A TRAVELING-WAVE ELECTRON DEFLECTION SYSTEM

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Summary

Several types of traveling-wave electron deflection structures that can be used in microwave oscillographs are described and compared. An interaction structure consisting of a folded wire over a plane is considered in detail, both theoretically and experimentally. A general analysis of the interaction of electrons with sinusoidally varying transverse electric fields is presented and is applied to traveling-wave deflection systems. This analysis gives quantitative information about the interdependence of deflection and drift space lengths, beam velocities, frequencies, and phase velocities along the structure. Limitations on the design and performance of traveling-wave deflection systems can be determined from this analysis.

Introduction

The utility of a relatively simple oscillograph with high sensitivity extending from dc into the microwave region can be appreciated by workers in many fields. In this paper the limitations imposed by conventional oscillographs are examined, in order to find the best solution for a given application. This examination shows that the traveling-wave type of electron deflection structure is one which offers great promise for a broad band, high sensitivity oscillograph. Sensitivity, frequency response (or transient response), useful field area, and writing speed are of primary interest in high-speed oscillography. When comparing oscillographs, all these factors, with the exception of frequency response, should be expressed in terms of trace widths on the fluorescent screen or film, since the trace width limits the amount of information which can be conveyed by a given picture. Thus, reducing the trace width by half would yield as much additional detail as increasing the deflection sensitivity by a factor of two, as long as this detail is within the frequency bandwidth of the deflection system. Actually, this "miniaturization" of the electron beam as well as of the deflecting structures is one of the principal methods used to extend the frequency range of all types of oscillographs. It does, however, often necessitate the use of optical or photographic magnification to produce an image of conventional size.

Writing Speed

The writing speed of an oscillograph, that is, the maximum rate at which the beam may travel across the screen and still leave a permanent record on a photographic film, is important for the observation of non-repetitive transients. Aside from purely photographic techniques and phosphor selection, high writing speeds may be achieved by using high beam energies. These energies are obtained by increasing the beam current, which in turn increases the trace width, or by increasing the beam velocity at the screen. It should be remarked that high writing speeds are not required for the observation of repetitive phenomena; in fact they may be deleterious, since deflection sensitivity is almost invariably sacrificed to obtain the high writing speed.

Bandwidth

The bandwidth of conventional oscilloscopes is normally limited by the associated amplifiers which, in the present state of the art, must be eliminated if the frequency range is to be extended into the microwave region. In the usual parallel plate deflection system, if no amplifiers are used, the frequency may be increased from dc until the transit time, or length of time that it takes the electrons to pass between the parallel plates, becomes an appreciable fraction of a cycle before a loss in deflection sensitivity occurs. This loss in sensitivity, called "transit time distortion of the first kind" in the literature, can be analyzed exactly, if purely transverse fields are assumed and edge effects are neglected. For the very long deflection structures considered later, these approximations are very well justified. The result of this analysis expressed[1,2] as the ratio of the deflection, A, occurring for a radian frequency, ω , divided by the deflection, A_0 for $\omega = 0$, is given by

$$A/A_0 = \frac{2\sqrt{2}}{1 + 2\frac{\tau}{T}} \left[\frac{1 - \cos \omega T \sin \quad t + \frac{\omega^2 T^2}{2}}{\omega^4 T^4} \quad \frac{1}{2}\frac{\tau}{T}\left(1 + \frac{\tau}{T}\right) \frac{\sin^2 \frac{\omega T}{2}}{\left(\frac{\omega T}{2}\right)^2} \right]^{1/2}, \qquad (1)$$

where T = transit time between deflecting plates

τ = transit time in drift space.

This expression is plotted vs ωT in Fig. 1, for various values of the parameter, τ/T, corresponding to various ratios of the drift space length to the deflection space length. Note that for a very short deflection space compared to drift space, as in conventional oscilloscope tubes, the response is the familiar

$$\frac{\sin\left(\frac{\omega T}{2}\right)}{\left(\frac{\omega T}{2}\right)} \text{ type of variation.}$$

There are two obvious ways of reducing the transit time of the electrons: 1) by increasing the beam velocity, and 2) by decreasing the size of the deflection plates. Unfortunately, sensitivity is sacrificed with either method. This direct approach has been carried about as far as is practical by Gordon M. Lee of Central Research Laboratories.[3] His "Micro-Oscillograph" uses deflection plates only two-tenths of an inch long, and a beam velocity of 50,000 v giving a frequency response which is down only 4 per cent at 3,000 mc with a deflection factor of 5 v per trace width.

