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LIGHT SOURCES FOR OPTICAL COMMUNICATION

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Abstract—Several modulated light sources of historical nature are described which have been used in transmitting intelligence to distant points. Some of the characteristics of cesium-vapor lamps and high-intensity short-arc xenon lamps are described. The phenomenon of acoustical resonance in enclosed arcs is discussed.

For centuries man has used light as a means of communication over distances greater than those over which his voice could be heard. American Indians used fires at night and smoke signals by day to transfer news to their distant friends. Such signals are simple, slow in execution, and very limited in range of usefulness.

Sailors use a blinker system of long and short flashes of light from a searchlight beam by means of which letters and words may be transmitted to a distant observer. While any message may be relayed in this manner, the speed is relatively slow—of the order of 6–8 words/min. The chief advantage of this system is simplicity of operation, since it consists merely of a shutter in front of a searchlight for the transmitter and the eyes of the observer for the receiver. By interrupting or "keying" the current through special incandescent lamps filled with hydrogen gas, and by using thyratron-controlled electrical circuits, one may obtain a speed of about 10–12 words/min.(1) This is limited by the heating and cooling times of the filament.

Accustomed to high-speed voice communication over telephone lines or radio, we would like to transmit speech over a searchlight beam as an improvement over the present blinker system. This idea is not new, for in 1880 Dr. Alexander Graham Bell, inventor of the telephone, described two methods of modulating a beam of light from a steady source with voice frequencies.(2) Sunlight was the light source, while his stethoscope was the receiver. These ideas were not developed into a practical device because of the mechanical difficulties involved. Bell's early experiments were limited to a range of several hundred yards. Optical systems have greater security than radio, which is very important in military applications. A searchlight beam is limited to horizon distances and cannot be intercepted or interrupted by unauthorized persons. Visual security is readily obtained with visibly-opaque but infrared-transparent filters.

MAJOR REQUIREMENTS FOR SPEECH TRANSMISSION

To transmit speech by light, three major requirements must be fulfilled. First, it is necessary to modulate a beam of light so that it varies in intensity and frequency with voice vibrations. Second, these variations in light intensity must be picked up at a distant station and transformed back into audible sounds by electric means. Third, the atmosphere must be sufficiently transparent to permit the transmission of radiant energy.

We have a choice of many light sources at our disposal, depending upon what auxiliary mechanical and electrical equipment is used. A vapor or gas-discharge lamp may be modulated with audio-frequency currents superimposed upon the normal direct current with good efficiency because of its low thermal inertia. In this scheme the source of light itself is modulated. An incandescent tungsten filament lamp of the common 120 V household type can be current-modulated with audio frequencies, but it has relatively poor efficiency, especially at the higher frequencies because of the relatively high heat-capacity of the filament. One may also modulate the flux of light emitted by any source of constant intensity—artificial or sunlight—with suitable mechanical or optical systems of small inertia. In this method the light beam is modulated after it leaves the source.

Modern photocells of the photoemissive or photoconductive types, with suitable electronic amplification, make satisfactory receivers. The most common are silver–oxygen–cesium vacuum or gas-filled phototubes, and selenium, thallous sulfide, and lead sulfide photoconductive cells.(3)

Between the light source and the receiver is the atmosphere that scatters, absorbs and transmits the signals with variable degrees of efficiency. This is a factor of great importance, but is generally neglected for short ranges of transmission. Even a small amount of smoke or fog greatly reduces both the visibility and the transmission of infrared energy. There is also the molecular absorption of water vapor and carbon dioxide gas in the air that limits long-range operations to a few isolated wavelength bands or windows in the infrared.(4)

Up to the present time the most useful spectral band of infrared energy for optical communication is in the zone between 8000 Å and 12,000 Å. A number of available-light sources and phototube detectors have good efficiency in this region, and there are also several filters that can be used to screen out the unwanted visible light, yet transmit this near-infrared energy very efficiently.(5) A serious objection to using this atmospheric window is that the near-infrared energy is readily detected with infrared image-converter tubes.(6) A more desirable communication system would be one that utilizes longer wavelengths in the infrared.

For low-power portable devices it might be desirable to use infrared-emitting phosphors excited by cathode rays as a source of pre-selected infrared energy.(7) In this system one of the longer-wave atmospheric windows could be utilized. Lead sulfide or lead selenide phototubes might then be used as detectors.

