DETERMINATION OF ELECTRON DENSITY IN PLASMA USED FOR THE WAVEGUIDE BAND-PASS FILTER CONTROL

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Introduction

Most of electromagnetic band gap (EBG) devices are realized by artificial metallic structures such as using wires to produce effective negative permittivity. In some number of papers it was shown that the glow discharge plasmas have high potentials as effective control elements in the EBG devices /1, 2/. Band-pass waveguide microwave filter can be considered as 1D EBG-structure /3/. Microwave filter constitutes waveguide section with diaphragms (metallic rods), which form the resonators with direct (or half wavelength) couplings. The frequency characteristic tuning of such waveguide microwave filter can be carried out by changing of resonators properties, for example, using plasma columns instead some metallic rods. In this case it turns out that the filter frequency characteristic is connected with plasma parameters and the possibility to determine the electron density appears. This possibility we demonstrate in this work.

In general, the permittivity of a plasma ε_{pe} for microwave at frequency ω propagated in plasma is given by

$$\varepsilon_{pe} = 1 - \frac{\omega_{pe}^2}{\omega^2(1 + i\nu/\omega)} = 1 - \frac{e^2 n_e}{\varepsilon_0 m_e \omega^2 (1 + i\nu/\omega)} \tag{1}$$

where ν is the electron collision frequency, e is the electron charge, ε_0 is the permittivity in vacuum and m_e is the electron mass. From this relation it is seen that ε_{pe} can be modified from unity to negative values according to n_e.

In the given work we have used the band-pass waveguide filter of the 3-centimeter wavelength ranges as a 1D periodical structure with gas discharge lamps GSh-5 for its control /4/.

Results and discussions

The 3-centimeter wavelength filter is formed by periodically distributed inhomogeneities in waveguide (with cross-section 23×10 mm^2 and length of 200 mm). In our case, the five open-end holes (diameter 4 mm) were drilling through the opposite wide waveguide walls with period l along waveguide. Different inhomogeneities (metallic or dielectric rods) can be installed in holes (Fig. 1).

The period of the location of rods (length resonators) is about $l = \Lambda_0/2$, where Λ_0 is a wavelength in the waveguide, which is expressed by relation

$$\Lambda_0 = \lambda_m (1-(\lambda_m/2a)^2)^{-1/2}, \qquad (2)$$

where λ_m is a wavelength corresponding to the middle of the filter bandwidth; a is the wide waveguide wall dimension ($a = 23$ mm). Thus, a character of resonance is half-wave and in case of five installed metallic rods (Fig. 1, *b*) we have four resonators with direct coupling. For the central frequency $f_0 = 10.2$ GHz ($\lambda_m = 29$ mm) the resonator lengths is $l = 19$ mm.

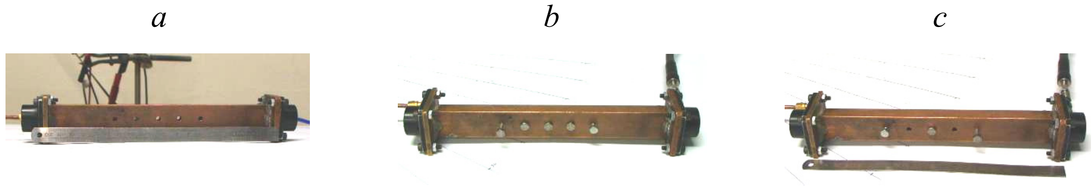

Fig. 1. Photos of the waveguide section with (*a*) hole, (*b*) 5 and (*c*) 3 metallic rods.

The amplitude-frequency characteristics (transmission spectrums) of the 3-centimeter microwave filter was measured using the vector analyzer Anritsu 37369C in the frequency range of 7–15 GHz (Fig. 2). The transmission characteristic of the filter with five metallic rods have one pass band at the frequency of about $f_0 = 10.2$ GHz. The transmission level for this band of about 10-15 dB lower than for the empty waveguide section. It can be explained by rough-and-ready manufacturing of this filter. Outside the bandwidth the transmission signal is less than -60 dB. For filter with three metallic rods installed in odd holes only (two resonators with $l = 38$ mm) the amplitude-frequency characteristic has three pass bands with the central frequencies $f_{01} = 7650$ MHz, $f_{02} = 10240$ MHz and $f_{03} = 13520$ MHz (fig. 2).

