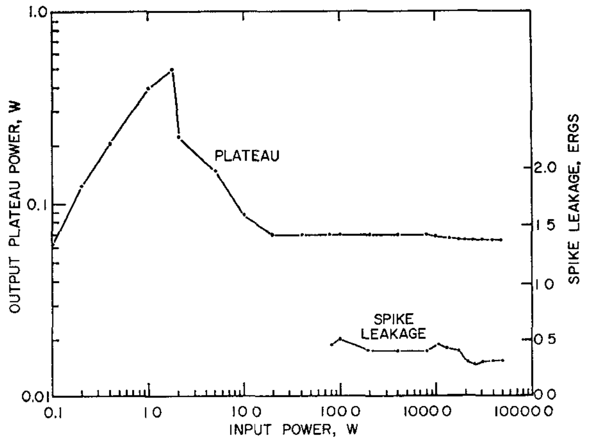

Fig. 13—Power response of four-section solid-state limiter.

Conclusion

The X-band limiter described in this paper indicates the feasibility of building an all solid-state device capable of complete crystal protection. Obviously, a substantial engineering effort is still required before this type of limiter can become practical for system use. Thus, a reduction in size, weight, cost and insertion loss is vital in order for this device to compete successfully with presently available TR tubes. Nevertheless, such improvements will undoubtedly come, particularly in those systems where the present TR tubes are not satisfactory.

Acknowledgment

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On Spurious Outputs from High-Power Pulsed Microwave Tubes and Their Control*

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Summary—**Excessive spurious outputs from high-power pulsed magnetrons, klystrons and traveling-wave tubes can cause intolerable radiation interference and deleterious effects in a high-power microwave system. The harmonic output from a klystron may vary appreciably with changes in operating conditions. Harmonic outputs from tubes cannot be eliminated but their radiation can be significantly reduced by using filters. If the parasitic or spurious oscillations are very strong, adverse effects such as amplitude and phase instability of the fundamental frequency output may occur. Some of the spurious outputs may be reduced or eliminated by redesign of the tube or its modulator.**

Introduction

THE emission of spurious outputs from microwave tubes has been known for a long time. Spurious outputs are defined as those frequency components other than the fundamental frequency with its normal sideband modulation components.

With steady increase in transmitter power level, receiver sensitivity, and density of radiating equipment, the problem of spurious outputs has taken on greater significance in terms of radiation interference [1], [2]. As the power levels of high-power tubes have increased so have the spurious output power levels. In a microwave system, the presence of spurious power may have deleterious effects such as arcing in chokes, arcing at flanges and undesired leakage through ionized duplexers. In addition, if a large amount of spurious power is generated, the tube efficiency may be decreased; it may cause other harmful effects to the tube and an objectionable amount of amplitude and phase instability may be added to the fundamental frequency output.

The presence of spurious frequencies usually can be detected at the tube output, provided that the spurious frequency is above cutoff of the output transmission line. If the spurious frequency is below cutoff and the spurious signal amplitude is sufficiently large, its presence may be inferred from any phase and amplitude instability of the fundamental frequency output. This instability may adversely affect the system of which the tube is a part without interfering with other nearby systems.

Although the frequencies can be measured with relative ease, the power levels are much more difficult to ascertain [3]–[6]. Spurious outputs other than harmonics are often quite erratic. Since a methodical redesign study of a high-power tube is generally costly,

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time consuming, and frequently inconclusive, the amount of progress made in suppressing these outputs has been limited.

This paper briefly summarizes the spurious outputs from high-power pulsed magnetrons, klystrons, and traveling-wave tubes. Some control methods are also discussed. Tubes which are designed for long pulse and continuous (CW) output operation may also generate spurious signals caused by ion oscillations [7]–[10]. These signals may modulate the amplitude of the beam, and the frequency may range from a few kc to a few Mc. Ion oscillations will not be discussed further in this paper.

MAGNETRON

Besides harmonics from pulsed magnetrons, anharmonic frequencies are occasionally generated which are due to moding within the RF structure of the magnetron. Although harmonic generation cannot be prevented due to the nature of the electron cloud within the magnetron, anharmonic frequencies can be controlled to a certain extent by appropriate design of the magnetron and its modulator. The second harmonic power may be about 40 db below the fundamental but the third harmonic can be as strong as 20 db below [4]. Filtering has been found successful in reducing the radiation of harmonics [11], [12] as well as anharmonic [13] frequencies. Additional spurious outputs from magnetrons may be due to space-charge effects [14], [15].

