Measurement Techniques for Multimode Waveguides

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Summary—**This paper surveys some of the techniques that have been worked out for multimode waveguide measurements. Equipment has been developed for measuring one mode at a time by taking advantage of the differences between the modes. Illustrations of its use are given.**

MULTIMODE waveguides are beginning to find applications in the communications art for a number of reasons. They are able to carry wider bands with less loss and delay distortion than single dominant mode rectangular waveguides, and they can transmit more than one simultaneous channel in the same pipe using the same frequency band. Because of their promising future, quite a little work has been carried out to develop their potentialities. This work, as well as the commercial use of multimode lines, has required new measurement techniques to be added to those previously in use. Sometimes these new techniques are modifications of older methods, but often new methods have been worked out. This paper gives a survey of some of them. These techniques are taken from various sources, and represent the contributions of many workers in this field.

Measurements of loss, attenuation, or Q factor are usually required for each mode of interest. Impedance and voltage standing-wave ratio measurements may be made also, but usually they are not as important in multimode work. In single mode guides, imperfections give rise to an impedance change and a reflected wave which is easily detected by such measurements. In multimode guides, however, such imperfections also cause another effect, since the perturbed energy, instead of going both ways in the dominant mode, may go forward in other modes, leaving very little energy traveling back toward the source to cause standing waves. This means that techniques to measure mode conversion as to amount and source location, are important in multimode work.

This points up another one of the important aspects of multimode measurements. It is necessary to measure the magnitude of the power in any particular mode, independently of the power in any of the others that may be present, even though there may be more power in the other modes. It is, therefore, necessary to separate the mode responses so that any mode can be measured by itself. This is done by taking advantage of all the differences that exist between the modes, both singly and in combinations.

One of the differences between the modes is that of electric and magnetic field configurations. Multimode measuring equipment often uses probes, loops, or iris holes to give a response depending on particular field components in the guide. A familiarity with the characteristics of such devices, and of the field configurations for the various modes, is all that is necessary for their effective use. They rarely respond to a single mode, but usually to groups of modes having field components in common. Their employment is quite important in measuring techniques, and they will be noted in many of the examples in this discussion. These devices are sometimes made movable, either radially, axially or, more often, circumferentially, in order to explore the field distribution within a guide, and to learn something about the amount and kind of modes that are present.

Another way of coupling to a particular mode using field configuration differences is by the use of transducers at the ends of the waveguide being measured. Transducers have been designed to convert most of the modes of interest in round waveguide into the dominant mode in small rectangular guide. The simplest example of such a transducer is the gradual taper from the round cross section to the rectangular cross section. This provides broadband, low-loss coupling between the TE_{11} dominant mode in the circular guide and the TE_{10} dominant mode in the small rectangular guide. The round guide can, of course, support any polarization of the TE_{11} mode. For this type of transducer the polarization depends upon the position of the axis parallel to the short side of the rectangular guide. In making measurements, or in using such guides, the transducer is often rotated to couple to any polarization. Any two perpendicular polarizations can, for most purposes, be considered as two independent modes. Since energy can be transmitted simultaneously in the same frequency band in each one of them, transducers have been developed to exploit this fact. They make possible the radio repeater antenna-to-equipment round waveguides using perpendicular polarizations now proposed for transmitting and receiving at the same time through a single antenna,[1] or the use of a single antenna for simultaneous operation with two frequency channels in the same direction.

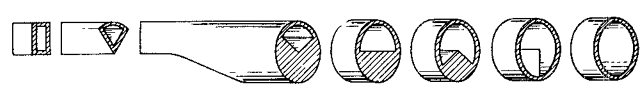

Fig. 1—TE_{10} rectangular—TE_{01} round transducer.

Another important example is the circular electric TE_{01} round to TE_{10} rectangular transducer,[2–3] illustrated in Fig. 1. Here the field configuration in one guide

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[1] A. P. King, "Dominant wave transmission characteristics of a multimode round waveguide," Proc. IRE, vol. 40, pp. 966-969; August, 1952.

[2] S. E. Miller and A. C. Beck, "Low-loss waveguide transmission," Proc. IRE, vol. 41, pp. 348-358; March, 1953.

[3] S. E. Miller, "Waveguide as a communication medium." *Bell Sys. Tech. Jour.*, vol. 33, pp. 1209-1265; November, 1954.

is forced into that desired in the other guide by shaping the walls in the proper way from one cross section to the other, always taking advantage of the fact that substantially only electric field components perpendicular to a good conducting surface can exist. Field configuration type transducers are in use for a number of lower order modes having relatively simple field distributions in both rectangular and round guides.

