A Two-Port Magnetoelastic Delay Line in the UHF Region

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Abstract—**Results are presented on the investigation of an experimental two-port magnetoelastic delay line using a single crystal rod of yttrium-iron-garnet, over the frequency range of 200 to 1000 MHz. A magnetic bias field is applied parallel to the rod axis. Data is given on delay time and insertion loss as a function of bias field. Both a slow and fast variation of insertion loss with bias field are noted. The slow variation of insertion loss is quite flat and insertion loss is at a minimum, over the range of 900 to 1050 oersteds, for all frequencies from 200 to 1000 MHz. A study of the fast variation of insertion loss shows that this variation occurs only over a portion of the pulse and if the pulse is short enough the fast variation is absent. A study of the effects of small permanent magnets that supply a biasing field orothogonal to the primary biasing field is presented. Insertion loss and pulse distortion are substantially reduced by these magnets.**

Introduction

THE FEASIBILITY of exploiting the slow velocity of propagation of elastic and/or spin waves in order to delay an electromagnetic signal in the microwave frequency range has been clearly established. Several different approaches have been shown to be practical [1]–[6]. One of these, the magnetoelastic delay line, involves the use of both spin and elastic waves. Usually a rod of single crystal yttrium-iron-garnet (YIG) is used, which serves both as the delay medium and also as the transducer to convert the electromagnetic energy to elastic energy, and vice versa. A basic advantage of this type of delay line over the pure elastic delay line is the ability to vary delay time continuously over a large range by means of a magnetic biasing field. However, two-port operation of the magnetoelastic line has been shown to result in high insertion loss [1], [2].

This paper reports on the investigation of a transmission type magnetoelastic delay line intended for operation over the range of 200 to 1000 MHz. Of particular interest is the use of auxiliary magnets to reduce insertion loss and pulse distortion.

Experimental Results and Theory

A schematic of the delay line is shown in Fig. 1. A single crystal YIG rod 0.63 cm in diameter$\times$1.20 cm long, with optically polished end faces, was placed in a brass enclosure of overall dimensions $3\times1.58\times2.54$ cm. The coupling wires were copper strips with a cross section of 0.01×0.25 cm. The external magnetic bias field (H_{dc}) was supplied by a 4 inch electromagnet parallel to the rod axis. The [111] direction of the crystal is also along the rod axis.

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Delay Time and Insertion Loss

Delay measurements were obtained as a function of the externally applied magnetic field for several frequencies, as shown in Fig. 2. All the curves approach a minimum delay of 3.2 μs at the high fields. At high fields the spin wave contribution to the delay approaches zero and thus the minimum delay corresponds to the time required for the elastic wave to travel the full length of the crystal. The velocity of propagation of the elastic wave calculated from the 3.2 μs delay is 3.75×10^5 cm/s. This is in good agreement with published values [7].

Detailed plots of insertion loss versus applied magnetic field were obtained at nine frequencies over the frequency range of 200 to 1000 MHz with the input and output of the delay line tuned with double stub tuners. The plot at 800 MHz is shown in Fig. 3. The insertion loss fluctuated very rapidly with small changes in applied field (henceforth called the fast variation in Schlomann's notation [8], [9]) making it impractical to show each fluctuation separately. Hence, only the enevelope of the fluctuations (henceforth called the slow variation) is shown on the graphs. It should be noted that this data was taken for relatively long pulse lengths.

Table I shows the minimum value of the slow variation of insertion loss for various frequencies. The minimum value decreases as frequency is increased from 200 to 600 MHz and is relatively constant from 600 to 1000 MHz. The slow variation of insertion loss is relatively flat and at a minimum over the field range of 900 to 1050 oersteds for all frequencies from 200 to 1000 MHz.

Measurements on a delay line without tuners, at 400 and 800 MHz, showed an increase in insertion loss of approximately 10 dB over the tuned line for a wide range of biasing field.

Fast Variation

In studying the fast variation of the insertion loss, it was observed that only a fraction of the delay pulse exhibited the fast variation, and the magnitude of this fraction varied with the biasing field. This is illustrated in Fig. 4, which shows time exposure photographs of the delay pulse as the biasing field was swept approximately ±10 oersteds around the values given in the figure. The pulse width is 2.5 μs. Since the change in H_{dc} required to move from one peak to an adjacent peak is in the range of 1 to 3 oersteds, the photograph of the oscilloscope trace of the portion of the pulse that fluctuates is a wide band. The upper and lower bounds of this band correspond to the minimum and maximum values of the fast variation of the insertion loss.

