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# Optically Powered Lightning Current Measurement System for High-Tower Observation

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**ABSTRACT** The measurement of lightning striking the high tower is one of the most important ways to obtain the full-wave of lightning current. However, importance has never been attached to this important work until recent years in China. During the implementation process, many difficulties have to be overcome, such as problems relating to the current sensor, signal transmission system, and the power supply. In this paper, an optically powered lightning current measurement system composed of two current probes, an optical fiber link transmission system and a data acquisition terminal is designed for high-tower observation. The system has the following advantages: 1) multi range design is adopted, which enables the system to simultaneously measure the lightning leader and return-stroke currents; 2) two self-integral Rogowski coils are used as the lightning current sensor, thus making the full wave measurement of lightning current more accurate and easier; and 3) driven by laser energy, the optical fiber link allows the system to be immune to electromagnetic interference and less dependent on electric power. Such a lightning current measurement system is now installed on the Zifeng Tower (450 m, the world's tenth, China's sixth tall buildings, as of August 9, 2016), which is expected to record the current of lightning striking the tower.

**INDEX TERMS** Lightning current measurement, optical fiber system, Rogowski coil.

## I. INTRODUCTION

Lightning current is one of the most important parameters for lightning physics research, lightning protection design and lightning damage evaluation, etc. Lightning current waveform can be acquired from lightning striking tall towers or artificially triggered lightning [1], [2]. Through the measurement on tall tower, a relative low costing work, the nature lightning current can be obtained, due to which there have been many researches carried out on lightning measurement on tall towers. Since the beginning of the observation on the Toronto Canadian National (CN) Tower (553 m) in 1978, many tens of lightning can be observed each year, in which process a large number of valuable data has been obtained [4], [5]. Many lightning flashes struck on other tall buildings have also been observed, such as Ostankino Television Tower in Moscow (540 m) [6], Empire State Building of New York City (381 m) [7], Palace of Culture and Science in Warsaw (230 m) [8]. Moreover, observation of current waveform of lightning strokes on electric power transmission towers was also reported [9].

For lightning current measurement, Rogowski coil is the most common current sensor. The current derivative at the CN tower is acquired with Rogowski coils and digitizers, with the transmission signal sent through optical fiber link [10]. Similar measurement method can also be found in [9], [10]. In the design described in this paper, Rogowski coil and optical fiber link are also used base on previous experience. However, some new feature can be found in the new design: for instance, the Rogowski coil can directly output the current waveform with the good self-integral performance, and the transmitter of optical fiber link is driven by laser energy.

The paper is organized as follows. Section II describes the overview of the structure of the lightning current measurement system. In section III, the self-integral Rogowski coils for return stroke current and lightning leader current measurement were presented with the structure design and calibration.

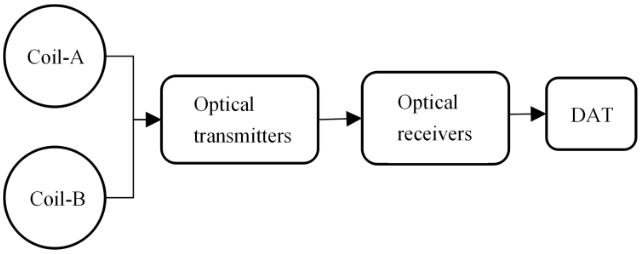


**FIGURE 1.** **The overall structure of the lightning current measurement system.**

In section IV, the optical fiber link with transmitter driven by laser energy is depicted, and finally conclusions are drawn in section V.

## II. LIGHTNING CURRENT MEASUREMENT SYSTEM

The lightning current measurement system in this paper is designed to measure both the lightning leader and return-stroke currents, with the overall structure of the system shown in Fig. 1. The lightning current measurement system is composed of three parts: the current sensors, the signal transmission system, and the data acquisition terminal (DAT).

