Report No. RD-65-96

INTERIM REPORT

LASERS AND POSSIBLE APPLICATIONS

A Continuing Survey

JULY 1965

FEDERAL AVIATION AGENCY
Systems Research & Development Service
Atlantic City, New Jersey

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Prepared by:

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ABSTRACT

This report updates, and supersedes a report of similar title, issued in November, 1963, and contains basic information necessary for the intelligent application of the laser to Agency problems. An introduction to the theory of laser operation, and a description of the three basic types of lasers (gas, optically pumped and semi-conductor) are included. Three application areas, communication, visual landing guidance, and instrumentation are treated briefly. An annotated bibliography provides additional source material of interest to workers in the field of civil aviation.

INTRODUCTION

One of the most important scientific discoveries of recent years has been that of the laser - the first practical device for the generation of monochromatic, coherent light waves. Because of the importance of the discovery, it was incumbent upon the Research Division to examine, from a broad viewpoint (and, therefore, of necessity, somewhat superficially) the potential of this discovery for promising safe, expeditious and efficient utilization of our airspace.

A first step toward fulfillment of this obligation culminated in the issuance of a memorandum report[1] surveying the field, in November 1963. Since that time, a number of advances in technology have occurred, and much literature has been published. It was, therefore, deemed necessary to update the 1963 publication, and this report is the result of that decision.

This report describes very briefly the principles, history and present status of lasers, and lists their promising characteristics. Some "brainstorming" has been done to show how laser devices, if meeting expectations, might be utilized within the mission assignment of the Agency. For convenience, this report has been prepared so as to supersede the 1963 publication, and, therefore, eliminate the necessity of referring to the earlier issue.

DISCUSSION

A. Principles of Laser Operation

1. General. Laser is an acronym for "Light Amplification by Stimulated Emission of Radiation". Both the development of the technique and the acronym were suggested by the success of the maser (Microwave Amplification by Stimulated Emission of Radiation). The physical principles involved in the operation of these devices stem from quantum mechanics.

Individual atoms and molecules can exist in specific energy states only. The energy state corresponds to a specific configuration of electron orbits. Orbits of larger diameter correspond to the higher energy states.

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1. R. P. Schindler, "Lasers and Possible Applications - A Preliminary Survey", November, 1963.

An atomic system may change its energy state through a collision with another atomic system or by the emission or absorption of a photon of energy. In the latter case, the energy of the photon is such that the frequency of the equivalent electromagnetic wave is given by Bohr's frequency relation.

$$f = \frac{E_2 - E_1}{h}$$

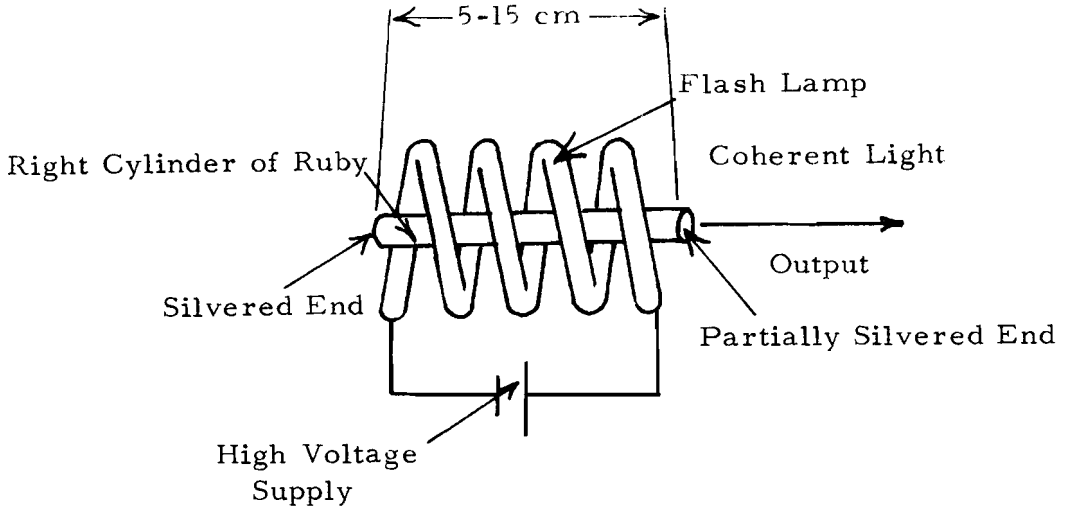
$(E_2 - E_1)$ is the energy difference and h is Planck's constant.

An atom in a high energy state will emit a photon spontaneously with a given probability depending on the type of atom and the specific energy state that it is in. It will have a higher probability of yielding its photon in the presence of an electromagnetic field at the frequency corresponding to the photon energy, in direct proportion to the strength of that field. This is termed stimulated emission, the phenomenon on which the operation of lasers and masers are based. The stimulated emission is coherent in space and time with the incident field. Before amplification can take place, the lower energy state must be largely depopulated or the photons released by stimulated emission will be absorbed, killing the in-phase buildup of the incident field.