At sufficiently low biasing fields, there are no fluctuations in any part of the delayed pulse as the biasing field is swept around its normal value. As the biasing field is increased, the back end of the pulse fluctuates first, and more of the pulse fluctuates as the biasing field is further increased. With sufficiently large biasing field, virtually all of the pulse will fluctuate. A plot of the fraction of the pulse that fluctuates and its corresponding insertion loss, as a function of the biasing field, is shown in Fig. 5.

Before discussing the reason for the fluctuations, let us examine the delayed output pulses from a single input pulse when the pulse length is relatively short and the bias field sufficiently small, so that fluctuations do not occur. This is shown in Fig. 6. Immediately following the main output pulse a smaller secondary pulse can be noted. (We need not consider the other output pulses seen in Fig. 6.) The delay times of the main and secondary pulses at 715 MHz as a function of biasing field are plotted in Fig. 7. Let T_m be the delay time of the main pulse and ΔT the difference in the delay time between the main and secondary pulse. Experimentally, it is found that $T_m-\Delta T$ is equal to 3.2 μs within experimental error for all biasing fields. As noted previously, 3.2 μs is the approximate time it takes an elastic wave to travel from one end of the YIG rod to the other.

The explanation for the fluctuations and the reason that $T_m-\Delta T$ is always 3.2 μs is given below. It is based in part on analyses presented by Kohane, Schlomann, and Joseph [9], and Strauss [10].

Referring to Fig. 8, the main output pulse is shown originating as a spin wave at the left turning point, becoming converted to an elastic wave at the crossover region, and traveling as an elastic wave to the left-end face. It is reflected there and travels to the right-end face, reflected again towards the right crossover region where it is converted to a spin wave, and then continues to the right turning point. It is then coupled to the electromagnetic field in the sample holder and then detected. The above conversions are not, however, completely efficient. For example, when the main pulse arrives at the right turning point, not all the energy is coupled into electromagnetic energy and detected. The portion that is not coupled is reflected back towards the right-end face. This energy is reflected again at the right-end face, travels toward the left, and is (partially) detected at the right turning point. The path of this secondary pulse is shown as a dashed line in Fig. 8. Secondary pulses may similarly originate at the left turning point; however, only the secondary pulse shown in Fig. 8 will be discussed for simplicity.

The travel time of the secondary pulse is clearly the time it takes for a pulse to travel from the turning point to its neighboring end face and return. If the pulse width is shorter than the travel time of the secondary pulse, then the secondary pulse will appear distinct from the main pulse. Also, from Fig. 8 it is seen that subtracting the travel time of the secondary pulse from the travel time of the main pulse leaves the travel time of a pulse going from one end face to the other end face. During this travel, the pulse propagates as an elastic wave and, as noted before, the time required for an elastic wave to travel the length of the rod is 3.2 μs. This explains why $T_m-\Delta T$ came out to be 3.2 μs.

If the pulse width is larger than the travel time of the secondary pulse by an amount τ, then the secondary pulse and a portion of the main pulse will be detected simultaneously at the right turning point. The time duration of this overlap is clearly equal to τ. The secondary pulse will cause an increase or decrease in the detected output during this overlap time, depending on the phase relation between the main and secondary pulses. Hence, as the biasing field is varied, causing the phase relation between the main and secondary pulses to change, the detected output pulse fluctuates during the overlap time. Since the round trip time between the turning point and neighboring end face decreases as the biasing field increases, τ and the fraction of the pulse that fluctuates, will correspondingly increase.

Auxiliary Magnets

It was observed during early experiments that the insertion loss was effected by orientation of the applied magnetic field with respect to the rod axis. This suggested a study of the effects of fields applied perpendicular to the YIG rod axis, in addition to the biasing field parallel to the axis. This was done by placing small permanent magnets on the outside surface of the delay line enclosure thus setting up nonuniform auxiliary fields perpendicular to the main axial field. The magnets used were barium ferrite permanent magnets that have the dimensions of 0.76 cm$\times$0.76 cm$\times$0.51 cm. The field at the surface of a magnet is approximately 700 oersteds; at a distance of 0.5 cm the field drops to approximately 120 oersteds. The approximate placement of the magnets is shown in Fig. 9. The procedure used in placing the magnets was to place one auxiliary magnet on the brass enclosure at a time and move it until the maximum decrease in insertion loss was observed, and then add the other magnets similarly.

