Measurement of S-Band Microwave Gas Breakdown by Enhancing the Electric Field in a Waveguide

Yi-Ming Yang, Cheng-Wei Yuan, and Bao-Liang Qian

***Abstract*—With the development of narrow-band high-power-microwave (HPM) technology, air breakdown has become a serious problem that concerns to the HPM applications. A new method is presented in this paper to determine the electric field of the microwave air breakdown near the atmosphere pressures. Two metal pins were used to strengthen the microwave electric field in a sealed waveguide, putting on the symmetry axis. Some parameters such as gas pressure, temperature, and humidity could be changed conveniently to achieve gas breakdown. Experiment was carried out at the S-band (2.86-GHz) microwave of 180-ns duration and 5-MW peak power, and typical phenomena of plasmas introduced by microwave are analyzed. Furthermore, a new definition of breakdown threshold has been proposed based on breakdown probability, and the electric field threshold is also analyzed.**

***Index Terms*—Air breakdown, electric field enhancement, microwave, waveguide.**

I. INTRODUCTION

IN RECENT years, devices generating narrow-band high-power microwaves (HPMs) have been extensively developed. As the HPM technologies gradually matured, the output power reached several gigawatts [1], [2], and breakdown phenomena could be found when the HPM pulse propagates in the air [3]–[5]. The plasma screen, which is formed in this process, could shorten the pulse duration, decrease the peak power of the microwave, change the microwave transmit direction, and even damage the microwave source [6], [7]. Therefore, it becomes more and more important to predict microwave gas breakdown threshold and solve the problem of HPM transmitting in the atmospheric air.

A lot of work are focusing on investigating microwave propagating in the air theoretically [8]–[12] or experimentally [13]–[16]. However, most of their work concentrate merely on continues wave, and the theoretical prediction was semi-empirical. To overcome this shortcoming, short pulse wave is studied in this paper, and measurement of microwave gas breakdown by enhancing the electric field in a waveguide is put forward. In addition, a definition of breakdown threshold has been put forward based on breakdown probability. The probability implies the breakdown influence degree on the transmission of the HPM.

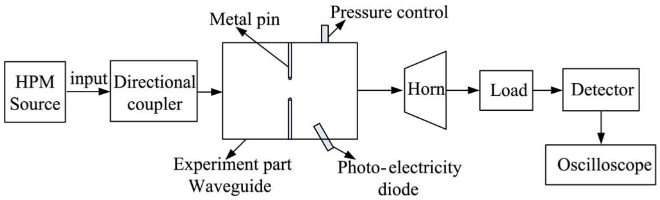


Fig. 1. Experimental scheme for microwave air breakdown by enhancing the electric field in the waveguide.

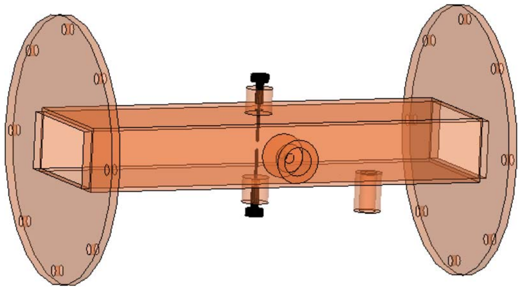


Fig. 2. Simulation model.

As shown in Fig. 1, two metal pins were put on the symmetry axis, and they are used to strengthen the electric field in the sealed waveguide. Experiment was carried out at the S-band (2.86-GHz) microwave of 180-ns duration and 5-MW peak power.

The advantages of this experimental setup are that the electric field strength near the pinpoint can be conveniently changed by adjusting the distances between the two metal pins, and it can be done under different conditions such as different gas pressures, temperatures, and humidity. In addition, breakdown can be visually determined by comparing the waveforms caught by the oscilloscope, and the light emissions from the plasma could be also taken by the photoelectricity diode. (The response wavelength of the photoelectricity diode is 200–1100 nm.)

This paper is organized as follows. Section II describes the experimental setup and simulation results. Section III presents the experimental results and discussions. Section IV describes the preliminary summary of the air breakdown threshold. Section V gives the conclusions.

