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A Profiled Stepped Reflector for Mode Selection in Power Microwave Generators of Ultrashort Pulses

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Received April 14, 2023
Revised October 12, 2023
Accepted November 7, 2023

Selective reflection of a spatially-developed mode of a cylindrical waveguide is investigated as applied to a radiation output and a feedback circuit closing in power microwave generators of ultrashort pulses. The profile and the ratio of the parameters of the stepped reflector has been found providing the maximum suppression of the spurious modes at the given loss level of the working mode within the wide frequency band. It is shown the frequency bandwidth of the reflector of the axial-symmetric mode E_{02} reaches 10% over the level 0.9 relative to the maximal value of the reflected power.

Keywords: profiled stepped reflector, generator of ultrashort pulses, electrodynamic mode selection, axial-symmetric mode, millimeter-wave range.

DOI: 10.61011/PJTF.2024.03.57037.19592

Realization of unsteady generation currently appears to be a promising approach for generating powerful pulses of radiation of short duration in the centimeter and, especially, millimeter wavelength ranges, which was reflected in the [1–6]. Unsteady generation based on the superradiation mechanism can provide both single ultrashort microwave pulses [7–10] and their quasi-periodic sequences. These sequences can be obtained, for example, in automodulation modes [11], in systems with brightened nonlinear elements included in the feedback ring [1–5], and by introducing reflections at the ends of the interaction space [6].

The pulses generated in these modes are characterized in a short duration and, correspondingly, wide bandwidth of the frequency spectrum. Increasing the output power of such radiation sources and their advancement into an increasingly higher frequency range require the use of spatially evolved electrodynamic systems operating at high eigenmodes. Thus, electrodynamic reflectors *4* (Fig. 1, *a*) that provide radiation output or feedback closing must have very high selectivity. Bragg reflectors and mode converters, widely used in high-power microwave electronics, are not always able to satisfy this condition, and therefore there is a need to develop alternative electrodynamic elements.

The reflector, which is a stepped extension of the waveguide [4,5,12–15], is the most compact one out of the alternative selective elements. However, its frequency bandwidth must be significantly increased to handle short duration pulses. An improved selective reflector with a profiled stepped extension was proposed and numerically simulated in [5], where it was designed for an 8-mm ultrashort pulse oscillator with two parallel emitting and absorbing electron beams. This oscillator was designed for the lowest mode HE_{11}, and the reflector had to

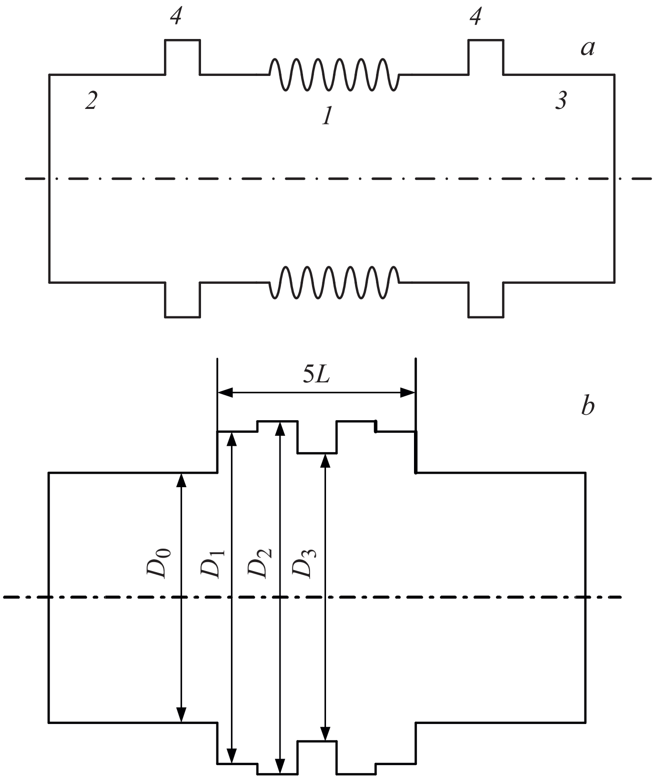

Figure 1. Schematic diagram of the electrodynamic system of a powerful microwave generator of ultrashort pulses. *a* — general scheme: *1* — interaction space, *2* — electron beam input, *3* — waveguide for radiation output, *4* — selective reflectors. *b* — simulated profile of a selective broadband five-stage reflector *4*.