MODULATED GAS FLAMES

Almost 100 years ago Koenig demonstrated that a small gas flame could be modulated with audio frequencies. He used a device called a manometric capsule (Fig. 1) which consisted

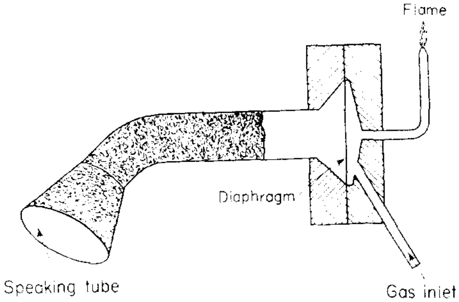

FIG. 1. Koenig's manometric capsule involving modulation of a gas flame.

of a shallow cavity in a block of wood, one side of which was covered with a flexible diaphragm.(8) Two pipes were connected with the cavity, one leading to the gas supply and the other to a lighted gas jet that formed a flame about 2 cm high. When words were spoken into the speaking tube, the gas in the small chamber changed its pressure rapidly and caused fluctuations in the height and brightness of the flame. Changes in light intensity were observed as reflections on the rotating mirror. Even with a modern photocell for a detector the quality of the sound emitted by this source is poor.

PHOTOPHONE

During 1916 Professor Rankine developed his photophone,(9) a device which could carry speech over a light beam to a distance of several miles. The theory of its operation is sketched in diagrammatic form in Fig. 2. A source of light, either artificial or sunlight, was focussed by a lens upon a small concave mirror that was mechanically coupled to a telephone-transmitter diaphragm. The mirror reflected the incident light to another similar lens and produced a real image of the source behind it. Similar grids of equally spaced opaque and transparent bars were mounted in front of each lens. When the mirror oscillated under the excitation of speech vibrations, the image of the first grid moved over the second grid and thus produced variations in the light intensity that emerged from the searchlight beam. This accomplished what Dr. Bell failed to do, in using a grid without inertia. In this system only half of the light is usable, since half is wasted by the opaque grids. Signals were received at a distant station on a selenium photocell that converted the light pulses into sounds. This device had not been developed to a practical state during World War I. A by-product of Rankine's research was the recording of sound by photographic means on a moving ribbon of film and the reproduction of the sound at a later time. This development added sound to silent movies.

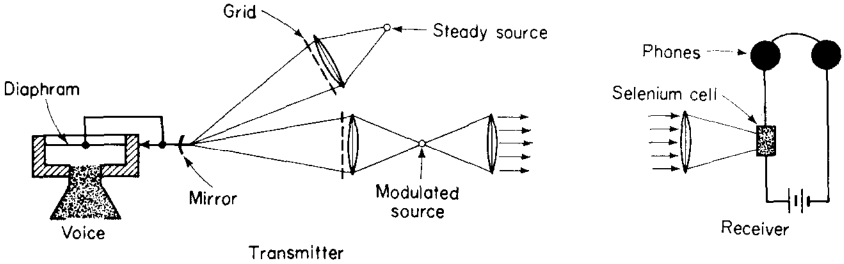

FIG. 2. Rankine's photophone involving voice transmission by modulated light.

GERMAN LICHTSPRECHERS

Since 1935 the German Army has used light-beam communication equipment which employed novel optical components.(10) As shown in Fig. 3, light from a small low-wattage tungsten-filament lamp is reflected from the inner surfaces of the glass prism and then out through the objective lens of the searchlight. Voice modulation is produced by rocking the small prism against the larger one. When the small prism is in contact with the large one, light passes through the interface to the observation tube. When removed by only about one wavelength of light (1/25,000 in.) practically all the light is transmitted by internal reflection to the searchlight objective lens. This system gives nearly 100 per cent light modulation in the beam. Fig. 4 illustrates the optical system of another *Lichtsprecher*. Here the opaque grids of Rankine's photophone are replaced by prisms of high optical performance. These devices are illustrations that the flux of light from a source of constant intensity can be modulated by mechanical–optical methods. With suitable filters these instruments could be turned into secret communication systems using only infrared radiation. The detectors were lead sulfide photoconductive cells cooled with dry ice to obtain increased sensitivity.

