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ECOM-0215-4

PULSED MAGNETIC FIELD FERROMAGNETIC MICROWAVE GENERATOR

Quarterly Report

By

L.D. Buchmiller--F.A. Olson

June 1968

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.
Contract DAAB07-67-C-0215

MICROWAVE ELECTRONICS, A Division of Teledyne, Inc.
Palo Alto, California 94304

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Technical Report ECOM-0215-4 June 1968

PULSED MAGNETIC FIELD FERROMAGNETIC MICROWAVE GENERATOR

Fourth Quarterly Progress Report

1 October 1967 to 31 January 1968

Report No. 4

Contract No. DAAB07-67-C-0215

DA Project No. 1H6-22001-A-055-05-06

Object

To develop a microwave nanosecond pulse generator using ferrimagnetic materials subjected to pulsed magnetic fields.

Prepared By

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Palo Alto, California

For

U.S. Army Electronics Command, Fort Monmouth, N.J. 07703

ABSTRACT

Methods of increasing the output power of the pulsed-ferrite X-band generator using multiple YIG ferrite spheres are described.

A preliminary survey of solid-state switch capabilities is given for possible future replacement of spark-gap switches used in the charged-line pulser.

Preliminary experimental work in triggering the nanosecond pulsewidth, spark-gap pulsers is described.

CONTENTS

ILLUSTRATIONS

PURPOSE

The purpose of this program is to determine the feasibility of a microwave generator in which a ferrite material is used to convert energy from a pulsed magnetic field into coherent energy.

The investigation includes studies of generator performance features and limitations, and the fabrication of an exploratory developmental model to demonstrate microwave generation of X-band power at nanosecond pulse widths by the use of a ferrimagnetic material immersed in a pulsed magnetic field. The design objectives are as follows:

RF Pulse Width	1 to 3 nanoseconds
Center Frequency	9.6 GHz
Frequency Tuning Range	9.6 GHz ±4 percent
Peak Power	2 kW
Pulse Repetition Rate	1 to 10 KHz

The unit is to be self-contained, including pulsing circuitry with only applied dc voltages required. Maximum over-all efficiency, reliability, life and simplicity of operation are desired characteristics.

PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

There were no publications, lectures or reports resulting from research carried on under this contract during the fourth quarter. A conference was held on 16 October 1967, with S. Snyder and M. Wiener of USAEC to review current work to determine the direction of future efforts.

Meetings with Dr. H.J. Shaw of Stanford University and Stanford Research Institute personnel, L. Young and A. Karp, were held on 13 September 1967 and on 27 November 1967.

FACTUAL DATA

I. INTRODUCTION

During this reporting period, considerable emphasis has been placed on methods for increasing the RF power output of the pulsed ferrite generator by means of multiple YIG ferrite spheres. Three approaches, listed as Types A, B, and C, are discussed in Section II-A and II-B. Pulser requirements for the Type-C pulser, and requirements of RF combining, are given in Sections II-C and II-D.

Conclusions for multiple-sphere operation are listed in Section II-E. The results of a preliminary survey of solid-state switches are described in Section III, and experimental work on triggering is discussed in Section IV.

II. MULTIPLE SPHERE OPERATION

A. Type-A and Type-B Circuits

Among the possibilities for multiple-sphere operation are structures in which there is a strip ("video") line periodically interrupted by series-pulsed field coils. The low impedance video line would be necked down in the vicinity of each coil, and each coil would contain an RF slot resonator, essentially as in previous and present single-sphere operation. Figure 5 of QPR No. 3 and Fig. 1 of this report show one such possibility, with individual wave-guides for each YIG sphere. This method requires separate RF combining circuitry. For future reference, this method will be called Type-A.

Another method, Type-B, is shown in Fig. 2, where the output waveguide now runs along the video line. (The slots needed in the narrow waveguide wall to avoid shorting the pulsed coils would be in non-radiating positions, as in present single-sphere designs. Other mechanical aspects appear easily re-solvable. In this design, the RF phase velocity in the waveguide must be made to match the velocity of the video waveform in the strip line. The latter velocity is that of a uniform line periodically loaded with inductance, giving a low pass filter characteristic with velocity dropping sharply [illegible] the cutoff frequency. In the waveguide, if the loops are assumed to be a small perturbation insofar as phase velocity is concerned, it appears feasible to use simple dielectric loading to lower the guide phase velocity to match that of the video line over some useful frequency band near 10 GHz.

The principal advantage of the Type-B arrangement of Fig. 1 is that, with video and RF energy traveling in the same direction at the same speed, phase locking of all RF outputs should occur and thus permit coherent summing.

Both of the above schemes (Type A and B) have a failing in that the sharp leading edge of the video waveform will deteriorate after passing through successive series inductive loops. Fortunately, the present loops have an inductance of

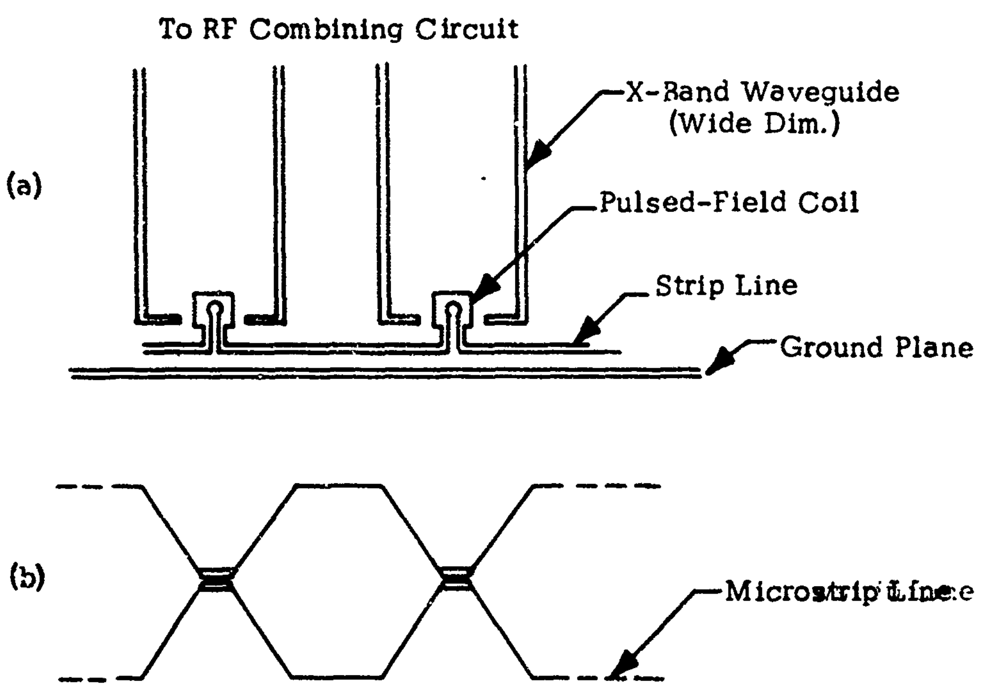


Fig. 1. Schematic of Type A multiple-sphere distributed circuit configuration. (a) side view: (b) top view of microstrip line.