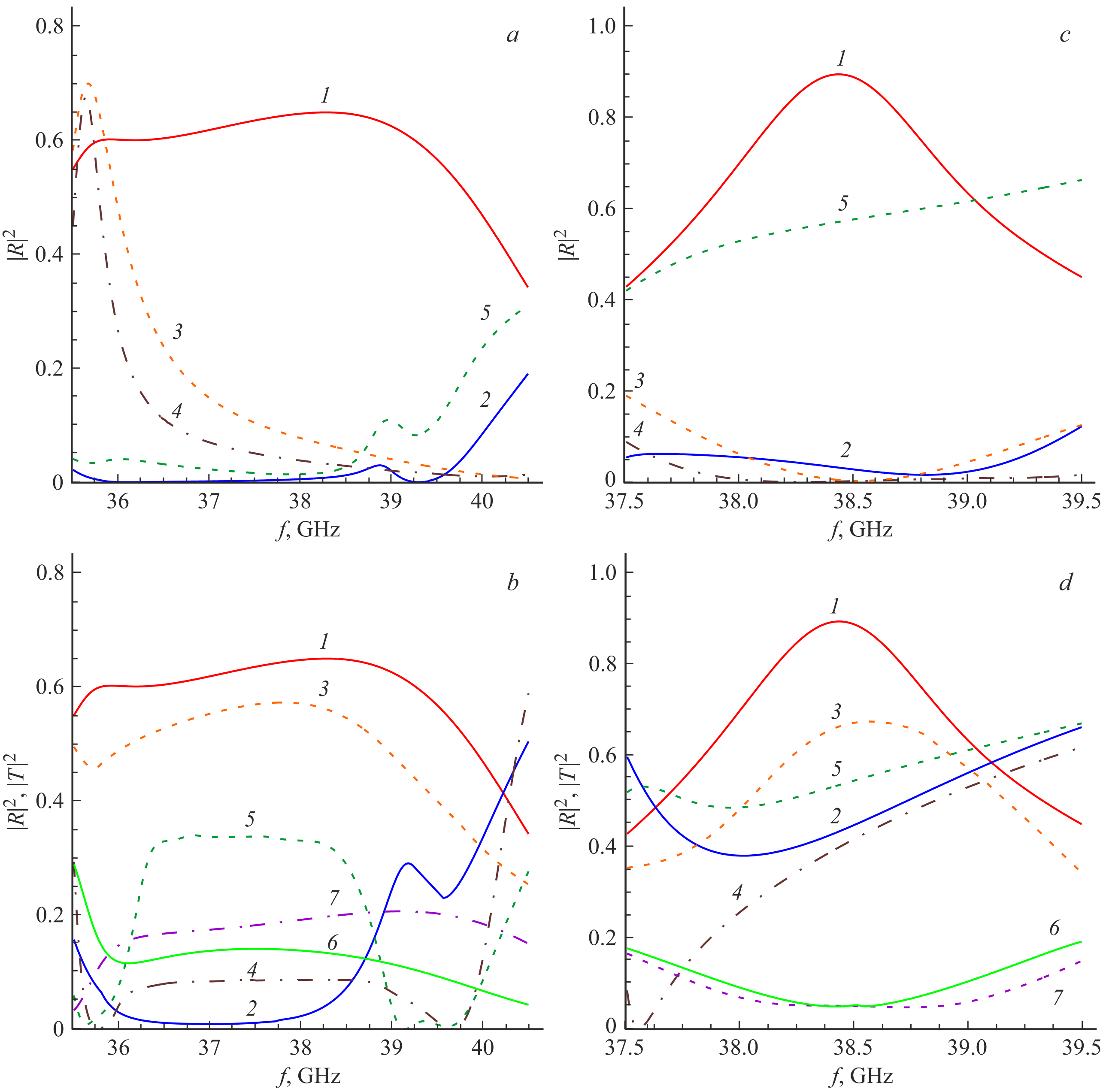

Figure 2. Frequency dependencies of reflectors with the maximum reflection levels 0.65 (a, b) and 0.9 (c, d). a, c — mode reflection E_{02} (*1*) and the lowest modes H_{11} (*2*), E_{01} (*3*), H_{21} (*4*), E_{11} (*5*); b, d — mode reflection E_{02} (*1*), reflection of higher modes H_{31} (*2*), E_{21} (*3*), H_{12} (*4*), E_{12} (*5*) and mode transformation E_{02} to the mode E_{01} reflected (*6*) and transmitted (*7*).

provide in the cylindrical waveguide outputting the radiation a broadband reflection of the lowest mode H_{11} while minimizing the reflection of the only parasitic mode E_{01}. Obviously, mode selection in ultrashort pulse oscillators with spatially evolved electrodynamic systems becomes much more complicated, since a minimum reflection in a wide frequency band must be provided for each of a large number of parasitic modes.