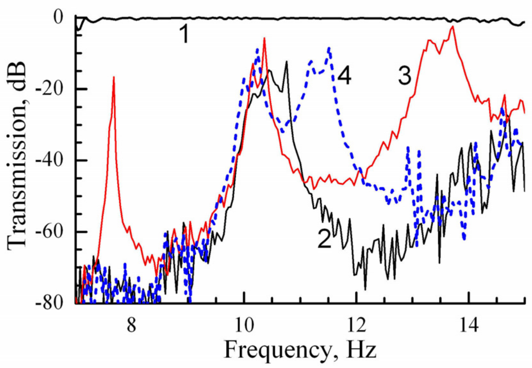

Fig. 2. Transmission of waveguide section without metallic rods (1), with 5 m. rods (2), with 3 m. rods (3), with 3 metallic and 2 dielectric rods (4).

In the experiments, the lamps GSh-5 was used as a control elements of microwave filters /4/. The total length of the lamp glass tube is 250 mm, and its internal diameter is about 3 mm. The GSh-5 lamp is filled by neon at a pressure of 70 Torr, that gives the neon atoms concentration of about $N = 2.5\times10^{18}$ cm^{-3}. If the diffusion current component is negligibly small compared with the drift and if the ion current is negligible compared with the electron one, the electron density n_e in the positive column is connected with values of current density j and the drift velocity $v_{dr}(E/N)$ by following relation:

$$j = e n_e v_{dr}(E/N), \qquad (3)$$

where *E/N* is reduced electric field in the positive column, *e* is electron charge. Current density was defined as the ratio of discharge current to the cross-section of the current area flow (internal cross-section area of GSh-5). Since the filamentary oxide cathode is used in this lamp the cathode drop voltage is small (a few tens of Volts) and electric field strength in positive column was defined as a ratio of the voltage between electrodes (about 200 V) and the interelectrode distance (200 mm). The dependence of the drift velocity of electrons from the reduced electric field in the plasma was calculated using BOLSIG + /5/. Electron densities at different currents defined by the formula (3) are presented in Fig. 3.

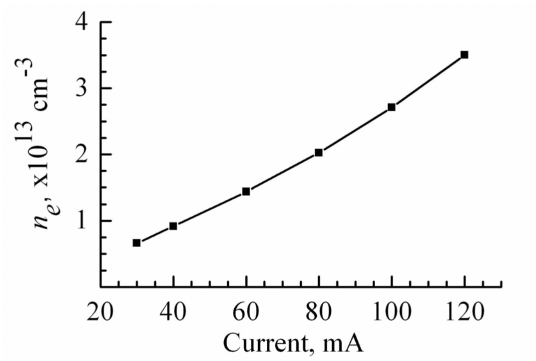

Fig. 3. Electron density in lamp against discharge current.

Let's consider the case when the filter is formed by combination of three metal rods and two lamps GSh-5 (Fig. 4, *a*). If the lamps are turn off, the waveguide section has two pass band in analyzer swath of 7-12 GHz - more narrow at 7.6 GHz and wider at 10.4 GHz (Fig. 4, *b*). With increasing current of lamps from 0 to 120 mA, a decrease of the transmission level of the bandwidth at 7.6 GHz from -10 to -50 dB was observed (Fig. 4, *b*) and it shifts toward high frequency.

The results of calculation of the filter transmission in this case for different values of electron density are presented in fig. 4, *c*. Calculations were carried out by the code HFSS Ansoft where n_e and v were used as variable input parameters. In this calculation it was supposed that $v = 2.8\times10^{10}$ s^{-1}. As it can be seen, a total suppression and shift of the transmission peak at 7.6 GHz is observed even at the electron density of 5×10^{12} cm^{-3}. This is in accordance with electron density