Tollowing are the results of using the auxiliary magnets.

1) *Insertion Loss:* Figures 10, 11, and Table II, show clearly that a very large decrease in insertion loss can be achieved through the use of the auxiliary magnets. Comparison of Figs. 10 and 5(b) show that a reduction of up to 15 dB is obtained at 715 MHz. In Fig. 11, it is noted that for a fixed biasing field a reduction in insertion loss due to the auxiliary magnets occurs over the frequency range of 600 to 900 MHz.

2) *Fast Variation:* Another effect of the auxiliary magnets is the reduction or elimination of the fast variation of insertion loss. This is shown quantitatively in Table II and is indicated in Fig. 10 where, for the most part, a single line instead of an envelope is used to represent the insertion loss when the auxiliary magnets are used.

3) *Reflection Mode:* Though most of the experiments (and all the data presented to now) were made using the transmission mode, some experiments were made using the reflection mode. In general, when auxiliary magnets were

not used it was possible to observe as the first reflected pulse, the pulse that traveled from the turning point to the left face, and back to the turning point. However, with the use of the auxiliary magnets it was possible to suppress the above pulse so that the first pulse that appeared in the reflection mode was the one that made a complete round trip through the length of the rod.

4) *Delay Time:* The auxiliary magnets did not appreciably change the delay time of the pulse for a fixed value of the primary field as is shown in Table III and Fig. 11. The maximum difference in delay time shown is 0.22 μs.

5) *Pulse Distortion:* Generally, a long pulse showed considerable distortions due to interference effects from secondary pulses and third trip, fifth trip etc., signals. However, by use of the auxiliary magnets it was possible to transmit very long pulses without any noticeable distortion.

There is at present no definite explanation as to why the auxiliary magnets cause the effects enumerated before. One possible hypothesis may be that the auxiliary magnets focus the "beam" while it exists as a spin wave or magnetoelastic wave [11]. According to Schlomann [8], [9], the "turning point" is not a plane perpendicular to the rod axis, as is commonly represented for simplicity. Rather the turning point lies on a curved surface and hence the magnetoelastic wave that is generated is not a plane wave. The auxiliary magnets may have a focusing effect that makes the magnetoelastic wave more nearly a plane wave. This hypothesis will explain a reduction in insertion loss, but alone does not seem to explain the elimination of the fast variation or the elimination of the first reflected pulse in the reflection mode.

A second hypothesis is that the auxiliary magnets alter the internal-field gradients sufficiently so that instead of the field gradients at a turning point decreasing in the direction of its neighboring end face (as occurs when no auxiliary magnets are present), the gradient decreases in the direction of the opposite end face. In this case, the wave in the rod would travel directly from one turning point to the other without traveling to the end faces.

This hypothesis would explain the reduction or elimination of the fast variation and the first reflected pulse, since both of these require that the wave in the rod first travel from the turning point to the associated end face before proceeding to the opposite end face. The lower insertion loss may be due in part to the wave transversing a crossover point only twice in going from one turning point to another instead of traversing a crossover point four times when no auxiliary magnets are used. The small change in delay time is not necessarily inconsistent with the smaller distance the main pulse has to travel assuming the auxiliary magnets change the direction of the field gradient at the turning point. An increase in the time the pulse spends as a spin wave may compensate for the decreased distance.

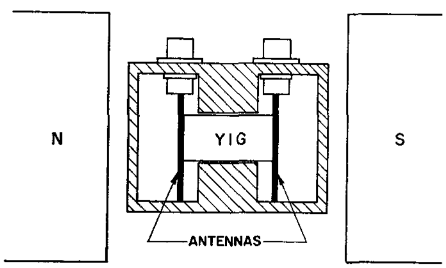

Fig. 1. Sectional view of YIG delay line.

