LB-855

FREQUENCY CONTROL OF MODULATED MAGNETRONS BY RESONANT INJECTION SYSTEM

RADIO CORPORATION OF AMERICA
RCA LABORATORIES DIVISION
INDUSTRY SERVICE LABORATORY

FEBRUARY 8, 1952

RADIO CORPORATION OF AMERICA

RCA LABORATORIES DIVISION

INDUSTRY SERVICE LABORATORY

LB-855

Frequency Control of Modulated Magnetrons by Resonant Injection System

Approved

Stuart W. Seeley

Frequency Control of Modulated Magnetrons by Resonant Injection System

Introduction

The purpose of the investigations described in this bulletin is to evaluate the merits of magnetron oscillators as transmitter tubes when they are frequency and phase controlled by injection-locking to a standard frequency source. The magnetrons used in this work were normal multicavity magnetrons containing a cathode, a plate, and an output loop. Special attention was given to the production of amplitude-modulated r-f carriers and also to the production of frequency- or phase-modulated carriers. The amplitude-modulated carrier was produced by modulating the d-c plate voltage of the magnetron. The angular-modulated magnetron carrier was produced by angular modulation of the standard frequency source. The investigations are not closed yet, but the results obtained are encouraging for the application of magnetrons to services where previously only triodes or tetrodes were considered as potential power tubes.

General Discussion

If the d-c plate voltage of an unstabilized magnetron is modulated with a superimposed a.c., varying output frequency will be observed. Continuous frequency changes are called "pushing" and discontinuous changes, "moding". Two systems, similar in operation, which eliminate these frequency changes will be discussed. The frequency controlling ability of one of the systems, which was worked out in most of its details, is effective in suppressing the pushing and also the moding, when 100 per cent amplitude modulation is applied to the magnetron carrier by modulation of the plate, or even when the magnetron is heavily over-modulated.

To use a magnetron as an amplitude modulated r-f power source and to keep the carrier frequency constant by injection of a current from a standard frequency source was proposed by Irving Wolff in 1936.[1] This idea preceded by many years the necessity of using carrier frequencies higher than the practical upper frequency limit of high-power amplifier tubes then available. Furthermore, the magnetron has been developed into a reliable power tube only during the past ten years.

Interest in the phase control of microwave oscillators by injection of a locking current was awakened as a result of work done at M.I.T. and reported in 1948. E. E. David, Jr.[2] showed that a klystron, at a frequency somewhat higher than 3,000 Mc, can be phase locked to another microwave oscillator. The power was injected into the oscillator by a directional coupler. David's results represented an important advance. His scheme, however, was not applicable for phase control of anode-modulated oscillators because a considerable part of the c-w injection power was absorbed by the loading resistor of the controlled oscillator. Thus the maximum obtainable amplitude-modulation factor would be rather limited in this system. Furthermore, the injection current flowed

[1] U.S. Patent 2,113,225.

[2] M.I.T. Report No. 63, "Locking Phenomena in Microwave Oscillators".

through an attenuator. Consequently, the requirement of the injection power was relatively high.

The Purpose of the Work

The present investigations were directed toward the problem of using uhf or microwave oscillators as r-f power generators to produce amplitude- and angular-modulated high-power carriers with a frequency and phase stability which meets practical transmitter requirements. Low injection power for stabilization is a prime requirement. The most attractive high-power generator is the magnetron with a carrier-output to d-c-input efficiency of about 60 per cent. The experimental work on the frequency stabilizing systems was done with developmental Type A-128 magnetrons[3] built at the RCA Laboratories and operated up to one-kilowatt level at carrier frequencies of 750 and 825 Mc. The Type A-128 magnetrons include an electron beam for frequency-modulation purposes. The frequency-modulator beam, however, was not used during these experiments. It is believed that the system can be operated also at higher power levels and at different frequency ranges.

The frequency deviation, due to the pushing of an amplitude-modulated unstabilized magnetron, is substantially independent of the modulating frequency, thus it is similar to a frequency-modulation process. Unstabilized pushing up to 1 per cent of the carrier frequency was observed during amplitude modulation, and several megacycles additional frequency change were observed when the amplitude modulation was increased through the low level moding region, which must be done if 100 per cent amplitude modulation of the magnetron carrier is desired. Measurements have shown that, when the magnetron is stabilized, the remanent effect of the previously observed pushing depends on the amplitude modulating frequency, and consequently, it is similar to the character of a phase modulation of low argument. The argument decreases only at very high amplitude modulation frequencies.

