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Development of a ground penetrating radar system for large-depth disaster detection in coal mine

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ABSTRACT

With the increasing coal mining efficiency, the geological disaster sources in the mine serious threat production safety, Ground Penetrating Radar (GPR) is widely used for detecting those hidden disaster sources attributed to the advantage of high precision, but with detection distance limitation. We describe a novel GPR system for large-depth disaster detection in mine, which has the large-depth detection ability and the explosion-proof capability to adapt to the mine working environment. In comparison with the existing GPR systems, this novel system is improved with the following design features: the step acquisition accuracy of the host control unit is improved to be 2 ps; the split pluggable low frequency combined antenna realizes the impedance matching and improves the detection distance; a photoelectric conversion module is developed to guarantee 6000 m transmission distance for the high-frequency synchronization signal in mine. We carry out some experiments to validate the design, and the measurement results show that: the proposed GPR system can realize the fine exploration and the accurate identification; the maximum detection distance can be up to 80 m with reflection method and 300 m with transmission method under uniform geological conditions, which break the current detection distance limitations within 30 m, simultaneously, the detection accuracy can be up to 3 m. We expect that the proposed GPR system will be used for the large-depth geological disaster sources detection and provide an advanced approach for improving mining safety.

1. Introduction

Coal is the pillar of China's energy industry, and >60% of the energy is from coal at present. The geological conditions of the China's coal mining are complex, and the different kinds of hidden disasters, such as mine water, small faults, broken zones, are the main causes of the coal mine accidents in China (Cheng, Fei, Suping, et al., 2014). With the development of mechanized coal mining technology, the mining progress has increased from 3 to 5 m/day ten years ago to 8–12 m/day, and the distance requirement for the advanced geological prediction of the roadway has increased from 30 m to >60 m. Therefore, the mine disaster source detection technology, in particular large-depth detection technology is becoming more and more urgent. In recent years, the high-resolution geophysical exploration technology, such as high-resolution seismic exploration technology, transient electromagnetic exploration technology, high-density electrical exploration technology, ground penetrating radar (GPR) and other technologies, provide strong technical supports for coal mine safety (Orlando, Cardarelli, et al., 2017). The GPR technology has been widely used in the disaster source detection, attributing to the obvious technical advantages among the several geophysical methods: high detection frequency, high precision, own launch excitation source, simple on-site operation (Fernandez-Alvarez, Rubio-Melendi, et al., 2017; Lai, Chang, and Sham, 2018). However, There are no explosion-proof radars with a detection distance of ≥60 m at home and abroad, the detection range and accuracy of the GPR still cannot meet the requirements of the coal production enterprise (Jishan and Jianxin, 2004; Zhenli, 2011; Najafi, Seyed, Khalokakaie, et al., 2015; Jianhua and Shucai, 2000).

Various factors limit the detection performance of the GPR technology, such as: (1) Because of the signal attenuation, the maximum effective detection depth of the current domestic mine explosion ground penetrating radar products is only 30 m, while the detection depth requirement of the major coal companies is 50 m (Elkarmoty, Colla, et al., 2017; Deping, Jiulong, et al., 2010; Wu, Jin, Xie, et al., 2013; Yonghui, Wu, and Wan, 2003). There is no explosion-proof radar products abroad, and the ground radar products can not be used in the mine; (2) The effective deep GPR signal is masked by the interference signal, resulting from the coal lane support steel, wire mesh and construction detection devices, and the excellent interpreted results can be acquired only if the interference signals are well eliminated from the GPR data (Anbazhagan, Dixit, and Bharatha, 2016; Cai, Chao, and Lu, 2017; Jin

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and Wang, 2014); (3) Compared with the ground half-space, the underground space belongs to the whole category. The ground antenna cannot be directly used in underground mine detection to achieve better results because of different degree of the environmental complexity, different impedance parameters, and different requirements for the antenna radiation directivity (Li, Zhou, et al., 2015; Wang, 2001); (4) Some pre-test results reveal that when wireless communication system is used to transport a synchronization signal from the transmitting unit to the receiving unit in the mine environment, the transmission delay time is so long that the stepping delay precision of the radar acquisition system is greatly reduced, which can not meet the requirements of instrument development. (5) To adapt to the mine working environment, the mine detection equipment needs to meet the requirements of explosion protection and safety standard, and have the ability of long detection distance and anti-interference. Compared with the ground detection equipment, the GPR system development is more difficult. Therefore, it is of great significance to develop a novel GPR system for large-depth disaster detection in mine to improve the ability of the ultra-large-depth geological structure detection and guarantee safety mining in coal mine (Cheng et al., 2014).

In this paper, we describe a novel GPR system to improve the large-depth detection ability for large-depth geological disaster sources detection in mine. The next section describes the GPR system design architecture. Then, the proposed microwave front end followed by the design of the low frequency combined antenna is detailed. We then report the experimental results. Finally, we draw our concluding remarks.