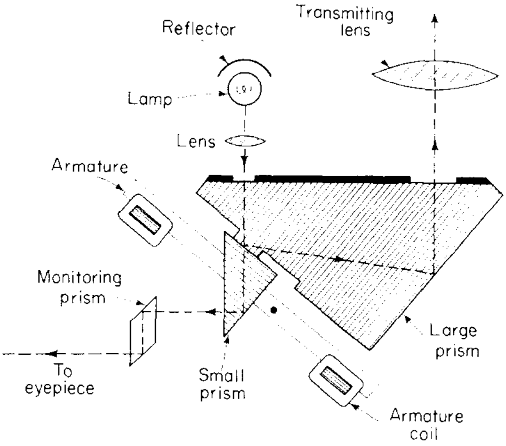

FIG. 3. Modulator system of German *Lichtsprecher*.

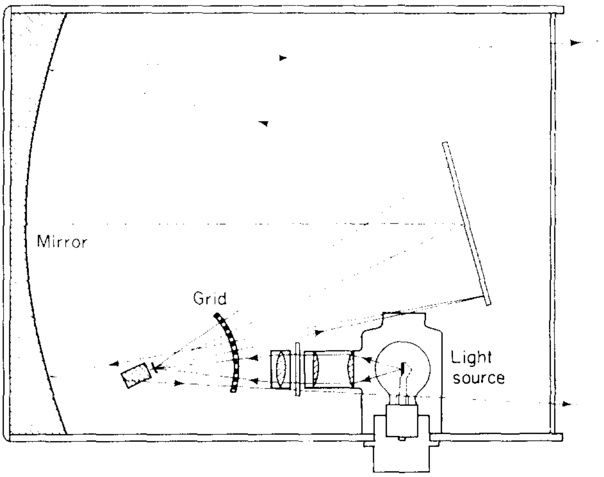

FIG. 4. Transmitter optics of long-range German *Lichtsprecher*.

CESIUM-VAPOR LAMPS

During 1944 the U.S. Navy sponsored researches in industrial and university laboratories that led to the development of a successful wireless-telephone system in which conversations were carried by a beam of infrared light. The assignment involved the development of the cesium-vapor arc into a practical light source.(11) Cesium vapor was selected because of the location of its resonance spectral lines at 8521 and 8944 Å. It was known that this type of radiation could be generated very efficiently; e.g. the yellow *D* lines of sodium vapor produce one of our most efficient light sources, and the 2537 Å resonance radiation of mercury vapor produces our most efficient ultraviolet source. This radiation is used for energizing fluorescent lamps and bactericidal lamps. By analogy with sodium and mercury vapor, cesium vapor should produce near-infrared rays very efficiently under suitable conditions. As a result of the use of a vapor, the lamp had high modulability for voice frequencies.

The research program resulted in the development of the CL–2 lamp shown in outline in Fig. 5. The source of light is the inner bulb, 1·37 in. in diameter and 5 in. long, with an arc length of 3 in. between electrodes. This size produced a 25° beam spread in a 15 in. reflector. The bulb has two electrodes to anchor the arc to its center. The lamp contains argon gas at about 20 cm of mercury pressure and several tenths of a gram of cesium metal. The partial pressure of cesium vapor during normal operation was about 3 mm of mercury pressure. An outer evacuated envelope is used to conserve heat, for the inner bulb operates at a temperature of about 325 °C. Spectrograms show that most of the useful energy radiated by this lamp is in the resonance lines, 8521 and 8944 Å. At a steady current of 5·5 A the useful life is over 500 hr. About 21 per cent of the power supplied to the lamp is

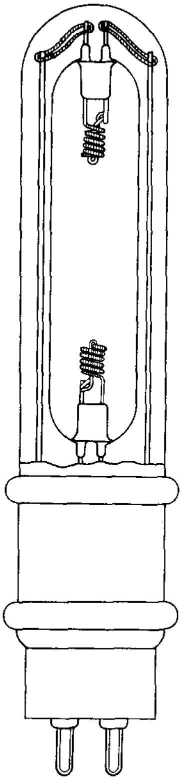

Fig. 5. 100 W cesium-vapor lamp.

radiated as near-infrared radiation. At 6 A and 17 V (102 W), it would require a 675 W tungsten-filament lamp to give the same total amount of infrared, as measured with a cesium photocell through filters that give the same visual security to the lamps. Throughout the life of the lamp the intensity of the infrared radiation remains practically constant. The end of life occurs when the infrared intensity drops very abruptly to a low value, as a result of the absorption of the cesium by the glass bulb. The discharge then becomes essentially an argon arc with very low infrared intensity.

