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Analysis of radiation evolution characteristics of the artificial triggered lightning channel

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Abstract: The spectrum of one triggered lightning with time resolution of 20 μs was observed by using the slitless spectrograph and the current intensity at the channel bottom was obtained, based on which the radiation characteristics of the lightning spectrum under different current intensities were analyzed. The duration of the spectral line was analyzed according to the excitation energy of the spectral line and the change of the channel current. As a result, the spectral lines were divided into three types. Furthermore, mechanisms of the continuous background radiation of short wavelength and long wavelength were analyzed, respectively. The influences of two radiation mechanisms on continuous background radiation attenuation were researched.

Key words: triggered lightning; channel plasma; lightning spectrum; channel current

人工触发闪电通道的辐射特性分析

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摘要:利用无狭缝光谱仪获得了一次人工触发闪电过程的发射光谱,其时间分辨率为20 μs,同时获得了通道底部电流强度,对不同电流强度下闪电光谱的辐射特性进行了分析。根据谱线持续时间将谱线分为三类,结合谱线激发能以及通道

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电流变化对影响谱线持续时间的原因展开了研究。对光谱总强度随时间的变化规律进行了分析,对闪电光谱短波段与长波段连续背景辐射的不同机制进行了分析,给出了两种辐射机制对连续背景辐射衰减的影响。

关 键 词:人工触发闪电;通道等离子体;闪电光谱;闪电电流

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1 Introduction

The lightning peak current can reach dozens of kA within 1 μs and the particle in the lightning channel may be dissociated and ionized, which form a typical plasma. The study of spectrum shows that the spectral line intensity change is the important basis of reflecting the plasma formation, increase and decrease. The spectral intensity and duration under different energies play imperative role in the study of the plasma generation mechanism and the threshold[1-4]. The lightning spectrum reflects that the microscopic physical process and breakdown mechanism occurred in the internal lightning channel. The lightning spectrum with the high temporal resolution paves an effective road for quantitative research in this area.

Much effort had been done on the lightning spectrum study during the past hundred years, however, there is no corresponding current observation data, most of the researches mainly focused on the spectral characteristics and the change of the channel parameters[5-8]. The combination analysis of the spectral characteristics and lightning discharge current is rare, many studies only focus partially on the spectral structures or the lightning discharge current characteristics. The recent development and application of artificially triggered lightning makes it possible to study using the combination of the spectral characteristics and the lightning discharge current characteristics. Artificial triggering lightning can measure the channel bottom current directly and obtain parameters such as lightning energy. It is an important way to reveal the lightning physics process based on the spectral characteristics in different discharge parameters, which reflect the fine-structure of lightning and the microscopic physical process inside the lighting channel.

In this paper, we studied the emission spectrum of an artificial triggering lightning process in Guangdong by using the slit-less spectrometer with time resolution of 20 μs. At the same time, the bottom current intensity was obtained, and the flashes of spectral radiation characteristics were analyzed in different current intensities.

2 Experiment and observation

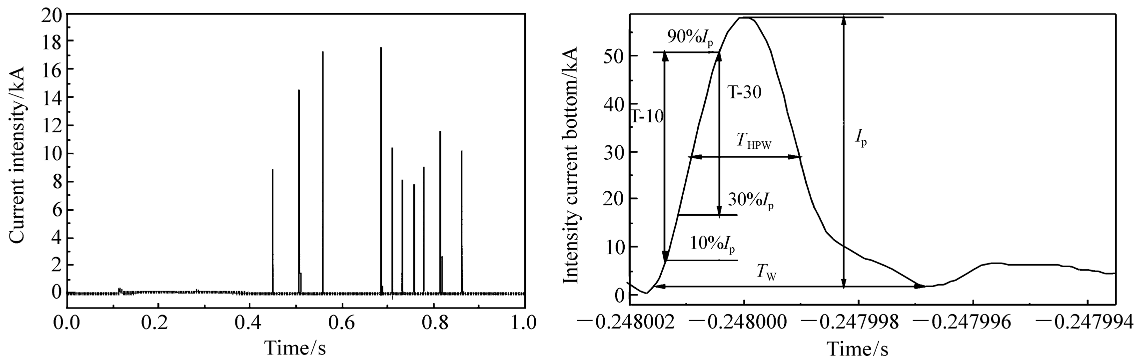
The spectral observation was carried out through slit-less grating spectrograph. The distance between spectral observation point and thunder point is about 1.9 kilometers and the recording system is Photron-SA5 high-speed cameras. At the same time, the time resolution was fixed as 50 000 frames per second, the spatial resolution was 512 × 272. Simultaneously, the grating was in front of the camera lens and the first level of spectral resolution was 1.3