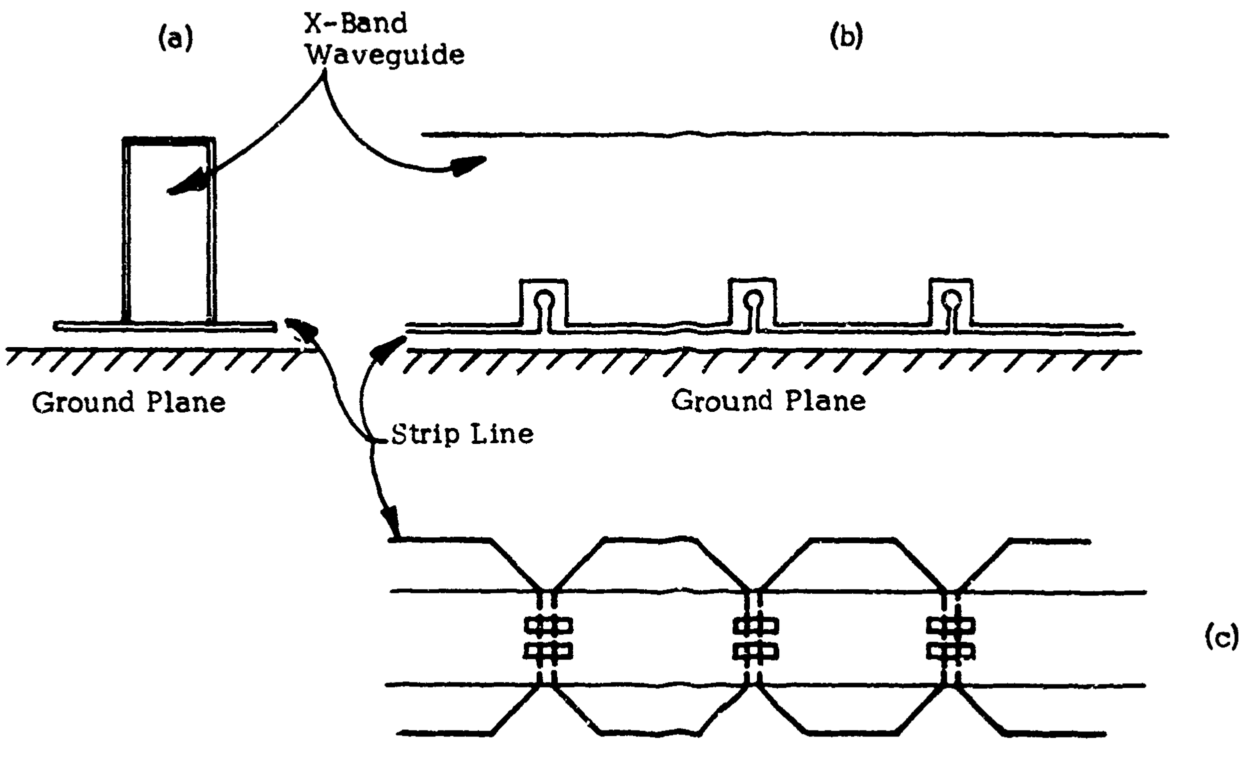


Fig. 2. Schematic of Type B multi-sphere distributed circuit configuration. (a) end view; (b) side view; (c) top view. Dielectric loadings are not shown.

only 10^{-9}H, and with a Z_o of 7 ohms the time constant $L/2Z_o$ is 0.07 ns and rise time should deteriorate by 2.2 $L/2Z_o$ or only 0.17 ns at each loop. Still, a significantly large number of loops could not be tolerated in these designs. (See Appendix A for pulse shape deterioration.) It is possible, however, to add shunt capacitance on each side of each loop to give a small π-network, artificial transmission line element whose Z_o matches that of the original strip line. This completely "smooth" result should ensure constant sharpness of the leading edge since energy extracted by YIG spheres is so relatively low. However, one can note that the Z_o of an artificial line varies with frequency and that there is a cutoff frequency $f_c = Z_o/\pi L$ associated with each π-network so that for $Z_o \approx 7$ ohms and $L \approx 10^{-9}$H, $f_c \approx 2 \times 10^9$Hertz. Because this frequency is relatively low for the time scale of interest in maintaining pulse sharpness, and the Z_o of the artificial line can be matched exactly at only one frequency, pulse deterioration will still occur.

B. Uniform Video Line, Type-C Circuit

Emphasis on maintaining an identical video-pulse waveform at all points along the distributed structure has given rise to new thinking in terms of a smooth, homogeneous two-conductor video transmission line as shown in Fig. 3. Generators using this uniform pulse or video line will be referred to as Type C. Ferrite spheres are spaced periodically in the interior of the uniform video line, embedded in a high-dielectric strength material.

If the cross-sectional dimensions of the transmission line are the same as the cross-sectional dimensions of the pulsed-field coil used for single-sphere operation, the pulsed magnetic field seen by a ferrite sample located at the center point of the cross section of the uniform video transmission line will be nearly the same as that for the same current in the pulsed-field coil.

