Stabilization of the Frequency of Relativistic S-Band Magnetron With Radial Output

Arkadii Sayapin, Andrey Levin, and Yakov E. Krasik

***Abstract*— The results of experimental research on the stabilization and tuning of the frequency of a relativistic S-band six-resonator magnetron powered by a linear induction accelerator ($U \approx 300$ κB, $I \approx 2.5$ kA, and $\tau \approx 150$ ns) are presented. The frequency of the microwaves was stabilized using a partial reflection of the generated microwave power $P \approx 300$ MW from the output of the magnetron and a proper adjustment of the phase of the reflected microwaves.**

***Index Terms*— High-power microwave compressor, relativistic magnetrons.**

I. Introduction

THE relativistic magnetron (RM) can be considered as promising powerful microwave source among other high-current relativistic microwaves generators [1], [2]. However, even though the RM generates microwave pulses with a power hundreds of times larger than the power obtained from conventional magnetrons with thermionic cathodes, the RM is not comparable with the latter in terms of the stabilization of the frequency of the generated microwaves. This drawback significantly limits RM application. For instance, experiments [3] showed that the RM can be used as a pumping source for microwave compressors. Namely, compression of the microwave pulses generated by the RM supplied by a ∼270 kV voltage pulse of 120 ns duration resulted in microwave pulses with a power of ∼1.1 GW and duration of ∼10 ns, which can be considered a remarkable result. However, this research also showed nonreproducible compressor operation because of the unsatisfactory amplitude and frequency stability of the microwaves generated by the RM. One of the reasons for the change in frequency could be the time and space evolution of the cathode plasma resulting in a change in the electrodynamic properties of the RM [4]. In addition, the oscillation circuit of the RM with a relatively low quality Q-factor is characterized by a sufficiently dense frequency spectrum. This can lead to mode competition during the voltage pulse, which is applied between the cathode and anode and is nonrectangular in form [5].

It was supposed [5] that the application of an additional resonator with a high Q-factor, which is commonly used for adjusting and stabilizing the frequency of microwaves generated by conventional nonrelativistic magnetrons, is limited because of the relatively short duration of the microwave pulses generated by RMs. In addition, the high power of the microwaves was considered as a very possible reason for electrical breakdown in the location of the connection between the RM and the additional resonator.

In recent research studies [6], it was shown that even insignificant mismatching of the RM with a load leads to a considerable change in the parameters of its operation. For instance, a small change in the thickness of the dielectric window of the output antenna causes a significant change in the spectrum of the generated microwave pulse [6]. It was also shown that a change in the frequency dependence of the reflection coefficient of the electromagnetic (e/m) wave from the load could cause either a fast decrease in the frequency of the generated waves or stabilization of the frequency. Thus, we can consider stabilizing and varying the frequency of e/m waves generated by RM by applying positive feedback, which could be formed by correct mismatching between the RM and load, and by adjusting the phase of the reflected e/m wave.

II. Experimental Setup

In this paper, two approaches were investigated for varying and stabilizing the frequency of e/m waves generated by a six-resonator S-band magnetron (Fig. 1). The magnetron consists of an anode (height: 72 mm and inner diameter: 46 cm) and a 19-mm diameter cathode. The microwave power was extracted through a slot (10×72 mm^2) made in the wall of one of the resonator cavities. Because the width of the cavity's external wall was 14 mm, in practice, we can consider this resonator to be open. Outside the anode, the slot continues as a waveguide; the height of its E-plane wall is increased and its cross section is 34×72 mm^2 at its end, which is typical for a conventional waveguide. The RM was powered by a linear induction accelerator delivering to the RM a pulse with voltage and current amplitudes ≤300 kV and ≤2.5 kA, respectively, and duration ∼100 ns at full width of half maximum. A pressure of ∼1 mPa inside the experimental system was maintained by turbo molecular pumps, and an external magnetic field formed by Helmholtz coils was varied in the range 2.2–3.2 kG. The parameters of the microwave radiation were measured and analyzed using an Agilent Infiniium DS080404B oscilloscope (4 GHz, 40 GSa/s). For the analysis of the microwaves' frequency [Fast Fourier Transform (FFT)], only one channel of the oscilloscope was used, resulting in a sampling rate of 40 Gs/s.

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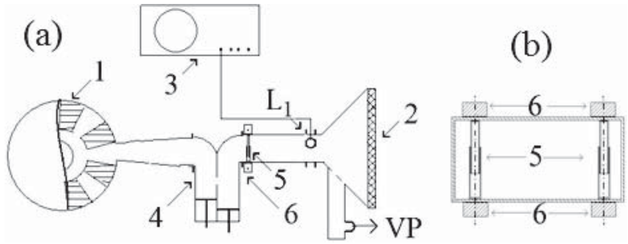

Fig. 1. (a) Experimental setup. 1. Magnetron. 2. Horn antenna. 3. Digitizing oscilloscope Agilent Infiniium DS080404B. 4. Phase shifter. 5. Reflector. 6. Neodymium magnets. L_1, is the B-dot loop. (b) Reflector with coaxial cylinders (5) and magnets (6).