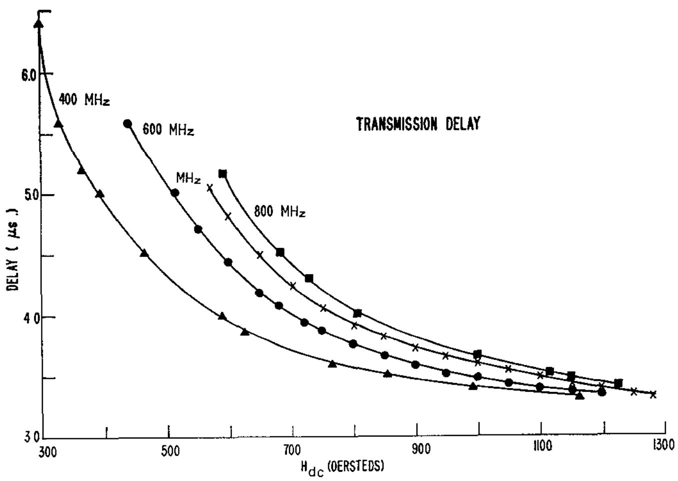

Fig. 2. Delay time as a function of applied magnetic field for several frequencies.

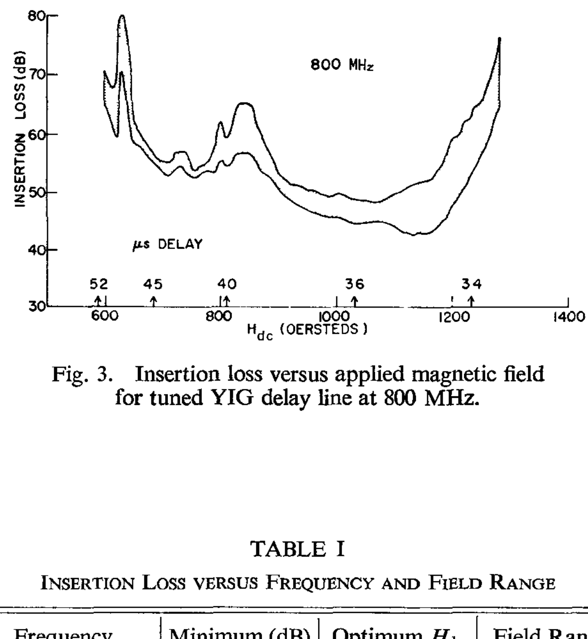

Fig. 3. Insertion loss versus applied magnetic field for tuned YIG delay line at 800 MHz.

TABLE I

INSERTION LOSS VERSUS FREQUENCY AND FIELD RANGE

Frequency (MHz)	Minimum (dB) Insertion Loss	Optimum H_{dc} (oersteds)	Field Range* (oersteds)
200	90	950	850–1080
300	63.5	920	760–1050
400	65	870	690–1070
500	54	980	780–1100
600	42.5	990	620–1110
700	41	1030	750–1120
800	42	1070	900–1200
1000	39	1190	820–1310

* Field range over which insertion loss is within 6 dB of its lowest value.

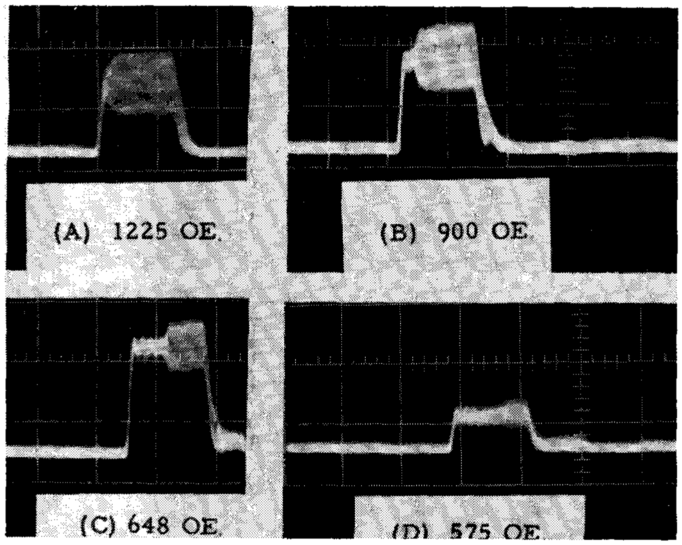

Fig. 4. Time exposure photographs of oscilloscope traces of delayed pulses as the biasing field is swept ±10 oersteds around the values indicated. Horizontal scale is 2 μs per major division. Frequency is 715 MHz.

