Published in final edited form as:

Appl Opt. 2017 May 01; 56(13): 3824–3830.

Experimental study of coherent accumulation based on sequence shifting and a genetic algorithm

Hongzhou Dong^{1,*}, Guoqiang Li², Mingwu Ao¹, Chunping Yang¹, and Yong Liu¹

¹State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Information, University of Electronic Science and Technology of China, Chengdu 610054, China

²Department of Ophthalmology and Visual Science, Department of Electrical and Computer Engineering, The Ohio State University, Columbus, Ohio 43212, USA

Abstract

Because there is a certain phase difference between the two adjacent samples of an analog-to-digital converter for a heterodyne signal, we propose to eliminate the random phases in the coherent accumulation by shifting the sampling sequences with different steps. A genetic algorithm is used to determine the shifting steps of the sequences. An experiment has been conducted to verify the effectiveness of our approach. The results prove that the approach can greatly increase the strength of the heterodyne signal compared with the accumulation with random phases. Our approach is easier to implement in comparison with existing technologies.

1. INTRODUCTION

In optical heterodyne technology, pulse coherent accumulation is a method available to realize the detection of a very weak signal [1–3]. Theoretically, the signal-to-noise ratio (SNR) may increase linearly with the number of the accumulation pulse [4]. But, this technology is effective under the premise that the echo pulses are coherent. In fact, various factors may cause the accumulation to be incoherent by attaching random phases to the pulses. In the transmitter part of a system, the random phase may be caused by the time jitter of a *Q*-switch [5]. In the receiver part, the arrival of an echo pulse is usually judged by a range gate [6]. Because of the instability of the system clock, an opening-time jitter of the range gate exists, which can generate a random phase. To realize the coherent accumulation, it is necessary to eliminate these random phases caused in the transmitter and receiver parts of a heterodyne system.

Coherent-on-receive processing (CORP) [7] can be used to eliminate the random phases caused in the transmitter of the system. Based on the fundamentals of CORP, some technologies have been proposed, such as injection phase locking [8], digital phase correction [9], and digital coherence correction [10]. In these technologies, the common feature is to “remember” the random phases by sampling the transmitter pulses. Then, taking

*Corresponding author: hzdong@uestc.edu.cn.

OCIS codes: (040.2840) Heterodyne; (030.1640) Coherence.

the sample pulse as a reference, one can eliminate the random phases by using analog or digital means.

For “remembering” the random phases, it is necessary to add extra optical paths, where the samples of the transmitter pulse are mixed with the stable local oscillator (LO) beams. Correspondingly, extra optical and electronic components are also needed, which makes the system quite complicated and results in difficulty in installation and adjustment. Because the processes of the echo pulse and the sample pulse are analogous in these technologies, there is a high requirement on the conformity, stability, and accuracy of the related electronic components. In general, such a technology is not easy to realize in practice. In addition, because the samples of transmitter pulses “remember” only the random phases caused in the transmitter, these technologies are invalid for that yielded in the receiver part, such as the random phase caused by the opening-time jitter of the range gate.

In this paper, a new approach for eliminating these random phases is presented. It is easy to realize and effective for the random phases caused in both the transmitter and receiver parts. Based on the fact that there is a certain phase difference between the two adjacent samples of analog-to-digital converter (ADC), we propose eliminating the random phases by shifting the data sequences of the accumulation pulses with different steps. The appropriate number of steps for shifting each sequence may be determined by genetic algorithm (GA). This work may be performed in a conventional microcontroller unit (MCU). Thus, the accumulation system in our approach is greatly simplified compared with that based on CORP, because there is no need to sample the transmitter pulse for “remembering” the random phases.

An experiment has been conducted to demonstrate the performance of our approach. To obtain controllable random phases, we replace the pulse detection by a continuous light detection. A certain number of sampling fragments are obtained from the continuous signal. Then, these fragments are seen as the pulse signals for the accumulation. The random phases can be attached to these fragments with random starting-time, which can be implemented by a time counter. Then, through controlling the count value of the counter, we can obtain the random phases in a desired range for different signal frequencies. This is helpful for the verification of our approach. The experimental results prove that the strength of the heterodyne signal can be improved significantly. The fact reveals that the approach is effective in eliminating the random phases to a certain extent.