KLYSTRON

There are several possible types of spurious outputs from a pulsed klystron, for instance, harmonics, diode oscillation, drift tunnel oscillation and others. The amount of spurious frequency power depends on many factors, but most heavily upon tube design, manufacturing tolerances and operating parameters.

Harmonics

Harmonic frequency components are usually present on the electron beam in a high-efficiency, high-power klystron. Measurements made on one klystron using multiple probe techniques have shown the second harmonic power may be 35 db below the fundamental frequency power and the third may be 40 db below [16]. There are many operating parameters on a klystron which will affect the harmonic power output, such as pulse length, frequency within band, detuned cavities, magnetic field, input RF drive power level, saturated power output, beam voltage and output load impedances at the spurious frequencies.

Fig. 1 illustrates the variation in second harmonic power radiated from a VA-87B klystron as a function of frequency within the design band [16]; it is to be noted that the power is a minimum near midband. Fig. 2 illustrates the variation in second harmonic power as a function of beam voltage. At the recommended beam voltage of 90 kv, the second harmonic power is a minimum. Additional measurements were taken and the results showed the large dependence of harmonic power on operating parameters. It should be mentioned that these data were obtained on a specific tube under specific operating conditions and that these are not necessarily representative of all klystrons.

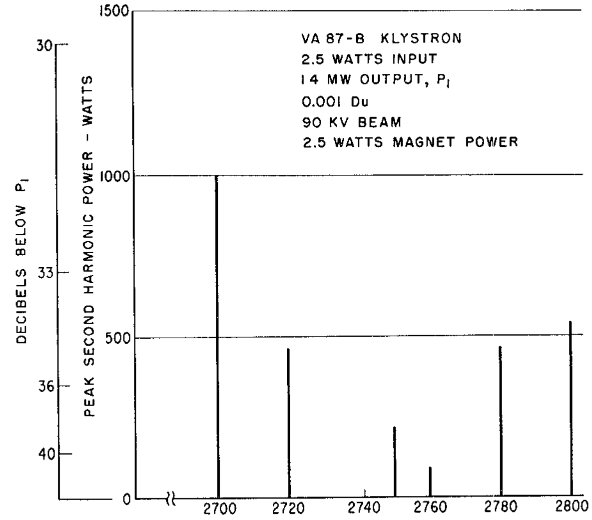

Fig. 1—VA 87-B klystron harmonic output as a function of frequency.

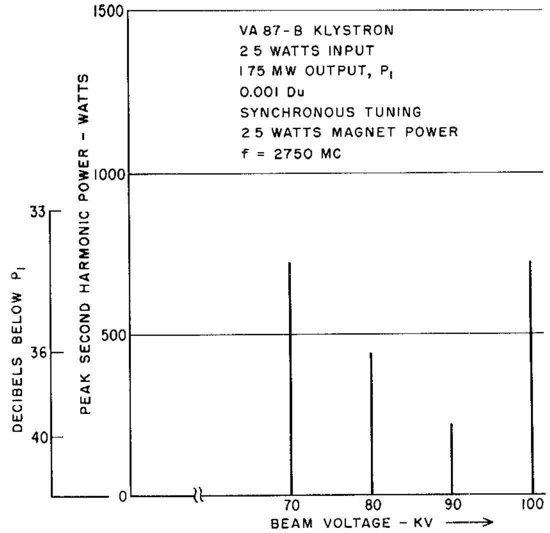

Fig. 2—VA 87-B klystron harmonic output as a function of beam voltage.

As for a control method, it is difficult to eliminate completely the harmonic components on the beam. An alternate method is to design cavities which would present low circuit impedances at the harmonic frequencies. Considerable work has been carried out on this approach at Cornell University with encouraging results [17]. For expediency, the use of filters has been found effective in reducing the amount of radiated power at the harmonic frequencies.

Diode Oscillation

Under certain operating conditions, Llewellyn shows that high-frequency oscillations are possible between a planar cathode and anode in the appropriate geometry [18]. These are called diode oscillations and this type of oscillation can sometimes be found in the electron gun of a high-voltage klystron. Diode-oscillation frequencies may be below, within, and even above the design frequency band of the tube.

The conditions required to cause these oscillations are

1) A dc beam transit angle of about $n+\frac{1}{4}$ RF cycle at frequency f is needed to generate a negative resistance across the diode, where n is any integer. The magnitude of this resistance must be sufficiently large to overcome the circuit losses.
2) An electromagnetic circuit with sufficiently high Q is resonant at frequency f.
3) Sufficient coupling exists between resonant circuit and electron beam.