[1] H. E. Hollmann, "The dynamic sensitivity and calibration of cathode-ray oscilloscopes at very-high frequencies," Proc. I.R.E., vol.38, no.1, pp.32-36; January 1950.

[2] R. C. Honey, "A traveling-wave electron deflection system, Tech. Report No. 63, Electronics Research Laboratory, Stanford University, California; May 1, 1953.

[3] G. M. Lee, "A three-beam oscillograph for recording at frequencies up to 10,000 megacycles," Proc. I.R.E., vol.34, no.3, pp.121W-127W; March 1946.

It should also be pointed out that there are ways of actually utilizing the transit time distortion occurring in one set of deflection plates — termed the inversion spectrum method by Hollmann.[4] In addition, if the same signal is applied to both the horizontal and vertical deflection plates, the transit time occurring between the two sets gives rise to "transit time distortion of the second kind," which may be utilized by the analysis of the resulting "ultradynamic Lissajous figures." However, if the applied waveform is at all complex, the interpretation of these patterns becomes very difficult, and is at best a last resort which may be applied to almost any type of tube after all else fails.

Sensitivity and Traveling-Wave Deflection Systems

The factors discussed thus far, i.e. writing speed and bandwidth, are increased only at the expense of sensitivity in the usual parallel plate deflection system. However, by using a slow-wave deflection structure that propagates a wave with the same velocity as the electron beam, the sensitivity may be very greatly increased for the same amount of transit-time distortion. The operation of these systems is similar to that of a conventional traveling-wave tube, except that the transverse rather than the longitudinal electric fields are utilized. Thus, an electron traveling along the structure with exactly the same velocity as the wave will always see the same phase of the wave, and its deflection will hence be independent of frequency as long as the phase velocity of the wave along the structure is independent of frequency. The bandwidth of such a deflection system would be limited only by the bandwidth of the transmission structure, and the sensitivity could be made as large as necessary by merely making the structure longer, keeping physical and electron-optical limitations in mind. Since the structure can be matched, an additional advantage arises from the fact that it may be inserted in series with a transmission line to monitor a signal.

The idea of utilizing this cumulative type of deflection by retarding the wave velocity is far from new. Haeff,[5] in 1936, patented several types of such deflection systems, principally variations of the helix. More recently, Pierce[6,7] has built a traveling-wave oscilloscope tube which operates up to approximately 1000 mc.

The Kobe Kogyo Corporation in Japan has made a number of traveling-wave oscilloscope tubes (UG-120-T) of a type described in a recent technical journal,[8] which use a balanced zig-zag line deflection structure. And G. M. Lee's micro-oscillograph has been altered to incorporate a disc-loaded coaxial line as a slow-wave deflection structure to increase the bandwidth to 10,000 mc and the sensitivity to 0.2 v per trace width.

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[4] H. E. Hollmann, "Ultra-high-frequency oscillography," Proc. I.R.E., vol.28, pp.213-219; May 1940.

[5] A. V. Haeff, U. S. Patent No. 2,064,469; December 15, 1936.

[6] J. R. Pierce, "Traveling-wave oscilloscope," Electronics, vol.22, pp.97-99; November 1949.

[7] J. R. Pierce, U. S. Patent No. 2,535,317; December 26, 1950.

[8] K. Owaki, S. Terahata, T. Hada and T. Nakamura, "The traveling-wave cathode-ray tube," Proc. I.R.E., vol.38, pp.1172-1180; October 1950.

A tube developed at the Naval Research Laboratory[9] is an excellent example of an oscillograph which uses a traveling-wave deflection system designed for high writing speeds. It uses slightly flattened, shielded strip helices for deflection structures and has a total beam velocity, including post-acceleration, of 35,000 v.

Theory of Traveling-Wave Deflection Systems

Before one can compare the many possible types of deflection systems, it is necessary to determine the limits on the length and bandwidth of a traveling-wave deflection system which are imposed when the phase velocity varies with frequency. To do this, the analysis which yielded the curves of Fig. 1 can be very simply generalized so that the transit time, ωT, for the parallel plate case becomes the angular phase difference as seen by the electron as it progresses down the structure, and hence is a function of the difference between the wave and electron velocities. Thus:

$$\omega = 2\pi \frac{v_p - w}{\lambda_g} \tag{2}$$

where w = electron velocity

v_p = phase velocity of wave

λ_g = wavelength along structure.