Since the transmission line constitutes essentially a uniform propagating structure for the pulsed-field current, the pulsed field wave-shape will remain constant as the current pulse propagates along the transmission line, so that

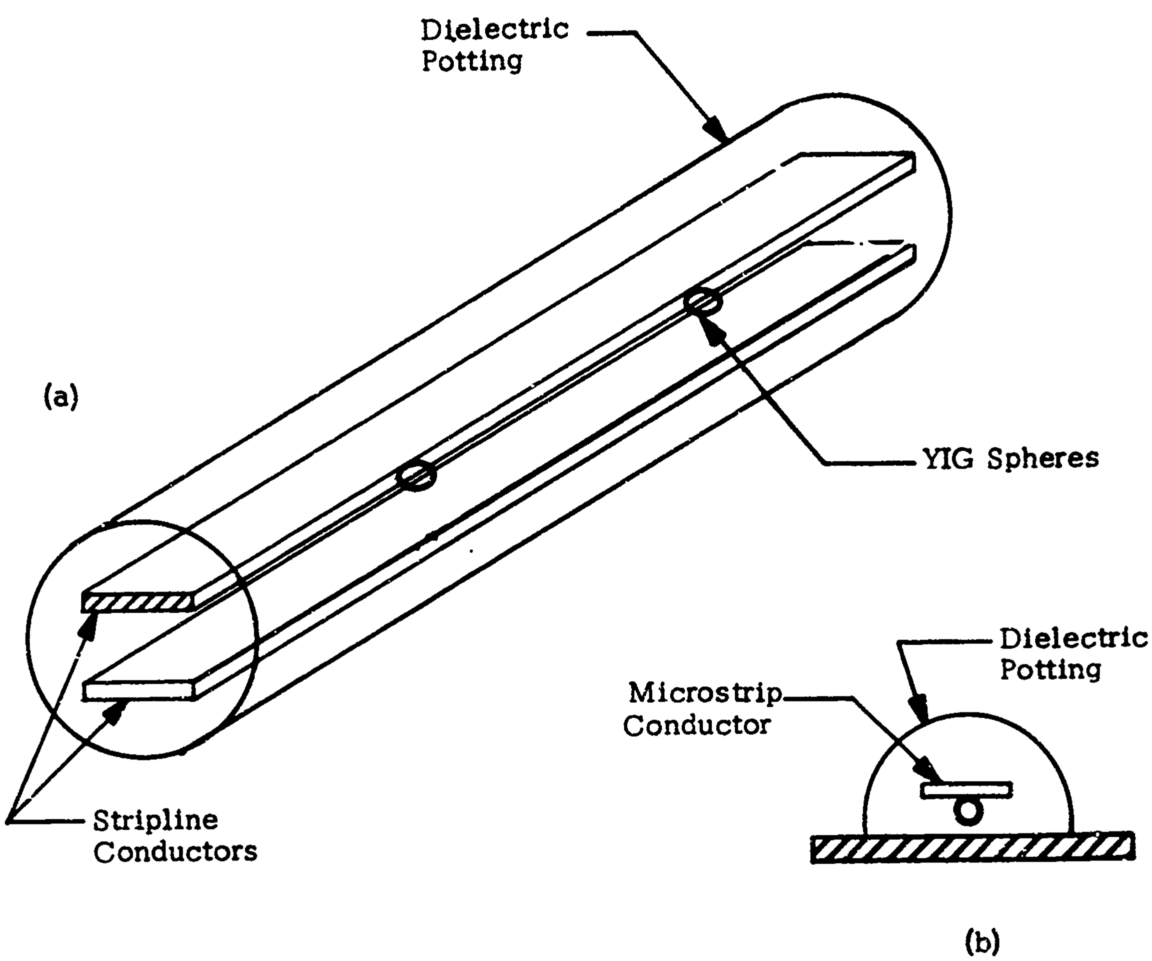


Fig. 3. Video-pulse line. (a) balanced; (b) unbalanced.

all ferrite samples will see substantially the sample pulsed field rate of rise, as well as other pulsed field characteristics.

Since the pulsed field coils have now been eliminated, with the integral slot-resonator for coupling to the ferrite, new coupling methods must be developed. In order to have the RF and pulsed magnetic fields orthogonal, the RF magnetic field generated by a YIG sphere is required to be axial (as shown in Fig. 3); hence, we require resonant coupling structures which can accommodate the uniform video line and couple to an axial H-field at each sphere. The lowest order resonant mode of a "life-saver" shaped dielectric resonator would be ideal, except that for $\epsilon > 20$ the resonator would be too small compared to the video line, and for $\epsilon < 20$, a dielectric resonator cannot in practice be made to work as a true dielectric resonator.

Another possibility is a TE^{o}_{011} cavity (with or without dielectric filling) which does have an axial H-field, and in which an axial tunnel to accommodate the video line can readily be provided. See Fig. 4. Tuning here would be easy because transverse end plates need not contact the cylindrical cavity walls. The disadvantage is the axial length needed to support the mode in the absence of dielectric, and an overly long total structure would result.

A $TE^{\square}_{201}$ resonator has also been considered, with the YIG-loaded rod located axially in the central region of high axial H-field. Unloaded, this cavity also takes up room axially. A variation on this resonator (Fig. 5) can, however, have its axial length reduced by loading with metallic posts. Actually, this structure consists of two transverse lengths of coaxial resonator so joined as to produce a strong axial H-field where needed. It turns out, however, that while axial length has been cut down, the transverse dimension becomes large (See "end view" of Fig. 5). In Fig. 6, one step further has been taken to simplify the structure. Each vertical post is an open-circuit-ended, half-wave TEM resonator.

Spurious resonances may occur in any of the above cavities, but they would certainly be decoupled from the YIG system. These cavities can all be easily revised to accommodate an unbalanced video-pulse line (Fig. 3-b).