Tab. 1 Current parameters of R9, R10

	Peak current/kA	10% -90% rise time/μs	Half peak time/μs	The full wave time/μs	Transfer charge/Q
R9	11.64	0.28	3.2	0.57	0.60
R10	10.34	0.2	3.08	0.60	0.45

nm[9]. The current measurement system was given in the references [10-11]. A negative polarity artificial triggered lightning was successfully obtained and the emission spectrum of the last two stroke channels was obtained by the spectrometer at 15:07:19, July 10, 2017.

The artificial triggered lightning has 10 return strokes, from which we obtained the spectra of the last two return channels, where R9 and R10 represent twice return stroke respectively. Fig. 1 shows the bottom current of artificial triggered lightning channel and the current pulse parameter definition. Tab. 1 shows the R9, R10 back current characteristic parameters. According to the current data of the bottom channel we extract the current waveform parameters including peak current intensity (I_p), the full wave time(T_w), half peak time(T_{hpw}), 10% – 90% rise time and transfer charge(Q). The definition of corresponding parameters is shown in Fig. 1 (b). The transfer of charge was obtained according to the current waveform and time integral[12-13].

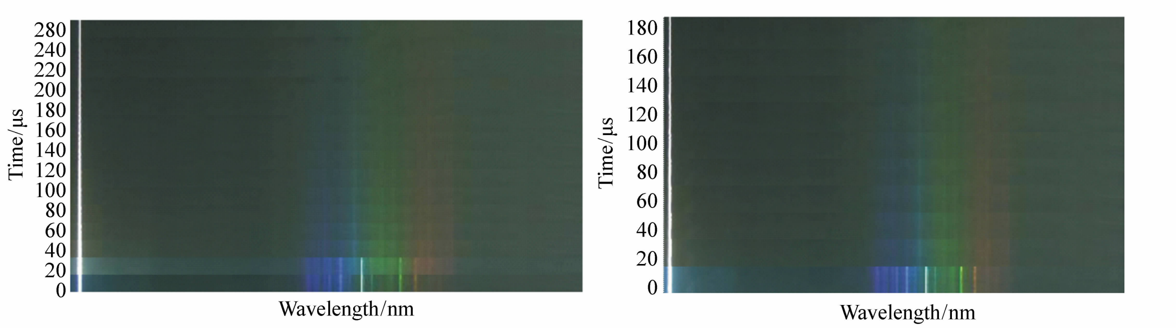


(a) Bottom current of artificial triggering lightning channel (b) Current pulse parameter definition

Fig. 1 Channel bottom current pulse and parameters of the current pulse

3 Data analysis

Fig. 2 shows the spectrum of the lightning return stroke channel changes with the time in R9 and R10, and the lightning channel is on the left. Fig. 3 shows the attenuation curve of the two return strokes, and the dot is the spectral moment. Fig. 4 shows the spectrum of two return strokes in 60 μs, where the horizontal is the wavelength and the ordinate is the relative strength of the spectrum.



