference beam, you can see not only the interaction of the reference and object points but the interference of between two object points. (Figure 2) Notice that the interference pattern of the two object points has a lower spatial frequency than the interference of the reference-object beams; i.e., the fringe spacing is larger. These fringes are arranged in different directions from the signal fringes. The reconstructing reference beam is then scattered in many different directions and does not contribute to the object wavefront. It introduces its own speckly pattern into the signal. Every pair of points on the object makes this interference amongst themselves.

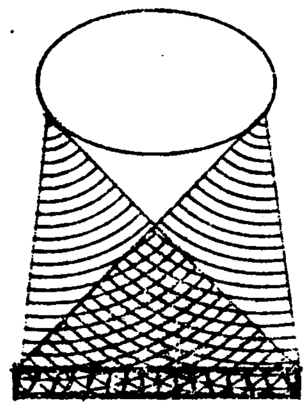
The spatial frequencies of the noise gets larger as the distances between the interfering points increase. The noise from

figure 3



noise from adjacent object points

figure 4

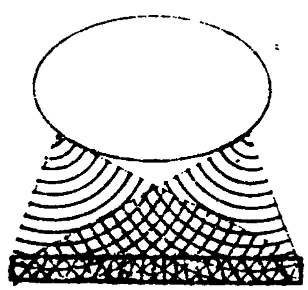


noise from endpoints of object

two adjacent points has low spatial frequency; the upper limit of spatial frequency is set by the light from the endpoints of the object interfering with each other. (See figures 3 & 4.)

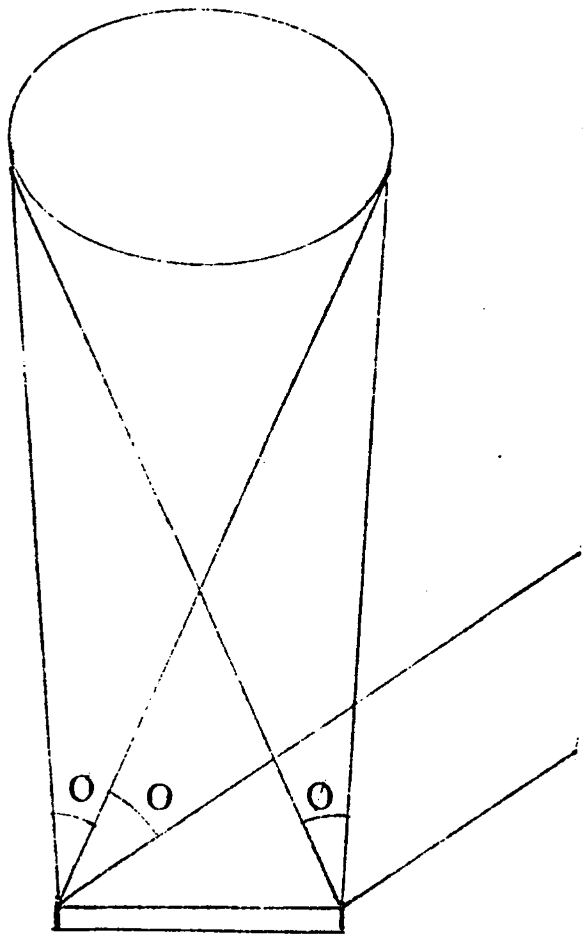
Larger objects will of course produce more of this noise because there are more pairs of interfering points. The noise also becomes more serious as the object gets closer to the film plane. The angle between the endpoints is larger, so the fringe spacing gets smaller and closer to the size of the signal fringes. (See figure 5 below.)

figure 5



noise from the endpoints of a near object

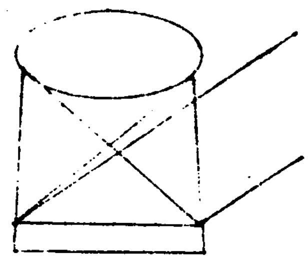
One method of minimizing the intermodulation noise is to keep the spatial frequency of the signal higher than the spatial frequency of the noise. The bigger the distance between the fringes, the smaller the angle of diffraction--the smaller the fringe spacing, the larger the angle of diffraction. By keeping the noise fringes' spacing larger than the signal's, we can diffract the noise to an angle different from the signal's. We can physically accomplish this in recording the hologram by having the smallest angle between the reference beam and any object beam greater than the largest angle formed by a pair of points on the object. (See diagram on the next page.) Of course, this is not always physically possible due to compositional factors.



Angle Ø is the largest angle between light from two points on the object. This sets the upper limit of the spatial frequency of the noise.

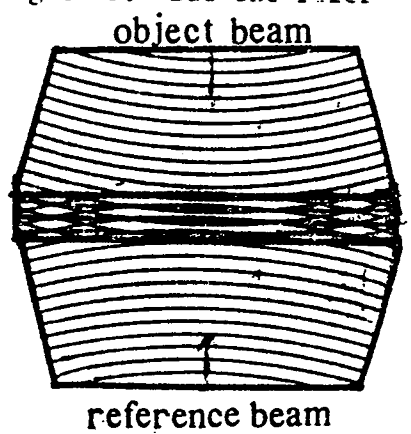
Angle θ is the smallest angle between light from a point on the object and the reference beam. This sets the lower limit of the spatial frequency of the signal.

If angle θ > angle Ø, then the noise will be at a minimum due to the set up. However, practical set ups look more like this:



with the range of the spatial frequencies of the noise and of the signal overlapping.

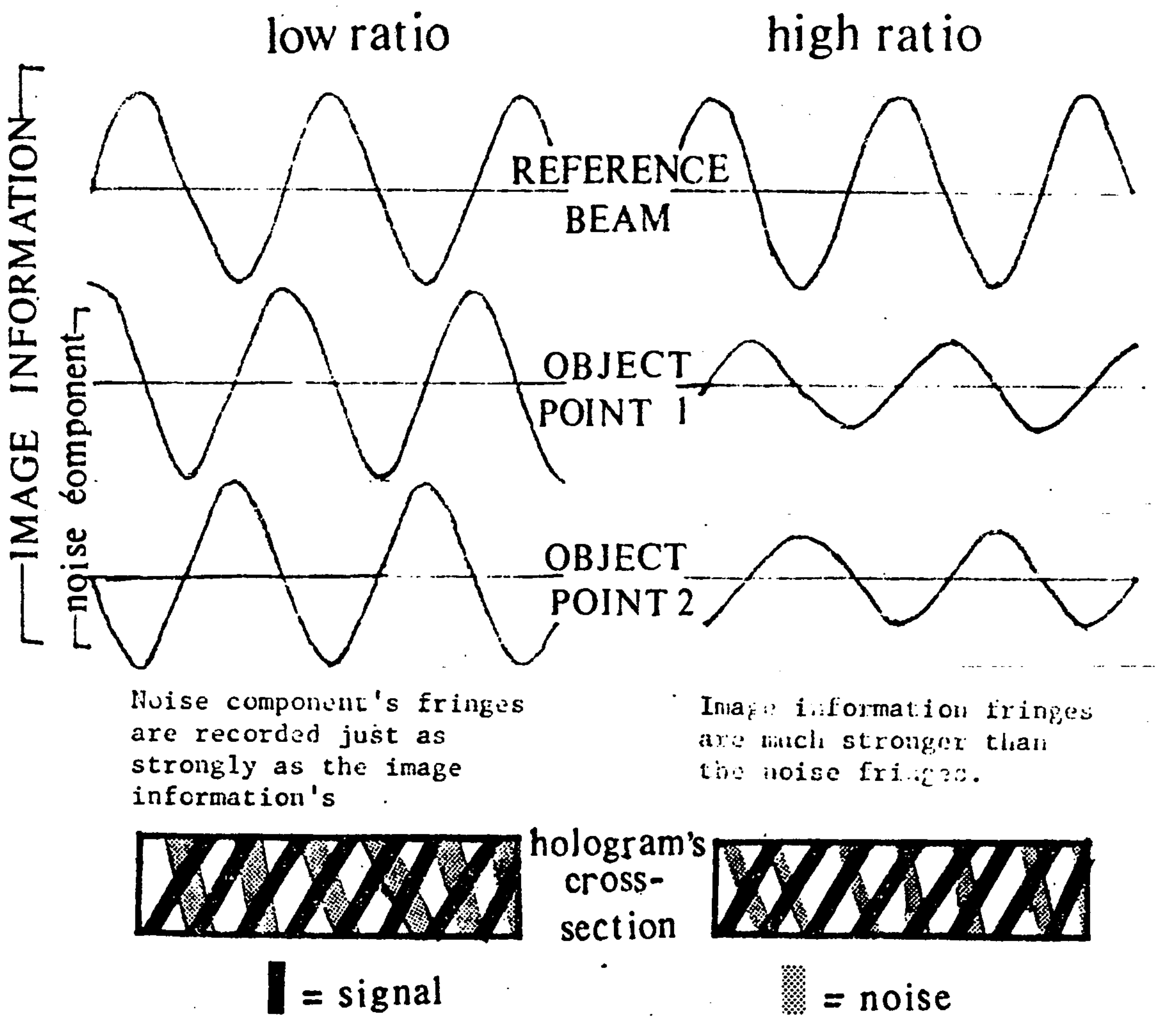
Reflection holograms are free from intermodulation noise because the noise fringes are arranged more or less perpendicular to the information fringes. Noise fringes are made by point sources on the same side of the film--in effect, a transmission hologram. Note the fringe arrangement shown in figure 3. But the reference and object beams come from different sides of the recording material in a reflection hologram, with fringes formed almost parallel to the film. So in reconstruction, the signal fringes reflect light back to the observer, while the noise fringes reflect light off to the side, out of the viewing bandwidth.



9/24/85
EW

Another method of minimizing intermodulation noise is by controlling the ratio of reference to object beams. Remember that the silver halide materials are negative acting; the more light that hits them the denser it gets, and less light leaves a corresponding lesser imprint. The areas of high density (even after bleaching) will act as areas of high reflectivity in the mirror analogy of the reconstructing mechanism, and the areas of low density will have low reflecting power. By making the combined carrier wave and signal stronger than the noise coming from the object, the carrier will expose more silver and create more highly reflective mirrors, while the noise will not contribute as much. This minimizes the effect of the noise because its reflective power is low.

RELATIVE AMPLITUDES



thickness of the line represents reflectivity

However, there is a drawback to using the high ratios because the noise is formed by the light from the object; if there islittle light from the object th then the carrier wave is not modulated as much. As a result the signal is weaker, so brightness of the reconstructed image is lower than when the reference beam is strongly affected by the object beam. There is a constant battle between brightness and noise.

The general rule of the thumb is this: Low reference to object beam ratios, like 1 to 1 or 2 to 1, will produce bright holograms with a good deal of noise, because the noise fringes are almost as reflective as the signal fringes. High ratios are less noisy because the carrier mirrors are more reflective, but the image is not as bright since the modulation of the reconstruction beam is low because the recording reference beam's modulation was low.

The holographer's job is to minimize noise and maximize brightness by controlling the geometry of the set up, the ratio of reference beam to object beam, and the processing of the recording material. All this depends on the object to be holographed. If a set up is too noisy, raise the ratio, but don't be surprised when the brightness decreases. Some applications may place emphasis on brightness first with little or no regard to laser speckle noise. Low ratios will do the job. Control of the ratios is one aspect of successful holography.

9/25/80
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THE ROLE OF THE BEAM BALANCE RATIO IN HOLOGRAPHY

Ed Wesly   Experiment E 632

When two coherent wavefronts intersect, an interference fringe pattern is formed. If the two waveronts are point sources, or collimated, and of equal intensity, the intensity distribution of the fringe system will vary sinusoidally from very bright to total extinction.

Let us look at the case of two collimated wavefronts schematically in Figure 1. Astraightline fringe system is generated, and if we wished to record it we would place a photosensitive plate in the field. Appropriate exposure and development would yield variations in the amount of silver deposited throughout the emulsion. A bright fringe would be represented by the maximum amount, the nulls by the minimum - ideally, none. When either one of the original wavefronts encounters this pattern, it is shaped into the other wavefront thanks to diffraction through the grating-like structure.

