JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 37, NUMBER 9 SEPTEMBER, 1947

Modulation of the Resonance Lines in a Cesium Arc*

J. M. FRANK, W. S. HUXFORD, AND W. R. WILSON
Department of Physics, Northwestern University, Evanston, Illinois

(Received June 16, 1947)

A detailed study has been made of the electrical characteristics and light-modulation properties of a 90-watt cesium vapor arc having a three-inch column. The range of frequencies used extend from 100 to 10^6 c.p.s. When operated on a d.c. biasing current of 5 amp., the arc has a positive resistance; below 20,000 c.p.s. its reactance is inductive, while above this frequency the reactance is chiefly capacitative. The modulation ratio for the resonance lines at 8521A and 8944A has a nearly constant value of 0.85 below 2000 c.p.s., and for higher frequencies varies inversely with the square root of the frequency.

I. THE CESIUM ARC

THE arc lamps used in this study were developed for use in infra-red communication systems as a wartime project by the Westinghouse Lamp Division. A detailed description of lamp structure and manufacturing techniques has recently been published.[1] Figure 1 is a photograph of two lamp models used for military purposes. In these lamps the inner Pyrex bulb contains the cesium metal and is filled with argon to a pressure of about 20 cm of mercury. This arcing chamber is mounted in an evacuated outer envelope so that during operation of the arc its temperature is sufficiently high to maintain a cesium vapor pressure of about 2 mm of mercury. The electrodes are coiled tungsten filaments which are used to preheat the inner bulb and vaporize the cesium, and to anchor the discharge along the tube axis. The larger model of lamp, type CL-2, having a three-inch arc column, was used in the present studies.

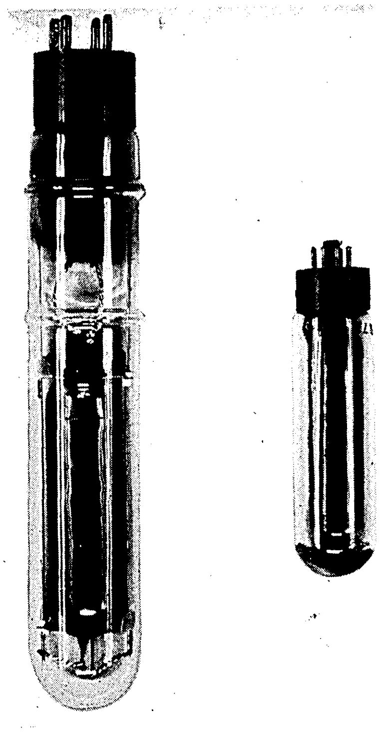

FIG. 1. The large lamp, type CL-2, has a 3″ electrode spacing. The small lamp is a 50-watt model, having $2\frac{1}{2}''$ distance between electrodes.

The discharge is a wall-stabilized form of low voltage arc requiring a copious supply of electrons from the cathode. For this purpose the filament used as cathode is coated with a barium-strontium oxide mixture. In starting the discharge the filaments are preheated for about two minutes, after which a one-ampere arc may be set up using a two- or three-hundred volt a.c. source and ballast, and the arc switched over to the d.c. source when sufficient metal has been vaporized; or the arc may be initiated after preheating of the inner bulb by attaching the d.c. supply and using a high frequency electrodeless discharge to effect ionization of the argon. Temperature equilibrium is established in the lamp six or eight minutes after the arc discharge is set up.

Figure 2 shows the static characteristics of one of the CL-2 lamps obtained by first increasing the arc current, and then decreasing it. If the arc current is allowed to flow for two or three minutes

* Presented at the Washington Meeting of the American Physical Society, May 1, 1947. This work was sponsored by the U. S. Navy, Bureau of Ships.

[1] N. C. Beese, J. Opt. Soc. Am. 36, 555 (1946).