(a) R9 (b) R10

Fig. 2 Original spectra of two return strokes variation with time in discharge channel

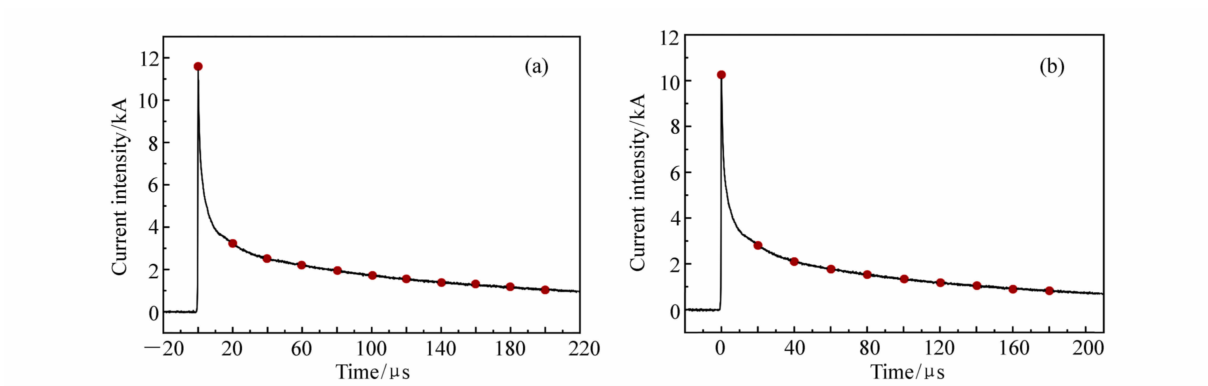


Fig. 3 Channel bottom current decay curves for two return strokes

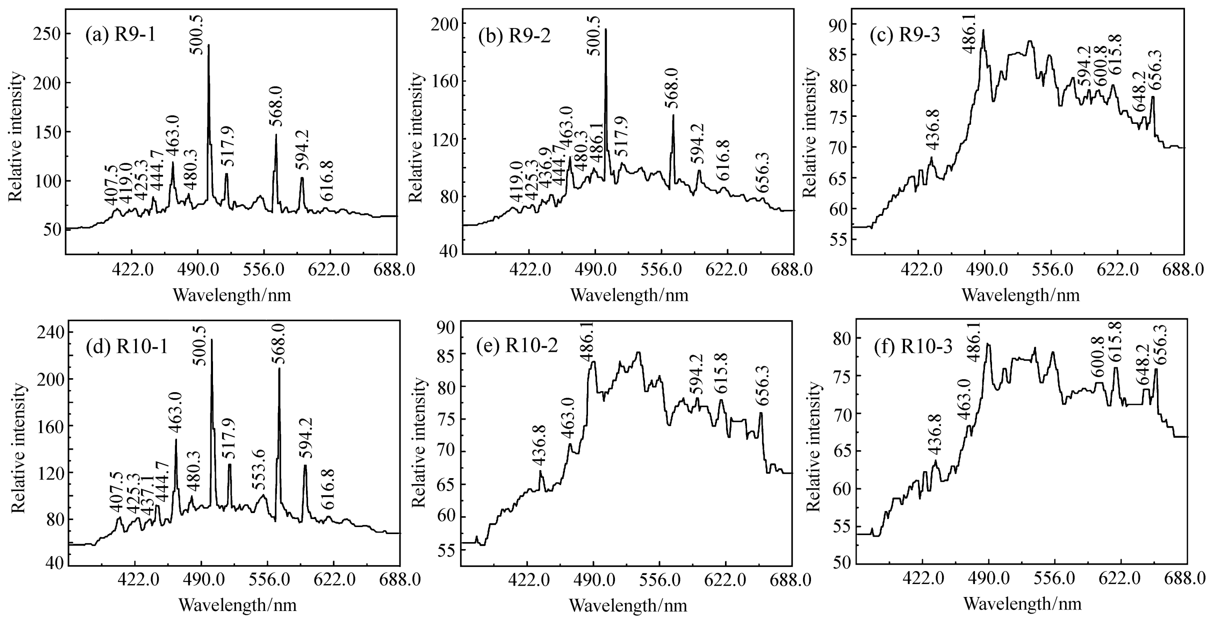
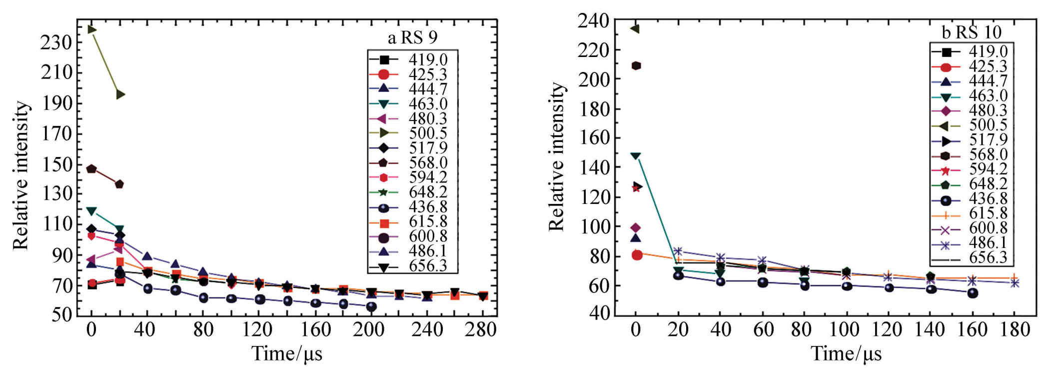