[3] J. S. Donal, Jr., R. R. Bush, C. L. Cuccia, and H. R. Hegbar, "A 1-Kilowatt Frequency-Modulated Magnetron for 900 Mc.", *Proc. I.R.E.*, Vol. 35, pp. 664 to 669, July 1947.

The Resonant Injection System

One form of the Resonant Injection System is represented in Fig. 1. A Class C amplifier tube is placed in cavity "k". The grid of this tube is excited with a subharmonic of the output frequency. The amplifier tube in this case is a grounded grid frequency doubler. The plate cavity of "k" is tuned to the magnetron frequency, f_m. In this circuit the r-f voltage of the magnetron is present between the plate and the grid of the Class C doubler tube because the plate cavity of "k" is excited also with magnetron voltage. The plate-cathode circuit of the triode is only loosely coupled to the magnetron voltage. Consequently, the triode absorbs little power from the magnetron. The grid-cathode gap is the most delicate part of the injection amplifier tube and must be protected from overloading. Parallel to this gap is coupled the grid exciting cavity, as indicated in Fig. 1. This cavity is tuned to one-half the magnetron frequency, $f_m/2$, consequently it has low reactance to the magnetron output frequency, f_m. Thus the magnetron output power cannot build up a high voltage between the grid and cathode, and the grid-cathode gap is, therefore, protected.

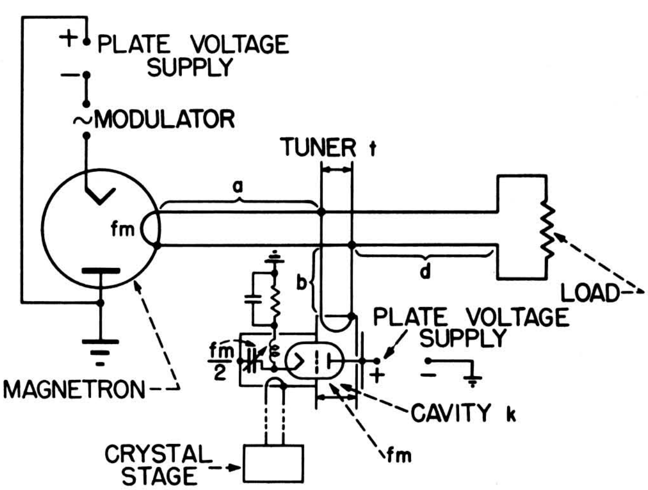

Fig. 1 – Resonant injection system.

The transmission lines "a" and "b" in Fig. 1 have optimum lengths. Line section "a" should be chosen to transform the dynamic input impedance of the oscillating magnetron into an impedance which at the low end of the amplitude-modulation cycle should be much smaller than the input impedance of the line section "d", seen from the junction point toward the load. The impedance of the section "d" toward the load is equal to the load resistance provided the "d" line section is matched. If the low input-impedance requirement for the section "a" is satisfied, the injection current from line "b", at the low end of the amplitude modulation cycle, is transmitted mainly to the magnetron and the load receives only a small portion of it. The length of line "b" is determined by the requirement of the injection-voltage transformation and of the magnetron loading. Additional tuners on the transmission line may adjust the proper loading of the magnetron.

In the case of an amplitude-modulated magnetron system, it is important that at the low end of the amplitude-modulation cycle the amount of injection power which flows to the load, if any, should be extremely low because this injection power reduces the depth of modulation of the output carrier. A 95 per cent modulation in the load, computed from the peak carrier voltage, can be obtained in this system. In this case the magnetron is 100 per cent modulated. The remanent 5 per cent amplitude, which is due to the injection power in the load, represents only 0.25 per cent of the peak output power.

The Power Requirement of the Injection Source

This above low power of 0.25 per cent of the peak power does not represent the entire required injection power. The condition can be analyzed by considering the standing wave patterns in the transmission line. Line 1 of Fig. 2 shows the standing-wave pattern of the injection voltage for the low power end of the modulation cycle when the magnetron output is 100 per cent modulated, so that no magnetron current flows in the line. The junction of the main transmission line and the injection transmission line is indicated by "X" in Fig. 2. At point "X", as a consequence of the previously described tuning condition, the injection has a low voltage, Δe_i, which is almost zero. The existance of an almost zero voltage plane of the injection standing wave, and the relative position of this plane with respect to the