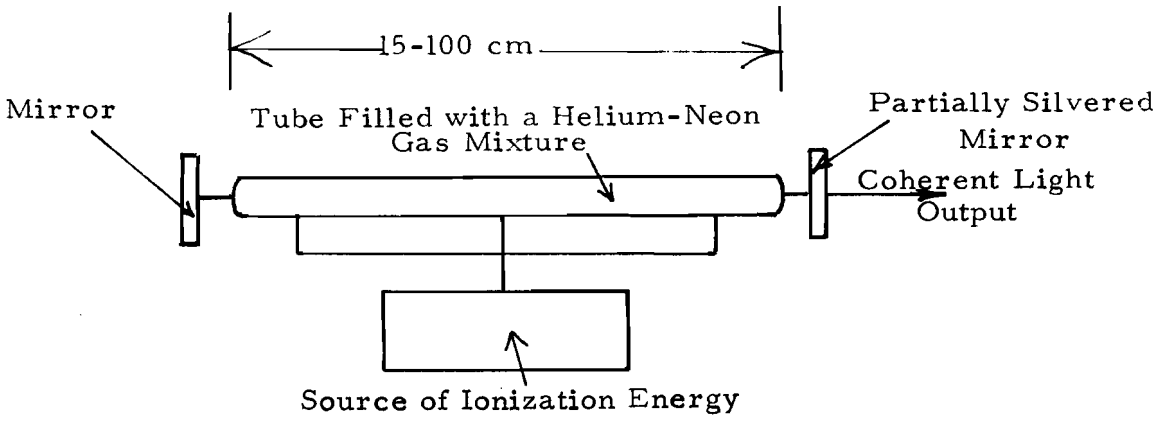
The most important application of lasers to date has been as an oscillator. In this application an optical feedback loop is established and coherent light is generated. Light amplifiers using the laser principle have not seen much application to date.

Three quite different types of coherent light generators have been developed using these principles. The main difference has been in the method employed to supply the large population of atoms in a high energy state. In the remainder of this section the operation of these three types of lasers will be discussed. The three types of lasers are depicted in Figure 1. The dimensions indicated are intended only as a rough guide to relative size.

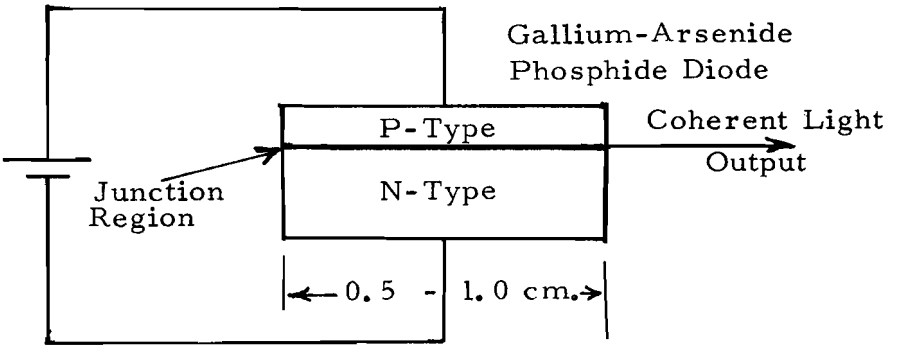
2. Optically Pumped Lasers. The first successful laser developed by Dr. T. H. Maiman at Hughes Research Laboratory was of the type employing a ruby. The trivalent chromium ion present in pink ruby has a broad absorption band in the green portion of the visible spectrum. This means that a broad band exitation source, such as a common flash tube, may be used as a radiation source to establish many of the chromium ions in a high energy state. In



(a) Optically Pumped Laser



(b) Gas Laser



(c) Semiconductor or Injection Laser

FIG. 1 THREE TYPES OF LASERS

their return to the ground, or zero level state, most of the ions go through a radiative transition whose energy difference is such that electromagnetic energy at a wavelength of 6943 Å (red) is emitted. Without optical feedback the ruby would simply glow red for a short time after being illuminated with the flash lamp. The optical feedback is supplied through design of the ruby. The ruby is of cylindrical shape with the ends ground optically flat and parallel to within a fraction of a wavelength and then silvered. As with electronic oscillators, internal noise, in this case spontaneous emission, triggers the oscillator. Spontaneous emission within the ruby starts to build up by the coherent addition of stimulated emission. The favored direction for the buildup of the coherent signal is along the optical axis of the ruby between the two silvered ends. Once a dominantly phased wave is established, it builds up very rapidly, sweeping back and forth through the ruby until the number of atoms at the high energy state are substantially reduced. The light output of the transition is made available by only partially silvering one end of the rod so that some of the signal "leaks" out this partially silvered end.

A high energy (a few thousand joules) flash tube is used to illuminate the ruby rod for a few milliseconds. As soon as illumination starts, the rod begins its incoherent glow and, after a millisecond or so, coherent oscillation begins. This coherent oscillation occurs in a series of randomly spaced pulses of approximately one microsecond duration which continues sporadically until the source of exitation is extinguished. Techniques (termed "Q spoiling") have been developed to keep the optical feedback loop open until the ruby rod is more completely saturated by the exitation source and then closing the feedback path while simultaneously extinguishing the exitation source. Mechanical shutters in the form of a rotating prism have been used successfully to control the feedback path. Shorter pulses of greatly increased peak power have resulted. Hughes Aircraft Company has reported achieving a peak power of 10^{10} watts in a 20 nanosecond pulse using this technique.[2]

The efficiency of optically pumped ruby lasers is approximately one percent and when operated as Q spoiled lasers 0.1 percent. Because of the low efficiency of these devices, the supply of primary power and heat dissipation are important operational problems. The normal solution has been to pulse the laser rather infrequently. A time delay on the order of one minute between pulses is typical for high power lasers.

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2. Electronic News, March 26, 1963, p. 72

The energy from a typical pulsed ruby laser is contained in a special interval of 0.1Å (10,000 mc/s). This can be improved upon, but for most applications of this type of laser, spectral purity is not of prime concern.

This type of laser has also been operated on a continuous basis at average power levels on the order of a watt.

3. Gas Lasers. Broad absorption bands do not exist for the free atoms in a gas. Ordinary broad band light sources which work so well with the solid laser will not produce the desired population of high energy atoms in a gas. Javan of Bell Telephone Laboratories developed the first gas laser by employing electron collision as the pumping mechanism. The gas used by Javan was a mixture of helium and neon. Since then, many other substances have been successfully employed in gas lasers. The helium neon mixture is still the most popular and will be described here as an example of gas laser operation.