Fig. 4 Spectra of two return strokes at 0, 20, 40 μs

From Fig. 4 we can see that the return stroke (R9, R10 in 0 μs(a, d), 20 μs(b, e), 40 μs(c, f)) lines at the beginning are mainly single ionized spectral lines of nitrogen, oxygen, such as OII 419. 0 nm and OII425. 3 nm, NII444. 7 nm, NII463. 0 nm, NII480. 3 nm, NII500. 5 nm, NII517. 9 nm, NII568. 0 nm, NII594. 2 nm and NII616. 8 nm. However, some lines are observed at the end of the return stroke, which mainly results from the lower excited neutral nitrogen, oxygen and hydrogen spectrum lines such as OI436. 8 nm, OI615. 8 nm, NI 600. 8 nm, Halpha, H beta, *etc.*

The rising time of the R9 and R10 (10% – 90%) was 0. 28 μs and 0. 20 μs respectively. The lightning channel currents reached the peak value in an instant, which ionized the particles in the channels. Therefore, the first line is single ionized spectral transition lines, followed by strengthening of continuous spectrum. The neutral atoms transition spectral line appeared at the end. The ion spectral line intensity of both R9 and R10 reached the peak in the first spectrum picture, namely 0 μs. In the second spectrum of R10, many ion spectral lines could not be observed. R9 ion spectral line was attenuated in the second picture. The main reason of R9 channel bright enhancement is that the continuous background radiation reached the peak. The transfer charge of R9 and R10 is 0. 60 C and 0. 45C respectively. Since the transfer charge of R9 is relatively higher, meaning higher energy in the channel, the ion spectral line of R9 lasts longer than R10.

Fig. 5 shows the time evolution of spectral lines for two return strokes. The spectral lines can be classified into three categories according to duration. The line intensity of the first kind of spectral reached the peak in 0 μs, and then attenuated quickly. RS9 disappeared in 20 μs, and RS10 disappeared in 0 μs. These spectral lines were the transition spectrum of a single ionized ion of nitrogen oxides, and minimum excitation energy was 20. 67 eV for NII568. 0 nm, such as OII419. 0 nm, OII425. 3 nm, NII444. 7 nm and 480. 3 nm, NII 500. 5 nm and 517. 9 nm, NII568. 0 nm and 616. 8 nm.



(a)RS9: disappeared in 20 μs (b)RS10: disappeared in 0 μs

Fig. 5 Time evolution of lines for two return strokes

The difference between the second kind of spectral line and the first one is the duration time, where the second was longer than the first one. For instance, NII463. 0 nm in R9 lasted to 80 μs, NII594. 2 nm in R9 lasted to 20 μs, and lasted to 100 μs in R10.

