The transmission spectrum switching speed of electromagnetic band gap plasma structure

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Abstract. The transmission spectrum switching speed of electromagnetic band gap (EBG) plasma structure formed by pulse discharges at atmospheric pressure was under investigation. The ability to obtain a nanosecond transmission spectrum switching time of plasma EBG structures was demonstrated. The time resolved $H_\alpha$ and $H_\beta$ lines profiles were registered. Time behaviour of electron density during the discharge and time evolution of electron concentration were determined. The dependence of current growth rate and fall rate of transmitted microwave power on the applied voltage pulses were determined.

1. Introduction

During the last decade, there has been an increasing interest in high-speed tunable microwave devices based on EBG structures for use in telecommunication systems that are capable of operating at high power levels. Gas discharge plasma as a control element of such devices has high potential for this purpose due to its variability in electron density and geometry [1]. The properties of one-dimensional EBG plasma structure in the X-band waveguide formed by discharges at low pressure were described in [2]. In [3], the possibilities of microwave control by long pulse atmospheric pressure discharges were demonstrated. The switching time characteristics of this structure in waveguide were estimated in [4]. The switching speed of transmission of such EBG plasma structure is under investigation in this work.

2. Experimental setup

The one-dimensional plasma EBG structure is formed by three pulse discharges at atmospheric pressure in a waveguide with rectangular cross-section $23 \times 10 \text{mm}^2$, just as it is presented in [3]. Discharges are ignited between two electrodes (diameter is 1 mm, interelectrode gap is 11 mm) in quartz tubes with an inner diameter of 1.6 mm and placed perpendicular to the wide walls of waveguide with period of 30 mm [1]. The chosen distance corresponds to a wavelength $\lambda_0$ in the waveguide for frequency $f_0 = 11.9 \text{GHz}$, which is expressed by relation:

$$\lambda_0 = \lambda_m \left(1 - \left(\frac{\lambda_m}{2a}\right)^2\right)^{1/2},$$

where $\lambda_m$ is the wavelength in air; $a$ is the waveguide wide wall dimension.

Helium, argon and Ar(> 96 %)–O₂(< 2 %)–H₂(< 2 %) mixture at flow rates about 1 l·min⁻¹ are used as working gases. The mixture is needed for the diagnostics purposes. Schematic diagram of
The experimental setup is shown in figure 1a. The discharges are ignited using high voltage rectangular pulse (Nanogen 1, RLC Electronic) of variable amplitude and duration (pulse rise time is about 25 ns). The discharge current is registered using current probe Pearson, Model 2877 and digital oscilloscope Tektronix, Model TDS 3034 (300 MHz, 2.5 GS·s⁻¹). The transmission spectra were registered using a ENA Vector Network Analyzer Keysight, Model E5071C. The microwave oscillator HP 8350B/83592B was used as source of probing wave at chosen frequency for time transmission control. The transmitted signal of probing wave is registered using a microwave diode and digital oscilloscope TDS 3034.

The discharge emission spectra are recorded using a high-resolution monochromator Acton Research Corporation, Model SpectraPro-300i and a high-speed ICCD camera PI-MAX 2 (Princeton Instruments). Instrumental broadening is 0.02 nm.

Figure 1. Schematic of the 1D plasma EBG structure (a) and transmission spectrum (b): 1 – empty waveguide, 2 – three quartz tubes in waveguide, 3 – simulation results for this case and 4 – thin metal rods in tubes.

3. Results and discussion

Modelling results were obtained using Ansoft HFSS software [5]. The measured and simulated transmission spectra of the EBG structure are shown in figure 1b. It is seen that three tubes form periodic structure (curves 2 and 3) with microwave signal suppression in forbidden bands of about -5 dB. Introducing cooper wires of 0.25 mm in diameter into the tubes leads to the transmission spectrum (curve 4). We consider this spectrum as a limit, which can be reached with high ionized plasma columns at same transverse dimensions as metallic wires.

In order to perform a spectroscopic diagnostics of pulse discharge plasma, the experiments were started with Ar-O₂-H₂ mixture. Three discharges with current of 8–9 A in each were obtained when applying high voltage pulses of 1 µs duration. Dispersion of discharge ignitions did not exceed a few nanoseconds. Waveform of current pulse in one tube is shown in figure 2a.

Photos of the discharge (figure 2b) were made using ICCD camera with time resolution less than 1 ms. It is shown that the diameter of luminous column is less than inner diameter of tube and column is not stable in tube space pulse-to-pulse. It should be noticed that diameter of luminous column doesn’t change significantly during current pulse and in afterglow plasma and is in the range of 0.25–0.3 mm. This dimension is used as a diameter of the discharge plasma channel.