To illustrate some of the many consequences of this generalization, it has been applied to a particular slow-wave structure whose experimentally measured phase velocity is known as a function of frequency (curve I in Fig. 2). The analysis reveals that the first deflection minima on either side of the measured curve, corresponding to relative transit times of $\pm$ 1 cycle, lie along the two dashed curves IV and V in the figure. The actual position of these curves depends, of course, on the length of the deflection structure. The longer the structure, the closer they will approach the measured characteristic. The curves shown apply to a dispersive deflection structure about 9 inches in length.

A further extension of the theory determines the beam voltage for which the maximum deflection occurs at a given frequency. It is physically reasonable that a curve of this beam voltage vs frequency will be a function of the length of the structure and will not coincide with the phase velocity curve except at the higher frequencies. Thus, at high frequencies, where the deflection structure is many wavelengths long, the electrons must stay very closely in phase with the wave in order to experience the maximum deflection. At lower frequencies, however, the optimum beam velocity departs from this until, in the limit of dc, the lower the velocity the greater the deflection. This behavior may be analyzed by inserting Eq. (2) into the general expression for the deflection, A, noting that $T = \ell/u$ where ℓ = length of deflection structure and setting

[9] S. T. Smith, R. V. Talbot and C. H. Smith, Jr., "Cathode-ray tube for recording high-speed transients," Proc. I.R.E., vol.40, no.3, pp.297-302; March 1952.

$$\frac{\partial A}{\partial w} = 0 \tag{3}$$

The resultant equation is then solved for the zero drift space case:

$$\frac{V_p}{W} = 8\left(\frac{\frac{\omega T}{2}}{\sin\frac{\omega T}{2}}\right)^2 \frac{1 - \cos\omega T - \omega T \sin\omega T + \frac{\omega^2 T^2}{2}}{\omega^4 T^4} \tag{4}$$

and for the long drift space case:

$$\frac{W}{V_p} = \frac{1}{2}\left(1 + \frac{\omega T}{2}\cos\frac{\omega T}{2}\right). \tag{5}$$

Equations (4) or (5) along with (2) and any given phase velocity curve are adequate for determining this optimum beam velocity, w, as a function of frequency. This has been done for the structure of Fig. 2, yielding curve II for the long drift space case and curve III for the zero drift space case.

The theory may also be used to determine the effects of mismatched output terminals since the reflected waves simply correspond to waves whose velocity differs greatly from the electron velocity, that is large values of ωT.

The analysis has been applied to a very dispersive structure in Fig. 2 since the dispersion is the factor which limits both the bandwidth and the length of the structure for broadband oscillographic applications. However, it is worthwhile to note that such a dispersive structure may have application as a spectrum analyzer since, for a given beam voltage, only a particular narrow band of frequencies will produce a deflection of the spot. Thus, for a beam voltage of 500 v in the example of Fig. 2, there is a sharp peak in the frequency response at 1400 mc.

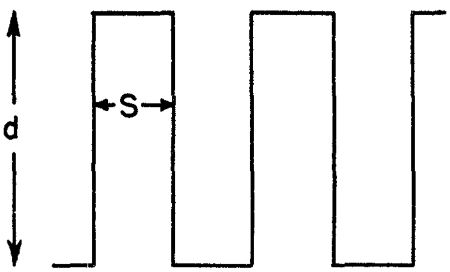
Phase Velocity Measurements on Zig-Zag Line

The experimental phases of this work were limited to a detailed investigation of a single type of slow-wave structure, namely a round wire folded back repeatedly upon itself and supported over a conducting plane. Actually, this structure is similar to that employed in the Kobe Kogyo tube mentioned earlier except that the unbalanced configuration is better adapted for use with conventional coaxial transmission lines. Furthermore, the line-over-plane structure avoids the possibility of a higher order mode propagating along the line-over-line structure whose longitudinal electric field components are not zero along the plane of symmetry dividing the two zig-zag lines.

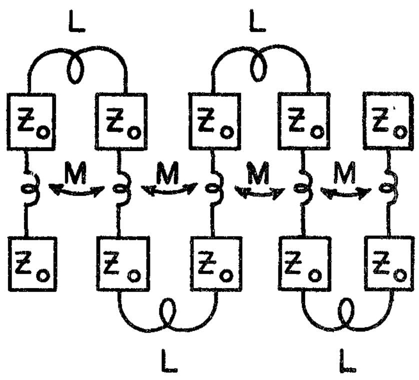
Fig. 3 shows a sample zig-zag line wound on adjustable polystyrene supporting frames. With this arrangement, a large amount of experimental data were accumulated which showed the effects of changing the various line parameters on the phase velocity characteristic of the line. A sample of the data is shown in Fig. 4 in which v_p/u is plotted as a function of frequency for a given line whose height over the plane is the only parameter which was varied. As before v_p represents the phase velocity of the wave, and u represents the geometrical velocity or the net longitudinal velocity a wave would have if it followed exactly the path of the wire with the velocity of light. As might be expected, the closer the line is placed to the plane, the less dispersive it becomes.