In order to measure the lightning leader and return-stroke current simultaneously, two self-integral Rogowski coils are designed as the current sensors, one of which has a measurement range of 1kA$\sim$120kA for the measurement of the return stroke current, and the other has a measurement range of 5A$\sim$2kA for the measurement of lightning leader current. Here, we call the coil for return stroke measurement coil-A, and the coil for lightning leader measurement coil-B.

The signal transmission of the coils relies on the optical fiber link which consists of two optical transmitters and two optical receivers. On one hand, the optical fiber link enables the system to be immune to electromagnetic interference caused by the lightning electromagnetic pulse (LEMP). On the other hand, the optical transmitters on the lightning rod are driven by laser energy through the optical fiber link. Therefore, neither the electrical wire nor battery is needed to install on the top of tower, thus making the system much safer.

As an industrial personal computer with a 50Msps PCI high speed data acquisition card, the DAT is connected to a remote control computer.

In the following sections, the detail design of the Rogowski coils and optical transmission system is presented.

## III. THE CURRENT SENSORS

It can be seen that two Rogowski coils are used as the current sensors. The principle diagram and equivalent circuit diagram of the coils are shown in Fig. 2. In the figure, $I_{\mathrm{L}}$ represents the input current, $I_{\mathrm{c}}$ indicates the induced current of the coil and $R_{\mathrm{s}}$ means the sampling resistor; $V_{\mathrm{o}}$ is the output of the coil, and the GDT is the protection gas discharge tube only for coil-B. As the coil-B used for lightning leader measurement has to withstand the return stroke current, an additional gas discharge tube (in the dotted line rectangle) is designed to protect the sampling resistor. According to the equivalent circuit diagram, the following formula can be drawn:

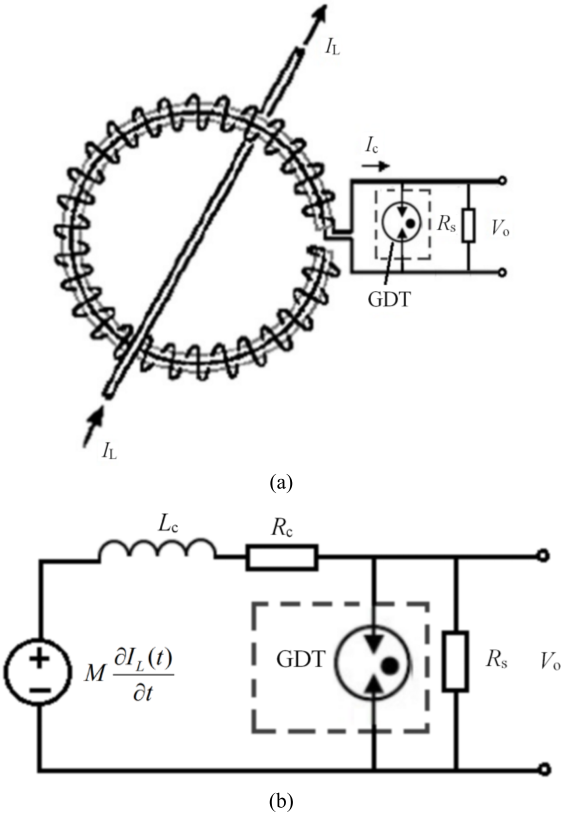


**FIGURE 2.** **The principle diagram and equivalent circuit diagram of the coils, (a) the principle diagram; (b) the equivalent circuit diagram.**

$$M\frac{\partial I_L(t)}{\partial t} = L_c\frac{\partial I_c(t)}{\partial t} + (R_c + R_s)I_c(t) \tag{1}$$