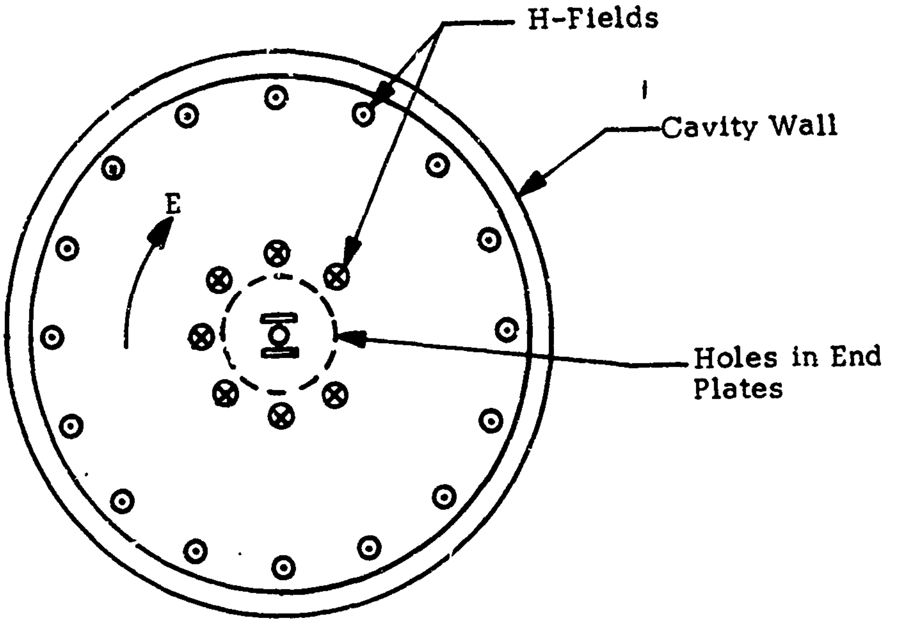
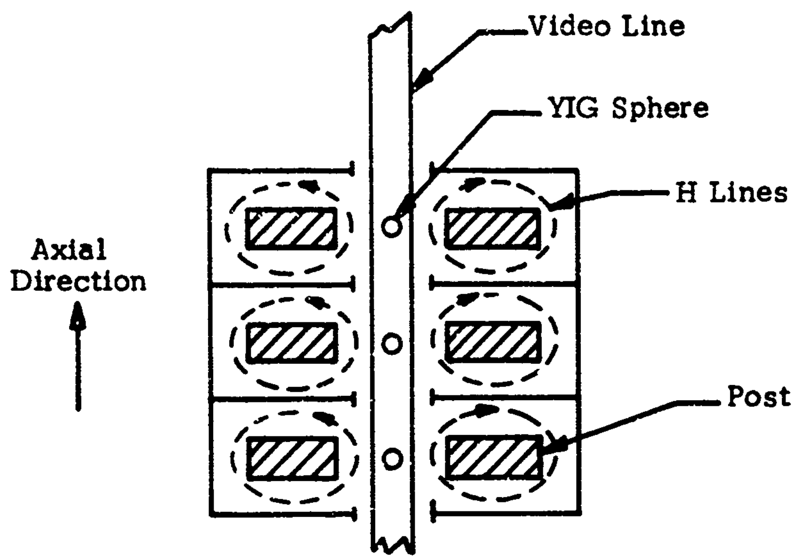
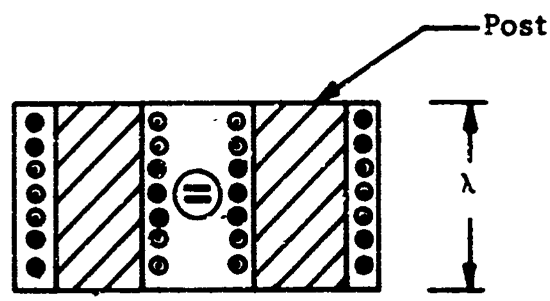


Fig. 4. Video-pulse line inserted in TE $^{o}_{011}$ cavity.



(a) Top view.



(b) End view.

Fig. 5. Cavity configuration with axial H-field and short axial length. (Variation of $TE'^{\square}_{201}$ mode.)

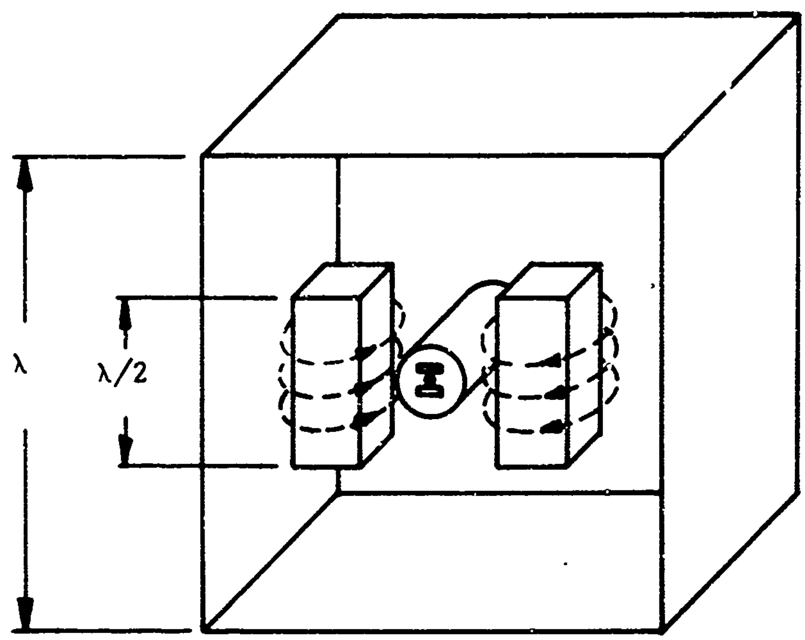


Fig. 6. Schematic of revised cavity resonator of short axial length. (Variation of $TE^{\square}_{201}$ mode.)

C. RF Combining

The problem to be considered now is the extraction of RF power from each resonator (surrounding each sphere) and combining the several outputs. We note Fig. 10 of Shaw, et. al.[1], which shows that the RF waveform from one sphere is stable from pulse to pulse, relative to some point on the video pulse. Also, since relatively few cycles (about 25) are produced, it would suffice to tune the output frequencies of the several spheres only to within a few percent of one another, and thus obtain an ad hoc coherence for summing, provided the initial phase is allowed for. Relative to any point on the video pulse as it arrives at the first sphere, the phasing of outputs from successive spheres would be known from the video-line velocity. However, there could well be an incremental phase deviation due to small inequalities between spheres, etc. Combining circuitry can therefore be rather complex.

Figure 7 indicates schematically the basic approach needed for interconnecting the various samples. We indicate the ferrite spheres arranged along a single line which represents the pulsed-current video transmission line of Fig. 3. We also indicate branch lines, one coming from each ferrite, which represents RF transmission lines or waveguides coupled to the individual ferrites by coupling loops to the cavities. Each RF transmission line contains a phase shifter. These phase shifters correct for the progressive phase shifts which are present in the excitation of the individual ferrites, such that the pulsed RF outputs from all the ferrites add in phase at the combined output terminal.

The lengths of the various RF transmission lines enter into the phasing also, of course, and the phase shifters shown are for the purpose of correcting both for the initial excitation phase of the ferrites and for the phase shifts in the RF transmission lines. In practice, in an experimental device, the phase shifters must be adjustable over a certain range in order to experimentally optimize the amplitude of the signal in the combined output port.