If three collimated beams of equal intensity arranged at the corners of an equilateral triangle are interfered, we would have three sets of patterns caused by the mutual interference of each pair of beams. (Figure 2) A beam coming from any one of these three positions would then reconstruct the other two. And of course this notion can then be taken further to n number of beams. Spherical wavefronts behave the same, except that their fringe pattern shapes are sets of hyperbolae instead of straightline patterns - off-axis zone plates rather than diffraction gratings.

Let us examine the recording process graphically. If we look at the intensity distibution of the fringes formed by two coherent sources of equal intensity we would see the cosinusoidal distribution of Figure 3. The fringes are of high contrast - the brightest fringe is the sum of like amplitudes squared, while the dimmest fringe's intensity is zero.

To make the recording with the highest reconstruction efficiency, we would like to map the intensity distribution onto the characteristic curve (density vs. log exposure) of the recording material so that I_{max} gives us the highest density and I_{min} (=0) gives us none. (Figure 4) Then the recording material will give us a fairly linear recording with the maximum modulation possible, yielding the brightest reconstruction.

In the three equal source case, the intensity again goes from zero to a maximum. The more complex intensity distribution throughout space is shown in Figure 5. Recording parameters are nevertheless the same as for the two beam case - the dimmest fringes are represented by the minimal amount of silver, while the brightest are the maximum.

But what if the coherent sources are not all equally intense? In the three beam case, let us call source #1 the reference and #2 and #3 the object beams. Also suppose that the combined intensity of #2 + #3 were ¼ that of #1. We would say then that the Beam Balance Ratio (BBR) would be 4:1, reference to object beams. The fringe system formed by #1 + #2 or #1 + #3 would have a DC bias as shown in Figure 6, and the entire intensity distribution would be as shown in Figure 7.

To record this fringe system so that we would get the brightest reconstruction we would find an exposure so that the DC component, which would cause overall fogging of the film is below its threshold of sensitivity. Then we must also tailor the time of development to get the proper gamma (slope) of the characteristic curve so that once again I_{max} gives us the maximum modulation density. (Figure 8)

So we would get a good recording of the fringe systems between #1 + #2 and #1 + #3. But what about between #2 + #3? Since this fring system is not as strong as the systems with Beam #1, it will record weakly or not at all, depending on where its intensity falls on the characteristic curve. (Figure 9)

So when this hologram is viewed, Beam #1 will reconstruct both object beams. A beam from position #2 will reconstruct the reference (Beam #1) but #3 weakly or not at all. Similarly for #3. So we have suppressed the intermodulation of #2 with #3.

When making holograms of objects, we interfere the refernce source, (or carrier), which could be a point source or collimated wavefront, with the complex wavefront of the signal, which is the object. If we think of the object as an infinite set of points in space, then each point on the object interferes not only with the reference beam but with each other. So the hologram records not only the interference of each object point with respect to the reference beam, but also the mutual interfernce of all the object points. This extra pattern results in what is call the intermodulation noise, which is evidenced in holograms by the absence of true blacks in the dark arts of the object - i.e. poor contrast. The object's interference pattern diffracts unwanted flux into the object's space.

The Beam Balance Ratio enables the hologram to discriminate between the true holographic information (reference plus object) and the spurious pattern of the object itself. If the reference and object beams are equal intensity, then the intermodulation noise fringes are recorded equally as well as the information fringes. But by making the reference beam much stronger than the object's light, we can put the intensity of the noise below the threshold of recording and minimize or eliminate it, as we did for the intermodulation of beams #2 and #3 in the three beam case. This results in a much more pleasant viewing experience with its higher signal to noise ratio.

For holograms of diffusely reflecting objects, a good separation of noise and signal fringes starts at about a 4:1 ratio and the typical usable rang extends up to about 16:1. The proper ratio for maximum diffraction efficiency and high signal to noise ratio is determined experimentally. Exposure and development tests are made at some fixed ratio and inspected for peak performance, or development is fixed and exposure and ratios are scanned. Experience gained in the field plays an important role in finding a suitalbe starting point and being able to judge quality.

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ENGINEERING NOTE

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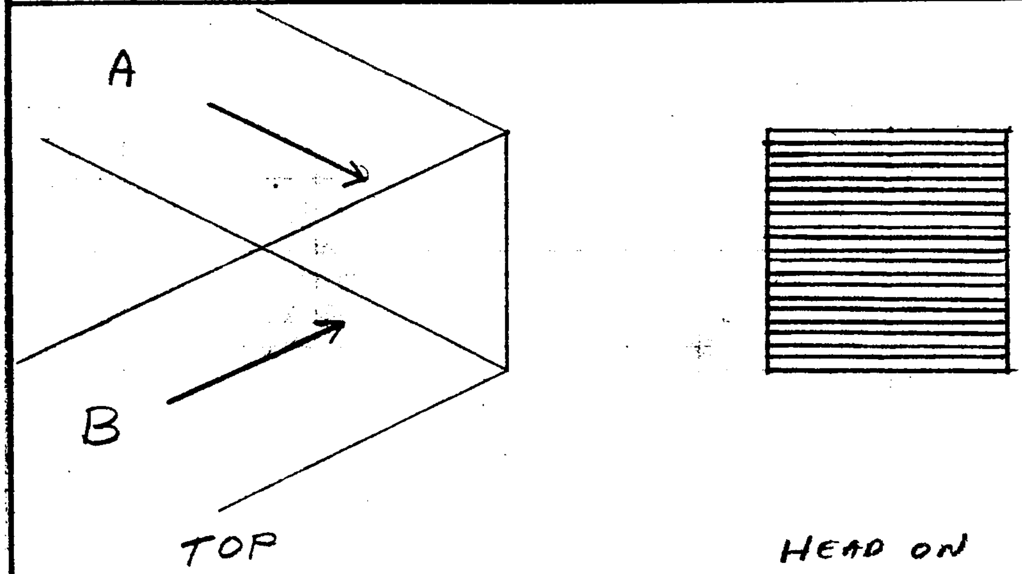

FIGURE 1

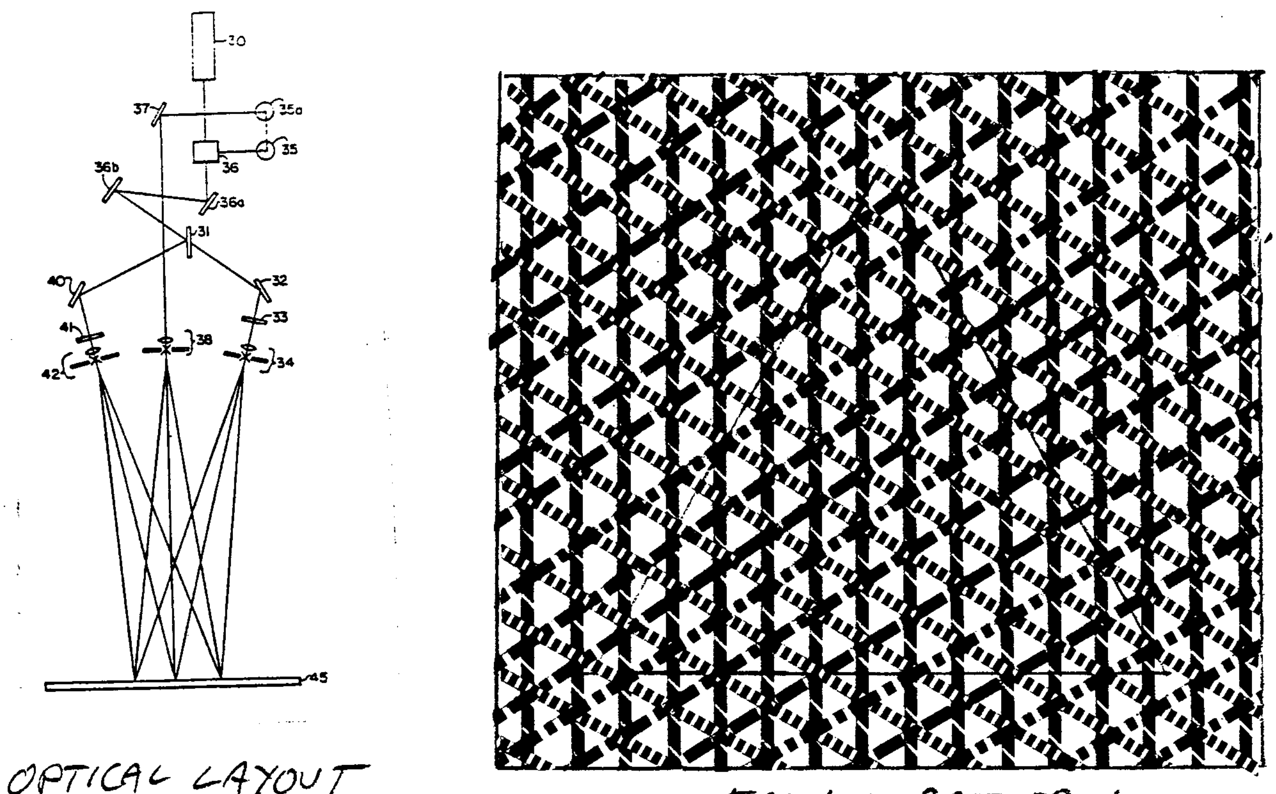

FIGURE 2

||||| = #1 + #2 \\\\ = #2 + #3
— — —·— = #1 + #3

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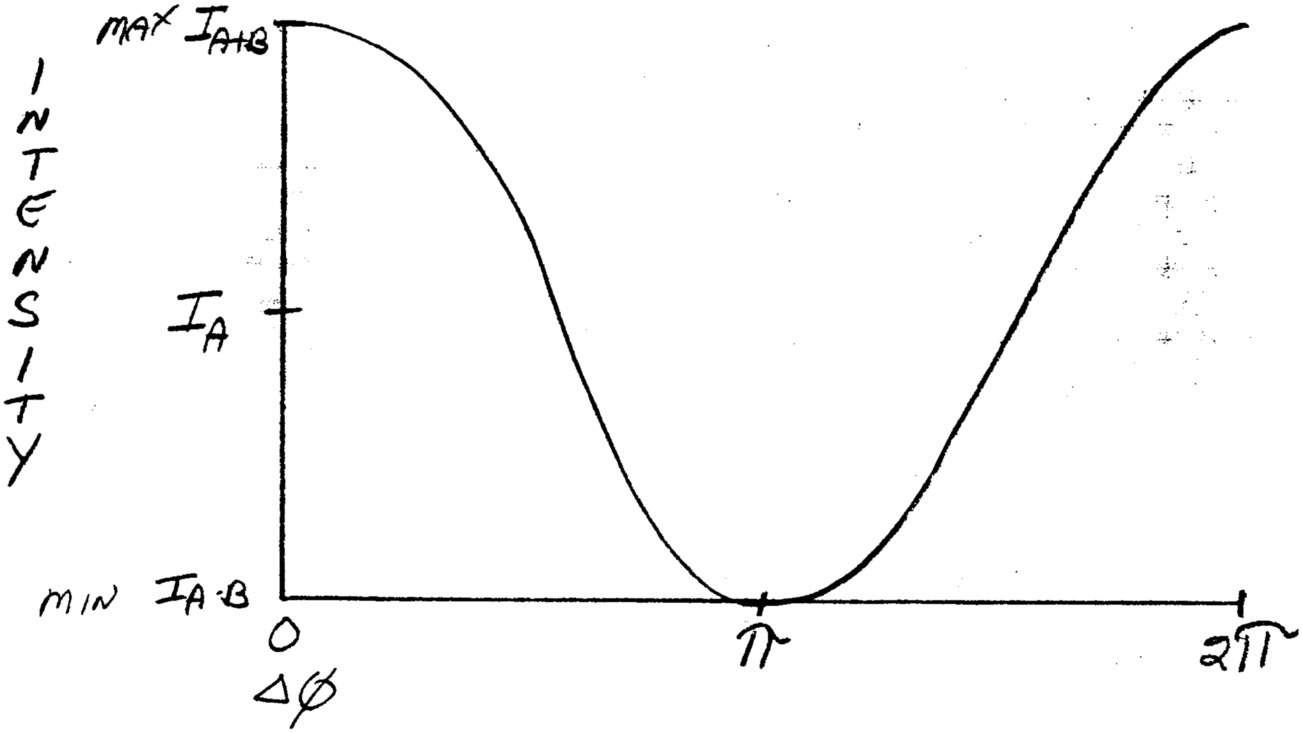