2. FUNDAMENTAL OF ELIMINATING RANDOM PHASE BY SEQUENCE SHIFTING

In this section, we explain how to eliminate the random phases by only shifting the sequences. To facilitate the elaboration of our approach, we simplify the signal current of the m th pulse as the following:

$$i_m(t) = a \{ u(t) \cos[\omega_h(t - mT) + \varphi_m] \}, \quad (1)$$

where

$$u(t) = E_0 \text{rect} \left(\frac{t - mT}{T_A} \right), \quad (2)$$

where $\text{rect}(\cdot)$ is a rectangle function, T is the pulse period, T_A is the width of pulse, a is a constant related to the quantum efficiency of a detector, E_0 is constant, $\omega_h = 2\pi f_h$ is the angular frequency of heterodyne signal, φ_m is the random phase of the m th pulse. The phase term $m\omega_h T$ in Eq. (1) may be merged into φ_m , so we omit it in subsequent parts.

Suppose that the sampling frequency of ADC is p times higher than f_h . We may get the sampling time interval $t = 1/pf_h$. Thus, t is rewritten as the following:

$$t = k\Delta t + t_0 = k/pf_h + t_0, \quad (3)$$

where t_0 is initial time, k is the index number of sampling data, and $k = 1, 2, \dots$. According to Eq. (1), the k th sample of $i_m(t)$ can be given by

$$i_m(k) = u(k) \times \cos[\omega_h(k\Delta t + t_0) + \varphi_m]. \quad (4)$$

As a function of k , Fig. 1 shows the sampling sequences of the different pulses.

It is obvious that a phase difference ϕ exists between $i_m(k)$ and $i_m(k+1)$, and

$$\Delta\phi = \omega_h \Delta t = 2\pi/p. \quad (5)$$

So, there should be another phase difference $\phi = l_m \phi$ between $i_m(k)$ and $i_m(k_m)$, where $k_m = k + l_m$, l_m is an integer. Based on this characteristic, we may shift the sequences of all the echo pulses with different steps, and then add them up. Thus, set $i_{\text{shif}}(k)$ for the sum of all sequences with different shifting steps. According to Eq. (4), it may be written as

$$\begin{aligned} i_{\text{shif}}(k) &= \sum_{m=1}^N i_m(k_m) = \sum_{m=1}^N \{u(k_m) \cos[\omega_h k_m(\Delta t + t_0) + \varphi_m]\} \\ &= \sum_{m=1}^N \{u(k_m) \times \cos[\omega_h(k\Delta t + t_0) + \varphi_m + l_m \Delta\phi]\}. \end{aligned} \quad (6)$$

When the following equation is satisfied,

$$l_m = \left[\frac{2\pi - \varphi_m}{\Delta\phi} \right]_{\text{int}}, \quad (7)$$

where the symbol $[\cdot]_{\text{int}}$ represents rounding to the nearest integer, φ_m can be eliminated to a certain extent and an approximate equiphase superimposition can be realized. Because the possible range of φ_m lies in $[0, 2\pi]$, so from Eqs. (5) and (7), l_{max} can be calculated according to $l_{\text{max}} = [p]_{\text{int}}$. Then l_m should be within $[0, l_{\text{max}}]$. For example, when $l_1 = 3$, $l_2 = 0$, $l_3 = 1$, ..., $l_m = 2$, the sum of the shifted sequences is shown in Fig. 1.

3. DETERMINATION OF SHIFTING STEPS BY GA

From the above introduction, one can find that the shifting steps l_m can be determined according to Eq. (7) only when the value of φ_m is known. But it is difficult to measure the value of φ_m in practice. As mentioned in Section 1, To “remember” φ_m , the technologies based on CORP have been realized in a complicated system. Here, we introduce how to use GA to determine the appropriate shifting steps.

It is sure that the combination of all the optimal shifting steps can result in an optimal SNR because of the coherent accumulation. Based on this fact, how to determine the shifting steps can be considered as a problem of combinatorial optimization, in which the shifting steps are discrete variables and the strength of the heterodyne signal is fitness (evaluation function). GA [11–13] has been widely applied to combinatorial optimization and proved to be effective. In this paper, we use GA to search the appropriate shifting steps.