Figure 6 shows how a cesium-vapor lamp is incorporated into a communication system. The lamp is mounted in a reflector with an infrared filter on the front to give visual security.

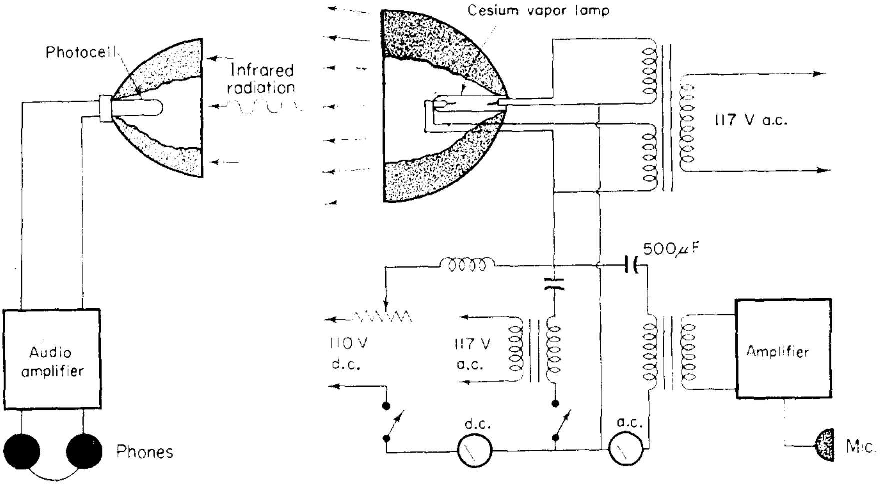

FIG. 6. Apparatus for transmitting speech over a light beam.

It operates on d.c. with amplified voice frequencies superimposed on the lamp current. The modulated light is picked up at a distant station with a thallous sulfide photocell, the current from which is amplified and converted to sound, which duplicates with excellent quality the original spoken words.

Both larger and smaller cesium-vapor lamps were made. A 50 W size, produced for the Air Force, operated on a 24 V supply, had good life, and an efficiency slightly less than the larger 100 W size because of the shorter arc length. Lamps of 500 W rating were made for use without optics to give 360° horizontal coverage. The efficiency of these lamps was greater; about 35 per cent of the power supplied to the lamps was converted into useful near-infrared radiation.

A study was also made of lamps having a power consumption of 10–20 W. They were similar to the larger sizes, but were mounted in sealed-beam automotive-type headlamps. Fig. 7 shows the general outline of the lamp. The bulb enclosing the light source is surrounded by a nichrome-wire heating element that forms part of the ballast for operating the lamp on a 12 V storage battery. The lens and the reflector of the sealed-beam lamp are cemented together with a thermosetting plastic cement, since fusing the edges of the lamp together, as is common practice in the production of automotive lamps, would be deleterious to the cesium lamp.

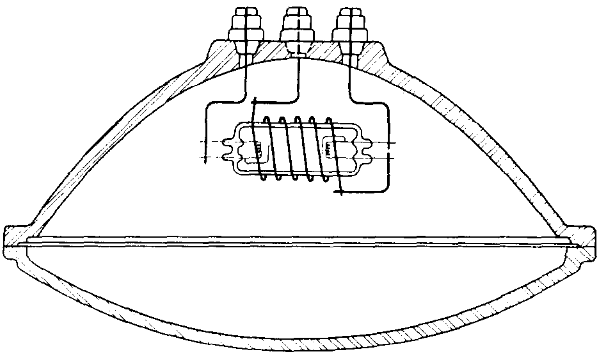

FIG. 7. Sealed-beam type of low-wattage cesium-vapor lamps.