FIGURE 3

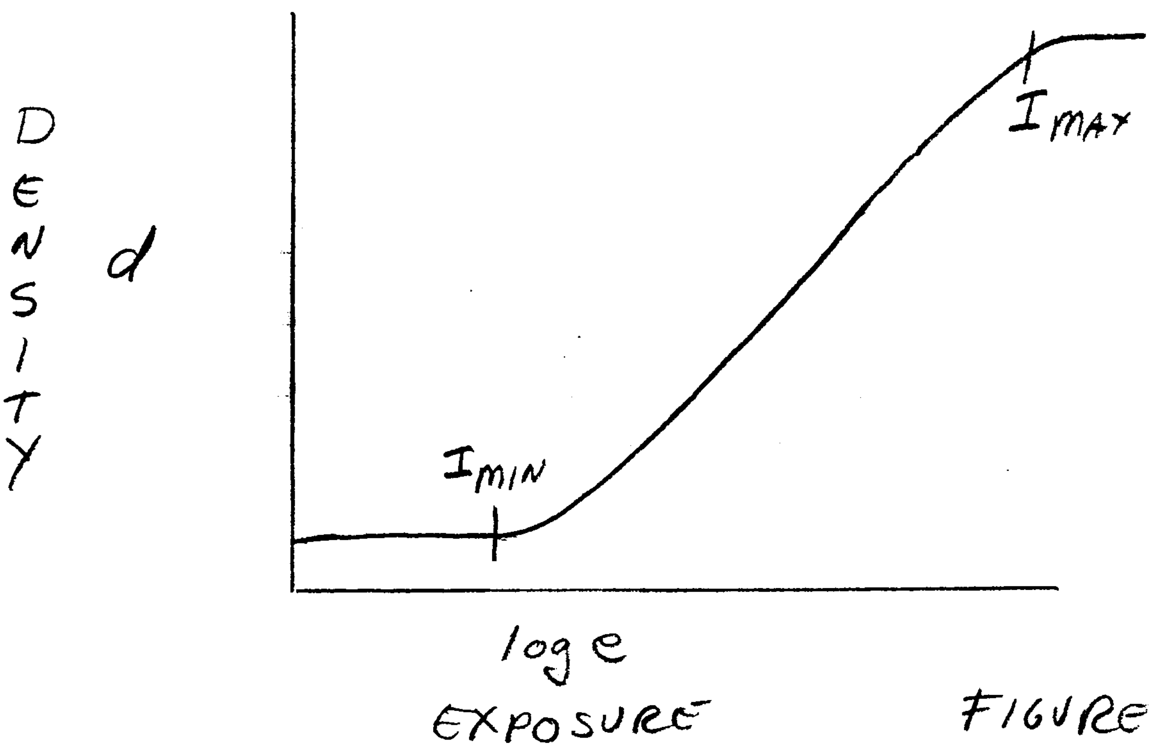

FIGURE 4

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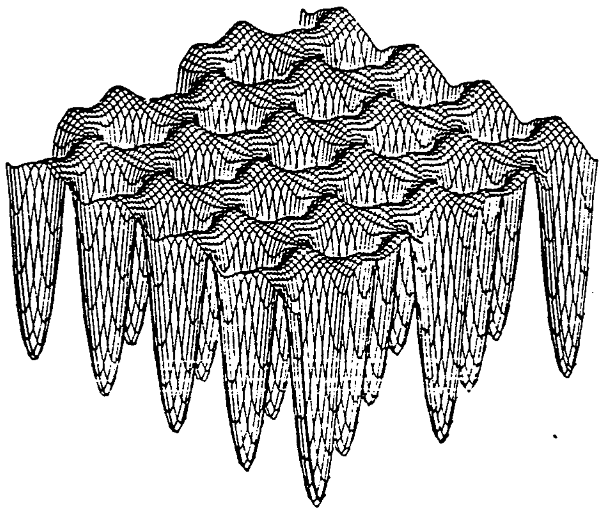

FIGURE 5

INTENSITY DISTRIBUTION IN SPACE OF 3 POINTS INTERFERING.

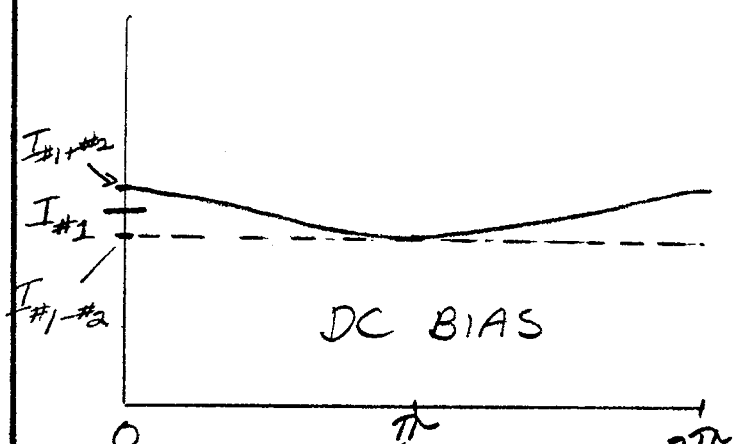

FIGURE 6

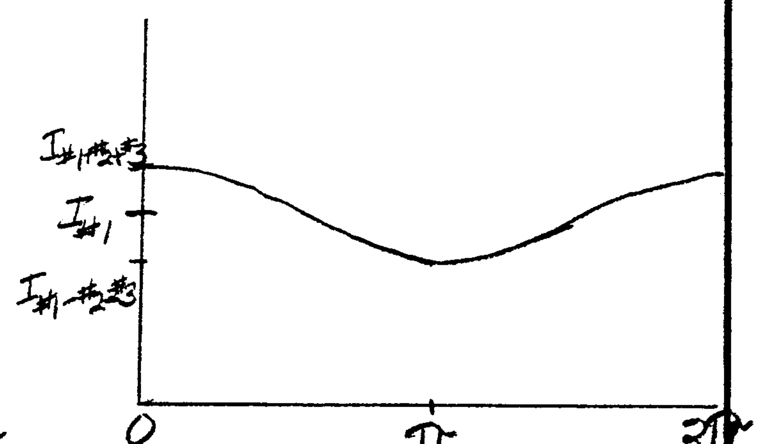

FIGURE 7

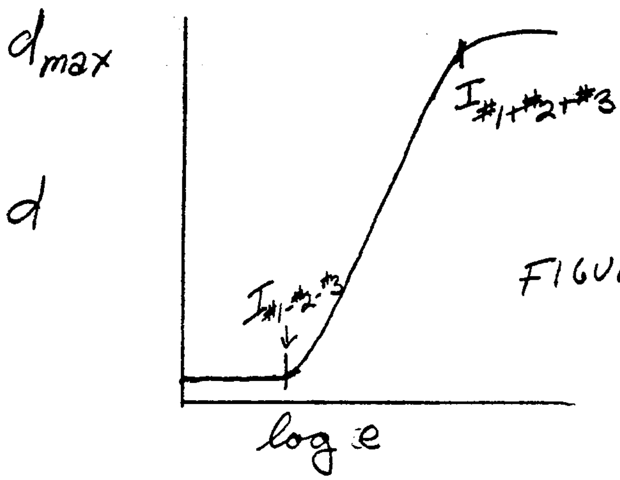

FIGURE 8

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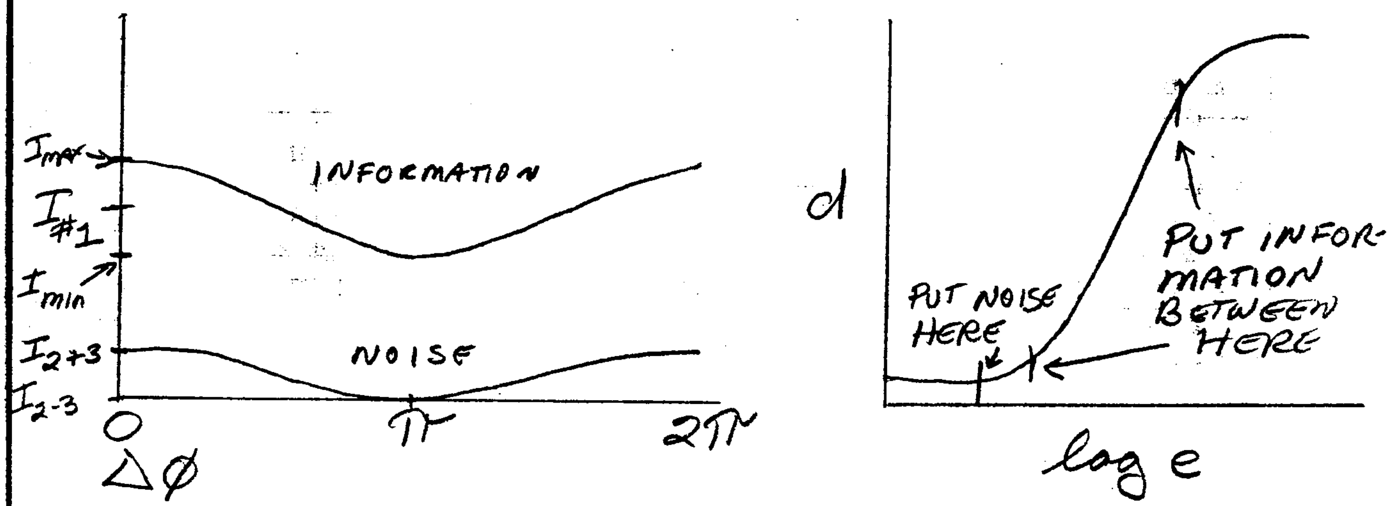


FIGURE 9

DPBI

Ed Wesly

Manufacturers brought out videodiscs not just to improve prerecorded video images but also to prevent bootlegging of programs, since expensive equipment is necessary to replicate them, unlike the videocassette. The demise of the disc was due to lack of standardization. Three systems appeared on the scene simultaneously, so none could survive splitting up a small market. Audio discs seem to be doing much better, since all discs work in all players. Sources of audio discs, also known as Compact Discs, herein referred to as CD's, smugly assert that their products deliver better sound reproduction, and charge about twice as much for a CD as for a record or cassette. They must feel that they are invulnerable to the pirating that occurs with the audio cassette.

Or are they? Certainly producers of embossed security holograms thought that they were counterfeitproof, but Jeff Blythe has blown that ship out of the water.[1] Could it be possible to duplicate the CD holographically?

This is not such a silly idea. The CD works optically, and as readers of this magazine we all believe that a hologram is the optical equivalent of the object holographed. In principle then the hologram of the CD should work just as well as the original!

The problems in attempting to prove that this works are not insurmountable. A Denisyuk recording scheme would be the logical way to start, simply contact copying the disc should suffice. The major obstacle is to get the hologram to replay at the wavelength of the laser in the disc player. CD units use near IR laser diodes, so if the disc were copied using He-Ne there would not be good Bragg diffraction at the longer wavelength. Swelling with triethanolamine could work, but trying to fine tune the reconstruction color in the infrared could be painstaking.

What I propose is to simply place the holographic film next to the disc and expose it as it plays! Our research at Northwestern University has shown that Agfa 10E75 has some sensitivity at nm as we have made holograms on it using a Diolite.I assume that 8E75HD has a similar spectral sensitizing dye or perhaps a more suitable recording medium could become available in the future.