Real-coded GA is used in our method, and its procedure is shown in Fig. 2. First, we produce randomly a population P_0 consisting of q chromosomes, namely $P_0 = [C_1, C_2, \dots, C_q]$, where $C_q = [l_1, l_2, \dots, l_N]$, l_N is the real shifting steps of a certain sequence, and it is evenly distributed within the search space $[0, l_{\text{max}}]$. After calculating the fitness denoted by R_q , we select q chromosomes as the “parents.” The selection is performed according to the roulette wheel method. The probability of a selection G_q and the cumulative probability H_q for each chromosome C_q are calculated as the following:

$$G_q = R_q / \sum_{j=1}^q R_j, \quad H_q = \sum_{j=1}^q P_j. \quad (8)$$

Then, we generate a random number in the interval $[0, 1]$. If the generated number is in the interval $[0, H_1]$, the chromosome C_1 is selected. If the number is in the interval $[H_1, H_2]$, C_2 is selected, and so on. Like this, the selection is repeated until q chromosomes are selected. Then, through single-point crossover with a probability p_c and mutation with a probability p_m , where the positions of crossover and mutation are all random, the “children” are reproduced and a new generation of population P_1 is obtained for the next iteration. The iteration is repeated until the number of iterations g is equal to the presetting maximum

$g_{\max}$. Finally, the chromosome with the largest fitness denoted by R_{ad} is the output as a result of the algorithm, as shown in Fig. 2.

In GA, the fitness as an evaluation function plays an important role in the selection of chromosomes. Here, we introduce the definition of the fitness in our method. Let $F_{\text{shif}}(f)$ denote the Fourier transforms of $i_{\text{shif}}(k)$ given in Eq. (6). Then, the fitness is defined as

$$R = |F_{\text{shif}}(f_h)|. \quad (9)$$

Equation (8) can be calculated when the heterodyne frequency f_h is known. In some practical applications, f_h is unknown, but the possible range in which f_h lies can be determined. Set Δf_h as the range. We can also get the fitness by replacing $|F_{\text{shif}}(f_h)|$ with $|F_{\text{shif}}^{\max}(\Delta f_h)|$ in Eq. (9), where $|F_{\text{shif}}^{\max}(\Delta f_h)|$ is the maximum of $|F_{\text{shif}}(f_h)|$ across the range of f_h . In the subsequent experimental analyses, f_h will be assumed to be unknown.

4. EXPERIMENTAL RESEARCH

A. Experimental System

The block diagram and the photography of the experimental setup are shown in Figs. 3(a) and 3(b), respectively. In the experiment, the beams from a continuous laser with a wavelength of 633 nm are split into two parts as LO beams and signal beams. The heterodyne frequency f_h is generated by the frequency-shift difference between two acousto-optic modulators (AOMs). The operating voltage of the AOMs is 12 ~ 24 V, and its minimum frequency-shift is 1 kHz. A processing circuit having an ADC is used to sample the signal current output from an avalanche diode. The ADC (AD7821) has a 100 kHz bandwidth and maximum 1 MHz sampling rate. The total unadjusted error of the ADC is less than ± 1 LSB over the full operating temperature range. When enough data has been sampled, it is sent to a PC by RS232. Then, the coherent accumulation according to our approach is performed in the PC. The field programmable gate array (FPGA) in the circuit can receive the random count values from the PC and forms a time counter by which the starting time of the sampling fragments can be controlled. When the count value of the counter is equal to the presetting random value, the ADC with an 8-bit wide is triggered by the FPGA (EP4CE15E22I7) and start to sample the fragment. A neutral density filter in the optical path is used to decrease the signal light power, which may test the performance of our approach in the presence of a weak signal.

B. Controllable Random Phases

The purpose of this paper is to verify our approach, so some controllable random phases are necessary for the investigation. Here, “controllable” means that the random phases may be generated in a desired range. In practice, if a time jitter is within 0 ~ 1 μs , the random phases caused by the jitter should lie in 0 ~ $\pi/50$ when the signal frequency is 10 kHz. It is clear that, for this frequency, these random phases will not exert too much influence on the accumulation. But, for a signal with a frequency 1 MHz, the range of the random phases caused by the same jitter becomes 0 ~ 2π . Obviously, the effect of the random phases on the

accumulation is more severe. In the experiment, our approach will be tested with different signal frequencies, and we hope the random phases lie in $0 \sim 2\pi$ for all frequencies. So, the controllable random phases are needed.