Another important difference between the modes is the value of their attenuation coefficients. This difference is used to get rid of some modes and leave the ones having the least loss for any particular system. A simple illustration of this is the method used for measuring the loss in round waveguide which carries the TE_{01} circular electric mode.[2–3] Fig. 2 shows the equipment arrangement. In this test, short bursts of rf energy approximately 1/10 of a microsecond in duration are injected into the line at intervals of 300 microseconds. Except for two small irises through which to couple the transmitter and the receiver, the waveguide line is short-circuited at both ends. The injected 1/10 microsecond pulse occupies at any instant a space interval 100 feet long. Therefore, as the pulse travels from one end of the line to the other, between the short circuits, it produces, at the receiver coupling iris, a burst of energy at the instant when a pulse is passing the sending end, which is amplified, detected and placed as a vertical deflection on the oscilloscope. The horizontal deflection on the oscilloscope is a linear sweep having a duration of a few microseconds. In order to look at the received pulse after a selected number of trips back and forth down the line, a variable delay is placed between the trigger and the oscilloscope's horizontal deflection circuits. Fig. 3 is a photograph of the oscilloscope response in this case. The outgoing pulse leaking directly across between the iris holes is shown at the time $\Delta t=0$. During the interval between $\Delta t=0$ and 1, no response is seen because the pulse is traveling down to the far end of the line, which is 500 feet away, and back again. At time $\Delta t=1$, energy returns. It is coming back in a number of modes, so a complicated response is seen. In this case the pulse is so long that the modes are not separated, and in the interval between $\Delta t=1$ and $\Delta t=2$, there are many modes returning and overlapping but as time progresses down to Δt equal to about 8 or 10, almost all modes have died out except one, which appears at regular intervals with a smoothly decaying amplitude. This one is the TE_{01} circular electric mode which has the least loss in this waveguide. The slope of its decay can be measured, in this region, over quite a long distance, and thus the attenuation of this mode in the line can be determined. In this case, it is about 3 db per mile.

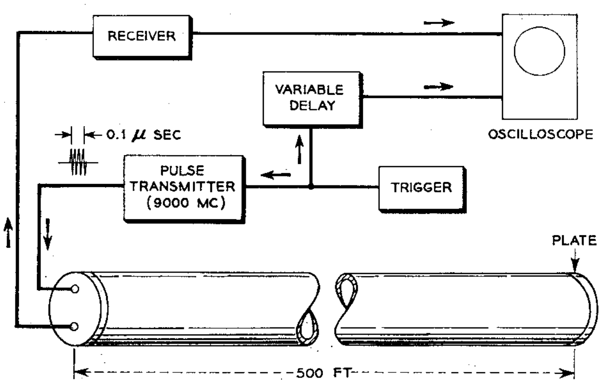

Fig. 2—Diagram of equipment used for pulse transmission tests in a multimode guide. This separates low-loss modes from high-loss modes.

Mode filters which selectively attenuate certain modes while passing others provide an important tool in multimode measurement procedures, and will no doubt find many applications in the commercial use of multimode waveguides.[2–3] Some of these filters are made by putting sheets of resistive material along the electric field lines of modes we desire to attenuate. Fig. 4 (below) is a photograph of mode filters designed to attenuate all modes except the circular electric ones in round waveguides. Here resistive sheets are located radially in the waveguide. They are at all times perpendicular to

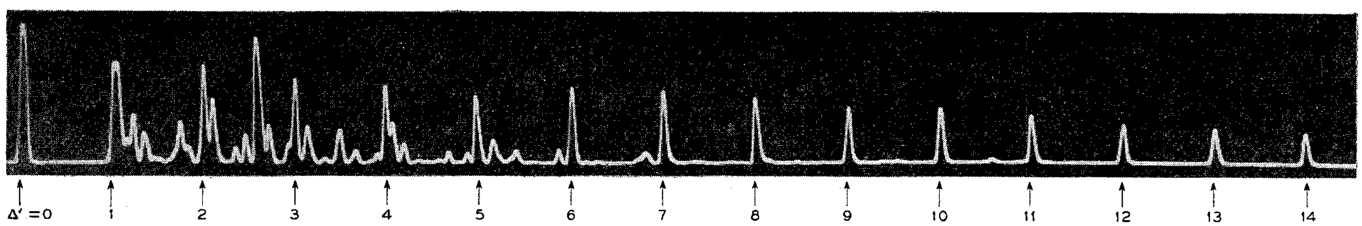

Fig. 3—Oscilloscope trace obtained when using the equipment of Fig. 2.