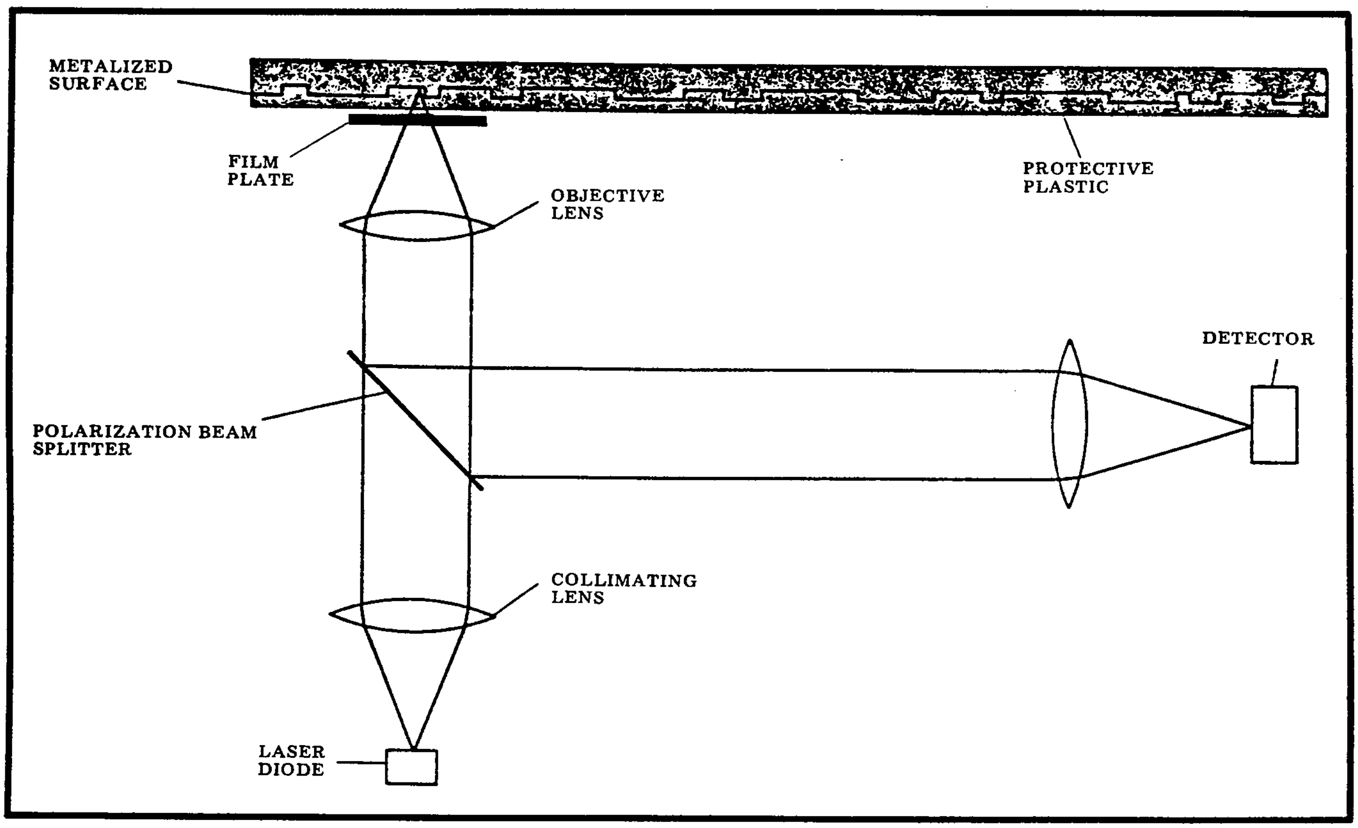
Exposure could be accomplished while the unit is running as then the reference angle will be exactly duplicated. A possible problem is that the thickness of the film may not let the information be read properly. The test would be to listen if the disc is being played while exposing. Good fringes will be formed regardless of the spinning motion, as it is the relative phase of the incoming beam and the one returned from the disc's surface that count. So the film must be stuck to the CD rather well. Because the beam interrogating the disc is focused well, there is the slight possibility of over exposing the film on a single playing/exposure, but what is more likely is that many passes are necessary or to run at a slower speed to suitably darken the film. A non-shrinking develop-rehalogenating bleach processing scheme like CWG2 is a must.

This magazine is prepared to give a *Lloyd Cross Award* to anyone who can make this work. It would certainly be fun if holographers could have their own exclusive disc-swapping network!

References

1 Jeff Blythe, *Security Display Hologram to Foil Counterfeiters*, Proceedings SPIE Volume 615, (1985) p. 18.

2 D. Cooke, A. Ward, *Reflection-hologram Processing for High Efficiency in Silver-halide Emulsions*, Applied Optics, Volume 23, No. 6, 15 March 1984, p. 934.



HOLOGRAPHY SUPPLEMENTARY MATERIAL
NOTES AND OBSERVATIONS LASER LECTURE

EYEWITNESS DEMONSTRATIONS: Recall what you saw.
What happened when the Ruby rod was bathed in UV?
What makes the mirrors in a laser special?
Why are laser beams almost parallel?
What makes a laser pulsed?

SCAVENGER HUNT: Enjoy these optical phenomena outside of class.
Look for lasers at the supermarket, CD and video disk players, concerts and light shows.

RELEVANT TRIVIA: Useful facts for this Chapter.
LASER is an acronym for **L**Light **A**mplification by **S**timulated **E**mission of **R**adiation.

OPTICAL SCIENTISTS AND INVENTORS: Remember the endeavours of these gentlemen which make them relevant to this lecture.
* Albert Einstein * Gordon Gould * Charles Hard Townes * Arthur Schawlow * Ali Javan * William Bridges *

IMPORTANT WORDS: Know what they mean!
* laser * maser * stimulated emission * laser transitions * population inversion * threshold * resonating cavity (oscillator) * high end reflector * output coupler (leaky mirror) * amplifier rods * power supply * anode * cathode * continuous wave * pulsed * Transverse Electromagnetic Modes * mode-restricting aperture * Gaussian profile * power * Watts * energy * Joules * longitudinal modes * coherence length * multimode * directionality * coherence (spatial and temporal) * intensity * monochromaticity * divergence * milliradians * polarization * power requirements * wall-plug efficiency * optically pumped * electrical discharge * Q-Switch * Pockels cell * Brewster stack * intra-cavity etalons * frequency selecting prisms * getters *

TYPES OF LASERS:

SOLID STATE	GAS	LIQUID	SEMICONDUCTOR
Ruby	Helium-Neon	Rhodamine 3G	Ga As
Nd:YAG	Argon		InGaAsP
Nd:YLF	Krypton		
Ti:Sapphire	Helium-Cadmium		
Alexandrite	CO_2		

BIBLIOGRAPHY: Outside reading for the truly faithful.
Optics Guide 5, pages 17-1 TO 17-38, 18-1 TO 18-36.
Understanding Lasers, Jeff Hecht, Radio Shack, 1988.
Laser Pioneer Interviews, High Tech Publications, Inc., 1985.

QUIZ CRIB NOTES:
Know the parts of a laser. Know what makes laser light special.

INTRODUCTION

What is a laser?

The term "laser" is an acronym for "Light Amplification by Stimulated Emission of Radiation." Thus, the laser is a device which produces and amplifies light. The mechanism which accomplishes the stimulated emission was postulated by Einstein in 1917. Lasers may generate energy in the ultra-violet, visible, or infrared spectrum. The first continuously operating (c.w. - continuous wave) helium-neon laser was reported in February 1961 by Javan, Bennett and Herriott of the Bell Telephone Laboratories. Helium-neon lasers produce an intense, coherent, visible light beam of wavelength 6328 A (Angstroms), or, expressed in another unit of length: 632.8 nm (nanometers). All exercises and lecture demonstrations contained in this book utilize low-power c.w. He-Ne (helium-neon) lasers.

How does the He-Ne gas laser operate?

Without delving into the mathematics and quantum theory involved in the operation of a laser, the simplest way to describe the device is to compare it with an electronic r.f. oscillator.

An electronic oscillator (Fig. 1) has four main parts: (1) amplifier, (2) resonant feedback network, (3) output coupling port, (4) power source. The corresponding parts of a laser are shown in Fig. 2. Here the amplifier is a glass tube which contains a gaseous mixture of helium and neon, with neon as the active lasing material. When the laser's power supply (the "pump") delivers enough energy to cause continuous glow discharge in the gas tube (much the same as a neon sign is pumped by an electrical discharge), the neon atoms are elevated to a higher energy state by colliding with the helium atoms. When the neon atoms drop back to their lower energy state, they give up energy at certain wavelength: in this example the wavelength is 632.8 nm, in the red portion of the visible spectrum. The light output will be random and scattered equally in all directions. Some of this light is

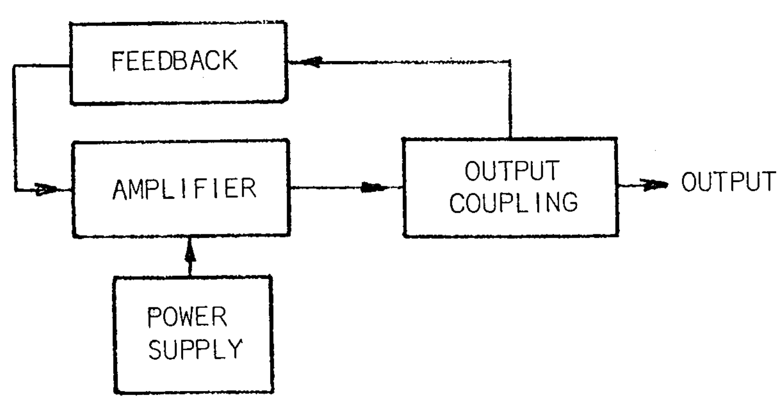


Fig. 1

lost through the side walls of the glass tube, but the portion that travels down the center of the tube strikes other excited neon atoms creating more light energy of the same wavelength.

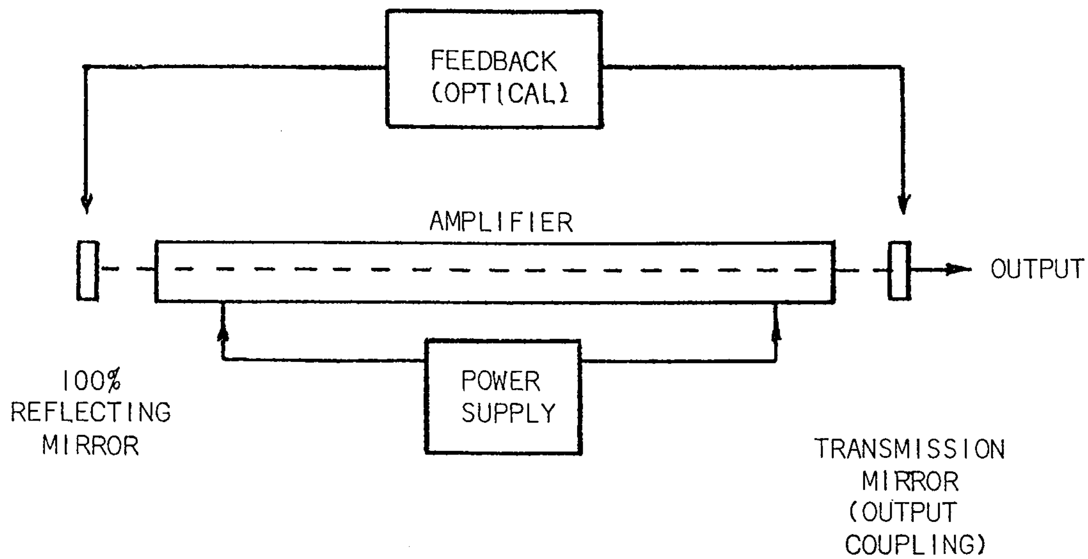


Fig. 2

The laser tube is placed in an optical cavity formed by two highly reflective mirrors positioned to face each other along a central axis. The mirrors reflect the initial beam which, as it bounces back and forth, eventually builds up enough energy to emerge through whichever mirror has the least reflectivity. This escaping light constitutes the highly directional beam of the laser. Since in the He-Ne laser, light amplification is only 1.02 on each pass of the beam from one mirror to the other, all losses must be kept below 2%. The so-called transmission mirror is coated to allow less than 1% of the generated light to escape. Thus, the beam emitted is less than 1/100th as intense as the beam between the mirrors.

Since the laser tube and the mirrors form an optical resonant cavity, the optical path length between successive reflections at a mirror must be of an integral number of wavelengths to produce reinforcement of the wave. Perfect alignment of the mirrors produces a beam which has an irradiance distribution that decreases smoothly from the center to the edge of the beam; the flux density pattern is ideally Gaussian over the beam's cross-section. This pattern, - a single disk area, - produces a single spot of light. It is designated "single mode," "uniphase," or TEM_{oo} mode. The last from <u>T</u>ransverse <u>E</u>lectric and <u>M</u>agnetic.

The TEM_{oo} mode has a number of properties which make it the most desirable mode in which to operate. The TEM_{oo} beam's angular divergence is smallest and can be focused down to the smallest sized spot. Furthermore, the TEM_{oo} (uniphase!) mode does not suffer any phase shifts or reversals across the beam as do higher order modes. It is completely spatially coherent. This is an important consideration in interferometric applications and holography.