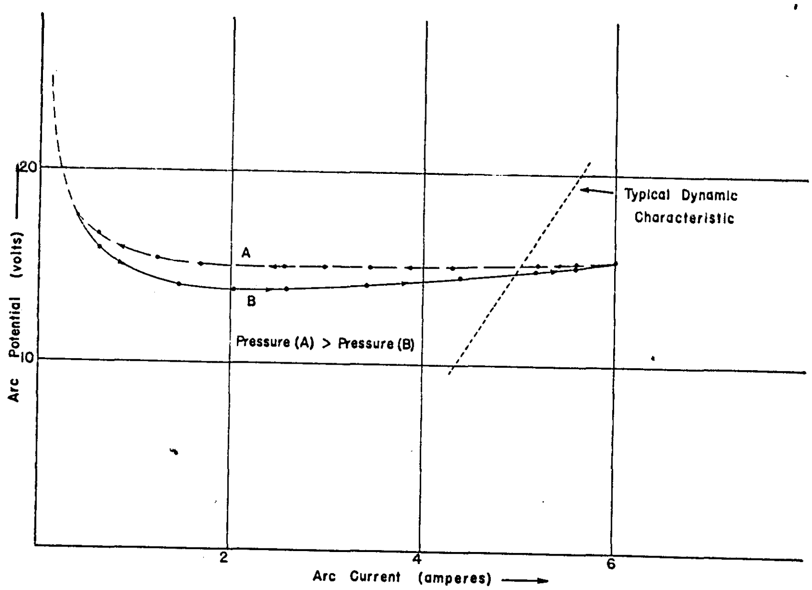

FIG. 2. Potential-current curve for the d.c. cesium arc and typical dynamic characteristic.

between readings a single curve is obtained. A typical dynamic characteristic is also shown.

The high infra-red efficiency of this lamp is due chiefly to the energy radiated in the two resonance lines of cesium at 8521A and 8944A. For laboratory studies this radiation is satisfactorily isolated by using a Wratten No. 87 filter and a Cs-Ag-O photo-cathode receiver. Measurements show that approximately 22 percent of the total power supplied to the arc is emitted as resonance radiation. For a new lamp containing an excess of cesium the intensities of the two resonance lines are nearly equal.

This source has proved of great value for infra-red communication purposes because of its high conversion efficiency and its excellent modulation characteristics. For both practical and theoretical reasons it is important to have complete and detailed information concerning the dynamic properties of the arc over the entire range of frequencies for which a useful component of modulated radiation can be obtained and for which accurate measurements can be carried out. The present study was undertaken to secure this information.

II. EXPERIMENTAL PROCEDURE

When the cesium arc is used as a source of modulated radiation the discharge is maintained by means of a biasing direct current, and this current is modulated by impressing an a.c. potential across the arc electrodes. The biasing current in the present work was supplied by a 120-volt bank of large storage cells. Three types of generators were used as alternating current sources. The first was an audio oscillator driving a power amplifier and having a frequency range from 100 c.p.s. to 30,000 c.p.s. The second source was a long wave power oscillator (25 kc/sec. to 300 kc/sec.) especially designed and constructed in this laboratory for use in exciting gaseous discharges. The third generator was a Navy type TDE transmitter having an average power output of 150 watts and capable of supplying currents ranging in frequency from 300 to 18,000 kc/sec. It was possible with these generators to supply alternating currents of good sine-wave form to the arc sufficient to secure at least 75 percent current modulation over the entire range of frequencies from 100 c.p.s. to 10^6 c.p.s.

When applying a.c. modulating potentials to the arc, provision was made for varying the depth of current modulation and making impedance matching adjustments. The alternating current was supplied to the arc through a coupling capacitor the size of which depended upon the lowest frequency at which measurements were taken. At audiofrequencies the dynamic impedance of the arc is of the order of two ohms, so that an 800-μfd electrolytic capacitor was employed for the lower modulation frequencies. Above 50 kc/sec. an 8-μfd capacitor was used.

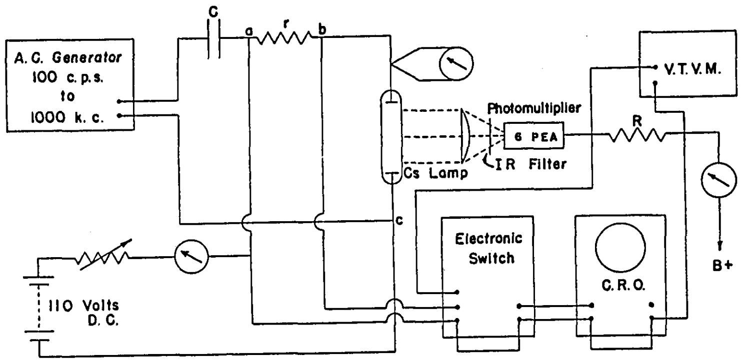

FIG. 3. Block diagram showing all components of the measuring circuit.