2. System design

The architecture of the GPR system is shown in Fig.1, it can be found that the GPR relies on the transmission of high-frequency electromagnetic waves through a transmitting antenna and the acquisition of the corresponding reflected signals by a receiving antenna to store and display the signals according to a computer. The signal Br1, performs as the trigger signal for the transmitting, is generated by the control module. The red line between the transmitting unit and the receiving unit is optical fiber, which is used to transport a high-frequency synchronization analog signal Br1′ to the receiving subsystem. As a delay signal of the Br1, the Br1′ is employed to trigger the acquisition module for data acquisition.

To improve the large-depth detection ability for large-depth geological disaster sources detection in mine, the key issues are microwave front end designs to improve the step acquisition accuracy of the host control unit, and low frequency antenna to improve the detection distance. Additionally, impedance matching and explosion-proof of the antenna are another issues to be solved.

3. Microwave front end designs

3.1. Stepping delay circuit design

For the signal acquisition system of the GPR systems that adopt equivalent sampling method, the precision of stepping delay circuit (SDC) is a significant factor that determines the signal acquisition accuracy, and the key of the SDC is constant current source circuit (CCSC). However, most literatures show that the precision of the CCSC can only guarantee the stepping delay output within 5–10 ps. Therefore, to develop a high-precision CCSC is the essential point to improve large-depth detection ability.

As shown in Fig. 2, this paper proposes a constant current source circuit based on operational amplifier, where, the constant current receiver is combined with the field effect transistor (FET) source. Both DA1 and DA2 are 16-bit DA converters that to control the constant current source charging current and to provide fast ramp switching voltage. DA1 can dynamically adjust the charging current for constant current source. The monostable trigger and high-speed diode D1 ensure that the charging capacitor C is quickly and fully discharged. A high-precision constant current source circuit is designed using the differential compensation method between N-channel and P-channel FET, thus the precision of the CCSC is obviously improved.

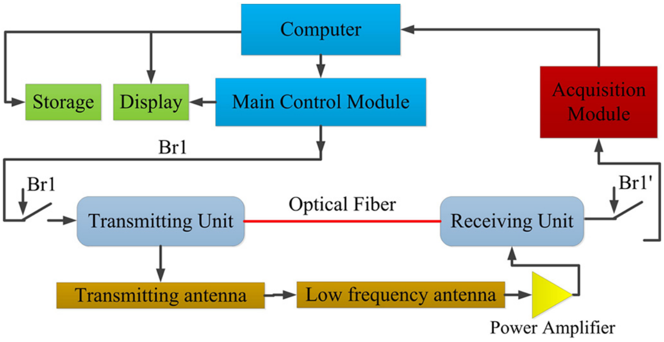

Fig. 1. Structure Diagram of the Mine Ground Penetrating Radar System.

Achieving the full discharge of capacitor C is implemented through a monostable trigger and high-speed diode D1. The measurements results illustrate that the stepping delay output can be controlled within 2 ps.

3.2. Microwave transmitting units

High-performance GPR system depends on high-quality transmitting pulses, produce by microwave transmitting unit, especially, the pulses with large amplitudes and low levels of ringing (Xia, Venkatachalam, and Huston, 2012 & James and Dehollain, 2011). An effective pulse excitation source network are designed and employed to establish a pulse transmitting unit in this paper. A 50-MHz pulse transmitting unit is taken as an example to explain the structural and functional design. As shown in Fig. 3, the UWB pulse transmitting unit includes three sections that a pulse shaping circuit to generate a trigger signal, a DC bias circuit to provide a reliable high amplitude voltage, and a high-voltage pulse generating circuit to produce the unipolar pulse.

Avalanche transistors can simultaneously provide a fast response and a large peak power. However, the width of the generated pulse still cannot meet the requirement. Compared with the achievement of the recent literature (Xia et al., 2013 & A. De Angelis, Dionigi, Giglietti, and Carbone, 2011), the output signal is with extremely narrow width (20 ns) and higher voltage (90 V), achieved by employing a four-step avalanche circuit. The generated 50 MHz transmitting pulse is plotted in Fig. 4a, and it can be found that the amplitude ratio of the pulse to ripple is obviously improved to be over 30 dB.

The 25-MHz transmitting unit is based on the same principle and is of the same design as that of the 50-MHz unit. Fig. 4b shows the generated 25 MHz transmitting pulse, which is with 40 ns wavelength and 120 V high voltage. Therefore, the proposed microwave transmitting unit is proved to have the good performance to improve the signal quality.

3.3. Microwave receiving units

The sensitivity and signal-to-noise ratio (SNR) are two important indicators to characterize the performance of the microwave receiving unit. In this paper, we describe a receiving unit that can obviously

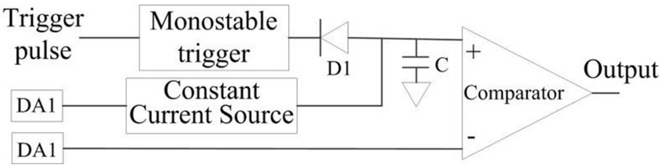

Fig. 2. Structural diagram of the SDC.