In gas lasers, energetic electrons are supplied by partially ionizing the gas with a d. c. arc discharge or a high power radio frequency energy source. The neon atoms produce the lasing action and the helium atoms act as buffers to more efficiently mechanically couple energy into four specific neon energy levels. Lasing action occurs between these states and other states which are normally sparsely populated and which cannot receive mechanical energy from the excited helium atoms. In a gas laser of this type, laser action occurs at low input power levels since in a gas a heavily populated ground state does not inhibit laser action as it does in the solid laser. The gas is normally contained in a glass tube. Partially silvered mirrors, external to the glass tube, are generally used to provide the feedback path.

The gas laser is characterized by low output power (usually measured in milliwatts) continuous operation and extreme spectral purity. Under ideal conditions, bandwidths of only a few thousand cycles (10^{-8} Å) have been noted.

The efficiency of gas lasers is even lower than that of optically pumped lasers (about 0.1 percent). Since they are operated at low power levels, cooling and primary power requirements are not significant operational problems. To date the gas laser has found more useful application in the laboratory than in the field.

Gas lasers have been used to generate coherent signals over a wide range of wavelengths. The shortest wavelength produced by a gas laser is 5900 Å in the yellow portion of the visible spectrum. The longest wavelength produced by a gas laser is 350,000 Å (35 microns) deep in the infrared portion of the spectrum.

4. Injection Lasers. The injection laser is the most recent addition to the laser family. The device was developed almost simultaneously by three laboratories: General Electric Co., Lincoln Laboratory of MIT, and IBM, late in 1962.

In this type of laser a photon is emitted when an electron drops from the conduction energy band to the valance energy band in the junction region of p-n junction diode. As with the other laser types, this emission may be spontaneous or stimulated. Conduction band electrons are continually supplied (injected) from the n region of the diode. Only certain types of semiconductor material have been found suitable for this application. Gallium arsenide (GaAs) was the first semiconductor successfully employed and since then several other semiconductor combinations have demonstrated lasing capability.

Feedback is provided by cutting and polishing two opposite sides of the junction diode, taking pains to assure that the sides are parallel. Silvering is not necessary as the semiconductor - air boundary provides a natural reflecting surface.

The amplitude of the coherent output signal is easily varied by varying the bias on the diode. The frequency of the signal may be varied over a seven percent band by changing the temperature of the junction from room temperature to 77°K. This sensitivity of the diode to its environment degrades the spectral purity of this laser type. Line widths of 2 Å are common. The main advantage accruing to semiconductor lasers is their operating efficiency. Efficiencies of 20% are common and efficiencies approaching 100% are theoretically possible. Peak power outputs as high as 280 watts at low duty cycle from a single gallium arsenide diode have been reported. While there has been some progress in room temperature operation of injection lasers,[3] high efficiency and high power operation generally requires operation at cryogenic temperatures. Current densities of 10^5 amperes per square centimeter are required for true laser action in GaAs diodes. The

3. H. Nelson, et al, "High Efficiency Injection Laser at Room Temperature", Proceeding of the IEEE (Correspondence) Vol. 52, No. 11, p. 1360-1361, November 1964.

area of the junction in a typical diode might be 10^{-4} square centimeters. The requirement for such high current density has restricted most semiconductor lasers to pulsed operation.

When operated at lower current densities the radiation from these diodes is dominated by spontaneous emission and the optical bandwidth widens to about 100 Å. In this incoherent mode, GaAs diodes may be operated continuously at power levels in the milliwatt range. While operating continuously, GaAs diodes have been successfully amplitude modulated up to 100 mc/s.

B. General Application Information.

1. The Generation of Narrow Light Beams. The ability to realize very narrow beamwidths is one of the most important characteristics of the laser. The narrow beam allows efficient power transfer over long distances.

Prior to the development of lasers, narrow light beams were generated only by using point sources of light at the focal point of a convex lens or a parabolic reflector. The point source was normally established by placing an ordinary lamp behind a very small opening in an opaque surface. The narrow beams generated in this manner have not been employed outside the research laboratory because the light output is low. Any attempt to increase the light output of such a device by enlarging the opening spreads the output light beam since the added energy is "out of focus". As mentioned earlier, the light output of a laser is spatially coherent. The output is a plane electromagnetic wave and may be focused to a point by a lens. All of the light generated by the laser is utilized in the beam.

The beamwidth of a plane electromagnetic wave, propagating through an aperture, may be calculated using the theory of Fraunhofer diffraction. The beamwidth is inversely proportional to the dimension of the aperture in wavelengths. For a circular aperture:

$$\Theta = \frac{2.44}{D/\lambda} \quad \text{radians}$$

Θ = beamwidth to the first nulls in the diffraction pattern

D = diameter of the circular aperture

λ = wavelength of the plane electromagnetic wave

Figure 2 illustrates this beamwidth relationship.