Method of Measuring Current Modulation

At one of the lamp terminals a calibrated thermocouple was inserted in the circuit so that both the d.c. and a.c. currents passed through it. The total current recorded by the thermocouple meter is referred to as I_t and the reading of the d.c. meter in the circuit is designated I_0. The r.m.s. value of a.c. current through the arc is given by

$$I_L=(I_t^2-I_0^2)^{\frac{1}{2}}.$$

The degree of current modulation is conveniently expressed in terms of the peak value of a.c. through the arc and the d.c. operating current. Thus, the percent current modulation is given by the relation,

$$M_I=(\sqrt{2}I_L/I_0)\cdot 100 \text{ percent.} \qquad (1)$$

Method of Measuring Light Modulation

The apparatus for determining the degree of modulation of the resonance radiation consisted of a condensing lens, a Wratten No. 87 infra-red filter, photo-tube multiplier, vacuum-tube voltmeter, and d.c. microammeter (see Fig. 3). The Wratten No. 87 filter was used because it passes both of the resonance lines of cesium and excludes all wave-lengths below about 7500A. The photo-tube multiplier was a Farnsworth-type 6PEA with Cs-Ag-O cathode having its maximum sensitivity at 8300A and threshold at about 13,000A. For frequencies below 100 kc/sec. a 5000-ohm load resistor was used in the final multiplier stage, and at higher frequencies a 1000-ohm resistor (R, Fig. 3). When the multiplier is used in this manner the a.c. current through the load resistor is accurately proportional to the flux received by the photo-cathode at all frequencies.

The unmodulated component of light flux produces a current i_0 in the d.c. output meter of the multiplier. The modulated component produces an a.c. potential across the photo-multiplier load resistor, R, equal to e_L r.m.s. volts. e_L was measured with a vacuum-tube voltmeter. The percent light modulation equals the ratio of the peak value of the alternating component of photo-current to the average d.c. value, or

$$M_L=(\sqrt{2}e_L/Ri_0)\cdot 100 \text{ percent.} \qquad (2)$$

The ratio of the percent modulation of resonance radiation to the percent current modulation has been designated the "radiation-current modulation ratio." Its value at any frequency was calculated from (1) and (2); thus, the modulation ratio M is given by

$$M=M_L/M_I. \qquad (3)$$

Studies of wave form of the current and light waves, and measurements of the current-potential and light-current phase angles were made by means of a cathode-ray oscilloscope and an electronic switch. For this work a DuMont Model 248 oscilloscope was used, and an electronic switch of special design. The latter consisted of a Hewlett-Packard square-wave generator used to deliver a 60-cycle, 50-volt negative maximum square wave to the plates of two triode vacuum tubes, driving them alternately to cut-off plate current. An a.c. potential drop proportional to the arc current was applied to the grid of one tube and the a.c. component of the arc potential, or a.c. output of the multiplier photo-tube, to the grid of the second tube. The cathode-follower

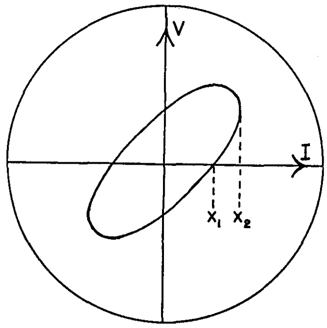

FIG. 4. $\text{Sin}\theta = x_1/x_2$, θ = angle between current and potential waves.

output of the two tubes was then applied to the vertical amplifier of the oscilloscope. In this way the current and light waves could be viewed simultaneously on the oscilloscope screen, and wave shapes and phase shifts accurately measured at all frequencies up to one megacycle.

The determinations of percent modulation of current and of radiation were checked at several frequencies by measurements of the amplitudes of these waves as viewed on the oscilloscope screen. By means of the electronic switch the zero-current deflection was indicated simultaneously on the screen along with the current waves. In all cases satisfactory agreement was found between scope measurements and those obtained by the use of the thermocouple ammeter and d.c. current measurements, and by the corresponding measurements for the light wave as indicated by the output current of the photo-tube multiplier.

III. ELECTRICAL CHARACTERISTICS

The electrical properties of the modulated arc are complicated functions of the d.c. biasing current, the frequency and depth of modulation, the cesium vapor pressure, the size of discharge tube, and length of the arc column and its position in the earth's gravitational field. For the present experiments the arc was operated in a horizontal position and on a d.c. current of 5 amperes. In the case of the electrical measurements all data refer to fifty percent current modulation at all frequencies used.

