A novel low-frequency coded ground penetrating radar for deep detection

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Abstract: This paper presents a novel design of low-frequency coded ground penetrating radar (GPR) for deep detection. In order to increase the signal-to-noise ratio (SNR) of the returned signals of the deep targets, 2048 groups of Golay codes with 8 chips and 1 kW peak power are radiated by the transmitter. The receiver has two receiving channels, the first channel with a gain of 10 dB is used to obtain the reference signals, and the second channel, which has a maximum gain of 50 dB for deep targets and a minimal gain of –10 dB for shallow targets, is designed to receive the radar echoes. The real-time impulse compression is computed with 280 DSP48 slices of FPGA in parallel. Two pairs of fiber modules are used for synchronization between the transmitter and receiver. The transmitter and the receiver are discussed in detail. The experimental results show that the proposed low-frequency coded GPR has good detection performance for deep detection applications.

Keywords: ground penetrating radar, pseudo random codes, Golay codes, deep detection, FPGA

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Due to the severe attenuation of the transmit signal, deep detection with low-frequency GPR is still a challenging technology [1]. When an impulse was chosen as the transmit signal, increasing the peak power usually results in a lower pulse repeated frequency (PRF) which reduces the average power. Increasing the pulse width at a fixed PRF gives higher mean power but reduces the range resolution [2, 3]. To overcome the difficulty, a GPR with pseudo random binary sequences (PRBS) had been designed for deep detection [4]. However, the length of the PRBS should be extended to reduce the side lobes. Theoretically, Golay codes have no side lobes [5]. Practically, the performance of Golay codes in terms of reducing side lobes is also better than that of m-sequence or other PRBS [6].

In this paper, in order to obtain higher SNR and lower side lobes, a series of Golay codes with a peak transmit power of 1 kW are chosen as the transmit signal for deep detection. Taking the detection depth and range resolution into account, the center frequency of the Golay codes with a carrier is assigned to about 12 MHz, and its bandwidth is also 12 MHz. The receiver has two receiving channels that are used to obtain the reference signals and radar echoes. Then the real-time impulse compression is performed with 280 on-chip DSP48 slices in a single FPGA. Additionally, due to the large distance between the transmitter and receiver, two pairs of fiber modules are used for synchronization. The digital transmitter and the dual-channel receiver with high sensitivity are discussed in detail. Two experiments are carried out to validate the detection performance of the proposed low-frequency coded GPR.

2 Design of low-frequency coded GPR

The proposed low-frequency coded GPR consists of a pair of resistively loaded wire dipole antennas with a length of 12.5 m, a signal generator for Golay codes, a power transmitter, a dual-channel receiver and a fiber synchronization module for the transmitter and receiver, which is shown in Fig. 1. The two ADCs are used for implementing the two receiving channels, and DAC1 and DAC2 are used to generate the Golay codes with a carrier and produce the control voltages for the time-gain amplifier (TGA) in the second receiving channel, respectively. The TGA in the second receiving channel equips with a variable gain ranging from -10 dB to 50 dB. A pair of analog fiber modules (AFM) is used to transfer the small transmit signal from the signal generator to the transmitter. The pair of digital fiber modules (DFM) is used to transfer the synchronized trigger signal for the power amplifier. Additionally, a Xilinx Kintex-7 FPGA is used to control the entire system and perform the real-time pulse compression. The power amplifier, AFM receiver and DFM receiver are placed in a metal box BOX1, while the signal generator, the dual-channel receiver, AFM transmitter and DFM transmitter are packaged into another

Fig. 1. The blocks of the proposed low-frequency coded GPR.

Table I. Main parameters of the proposed low-frequency coded GPR

Peak transmit power	1 kW
Transmit signal	2048 groups of Golay codes with a carrier
Time width of one chip	80 ns
Bandwidth in 10-dB of the transmit signal	5~18 MHz
Pulse repeated frequency (PRF)	200 KHz
Receiving sensitivity	-130 dBm
Equivalent-time sampling interval	2.5 ns
Real-time sampling clock of ADC	100 MHz
Resolution of the ADCs	16 bits
Time window	4.2 us
Scanning rate	24 Scans/s
Antenna type	Wire dipole antenna
Frequency band of the antenna	4~25 MHz
Length of the antenna	12.5 m

metal box BOX2. The main parameters of the proposed low-frequency coded ground penetrating radar are listed in Table I.