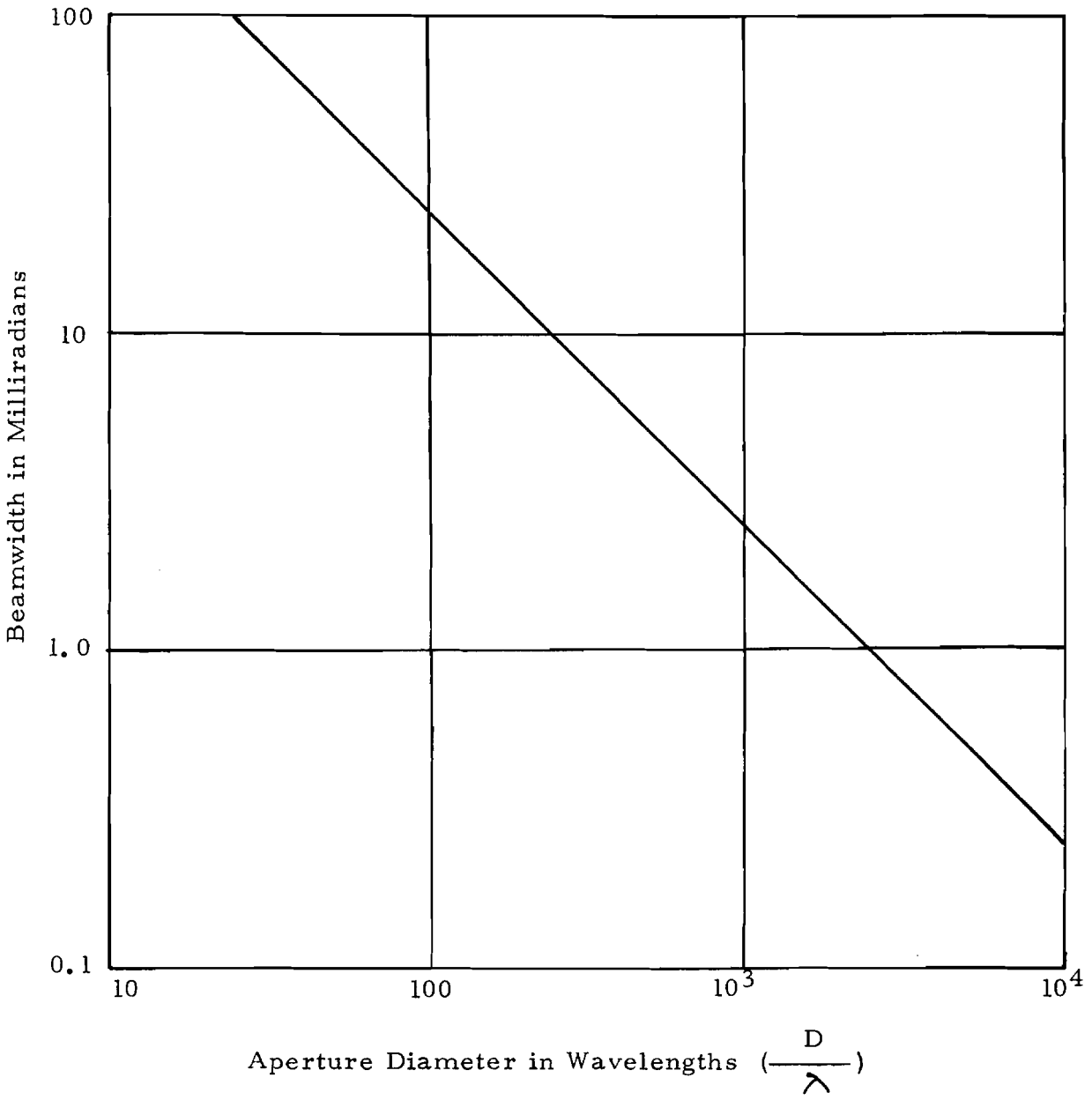

FIG. 2 BEAMWIDTH OF A PLANE ELECTROMAGNETIC WAVE PROPAGATING THROUGH A CIRCULAR APERTURE

Lasers are not perfectly coherent and have a beamwidth somewhat broader than that predicted by diffraction theory. Some optically pumped gas lasers have come to within a factor of ten of achieving the beamwidth predicted by theory while injection lasers are still about a factor of 100 from this goal. In general, minimum beamwidth is achieved by lasers operating at low power levels. Typical beamwidths of operating lasers have been on the order of one to ten milliradians.

It should be understood that lasers are not limited to narrow beam operation. It is always possible to add beam spreading with a simple optical system.

2. Utilization of the Information Bandwidth of the Optical and Infra-red Spectra. The generated frequencies available from lasers range from 10^{13} to 10^{15} cycles per second. Coherent signals from audio frequencies to 10^{11} cycles per second had previously been generated by more conventional means. The spectrum made available by laser technique is thus roughly 10^4 times the total that was previously available. However, it is not necessarily true that the laser will relieve the congestion of the other frequency bands. VHF and microwave frequencies did not supplant broadcast and HF frequencies but rather performed new services not possible at the lower frequencies. The laser will find its major application in performing new tasks uniquely suited to its characteristics.

The wide frequency spectrum available, the possibility of using very narrow beams, and the fact that diffraction of energy beyond the geometric horizon is negligible at optical frequencies, all indicate that mutual interference between laser systems should not be a significant operational problem.

3. Modulation of Lasers. The modulation of solid and semiconductor lasers is accomplished by the pumping mechanism. The modulation of gas lasers is normally accomplished separately from laser action by a shutter utilizing either a magneto-optic or electro-optic effect.

The Faraday effect is the strongest of the magneto-optic effects. Crystals exhibiting this effect twist the polarization of light propagating through them when under the influence of a magnetic field. The degree of twist is directly proportional to the magnetic

field strength in the direction of light propagation and the distance traveled through the crystal. In a modulator a crystal exhibiting a large Faraday effect is placed between two crossed Nicol prisms. With no magnetic field present this device is opaque. When a magnetic field is present the transmissivity is proportional to the field strength. The modulated magnetic field is normally provided by placing the crystal in a microwave cavity. To increase the efficiency of the modulator, it is common to operate these devices at about 4° Kelvin.

Modulators employing crystals and liquids exhibiting electro-optic effects have proven to be more practical in this application. The Kerr electro-optic effect has been employed in most light modulators developed for lasers. Crystals and liquids exhibiting this effect become double refracting when placed in an electric field. Thus, linearly polarized light becomes elliptically polarized after passage through the substance and the degree of ellipticity of the polarization is proportional to the electric field present. Physically the Kerr effect modulator is very similar to the Faraday effect modulator in that the crystal is bracketed by crossed Nicol prisms and installed in a microwave cavity.