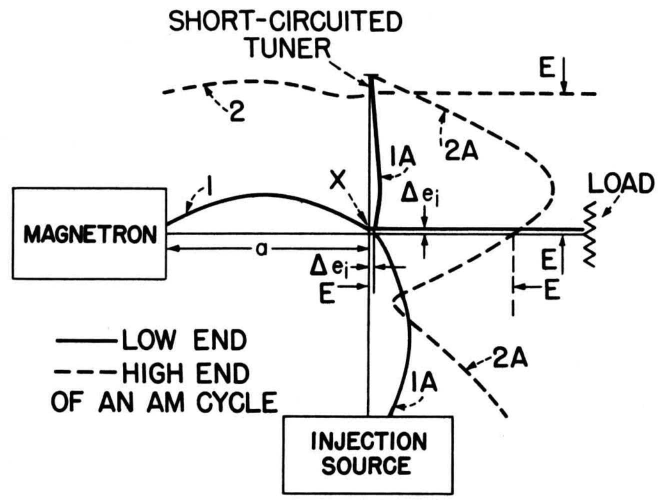

Fig. 2 - Standing-wave ratio in a resonant injection system.

magnetron input, proves that the magnetron shows an almost pure reactance of low absolute value to the injection voltage at the low-power end of the AM cycle where the magnetron is cut off. The reactance can be inductive or capacitive, depending on the setting of the internal magnetron tuner. The load, coupled into the system at point "X", absorbs only a very low amount of injection power at the low-power end of the modulation cycle. If the magnetron input reactance changes, and the standing wave pattern does not have an almost zero voltage plane at "X", a finite injection voltage appears on the transmission line which is terminated by the load. This happens at different output power levels; thus, the load absorbs more injection power during most of the AM cycle than it does at the low end of the cycle. The modulated output envelope, which is composed of the magnetron carrier and, at some levels, injection power, is almost perfectly linearly related to the voltage input to the modulator.

The injection source must also deliver power to cover the losses of the circulating high resonant injection current in the transmission line and in the cavities. The investigations are not yet completed on the question of the requirement of the power capacity of the injection source. As a practical example, for one kilowatt of magnetron peak power, a grounded grid triode, similar to the type-5588, in frequency-doubler service produces sufficient injection current at carrier output frequencies below 1,000 Mc.

Standing-Wave Ratio of the Magnetron

Line 2a in Fig. 2 represents at the high end of the amplitude-modulation cycle the voltage standing wave, produced in a short-circuited tuner and in the injection line terminated by a lossless injection source. The voltage standing-wave pattern in line "a" is represented by nearly unity standing wave ratio in Fig. 2 by line 2. In a properly tuned system the standing-wave ratio is close to its minimum at the high power end but it is not necessarily unity. However, the standing-wave ratio in line "a" is subject to changes during an amplitude-modulation cycle. The standing-wave ratio increases as the power is lowered. The magnetron frequency and phase are determined by its own internal tuning and by the external impedance presented by all the circuit elements coupled to the transmission line. The presence of injection power in the load and the variation of the same dynamically changes the impedance of the load seen from the magnetron, thus influencing the phase of the magnetron output. The injection current acts for the magnetron as an externally applied reactance. The effect of the reactances, presented to the magnetron by the injection currents is a synchronized operation of the magnetron with the injection source.

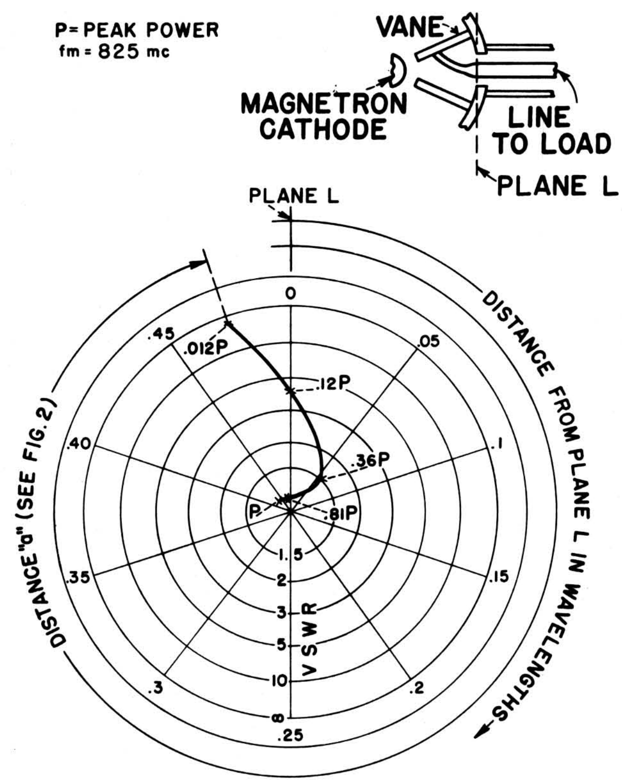

Fig. 3 – External load measured at plane L during AM cycle.