Properties of laser light.

Laser light is quite different from light normally encountered. It has four unique characteristics that make the device a useful tool: (1) it is highly directional, (2) coherent, (3) very bright, and (4) monochromatic.

1) The directionality of the laser light is because only the light on the axis between the mirrors can escape from the laser. The beam emerges inherently well collimated and highly directional, and thus useful for applications where high concentration of light in a given direction is important.

2) The coherence of laser light in time and space is the one previously unobtainable property that makes it such an important source of light. Only light whose multiples of half a wavelength fit exactly between the mirrors is allowed to escape from the laser. Thus, standing waves are established between the mirrors, and each light particle is in step with the others. Since the light produced by the laser can be thought of as a wave oscillating some 10^{14} times a second, for such a wave to be coherent two conditions must be fulfilled: 1) It must be very nearly a single frequency (the spread in frequency or linewidth must be small). If this condition is fulfilled, the light is said to have temporal coherence, and 2) the wavefront must have a shape which remains constant in time. (A wavefront is defined to be the surface formed by points of equal phase. A point source of light emits a spherical wavefront. A perfectly collimated beam of light has a plane wavefront.) If this second condition holds, the light is said to be spatially coherent.

3) Intensity and monochromaticity go hand in hand. Since the laser builds up energy of only one frequency, all its power per interval of wavelength is much greater than the power available from other sources, this is simply because of its greater monochromaticity.

4) Monochromaticity (single coloredness) is the result of the narrow pass band of the amplifier plus the selectivity of the resonant feedback mirrors. For example, the wavelength of the red light emitted by a He-Ne laser is 632.8 nm. It is possible to limit the wavelength spread to a small band, say from 1 nm to 10 nm and produce light of high chromatic purity. Such light is called roughly "monochromatic" light, meaning light of a single color. If we refer to monochromatic light of 633 nm, it means a small band of wavelengths around 633 nm.

The anatomy of a He-Ne gas laser.

A) The Plasma Tube.

The plasma tube is a long capillary tube, two millimeters in diameter, surrounded by a hermetically sealed outer tube, one inch in diameter. The laser action which produces the beam occurs in the central capillary tube as the high voltage D.C. is applied to a mixture of gases, approximately 85% helium and 15% neon, at a pressure of about 1/300 of an atmosphere. As the electric energy is applied, the electrons of each atom respond by changing their orbits from the normal ground level configuration to the larger and more complex orbits associated with higher energy levels. After a short time in the energized state, the electrons spontaneously revert to their original conditions and the characteristic spectra of both helium and neon gases may be observed as each of the atoms radiates its recently acquired energy. This produces the characteristic blue light of helium gas and the familiar red glow of neon which may be observed in the laser tube. IMPORTANT NOTE: Do not look into the laser! Hold a piece of thin paper in the beam path near the exit window of the laser to observe the colors.

Although neon radiates several different wavelengths of light as its electrons fall from higher energy levels to the ground state, one of the strongest radiations in the visible light range (632.8 nm) is produced when the orbital electrons fall from the $3S_2$ to the $2P_4$ level. When one of the neon atoms undergoes this particular transition, a photon of light travels down the laser tube and other energized neon electrons along its path are stimulated to undergo the same transition. This frequency action produces additional radiations of the same frequency. The phenomenon is called stimulated emission or radiation. The stimulated emission results in a combined wave of increasing amplitude. Upon reaching the end of the laser tube, the wave encounters a mirror which sends it back through the tube to stimulate more energized neon atoms and increase its amplitude by a factor of 1.02 with each pass. With a flar mirror at each end of the laser tube, perfectly aligned waves of high amplitude are generated in a very short time.

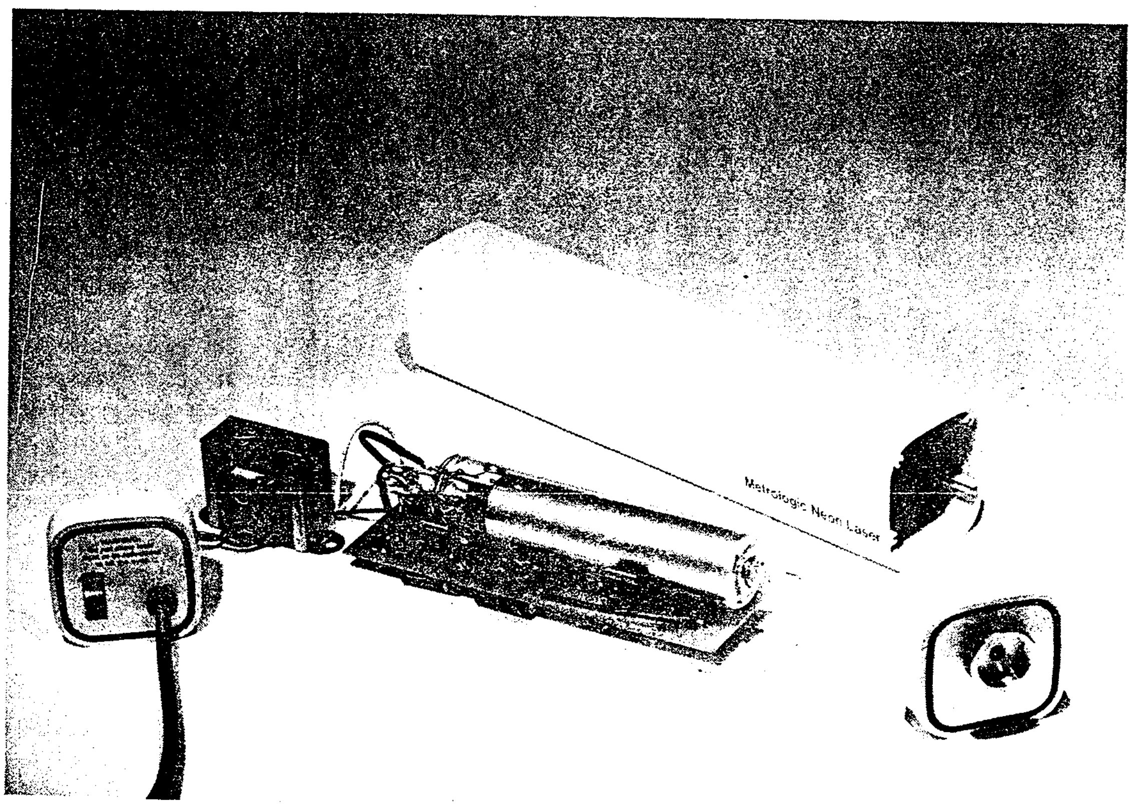


Fig. 3. Exploded view of laser

These waves are coherent in time because only those waves with an integral number of half wavelengths from mirror to mirror can sustain oscillation.

The situation is similar to the standing waves in a jump rope.

To produce an external laser beam, the mirror at the front of the laser tube is a partial reflector which reflects 99% of the light and transmits approximately 1%. The mirror at the back end of the laser tube has a higher reflectivity and reflects about 99.9% of the light while transmitting less than 0.1%.

During the manufacturing process, the coatings of the two mirrors are carefully adjusted so that the laser will resonate at 632.8 nm emission at the expense of other radiations produced by the neon gas.

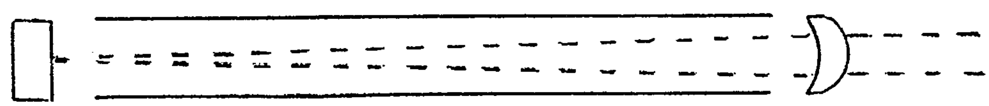


Fig. 4. The capillary plasma tube

A "semi-confocal" mirror arrangement is used in the plasma tube (Fig. 4). This consists of a flat mirror at the back of the laser tube and a concave mirror at the end where the beam emerges. Although a greater power output could be obtained with a flat mirror (or a long radius curved mirror) at each end of the laser tube, flat mirrors are very difficult to align; it is even more difficult to maintain their alignment when the laser is subjected to minor mechanical stresses during operation. With the semi-confocal arrangement, some power is sacrificed but the laser is so stable it can withstand the rough vibration and stress which occurs in a typical student laboratory. Furthermore, the curvature of the mirror at the output end of the laser tube is calculated so it will focus the laser beam at approximately the plane of the distant flat mirror. This curve/flat arrangement produces a laser beam which is cone shaped between the mirrors, the point being at the flat end, and diverging at the curved end. To compensate for this divergence, an additional converging lens surface is placed on the laser output mirror to produce a beam whose edges are very close to parallel.

Because of the internal geometry of individual laser tubes, it is found that the beam tends to vibrate more strongly in a particular plane than at any other possibilities. That is, the beam tends to be elliptically polarized. It is also observed that there is sometimes a secondary beam, polarized at right angles to the favored direction of vibration. In a short laser tube, one will find that the output beam is polarized at a given instant and that this plane of polarization appears to shift between two favored directions at right angles to each other in a somewhat unpredicatble manner. This interesting effect may be observed by passing the laser beam through a polarizing filter and observing the changes in beam intensity.

The capillary tube in which the laser action occurs is surrounded by a second tube about one inch in diameter. This outer tube has two purposes:

1) It supports the inner capillary and the two end mirrors in a rigid permanent alignment, 2) it provides a large reservoir for the neon gas which replenishes the supply in the laser cavity as it is slowly absorbed by the cathode during laser operation.

Helium gas is included in the laser because it has been found to enhance the output of the neon gas by a factor as high as 200x. As the helium atoms are energized by the high voltage direct current, they collide with nearby neon atoms in a most efficient energy transfer process. Although it has been found that the neon gas alone will provide lasing action, the output is about 200 times as great when helium and neon are mixed in proportions of about 6 to 1 (i.e., about 85% helium and 15% neon).

B) The D.C. Power Supply

The D.C. power supply receives 110 volts A.C. from the linecord and produces a D.C. voltage of 2000 volts. To do this, a transformer steps up the 110 volts to 630 volts A.C. with peak-to-peak voltage excursions of about 1000 volts positive and 1000 volts negative. Solid state rectifiers act upon the positive and negative excursions of the transformer output separately to produce two independent outputs of 1000 volts. These voltages are then added in series using a voltage doubler circuit to produce a combined output of approximately 2000 volts. This is reduced to the required 1100 volts with the aid of a string of ballast resistors. To start the initial laser action and ionize the gas in the tube, a separate circuit provides a pulse of about 2000 volts which is automatically removed when the laser action starts.

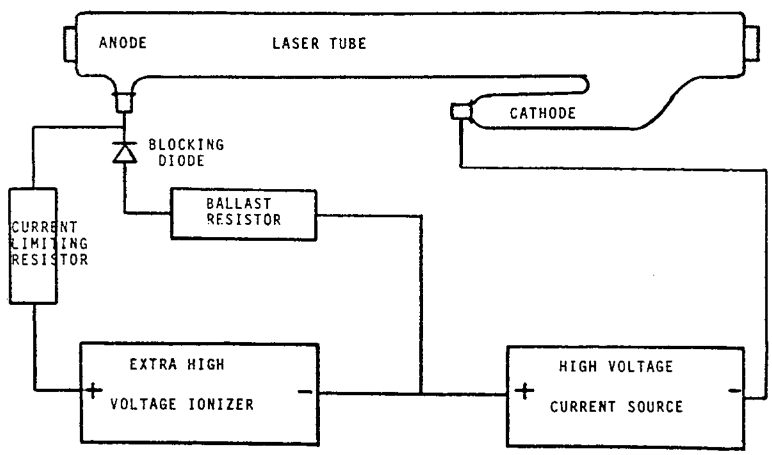


Fig. 5. Gas laser power supply

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Knowles, C.H., Popular Electronics p27 (Jan '69)
Gottlieb, H.H., "Experiments Using a He-Ne Laser," Metrologic Instruments, Inc., Bellmawr, N.J. (1971)
Kruger, J.S., Electro-optical Systems Design p12 (Sep '72)
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H. Weichel, Am J Phys v44 p839 (Sep '76)

Laser Safety

Powerful pulsed lasers are used for welding and, also, are capable of drilling holes in metal. High-power lasers are used in surgery, in resistor trimming, in non-destructive testing, and even in static and dynamic art exhibits. More and more graduate research is performed with high-power lasers in the 10^2 - 10^{12} W/cm^2 range. Therefore, it is essential that all persons who are exposed to laser hazards be informed on the subject of laser safety.