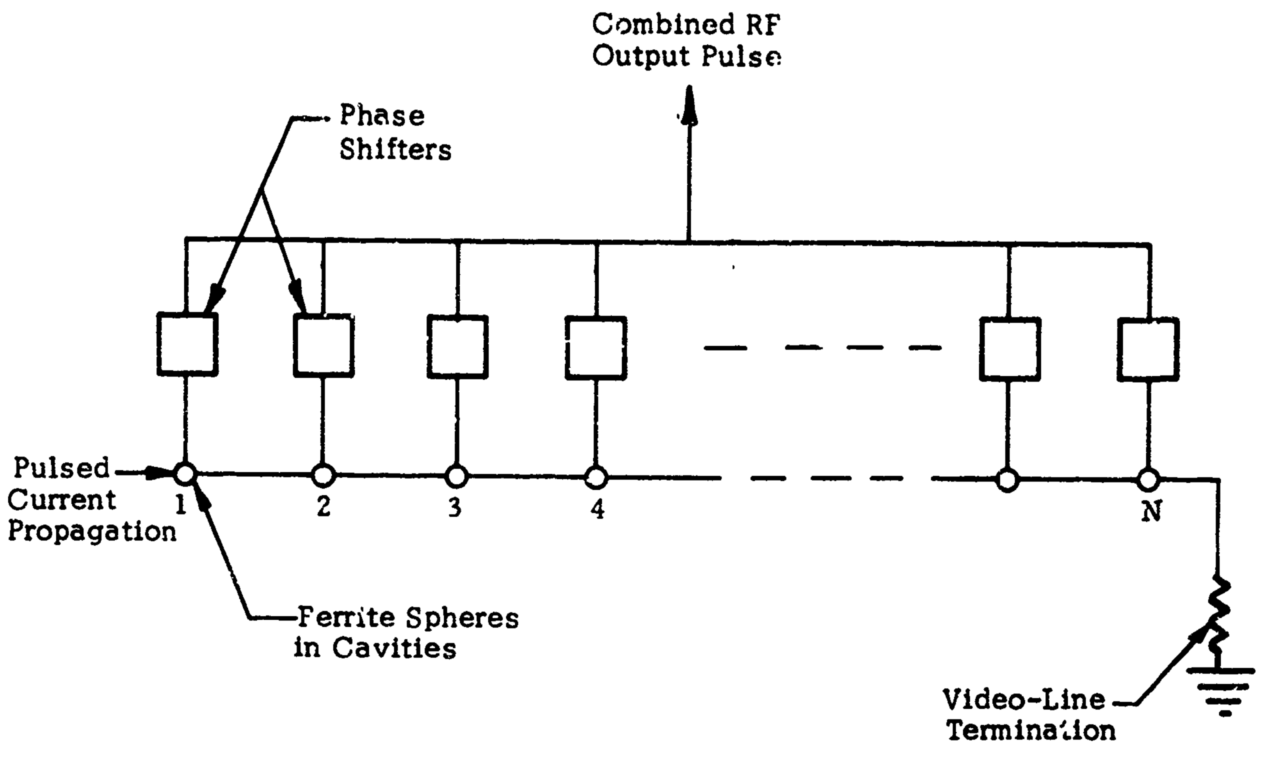


Fig. 7. Schematic representation of an RF combining circuit using phase shifters or line stretchers.

It should also be noted that because of the wide bandwidth of the RF output pulse from this device, the phase shifters would have to be designed for wide bandwidth, and would also need to have the property that their frequency response does not change as the phase shift is varied.

A scheme for use in an experimental form of this device (which would avoid the necessity for the phase shifters and thus materially simplify the design and the experimental adjustment of the device) is presented schematically in Fig. 8. Here the RF transmission line from each sample leads directly to an antenna. For simplicity let us assume that these antennas are mutually uncoupled and also that each antenna is essentially non-directional in the vicinity of the radiation direction which is of interest here. The main point is that, because of the progressive phase shift in the excitation from ferrite to ferrite, there will be a progressive phase shift in the aperture fields from antenna to antenna--with the result that the antenna array will automatically pick a direction in which to radiate, and that direction will be the one in which the RF output pulses from all ferrites add in phase. In this system, therefore, the antenna array would automatically optimize the combined outputs from all ferrites, using radiation direction as a parameter.

D. Pulser Requirements for the Type-C Generator

The Type-C multiple-sphere generator technique employing a uniform video line, as described in II-B, imposes severe requirements on the pulser. These arise since (1) the video line is now terminated so that current doubling does not occur as in the single-sphere case, where the coil effectively shorts the video line output, and (2) the characteristic impedance Z_o of the video line is now approximately a factor of ten larger than for the single-sphere case. Z_o is high since the uniform line must be the same width as the pulsed-field coil to obtain the same magnetic field-to-current ratio, H/I = 2.75 Oe/A, as the coil.

For a stripline width equal to the coil width of 112 mil, and a stripline spacing equal to the YIG sphere diameter of 48 mil, Z_o is 90 ohms for a dielectric constant