The typical operating mode for realized short duration microwave pulse sources is an axially symmetric oscillation of E-type [7–10]. Simulation of the selective broadband reflector in the framework of the present work was carried out for the axially symmetric mode E_{02}, the selection of which allows one to successfully realize additional cyclotron resonance selection in Cherenkov relativistic oscillators [16,17]. The Brillouin angle of the working mode in the cylindrical waveguide was constrained in the limits 40–50° to adapt to the characteristic design of high-power, short duration microwave oscillators. The 8-mm wavelength range was selected for simulation. The simulations were carried out using ANSYS Electromagnetic Suite 2022 R2 [18] software code in neglecting ohmic losses.

The profile of the selective broadband five-stage reflector obtained from the simulation is shown in Fig. 1, *b*. The profile is symmetrical and the lengths of its five sections are identical. The operating oscillation of a broadband reflector is a normal oscillation of two partial modes of unprofiled stepped expansion [5]. The strain profile and the ratio of its parameters were preliminarily evaluated via the perturbation method [5,19] to obtain the required coupling and frequency detuning between these partial modes, as well as to ensure the absence of parasitic resonances over a wide frequency band. The central strain section is designed to offset in frequency the parasitic resonances due to propagating modes with radial index smaller than that of the working oscillation. The sections adjacent to the strain center are designed to offset parasitic resonances due to propagating modes with the same radial index as the working oscillation, and primarily the nearest mode H_{12}. Tuning of the reflector to a given center frequency is performed by selection of parameters of two extreme strain sections.

The selective broadband profiled stepped reflector can also be simulated in a similar way for both the H_{12} mode and the E_{0p} and H_{1p} modes with higher radial indices.

The simulation results of the profiled stepped reflector demonstrated its high selectivity at different reflection levels of the working mode. The power-normalized frequency dependences of reflectors with maximum reflection levels of 0.65 and 0.9 for the mode E_{02} are presented in Fig. 2 (R and T — reflection and transmission coefficients). The frequency band for the first reflector variant reaches 10% above 0.9 of the maximum reflected power; for the second variant it reaches 1.5%. The first variant reflector profile (Fig. 1, *b*) is described by the parameters $D_0 = 19.7$ mm, $D_1 = 24.8$ mm, $D_2 = 28.9$ mm, $D_3 = 19.9$ mm, $L = 1.9$ mm; the second variant profile (Fig. 1, *b*) is described by the parameters $D_0 = 20.8$ mm, $D_1 = 26.7$ mm, $D_2 = 29$ mm, $D_3 = 23.2$ mm, $L = 2$ mm.

Thus, the conditions that maximize the reflection level contradict the conditions that maximize the frequency bandwidth, which requires a compromise to be found when implementing a reflector for each specific source. The frequency dependences of the working mode in both variants are smooth and almost symmetrical with respect to the carrier frequency (Fig. 2); hence, such a reflector will not introduce significant distortions in the shape of the reflected pulse.

Low reflectances for parasitic modes prevent the possibility of their self-excitation in a wide frequency band (Fig. 2). The simulation of each reflector variant also took into account that it should provide a small level of transformation of the working mode E_{02} to the reflected parasitic mode E_{01} (Fig. 2, *b*, *d*). Nevertheless, electronic selection of the most dangerous parasitic modes should be provided in the design of each particular source. Thus, the mode E_{21}, the closest to the working mode among E-modes, may require exactly electronic selection, since the shifts in the frequency of their partial oscillations caused by wall profiling are almost indistinguishable.

The range of values of maximum electric field strength on the reflector surface at rounding of its sharp edges with a small radius of curvature $(0.05-0.1)\lambda$ [13], typical for microwave oscillators of ultrashort pulses with a characteristic peak power level of 1 GW, was determined during simulation. The maximum electric field strength on the reflector surface for both its variants is within $1-1.4$ MV/cm, which does not exceed the values typical for high-power pulse devices [13,14].

The results obtained allow us to conclude that the proposed reflector can be used at least up to the upper limit of the submillimeter wavelength range, where the influence of fabrication errors can be significant.

Note that profiled stepped reflectors can also find application in microwave oscillators operating in quasi-steady-state modes. In relativistic inverse wave tubes, they can be a compact replacement for Bragg reflectors, where they are used both for radiation output and to form the optimal longitudinal structure of the high-frequency field [17]. In Cherenkov relativistic oscillators with resonant elements, they can ensure their selective operation by using supersized electrodynamic systems [13,14,20,21].

Funding

The work was performed within the framework of the state assignment № 0030-2021-0027 (program „Development of equipment, technologies and scientific research in the field of atomic energy use in the Russian Federation for the period up to 2024").

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Kondaurov