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SHORT COMMUNICATIONS

Amplitude–Frequency Characteristics of an Electromagnetic Field in the High-Frequency Torch Discharge

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Abstract—Measured axial distributions of harmonic components of the electric field of the torch discharge in argon at different frequencies of the fundamental harmonic are presented. It is found that the fourth electromagnetic field harmonic decays in the resonance manner.

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It was found that the first two harmonics of the electromagnetic wave that propagates along the high-frequency torch discharge in air do not decay [1]. No attenuation of the first three harmonics was observed in the discharge in argon. At the same time, attenuation of the electromagnetic wave propagating along a conducting cylinder must increase with its frequency. To explain these results, an assumption was made that a parametric interaction between the external electric field and plasma natural oscillations exists in the torch discharge plasma. Because this effect is most pronounced for the discharge in argon, it is of particular interest to analyze electromagnetic wave propagation in argon discharge plasma in more detail.

This paper studies the effect of the discharge frequency on attenuation of harmonic components of the discharge electromagnetic field.

A diagram of the experimental setup is shown in Fig. 1. The discharge was initiated in a 500-mm-long quartz tube 28 mm in diameter in an argon medium. The frequency of the electromagnetic field was varied from 36.4 to 39.6 MHz. The argon flow rate was 0.5 m^3/h. The discharge power was within 0.5 to 1.0 kW.

The frequency components of the discharge electric field were measured by a capacitive probe, whose output signal was guided through a double-screen line to the input of a GSP-827 spectrum analyzer. The capacitive probe had the form of a copper post 1 mm in diameter and 3–5 mm long. The distance from the discharge axis was 60 mm. The electron temperature of the discharge plasma was measured simultaneously with the electromagnetic field characteristics of the torch discharge. The electron temperature was measured by a Shamrock SR-303i spectrograph by two methods. The first method relied on relative intensity of the copper spectrum lines. We used the 5106, 5153, and 5218 Å lines. Energies and relative probabilities of the transitions that correspond to these lines were borrowed from [2]. The second method relied on the frequency dependence of the relative intensity of the continuum of argon atoms in the wavelength range from 3300 to 4000 Å. The electron temperature was measured based on the frequency dependence of intensity of the continuum according to the technique reported in [3].

The measurements revealed that, when the discharge occurs in the frequency range from 23 to 40 MHz, the electron temperature varies insignificantly, being within 8300–8600 K on the axis of the discharge channel and within 7600–7900 K on the interface between the discharge channel and its diffusion shell. As the frequency decreases, a slight increase in the temperature is observed.

The measured axial amplitude distributions for the first four harmonics of the electric field in the torch discharge are shown in Fig. 2. The abscissa axis plots the distance from the electrode to the measurement

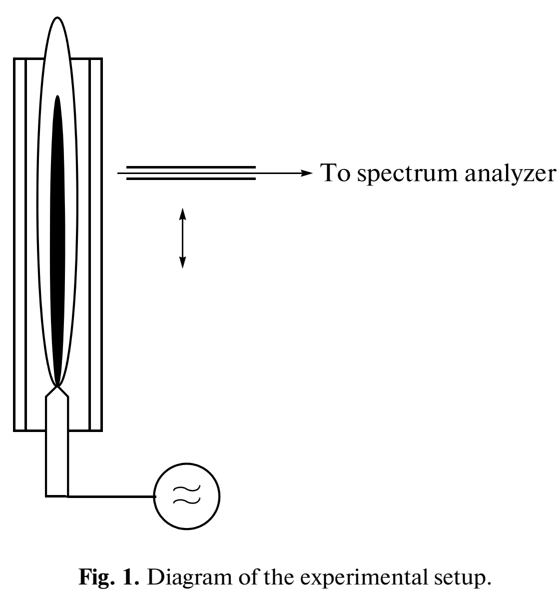

Fig. 1. Diagram of the experimental setup.