Figure 8 shows a circuit used in our laboratory for operating the lamps on a 12 V storage battery. The battery is tapped at 8 V to supply the preheat current of 1·5 A through the cathode and ballast resistor, which is allowed to run for several minutes before the starting circuit of 150 V a.c. is turned on. After another 1–3 min the arc concentrates between the electrodes, at which time the starting circuit can be disconnected and the lamp operated on the 12 V supply. Some lamps have burned with practically constant infrared output for 250 hr under these conditions.

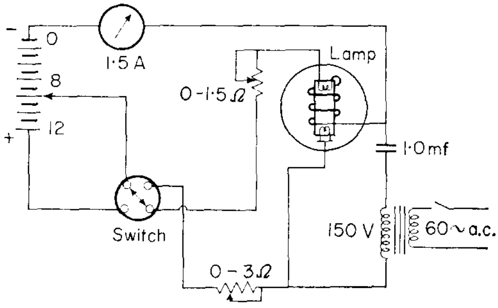

FIG. 8. Circuit for operating small cesium-vapor lamps on 12 V battery.

HIGH-INTENSITY SHORT-ARC LAMPS

During and after World War II Professor Paul Schulz in Germany developed the high-intensity short-arc xenon lamp which has an operating pressure of 20–40 atm.⁽¹²⁾ The xenon lamps emit radiations of almost constant spectral intensity throughout the visible region, and strong radiations in both near-infrared and near-ultraviolet regions.⁽¹³⁾ These lamps are now being used in Europe as replacements for carbon arcs in small and medium size movie theatres.

Experimental lamps were made with heavy-wall quartz bulbs and were filled with mercury vapor, xenon gas, and combinations of mercury and xenon for power ratings of 500–2000 W. The electrodes were machined from solid tungsten rods. The cathodes supplied heavy currents largely by field emission rather than by thermionic emission and were made with pointed conical tips. The anodes had to be quite massive to dissipate the large amount of heat generated at that electrode. Fig. 9 is a sketch of an experimental high-intensity short-arc xenon lamp. The lamp is enclosed in a heavy-wall plastic housing during handling and storage to prevent a dangerous explosion since it is filled to several atmospheres pressure.

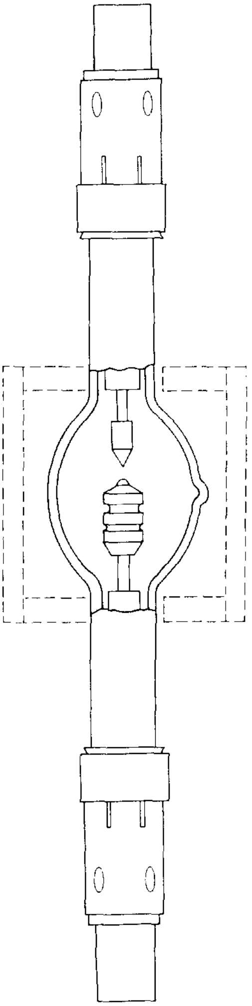

FIG. 9. Short-arc xenon lamp.

Spectral energy distributions were made with a Perkin–Elmer infrared spectrometer in the region between 0·8 and 1·7 μ. A high-pressure xenon lamp emits ten to twelve strong spectral lines in the zone between 0·8 and 1·0 μ and a small amount of continuous energy throughout the near-infrared region. A high-pressure mercury lamp emits a strong spectrum line at 1·01 μ and six other lines of lesser intensities between this line and 1·7 μ, and also some continuous energy throughout this region. A composite mercury–xenon lamp with high pressures of both components exhibits the combined spectra of both elements with good intensity. This is quite different from low-pressure discharges in which only the spectrum of the metallic element is recorded. The relatively high intensity of the xenon arc lines makes this a desirable source for those applications where a small, intense, efficient and readily modulable source of radiant energy is desired.

Xenon lamps operate at higher currents and lower voltages than mercury vapor lamps of similar structure. Mercury–xenon lamps have intermediate operating characteristics that depend upon the partial pressures of the two components. Some of our experimental high-intensity xenon lamps with a spacing of 4 mm between the electrodes have operated at 25 ± 2 V over a current range of 25 A to 75 A. Because of the strong convection currents inside the lamps, it is desirable to burn the lamps in a vertical position, anode end on top, to attain stable, constant light intensity.