In a recent demonstration[4] of broad band modulation of lasers the Pockels effect (another electro-optic effect) was used to modulate a gas laser beam with five television channels simultaneously.

The bandwidth of these light modulators is limited by the techniques employed in supplying the varying electric or magnetic field, not by the magneto-optic or electro-optic effects themselves. Traveling wave techniques show promise for increasing the bandwidth and decreasing the modulator driving power required.

4. Detection of Laser Signals. The detection of laser signals is facilitated by their spectral purity. Optical filters are available with bandwidths as narrow as 5 Å. These filters may be used to reduce background noise due to sunlight to 0.05% of its normal value. When such filters are employed, the sensitivity of a receiving system may be limited by noise internal to the receiver rather than external background noise. Many types of laser systems should work as well in daylight as at night.

At optical and infrared frequencies the energy per photon is so high that the ultimate sensitivity of most detectors is limited by

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4. Johnson, J. M. and D. D. Eden, "Solid-State Modulation and Demodulation of Light with Information from Five Television Channels Simultaneously", Proceedings of the IEEE (Communications) Vol. 53, No. 4, pp. 402-403, April 1965.

quantum noise rather than thermal noise. At optical frequencies, photo-emissive detectors such as the photo-multiplier tube are quite efficient. Conventional photo-multipliers can be used to detect modulation frequencies up to about 1,000 mc/s. Special traveling wave tube amplifiers with photo-emissive cathodes have been developed for the detection and amplification of modulation at microwave frequencies.

At infrared frequencies, photo emissive detectors are no longer efficient and semiconductor photo conductive detectors must be used. These are somewhat less sensitive than the photo emissive detectors.

Amplifying the return signal with a laser amplifier will not add significantly to system sensitivity. The shot noise of a laser amplifier would be of the same order as that of a photo emissive detector.

It is also possible to use superheterodyne receiving techniques at optical frequencies. Photomixing has been accomplished on a photocathode surface by illuminating the surface with two laser beams simultaneously. This technique has a slight advantage in ultimate sensitivity as limited by quantum noise but more important it is possible to eliminate shot noise and approach the quantum noise limit. A laser local oscillator must be such that it is in spatial phase with the received signal across the photocathode surface.

5. Special Non-linear Effects. Many transparent materials become non-linear when subjected to the high electric fields associated with powerful solid lasers. This non-linearity distorts the wave shape of the electromagnetic wave traversing the medium, generating harmonics. Second harmonics containing 20% of the incident energy have been observed.

The mixing of two laser beams to produce sum and difference frequencies is also possible as mentioned in the section on the detection of laser signals.

The laser signal may also "mix" with the vibrational frequencies of individual molecules of the media through which it passes. This is known as the Raman effect and has been observed with ordinary monochromatic light for many years. However, when coherent light is used, the Raman spectrum lines are also coherent and may have an intensity of up to half of the incident beam.

6. Atmospheric Attenuation. The atmospheric attenuation at optical frequencies is due to absorption by the molecules constituting the atmosphere and scattering from both molecules of the atmosphere and particles suspended in the atmosphere.

Molecular absorption occurs in discrete frequency bands beginning in the upper end of the microwave spectrum and extending through the optical spectrum. Most of the absorption bands are due to the vibrational resonance frequencies of molecules. The absorption bands are all well known, and, therefore, avoidable when designing a system.[5]

Attenuation by scattering is not so easily avoided. Scattering is essentially independent of wavelength for all wavelengths shorter than the major dimension of the scatterer. For wavelengths much longer than the major dimension of the scatterer, scattering is almost negligible.

For wavelengths shorter than about 0.3 microns in the ultraviolet, the atmosphere is practically opaque due to molecular scattering. For all wavelengths longer than 0.5 microns, scattering by the molecules of the atmosphere may be safely ignored.

Precipitation particles are so large that attenuation due to scattering by them is independent of frequency on down to the high frequency end of the microwave spectrum. Attenuation due to scattering in haze and fog is a function of the drop size distribution. In haze the diameter of individual droplets is usually around 1 to 5 microns. The attenuation, through haze, is independent of wavelength in the visual spectrum but falls off in the infrared.

Haze is usually quite transparent at a wavelength of 10 microns. Drop sizes within fogs may vary from 5 to 100 microns, and attenuation due to scattering is independent of wavelength over the visual and infrared spectra. Since attenuation due to scattering is not due to a resonance phenomenon, there is no hope for finding spectral regions of low attenuation or so-called "windows" in haze and fog.

Arnulf and Bricard[6] measured attenuation due to scattering by haze and fog. Figure 3 illustrates the range of values measured in this program. It can be seen that atmospheric attenuation, due to fog,

5. Gebbie, H. A., W. R. Harding, C. Hilsum, A. W. Pryce and V. Roberts, "Atmospheric Transmission in the 1 to 14 Micron Region", Pros. Roy. Soc., Vol. 206 (1951)
6. Arnulf, A. and J. Bricard, "Transmission by Haze and Fog in the Spectral Region 0.35 to 10 Microns", J. Opt. Soc. Am., Vol. 47 No. 6, Issued 1957, pp. 491-498.