II. EXPERIMENTAL SETUP AND SIMULATION RESULTS

First, we set up the simulation model, as shown in Fig. 2, and the electric field distribution in the waveguide is shown in Fig. 3. Apparently, the electric field at the top of the metal pin is greatly strengthened. In addition, microwave reflectance, as long as the transmission power is obviously changed along with distance D (D represents the distance between the two pins), changed between the two pins.

Manuscript received May 2, 2012; revised August 23, 2012; accepted September 25, 2012. Date of current version December 7, 2012.

The authors are with the College of Optoelectronic Science and Engineering, National University of Defense Technology (NUDT), Changsha 410073, China (e-mail: yymkko@yahoo.com.cn; ehfz_ycw@163.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPS.2012.2222450

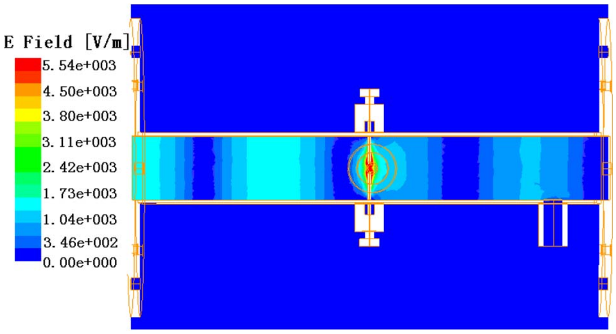


Fig. 3. (Color online) Electric field in the waveguide.

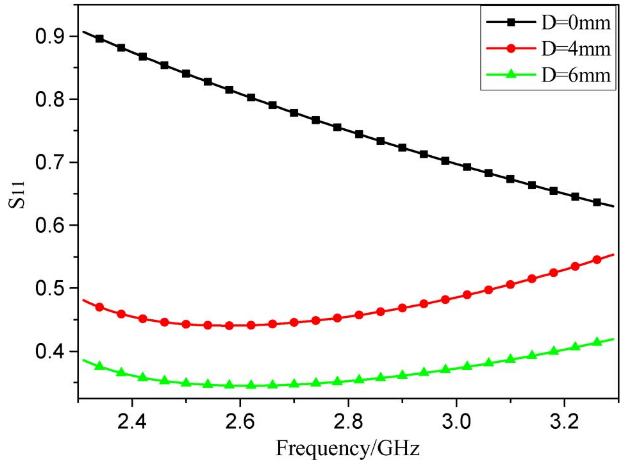


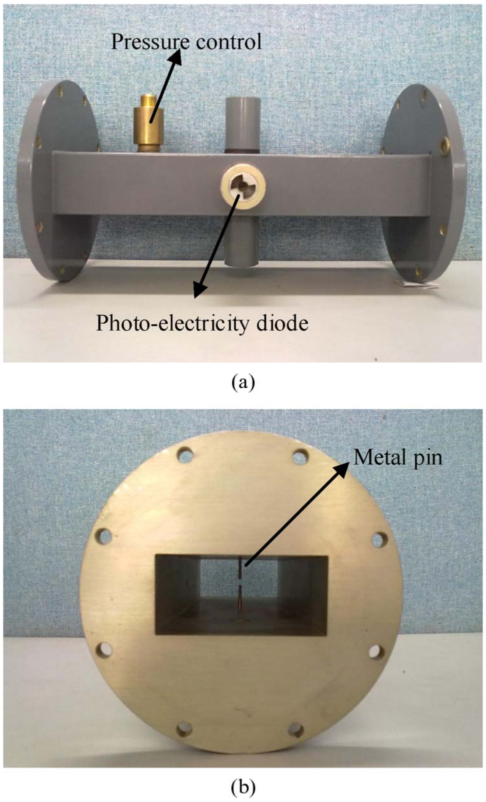
Fig. 4. (Color online) Reflectance S11 versus microwave frequency for different distances D of the two metal pins in the waveguide of $a \times b = 72.14$ mm $\times$ 32.04 mm.