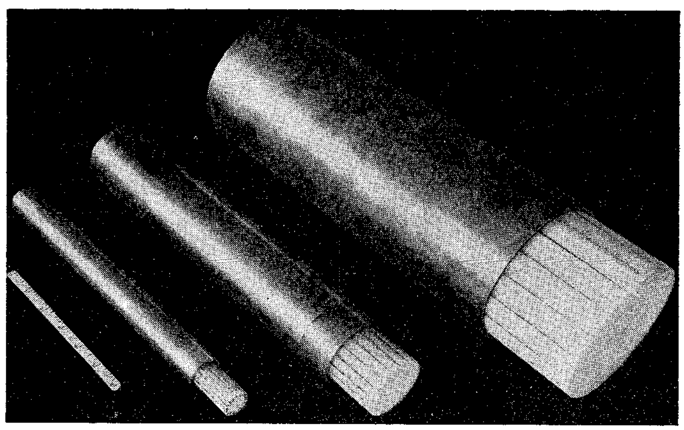

Fig. 4—Mode filters which attenuate all modes except the circular electric TE_{om} family.

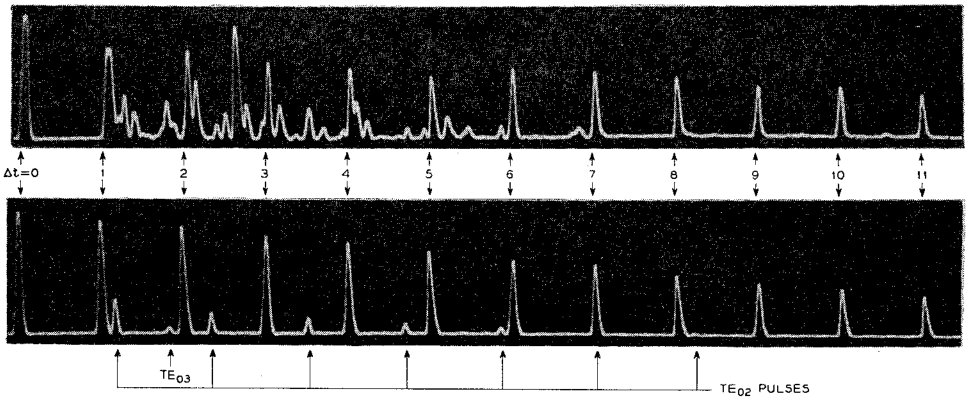

Fig. 5—The effect of a mode filter like those shown in Fig. 4 on transmission in a 500-foot waveguide. The upper trace is like Fig. 3 for which no filter was used. The lower trace was obtained with the filter in the guide. The unlabeled pulses in the lower trace are in the TE_{01} mode.

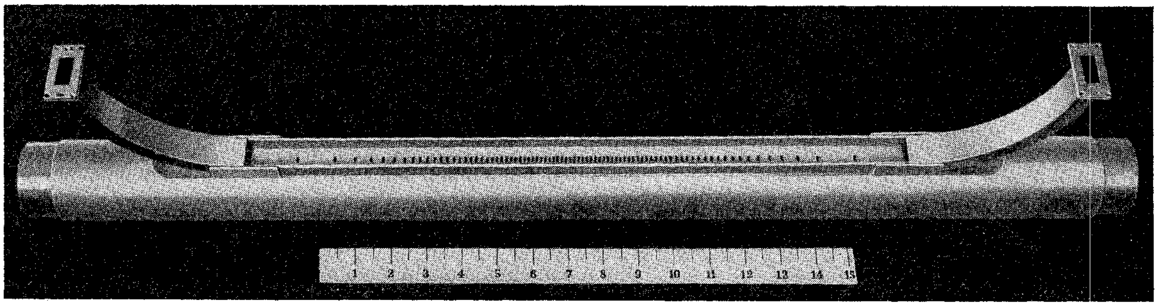

Fig. 6—A coupled-wave transducer. The top plate is removed to show the coupling holes.

the electric field of the circular electric waves, while all other modes have fields along the resistance path and are rapidly attenuated. We prefer absorbing filters of this type to ones made of metal sheets or wires along the field lines, which reflect the undesired mode energy backwards, where it may cause resonance or other troubles in the system.

The effect of such a filter in increasing the attenuation of most of the modes can be seen in Fig. 5. Here the upper oscilloscope trace is the same as the one just shown, where many modes are present, while in the lower photograph mode filters have been inserted in the multimode line. The highest pulses in this series are in the TE_{01} mode. There is a group of pulses shown in the TE_{02} mode and marked on the photograph. One pulse is seen in the TE_{03} mode. This shows how such filters greatly increase the attenuation differences and make possible many multimode measurements that otherwise would be difficult due to the presence of undesired modes. These filters can also be used to reduce signal distortion effects due to mode conversion and subsequent reconversion in long waveguides.[3]

Another useful difference between the modes is their different velocity of propagation, phase constant, or guide wavelength, all closely related phenomena. This difference formed the basis for the design of coupled wave transducers by Miller.[3-4] These are very important devices in multimode measurements and practical applications. It is important to be able to transform energy between a dominant mode rectangular guide and any one of the modes of the multimode guide without appreciable coupling to other modes.