We test the transmission of the investigated EBG structure using the continuous microwave radiation at frequency 9.15 GHz and power about 20 mW incident to waveguide. Chosen frequency corresponds to middle of forbidden band of the investigated EBG structure (figure 1b, curve 4). Figure 2c shows the waveform of transmitted signal changes from moment of discharges ignitions. It is shown that transmitted signal is minimal during current pulse at 1 µs after pulse. Then the transmission is restored only up to 10⁶ microsecond. It is an existing time of afterglow plasma.
Figure 2. a – current pulse in case of Ar-O₂-H₂ mixture, b – photos of discharge inside the tube (exposure time 100 ns), c – transmitted power through the EBG structure.

Time evolution of electron concentration in the discharge was estimated using the profiles of the H₆ and H₂ spectral lines. These lines are observed both at current stage of discharge and in afterglow plasma. Their profiles were registered by spectrometer including ICCD camera with resolution of 100 ns. Performed estimations of these lines broadenings due to different mechanisms (instrumental, Van-der-Waals, Doppler, Stark) according to [6] showed that Stark broadening is principal. The Van-der-Waals broadening was taken into account at low electron concentrations less than 10¹⁵ cm⁻³ in afterglow plasma and only for H₆ line. The time evolutions of electron concentrations in afterglow plasma received using both lines profiles [7] are presented in figure 3a. Maximal electron concentration is about 2×10¹⁷ cm⁻³ after current pulse. Then, the electron density decreases over time and by 5 μs after the start of the discharge is less than 10¹⁵ cm⁻³.

Figure 3. a – experimental time dependence of electron concentration and b – microwave signal passed through EBG structure in case of mixture and simulated transmission. (circles).

The obtained electron densities in the discharge were used as initial data for modeling the propagation of microwaves in the created plasma EBG structure in the waveguide. Using the Ansoft HFSS software, the levels of the transmitted microwave signal were estimated for different values of the electron density in the discharge plasma. The discharge diameter estimated from a series of photos (figure 2b) made with ICCD camera is assumed to be equal to 0.25 mm. It is shown that the simulation results of transmission (figure 3b, symbols) are in satisfactory agreement with experimentally registered ones. We could not determine electron concentration using hydrogen lines profiles during current stage of discharge since these lines were strongly broadened or had weak intensities. However,
we estimated electron concentration in pulse time using measured transmission in these moments. These values are shown in figure 3b (triangles) as well.

The time dependences of the transmitted microwave power at a frequency of 9.15 GHz for discharges with different working gases (Ar, He, Ar-O2-H2) at the same discharge current of about 9 A are shown in figure 4a. It is seen that the maximal suppressions of microwave signals during pulse are the same for all working gases. However, a suppression after pulse is saved longer time in case of argon. Smaller time of afterglow plasma has a mixture discharge. The reason of this can be a presence of molecular gas.

![Graphs showing transmitted microwave power and switching time vs pulse voltage](image)

**Figure 4.** a – decay time of afterglow plasma in 1 – helium, 2 – Ar-O2-H2, 3 – argon, and b – the switching time vs pulse voltage for different gases. Dashed lines are breakdown voltages.

Let’s consider that a switching time is characterized by the time of changing the transmitted signal from 90% to 10% of incident one. The switching times for different working gases determined in such way in dependence on the voltage applied to the electrodes are presented in figure 4b. It is shown that the switching time is less in Ar and Ar-O2-H2 discharges (for example, about 35 ns at pulse voltage 4.5 kV) than in case of He (150 ns) discharges. At the pulse voltages less than 4.5 kV the switching time increases for all working gases. It is due to different breakdown voltage for different gases and due to the increasing scatter of ignitions of each three discharges.

### 4. Conclusions

The transmission spectrum switching speed of electromagnetic band gap plasma structure has been studied. Specially designed discharges were created in different working gases. It was shown, that the switching speed is higher in case of using argon and Ar-O2-H2 discharges as EBG structure inhomogeneities than discharges in helium 35 ns switching time was obtained. The time resolved Hα and Hβ lines profiles were registered and a time behavior of electron density during the discharge was determined. Maximal electron concentration is about $2 \times 10^{17}$ cm$^{-3}$ after current pulse. Time evolution of electron concentration was determined.

The obtained results demonstrate the possibility of developing high-speed microwave elements (switches, limiters, attenuators) under plasma control.

### References

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