The effect of the pins on the propagation of the microwave is that the microwave could be little reflected if the breakdown does not happen. However, when the breakdown happens, the plasma would fill the gap and make the reflection greatly increased. At the same time, the microwave would be absorbed by the plasma, resulting in the decrease in the transmitted microwave power. We employ a microwave at S-band of 2.86 GHz, putting two metal pins with hemispherical ends in the standard waveguide WR284 (72.14 mm × 32.04 mm) with the radius of the pins being 1 mm. Simulation results are given in Fig. 4. It shows that the reflectance S11 versus the microwave frequency for different distances D, indicating the reflectance S11 apparently decreases with increasing the distance D. This phenomenon can be obviously observed from the waveforms caught by the oscilloscope, and then the breakdown can be determined. On the other hand, the photoelectric signal is also an effective evidence of the breakdown [10], [11].

The waveguide and the metal pins are the key parts of the experimental setup. We can use the electromagnetic software to optimize the dimensions of the waveguide, the radius of the metal pins, and the gas pressure in the experiment.

III. EXPERIMENTAL RESULTS

By enhancing the microwave electric field in the waveguide, we have done the air breakdown experiment employing the S-band (2.86-GHz) microwave. For convenience, we employed the standard waveguide WR284 (72.14 mm × 32.04 mm), and the radius of the cylindrical-shaped pins was 1 mm with hemispherical ends, as shown in Fig. 5.



(a)

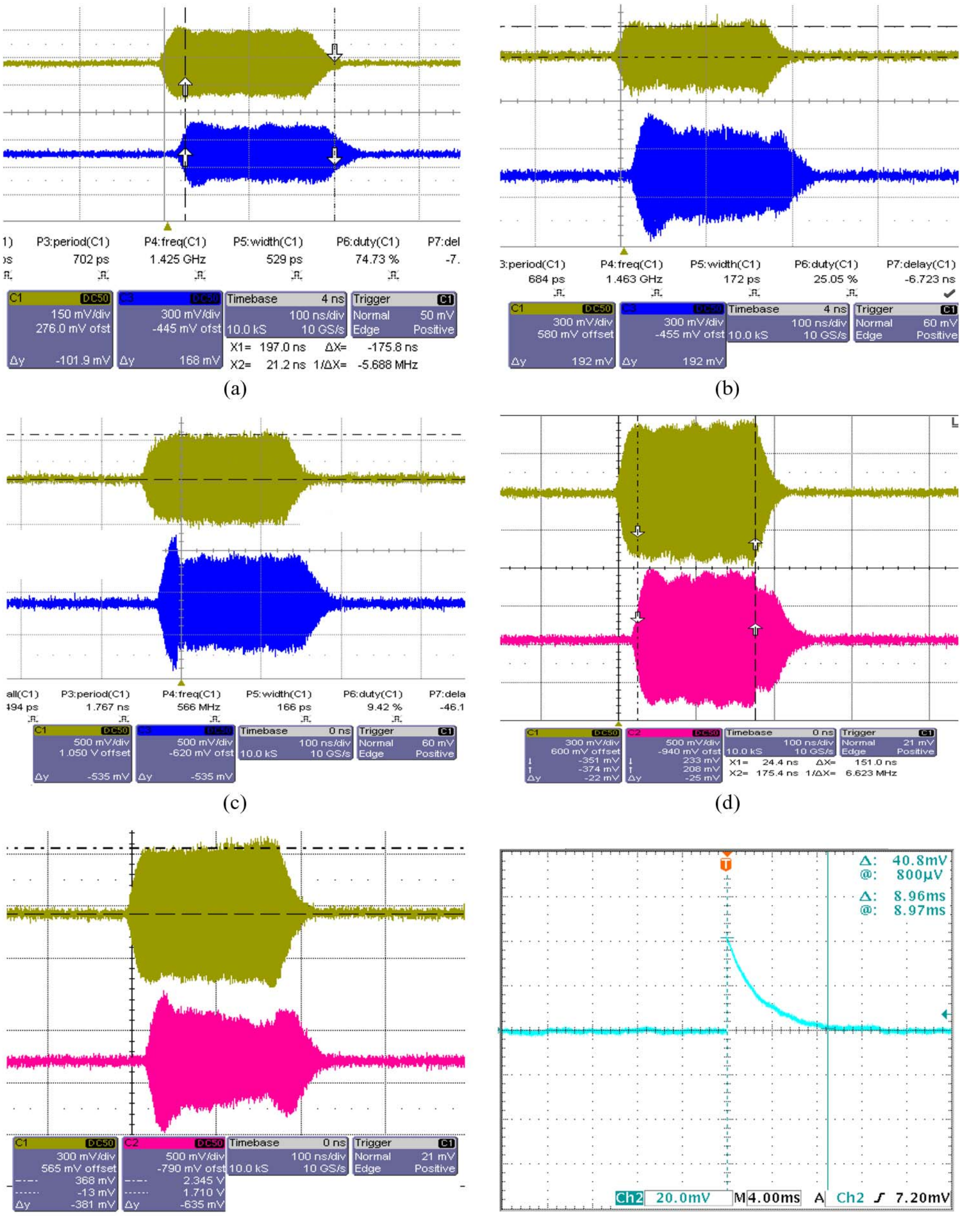
(b)