Accordingly, if $L_c\frac{\partial I_c(t)}{\partial t}$ is much smaller than $(R_{\mathrm{c}}+R_{\mathrm{s}})I_{\mathrm{c}}(t)$, $M\frac{\partial I_L(t)}{\partial t}$ is approximately equal to $(R_{\mathrm{c}}+R_{\mathrm{s}})I_{\mathrm{c}}(t)$. Therefore, the coil is a differential coil, for which an additional integrator is required. On the contrary, if $L_c\frac{\partial I_c(t)}{\partial t}$ is much greater than $(R_{\mathrm{c}}+R_{\mathrm{s}})I_{\mathrm{c}}(t)$, $M\frac{\partial I_L(t)}{\partial t}$ is equal to $L_c\frac{\partial I_c(t)}{\partial t}$, thereby getting $I_{\mathrm{c}}(t)$ is equal to $L_{\mathrm{c}}(t)I_{\mathrm{L}}(t)/M$. The coil is then a self-integral coil, and the output waveform of $V_{\mathrm{o}}$ has almost the same shape as that of the input current $I_{\mathrm{L}}$.

To meet the self-integral condition, the frequency of the input current should be:

$$\omega \gg (R_c + R_s)/L \tag{2}$$

Then $\omega_{cL} = (R_c + R_s)/L$ can be taken as the lower-cut-off frequency for self-integral coil.

According to the principle, two self-integral Rogowski coils have been designed as the current sensors, which have been installed on the lightning rod on the top of the Zifeng Tower (450m, the world's tenth, China's sixth tall buildings, as of August 9, 2016). Fig. 3(a) presents the photograph of the coil, and the two coils share the same appearance

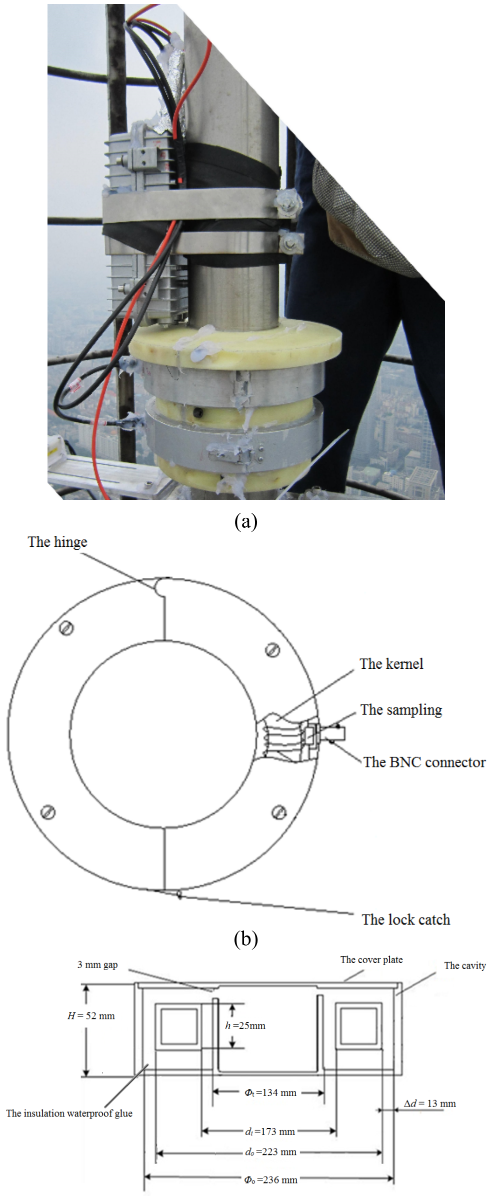


**FIGURE 3.** **The Rogowski coil (a) the photograph of the coil; (b) the overlooking structure diagram; (c) the section structure diagram.**

and similar structure. Fig. 3(b) and (c) are the structure diagrams of the coils. As shown in Fig.3 (b), the coils have an opening-and-closing structure with a hinge and a lock catch. Each coil takes two semicircle Fe-based amorphous magnetic cores with $\mu_r$ of 283 as the coil kernel. In terms of the Fe-based amorphous magnetic cores, they are provided with high magnetic saturation characteristics with a 1.5T saturation magnetic field value, which can thus meetting the requirements of hundred kilo-ampere lightning current measurement. Enameled copper wire is winded on the magnetic cores. Besides, a sampling resistor is used to output the signal with a BNC connector. As shown in Fig. 3(c), the coil kernel is placed in the aluminum shell composed of a cavity and a cover plate. A 3 mm gap is designed to make the magnetic field pass through the shell by cutting off current flow path. Insulation waterproof glue could fill up the space between the shell and the kernel. Furthermore, the size of the coil shown in the figure is specially designed according to the size of the lightning rod.