On a particular S-band multimegawatt klystron which had erratic diode oscillations, probing techniques showed that two of the resonant electromagnetic modes associated with the diode oscillations were localized in the annular region between the cathode and anode housing [19]. These two resonant modes had a Q in excess of 1000, and the modes were identified as the TE_{41} and TE_{61} modes in a coaxial line. Although the fields of the resonant modes were not in close proximity with the negative-resistance electron beam, there was sufficient coupling to drive the circuit into oscillation. The erratic oscillations had approximate frequencies of 1400, 2500 and 3650 Mc; these frequencies agree very closely with calculated values.

The geometry of the electron gun has a profound influence on the frequencies and on the likelihood of diode oscillations. The oscillations can be prevented by failing to satisfy the three conditions listed above, *e.g.*, by lowering the Q of the resonant circuit [20]. Filters can prevent radiating these spurious frequencies; however, if the oscillation is sufficiently severe, it may cause a detrimental amount of amplitude and phase instability of the fundamental frequency output. The latter adverse interdependent effect is a result of the electron beam which couples to both the diode oscillation and amplifying circuits. Unfortunately, this adverse effect cannot be eliminated by using a simple filter.

Drift Tunnel Oscillation

Based on the report of spurious output from a Stanford University klystron [21], an analysis was made on the possibility of TE°_{11}-mode oscillations in the circular drift tunnels between cavities [22]. The calculated frequency agrees very closely with the reported spurious frequency of 5770 Mc. The conditions for oscillation are the same as those listed above for diode oscillation, with the exception that the transit angle refers to transit through the tunnel. The transverse electric field in the resonant circuit displaces the beam transversally. The displaced beam provides the coupling between beam and circuit, and it converts some of the kinetic energy of the beam to a negative RF resistance in the circuit. The latter is a consequence of beam deceleration from an antiphased longitudinal component of the fringing microwave field at the emergent end of the drift tunnel [23].

If drift tunnel oscillations occur, the frequencies may be two or three times higher than the design frequency band of the klystron. These spurious frequencies must be above cutoff of the TE°_{11} mode in the circular drift tunnel and this cutoff frequency f_c is given by [24]

$$f_cD = 6917 \text{ Mc}\cdot\text{inch}$$

where D = tunnel diameter in inches.

Very little can be stated at present as to control since the erratic oscillation behavior has generally prevented a systematic study of it. Undoubtedly a strong magnetic focusing field would reduce the amount of transverse-beam displacement, and hence, the possibility of oscillation.[1] Also, a smaller beam diameter may reduce the coupling. Filters could prevent radiation of this spurious signal, but if severe, an objectionable amount of phase and amplitude instability of the fundamental frequency output may occur.

Monotron Oscillation

Within a single cavity, an oscillation may occur which is called monotron oscillation [25]–[29]. The conditions for oscillation and the means for its suppression are the same as for diode oscillations.

Other Spurious Outputs

Other spurious signals may be generated due to unintentional feedback either external or internal to the tube.

TRAVELING-WAVE TUBE

Some of the spurious outputs from a high-power pulsed traveling tube are similar to those from a high-power klystron, while others are not. The tube design, manufacturing tolerances and operating parameters have large effects on the power level of the spurious outputs.

Harmonics

Harmonic frequency components are usually present on the electron beam in a high-efficiency, high-power traveling-wave tube. Limited measurements [16], [30] show that the second harmonic power may be 20 to 40 db below the fundamental frequency power. The operating parameters affect the harmonic power levels the same way they affect the klystron. Filters have been

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[1] Beam diameter enlargement and asymmetry may be caused by the magnetic field of the heater current. See A. S. Gilmour, Jr., "Effect of filament magnetic field on the electron beam from a Pierce gun," Proc. IRE (Correspondence), vol. 49, p. 976; May, 1961.

found effective in absorbing the undesired harmonic power.

Diode Oscillation

There is basically no difference in the design of electron guns for klystron and traveling-wave tube for the same power level. Hence, the cause and adverse effects of diode oscillations and redesign methods to eliminate these oscillations are the same as for the klystron.

Band-Edge Oscillation

When traveling-wave tubes are pulsed, "band-edge" or "rabbit-ears" oscillations are sometimes detected in the output [31], [32]. These extremely short pulses occur at the beginning and at the end of the beam current pulse. The frequency is approximately equal to the high-frequency end of the pass band of the tube structure, hence the name, band-edge oscillation. The frequency-time relationship of these oscillations is shown graphically in Fig. 3.