Fig. 5. Waveguide used in the experiment. (a) Side view of the waveguide (72.14 mm × 32.04 mm). (b) Front view of the waveguide (radius of the cylindrical-shaped pins was 1 mm with hemispherical ends).

During the experiment, the pulse duration of the microwave was 180 ns, and the microwave peak power was 5 MW. The microwave power, the pressure of the air, and the distance between the two pins were controlled to lead to the air breakdown. Some typical waveforms were obtained, as shown in Fig. 6, indicating the process of air breakdown due to the strong microwave. Here, D still represents the distance between the two pins, and P is the pressure. In all of those oscilloscope waveforms, the up waveform is the incidence wave, and the below one is the received signal.

In the case of $D = 6$ mm, $P = 1$ atm, and the microwave power is relatively low, the incidence and the transmit waveforms are shown in Fig. 6(a), and they are similar, indicating that no breakdown happened, and then kept D and P but gradually increased the microwave power until breakdown happened. Fig. 6(b) depicts the waveforms when breakdown slowly occurred. It can be clearly seen that the transmit power slowly decreases with time, which means that the reflectance slowly increases. The increased electric field near the pinpoint leads to the air breakdown, forming the plasma that fills in the gap of the two metal pins, just like connecting the two pins.

Fig. 6(c) shows the waveforms when D is 4 mm, P is 1 atm, and the microwave power is relatively strong. It is shown in Fig. 6(c) that the air breakdown quickly occurs at about 10 ns, which means that the formed plasma quickly expands and leads to the breakdown phenomenon, which is to say that



(a) (b)

(c) (d)

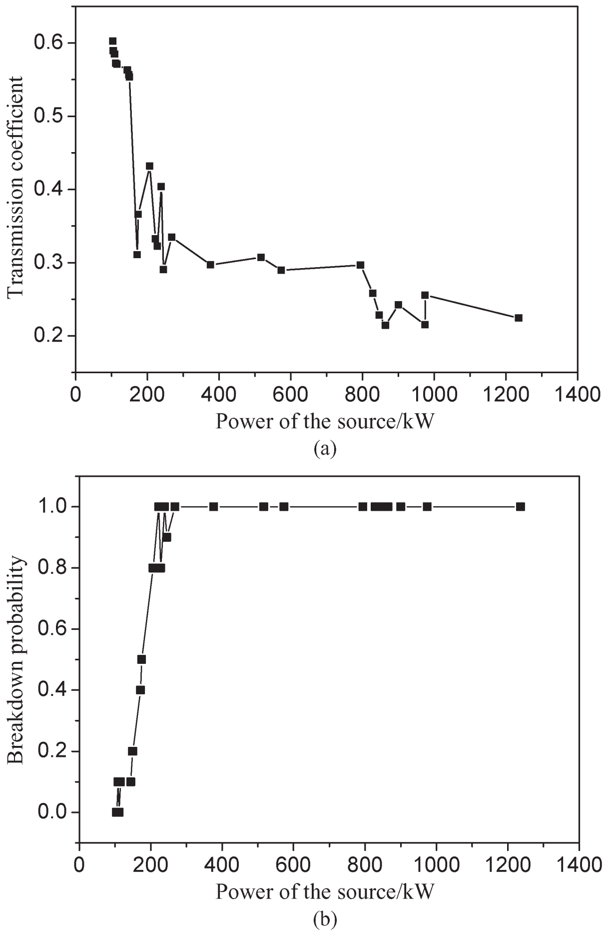
(e) (f)