Potential-Current Phase Angle

The oscilloscope was used to measure the phase angle between arc potential and arc current as a function of frequency. A special non-inductive resistor having a resistance of 0.25 ohm was inserted in the circuit so that both the d.c. and a.c. components of arc current flowed through it. (r, Fig. 3.) The a.c. component of voltage developed across this resistor, which is proportional to the a.c. component of lamp current, was applied to one set of deflecting plates. Very good ellipses were formed on the oscilloscope screen for depths of current modulation not exceeding fifty percent. The phase angle was measured as indicated in Fig. 4. The accuracy of the method is about $\pm 1°$ for small angles and $\pm 5°$ for angles in the vicinity of $\pm 90°$.

Figure 5 gives the results of phase-angle

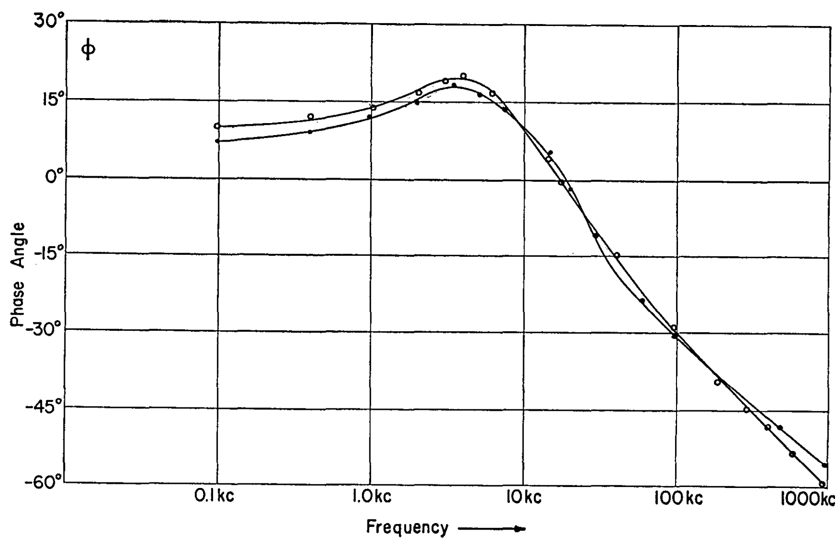

FIG. 5. Measured angle of lag of current behind potential plotted as a function of the modulation frequency.

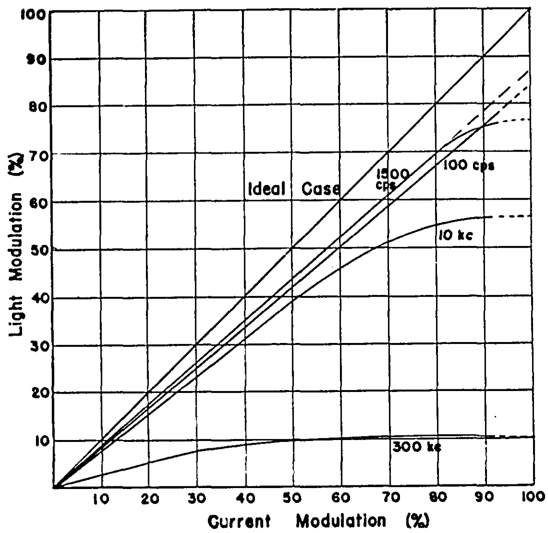

FIG. 6. Variation of observed percent light modulation with depth of current modulation at several frequencies.

measurements for two arcs. The potential wave leads the current wave by progressively increasing angles from 100 c.p.s. to about 3000 c.p.s. Beyond this point the angle decreases and passes through zero phase shift at 20 kc/sec. For frequencies above 20,000 c.p.s. the angle is negative and the a.c. arc current leads the potential by increasing amounts up to a value of $\theta = -55°$ at one megacycle.