If the free-running magnetron frequency is nearly equal to that of the injection source at the top of the amplitude modulation cycle, then the maximum frequency correction must be supplied at the low end of the cycle. At this point the externally applied dynamic susceptance, due to the injection source, must have its greatest value. The voltage standing-wave ratio in the line outside the magnetron will be highest at the low end of the amplitude-modulation cycle, as is the case in Fig. 3. It should be noted that as the magnetron power is decreased toward the low end of the amplitude modulation cycle there is a decrease in the effective load resistance presented to the junction between the line and the magnetron loop. This junction is marked as plane L in Fig. 3.

The Limits of the Amplitude Modulation

Oscilloscope pictures of the demodulated carrier are reproduced in Fig. 4. If the sine-wave modulation, represented by Fig. 4a, is increased up to the limit where the magnetron carrier is 100 per cent modulated, the detected envelope shows the form of Fig. 4b. The remanent injection voltage amplitude, Δe_i, can be observed now on the scope. The magnetron starts and stops oscillating at each modulating cycle without breaking out of synchronism. At different modulating frequencies up to 100 kilocycles square-wave modulation was applied to the magnetron. The r-f envelope, detected by a diode, reproduced the square wave with low distortion, (Fig. 4c). Amplitude-modulating frequencies up to several megacycles can be applied. The r-f bandwidth which can be transmitted is about 2 per cent of the carrier frequency.

Angular Modulated Magnetron Output Carrier

It was proven experimentally that if the injection power is frequency or phase modulated, the frequency of the magnetron output carrier

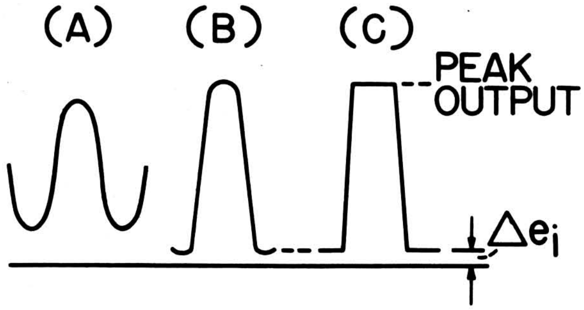

Fig. 4 – Demodulated output envelopes.

follows the angular modulation with high fidelity at least up to several hundred kilocycles deviation. The magnetron carrier frequency deviation is increased between the angular-modulated stage and the magnetron output. If the grid of the driver tube has, for example, 100 kilocycles deviation, the magnetron carrier has 200 kilocycles deviation. This is natural in the previously discussed circuit. It is true also, however, in a different phase control scheme, where the control frequency is different from the magnetron output frequency. Such circuits will now be described.

Synchronizing by a Subharmonic Frequency

Besides the previously described system, another synchronizing system was developed. In the system, represented by Fig. 1, the driving frequency of the injection source is a subharmonic of the magnetron output frequency. The plate-cavity of "k", however, is tuned to the magnetron frequency, f_m, and the injection current has the same frequency. In the system, represented by Fig. 5, the plate-cavity of "k" is tuned to a subharmonic of the output frequency and the synchronizing current, injected into the magnetron cavities, is also a subharmonic of the magnetron frequency. A magnetron output frequency of 750 Mc was used in the experiments and the subharmonic frequency was chosen as 375 Mc. The magnetron was loaded by a dummy antenna which terminates the transmission line. The magnetron output loop with line sections "a" and "b" and cavity "k" are tuned now to 375 Mc. The length of "a" is limited for 375 Mc by a high-pass filter. Thus, the injection power does not flow toward the load. The high-pass filter had a simple construction.

In some experiments an open circuited 750-Mc half-wave-length line was connected parallel to the main transmission line. This line element shows high impedance for the 750-Mc magnetron frequency at the junction, but represents a quarter wavelength open-circuited line, which produces a virtual short-circuit for the 375-Mc injection frequency. A Class C amplifier tube placed in cavity "k" excites this resonant system with 375 Mc. The grid circuit of the Class C amplifier tube was driven by the sixth subharmonic of the magnetron output frequency. The magnetron cavity was tuned to 750 Mc and, although it also forms part of a 375-Mc tuned system, it oscillates only at 750 Mc. The magnetron output carrier locks to the doubled control frequency.