Fig. 6. (Color online) Typical waveforms obtained in the experiment. (a) Waveform when microwave efficiently transmits through the two pins. (b) Waveform when breakdown slowly occurred. (c) Waveform when breakdown quickly occurred. (d) Waveform when breakdown occurred at 150 ns. (e) Waveform when microwave power is low enough. (f) Photocurrent detected by the photoelectricity diode.

the pins quickly “connect,” making the reflectance increased. Furthermore, the transmitted power retains steady after 10 ns. Fig. 6(d) shows the detected waveforms when D is 6 mm and P is 0.6 atm. It is shown in Fig. 6(d) that the air breakdown happens at 150 ns, and the microwave effectively transmits until 150 ns when plasma fills in the gap, making the transmit power quickly decreased. This process can be explained as follows: When the electric field near the pins is strong enough, the seed electrons in the air will be accelerated to high speed and electron-neutral collision is not elastic collision but ionizing collision, the process repeated, and the electron density quickly increased until avalanche ionization. When the frequency of the plasma was equal to the frequency of the microwave, the breakdown occurred and the phenomenon of trail erosion appeared (reflection). Fig. 6(c) and (d) suggests this process, and it implies that breakdown has relationship with the microwave interaction duration.

Fig. 6(e) shows the waveform when D is 6 mm and P is 0.6 atm. In this figure, it is shown that the transmitted microwave power slowly decreases after the breakdown but increases again at some time. It means that the plasma expands inside the gap at the beginning, “connecting” the pins, reflecting and absorbing the microwave. However, after some time, ionization cannot maintain due to the reduced microwave power, and the electrons and ions in the plasma would quickly recombine; hence, the gap between the pins re-increases, and the transmitted microwave power re-increases.

During the experiment, we also detected the photocurrent of the plasma using the photoelectricity diode, as shown in Fig. 6(f). It shows that the amplitude and radiation time of



(a)

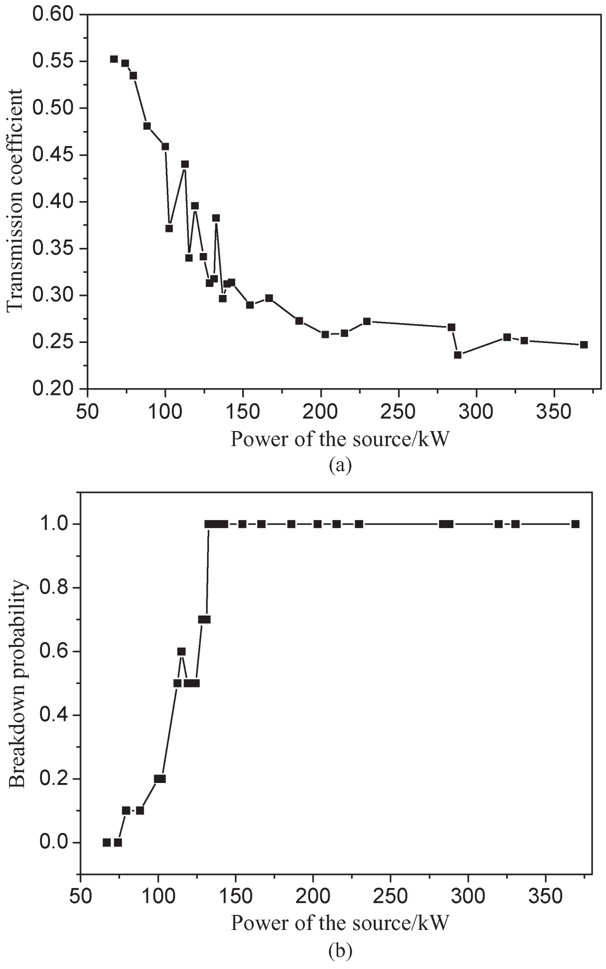
(b)

Fig. 7. (a) Transmission coefficient of microwave versus the microwave power for $D = 6$ mm and $P = 1$ atm. (b) Probability of breakdown versus the microwave power for $D = 6$ mm and $P = 1$ atm.

the photocurrent were connected with the microwave power. Limited by the environment, the oscilloscope cannot take the current signal when the current is very low (for example, when the oscilloscope signal is less than 5 mV). It is shown in Fig. 6(f) that the current existed for about 9.0 ms, indicating a rough estimation of the lifetime of the plasma.