The number of wire turns ($n$) of both the two coils is 850, and the diameter of the enamel wire ($d_w$) is 0.51mm. The actual measurement values of coil inner resistances ($R_c$) are both 7.4 Ω. As the coil with low-value sampling resistor can be used for large current measurement, a 0.75Ω sampling resistor ($R_s$) is chosen for coil-A. However, as large-value sampling resistor should be used for low current measurement, an 800 Ω resistor is chosen for coil-B. Self-inductances ($L_c$) can be calculated as follows [11]:

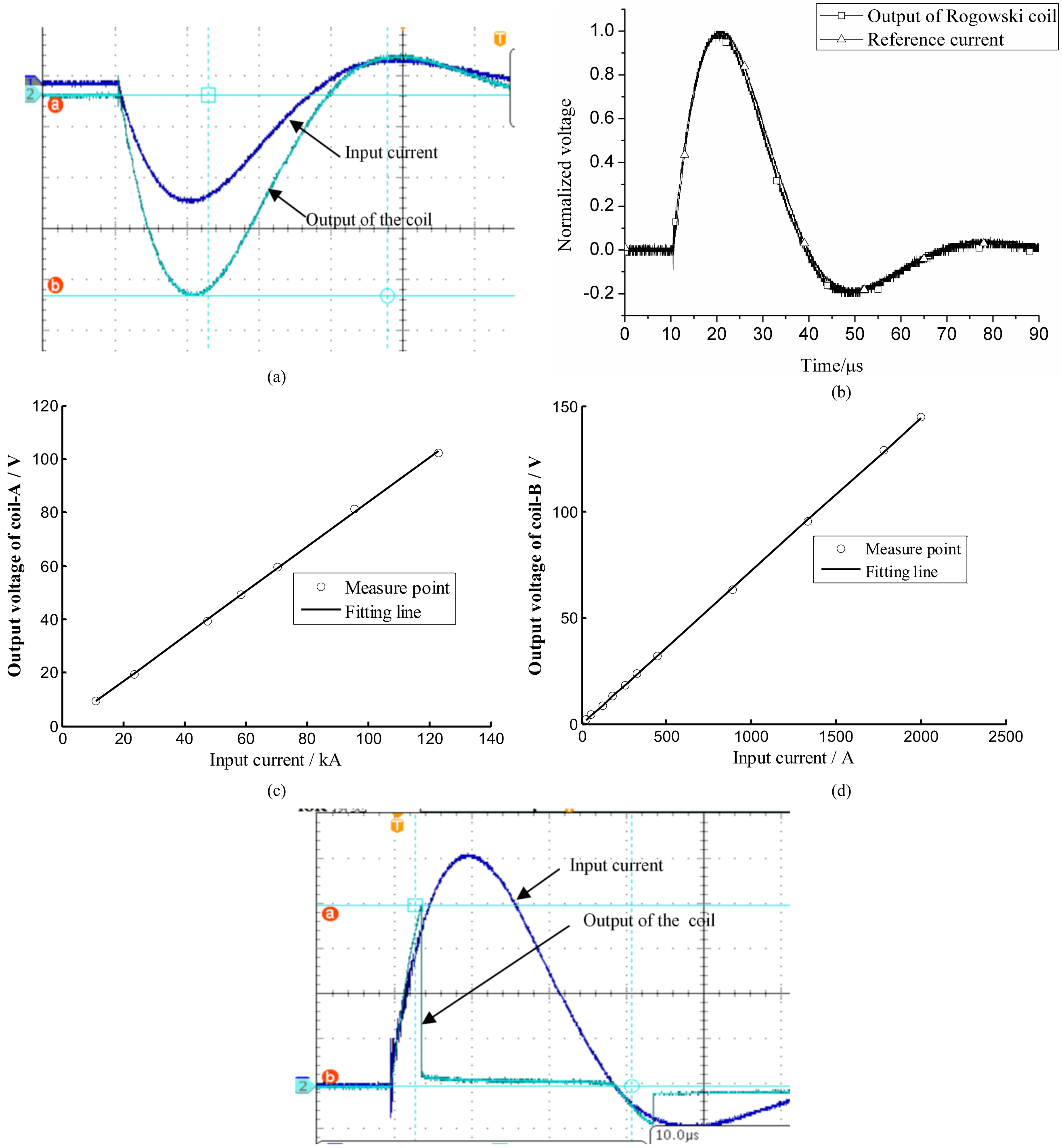
$$L_c = n^2 M \frac{\mu_0 \mu_r h}{2\pi} \ln \frac{d_o}{d_i} = 259\text{mH} \tag{3}$$