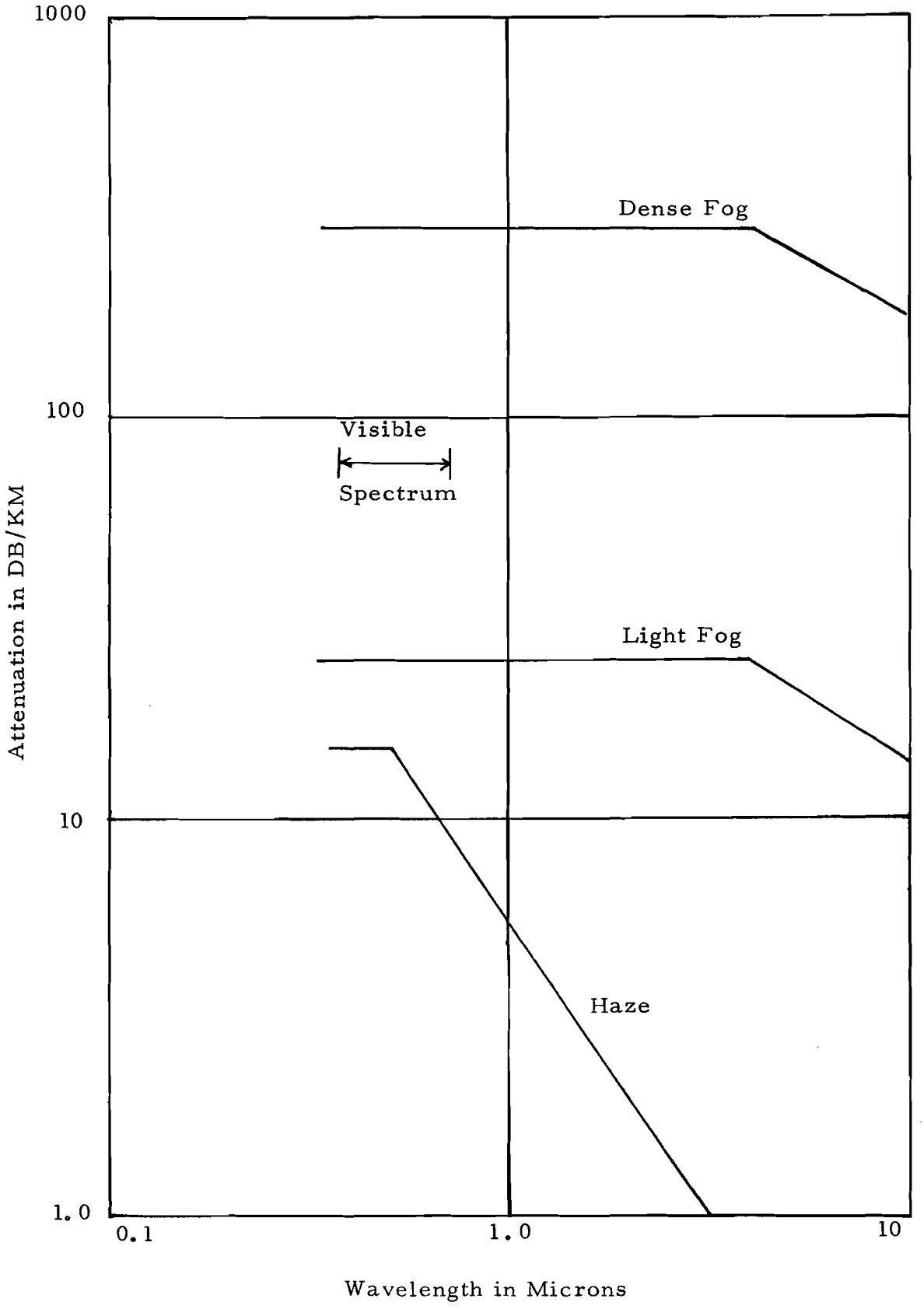

FIG. 3 ATTENUATION BY HAZE AND FOG

may be as much as 300 db per kilometer (550 db per nautical mile) in the visible spectrum.

C. Application of the Laser to FAA Problem Areas. In the few years since the demonstration of the laser principle, many applications have been suggested, and a surprising number of hardware items have been developed and tested. In this section the possibilities of application of the laser in some problem areas peculiar to the Federal Aviation Agency will be discussed and superficially analyzed.

As applications in other Agency problem areas are suggested, and as the development of laser technology progresses, other reports on laser applications may be written.

1. Communications. There will be many applications for lasers in the general field of communications. The bandwidth and high peak power available, the monochromaticity, and the degree of collimation possible, all indicate that lasers will be capable of performing many communication tasks heretofore considered impossible.

The principal types of communication links used by the FAA are intra-facility, inter-facility and between facilities and aircraft. The problems of intra and inter facility communication are sufficiently similar to the general ground communication problem so that it would be quite safe to assume that the application of lasers to these problems will be advanced where practical by private industry without FAA support.

Lasers are not presently feasible for use in general air-ground-air communications. The most serious limitation in this application is the attenuation caused by scattering from clouds, fog and precipitation.

For applications requiring a voice modulated carrier, lasers are handicapped by the fact that their average power output is quite low. Optically pumped and gas lasers are physically small and until the efficiency of these devices is increased considerably heat dissipation will be a severe limitation. Injection lasers are much more efficient and an average power output of four watts has been claimed for these devices. The cryogenic cooling required for such high power operation complicates the practical application of these lasers. Until lasers are capable of higher average power, communications employing

a modulated laser carrier will be restricted to point-to-point operation over relatively short ranges. For example, a laser could be used by a tower operator to transmit messages to individual aircraft, much as a light gun is used today. The laser could be voice modulated. The receiver in the aircraft would consist of an optical filter, a photo diode and an audio amplifier. A system of this type should be capable of operating in full sunlight. Application of a point-to-point system for air-ground-air communication would be hampered by the aiming problem.

High power pulsed lasers are more attractive for broadcast or omnidirectional communication systems and also may be useful when atmospheric conditions are less than ideal, but the data rate would be low. In an adaptive system, where it would be possible to trade off peak power for duty cycle, the data rate would be lowest for the worst atmospheric conditions.

