

1D electromagnetic band gap structure formed by plasma

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Introduction

During last two decades, metamaterials and especially electromagnetic band gap (EBG) structures have been intensively developed and investigated all over the world due to their unusual properties such as negative permittivity or permeability [1-3]. The possible applications of EBG structures in the microwave (MW) frequency range include such as power limiter, antennas, filters, multiplexer etc. Most of these devices are constructed with metallic elements, have fixed parameters and do not provide a fast reconfiguration and adjusting. At the same time, glow discharge plasmas are promising to be an effective control element in devices based on EBG materials [1]. In general, the permittivity of plasma, ϵ_{pe} , for microwave at frequency ω is given by

$$\epsilon_{pe} = 1 - \frac{\omega_{pe}^2}{\omega^2(1 + i\nu/\omega)} = 1 - \frac{e^2 n_e}{\epsilon_0 m_e \omega^2 (1 + i\nu/\omega)} \quad (1)$$

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. It is seen from this relation, ϵ_{pe} can be modified from unity to negative values according to n_e . In this paper we present the results of the MW propagation through the 1D EBG structure formed by plasma in a typical X-band waveguide.

Experimental situation

1D EBG structure in an X-band waveguide can be formed by inserting metallic/dielectric inhomogeneities distributed uniformly along the direction of wave propagation [2]. We use a waveguide with the cross-section of $23 \times 10 \text{ mm}^2$ and with 3 holes of 4 mm in diameter drilled through the opposite wide waveguide walls. The holes are separated equidistantly by $l = \Lambda_0$; here, Λ_0 is wavelength in the waveguide and is expressed by $\Lambda_0 = \lambda_m (1 - (\lambda_m/2a)^2)^{-1/2}$, where λ_m is the wavelength corresponding to the middle of the filter pass band, and a is the wide waveguide wall dimension ($a = 23 \text{ mm}$). Thus, for central frequency $f_0 = 10.24 \text{ GHz}$ ($\lambda_m = 29 \text{ mm}$), the resonator lengths are $l = 38 \text{ mm}$. 1D EBG structure is formed by inserting metallic rods (3 mm in diameter) into the opposite holes. The transmission spectrum of such a periodical structure, which was registered in the frequency range of 7–11 GHz with help of vector analyzer Anritsu 37369C, is shown in Fig. 1, *b* (curve 4). As it can be seen, there are two pass bands with central frequencies $f_{01} = 7.6 \text{ GHz}$, $f_{02} = 10.2 \text{ GHz}$.

In order to obtain the periodical structure in waveguide section using solely plasma, we use the positive columns of low pressure commercial gas discharge lamps (GSh-5). The lamps GSh-5 have the total glass tube length of 200 mm with internal diameter of 3 mm. They are filled with neon at a pressure of about 70 Torr. The operating DC current of each lamp is 70 mA at the interelectrode voltage of about 200 V. As it is shown with the performed estimations, electron concentration in the positive column of GSh-5 lamp increases from $0.7 \times 10^{13} \text{ cm}^{-3}$ to $3.5 \times 10^{13} \text{ cm}^{-3}$ with the current increase from 40 mA to 120 mA. These values are one-two orders higher than the critical electron concentration for microwave at 7 – 11 GHz which is $6.1 \times 10^{11} – 1.5 \times 10^{12} \text{ cm}^{-3}$. In order to increase the electron density, we use a pulse operating regime of the lamps through applying pulse voltage (up to 3 kV) from a special power supply.

A special measurement schematic was developed to measure the changes in transmission signal of waveguide section in pulse operating regime of the lamps, because microwave spectra had to be registered during short time (a few microseconds). This schematic includes a MW detector (a time evolution of transmission on chosen frequency) or analyzer of pulse signal S4-80 (determination of spectral transmission level) with a strobing analyze window of about 3 μs . Light intensity pulses are registered by photodiode FD and oscilloscope S8-40.

Transmission of 1D EBG structure formed by GSh-5 lamps at low MW power.