Then, the lower-cut-off frequencies for the coils are 5.67 Hz (coil-A) and 561 Hz (coil-B), respectively. As most of the energy of lightning current would be from several kHz to about 2 MHz, both the coils can meet the self-integral condition.

Fig. 4 shows the calibration waveform of the coils, 8/20$\mu$s lightning current waveform generator is used to generate the reference input current. Fig. 4(a) and (b) show the input/output waveforms of coil-A (The waveforms of coil-B are similar, which are not listed in the paper). Moreover, the figures above show that the output waveforms of the coils are almost entirely consistent with those of the input currents, suggesting that the coils have an excellent integration performance with 8/20$\mu$s waveform. During the measurement process, just the sensitivity coefficient is needed to obtain the lightning current. Fig. 4(c) and (d) show the fitting lines of the measure point of the two coils, from which the good linearity of the two coils can be seen, with the measurement sensitivity coefficients being 0.836 V/kA ($K_1$) and 0.071 V/A ($K_2$) for coil-A and coil-B, respectively. The calibration shows that the measurement ranges of coil-A and coil-B reach 1 kA~120 kA and 5 A~2 kA at least. Besides, as the peak value of lightning return stroke is tens of kA, and that of the leader is about tens of A to several kA [12], the measurement range of the coils can thus meet the requirements.

As the coil-B is used for lightning leader measurement, relative low current can be measured. To avoid the probable damage of the coil in the case of the passing large return-stroke current, a gas discharge tube is in a parallel connection with the sampling resistor. When the induced voltage is greater than the breakdown voltage of the gas discharge tube, the tube's breakdown would occur to protect the sampling resistor. Fig. 4(e) shows the breakdown waveform of the coil-B. However, in case the induced voltage is lower than the breakdown voltage of the gas discharge tube, the output waveform of the coil accords with input source current.

In addition, current waveform of 10/350$\mu$s, 10/700$\mu$s, and 0.6/1300$\mu$s have been taken as the source current



(a)

(b)

(c)