All exercises and lecture demonstrations described in this book can be performed with lasers whose output falls in the 1-5 mW range. A recent study concludes that with ordinary caution even the highest power lasers in this range (1-5 mW) are safe. Over 90% of the exercises described for the student laboratory, from elementary school science to undergraduate physics level, can be performed with low-power helium-neon gas lasers in the 0.5-1.0 mW range. The Metrologic ML-669 modulatable student laser used in most exercises covered in these pages has a nominal 0.8 mW visible output which places the device within the Class II category, as defined by the Department of Health, Education and Welfare for laser safety. To insure absolute safety, however, the following precautions and safety procedures are recommended:

1) Treat all laser beams with great respect.

2) Never look into the laser window (even when turned off) or stare into the beam (on axis) with either the naked eye or through binoculars or a telescope at a distance.

3) Do not rely on sunglasses as eye-protecting devices.

4) Never point the laser beam near anyone else's eyes.

5) Cover all windows to protect passers-by.

6) Never leave lasers unattended while activated. If not in use, disconnect A.C. power cable.

7) Room illumination in the work area should be as high as is practicable to keep the eye pupil small and reduce the possibility of retinal damage due to accidental exposure.

8) Remove all superfluous and highly reflective objects from the beam's path. These include rings, watches, metallic watchbands, shiny tools, glassware, etc.

9) Beware of electrical hazards: Ungrounded frames or chassis' and inadequately insulated power cables. Adequate grounding should be provided for the laser case and the laser should never be operated without a protective cover.

10) Never attempt any adjustments to the laser plasma tube or associated electronics with the laser plugged in. First, disconnect the power

cable and then discharge capacitors. Lethal current levels at high voltage is present inside the laser chassis.

11) While operating outdoors (laser communications, speed of light experiments, etc.) do not point the laser at passers-by and do not track vehicular or airborne traffic with the laser beam.

12) Do not operate the laser in rain, snow, fog or heavy dust. Potentially dangerous, uncontrolled specular reflections can result.

References:

Lloyd, L.B., Popular Electronics p41 (Dec '69)
Myers, G.E., Electro-optical Systems Design p30 (Jly '73)
Tinker, R., Physics Teacher v11 p455 (1973)
Weichel, H., Danne, W.A. and Pedrotti, L.S., American Journal of Physics v42 p1006 (Nov '74)
Federal Register v40 n148 Pt. II (31 Jly '75)

Care and Maintenance of Equipment

The following suggestions for routine care of the equipment will help to prolong its useful life:

1) To save the plasme tube, the laser should be shut off and disconnected when not in use.

2) To prevent dust from entering the laser housing, the laser should be stored in a dry room and covered with plastic or other suitable covering.

3) If possible, all chemicals should be kept in a separate store-room, away from the laser and its accessories.

4) Before and after each use wipe smudges and fingerprints from lenses, prisms and other accessories with a soft cloth, or, preferably with a good quality lens tissue.

5) After each use, wrap lenses, prisms, glass plates, filters and all fragile accessories in lens paper or soft tissue and place them in individually marked envelopes or boxes. In this way they may be easily located and safely stored.

6) Never use solvents to clean plastic parts, polarizing and color filters, photographic films such as holograms, diffraction grating replicas and similar items.

DECIPHERING LASER SPECIFICATIONS

When shopping for a laser, you may run across some facts and figures that may seem baffling at first but quite simple, after learning the jargon.

Lasing Medium: The material that lases, falling into the broad categories of solid state, liquid, gas, or semiconductor.

Wavelength: The color of emission. Some may be in the infrared (Nd:Glass, YAG, or YLF; certain dyes; CO2; semiconductors) or ultraviolet (Nitrogen, some Argon or Krypton lines), or possibly tunable over a certain range (Alexandrite, Ti: Sapphire; most dyes). Frequency doubling or tripling, also called first or second harmonic generation, is applicable to some instruments, halving or thirding the wavelength of the fundamental laser line.

CW or Pulsed: Whether the laser emits a Continuous Wavetrain and is on indefinitely like a lightbulb, or emits light in short blasts in finite units of time. The ability to do either mode depends on the intrinsic energy storage capability of the medium, and or intracavity devices like mode lockers. Pulses can be emitted as a gigantic one, (Q-Switched) or a series of dribbles. Solid state lasers operating in the free-lasing mode (also called free-running or open mode) emit a pulse as soon as they reach threshold (population inversion) in a random bunch of pulse widths of varying energies intermittently while they are being optically pumped. But mode-lockers inside the laser cavity order the pulses to be the same in duration, delivered regularly with respect to time, and consistent in energy. The duration or pulsewidth is measured in fractions of a second, the delivery rate or frequency is in Hertz (remember that anything higher than about 16 Hz will look continuous to our eyes). A typical spec for a mode-locked Nd:YAG laser would be something like 10 picosecond pulses, 60 times a second, (60 Hz), with energies of 10 milliJoules each.

CW Power: Is measured either in full Watts (W) or milliWatts (mW, thousandths of a Watt). The range of power in the visible ranges from .5 mW of the gentle Helium-Neon to the 25-30 Watts of a fire-breathing Argon.

Pulsed Energy: Is measure either in full Joules (J) or milliJoules, (mJ, thousandths of a Joule), a Joule being one Watt of light emitted over a period of a second. (a Watt-second) The shorter the pulsewidth, the higher the peak power.

TEM Mode: This is a map of the Transverse Electromagnetic Modes of the laser, a picture of the beam's cross-section. The subscript numbers tell how many gaps there are across the beam first in the x (horizontal) direction then in the y (vertical), but a 01 mode looks like two semi-circles on top of each other. See figure from M-G. For cylindrical lasers the orientation is a moot point. TEM00 mode is called the fundamental lowest order, or Gaussian mode, and all the rest are called higher order or multi-modes.

Another common laser mode is the donut mode, a round beam with a black center.

The modes are created by interference effects inside or outside the cavity. If the diameter of the beam is big enough, and the divergence caused by the non-flat optics in a confocal or hemispherical resonator form a geometry which causes parts of the beam to be out of phase with each other in certain locations, and is especially troublesome in high gain media like Ruby or Argon. The black lines or spots appear, and the energy that should be there is shifted into the bright areas, because constructive interference effects occur there. Apertures, either holes drilled in metal or variable irises, to decrease the working diameter of the bore of the lasing tube can remedy this situation. Of course this decreases the output power, but what is left can be put to use much more effectively. To decrease the price per milliWatt ratio, some He-Ne manufacturers offer the same length tube but equipped with a bigger bore capillary tube to use more gain medium, for higher, albeit multi-moded, output.

For holography, the fundamental mode, or TEM 00, is preferred, as well as for any application requiring the focussing of a beam to a small spot. Any other type of beam profile, without a pair of 0's, is useful for things where a simple beam is necessary, like laser light shows, where the audience never gets to see the beam standing in one place for long.

BEAM DIAMETER: This is measured near to the output port of the laser, as it is usually diverging and growing a long distance away. Since the beam is Gaussian, with the center brighter than the edges, the measured specification is made from the points where the intensity is $1/e^2$; (e is an irrational number invented by Gauss; its value is 2.something) where the intensity is what fraction of the center.

POLARIZATION RATIO: Lasers emit light whose polarization varies from horizontal to vertical to anything inbetween for varying random periods of time, hence randomly polarized, unless they are equipped with some sort of intra-cavity polarizer, like a Brewster window. The purity of polarization depends on how many of those devices are in there, along with the characteristic of the gain media, and the figure of merit is given as a ratio of the dominant polarization to the orthogonal one. A typical He-Ne with one Brewster window has a polarization ratio of 500:1, meaning the vertical polarization is 500 times as strong as the horizontal.

Although Argon lasers have two Brewster windows, their polarization ratio is less because of the higher gain of the gas, like only 100:1, while Ruby lasers have a Brewster stack, many tilted pieces of glass, with a higher ratio.

LONGITUDINAL MODE SPACING: This figure is derived from the formula $f = c/2l$, le being the cavity length. This tells the spacing between all the frequencies that can resonate comfortably between the laser's mirrors. It is accepted as a measure of coherence length, although it is a rough estimate, as the coherence length is also a function of the gain curve of the medium, so some of the predicted sidebands may not have enough oomph to get over threshold. A typical 5-7 mW He-Ne lists Longitudinal Mode spacing of about 370 MHz, which gives a practical coherence of about 30 cm.

Mode spacing in the kHz means excellent coherence, like meters.

MODE SWEEP: Something that shouldn't be happening, as the laser should be stable and not let the beam wander in either pointing or coherence.

WEIGHT: Usually anything that could cause eye damage is too big to be casually picked up.

OPERATING CURRENT: Dependent on the characteristics of the medium, from milliAmperes for diode and He-Ne's, to tens of full Amps for Argon-Krypton.

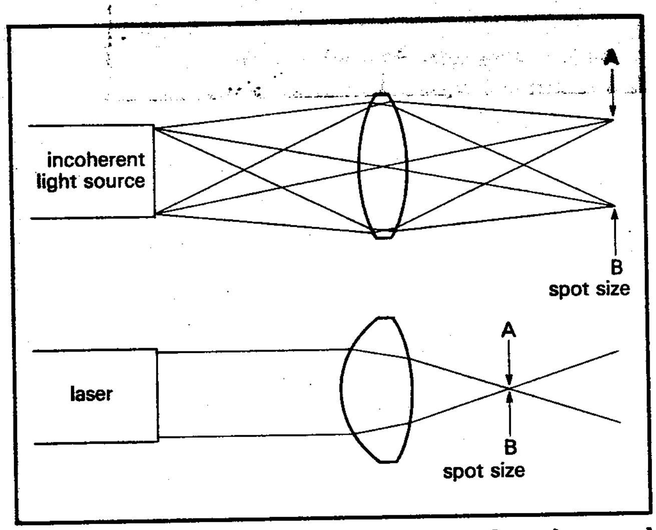
OPERATING VOLTAGE: Dependent on the characteristic of the medium, from just a few Volts for diode lasers to hundreds of volts for Argon to thousands of Volts for He-Ne's.

ELECTRICAL REQUIREMENTS: What type of electrical service the laser power supply plugs into, which can be a couple of AAA batteries for some diode models to regular 110 Volt 60 Hz AC for most lasers to 440 Volt 3 Phase with each phase supplying up to 70 Amps for some jumbo Argon or Krypton models.

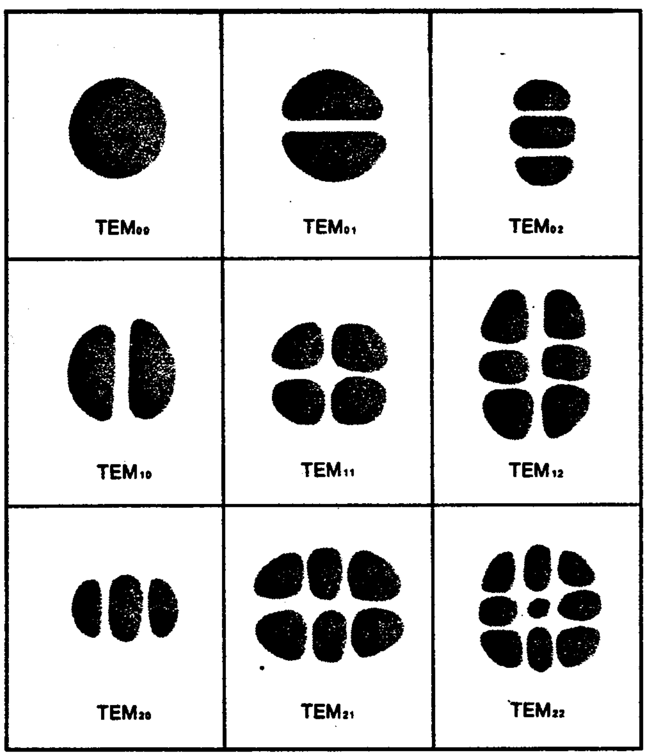
DIMENSIONS: It appears that anything that can cause eye damage is just physically so big that it can't be picked up.

COOLING: Air can either be forced across the laser, or allowed to naturally rise out of the unit, or water can circulate over the medium.