Equivalent Reactance of the Arc

The results of potential-current phase-angle measurements indicate that the cesium arc may be thought of as a parallel combination of inductance, capacitance, and resistance which is resonant at 20.0 kilocycles. At frequencies below 20 kc/sec. it can be resolved into an equivalent electrical circuit consisting of a resistance in series with an inductance. When a variable resistor was placed in series with the modulated arc, it was found impossible at any frequency to obtain a 90° phase shift which would be produced if the arc resistance at any point were negative. Bridge measurements carried out in the audio-frequency range resulted in a mean value of resistance of the 5-amp. arc of +1.5 ohms, and an equivalent inductance of approximately $70 \cdot 10^{-6}$ henries. Such bridge measurements are not satisfactory, however, since the small amplitude a.c. currents used in the arms of the bridge produce negligible modulation in the arc, and hence do not reveal dynamic impedances characteristic of normal operation of the arc. The nature of the arc reactance at a modulating frequency of 1000 c.p.s. was indicated by shunting the arc with a condenser of capacitance equal to one micro farad. This caused the eccentricity of the ellipse to increase, showing that the discharge behaves inductively in this frequency region.

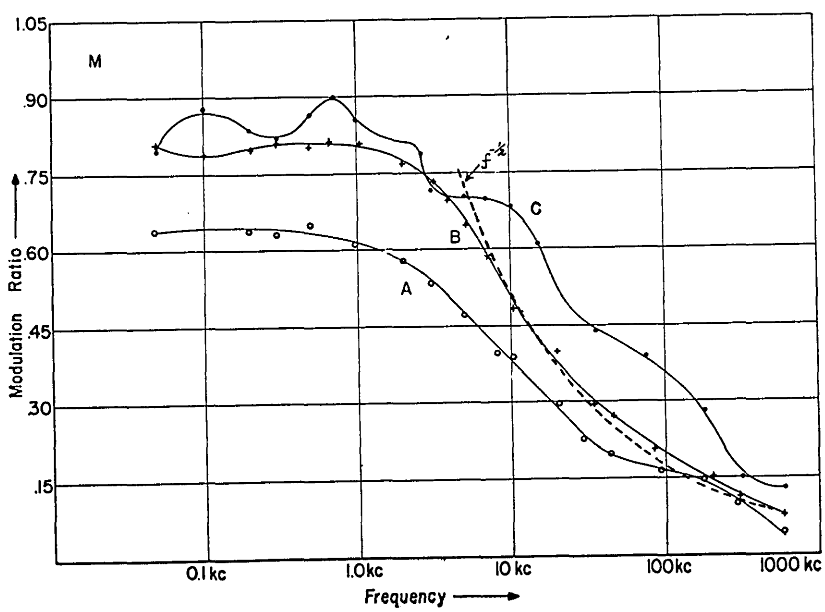

FIG. 7. Radiation-current modulation ratios for three lamps. The dashed curve in the case of lamp *B* shows how the ratio would vary if it is assumed that it is inversely proportional to the square root of the frequency.

IV. CHARACTERISTICS OF THE MODULATED RADIATION

Radiation-Current Modulation Ratio

Figure 6 shows measured values of percent modulation of the cesium resonance radiation plotted as a function of the depth of current modulation. The line having an inclination of 45° represents the ideal case for which the ratio M_L/M_I is unity. The parameter for these plots is the modulation frequency. For any frequency less than 10 kc/sec. the modulation ratio is constant for current modulations up to nearly 85 percent. As the modulation frequency is increased, however, the modulation ratios are constant over smaller and smaller ranges of values of percent current modulation.

Modulation ratios as defined in Eq. (3) were determined for a number of CL-2 lamps using a constant current depth of 50 percent. The results of these measurements are shown in Fig. 7. The irregular curve is typical of lamps which have been used for a hundred hours or more and in which most of the cesium has been lost through chemical reaction, probably at the bulb walls. In such lamps the glass walls became partially opaque and assumed a brownish color. The smooth curves are typical of normal lamps with clear bulbs in which an excess of cesium metal is always visible on the cooler portions of the inner tube.

The maximum modulation ratio for normal lamps is approximately 0.85, the curves being nearly constant at this value over the frequency range from 100 c.p.s. to 2 kc/sec. Beyond this region the light-modulation ratio decreases, varying approximately inversely as the square root of the frequency. This relation has also been found to hold at higher modulation frequencies for the high pressure mercury arcs studied by Mangold.[2] Mangold also found empirically that the frequency beyond which the modulation ratio was not constant was a function of the arc length, the "turnover point" occurring at lower frequencies for arcs having greater electrode distances.