2.1 The transmitter

As shown in Fig. 1, the signal generator for Golay codes is consists of a FPGA, a 16-bit DAC at a update rate of 250 Msps, a low pass filter (LPF) and a low-noise amplifier (LNA) with a gain of 10 dB. In order to obtain the Golay codes with a carrier of 12 MHz, the sampling clock of the DAC is 250 MHz and each chip of the Golay codes includes 20 samples. Hence, the time width of a chip is about 80 ns. As shown in Fig. 2(a), the value “1” of the Golay codes represents a single positive impulse, while the value “-1” of the Golay codes represents a single negative impulse. 2048 groups of Golay codes are stored into 2048 ROMs in FPGA, and each group of Golay codes with 8 chips includes 160 samples. In this work, some groups of Golay codes could be repeated in the 2048 groups. Under the control of the FPGA, the 2048 groups of Golay codes are through the multiplexer (MUX) to the DAC to generate the analog Golay codes with a carrier at a time.

Fig. 2. The relative signals. (a) The signal generator for 2048 Golay codes with a carrier. (b) The waveform of a group of Golay codes with a carrier. (c) The frequency characteristic of the transmit signal. (d) The corresponding radar echo sampled by Agilent oscilloscope.

In order to obtain the reference codes, the analog Golay codes with a carrier are divided into two ways by the power splitter. One way is sent to the first receiving channel, and sampled with the equivalent-time sampling as shown in Fig. 2(b). The frequency characteristic is shown in Fig. 2(c). The other way is sent to the 1 kW power amplifier (PA) by the pair of AFM and a fiber with a length of 16 m. Meanwhile, the trigger signal synchronized with the Golay codes is sent to the PA by the pair of DFM and another fiber of 16 m. The radar echo could be sampled by Agilent oscilloscope MSO9404A as shown in Fig. 2(d).

2.2 The receiver

In order to real-time obtain the impulse response functions of the deep targets, a high-sensitivity receiver with real-time pulse compressor should be designed carefully [7]. In this work, the receiver has two receiving channels with the same equivalent-time sampling interval. As shown in Fig. 1, the first receiving channel is used to real-time obtain the transmit signal from the signal generator as the reference signal, which consists of a LPF, a LNA with a gain of 10 dB, a 16-bit ADC at a sampling rate of 100 Msps and a programmable delay line. The second receiving channel is to receive the radar echo, which consists of a power limiter, two LPF, a time-gain amplifier (TGA), a 16-bit ADC at a sampling rate of 100 Msps and a programmable delay line. The two data acquisition controllers in FPGA, DAQ1 and DAQ2, control the time-delay of the programmable delay lines for the equivalent-time sampling. The two clocks of 100 MHz of the two ADCs are synchronized. ON Semiconductor's MC100EP196B programmable delay lines has been used to provide a stable time-delay of 2.5 ns for the ADC sampling clock, and it needs 4 rounds of equivalent-time sampling to obtain a radar echo or a reference signal. Each reference signal includes 280 samples, and each radar echo consists of 1600 samples.

Fig. 3. Design of the TGA. (a) The main architecture of the TGA. (b) The photo of the TGA. (c) The three kinds of gain characteristics of TGA.