The question may arise as to how the injected half-frequency voltage controls the magnetron output frequency. Cold test has shown that the magnetron vanes, where the output loop is coupled, were excited with the 375-Mc voltage. Injection voltage of 6 per cent of the d-c plate voltage was measured on the end of these vanes. Such an a-c voltage is sufficient to 100 per cent amplitude modulate the magnetron carrier, if it is superimposed on the d-c plate voltage. This, however, happens here only for some vanes. One kind of interaction may be due to the plate voltage changes with the injection frequency. Another possible kind of interaction is a conversion process which produces the doubled injection frequency in the magnetron which is a diode type device. The doubled injection frequency is the magnetron output

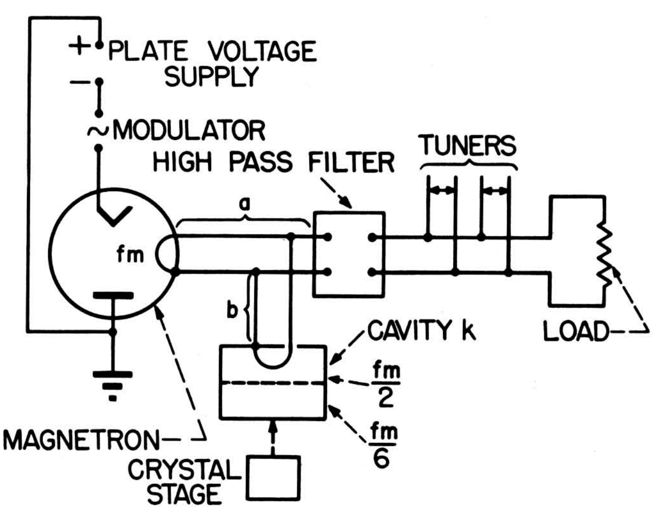

Fig. 5 – Subharmonic resonant injection system.

frequency and the system may work as in the previous case.

The reactive elements, which are the line "b", the coupled cavity "k", and sometimes the high-pass filter, may, in certain combinations, introduce unwanted magnetron standing waves. This effect can be reduced properly by the stub tuners. These have no action on the tuned circuit of the synchronizing frequency if they are placed on the load side of the high-pass filter where no synchronizing frequency is present. The amplifier tube in cavity "k" cannot be damaged by the magnetron power because no high magnetron voltage can be built up in this cavity as it is tuned far away from the magnetron frequency.

General Requirements of Resonant Locking Circuits

The requirements of a practical resonant locking system can be summarized as follows:

1. A high circulating synchronizing current should be produced in the magnetron cavity to obtain stable phase locking. This requires a resonant tuning of the injection source, including the magnetron input element.

2. The synchronizing current (at least on the low power end of the modulation) should not flow to the load, in order to permit deep amplitude modulation and also to avoid loading of the injection source.

3. The injection tube should be protected from the magnetron power with reactive and not with resistive circuit elements. In this manner the protective elements work practically without injection- and magnetron-power loss.

All these requirements are fulfilled in both described circuits. In Fig. 1 the proper selection of the electrical lengths of the transmission line satisfied the second requirement alone. In the case of subharmonic synchronizing, as shown in Fig. 5, a high-pass filter was added for the same purpose, but the high-pass filter could be omitted and the same effect could be obtained by proper selection of the line lengths also at subharmonic synchronizing frequencies.

Summary of Results

The characteristic behavior of a magnetron stabilized by the previously described systems is radically changed. Not only are the natural jitter and the pushing due to plate modulation practically suppressed, but also the low-level moding disappears. A magnetron which, with a given load, uncontrolled, cannot be modulated to a power output below 100 watts, due to low-level moding, in controlled condition starts dynamically and statically from no output, and its power can be increased up to the peak output without the production of any other frequency than that determined by the crystal. Of course, the sideband frequencies are also produced if the magnetron is modulated. The plate power efficiency at the peak of the modulation cycle is about 60 per cent. If the r-f output power is reduced, due to modulation, the plate power input is reduced also, almost proportionally.

The crystal-controlled magnetron can be applied practically in a manner similar to a Class C stage, even if electronically no analogy exists between them. These experiments demonstrate a way of obtaining high crystal-controlled transmitter power with good efficiency in the high-frequency regions where conventional amplifier tubes are limited in output power.

L. L. Koros

L. L. Koros

RCA Victor Division