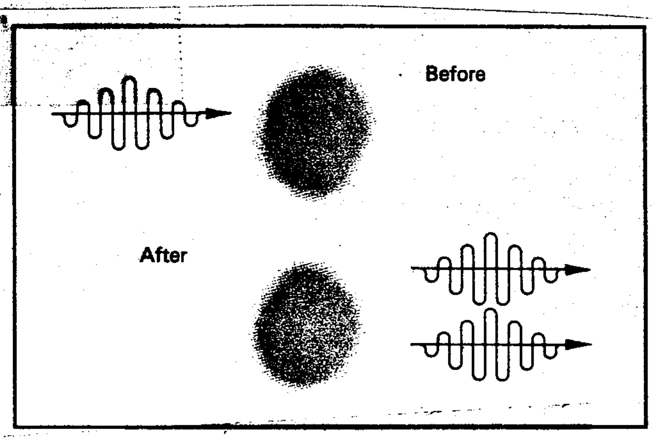
PRICE: Always the bottom line. Bargains in new lasers would be <$100 per milliWatt in He-ne's, <$5 per mW in Argon, <$40 per millJoule in Ruby.



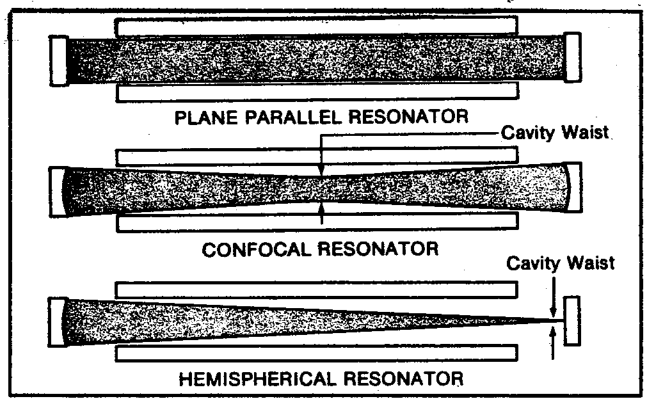
FOCUSABILITY COMPARISON for light from laser and conventional sources. Extended sources have extended images. The laser is the functional equivalent of a true point source situated at the corner of the cavity waist.



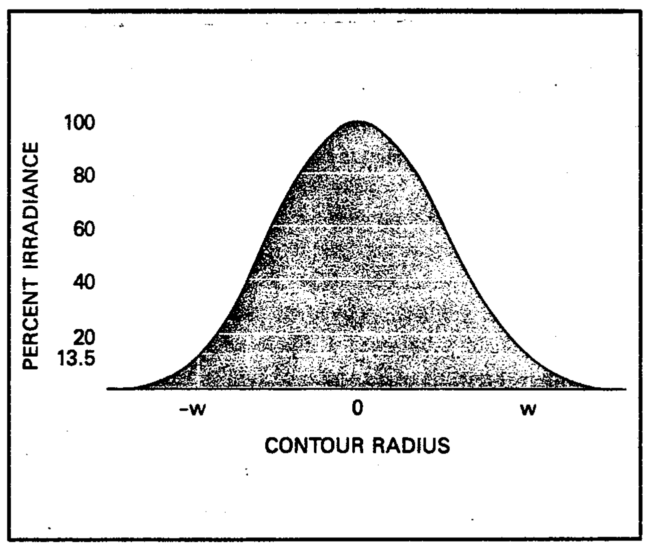
TRANSVERSE ELECTRIC AND MAGNETIC MODES of a laser cavity.



STIMULATED EMISSION, an artist's conception.



LASER CAVITY TYPES, showing the shape and size of the active plasma volume.



GAUSSIAN IRRADIANCE PROFILE for TEM$_{00}$ mode, showing definition of beam radius w.

BEAM DIVERGENCE

INSIDE JK LASERS

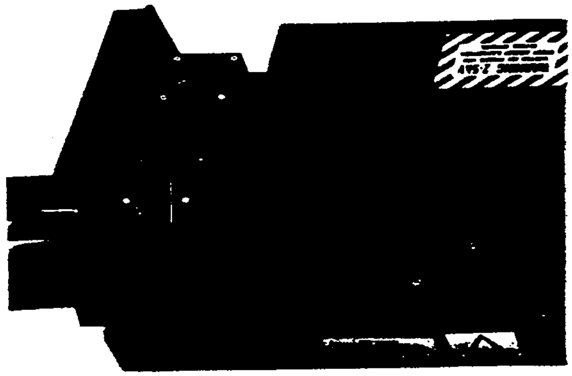


Photo: Courtesy of Lumonics Inc.

Ed Wesly

Even the competition would have to agree that JK Lasers are the very best ruby lasers ever made for holography. The availibility of extremely high quality light from these lasers is the foundation of the coming boom in pulsed laser portraiture. Maybe just the holographers are getting better, but holograms made with these lasers surpass anything made in the past with anything else with the exception perhaps of the Conductron laser.[1,2]

In 1967 the Conductron laser was the first one to record holograms of living people. It used Korad parts in a unique configuration and pumped with enough tender loving care to give enough energy to shoot the famous portrait of Dennis Gabor, the trio of beer-drinking poker players (used in Salvador Dali's "Holos! Holos! Velazquez! Gabor!") and the underwater scene with seven divers, the reference beam coming out of a flashlight held by one of them, amongst other things. It was donated to the Smithsonian Institution, borrowed by Peter Nicholson, and present whereabouts unknown.[3,4]

Ruby lasers belong to the solid state family of lasers, which includes Nd:YAG, Nd:Glass, and Alexandrite. All these lasers are optically pumped; the lasing medium's atoms are raised to a higher energy state by liberal doses of light, rather than by an electrical discharge through the gas, like the more familiar HeNe's and Argons.

They are dubbed solid state because the rods are in that form rather than a gas. Although transisters and diodes are known as solid state devices, laser diodes are usually referred to as semiconductor lasers to avoid confusion.

Ruby was the first material to lase back in May 1960 thanks to T.H. Maiman at Hughes Aircraft. This was quite a surprise, as physicists thought that ruby would not be successful since its quantum efficiency was calculated erroneously to be only about 1%. It really is about 75%, and loves to lase. Even Art Schawlow ended up with egg on his face because he gave a paper in which he commented that ruby wouldn't lase since the ground state would have to be completely depopulated—the rod would have to have every atom pumped up.[5]

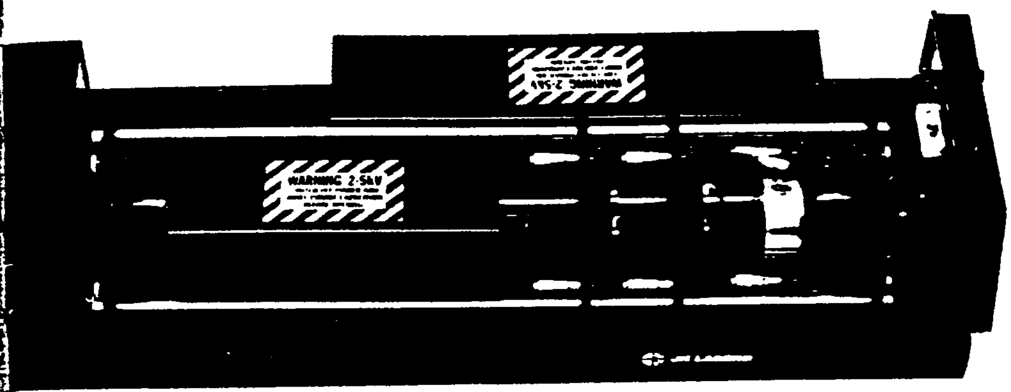
I remember that as a child in about 1960 or 61 I saw Professor Schawlow on "I've Got a Secret" (an early game show) break a colored balloon inside of a clear one using a ruby laser, although I didn't understand that at the time. My parents couldn't explain it, either. But even today, the Nobel Prize Laureate still does that demonstration whenever he gives a talk, using a small ruby rod inside a toy raygun body.

The JK comes from John Kenneth Wright, one of the founders of the company in 1971. Their goal was to build a wide range of solid state lasers, and at that time the market was ill-defined, so a modular approach of design was adopted, with reliable basic building blocks of optics and electronics which could be assembled to suit the customer needs. But after a while certain specifications were recurrent, setting a standard for particular applications, so that various product lines were developed, integrating certain components into basic models.

The earlier System 2000 ruby lasers used an inverted tee optical rail, on one side of which the optics and mechanical subassemblies were bolted, with the electrical cables and plumbing hoses on the other. The current HLS series uses an optical bed which is more stable, but the cabling arrangement is less convenient as all the connections are made from below.

Also available from JK are a Plasma Ruby model, which is basically identical to the HLS except for the absence of etalons, which are unnecessary for its use in Thompson scattering experiments. JK also make Nd:Yag and Nd:Glass models, based on similar design philosophies.

All ruby lasers start with rods from the same source—Union Carbide. Their KORAD division is history, but they still keep growing the crystals. What separates JK from the rest is extremely sensible engineering. The rod is held in a ceramic pumping chamber with 2,4 or 6 linear flashlamps parallel to it. Theoretically, helical wraparound flashlamps should get more of the population inverted and provide a nice round profile, but when the current is dumped into the helix, it tries to unwind the tube, causing premature breakage. The straight tubes do not have that problem. Many manufacturers leave the grounds side of the flashtube in the pumping chamber *in the cooling water*! The JK's lamp ends are outside the chamber. Changing a helical flashlamp requires removing



A view of a 10J, HLS-4 pulsed ruby laser from Lumonics.

the ruby rod. Not so for JK's design. To get the rod nicely pumped up, JK uses a ceramic pumping chamber so that light not going directly to the rod from the lamp hits the wall of the chamber and penetrates the glaze and comes out of it in all directions, diffusely illuminating the rod, so that it is evenly pumped. In practice this arrangement does just fine, as evidenced by the burn patterns taken after a variety of rods pumped by 2,4 or 6 lamps. (figure A). Notice that there are no quadrilateral or hexagonal shpes to the beam profile.

The oscillator is the most complicated part of the laser, and the source of the high quality of the light. It includes a ¼"×4" rod in its own pumping chamber, with mirrors at either end of the resonating cavity, a pair of etalons, a polarizer and a Pockels cell Q-switch, all held in robust mounts with micrometer adjusters to a trio of ½" Invar steel rods, for an extremely stable cavity. All the hardware and attachments are of sound design principles. As a testament to that, a klutz like the author has completely taken the oscillators of a couple of these lasers apart for cleaning and returned them to full factory tune. Documentation for the chore is good but, a HeNe alignment laser up the butt of the oscillator is essential for the alignment procedure.

When the flashlamps go off, the ruby rod is flooded with light and starts to glow with a pink florescence. The oscillator rod is positioned between two mirrors in the usual sort of resonating cavity arrangement, so that light can traverse back and forth through it, gaining energy with every pass and coming out of the front one which is 20% transmissive. This light is good enough to burn holes in razor blades but not coherent enough for the demands of holography. Other devices in the resonating cavity purify the output. On the box containing the pumping chamber there is a polarizer on the side toward the rear mirror. After passing through it the light encounters a pair of etalons.

The etalons, a thick one and a thin one (other manufacturers take note), are about 20mm in diameter and have approximately a 6mm diameter surface exposed, so that if there is any damage a fresh part can be rotated into position. The free spectral range of the ruby has a notoriously wide bandwidth, (lots of different wavelengths can lase simultaneously) but these two little cavities in the bigger cavity really work. Although JK conservatively guarantees one meter coherence for 90% of the shots, they rate this at full pumping. I have seen greater than three to four meters coherence in holograms with the laser being run just above threshhold. The original system 2000 ruby lasers had oven temperature regulated housings; the etalons are tied into the water cooling circuit in the current HLS series.

Normally when the ruby laser is fired, it emits what appears to our eyes a single pulse of light, but really is a series of emissions of about 20 short pulses over the period of a millisecond. These spurts come about because the rod is pumped for a few milliseconds by the flashlamps and as the rod reaches threshhold it emits a little light and loses a little bit of energy, but it is still being pumped so it gains more energy and emits again, and again and again until all the energy in the rod is depleted. But if there is something blocking one of the mirrors, there will be no lasing action until it is removed. This is the job of the Q-switch—to prevent laser action until just the right moment when the rod is pumped up with as much energy as it can take, just raring to let out a big wad of light. The origin of the name "Q-switch" is interesting. In electronic engineeringese the measure of the quality a radio resonator cavity is termed its "Q." By blocking this cavity you spoil its "Q." So at first these things were called Q-spoiling switches, then simply Q-switch.