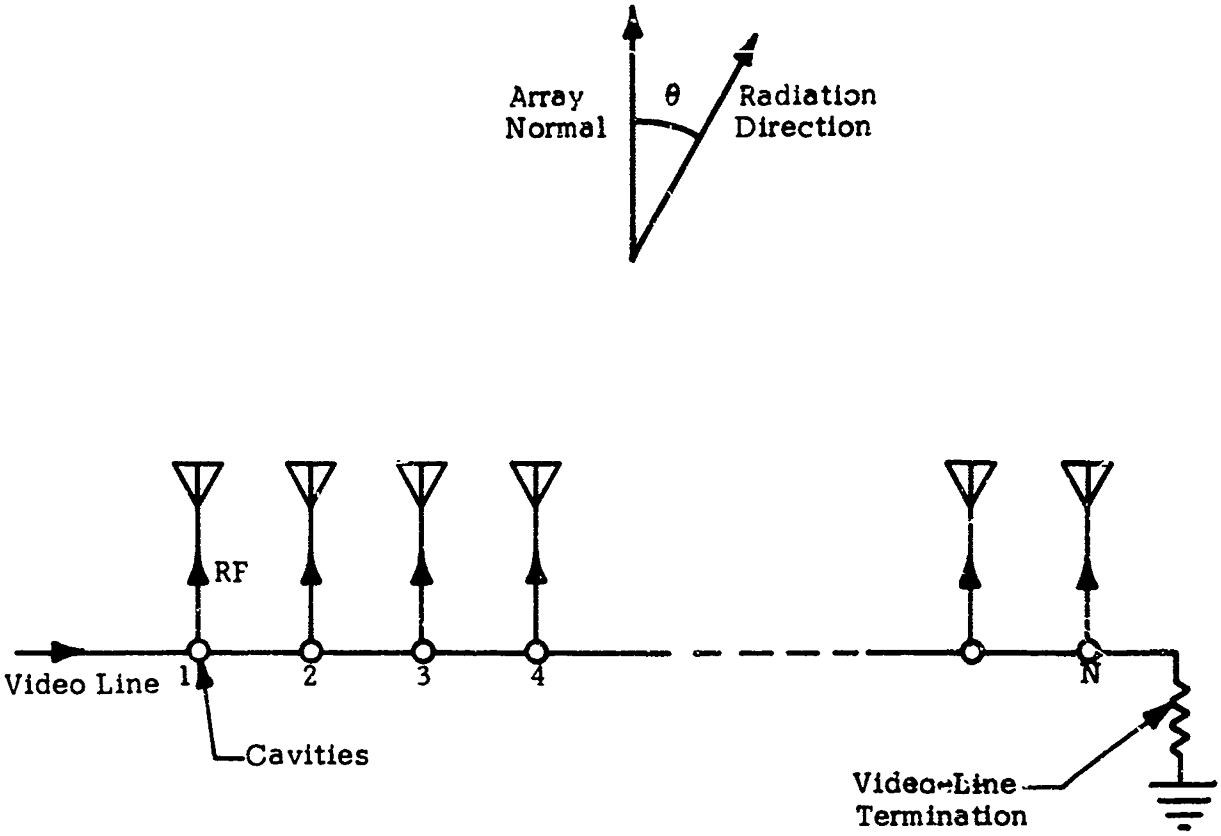


Fig. 8. Schematic representation of RF combining circuit employing an antenna array.

of about 3. Assuming that the YIG sphere can be partially placed in indentations in the strip line, a stripline spacing of 24 mils and an impedance on the order of 45 ohms will be obtained. For operation up to 10 GHz, a pulse current of 1300 amperes is required for terminated video line operation. The pulse voltage required to supply this current in a 45-ohm line is then on the order of 60 kV.

The stripline dielectric must therefore withstand E-fields of 2.5 kV/mil. High dielectric strength materials are being investigated. Although it appears that Mylar immersed in Freon C-318 may be satisfactory (see DuPont Bulletin M-4C) the effects of nonlinearities on pulse shape must be evaluated. Other methods such as quartz-clad molybdenum may also be feasible. The fact that pulse widths are only 2 ns is expected to help the breakdown problem as the breakdown mechanism has insufficient time to cause sparking[5].

E. Conclusions for Multiple-Sphere Operation

It is concluded that (1) types A and B which use series pulsed-field coils spaced along the video line are subject to pulse-current distortion which will result in decreased output per sphere and increased RF combining problems, and (2) the most feasible approach to an increase in power by an order of magnitude is to use a uniform video-line approach in which the video line passes through a resonant cavity containing the YIG sphere (Type C). The disadvantage of the Type-C generator is that the pulser requirements are increased. (60 kV, 1.3 kA)

Experimental work will be concentrated principally on the Type-C generator as it inherently has the capability to operate at high power levels.

III. INVESTIGATION OF SOLID-STATE SWITCHES

A. Introduction

A high amplitude, pulsed magnetic field, with a steeply rising leading edge is necessary if significant output powers and reasonable efficiencies from pulsed ferrite microwave sources are to be realized.

The thyristor (PNPN semiconductor structure) appears to be the most promising device for obtaining rapid switching of large currents. Semiconductor pin structures and glass threshold switches[4] are also being considered.

B. Thyristor Switching Characteristics

The time required to turn on a thyristor is characterized by the rate of change of current through the device during the turn-on cycle and is referred to as the di/dt capability. In practical devices the di/dt capability is limited in two distinct ways: (1) By the time required to redistribute charge along the axis of current flow in the various sections or layers of the device in order to promote the low-impedance state; and (2) The time required for a small initial "turned-on" region to propagate laterally over all of the intended active area of the device. The first limitation is intrinsic to the device and the second relates to structural non-uniformities that occur during fabrication and to the physical geometry of the device.

The effects of the lateral propagation of the "turned-on" region on the di/dt capabilities of practical power thyristors has been discussed at length in recent technical literature. In present devices, designed to switch large currents, the di/dt capability is determined primarily by the rate of lateral spread of the "turned-on" region. However, it is clear that improvements in fabrication techniques, and changes in triggering methods, can increase the percentage of the area of the device that is turned on initially and can subsequently reduce the effects of the spreading of the "turned-on" region.

It has been concluded that the intrinsic limit on the di/dt capability of thyristors depends on the rate at which the longitudinal charge distribution can be changed from that of the high-impedance state to that of the low-impedance state.

C. System Aspects of Thyristor Application

The application of thyristors to the switching circuit for the ferrite microwave generator can be enhanced in several ways by system design concepts. It is better to trade a larger blocking voltage for a smaller peak current. In systems where multiple ferrite spheres are used, the current loops associated with each sphere should be operated in series rather than in parallel if a single pulse source is necessary. Because thyristors may be triggered with more temporal accuracy than spark gaps, individual pulsers for each sphere of a multi-sphere system should be considered.

IV. EXPERIMENTAL PULSER WORK

A. U-V Triggering

The metal-ceramic U-V triggered spark-gap described in QPR No. 1 and No. 2 was repaired and tested in the 4-ohm coaxial line. The schematic diagram of the circuit is shown in Fig. 9. A 10-ns U-V triggering pulse is generated with a 17-ohm coaxial line charged to 4 kV and a mercury-wetted relay switch. This pulser supplies approximately a 2-kV, 100-amp pulse to the trigger gap. This current level was used by Godlove[2] for U-V trigger air gaps at atmospheric pressure. The mercury-wetted relay was modified to withstand 5 kV and was driven with a transistor multi-vibrator.

Successful U-V triggering was obtained only with the main gap pressurized to less than 20 to 30 pounds. As pressure was increased to the 80 or 100 pounds required for pulse sharpening, the triggering failed because of absorption of U-V by the gas. Stronger sources of U-V are evidently required to trigger these high pressure gaps directly.

An alternative method of U-V triggering would be to precede the main gap with a low pressure gap which is U-V triggered. This would then be followed by a sharpening gap to form a three-gap system.