The third kind of spectral lines showed the characteristics that it was not observed in 0 μs but reached the peak in 20 μs, and then receded slowly. These spectral lines lasted for a long time, such as OI436. 8 nm, OI615. 8 nm NI600. 8 nm, NI 648. 2 nm, H_α and H_β. The strongest strength lines was H_β. This kind of spectral lines were the transition spectral line of neutral nitrogen, oxygen and hydrogen atoms, with low excitation energy between 12 – 13 eV.

Since the lightning channel current reached its peak in an instant and then began to attenuate rapidly, the high excitation energy appeared firstly and attenuated rapidly. The persistent low current in the return channel and the recombination process of the ions made the neutral particles in the channel more exsiting in excited states. Therefore the third kind of spectral line can last longer.

Fig. 6(a) shows the variation of total spectral intensity over time. The 6(b) and 6(c) in the bottom show the stack line by the offsets of R9, R10 spectra over time respectively. The total intensity of the spectrum is defined as the area surrounded by the spectral curve and the x-coordinate. R9 ion line reached its peak of total intensity at 0 μs, and total spectral intensity reached the peak in 20 μs. Combined with the relationship between spectral stacked graph and time, the main reason of the total spectral intensity reaching its peak in 20 μs is that the continuous background radiation enhanced in 20 μs.

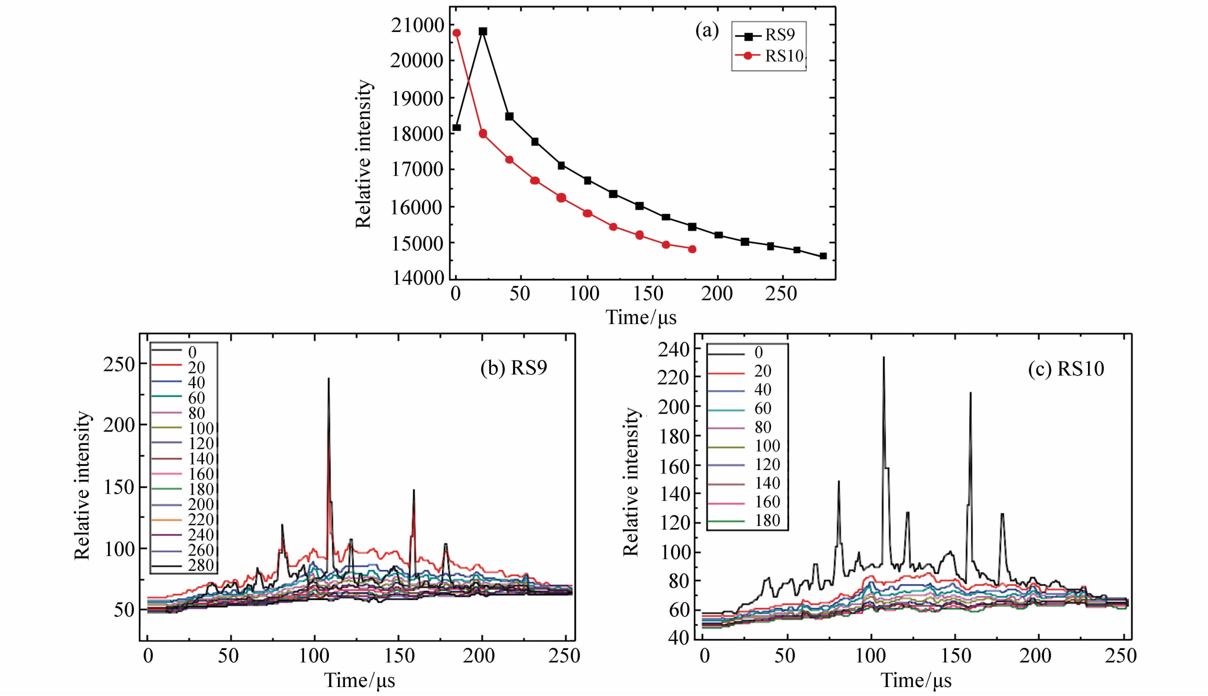


Fig. 6 Time evolution of total spectral intensity for two return strokes

According to the plasma radiation theory, the continuous spectrum mainly comes from the bremsstrahlung radiation and recombination processes in plasma[14-15]. The bremsstrahlung radiation is the process of emitting photons by the collision of high-temperature free electrons and other particles in the plasma, *i. e.* :