Current-Radiation Phase Angle

An attempt was made to measure the phase angle between the a.c. component of the current in the modulated arc and the a.c. current output of the photo-tube multiplier, using the method described above for determining the potential-current phase angle. Figure 8 indicates typical oscillograms using this procedure. The traces are distorted ellipses from which no accurate calculations could be made. They indicate that the angle of lag of the light wave behind the current wave

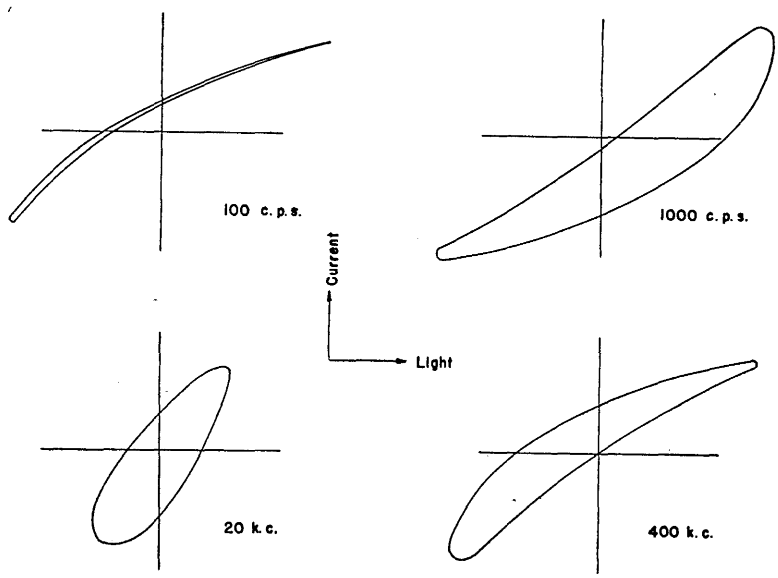

FIG. 8. Typical oscillograms obtained when the current and light waves are applied to the vertical and horizontal sweeps of the oscilloscope.

[2] H. Mangold, E. N. T. **17**, 57 (1940).

increases with frequency up to about 20 kc/sec. and then decreases for higher modulation frequencies.

The use of the electronic switch previously described to secure two separate signal traces on the oscilloscope screen, one representing current and the other representing the radiation as measured by the photo-tube current, is illustrated in the circuit arrangement shown in Fig. 3. By comparing the displacement of corresponding points on each trace to the length of the complete cycle, the phase shift is obtained directly.

Oscilloscope traces obtained at several frequencies are shown in Fig. 9. In general it was found that the phase displacement of the positive peaks of the two sine curves differed from the phase displacement of the negative peaks. Accordingly, the phase angle was recorded for both the positive and negative halves of the two waves representing current and light.

The measured phase angles are plotted in Fig. 10 as a function of the modulation frequency. These results refer to observations made at current modulations of 50 percent. At 100 c.p.s. the phase difference between light and current waves was zero for both peaks. Between 500 and 1000 c.p.s. the positive current peaks lead the positive light peaks by angles which vary from 1° to 9°, while there is a shift in the opposite direction of several degrees for the negative peaks. At frequencies from 2 to 5 kc/sec. both halves of the light wave show the same lag angle of about 20°. In the region between 5 kc/sec. and 600 kc/sec. both halves of the light wave lag behind the corresponding portions of the current wave, the positive peaks always by a greater angle than the negative peaks. Maximum angles of lag of 98° and 90° occur at a frequency of 30 kc/sec., and from there on both lag angles decrease with increase of modulation frequency.

DISCUSSION

In all of the arcs studied it was observed that at approximately 5 kc/sec. an unstable shifting of the luminosity of the arc column occurred, such as might have been produced if a standing sound wave were present. Again at about twice this frequency a bowing up and shifting of the arc column appeared. It is believed that oscillations of the arc plasma may have been excited in this frequency region, and that anomalous changes in the shape of the light wave due to this complication may explain the peculiar shift of the wave peaks and merging of the positive and negative phase angles observed between 2 kilocycles and 10 kilocycles (Fig. 10).