Three GSh lamps were put into the holes of waveguide section as shown in Fig. 1, *a*. Manual turning oscillator G3-14 with output power up to 5 mW in the frequency range of 7–11 GHz

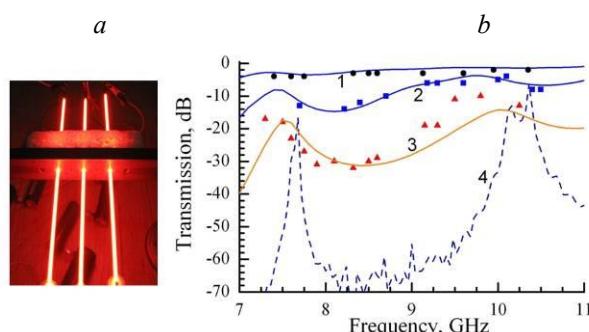


Fig. 1. Photo (*a*) and transmittance spectrum (*b*) of the waveguide section with 3 discharge lamps with different inner diameter at same current density $j = 1.4 \text{ A/cm}^2$: 1 – 1.5 mm, 2 – 3 mm, 3 – 6 mm and 4 – three metallic rods, solid lines – calculation with HFSS code.

was used as a MW power source. In Fig. 1, *b* (curve 1-3) one can see the transmission spectra of 1D EBG structure formed by lamps with different inner diameters (1.5 mm, 3 mm and 6 mm). It should be noticed that the measurements were performed at same current density $\sim 1.4 \text{ A/cm}^2$. It is assumed that electron concentration in all these cases was the same as well. One can see

that the forbidden band, which is situated between two pass bands, is clarifying with a rising diameter, but it is not so deep as for the case with metallic rods.

Electron concentration can be increased in pulse operating regimes of the lamps. The corresponding waveforms of applied voltage, discharge current and light intensity are shown

in Fig. 2, *a*. The discharge current rise up to 4 A should increase electron concentration more than one order of magnitude. Although this active current phase does not exceed a few microseconds, the electron density decreases over a longer period of time. This fact is demonstrated in Fig. 2, *b*, where temporal transmissions of the waveguide section at different frequencies are shown. In this case, 1D EBG structure exists during more than 20 μ s. The

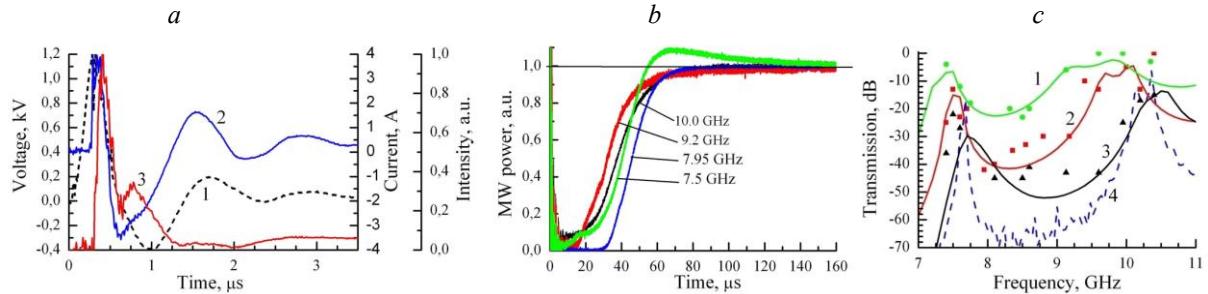


Fig. 2. The voltage (1), current (2) and light (3) pulses (*a*) at the lamp GSh-5, temporal transmission (*b*) of the waveguide section at different frequencies and transmission spectra (*c*) of 1D EBG structure formed by 3 lamps at lamp with diameters of 1.5 mm (1), 3 mm (2) and 6 mm (3) and with 3 metallic rods (4) (dots – experiment, solid lines – calculation with HFSS code).

transmission spectra were registered with 2 μ s delay relative to the leading edge of voltage pulse (Fig. 2, *a*). The suppression in forbidden band increased up to 20 dB, 40 dB and over 40 dB in cases of 1.5 mm, 3 mm and 6 mm in diameter, respectively (Fig. 2, *c*, curves 1, 2, 3). Therefore, it can be concluded that both the inner lamps diameter value and electron density increase lead to a significant suppression of transmitted signal in forbidden band.

Variation of MW pulse duration using a 1D EBG plasma structure.