$$e(h) + M \longrightarrow e(l) + M + h\nu . \quad (1)$$

In this formula, e(h) and e(l) are free electrons at the higher temperature and lower temperature, respectively; M is the third body particle; and ν is the frequency of recombination radiation. The recombination radiation of the channel plasma is realized mainly through two processes[14-15]. One is the dissociation progress of atmosphere ions and free electrons, namely:

$$\begin{array}{l} N^+ + e + M \longrightarrow N^* + N + M + h\nu \\ O^+ + e + M \longrightarrow O^* + O + M + h\nu \end{array} . \quad (2)$$

In the formula, N^+ and O^+ are nitrogen ions and oxygen ions. N^* and O^* are excited nitrogen atoms and oxygen atoms, respectively. The other process is the direct compound process of positive and negative ions, namely:

$$\begin{array}{l} N^+ + O^- \longrightarrow N_2 + O_2 + h\nu \\ O^+ + O^- \longrightarrow O_2 + O_2 + h\nu \end{array} . \quad (3)$$

Through the stack line of R9 and R10, we can see that the continuous spectrum had been decreasing since it gets its peak, but the amplitude of decrease in the long wave band is less than that of the short-wave band. This is associated with the radiation mechanism of continuous spectrum. At the beginning of the return stroke, plasma temperature and density lied in the highest due to channel current getting its peak instantaneously at the same time. Therefore, stroke continuous background radiation at the beginning of return is given priority to bremsstrahlung radiation. With time elapsing, the channel current decreased rapidly, channel radius increased, channel temperature and electron density decreased. Compound radiation enhanced gradually, but the amplitude enhancement of recombination radiation is less than that of the bremsstrahlung radiation reduction. This lead to continuous declining of radiation. Because the continuous background radiation produced by the recombination radiation is mainly concentrated in the long-wave band, the amplitude reduction of long wave band is less than that of short-wave band.

4 Conclusions

Based on the analysis of the emission spectrum with the time resolution of 20 μs and the bottom current of the artificial triggered lightning channel, the following conclusions can be drawn:

(1) 10% to 90% of the rise time is less than 1 μs, which makes the lightning channel current get its peak instantly. Single ionized ion transition spectral line appeared firstly in the return stroke channel, followed by increase of continuous spectrum. Finally, neutral atoms transition spectral line appeared. The higher transfer charge has higher channel energy and the ion spectral line can last longer.

(2) The spectral line can be classified into three types according to the duration of the spectral line. The high excitation energy appeared firstly and attenuated rapidly. There are lasting lower current and the recombination processes of the ions at the later stage, which made the neutral particles more existing in the excited states. The third kinds of spectral line can last for a long time, for example, OI、NI、H_α、H_β and so on.

(3) The continuous bands mainly come from bremsstrahlung and recombination. Because the background radiation produced by the recombination radiation is mainly concentrated in the long-wave band, the decrease amplitude of long-wave band is less than that of the short-wave band.

References:

[1] 李安,王亮伟,郭帅,等. 激光诱导击穿光谱增强机制及技术研究进展[J]. 中国光学,2017,10(5):619-640.
LI A,WANG L W,GUO SH,*et al.*. Advances in signal enhancement mechanism and technology of laser induced breakdown spectroscopy[J]. *Chinese Optics*,2017,10(5):619-640. (in Chinese)

[2] 刘利锋,肖沙里,钱家渝. 激光等离子体X射线能谱诊断[J]. 光学 精密工程,2017,25(5):1192-1196.
LIU L F,XIAO SH L,QIAN J Y. X-ray spectral diagnosis for laser plasma[J]. *Opt. Precision Eng.*,2017,25(5):1192-1196. (in Chinese)