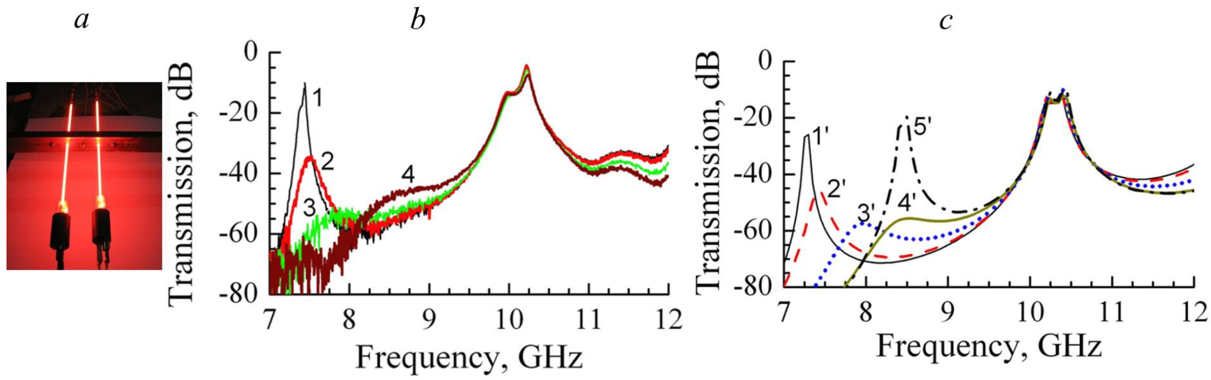

Fig. 4. Photo of waveguide section with 2 lamps and 3 rods (*a*) and corresponding experimental (*b*) and calculated (*c*) transmittance spectra.
1 – 0 mA; 2 – 6.5 mA; 3 – 29 mA; 4 – 85mA.
1' – 0 cm^{-3}; 2' – 1*10^{12} cm^{-3}; 3' – 5*10^{12} cm^{-3}; 4' – 1*10^{13} cm^{-3} $v = 2.8\times10^{10}$ s^{-1}; 5' – 1*10^{13} cm^{-3} $v = 0$ s^{-1}.

at discharge current of ~ 30 mA ($n_e = 6.6\times10^{12}$ cm^{-3}) (fig. 3). It should be noted that position of the shifted peak practically does not depend on the collision frequency. Let's use this fact in order to determine electron density in lamps.

First of all we should calibrate a pass band shift in accordance with change of plasma permittivity. For calibration we used the two alumina rods (4 mm in diameter) with known permittivity $\varepsilon = 9$ instead discharge lamp. Corresponding amplitude-frequency characteristics are shown in fig. 2. The increase of changed filter elements permittivity from 1 to 9 ($\Delta\varepsilon = 8$) leads to shifts of both the left and right pass bands toward the low frequency at the saving of the central pass band position. Unfortunately, the shift of the left pass band is so large that it is outside of analyzer swath. However we can use the shift of the right pass band ($\Delta f \sim 2200$ MHz) for calibration. It corresponds to $\Delta\varepsilon/\Delta f \sim 0.0036$ MHz^{-1}.

As it can be seen in fig 4, *b*, at discharge current of 30 mA the left pass band frequency shift $\Delta f_{\rm pe}$ is about 200 MHz and at 85 mA – 900 MHz. Then the plasma permittivity change $\Delta\varepsilon_{\rm pe}$ can be defined as the following:

$$\Delta\varepsilon_{\rm pe} = (\Delta\varepsilon/\Delta f)\times\Delta f_{\rm pe}\times(V_{\rm d}/V_{\rm pe}), \tag{5}$$

where $V_{\rm d}/V_{\rm pe}$ is a ratio of the volumes of dielectric and plasma column in waveguide. Thus we obtain $\Delta\varepsilon_{\rm pe}$(30mA) = -0.03 and $\Delta\varepsilon_{\rm pe}$(85mA) = -4.5. It gives according to (1) and without consideration of the collision frequency the electron density of 7.2×10^{11} cm^{-3} and 3.8×10^{12} cm^{-3} at 30 and 85 mA, correspondingly. If we take into account the collision frequency (2.8×10^{10} s^{-1}) according to the HFSS calculation, the electron density magnitudes will be n_e(30 mA) = 1.1×10^{13} cm^{-3} and n_e(85 mA) = 5.7×10^{13} cm^{-3}.

Thus, the electron density determined using resonance properties of direct coupling waveguide microwave filter of 3-cantimiter wavelength range (EBG-structure) is in good agreement with estimation obtained by using reduced electric field in positive column of discharge lamp. Developed method will be applied in future at the usage of the atmospheric pressure glow discharges as controlling elements of waveguide filters.

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References

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