IV. PRELIMINARY SUMMARY OF THE AIR BREAKDOWN THRESHOLD

The threshold of air breakdown is an important parameter. However, the process of microwave air breakdown is very complex, and there is no universal definition of air breakdown threshold. Several criteria of air breakdown can be found in former literature works [11], [14], [17]–[19]. In our experiment, we found that the breakdown could occur even if the microwave power is quite low, but sometimes, it could not happen even if the microwave power is very high. We believe that the air breakdown is something of probability. Therefore, we considered the stability of the microwave power and the effect of the breakdown on the microwave transmission and repeated the experiment at least 10 times under the same condition. We define that the critical breakdown happens when the probability of breakdown is about 20%. Breakdown can be justified by the waveform obtained from the oscilloscope, and the microwave electric field can be calculated using the experimental data.



(a)

(b)

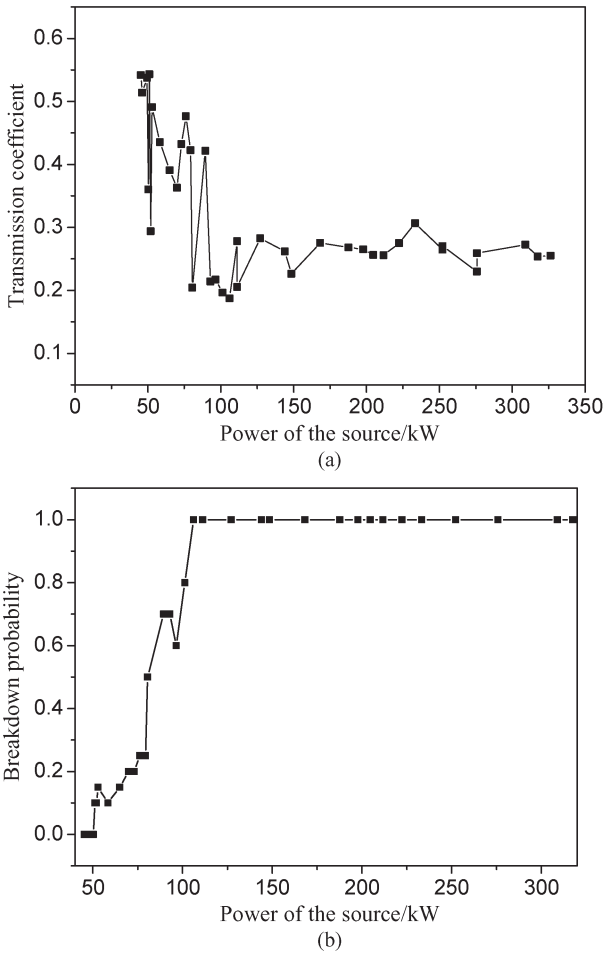
Fig. 8. (a) Transmission coefficient of microwave versus the microwave power for $D = 4$ mm and $P = 1$ atm. (b) Probability of breakdown versus the microwave power for $D = 4$ mm and $P = 1$ atm.

According to the approach and diagnosis method introduced above, we have done a lot of experiments under different conditions, and the results are summarized as follows.

A. Data Analysis When D is 6 mm

We kept D to be 6 mm and P to be 1 atm. Under this condition, the intermittent air breakdown happened when the microwave power was about 170 kW; hence, a number of experiments have been done around this power. In the experiments, each power level has been done for more than 10 times at the same power, and the interval between each experiment was longer than 60 s. The curves of the transmission coefficient of microwave and breakdown probability versus the microwave power are shown in Fig. 7.