In practical detection applications, the reflected signals of the shallow targets should be attenuated due to large transmit power, while the reflected signals of the deep targets should be amplified with high gain. Hence, the second receiving channel equips with a TGA with a minimal linear gain of -10 dB and a maximal linear gain of 50 dB. The TGA consists of three variable attenuators (VAT), three LNAs with a fixed gain and three LPFs, which is shown in Fig. 3(a) and Fig. 3(b), respectively. In order to satisfy the deep detection in different areas with different dielectric constant, the step of the gain can be chosen from the three kinds of gain characteristics as shown in Fig. 3(c). The two different control voltages, VCS1 and VCS2, are generated by the 14-bit DAC DAC2 at 400 Msps convert rate. Thus, the three kinds of gain step are 0.1 dB/ 2.5 ns, 0.2 dB/ 2.5 ns and 0.4 dB/ 2.5 ns, while 0.2 dB/ 2.5 ns is the defaulted gain step. Moreover, the starting gain of the TGA can be programmable from -10 dB to -3 dB.

Once the Golay codes with a carrier has been sampled by the first receiving channel in close-loop situation and the radar echo has been received by the second receiving channel, the cross-correlation between the two sampled signals can be computed in parallel. In this work, the 280 on-chip DSP48 slices of FPGA are used to compute the cross-correlation at a clock of 100 MHz, and the time it takes to compute the cross-correlation is about 20 μ s. When the 2048 cross-correlations of the 2048 groups of the Golay codes have been performed, the sum of them is the ultimate impulse response function. Therefore, the time it takes to obtain an impulse response is about 41 ms, and the scanning rate of the GPR system is 24 scans/s.

3 Experiments and results

Two sets of the experimental results are presented in this section, where the two antennas were placed front and back as shown in Fig. 4. Meanwhile, the two fibers

Fig. 4. Experiment setup.

are fixed on the surface of the antennas to protect from damaging. In first experiment, the geological structure is composed of dry sand and rock, and there are some electric wires and signal towers on the ground. Due to the small dielectric constant of the dry sand and rock, the starting gain and the gain step of the TGA are set to -10 dB and 0.1 dB/2.5 ns, respectively. Assuming that the relative dielectric constant of the ground is 8.5, and the total measured distance is about 3.3 km. The detection result after some simple signal processing is shown in Fig. 5, which indicates that the first layer is about 25 m deep. Obviously, much strong interference occurs on the detection profile, which swallows the weak returned signals of the deep targets. As it can be seen in the region from 1.9 km to 2.8 km, the second layer is about 47 m deep. Meanwhile, we found that the water content of the region from 1.6 km to 3.3 km is larger than that of the region from the starting point to the 1.6 km. Additionally, two unknown layers are about 150 m and 175 m deep in the region from 1 km to 1.7 km, respectively. In the second experiment, the geological structure is composed of dry sand, rock and metal ore. According to the drilling data at the point of 1.5 km of the measured trace, there are about three layers which locate in 10 m, 26 m and 43 m. The starting gain and the gain step of the TGA are set to -3 dB and 0.2 dB/2.5 ns, respectively. The measured distance is 2.5 km, and there is no electric wire and other strong interference on the ground. Assuming the relative dielectric constant of the ground is also 8.5. The detection result after some simple signal processing is shown in Fig. 6, which indicates that the first and the

Fig. 5. The detection result of the first experiment.

Fig. 6. The detection result of the second experiment.

second layer are about 12 m and 25 m deep, respectively. Lastly, the layer of metal is about 42 m deep.

4 Conclusion

This paper presents a novel design of low-frequency coded ground penetrating radar for deep detection applications. 2048 groups of Golay codes with 1 kW peak power can degrade the side-lobe and improve the SNR. The high-sensitivity receiver with TGA could obtain the weak returned signal from the deep target. The real-time impulse compression in FPGA can increase the scanning rate. The fiber modules can overcome the synchronization between the transmitter and receiver. However, the fiber synchronization is not convenient and reliable in some severe detection environments. The two experiments and results show that the proposed low-frequency coded GPR has good detection performance. However, it is difficult to validate the ability of detecting deeper targets due to drilling in the measured traces and the strong interferences on the measured ground.

Acknowledgments

This research work was supported by the National High Technology Research and Development Program of China (“863” Program) under Grant 2012AA121901. The authors wish to express their gratitude to the editor and the anonymous reviewers.