Fig. 6 shows such a transducer, with the top plate of the rectangular waveguide removed to show the coupling holes. Two parallel transmission lines are coupled together over a length interval which typically could be one-half to twenty wavelengths long. The phase constant of the dominant mode rectangular line is made equal to the phase constant of the desired mode in the multimode line. Under these circumstances, the over-all power transfer which takes place is predominantly in the single mode of the multimode line, whose phase constant is matched by that of the dominant mode line. Energy in other modes of the multimode line passes by the coupling array without appreciable effect. In the single mode selected, this device may be made directional. The dominant mode rectangular waveguide may be oriented to accept either polarization of the field components in the round waveguide. In this way, by using a combination of phase constant differences between the modes, and field configuration differences between the modes, additional useful transducers may be obtained. For example, they may be made to couple to either the TE_{01} circular electric mode, or the TM_{11} mode, two modes which have the same phase constant in the round guide, by utilizing the polarization effect too, so that either one can be accepted with the exclusion of the other in the rectangular guide.

[4] S. E. Miller, "Coupled wave theory and waveguide applications," *Bell Sys. Tech. Jour.*, vol. 33, pp. 661–719; May, 1954.

An illustration of the use of transducers in making measurements of multimode line loss is shown in Fig. 7. In the measurements, cw power input to the line is used as a reference by closing the shorting switch shown on this figure, and the magnitude of the wave reflected back to the measuring set is observed. Then, the shorting switch is opened, and the energy allowed to propagate through either transducer, depending on which mode we wish to measure, down to the end of the line, back through the transducer again, and thence to the measuring set. The difference between these readings is twice the sum of transducer plus line loss, and by making a separate measurement of transducer loss, the line loss is determined.[2] In the case of low loss lines, the accuracy of such a measurement will not be very good unless quite a long line is available for test.

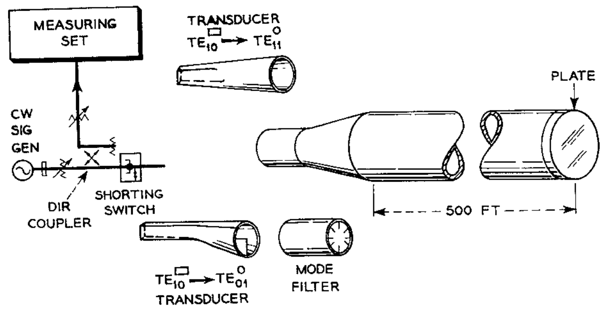

Fig. 7—Equipment layout for cw measurement of transmission loss for either of two modes in a multimode guide.

The difference in guide wavelength of the different modes is also utilized for a variety of resonant cavity measurements to determine waveguide attenuation. A section of guide is closed at both ends by short-circuiting pistons, one of which is made adjustable, usually with micrometer control. Iris coupling to the desired mode is arranged, either in the piston or in the side wall of the waveguide.[5-8] In one arrangement, due to W. A. Tyrrell, radar pulses several microseconds long are used. The guide length is adjusted to resonate the desired mode, and the decay or ringing time of the cavity is measured on an "*A*" scope presentation. After removing piston losses and coupling iris losses, the waveguide attenuation is found. *Q* factors in the order of half a million in multimode cavities are measured with this equipment.

The equipment developed to measure wire conductivity at 9,000 megacycles[9] is also used for resonant waveguide measurements of this type for *Q* values of a few hundred to about fifty thousand. In this method a cw oscillator is frequency modulated over a particular resonance of the desired mode, obtained by adjusting the movable piston, and the ratio of the peak frequency to the half-power bandwidth of the resonator measured with the aid of an oscillographic display of its amplitude vs frequency characteristic. This gives the loaded *Q* of the waveguide cavity being measured. The amplitude characteristic of the frequency modulated signal generator, on which a wavemeter marker appears, is viewed simultaneously and used as a reference. By correcting the result to obtain the unloaded *Q* of the resonant cavity alone, the effective waveguide loss is obtained for the mode for which resonance was set up.