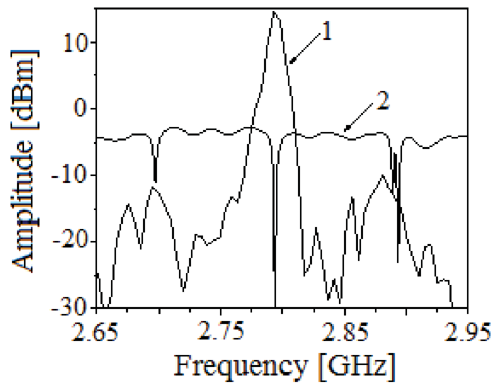

Fig. 2. 1. FFT microwave pulse. 2. Reflection coefficient at the entrance to NR.

III. Experimental Result

In the first approach (Fig. 1), a microwave signal was registered by a B-dot loop (item L_1, Fig. 1) placed at the input of the horn antenna. A reflector (item 5, Fig. 1) and waveguide phase shifter (ATM-WR-410) (item 4, Fig. 1) was placed between the magnetron and antenna. The reflector comprises a rod consisting of two thin ($\delta = 0.3$ mm) coaxial cylinders inserted one inside the other and having closed tops. The cylinders were made of magnetically soft steel and the internal diameter ($d = 4$ mm) of the outer cylinder was equal to the outer diameter of the inner cylinder. This design allows one to vary the length of the rod, which was placed inside the waveguide parallel to its narrow walls, thus short circuiting its wide walls. Outside, on both sides of the waveguide, neodymium magnets (item 6, Fig. 1) were placed. These magnets attract the cylinders, thus providing electrical contact between the cylinder's top surfaces and the walls of the waveguide. In experiments the rods were placed at a distance of 10 mm from the narrow wall (E-plane) of the waveguide, which results in a reflection coefficient (module value) $\Gamma \approx -4$ dB of the e/m wave from the location of the rods. Now, we can consider a new resonator (NR) consisting of the magnetron's resonator and the space between the rod and magnetron. The e/m wave reflected at the resonance frequency of the NR will be in the same phase as that of the e/m wave in the resonator of the magnetron, thus providing positive feedback of the magnetron. The resonance frequencies of the NR were determined using the values of the reflection coefficient of the e/m wave from the NR's input. These cold measurements were performed with a network analyzer (ROHDE&SCHWARZ–ZVL, 9 kHz to 3, 6, or 13.6 GHz, wide dynamic range: >115 dB, typ. 123 dB) connected to the B-dot loop which was inserted in the NR, i.e., into the space between the magnetron and rods. The minimum in amplitude of the reflected signal from this B-dot loop corresponds to the resonance frequency of the NR. It was found that the NR is characterized by three resonance frequencies in the range 2.7-3 GHz. This range matches the frequency band of the RM operating on a matched load at different values of magnetic field. Thus, three resonances can be tuned using positive feedback frequency in the range from 2.7 to 3 GHz. The values of the resonance frequencies of the NR were determined by the position of the phase shifter. The degree of matching of the NR at different resonance frequencies changes differently depending on the shift from resonance frequencies (Fig. 2). For the major part of the frequency range, the degree of matching of the NR at different resonance frequencies was approximately the same. Only for some values of the phase-shifter positions, corresponding to one or two resonance frequencies of the NR, did the degree of matching become significantly high.

The level of the matching of the resonator at a resonance frequency is determined by the energy losses of the e/m wave in the resonator. We can suppose that different matching of the NR is related to the frequency dependence of the energy losses through the open edge surfaces. At two positions of the phase shifter, a major part of the generated microwave pulses has FFT with only one amplitude maximum, and the frequency of microwaves coincides with one of the feedback frequencies (Fig. 2). In these cases, the RM generates microwave pulses with $f = 2780$ MHz at $B = 2.6$ kG and $P = 250 \pm 30$ MW and $f = 2820$ MHz at $B = 2.4$ kG and $P \approx 200 \pm 30$ MW. A decrease in the value of the magnetic field led to a decrease in the power of the microwave pulse. In the intermediate positions of the phase shifter, the FFT characteristic showed two or three maxima that differed from each other by ≤ 3 dB. Thus, the application of positive feedback simultaneously at several resonance frequencies leads to competition in the microwaves generation at different frequencies and, respectively, to rather sharp fluctuations of the amplitude of the generated pulses and to a decrease in the level of the generated power.