In any communication system using frequencies in or near the spectrum of visible light, the path attenuation for the communication link is inversely proportional to the visibility. Path attenuation is highest when visibility is the poorest. Any attempt to achieve all-weather performance of a laser system by simply increasing the transmitted power of the laser must be checked carefully to guarantee that no physical damage to aircraft or passengers would occur in the event of a sudden clearing of the transmission path.

2. Runway Lighting and Visual Landing Guidance.

a. Visual Detection Theory. In any proposed laser system where the detector is the human eye, the characteristics of the human vision system must be taken into account. Since lasers must compete with non-coherent light in these applications, comparisons will be drawn between the two types of light sources where possible.

When the human vision system is to be used as the detector in a laser system, one must take into account first of all the efficiency of the human eye as a function of wavelength. This is normally accomplished by expressing the time rate of flow or radiant energy in terms of lumens rather than watts.

Power in lumens is equal to the power in watts times the spectral luminous efficiency of the eye at the wavelength being viewed. At the wavelength of maximum efficiency (5,550 angstroms),

the spectral luminous efficiency is 680 lumens per watt. The variation of efficiency as a function of wavelength is given in any standard text on lighting.[7] The use of this standard curve presumes that the human involved has normal vision and that he is looking directly at the object so that its image is falling on the portion of the retina capable of the greatest resolving power.

Lasers for human detection may be operated continuously or pulsed. If pulsed, they may have a pulse repetition frequency sufficiently high to appear flicker-free to the eye or they may be pulsed so that the individual flashes are distinct.

The pulse repetition rate for a flicker-free presentation is a function of the intensity of illumination. A very low-intensity light source may become flicker-free at pulse repetition frequencies as low as 10 cycles per second while a high intensity light source may require a pulse repetition frequency of over 40 cycles per second to become flicker-free. Talbot's law states that when flicker is not perceptible the apparent intensity of a periodic light source is the actual intensity during the "on" period times the duty cycle of the light source; that is, the eye responds to the average value of light intensity from a pulsed light source which has a pulse repetition frequency sufficiently high to be flicker-free.

For flashes of light which are observed as individual flashes, the Blondel-Rey law applies. The apparent intensity of the flash is equal to that of a steady light of intensity E where:

$$E = E_o \frac{t}{a + t}$$

E_o = Actual intensity of the light during the flash, in lumens

t = Time duration of the actual flash in seconds

a = A constant

For the important case when the apparent intensity is near the threshold of human vision, the constant "a" is approximately 0.2 seconds. When the apparent intensity is high, this constant is smaller.

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7. "IES Lighting Handbook", 3rd Edition, Illuminating Engineering Society, New York City, 1962, pp. 1-4.

For all pulsed lasers of interest, the pulse length is much shorter than 0.2 seconds and the Blondel-Rey law may be rewritten thus:

$$E = \frac{1}{a} (E_o \cdot t)$$

indicating that for very short pulses the apparent intensity is proportional to the pulse energy.

b. Lasers as Flicker-Free Light Sources. In applications where flicker-free lighting is desirable, lasers with the highest average power output capability must be selected. Average power outputs of 15 watts are claimed for some ruby lasers capable of pulse repetition frequencies of 30 to 45 cycles per second.[8] Most of the high-power lasers listed as being available to date have employed ruby rods lasing at a wavelength of 6943 angstroms. At this wavelength, 15 watts is equivalent to only about 50 lumens (15 watts x 3.3 lumens/watts). Assuming a laser efficiency of 1 per cent, these units must dissipate almost 1,500 watts. It is clear that before any great strides in average power output are possible, the efficiency of these lasers must be improved.

Because of their inherently high efficiency, injection lasers show promise for high average powers. As mentioned previously, an average power output of four watts has already been achieved from a single diode. (This diode operated in the infrared portion of the spectrum but high-power diodes operating in the visible portion of the spectrum will no doubt be developed in the near future.) Since heat dissipation is not such a critical factor, it may be possible to group several diodes into a single head to increase power output.

c. Lasers as Flashing Light Sources. For applications where intermittent pulses of light are acceptable or desirable, the high-power solid lasers are the obvious selection from the laser family. Here we must apply the Blondel-Rey law to determine apparent intensity of the most powerful ruby lasers available. Using the second form of this law, the apparent intensity in lumens is the energy output of the laser in lumen-seconds divided by 0.2 seconds.

The highest reported energy output for a single laser pulse is 1,500 joules (watt-seconds). Assuming a wavelength of 6943 angstroms, this would be an output of 5,100 lumen-seconds. If such

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8. "Lasers Available", Electronic Products, September 1963, pp. 44-49 and "Survey of Laser Products', Microwaves, October, 1964, pp. 34-54

a laser were to be developed at a wavelength of 5550 angstroms, its output would be over 10^6 lumen-seconds. The apparent intensity using the Blondel-Rey formula would be 25,500 lumens for the ruby and 5×10^6 lumens for the "optimum wavelength" laser. The energy input for the 1,500 joule laser was 120,000 joules. A typical xenon filled flash tube pumping source with this power input would have an output of over 10^7 lumen-seconds.[9] Again using the Blondel-Rey formula, the apparent intensity of the flash tube pump would be 5×10^7 lumens or 10 times that of the laser operating at the optimum wavelength. The recycle time of this laser was not given but it would very likely be on the order of a minute or more.

d. Lasers vs Non-coherent Light Sources. The foregoing discussion makes it quite clear that lasers do not offer any illumination power advantage over non-coherent light. Both the continuous and flicker-free pulsed lasers have very limited average power output. High power intermittently pulsed lasers are capable of apparent intensities which are quite high but these are pumped by flash lamps of from 10 to 1,000 times the laser output power.