The 1D EBG structure formed by three GSh-5 lamps can be used for the pulse parameters control, for instance, for attenuation or pulse duration variation. It can be realized through

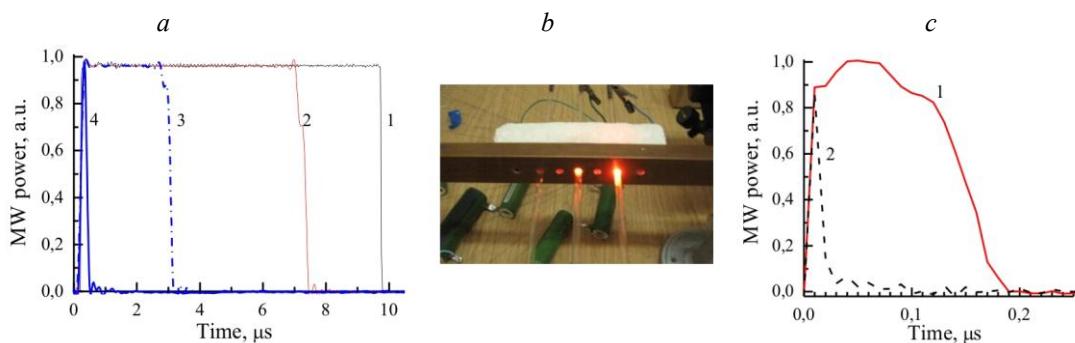


Fig. 3. The transmitted microwave pulses waveforms at different delay 7 μ s, 3 μ s and 0.050 μ s, curves 2, 3 and 4 relatively, 1 – initial pulse (*a*); photo of the GSh-5 lamps ignited under influence of high power microwave (*b*) and waveforms (*c*) of initial (1) and transmitted (2) high power microwave pulses.

changing delay time between the leading edge of microwave pulse and the lamps ignition time. This delay will define the duration of the MW pulse of transmitted through waveguide section. In Fig. 3, *a*, the waveforms of the transmitted microwave pulse with initial duration of 10 μ s at frequency 8.5 GHz are presented; curve 1 relates to the case when the lamps were

turned off, while curves 2, 3, and 4 correspond to the lamp ignition with time delay of 7 μ s, 3 μ s and 50 ns respectively. Thus, it can be seen that it is possible to control pulse duration in the range from ten microseconds up to a few tens of nanoseconds.

In the next experiment the oscillator with output pulse power up to 50 kW at frequency 9.15 GHz, pulse duration 200 ns and repetition frequency 2 kHz was used. The pulse power is larger than the one needed for gas breakdown in lamps. Resulting this breakdown, microwave discharges with different luminosities are observed in the lamps (Fig. 3, *b*). Simultaneously, it is registered that there is a reduce in duration of the pulse transmitting through 1D EBG waveguide structure from 150 ns up to about 20 ns (Fig. 3, *c*).

Transmission of 1D EBG structure formed by atmospheric pressure glow discharges.

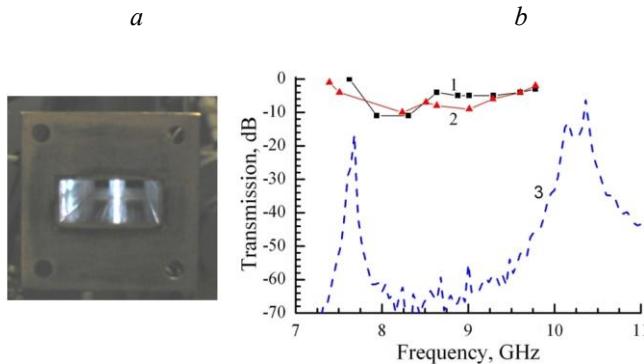


Fig. 4. Photo of the APGDs in X-band waveguide (*a*) and (*b*) the transmission spectra of 1D EBG APGD plasma structure at discharge current of 200 mA in helium (1) and (2) in argon.

seen in Fig. 4, *b* the suppression effect in forbidden band (8-9.5 GHz) is insufficient (only about 10 dB). It can be explained by strong contraction of positive column of argon discharge and low electron density in helium discharge. Pulse regimes of the glow discharges will be more preferable.

Conclusions

The microwave propagation control by plasma column as elements of 1D EBG periodical structure in waveguide and possibilities of the development of the MW devices based on these plasma structures (attenuation, pulse duration variation, switching) are demonstrated.

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References

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In this experiment, the array from three atmospheric pressure glow discharges (APGDs) in helium or argon [4] at DC current 200 mA is used as elements of 1D EBG plasma periodical structure (Fig. 4, *a*). The positive columns of discharges are bound inside the waveguide with glass tube with inner diameter 3 mm. As it can be