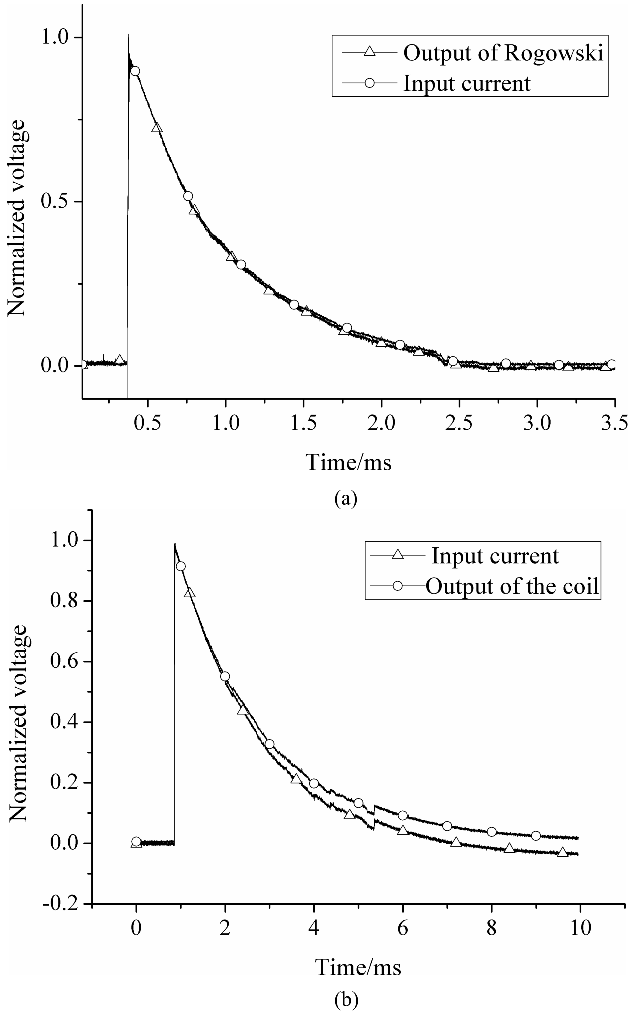
(d)

(e)

**FIGURE 4.** **The calibration waveform of the coils, (a) the output waveform of coil-A; (b) the normalized waveform of coil-A; (c) the fitting line of the measure points of coil-A; (d) the fitting line of the measure points of coil-B; (e) the breakdown waveform of the coil-B.**

to check the response of the coil. Fig. 5 shows the response of coil-B with 10/700$\mu$s and 0.6/1300$\mu$s input current. When the input current reaches 10/700$\mu$s, output current has almost the same waveform with the input current.

However, a slight low frequency distortion can be found in the output current with 0.6/1300$\mu$s input current, which is caused by the frequency component of current lower than the lower-cut-off frequency. Because the current range of the current generator is less than 2kA, this test was not done for



(a)

(b)

**FIGURE 5.** The response of the coil-B with 10/700$\mu$s and 0.6/1300$\mu$s input current.

the coil-A. In spite of this, we can see from Fig.4 that the coil-A also has good low frequency response. As the average rise time and during time lightning current reach about hundreds of ns and tens of microseconds, respectively, the coils can satisfy the measurement requirements.

## IV. THE OPTICAL FIBER LINK

The output signal of the coils can be transmitted to the DAT with coaxial cable or optical fiber link. Coaxial cable can provide simpler connection. However, due to the strong LEMP, high voltage will be induced on the coaxial cable, which could threaten the security of the DAT. Nevertheless, immune to the LEMP, the optical fiber link is more suitable for the measurement. Thus, the optical fiber link is finally adopted.

As shown in Fig. 6, two optical transmitters (transmitter-A and transmitter-B) are used to convert the output electrical signal of the two coils to optical signal. As the transmitters are installed on the lightning rod, it is difficult to supply required electrical power for them. For security, a design of laser energy supply is used for the transmitters. Fig. 7 shows the laser power modules of the transmitters, each of which can provide 0.5W laser power with 830nm wavelength laser. In each transmitter, the laser energy is converted to electric power through a laser energy battery (PPC_Battery) for driving the circuit.