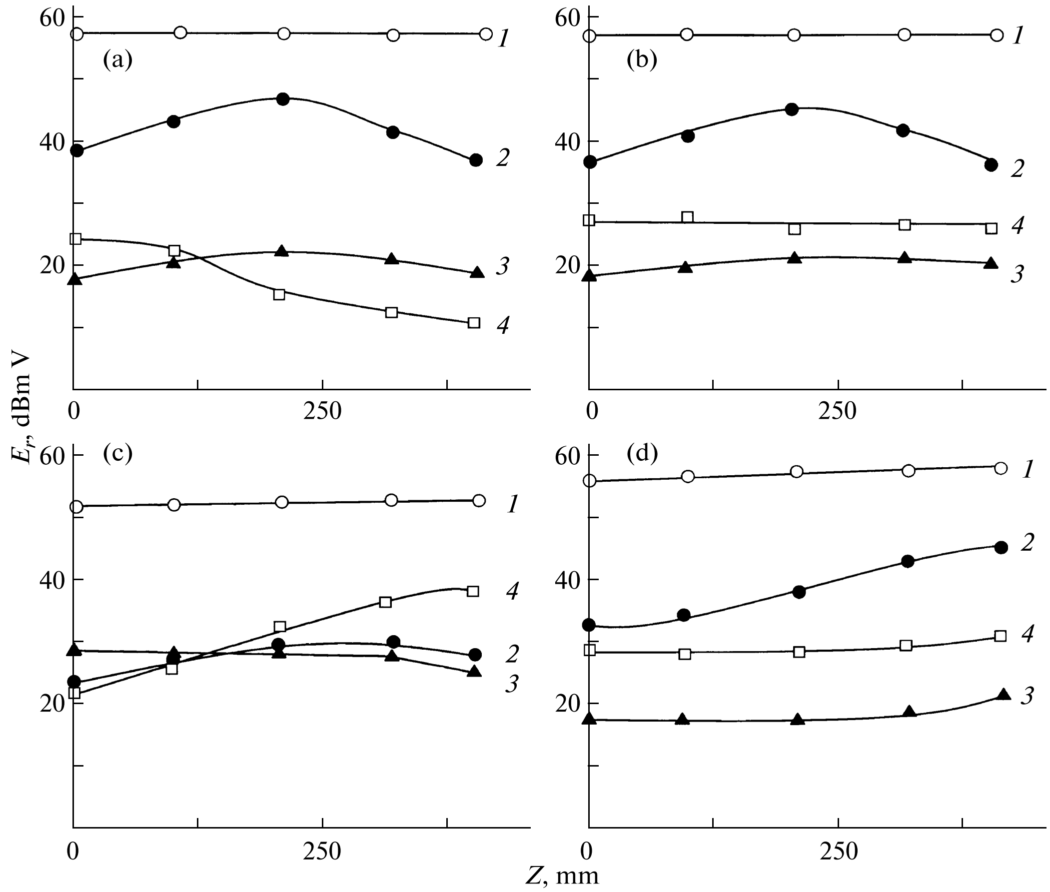

Fig. 2. Axial distribution of harmonic components of the electric field of the high-frequency torch discharge in argon: (*1*) the first, (*2*) second, (*3*) third, and (*4*) fourth harmonics at (a) 39.6, (b) 38.4, (c) 37.4, and (d) 36.4 MHz.

point; the ordinate axis, the signal amplitude on the logarithmic scale. Amplitudes of the higher-order harmonics are as a rule no higher than 10 dBmV; therefore, we do not consider them here.

It is seen from Fig. 2 that the second and fourth harmonic components of the electromagnetic field vary along the discharge axis most pronouncedly. The behavior of the amplitudes of the harmonics along the discharge axis is close to the sinusoidal law. When the discharge frequency is varied, the maximum of the amplitude moves along the axis. Note that, at the frequency of 39.6 MHz, the fourth harmonic decays over the length of the discharge channel by a factor of 4. At the same time, at 37.4 MHz, its amplitude on the contrary increases by a factor of 4 to 4.5. Such a dramatic change in the behavior of the fourth harmonic component of the electromagnetic field in response to an insignificant change in the frequency suggests that a resonance takes place between natural oscillations of the plasma and oscillations of the external electromagnetic field.

On the other hand, the behavior of the harmonic field components on the discharge axis suggests that a standing wave appears as a result of overlapping of the direct wave and the wave reflected from the end of the discharge channel. Therefore, this behavior of the amplitude of the fourth harmonic can also be a consequence of the superposition of electromagnetic waves. However, our calculations performed for the case of a homogeneous electric line have shown that the change in the behavior from a pronounced decay to a pronounced growth of the field amplitude is only possible if the wavenumber of the electromagnetic wave changes manifold. Taking into account the fact that, in the case of a conducting cylinder, the wave number is proportional to the square root of the frequency, we find that the frequency must change by a factor of no less than several tens. In our case, the frequency changes only by 5–7%. Therefore, our experimental results cannot be explained only in terms of the assumption that the electromagnetic wave is reflected from the end of the discharge channel.

Let us estimate the natural frequencies of the argon torch discharge plasma. Although the argon plasma is nonequilibrium, the electron concentration can approximately be estimated by the Saha formula for the two-temperature plasma [4]. For the above electron temperatures, it yields $n_c \sim (0.2–1.0) \times 10^{21}$ m^{-3}. In this case, the electron plasma frequency will be within $\nu_e \sim (1.3–2.8) \times 10^{11}$ Hz; the ion plasma frequency, within $\nu_i \sim (450–1000) \times 10^6$ Hz. Consequently, the frequency of the fourth harmonic, $\nu \sim$ 150 MHz, will be lower than both the electron and ion plasma frequencies. Thus, for the fourth harmonic of the electromagnetic field of the torch discharge in argon, the condition for the parametric resonance holds, which, for an unbounded plasma [5], has the following form: $\nu \le \nu_e$.

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