DUDDELL'S SPEAKING ARC

An electric arc operated in air may be modulated with voice frequencies and so produce sounds directly. Duddell in 1901 operated an arc light on direct current and then superimposed audio frequencies by the scheme indicated in Fig. 10.(14) In this case the light emitted by the arc is of secondary importance since it is not used or wanted. The variations in air pressure caused by changes in current through the arc produce the sound vibrations. The arc emits sounds of sufficient intensity to be audible to several hundred people in an auditorium of moderate size. If the arc is enclosed in an outer jacket or bulb, the sound energy is confined within the lamp. We would like to use the light of a modulated arc lamp and discard the accompanying sound energy.

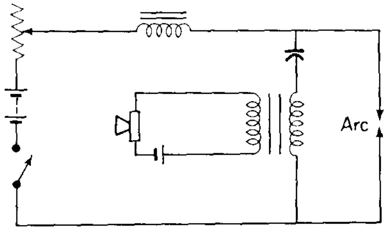

FIG. 10. Duddell's speaking arc.

STANDING SOUND WAVES IN ARC LAMPS

Enclosed arc lamps operated on a.c. power in the audio-frequency range or on d.c. and modulated by a.c. currents may cause sound vibrations to be produced within the arc chamber. They are caused by thermally induced variations in gas pressure that result from changes in current density in the arc. At certain critical frequencies resonance of appreciable intensity is built up by reflections from the bulb walls. The size and shape of bulb, kind of gas or vapor filling, temperature and operating conditions determine the frequency of the plasma oscillations that are similar to standing sound waves in the discharge. Ordinarily this phenomenon is not observed because lamps are operated on d.c. or low-frequency a.c. with sufficient ballast to insure stable operation. In long tubes the discharges assume a constricted, snakelike appearance at the critical frequencies and are caused by sound energy reflected from the ends of the bulb. In a spherical bulb the sound waves spread to the bulb walls and are then focused back upon the arc to produce instability at the electrodes.

The simple lamp structures shown in Fig. 11 illustrate the acoustical resonance phenomena.

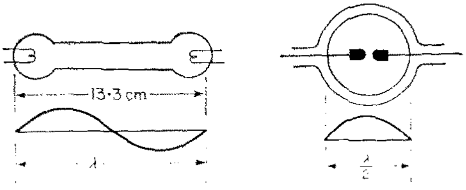

FIG. 11. Illustration of standing sound waves in experimental lamps.

The lamp at the left is about 1·5 cm in diameter, 13·3 cm long and contains xenon gas at 34 mm mercury pressure at room temperature. When operated on 3 A d.c. current with 2 A a.c. modulation superimposed, the arc showed violent distortions at 2250 c/s, but was quiescent at 2000 and 2500 c/s. With 5 A d.c. and 3 A a.c. modulation at 2500 c/s, the discharge again showed pronounced disturbances, but was stable at 2300 and 2700 c/s. The instability may start at either electrode, whereupon the discharge constricts into a thin luminous ribbon with sinusoidal shape, and the voltage increases because of increased arc length. Harmonics of the fundamental frequency may also be observed.

The following theory applies to this phenomenon. Laplace showed that the velocity of sound in a gas is determined by the equation $V = \sqrt{(\gamma p/d)}$. From the universal gas law $pv = RT$ and the definition of density $d = m/v$ one can rewrite Laplace's equation with equivalent quantities as $V = \sqrt{(\gamma RT/M)}$. V is the velocity at absolute temperature T, R is the universal gas constant $8{\cdot}3 \times 10^7$ ergs/degree, M is the mass in grams of one mole of gas, γ is the ratio of the specific heats of the gas and is a constant, e.g. 1·42 for air and 1·66 for argon, xenon and mercury vapor.

Assuming an effective temperature of 600 °C (= 873 °K) for xenon gas in the first illustration above, one obtains a value of 30,300 cm/sec as the velocity of sound in the lamp. Since velocity = frequency × wavelength, in the above example the wavelength of the sound produced inside the lamp bulb would be:

$$\lambda = \frac{30{,}300 \text{ cm/sec}}{2250 \text{ c/s}} = 13{\cdot}5 \text{ cm}$$

This is approximately the length of the lamp. In this lamp standing sound waves one wavelength long have nodes at the ends and center of the lamp, illustrated with a sine wave in Fig. 11. With the higher current rating and acoustical resonance at 2500 c/s, assuming a gas temperature of 800 °C, one finds that the velocity should be 33,500 cm/sec and the generated wavelength to be 13·4 cm. Having observed the relationship between bulb dimensions and acoustical resonance, one can estimate the temperatures of the gas or vapor in a discharge lamp by this method.