[3] 唐蕾,王永杰,袁春琪,等. 三种电极的大气压氩等离子体射流光学特性[J]. 发光学报,2018,39(4):547-554.
TANG L,WANG Y J,YUAN CH Q,*et al.*. Optical property of the atmospheric pressure argon plasma jet generated by three types of electrodes[J]. *Chinese Journal of Luminescence*,2018,39(4):547-554. (in Chinese)

[4] 李安,邵秋峰,刘瑞斌. 新型便携式激光诱导击穿光谱系统综述[J]. 中国光学,2017,10(4):426-437.
LI A,SHAO Q F,LIU R B. Review of new type portable laser-induced breakdown spectroscopy system[J]. *Chinese Optics*,2017,10(4):426-437. (in Chinese)

[5] SALANAVE L E,ORVILLE R E,RICHARDS C N. Slitless spectra of lightning in the region from 3850 to 6900 angstroms[J]. *Journal of Geophysical Research*,1962,67(5):1877-1884.

[6] XUE S M,YUAN P,CEN J Y,*et al.*. Spectral observations of a natural bipolar cloud-to-ground lightning[J]. *Journal of Geophysical Research*,2015,120(5):1972-1979.

[7] MU Y L,YUAN P,WANG X J,*et al.*. Temperature distribution and evolution characteristic in lightning return stroke channel[J]. *Journal of Atmospheric and Solar-Terrestrial Physics*,2016,145:98-105.

[8] ZHANG H M,YUAN P,ZHANG Y J,*et al.*. Plasma characteristic of lightning discharge channel[J]. *High Voltage Engineering*,2013,39(10):2452-2458.

[9] 张华明,张义军,吕伟涛,等. 一次人工触发闪电通道光谱结构分析[J]. 光谱学与光谱分析,2017,37(6):1692-1695.
ZHANG H M,ZHANG Y J,LÜ W T,*et al.*. The spectra structure characteristic of triggered lightning channel[J]. *Spectroscopy and Spectral Analysis*,2017,37(6):1692-1695. (in Chinese)

[10] ZHANG Y J,LÜ W T,CHEN SH D,*et al.*. A review of advances in lightning observations during the past decade in

Guangdong, China[J]. *Journal of Meteorological Research*, 2016, 30(5): 800-819.

[11] ZHANG Y J, YANG SH J, LU W T, *et al.*. Experiments of artificially triggered lightning and its application in Conghua, Guangdong, China[J]. *Atmospheric Research*, 2014, 135-136: 330-343.

[12] 周方聪,张义军,吕伟涛,等. 人工触发闪电连续电流过程与 M 分量特征[J]. 应用气象学报, 2014, 25(3): 330-338.
ZHOU F C, ZHANG Y J, LÜ W T, *et al.*. Characteristic analysis of continuing current process and m-component in artificially triggered lightning[J]. *Journal of Applied Meteorological Science*, 2014, 25(3): 330-338. (in Chinese)

[13] 肖桐,张阳,吕伟涛,等. 人工触发闪电 M 分量的电流与电磁场特征[J]. 应用气象学报, 2013, 24(4): 446-454.
XIAO T, ZHANG Y, LÜ W T, *et al.*. Current and electromagnetic field of M component in triggered lightning[J]. *Journal of Applied Meteorological Science*, 2013, 24(4): 446-454. (in Chinese)

[14] 项志遴,俞昌旋. 高温等离子体诊断技术[M]. 上海: 上海科学技术出版社, 1982: 68-73.
XIANG ZH X, YU CH X. *High Temperature Plasma Diagnosis*[M]. Shanghai: Shanghai Science and Technology Press, 1982: 68-73. (in Chinese)

[15] 林兆祥,李小银,程学武,等. 激光大气等离子体时间演化特性的光谱研究[J]. 光谱学与光谱分析, 2003, 23(3): 421-425.
LIN ZH X, LI X Y, CHENG X W, *et al.*. Spectroscopic study on the time evolution behaviors of the laser-induced air plasma[J]. *Spectroscopy and Spectral Analysis*, 2003, 23(3): 421-425. (in Chinese)

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