B. Impulse Charging

The pulsers used by McDonald, et al[2], use a charged condenser to impulse-charge the pulse-forming line. In this type of pulser, the pulse-forming line is charged in a time shorter than the statistical breakdown time of the first gap. The advantage of this impulse-charging is that the pulse-forming gap can be highly overvolted so that a relatively fast rise-time pulse is obtained. This pulse can then be further sharpened in the usual way with a sharpening gap. A further advantage of impulse-charging with a condenser is that the pulse-forming line is subjected only to short pulses rather than dc. Longer lifetime for the

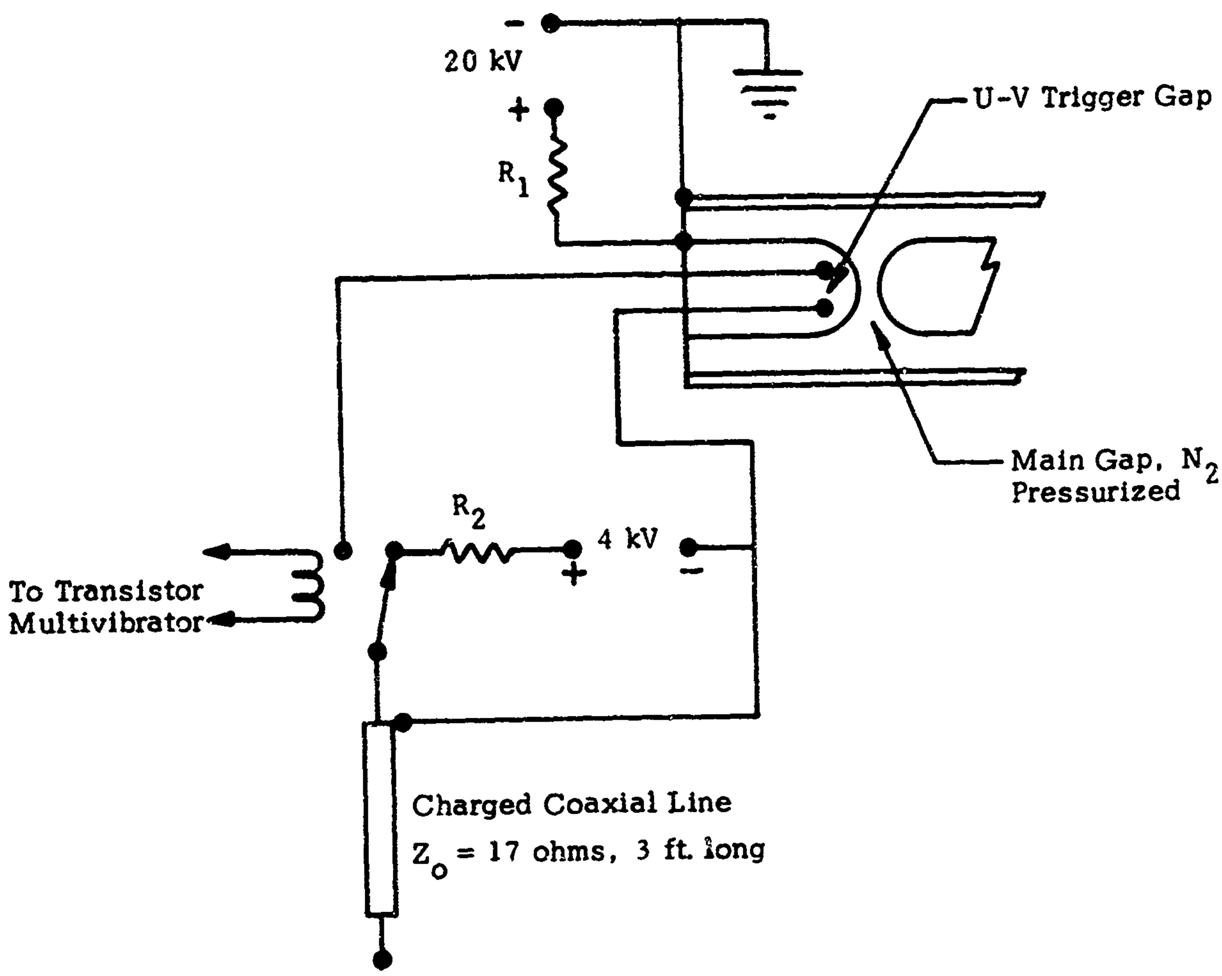


Fig. 9. Schematic diagram of the U-V trigger circuit using a charged line coaxial pulser switched with a modified mercury-wetted relay.

dielectric material can therefore be expected. This will be of importance for generator operation above X-band where higher pulse currents are required and for multiple-sphere operation with a uniform video line where voltage is very high. (See Section II-D.)

C. Pulse-On DC Triggering

U-V triggering has the disadvantage of adding another spark gap, with attendent life problems, to the pulser system. Triggering of spark gaps is also possible by charging the gap with a dc voltage somewhat below the breakdown voltage and then superimposing a trigger pulse. This trigger method was tested with a modification of the SCR switching circuitry described in QPR No. 2. The ITT trigger transformer shown in that circuit was replaced by an isolating transformer and an EG & G TR-69 pulse transformer. A 15-kV pulse with 5-μsec rise time was obtained with an open circuit load. This pulse amplitude was reduced to 8 kV when connected to the 4-ohm coaxial-pulse forming line, which has a capacitance of 200 pF. Triggering performance was poor due to interaction between the triggering circuit and the dc charging current. Although further circuit refinements might give improved performance, this triggering method will be dropped in favor of triggering circuits using impulse-charging or U-V triggering.

D. Thyratron Pulser

A charged condenser pulser with a 6279 Amperex thyratron is being constructed. This pulser will be used to: (1) test impulse-charging with a charged 2000-pF condenser and, (2) provide a 16-kV source for U-V triggering of a low-pressure spark gap. (0 to 20 pounds.)

V. CONCLUSIONS

Detailed consideration has been given to various approaches to increasing RF output power by the use of multiple YIG ferrite spheres. It is concluded that (1) types which use series pulsed-field coils spaced along the video line are subject to pulse-current distortion which will result in decreased output per sphere and increased RF combining problems (Type A and B) and, (2) the most feasible approach to increasing power by an order of magnitude is to use a uniform video-line approach in which the video line passes through a resonant cavity containing the YIG sphere (Type C). The disadvantage of Type-C is that the pulser requirements are increased. (60 kV, 1.3 kA.)