Weizel, Rompe, and Schulz[3] predict an increase in phase angle between current and temperature

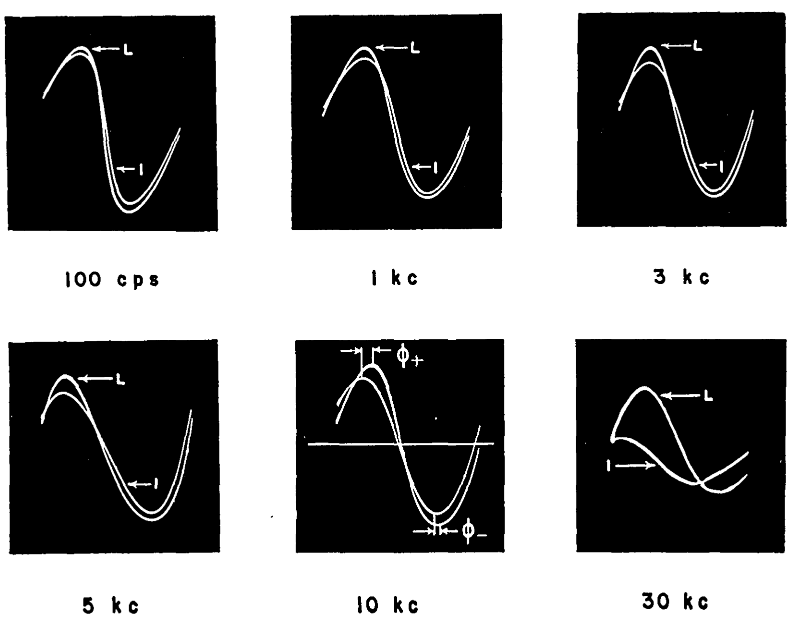

FIG. 9. Photographs of oscilloscope traces of superimposed current and light waves for several modulation frequencies.

[3] W. Weizel, R. Rompe, and P. Shulz, Zeits. f. Physik **117**, 545 (1941); **119**, 237 (1942).

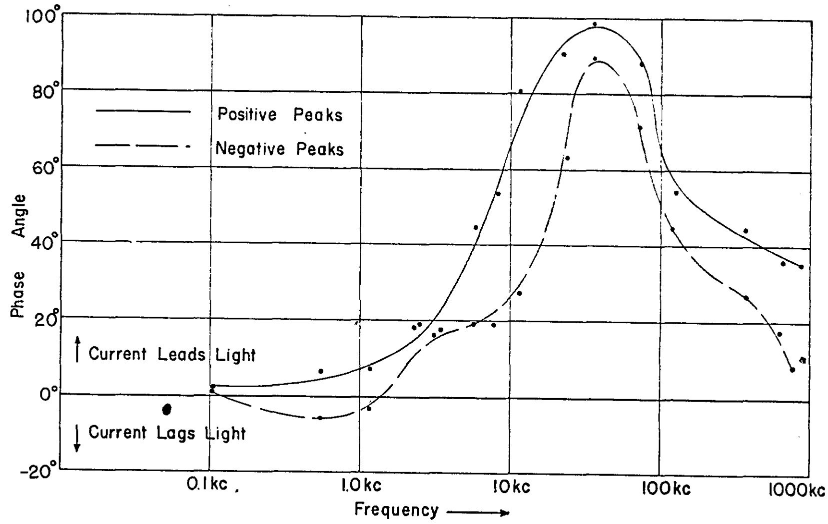

FIG. 10. Variation of the phase angle between current and light waves for both positive and negative peaks.

waves with increasing frequency, the shift approaching $\pi/2$ at high frequencies. Mangold[2] observed phase shifts between current and light waves in the case of a convection stabilized mercury arc discharge and found that the lag angle increased to a value of about $\pi/2$ at $f=10^5$ c.p.s., the highest frequency used. No decrease in angle with frequency was noted, and no separation was made of the shifts corresponding to positive and negative wave peaks. If, as should be the case at the lower frequencies, thermal excitation of radiation is the predominant mechanism, increase of phase lag with frequency is to be expected. Also, because of thermal hysteresis effects, the lag should be greater for the positive half of the cycle than for the negative half, and the light wave should be distorted, the maxima somewhat pointed and the minima (or negative halves of the wave) flattened. Indications of such distortions are clearly evident in the radiation-wave forms of Fig. 9.

Above a certain frequency the amplitude of the cyclic temperature variations becomes very small and the production of modulated radiation depends chiefly on excitation by the impressed high frequency field. For this method of excitation the phase angle between current and radiation waves will now depend on a lag which is determined by collision processes between electrons and atoms in an alternating field. A theoretical study of the excitation processes in the modulated arc is contemplated.