A somewhat similar effect is observed when making transmission measurements in multimode lines over small bandwidths with an arrangement like that shown in Fig. 8. Here energy from a frequency modulated transmitter is sent into a waveguide through a TE_{01} transducer, mode filter, and taper, as shown at the left of this figure. Substantially all the energy is in the TE_{01} mode in the line. However, there is a little mode conversion to TE_{02}, at the taper, so a small amount of TE_{02} energy appears in the line too. This travels down to the receiving end of the waveguide. Here the line tapers down beyond cutoff for the TE_{02} mode, so the TE_{02} energy cannot get out, but is reflected as if by a piston and goes back to the sending end, together with a little more TE_{02} energy from mode conversion at this taper. Here again it finds a taper beyond cutoff, which acts like a piston, so the energy cannot get out here either. This means that the line section between the tapers acts like a short-circuited resonant cavity for all modes beyond cutoff in the small guides at the end. When the FM transmitter crosses a resonant frequency for a particular mode in this section of the line, there is a dip in the energy appearing in the desired mode at the receiver, since more energy is taken at resonance from the desired

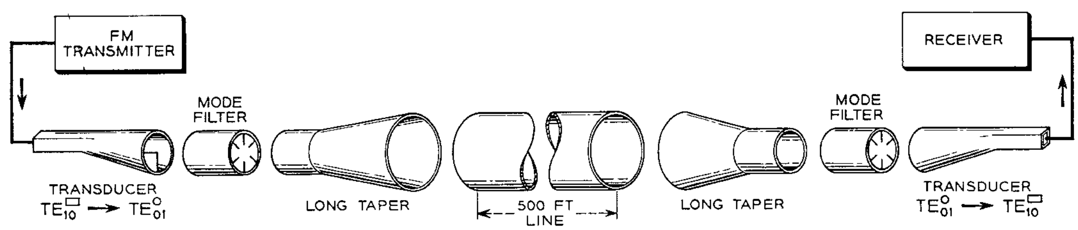

Fig. 8—Equipment arrangement for making transmission measurements in multimode guides with a frequency modulated transmitter.

[5] R. W. Lange, "Measurement of High *Q* Cavities at 10,000 Megacycles," AIEE Tech. Paper 47-23; December, 1946.

[6] I. G. Wilson, C. W. Schramm and J. P. Kinzer, "High *Q* resonant cavities for microwave testing," *Bell Sys. Tech. Jour.*, vol. 25, pp. 408–434; July, 1946.

[7] J. P. Kinzer and I. G. Wilson, "End plate and side wall currents in circular cylinder cavity resonators," *Bell Sys. Tech. Jour.*, vol. 26, pp. 31–79; January, 1947.

[8] J. P. Kinzer and I. G. Wilson, "Some results on cylindrical cavity resonators," *Bell Sys. Tech. Jour.*, vol. 26, pp. 410–445; July, 1947.

[9] A. C. Beck and R. W. Dawson, "Conductivity measurements at microwave frequencies," Proc. IRE, vol. 38, pp. 1181–1189; October, 1950.

mode to the mode that resonates. The scope photograph at the top of Fig. 9 shows the result. This is, in effect, a plot of receiver response vs frequency. Since it is a long line, there are many resonances, and the result is a rippled transmission curve. The fact that the trace is

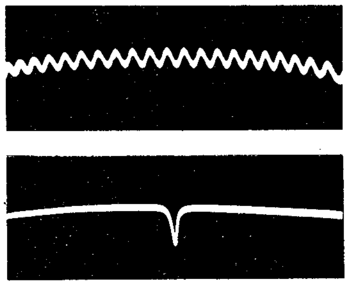

Fig. 9—Oscilloscope traces obtained with the arrangement of Fig. 8. The ripples in the upper trace are due to TE_{02} resonances. For the lower trace, the 500-foot line is omitted, and a single TE_{02} resonance dip is shown.

not straight, but is higher in the middle than at the ends, is due to the varying power output of the klystron used in the transmitter as it is modulated over this bandwidth. If there were other mode conversions in the waveguide so that other higher order modes could be generated, the pattern gets very ragged as the oscillator goes through many more resonances for the same frequency sweep. In this case there were no appreciable conversions except that to TE_{02}. In the lower photograph the 500-foot line has been omitted, the two tapers put directly end to end, and the frequency varied over a range which gave only one resonant TE_{02} absorption between the tapers. This of course looks the same as an ordinary wavemeter dip. Due to the resonance build up, this can be made a rather sensitive method of determining mode conversion in multimode lines.

Another testing method using the velocity of propagation difference to separate modes is illustrated in Fig. 10. If a pulse in two modes travels a sufficient dis-

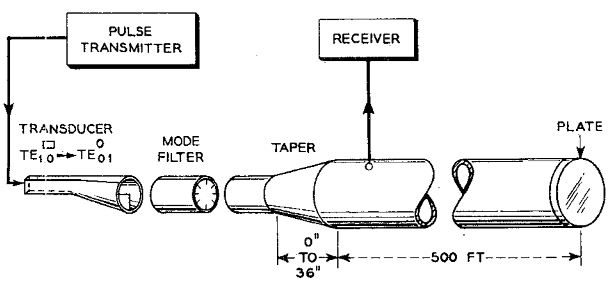

Fig. 10—Equipment layout for pulse measurement of mode conversion in a taper.