According to the critical threshold defined above, it can be obtained from Fig. 7(b) that the threshold under this condition is 150 kW. Using $P = abE^2/480\pi\sqrt{1-(\lambda/2a)^2}$ for the waveguide, we obtain that the electric field in the waveguide is 3.56 kV/cm. In addition, we have calculated from the electromagnetic software that the electric field enhancement factor is 17.6. Therefore, the preliminary result of the air breakdown threshold for the microwave of 2.86 GHz and 180 ns is about 63 kV/cm in the case of $D = 6$ mm and $P = 1$ atm.



(a)

(b)

Fig. 9. (a) Transmission coefficient of microwave versus the microwave power for $D = 6$ mm and $P = 0.6$ atm. (b) Probability of breakdown versus the microwave power for $D = 6$ mm and $P = 0.6$ atm.

B. Data Analysis When D is 4 mm

We kept D to be 4 mm and P to be 1 atm. Under this condition, we obtained the microwave power threshold to be 100 kW, as shown in Fig. 8, and the preliminary result of the air breakdown threshold is about 62 kV/cm. Compared with the result we obtained in the case of $D = 6$ mm, the difference is little. Therefore, we can conclude that the electric field breakdown threshold for the microwave of 180 ns and 2.86 GHz is about 62.5 kV/cm.

C. Data Analysis When P is 0.6 atm

We pumped the pressure in the sealed waveguide to be 0.6 atm and kept D to be 6 mm. Under this condition, we obtained the power threshold to be 70 kW, and the electric field breakdown threshold under this condition is about 43 kV/cm. The curves of the microwave transmission coefficient and probability versus the microwave power are shown in Fig. 9.

V. CONCLUSION

A new method has been presented in this paper to determine the electric field of the microwave air breakdown near the atmosphere pressures. Experiment was carried out for the S-band (2.86-GHz) microwave of 180-ns duration and 5-MW peak power; typical phenomena of plasmas introduced by microwave are analyzed. It can be found that plasma introduced by microwave could not only shorten the pulse duration but also decrease the peak power of the microwave. In addition, a new definition of breakdown threshold has been proposed based on breakdown probability. We obtained that the breakdown electric field threshold for 1 atm is about 62 kV/cm, and for 0.6 atm, it is about 43 kV/cm.

HPM gas breakdown is still a big subject nowadays; it concerns to the application and experiment of HPM. Limited by time and the equipment, the data we got are not enough; we will do more experiments in the future and compare with the other groups.

REFERENCES

[1] Y. W. Fan, H. H. Zhong, H. W. Yang, Z. Q. Li, T. Shu, J. Zhang, Y. Wang, and L. Luo, “Analysis and improvement of an X-band magnetically insulated transmission line oscillator,” *J. Appl. Phys.*, vol. 103, no. 12, pp. 123301-1–123301-4, Jun. 2008.

[2] J. Zhang, H. H. Zhong, Z. Jin, T. Shu, S. Cao, and S. Zhou, “Studies on efficient operation of an X-band oversized slow-wave HPM generator in low magnetic field,” *IEEE Trans. Plasma Sci.*, vol. 37, no. 8, pp. 1552–1557, Aug. 2009.

[3] Y. W. Fan, H. H. Zhong, Z. Q. Li, T. Shu, H. W. Yang, H. Zhou, C. W. Yuan, W. H. Zhou, and L. Luo, “Repetition rate operation of an improved magnetically insulated transmission line oscillator,” *Phys. Plasmas*, vol. 15, no. 8, pp. 083102-1–083102-5, Aug. 2008.

[4] J. H. Yee, D. J. Mayhall, G. E. Sieger, and R. A. Alvarez, “Propagation of intense microwave pulses in air and in a waveguide,” *IEEE Trans. Antennas Propag.*, vol. 39, no. 9, pp. 1421–1427, Sep. 1991.

[5] Y. Hidaka, E. M. Choi, I. Mastovsky, and M. A. Shapiro, “Imaging of atmospheric air breakdown caused by a high-power 110-GHz pulsed Gaussian beam,” *IEEE Trans. Plasma Sci.*, vol. 36, no. 4, pp. 936–937, Aug. 2008.