Theory of Zig-Zag Line Slow-Wave Structure

In order to develop a better understanding of the factors which influence the dispersive characteristics of the line, an equivalent circuit was employed, using sections of wire-over-plane transmission line inductively loaded at intervals corresponding to the bends, with mutual coupling between adjacent sections.



ZIG-ZAG LINE



EQUIVALENT CIRCUIT

The various parameters, Zo, M, and L, were calculated approximately, from standard handbook formulas[10] for a line over a plane, though some adjustment was required to obtain a good fit on the experimental curves. (Fig. 2.) The final agreement is quite good except where the structure approaches cutoff and the assumption of lumped perturbations breaks down. The principal purpose of the equivalent circuit was to predict the effects on the phase velocity characteristic of varying one parameter alone, not necessarily to obtain exact agreement with predetermined values of the parameters. For instance, a broad ridge along the center of the ground plane should decrease M and leave L unaffected, resulting in a less dispersive characteristic. This has been checked experimentally.

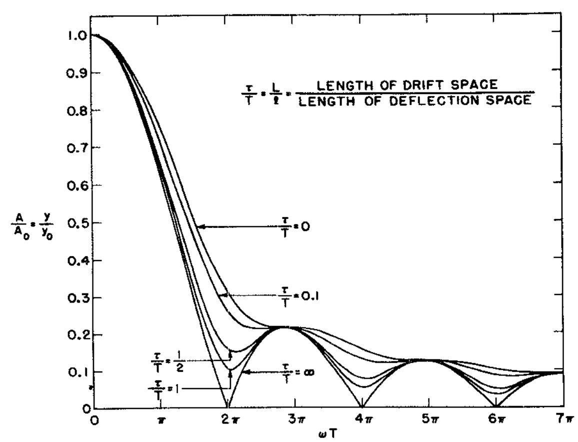
[10] Compare F. E. Terman, "Radio Engineers' Handbook," McGraw-Hill Book Co., Inc., New York, N. Y., pp.51-53, 174; 1953.

Performance of Zig-Zag Line Oscillograph

A dispersive zig-zag line similar to the one whose characteristics have been shown in Figs. 2 and 5 was wound on Teflon forms and enclosed in a section of 10 cm waveguide for use on a continuously pumped vacuum system. Fig. 6 shows the entire tube complete with the electron gun from a 5CP series cathode ray tube, removable drift space, and fluorescent screen. The large amount of experimental data accumulated on this tube confirmed in all details the extension of the theory mentioned earlier. The tube exhibited deflection minima and maxima very close to those predicted theoretically (Curves II to V in Fig. 2). The measured deflection sensitivity when operating along the phase velocity Curve I was almost exactly that which would be predicted for a parallel plate deflection system of the same length operating at dc. This measured deflection at dc is shown in Fig. 7, along with a theoretical curve which does treat the deflection structure as a flat plate. The deflection, when expressed in terms of input power, depends of course on the impedance of the line which in this case was several hundred ohms. Thus, deflections of 1 mm were obtained for 25 μw input power from dc to about 500 mc at 1800 v. Since this particular structure was quite dispersive, the sensitivity increased as the beam voltage was lowered and the frequency increased, until at 1500 mc and 500 v, a deflection of 1 mm was obtained for 8 μw input power.

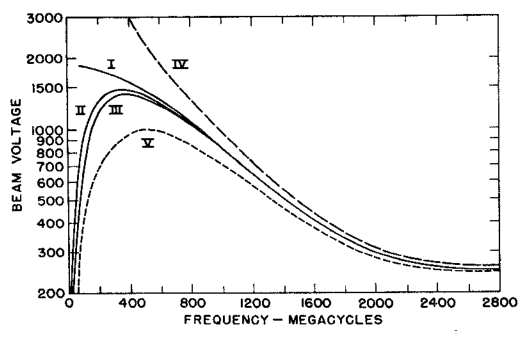
Conclusions

The extensions of the usual parallel plate deflection theory to cover traveling-wave deflection systems have been shown to be valid, the limitations on the bandwidth and sensitivity of such systems being evaluated in terms of this theory. The zig-zag line structure may be made relatively non-dispersive by suitable geometry, although the structure itself is considerably more dispersive than the shielded helix for the same line-to-shield spacing and turn-to-turn spacing.