tance with different velocities, two separate pulses are observed, one for each mode. In the arrangement shown in this figure, a pulse is sent into the small line just to the left of the taper in the TE_{01} circular electric mode by using a good transducer and a mode filter. This line is then tapered up to a large 5-inch diameter multimode waveguide about 500 feet long. As mentioned before, the taper produces mode conversion from the TE_{01} circular electric mode to the TE_{02} circular electric mode. These two modes then travel down the 500-foot line to the plate at the end and return to the sending end after reflection. Here a small iris coupling hole is used to sample the energy in these modes and send it to a receiver with an oscilloscopic display. Fig. 11 shows photographs of the resulting trace. The transmitted pulse is seen at the left. After traveling approximately 1,000 feet down and back in this waveguide,

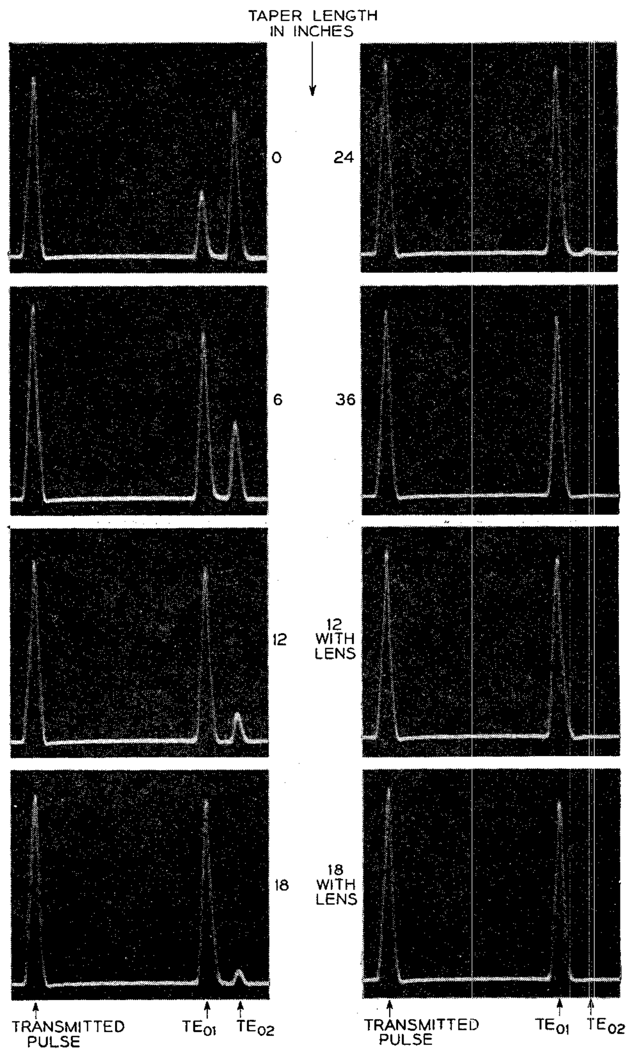

Fig. 11—Oscilloscope trace photographs showing observed effects of mode conversion in a taper, and the improvement when using a suitable lens.

these two modes have become well separated in time and appear as separate pulses. In the upper left-hand photo, where an abrupt zero length taper or transition from the 2-inch to the 5-inch line was used, there is more energy in the TE_{02} mode than in the TE_{01} mode. As the taper length is increased, there is less mode conversion, and the pulse in TE_{02} energy is seen to drop until with a 36-inch taper, which is shown as the second photograph on the right, it is scarcely observable at this receiver gain setting.

Mode conversion can be considered in terms of field distortion within the guide. In a taper, the path length along the axis is shorter than the path length near the guide wall. This causes the plane wavefront of a single circular mode to become a spherical wavefront, which can be analyzed as the sum of a number of circular modes. This suggests the use of a lens inside the guide to change the distorted field distribution back to that of a single mode. Special lenses to do this have been developed. The two lower photographs on the right of Fig. 11 show that such a lens can be used together with a shorter taper to give much less mode conversion than with the taper alone.

The difference in velocity of propagation of the different modes can be used to separate more than two modes. If a number of modes are present in one short pulse of energy at a given place in a waveguide, they will separate in time as they travel along the guide, and at some location further down the line a number of pulses will be observed, the number depending on the number of modes. This is illustrated in Fig. 12. Here a moderately long length of 3-inch diameter-round waveguide which will support 12 modes is used. One end is short-circuited. The sending end, however, is terminated to absorb all energy reaching this point.