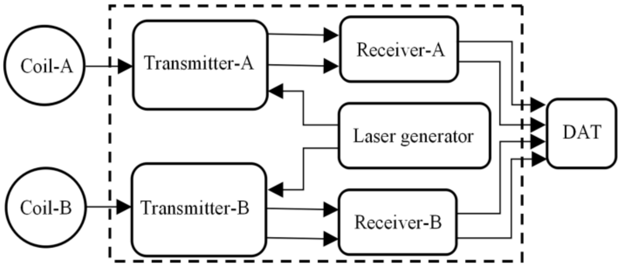


**FIGURE 6.** The signal flow chart of the measurement system.

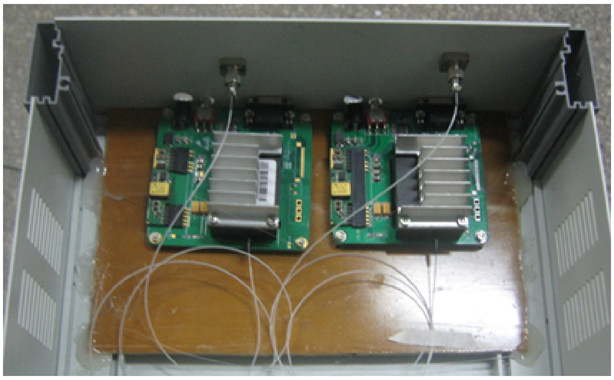


**FIGURE 7.** The laser power modules of the transmitters.

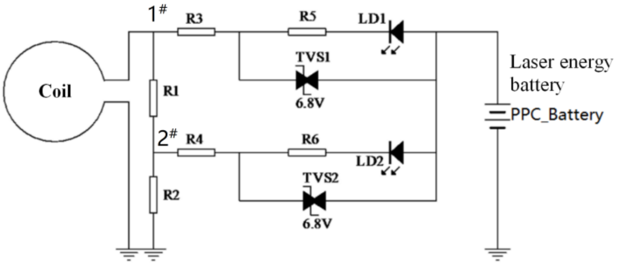


**FIGURE 8.** The circuit principle diagram of the optical transmitter.

The circuit principle diagram of the transmitter is shown in Fig. 8. In order to expand the dynamic range of measurement, a two-gain mode design is adopted. The output of the coil is divided into two transmission channels with different attenuations by $R_1$ and $R_2$. When the current is lower than the saturated current, channel $1^\#$ with higher sensitivity can correctly output measurement waveform. However, if the current is larger than the saturated current, channel $1^\#$ will be saturated, and the correct waveform can be obtained through channel $2^\#$ with low sensitivity.

Fig. 9 shows the output waveforms of coil-A. The input current is larger than the saturated current of coil-A, and

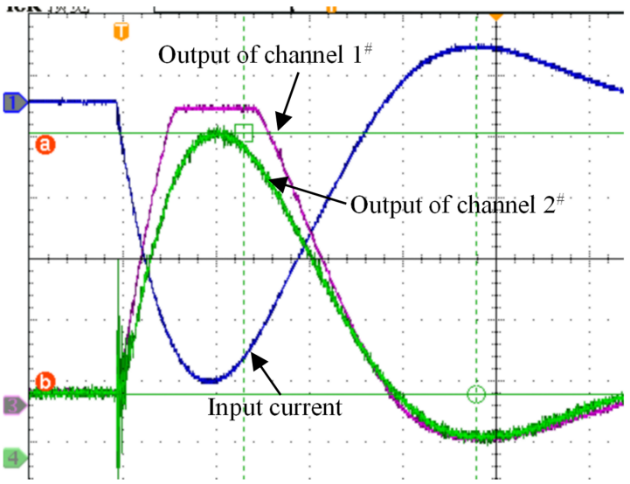


**FIGURE 9.** The output waveforms of coil-A for large current.

channel $1^{\#}$ is found to be saturated with flat-top waveform. However, channel $2^{\#}$ shows the correct waveform. In addition, the TVS tubes can protect the luminotrons LD1 and LD2. In the circuit, the maximum current $I_{\mathrm{dm}}$ of luminotrons LD1 and LD2 is 100mA. When the current reaches $I_{\mathrm{dm}}$, the voltage drop $V_{\mathrm{dm}}$ at the two ends of the luminotron is 2V. The transient voltage suppression (TVS) diodes are designed to protect LD1 and LD2, and the reverse stand-off voltages $V_{\mathrm{rwm}}$ of them are both 6.8V. Then, the resistance value of $R_5$ and $R_6$ can be calculated by:

$$R = \frac{V_{rwm} - V_{dm}}{I_{dm}} = \frac{6.8 - 2}{0.1} = 48\Omega \tag{4}$$

In the actual circuit, the resistance value of $R_5$ and $R_6$ are 50 Ω. In coil-A, the resistance value of divider resistors R3 and R4 are both 200 Ω; besides, $R_1$ is 10 Ω, $R_2$ is 1 Ω, and the maximum modulation currents $I_{\mathrm{m}}$ of LD1 and LD2 are both 50 mA. Hence, the maximum measurement lightning current in channel $1^{\#}$ and channel $2^{\#}$ can be calculated by:

$$I_{1mA} = \frac{R_3 + R_5}{K_1} \times I_{\mathrm{m}} = \frac{200 + 50}{0.836} \times 0.05 \approx 15\text{kA} \tag{5}$$

$$\begin{aligned} I_{2mA} &= \frac{R_4 + R_6}{K_1} \times I_{\mathrm{m}} \times \frac{R_1 + R_2}{R_2} \\ &= \frac{200 + 50}{0.836} \times 0.05 \times 11 \approx 164\text{kA} \end{aligned} \tag{6}$$

where $K_1$ is the measurement sensitivity coefficient of coil-A.

For coil-B, $R_1$ is 51 Ω and $R_2$ is 12 Ω. The equivalent resistance of measuring circuit is 50 Ω, which is the same as the matching resistor for calibration. Therefore, the maximum measurement lightning current in channel $1^{\#}$ and channel $2^{\#}$ can be calculated by:

$$I_{1mB} = \frac{R_3 + R_5}{K_2} \times I_{\mathrm{m}} = \frac{200 + 50}{0.071} \times 0.05 \approx 176\text{A} \tag{7}$$

$$\begin{aligned} I_{2mB} &= \frac{R_4 + R_6}{K_2} \times I_{\mathrm{m}} \times \frac{R_1 + R_2}{R_2} \\ &= \frac{200 + 50}{0.071} \times 0.05 \times \frac{50 + 12}{12} \approx 910\text{A} \end{aligned} \tag{8}$$

The circuit power supply depends on the PPC_Battery. Meanwhile, the static working point currents $I_{\mathrm{sw}}$ of LD1 and LD2 are both 15 mA and the voltages $V_{\mathrm{sw}}$ at the two ends of them are 1.65 V, for which the power dissipation in channel $1^{\#}$ ($P_1$) and channel $2^{\#}$ ($P_2$) can thus be calculated:

$$P_1 = (R_3 + R_5)I_{SW}^2 + V_{SW}I = 0.081\text{W} \tag{9}$$

$$P_2 = (R_4 + R_6)I_{SW}^2 + V_{SW}I = 0.081\text{W} \tag{10}$$

Thus, the total power dissipation of the circuit is 0.162 W, which is less than the output power of PPC_Battery (0.5 W).

As each optical transmitter has two outputs, two optical fibers are used to connect one transmitter with one receiver. After converting the optical signal to electrical signal, the optical receivers then send electrical signal to the DAT. The DAT is an industrial personal computer with a 50Msps PCI high speed data acquisition card. Equipped with four channels, the PCI data acquisition card can simultaneously record the four output signals of the two optical receivers. Besides, the DAT is set to automatic acquisition mode so that it can automatically record the lightning current data.

## V. CONCLUSION

In this paper, the design of optically powered lightning current measurement system for high-tower observation is presented.

The system has the following advantages:

(1) Multi measurement range design is adopted. Two Rogowski coils with different measurement ranges were used for simultaneous measurement of lightning return stroke and leader current.

(2) Self-integral Rogowski coil design is adopted. Self-integral Rogowski coils can provide simpler measurement by directly obtaining the correct waveform without additional integrator.

(3) The optically powered optical fiber link is adopted to transmit the signal. Driven by laser energy, this optical fiber link can enable the system to be immune to electromagnetic interference and less dependent on electric power. In addition, a two-gain mode design of the optical transmitter is used to expand the dynamic range of measurement.

Such a lightning current measurement system was installed on the Zifeng Tower not long ago, and it is expected to provide us with as more lightning current data as possible.

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