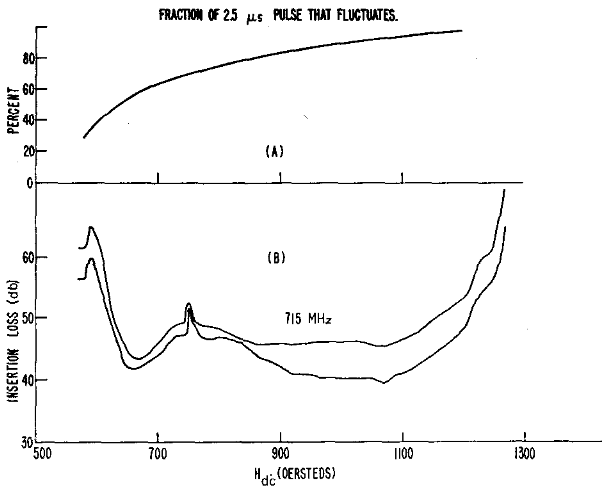

Fig. 5. Fraction of pulse that fluctuates (A), and its corresponding insertion loss (B), as function of applied field.

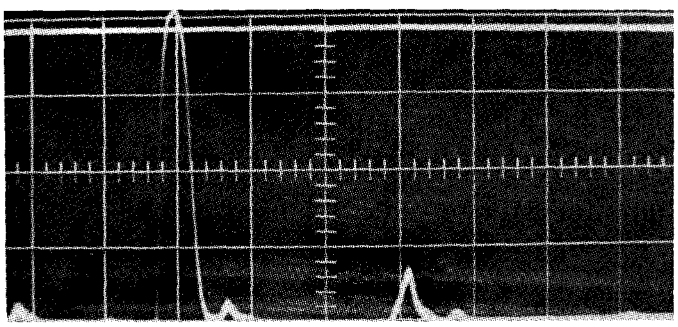

Fig. 6. Oscilloscope trace of output pulses due to a single input pulse. The main delayed pulse is the largest pulse shown. Immediately to the right is the secondary pulse. The pulses further to the right need not be considered. The pulse to the left is a sample of the undelayed pulse. Horizontal scale is 2 μs per major division. Test frequency was 715 MHz and the bias field 680 oersteds.

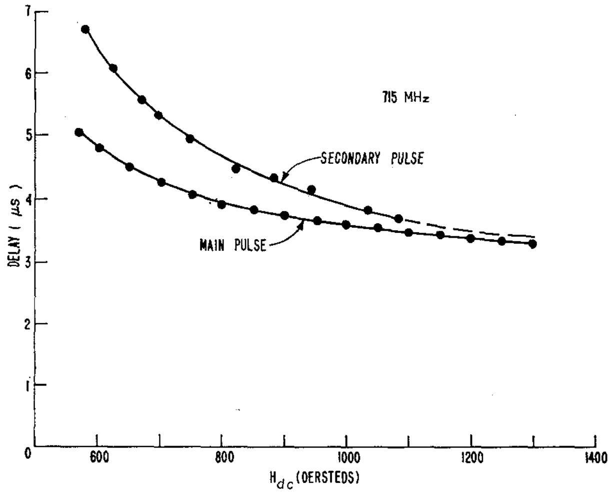

Fig. 7. Delay time of main pulse and secondary pulse versus applied magnetic field.

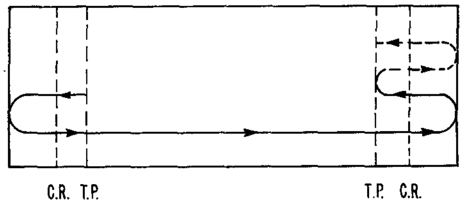

Fig. 8. Paths taken by the main and secondary pulses in the YIG rod. The solid line represents the path of the main pulse and the dashed line the path of the secondary pulse. Spin waves originate at the turning point (T.P.) and elastic waves at the crossover region (C.R.).