The experimental setup for the second approach that allows one frequency, at which positive feedback frequency of the RM is realized, to be selected, is shown in Fig. 3. In this setup, the phase shifter (item 4), placed at the output of the RM, was connected with the input of the directional coupler (item 5) having a matched load (item 7) at its output. Between the matched load and coupler, a tee waveguide (item 6) was inserted with its open output connected to the waveguide terminated by a movable short-circuited plunger. This tee waveguide reflects the forward e/m wave almost completely at some discrete frequencies. This method of e/m wave reflection is used to obtain the resonance condition for microwave compressors [7]. In the present setup, the tee waveguide is a reflector that allows one to realize feedback at

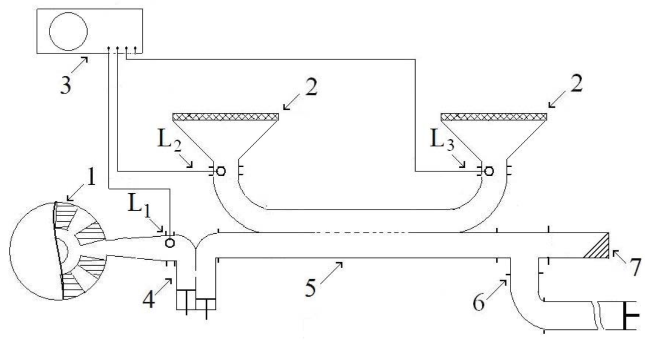

Fig. 3. Experimental setup. 1. Magnetron. 2. Horn antenna. 3. Oscilloscope (Agilent Infiniium DS080404B). 4. Phase shifter. 5. Directional coupler. 6. Tee waveguide with one of the outputs connected with the waveguide which is short circuited by movable plunger. 7. Matched load; $L_{1,2,3}$-B-dot loops.

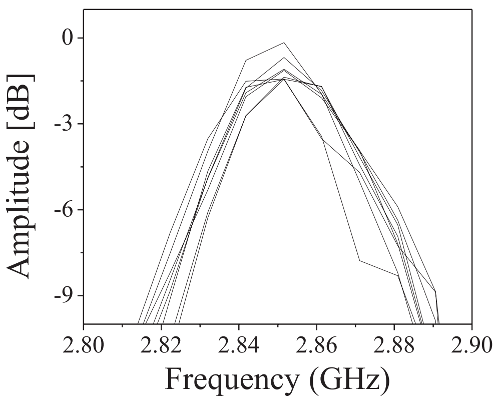

Fig. 4. Frequency characteristics of the pulse train at a resonance at a frequency $f = 2.850$ GHz and the magnetic field $B = 2.8$ kG.

several frequencies. The coupling coefficient of the directional coupler was $K \approx -6$ dB. In this case, around half of the microwave power entering the directional coupler was radiated in free space by two horn antennas (here, forward e/m waves and e/m waves reflected from the reflector were considered). The remaining part of the power was returned to the RM. The phase of the reflected e/m wave, determined by the condition of the resonance of the NR, was set using the phase shifter. Here, the NR consists of the RM resonator, waveguide shifter, and input waveguide of the directional coupler. If the electrical lengths of the NR and short circuited part of the tee waveguide do not coincide, the NR will have resonance only at a frequency that corresponds to the total reflection of the e/m wave from the tee waveguide. For the length of the short circuited part used in this experiment, the e/m wave was reflected from the tee waveguide at three frequencies that were in the range 2.7–3.0 GHz corresponding to the range of frequencies of the microwave radiation generated by the RM operating on a matched load with different values of the magnetic field. Using a phase shifter, the electrical length of the NR was changed showing resonances of the NR at one of these three frequencies. Using this setup, it was found that the RM generates reproducible microwave radiation at two feedback frequencies. The power radiated by antennas was measured using B-dot loops ($L_{2,3}$) placed at the input to antennas. The total microwave power radiated by two antennas was $P = 300$ MW at $f = 2848$ MHz and $P = 250$ MW at $f = 2940$ MHz. Several FFT of microwave pulses presented in Fig. 4 shows stable RM operation at $f = 2848$ MHz. Here, let us note that, for each feedback frequency, the maximal power of the generated microwave radiation was obtained at different values of the magnetic field. For instance, for $f = 2848$ MHz the maximal power was obtained at $B = 2.8$ kG and for $f = 2940$ MHz the maximal power was obtained at $B = 2.4$ kG. The frequency that corresponds to the maximal amplitude of FFT remains constant with accuracy $\Delta f = \pm 5$ MHz limited by resolution of Infiniium DS080404B oscilloscope. Finally, when the position of the phase shifter was adjusted for the third lowermost feedback frequency, $f \approx 2760$ MHz, a change in the RM operation was not obtained as compared with its operation on the matched load. In this case, the generated power was dissipated in the matched load and, partially, i.e., at -6-dB level, was radiated into free space by one of the antennas.

IV. Summary

To summarize, this paper showed that the frequency of the microwave radiation generated by the RM with radial output can be stabilized by partial reflection of the generated microwave power from the output of the magnetron using a proper adjustment of the phase of the reflected e/m wave. It was also shown that within the total spectra of possible frequencies generated by the RM, the frequency of the microwave radiation can be stabilized at the frequency of the positive feedback of the magnetron.

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