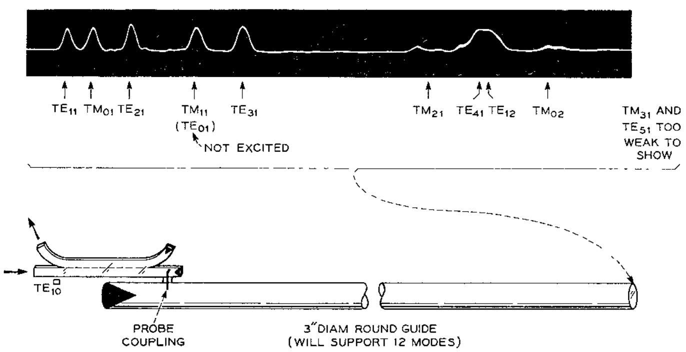

Fig. 12—Arrangement of equipment for showing the separation of modes on a time basis. The pulses in the photograph of the oscilloscope trace are all due to reflection from the piston. The outgoing pulse due to directional-coupler unbalance is not shown. The pulses are about six millimicroseconds long.

A directional coupler is used to send energy into this line through a short probe which excites most of the modes which can be supported in this guide. Short pulses[10] about 6 millimicroseconds long are sent into the directional coupler where the arrow is shown at the left-hand side of this diagram. This energy travels down the waveguide in the different modes to the piston at the far end, and is reflected back. At the time it returns to the sending end, the probe picks up these pulses and they are sent through the directional coupler to the receiver where the arrow is seen leaving the upper rectangular guide at the left. At the top is shown a picture of the oscilloscope trace of the returned energy, the outgoing pulse in this case being a considerable distance off the edge of the photograph to the left. It is seen that many pulses are received, although only one was sent in, and the modes to which the received pulses correspond are marked beneath them on this figure. This is a very useful method of separating modes for the purpose of making various multimode measurements. The explanation can be obtained from Fig. 13. The curves

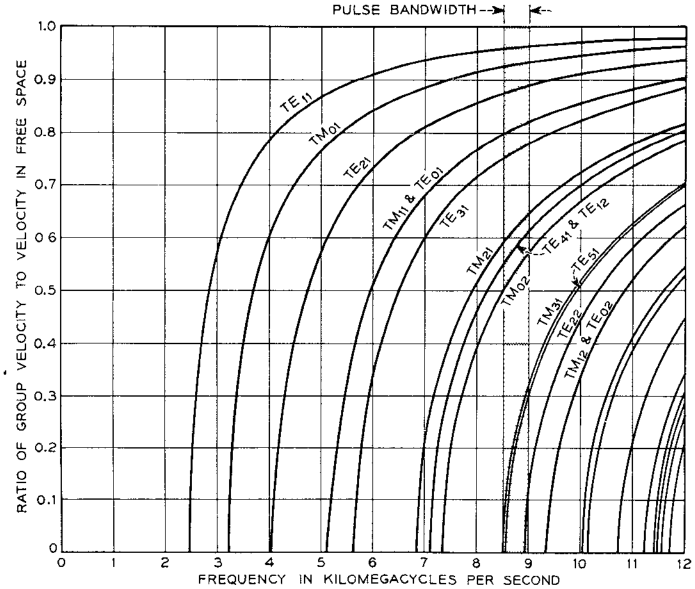

Fig. 13—Group velocity plotted against frequency for a 3-inch diameter waveguide.

shown here are plots of the ratio of group velocity to velocity in free space for the designated modes vs the frequency in kilomegacycles per second. At cutoff for any mode, the group velocity is zero, which is shown by the intersection of these mode curves with the zero axis of this plot. As the frequency is increased, the group velocity rises rapidly and then, of course, finally at infinite frequency reaches the asymptotic velocity of electromagnetic waves in free space. This short pulse has a bandwidth of about $\frac{1}{2}$ a kilomegacycle between $8\frac{1}{2}$ and 9 kilomegacycles, as shown by the shaded vertical bar on the figure. The TE_{11} mode has the highest group velocity at the pulse frequency, and the other modes have lower group velocities, as shown by the place where the curve for each one goes through the shaded area. If the spacing between the pulses on Fig. 12, from left to right, is compared with the spacing between the mode curves in the shaded area on Fig. 13, from top to bottom, it will be seen that they agree very closely. The broadening and distortion of the later pulses is due to delay distortion over the wide bandwidth used for this testing. This can be understood by noting that the TE_{11} curve at the top is reasonably flat across the pulse bandwidth shaded area, while for the modes somewhat further down, such as the TM_{21}, TE_{41}, TM_{02}, there is more change in group velocity across the bandwidth of the pulse. Since one

[10] A. C. Beck, "Microwave testing with millimicrosecond pulses," Trans. IRE, vol. MTT-2, no. 1; April, 1954.

edge of the pulse band has a different velocity than the other, the pulse is broadened and distorted as it travels along in the guide.