For pulses of light much shorter than 0.2 seconds duration, the human eye responds to pulse energy, not to the peak power during the pulse. Therefore, whether the light pulse is the 1 to 2 millisecond pulse coming from the flash lamp exciter, or the 1 microsecond pulse from a laser, response is maximized by the use of the higher energy source. However, the detectability of a light depends not on the power (lumens) radiated, but rather on the power density at the observation point. Here, two of the most important characteristics of the laser may be utilized. These are the capability of generating very narrow beams and the property of being highly monochromatic.

Powerful non-coherent light sources are generally restricted to beamwidths greater than approximately 1° (3×10^{-4} steradians) due to focusing and other design problems. Powerful lasers have been developed with beamwidths on the order of 0.1° (3×10^{-6} steradians). The intensity increase due to this beamwidth factor would be 100 fold.

However, in many airport lighting applications a narrow beamwidth may not be desirable from the system standpoint. A very accurate tracking system would be required to make the beam visible

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9. Illuminating Engineering Society Lighting Handbook, 3rd Edition, pp. 8-117.

to the pilot continuously. If the beam were stationary, the aircraft would normally pass through the beam very quickly and perhaps miss it entirely. The utilization of narrow light beams would require the development of new systems. Present airport lighting and visual landing-aid systems require beamwidths of over 1 degree to be effective.

To take advantage of the monochromaticity of lasers, a filter must be placed in front of the receiving system. The human receiver could be fitted to filters in the form of goggles. This does not increase the power density at the receiving point as does the narrowing of the beam. Instead, the filter reduces the power density from extraneous light sources. Filters are available which would reduce background radiation due to reflected sunlight by a factor of 1,000 while reducing the light from a laser source by a factor of only 2. Such filters would not discriminate against the interfering background illumination caused by scatter of the laser beam itself due to fog, precipitation, etc. The normal vision of anyone wearing these filters would be seriously impaired.

3. Laser Instrumentation Systems.

a. Laser Radar Altimeter. Practical laser radar range finders have been developed for use by the Army. These are simply a pulsed laser collimated with an optical receiver which includes timing circuits. Similar units could certainly be used in the air as altimeters.

Such a device would have some advantages over microwave radar-altimeters. The tops of telephone poles and snow banks which would not provide a return signal at microwave frequencies could return useable signals to a laser radar. Like microwave radar altimeters, laser radars can operate with short pulses allowing system operation at extremely low altitudes for automatic landing systems applications. The accuracy of a laser radar could be as good as the best of microwave radars. The increased attenuation and backscatter from clouds, fog, and precipitation particles would be the principal disadvantage of the laser radar altimeter when compared to its microwave competition. At the short ranges required for computation of flare-out a laser radar may be feasible in all types of weather.

At flight altitude a laser radar altimeter may have limited usefulness since it could not penetrate dense cloud cover and the differentiation of the backscatter from cloud banks and the ground would be difficult.

b. Laser Radar Ceilometer. Ceilometers in current use determine the altitude of the cloud base by triangulation. Two ground stations are required to form the base of the triangle. The measurement accuracy decreases with cloud base height.

A simple vertically directed laser radar would function as a single site ceilometer whose accuracy would not vary with cloud base altitude. Through the addition of a scanning system cloud base altitude could also be measured in a limited area around the ceilometer with decreased accuracy.

The General Electric Company has done some experimental work with such a vertically directed scanning laser radar. The laser employed was operated as a Q spoiled device and therefore the output light pulse was short (less than 0.1 microsecond) and had high peak power (between 1 and 10 megawatts). With this laser they were able to measure the height of both the base and the top of most cloud formations. There is some evidence that on a clear night they detected a wind shear layer at 11,000 feet.

A laser radar ceilometer could give considerably more information than existing ceilometers. Some of the problem areas which may make the implementation of such a device difficult would be cost, increased effort required to interpret the information, and safety of personnel who may be exposed to the beam.

c. Laser Radar for Measurement of Visual Range. Through a different interpretation of the backscattered signal the laser radar ceilometer could be used to give an indication of visual range through fog and precipitation.

The main advantage of a laser radar in this application would be that the receiver is colocated with the transmitter. The same laser radar could make measurements along the runway, straight up, or up the glide slope. The latter two measurements cannot be made with current transmissometers.

The primary difficulty with this system would be relating the return signal with visual range. Visual range is reduced through both absorption of light energy and by scattering of light energy. A laser radar return signal consists of scattered light energy only. An

extreme example would be thick black clouds of smoke. A transmissometer would correctly determine the degree of opaqueness of such a cloud, while a laser radar return signal might indicate light haze. While such an extreme condition may be highly unlikely, mixtures of smoke and fog (smog) are sufficiently common around some of our busiest airports to complicate the interpretation of the backscattered signal.

GENERAL CONCLUSIONS

The laser techniques and proposed hardware items which, at this time, appear to be of possible future benefit to the FAA mission are being exploited to a satisfactory degree by other organizations outside the FAA. Any early application of the laser in the FAA will likely be in the instrumentation field.

Attenuation, due to scattering by fog, haze, precipitation, etc., is the most significant handicap to the application of lasers in the FAA.

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100-x	BOOKS
200-x	BIBLIOGRAPHIES
300-x	JOURNAL ARTICLES AND REPORTS
310-x	General
320-x	Optically pumped lasers
330-x	Gas Lasers
340-x	Injection Lasers
350-x	Applications
351-x	Communications
352-x	Optical transmission lines
353-x	Radar
354-x	Rotation rate sensing
359-x	Miscellaneous
360-x	Atmospheric Propagation
370-x	Laser Components
380-x	Modulation Techniques
390-x	Demodulation and Receiving Techniques

NOTE: "x" represents a serial number, beginning with "1" for each of the above classifications, e.g., 351-6 would be the sixth journal article on communication applications to be cited.

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