In a spherical bulb with electrodes at the center (Fig. 11) acoustical resonance occurs when the bulb diameter is equal to one-half wavelength. It was found that the mirror-like reflections of sound energy from spherical bulb walls could be minimized by locating the arc below the center of the bulb. This defocuses the echoes of the sound energy so that some is dissipated at the electrodes or on the bulb walls. An arc centered in a spherical bulb will literally "blow itself out" by its own sound waves, if any of the strong resonance frequencies are applied to the lamp for any appreciable time. A narrow enlarged band formed on a cylindrical shaped envelope directly opposite the constricted arc also defocuses the echo sound waves. These simple modifications can be used to improve the stability of modulated high-intensity arcs.

An experimental lamp was made to study standing waves in a low-pressure discharge containing argon gas at several mm pressure and mercury vapor. A diagram of the lamp is shown in Fig. 12 as well as the characteristic relations of current, gas pressure and light output on both a.c. and modulated d.c. power. The lamp was 1·5 in. in diameter, 28 in. long and had a spacing of 12 in. between electrodes. A movable glass sleeve, closed at one end, permitted tuning of the resonating cavity at one end of the lamp. A resonant frequency of about 600 c/s was established with 1·5 A d.c. flowing through the lamp and 1·0 A a.c. superimposed. If the movable end-chamber was placed 6 in. from the electrode, both electrode regions showed a symmetric pattern of constricted arc as shown by the cross-hatched area inside the lamp. An audible 600 c/s tone was heard several feet from the lamp during this condition of operation. Sound generated inside the lamp was transmitted through the bulb walls to the air in the room. If the movable end-chamber was placed closer to or further from the electrode the disturbance at that electrode was minimized or disappeared completely with 600 c/s excitation while the constricted pattern of arc disturbance did not change at the other electrode.

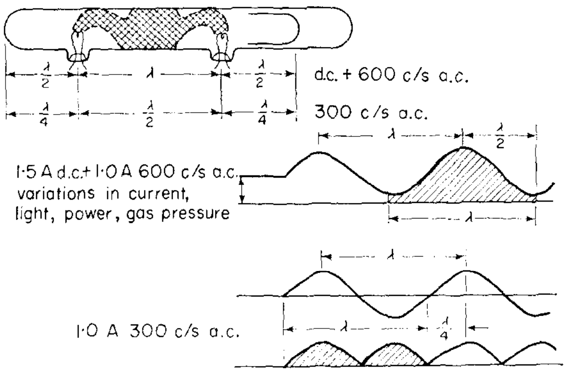

FIG. 12. Demonstration of acoustical resonance.

In this low-pressure discharge lamp, assuming an average gas temperature of 250 °C, the velocity of sound in mercury vapor was 19,000 cm/s calculated by Laplace's formula.

$$\text{The wavelength} = \frac{\text{velocity}}{\text{frequency}} = \frac{19{,}000\ \text{cm/sec}}{600\ \text{c/s}} = 31{\cdot}7\ \text{cm}$$

This is very close to the electrode spacing of 30·5 cm or 12 in. With a d.c. bias and audio-frequency modulation there is a single light pulse and a single pressure pulse in each wavelength. Maximum disturbance or turbulence at the electrodes occurs at $\lambda/2$ from the nodes which are at the ends and center of the lamp.

When the lamp was excited with 1–2 A a.c., with no d.c. bias, the critical frequency required to cause pronounced disturbance or turbulence at the electrodes occurred at about 300 c/s. This was just half the preceding frequency with d.c. bias. In this case there are two pressure pulses for each wavelength and the spacing between electrodes is equal to a half wavelength for the resonant frequency.

$$\lambda = \frac{19{,}000\ \text{cm/sec}}{300\ \text{c/s}} = 63{\cdot}3\ \text{cm}$$

The distance between a node at the end of the lamp and the electrode would again be about 16 cm for maximum disturbance. This simple discharge tube readily demonstrates the phenomenon of acoustical resonance.

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