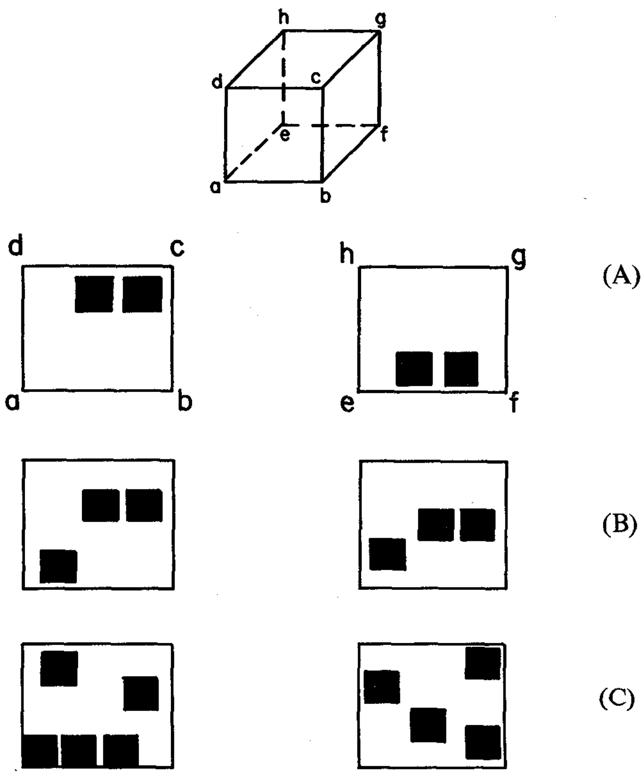

Fig. 9. Location of auxiliary magnets on the two 3×2.54 cm faces of the brass enclosure. (A) 4 auxiliary magnets, (B) 6 auxiliary magnets, (C) 9 auxiliary magnets.

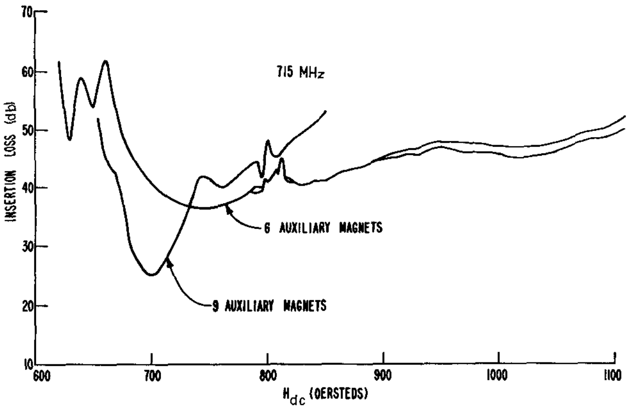

Fig. 10. Insertion loss versus applied magnetic field for two cases of auxiliary magnets.

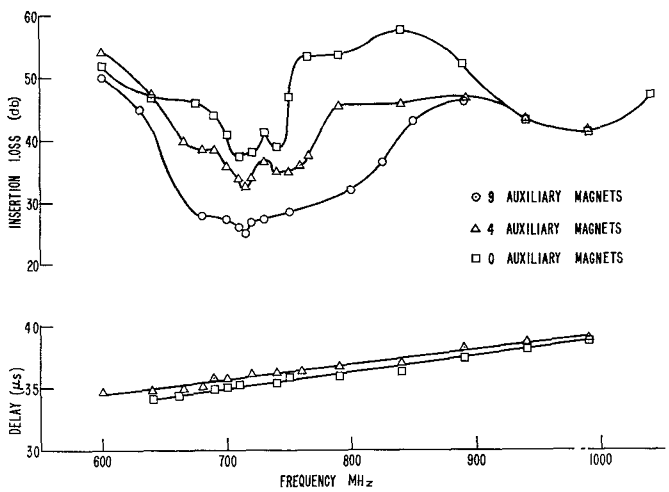

Fig. 11. Insertion loss and delay versus frequency for the case of 0, 4, and 9 auxiliary magnets. The primary field was 1025, 1025, and 700 oersteds, respectively.

Conclusions

Data have been presented on both a slow and fast variation of insertion loss covering the frequency range of 200 to 1000 MHz. The fast variation is apparently due to interference effects between the main pulse and a secondary pulse which is generated by reflection due to a "mismatch" at the turning point. The fast variation has been shown to occur only over a portion of the pulse and may be absent if the pulse is sufficiently short. The use of auxiliary magnets which generate a field perpendicular to the main axial field was found to reduce transmission insertion loss, reduce or eliminate the fast variation, and reduce distortion in long pulse lengths.

TABLE II

Effect of Auxiliary Magnets on Insertion Loss

H_{dc}	Insertion Loss Range (dB)		Maximum Fluctuations (dB)	Number of Auxiliary Magnets
	Main Pulse	Secondary Pulse		
600–900	65–42	59–67	± 2.0	0
650–900	55–34	54–59	± 1.5	4
650–900	62–36	80–75	± 0.5	6
650–850	53–25	not observed	0*	9

* Less than measurement sensitivity of 0.1 dB.

TABLE III

Transmission Delay for Various Auxiliary Fields at $H_{dc}=695$ oersteds, $f=715$ MHz

Delay (μs)	Number of Auxiliary Magnets
4.27	0
4.49	4
4.48	6
4.42	9

Acknowledgment

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