[6] S. P. Kuo and Y. S. Zhang, “Propagation of high power microwave pulses in air breakdown environment,” *J. Appl. Phys.*, vol. 67, no. 6, pp. 2762–2766, Mar. 1990.

[7] P. Felsenthal, “Nanosecond-pulse microwave breakdown in air,” *J. Appl. Phys.*, vol. 37, no. 12, pp. 4557–4560, Nov. 1966.

[8] L. Gould and L. W. Roberts, “Breakdown of air at microwave frequencies,” *J. Appl. Phys.*, vol. 27, no. 10, pp. 1162–1170, Oct. 1956.

[9] G. E. Sieger, J. H. Yee, and D. J. Mayhall, “Computer simulation of nonlinear coupling of high-power microwaves with slots,” *IEEE Trans. Plasma Sci.*, vol. 17, no. 4, pp. 616–621, Aug. 1989.

[10] G. X. Cheng and L. Liu, “Effect of surface produced secondary electrons on the sheath structure induced by high-power microwave window breakdown,” *Phys. Plasmas*, vol. 18, no. 3, pp. 033507-1–033507-9, Mar. 2011.

[11] J. T. Krile, A. A. Neuber, and H. G. Krompholz, “Monte Carlo simulation of high power microwave window breakdown at atmospheric conditions,” *Appl. Phys. Lett.*, vol. 89, no. 20, pp. 201501-1–201501-3, Nov. 2006.

[12] D. Anderson, M. Lisak, and T. Lewin, “Breakdown in air-filled microwave waveguide during pulsed operation,” *J. Appl. Phys.*, vol. 56, no. 5, pp. 1414–1419, Sep. 1984.

[13] K. V. Aleksandrov, L. P. Grachev, and I. I. Esakov, “Microwave breakdown of air initiated by a short electromagnetic vibrator,” *Tech. Phys.*, vol. 52, no. 12, pp. 1557–1561, Dec. 2007.

[14] G. C. Herring and S. Popovic, “Microwave air breakdown enhanced with metallic initiators,” *Appl. Phys. Lett.*, vol. 92, no. 13, pp. 131501-1–131501-3, Mar. 2008.

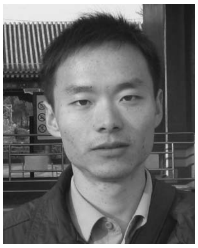
[15] G. Edmiston, J. Krile, and A. Neuber, “High-power microwave surface flashover of a gas–dielectric interface at 90–760 torr,” *IEEE Trans. Plasma Sci.*, vol. 34, no. 5, pp. 1782–1788, Oct. 2006.

[16] D. G. Anderson, M. Lisak, and P. T. Lewin, “Thermal lowering of the threshold for microwave breakdown in air-filled waveguides,” *IEEE Trans. Microw. Theory Tech.*, vol. MTT-35, no. 7, pp. 653–656, Jul. 1987.

[17] J. Y. Liu, J. Y. Fang, Z. M. Song, W. H. Huang, and G. Z. Liu, “Research on the short-pulse high power microwave air breakdown in waveguide and free space,” *High Power Laser Part. Beams*, vol. 12, pp. 497–500, 2000.

[18] D. Anderson and M. Lisak, “Generalized criteria for microwave breakdown in air-filled waveguides,” *J. Appl. Phys.*, vol. 65, no. 8, pp. 2935–2945, Apr. 1989.

[19] D. Dorozhkina and V. Semenov, “Investigations of time delays in microwave breakdown initiation,” *Phys. Plasmas*, vol. 13, no. 1, pp. 013506-1–013506-7, Jan. 2006.



Yi-Ming Yang was born in Jiangsu, China, in February 1986. He received the B.S. degree in 2008 from the National University of Defense Technology, Changsha, China, where he is currently working toward the Ph.D. degree in the College of Opto-Electric Science and Engineering.

He is currently with the College of Optoelectronic Science and Engineering, National University of Defense Technology. His current research interests include the generation and radiation of high-power microwave.

Cheng-Wei Yuan, photograph and biography not available at the time of publication.

Bao-Liang Qian, photograph and biography not available at the time of publication.