Another related testing procedure sometimes used in multimode work takes advantage of proximity to cutoff. While Fig. 13 shows the ratio of group velocity vs frequency for a fixed waveguide size, at a fixed frequency similar curves can be plotted against the diameter of the multimode guide. In some cases deliberate changes in diameter have been made to eliminate certain modes by placing them beyond cutoff in the smaller multimode guide, thus leaving the modes being measured free from interference with higher modes. When this is done, one must be careful to avoid resonances of the higher modes in the larger guide.

The mode velocity difference produces different phase or frequency shifts of a frequency modulated signal traveling in more than one mode. These shifts can be measured by comparing the received signals with the transmitted signal. The technique is similar to that used in radio altimeters for airplanes.[11]

Another example of mode conversion measurements made by using this velocity difference is shown in Fig. 14. Here the pulse is sent into the line through a good rectangular-to-TE_{01}-round transducer. Mode filters are used here to further purify the TE_{01} mode being sent into the waveguide. Just beyond this a TE_{21} coupled line transducer is installed in the guide. Connecting the receiver to see the return as shown by the arrow gives a response from the large waveguide for the TE_{21} mode only. Oval sections of waveguide cause a conversion from the TE_{01} mode to the TE_{21} mode. Consider first what would happen with the far end squeezed section alone, omitting the near end squeezed section from consideration. The TE_{01} mode energy now travels down the 250 feet of 3-inch diameter-round guide to the far end. At this point a short section of the guide has been purposely squeezed to form an oval cross section. Conversion now takes place from the TE_{01} mode to the TE_{21} mode. Both these modes travel back up the waveguide to the sending end. The group velocity of the TE_{21} mode is higher than the group velocity of the TE_{01} mode, so energy in these two modes separates, and if a receiver were used which responded to both, two pulses would appear, and there would be a time separation between the pulse in the TE_{21} mode and the pulse in the TE_{01} mode. In this case, since the receiver is connected to the line through the coupled line transducer which is only responsive to the TE_{21} mode, only one pulse is seen, due to this mode alone. This would be the center pulse in the figure at the top, so if the near end squeezed section were not present, only this one pulse would be seen at the receiver. It would be spaced away from the outgoing pulse a distance that corresponds in time to one trip of TE_{01} down to the far end and one trip of TE_{21} from the far end back to the receiver. Now consider what would happen if the near end squeezed section alone were present. When the TE_{01} wave passes this oval section which is right next to the coupled line transducer, conversion takes place, and the energy travels down the line in both the TE_{01} and the TE_{21} modes, going faster in group velocity in the TE_{21} mode. These two signals are reflected by the piston at the far end and return to the sending end. The TE_{21} signal comes through the coupled line transducer and appears as the pulse at the left of the photo shown. The TE_{01} energy has now lagged behind the TE_{21} energy, and when it gets back to the near end squeezed section, a second mode conversion takes place, and TE_{21} energy is produced which appears on the receiver. This is the right-hand pulse. When both oval sections are present, all three TE_{21} pulses occur, which was the case in the actual setup used to take this photograph. For a single oval place occurring at any point in the line, except at the far end, two pulses will appear on the scope. The spacing between these pulses represents the difference in group velocity from the point of the discontinuity down to the piston at the far end, and then back to the discontinuity. By making a measurement of pulse spacing, the location of the section causing the mode conversion can be determined. This same general type of measurement has been used for the analysis of a number of other kinds of mode conversion in waveguides by using different types of transducers at the ends.

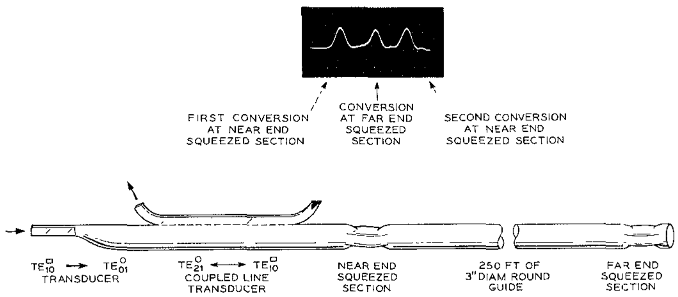

Fig. 14—Arrangement for measuring mode conversion from an oval section of guide, and resulting oscilloscope trace.

In this brief report, there is no attempt to fully cover the subject of multimode measuring techniques. There are numerous other types of multimode measurements that have been worked out for special cases. This is a new and complicated branch of the microwave art, and no doubt a great many more techniques will be needed as multimode guides find more uses. These illustrations show a few of the measurement methods that have met specific needs and, it is hoped, help indicate some of the ways to solve other problems as they arise. As in any other field, a thorough understanding of the basic physical fundamentals, and of the existing facilities enables the worker to design equipment to obtain the measurements he needs to solve the problems he meets.

[11] L. Espenschied and R. C. Newhouse, "A terrain clearance indicator," *Bell. Sys. Tech. Jour.*, vol. 18, pp. 222–234; January, 1939.