The mechanism for generating band-edge oscillation can be explained by referring to Fig. 4 which shows an ω-β plot of a traveling-wave tube. The slope of the line passing through the origin is equal to the velocity of the electron. At the rated beam voltage, the electron velocity is equal to the circuit phase velocity.

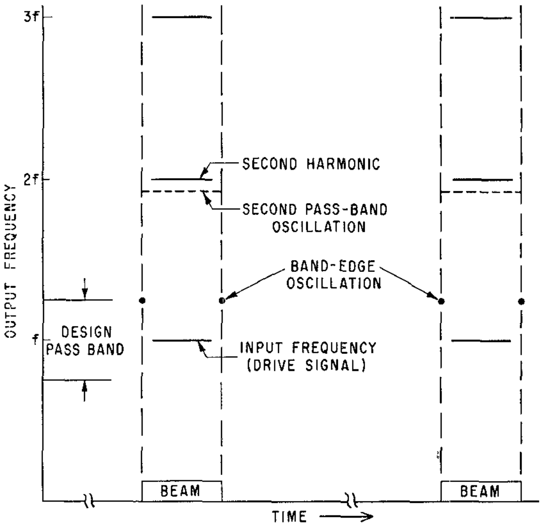

Fig. 3—Spurious output from traveling-wave tube.

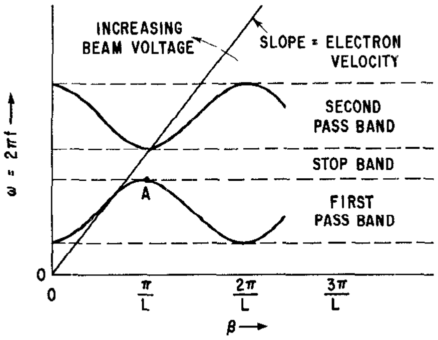

Fig. 4—ω-β diagram for traveling-wave tube.

When the electron velocity starts from zero, as under pulsed operation, the line passing through the origin will start with a small slope which progressively increases as the beam voltage increases. Prior to reaching the rated voltage, the line will pass through point A on the first pass band ω-β curve. It is at this brief instant of time when a backward-wave oscillation occurs within the tube.

Band-edge oscillations may be eliminated if the rise and fall in beam voltage can be made sufficiently fast. They can also be eliminated in a tube which employs a control grid or modulating anode. Filters can prevent radiating these spurious outputs.

Second Pass-Band Oscillation

Depending on its structure and operating parameters, a traveling-wave tube while amplifying a signal whose frequency is in the first pass band sometimes may oscillate simultaneously at a higher frequency in the second pass band. Since this spurious oscillation is quite rare, very little is known of techniques for its suppression. While filters may prevent the radiating of the second pass band oscillation, a severe oscillation in the tube may cause adverse amounts of phase and amplitude instabilities in the signal being amplified. It is conceivable that oscillations may occur at frequencies in pass bands higher than the second.

Other Spurious Outputs

Other spurious outputs in a traveling-wave tube that are associated with higher-order asymmetrical electromagnetic modes within the slow-wave structure, and generated by rotationally asymmetrical components of the beam current may be possible.

CONCLUSION

Several types of spurious outputs from high-power pulsed microwave tubes have been discussed. At least three of the spurious outputs, *viz.*, diode, drift tunnel and monotron oscillations, are caused by negative resistances generated from beam transit time effects. Some control methods are mentioned.

Filters are useful in suppressing the radiation of many spurious frequencies, notably harmonics, generated by high-power microwave tubes. Severe spurious oscillations may cause objectionable phase and amplitude instabilities of the output at the fundamental frequency. Further study is required to eliminate all spurious outputs from high-power tubes.

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Practical Design and Performance of Nearly Optimum Wide-Band Degenerate Parametric Amplifiers*

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***Summary*—The design of a two-resonator single-diode degenerate parametric amplifier is described, which incorporates features that give it nearly optimum wide-band performance. These features include the use of almost lumped circuit elements, a separate pump resonator which is very lightly coupled to the diode and pump circuits, and a diode resonated in series rather than in shunt, from which several advantages accrue. A bandwidth of 21 per cent with 15-db midband gain (double channel) is obtained at 1 Gc using two resonators, as compared with 8 per cent using one resonator. Both measured responses are found to be in excellent agreement with theoretical responses obtained with a digital computer. The measured double-channel noise figure was 1 db. Theoretical and experimental results are presented which show this type of amplifier to be remarkably insensitive to tuning errors. Good results were also obtained using two identical amplifiers in balanced operation with a 3-db coupler so as to eliminate the need for a circulator.**

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