RATIO OF DYNAMIC TO STATIC DEFLECTION FOR VARIOUS DRIFT SPACES

Fig. 1



CHARACTERISTICS OF A DISPERSIVE ZIG-ZAG LINE DEFLECTION STRUCTURE

Fig. 2

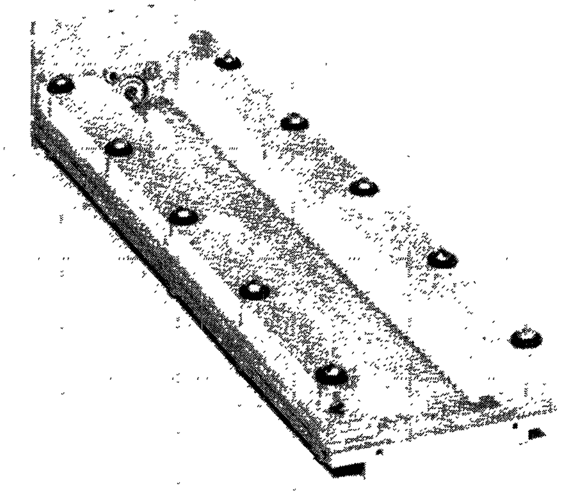


Fig. 3 - Structure for measuring phase-velocity of zig-zag lines.

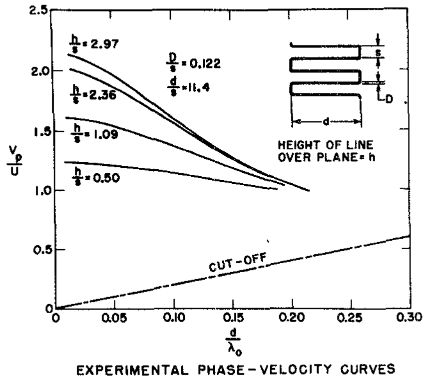


Fig. 4

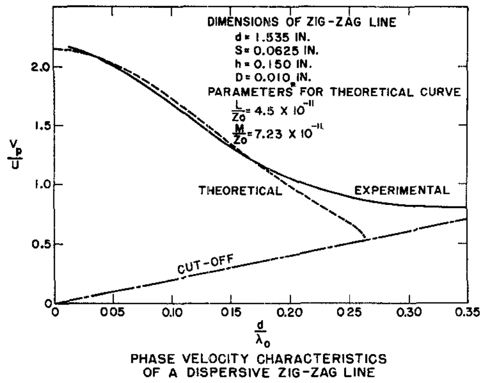


Fig. 5

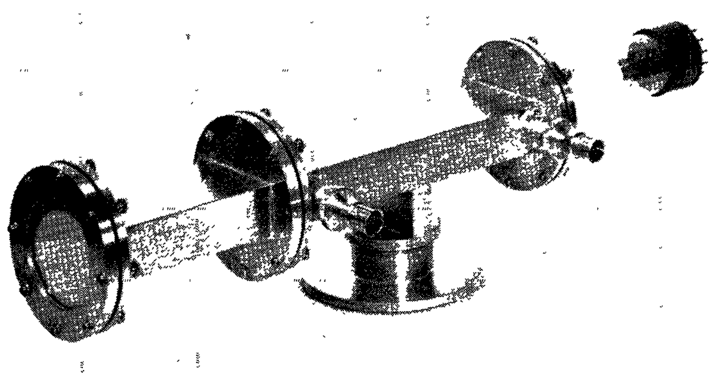


Fig. 6 - Oscillograph for testing deflection structure.

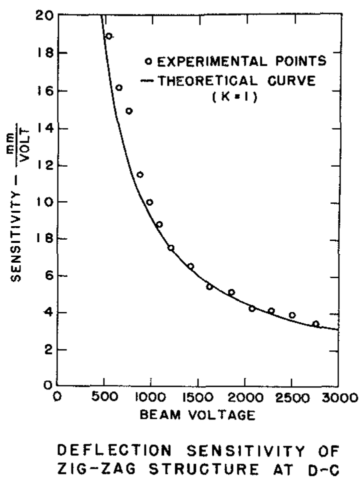


Fig. 7