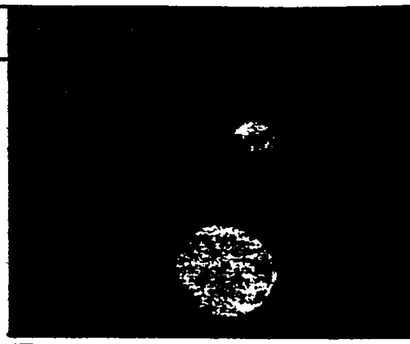
Any laser can be Q-switched by using a rotating rear mirror. The front and rear mirrors will only be aligned properly for laser action for an instant. This type of arrangement is not very popular as it is difficult mechanically to accomplish.

Another form of a Q-switch was a bleachable dye cell in the resonator place in-between the rod and the rear mirror. This dye was opague until enough light bleached it clear, so that then light could pass through it and off the mirror and back into the rod and off the other mirror and back through the rod again, gaining energy with every pass in a very short length of time and letting out one single giant pulse. This type of Q-switch was first invented by Peter Sorokin in the mid-60's, back when the power of ruby lasers was measured in Gillettes, the number of razor blades a laser could burn through. The dyes are hard to work with, as repeated use destroys them, but they are still used sometimes as they have a slow turn on rate, which allows more passes through the etalons, making them more selective for better coherence.

The JK uses a Q-switch that is electronically controlled, the Pockels cell, for precise timing of emission and double pulse capability. Some crystals exhibit the Pockels effect, which makes them act like retardation plates when the stress of electric current passes through them. Their lattices line up depending on the voltage applied to them, and they can act like ½ or ¼ wave plates for a particular wavelength. JK uses a KDP (Potassium, Deuterium and Phosphorus) crystal, which requires relatively less voltage than others. At the end of the oscillator's pumping chamber is a Brewster stack to vertically polarize the light coming out of it. Then the light passes through the etalons to the Pockels cell whose voltage is adjusted to give it quarter wave properties at the ruby wavelength. A quarter wave plate circularly polarizes light that has already been polarized in one plane. This circularly polarized light reaches the back mirror, is reflected back, still circularly polarized but in the exactly opposite direction. When this circularly polarized light goes back through the Pockels cell, it becomes linearly polarized again, but orthogonal to its original direction, so it is now horizontal. When this horizontally polarized light encounters the vertically oriented Brewster stack, it is rejected. So the Pockels cell acts as a blockade to the light.[6,7]

After a certain delay to ensure full pumping of the rod, the "plug is pulled," so to speak, on the Pockels cell, so that it no longer acts like a ¼ wave plate but as a plain piece of glass. All the light bouncing off the rear mirror goes back into the rod and through it to the front mirror and back and forth and the rod lets go with one short, high peak power pulse. This emission lasts 20 nanoseconds, which is 20 billionths of a second—an incredibly short period of time. (To understand just how short a nanosecond is, consider this analogy. Let one second be equal to one nanosecond. At this scale, one full second would then be one billion seconds, which is greater than 31 years!) It is interesting to note that with pulsed lasers there is a definite beginning and end to the "bolt of light" emitted from them. Taking c to nominally be 300,000,000 meters per second, a 20 nanosecond emission is 6 meters long, thanks to distance=rate times time, or $(3x10^8)$ m/s × (20×10^{-9}) s=60×10^{-1} m or 6 meters. It is to JK's etalons' credit that most, if not all, of their wave train has the same wavelength.

One would think that a 20 nanosecond pulse would be able to stop any and all motion. Not so. The quarter wavelength movement tolerance is often bandied about, so let's calculate.



(*Figure* A) *Burn patterns are produced by zapping a piece of blackened photographic paper with laser light.*

Rounding 694 nm, the ruby wavelength, to 700 nm for simplicity, then ¼ wavelength becomes 175 nanometers. The velocity, v, for something to move 175 nm in 20 nanoseconds would be given by v=d÷t, so (175×10^{-9})m – (20×10^{-9}) =8.75 meters per second.

A more stringent requirement, one eighth of a wavelength for brighter holograms would be half that, about 4.5 m/s, and in kilometers per hour that is 16.2, which translates to the more familiar 10 miles per hour! For living things sitting still this is fine, but if you notice in the old TRW holograms of bullets they are in silhouette![8] Even shorter pulses are necessary for speedier events. The light is emitted from the oscillator through a mode restricting aperature. This 1.7 mm hole in a stainless steel disk is there to ensure that the beam profile is nice and round—a good Gaussian Tem$_{00}$ shape, using the best light from the center of the rod, as without it the edges are quite ragged, depending on how well the rod is pumped up.

After the beam comes out of the oscillator, it is cleaned-up by a spacial filter, consisting of a 150mm positive lens focusing the light through a 250 micron diamond pinhole. In case of slight misalignment, the diamond is the only material that could take the beating. Normally, we think of the gem cut diamond, nice and transparent, but the material itself in the pinhole looks like a dark grey metal. There is no breakdown of the air here as one would expect, as the spot size is rather large and the energy density is rather low. The spatial filter also starts the beam diverging slowly, to fill up the following amplifying rod(s).

Not only can a ruby rod act as an oscillator, sending out a single frequency signal built up after many round trips inside the resonating cavity, it can also act as a single pass amplifier. When a beam of coherent light from the oscillator passes through another rod that is all pumped up and raring to go, it cuts loose with a vengeance, amplifying the power many times from what it receives. There is no need to enclose the amplifier rod with its own mirrors! It always amazes me that the amplifier rods preserve that single frequency that comes out of the amplifier, but they do it so well that there is as much highly coherent 6943 Angstrom light as you want (or can afford).

This is not to insinuate that amplifier rods are dumb, but they will amplify anything passing through them equally well in either direction. For instance, the reflection from the nicely cleaved end of a 600 micron fiber optic went back into the third amplifier rod of the Fermilab laser, got stronger, through amplifier number two and, even more so, and amplifier number one took it on the chin, so to speak, developing a nice one inch deep crack. Thanks to the conservative filling factor of JK, the oscillator pump beam could be steered around the blistered spot and the laser could be used nevertheless.

It is the amount of amplification that distinguishes the differences between the JK models. Their HLS 1 is simply the oscillator described above, putting out about 50 mJ. This is not enough to do a portrait, but at Northwestern University we have taken 4"×5" Single Beam Reflection holograms quite comfortably with the oscillator alone, and I believe that the one rod is sufficient to do even 8"×10"s.

An HLS 2 is the oscillator pumping a ⅝"×8" ruby rod in its own separate chamber surrounded by four flashlamps, emitting one joule. More efficient use is made of the ⅝" rods of an HLS 2 to pump a final ⅝"×8" rod for 10 giant joules. All the above lasers come in identical packages, with variations in layout on the optical bed inside. But if ten joules is not enough, then there is the great-granddaddy of them all: the 25 joule HLS 5. I had the fortune of working with the only one made so far at the 15-foot Bubble Chamber at Fermilab for recording physics events with Gabor-type holograms. It has all the rods of an HLS 4 pumping a monster 1"×8" ruby rod. This is a sinful amount of light. Perfect smoke rings would puff off the burn papers. This laser is a testimonial to the extremely efficient engineering of JK, as it survived all the punishment the physicists would give it over a period of greater than 200,000 shots and is still going strong.

Originally the System 2000 and HLS series came in a plain Jane vanilla-white and black package. Although the JK personnel weren't too happy about switching over to the Lumonics group colors after their acquisition, it gives them the slickest looking laser in my book, stealing the title away from the old favorite, the Coherent Innova series. It's hard to believe that a navy and powder blue laser with racing stripes would look good, but check out the photograph!

Electronics are not this beam jockey's forte, but from the looks of the tidy power supply cabinets it would appear that they are designed as well as the optics. A box about the size of a huge stereo amplifier controls the timing of the Pockels cell and firing of the flashlamps. Ten digit thumbwheels dial in the voltages supplied to the flashlamps which ultimately sets the output of the laser. This is how exposure of the hologram is controlled, as time is fixed by the Q-switch. This controller sits on top of a refrigerator-sized metal cabinet containing the capacitor banks that store electricity in a manner similar to the way the tank on your toilet stores water. These capacitors are almost the same size as the toilet tank. An efficient "hum" accompanies the charging of the capacitor bank, and their large thirst is the reason that the rep rate is limited to six pulses per minute, except for a special 1 Hz oscillator only model. On demand to flash (or flush), the stored-up juice is released into the Xenon-filled flashlamps with a resultant bright burst of light to pump the ruby rods. Three of these boxes drive the Fermilab laser, and when it was fired the magnetic field set up by the current leaving the cap's sucked in the sides of the cabinet which then resounded like a tympani trio.

The amount of juice stored in the no PCB's is lethal. Thousands of volts at high amperages are necessary to fire the lamps, so all the equipment is safely tucked away behind plexiglass covers. Before removing them, the unit is grounded out with shorting cables to prevent shock. Five kilojoules is the dose the electric chair deals out; ten times that is used to get the 25 joules of light that the biggest delivers, giving some idea of the efficiency of these lasers. Typically, they are wired to plug into 220 volt single phase AC for the states, which is used for electric stoves and household air-conditioning, not like the industrial strength 208 VAC three phase requisite for ion lasers.

But there is no reason for the average user to get into these works. The only problem that I've seen occur with these units are relay contacts frying when an attempt is made to dump the capacitors while they are in the charge cycle, which is not a very bright thing to do. But a safety circuit has been installed to prevent this from happening on more recent models. The only complaint I can register is the inaccessibility of the temperature guage and level checking for the cooling circuit.

The problem with using red laser light for portraiture is its ability to penetrate the skin. Red light doesn't bounce off the surface of tissue but into it a bit and then out. A flashlight beams mainly red light through your hand. Look at the sun or a bright electronic flash and you see red, not because of the blood in the skin but because the red light can penetrate through the tissue while the green and the blue are reflected or absorbed. Take a look at your hand under the gentle HeNe and it is hard to distinguish even the fingerprints. Look at the same thing under the green Wratten #3 safelight and you can certainly see the texture much better. This explains the waxy look of holoportraits. The solution is to, of course, use a pulsed green laser, and the only one that seems suitable for holography is the model SLM (single longitudinal mode) frequency doubled Nd:YAG from JK, with about 200mJ output at 530 nm. Of course then the problem is to find a good green-sensitive recording material, and both Agfa and Ilford have a long ways to go on that.

FOR YOUR INFORMATION

A joule is a measure of energy—one watt second. It is the product of power (watts) over a period of time in seconds. For instance, to feel the effect of one joule, I devised a test of strength where a one-watt Argon laser beam would be shuttered so that it would hit a callous on my palm for one second. Needless to say, I flunked it as I jerked my hand out of there immediately, with a nice blister to boot. So one joule=1 watt for 1 second, or 10 watts for 1/10 of a second, 100 watts for 1/100 second.... One joule in the 20 nanosecond Q-switched realm means a peak power of 50 MV—read that with a capital "M" for Mega which means Million!

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Footnotes

1) *D.A. Ansley, "Techniques for Pulsed Laser Holography of People",* Applied Optics. *Vol. 9 #4, p.815.*
2) *Collier, Burkhardt, Lin.* Optical Holography. *Academic Press, chapter 11.*
3) *"Center for Experimental Holography Completes First Phase of Research".* holosphere, *January 1978. p.4.*
4) *"Nicholson to Offer Pulsed Holograms to Advertisers/Sales Promoters".* holosphere, *June 1980. p.1.*
5) *Laser Pioneer Interviews, Editors of* Lasers and Applications, *Theodore H. Maiman interview. pp 85-99.*
6) *For a discussion of the isolating properties of quarter wave plates, see Melles Griot* Optics Guide 3, *pp 303-304.*
7) *For more details, see* Light Modulator and Q-Switch Operations Manual *from Lasermetrics, Englewood, New Jersey.*
8) *R.E. Brooks, et al., "Holographic Photography of High-Speed Phenomena with Conventional and Q-switched Ruby Lasers",* Applied Physics Letters, *Vol. 7 #4. p. 92.*