VI. IDENTIFICATION OF KEY TECHNICAL PERSONNEL

Key technical personnel and respective man-hours devoted to the contract during this reporting period are listed below.

L.D. Buchmiller, Senior Research Engineer	239 hours
W. Mitchell, Research Technician	165 hours

VII. FUTURE WORK

Work will concentrate chiefly on the Type-G generator to (1) develop optimum cavity resonators and RF combining circuits and, (2) develop a suitable Darlington-type pulser.

Experimental evaluation of the modified pulsing technique in which the angle between pulsed and dc magnetic field is optimized for maximum power output will be completed.

Some further evaluation of pulse-current distortion in Types A and B, which use series pulsed-field coils, will be performed.

The feasibility study concerning the solid-state switch will be directed toward obtaining a theoretical estimate of the intrinsic limit of the di/dt capability of thyristors. Other types of solid-state switches, as represented by the glass threshold[1] switch and the pin structure, will also be evaluated.

The final experimental model of a triggered pulsed-ferrite generator will be delivered.

VIII. REFERENCES

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4. ... glass switch is mentioned in the February 1968 issue of Scientific American, p. 52. References to the original work is being sought. The switching time can be less than 150 ps. Threshold voltage is said to be "many hundreds of volts".

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APPENDIX

The responses of an inductively loaded transmission line of characteristic impedance Z_o to a step-voltage input are shown in Fig. A-1. These responses were calculated using Laplace transform techniques applied to transmission line terminations. The coil separations for the 2- and 3-inductor case are sufficient so that the coils are isolated from each other in time. That is, the time delay between coils is greater than the pulse width. This is similar to the isolating lines used in the spark-gap pulse generator. The limiting case shown in Fig. A-1 is for the three coils connected so closely together that they combine to form an inductance of 3L. Note in particular the degradation of the initial response for two and three coils widely spaced, where a parabolic-shaped response is obtained. Typical values of Z_o and L are 7 ohms and 10^{-9} henry so $\tau = L/2Z_o \approx 0.07$ ns.

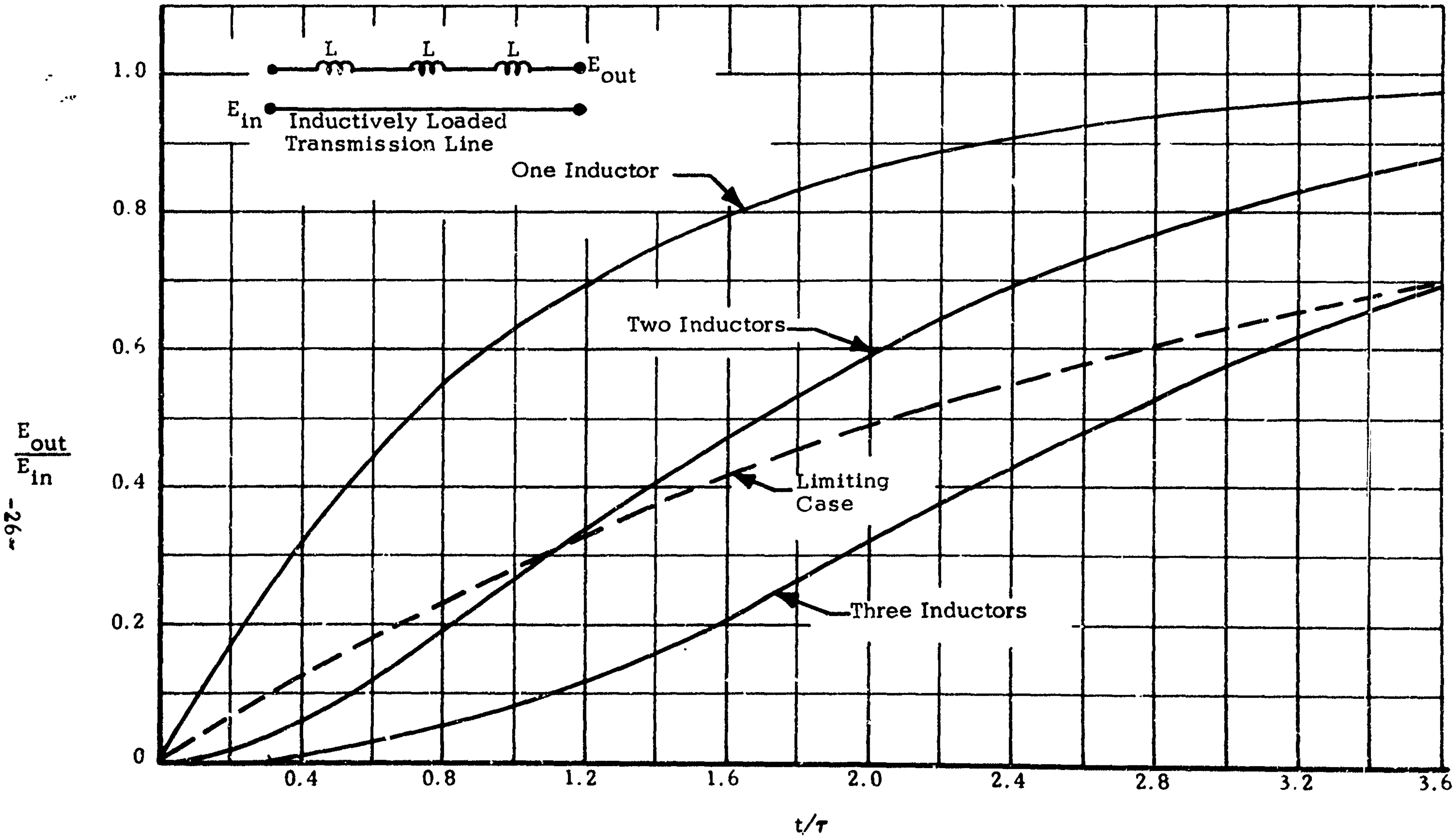

Fig. A-1. Calculated responses to step-voltage input for inductively loaded transmission lines.

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	U.S. Army Electronics Command Fort Monmouth, New Jersey 07703 Attn: AMSEL-KL-TG

13. ABSTRACT

Methods of increasing the output power of the pulsed-ferrite X-band generator using multiple YIG ferrite spheres are described.

A preliminary survey of solid-state switch capabilities is given for possible future replacement of spark-gap switches used in the charged-line pulser.

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Nanosecond Pulses						

INSTRUCTIONS

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