For obtaining them, we use the sampling fragments of a continuous heterodyne signal to replace the accumulation pulses. The random phases may be attached to these fragments by letting their starting-time be random, which can be realized by a time counter controlling the delay between the adjacent starting time. Thus, a random delay will result in a random phase, as illustrated in Fig. 4. For example, when the clock frequency of the counter is 50 MHz and the heterodyne frequency $f_h = 1$ kHz, we may obtain the random phases lying in $0 \sim 2\pi$ through choosing randomly the count values in the range $0 \sim 5 \times 10^4$. For $f_h = 20$ kHz, the values should lie in the range $0 \sim 2.5 \times 10^3$. Like this, whatever the heterodyne frequency is, we can generate the random phases in a desired range only through changing the range of these count values. In our experiment, a MATLAB tool is used to generate these random count values. Then, they are sent to the FPGA by RS232 and saved in its RAM for the calling.

C. Several Considerations of Sequence Shifting

In the data processing, all sequences are shifted to the right, and these empty positions are filled by zeros, as illustrated in Fig. 5. The possible maximum of the shifting steps depends on related frequency parameters. For example, when $f_h = 1$ kHz and the sampling frequency is 200 kHz, there are 200 sampling points in a period of the signal. Then, a sequence shift of 200 steps can cause a phase shift of 2π . Thus, when the phase shifts are expected to be within $0 \sim \pi$, we may set $I_{\max} = 100$ in the GA.

When the heterodyne frequency is unknown, we may estimate $I_{\max}$ according to the possible range in which f_h lies. In this situation, the value of $I_{\max}$ should depend on the possible lowest frequency. For example, if the possible range is 5–50 kHz and the sampling frequency is still 200 kHz, there should be $I_{\max} = 20$, which may ensure that the smallest range of the phase shifts is $0 \sim \pi$ for all possible frequencies.

D. Experimental Results

In the experiment, the heterodyne frequency and sampling frequency are 1 kHz and 200 kHz, respectively. The random phases are generated in $0 \sim 2\pi$. Forty sampling fragments are obtained for the accumulation. Among them, three adjacent fragments with 1000 sampling points are shown in Fig. 6, where the amplitude strength is described by the quantization value of ADC. From the figure, we can see that the random phases have been attached to these fragments.

It could be understood that, if no random phases exist, the accumulation amplitude should be 40 times larger than that of the single fragment. In other words, the quantization value of the accumulation amplitude should be nearly 4000, because the amplitude of the single fragment is nearly 100, as shown in Fig. 6. Figure 7 shows related experimental results, where the heterodyne frequency f_h and sampling frequency are 1 kHz and 200 kHz, respectively. The numbers of the accumulation fragments and the sampling points are 40 and 1000,

respectively. In the GA, the number of iterations $g_m = 488$, the number of chromosomes in the population $q = 32$, the crossover probability $p_c = 0.6$, the mutation probability $p_m = 0.1$.

In Fig. 7(a), where the accumulation result with random phases is given, the value of the accumulation amplitude is nearly 500. The result is equivalent to the equiphase superposition of only five fragments. This indicates that the performance of the accumulation is degraded severely by these random phases. Using the same 40 fragments, the accumulation result yielded by our approach is given in Fig. 7(b), where the value of the accumulation amplitude is nearly 3000. It is clear that there is a notable improvement of the signal strength when our approach works and the spectral amplitude at the heterodyne frequency is enlarged by 5.1 times, as shown in Fig. 7(c), where r denotes the ratio of the two amplitudes. It can also be noticed that, in Fig. 7(b), there is a waveform aberration in the first period of the accumulation result. Because these empty positions are filled by zeros when these fragments are shifted to the right and the shifting steps are different for different fragments, it is reasonable that the aberration appears as illustrated in Fig. 5. In general, the above results demonstrate that the combination of sequence shifting and GA is effective to eliminate these random phases.

For examining further the performance of our approach, we decrease the signal light power by a neutral density filter having 10% transmission. The related results are shown in Fig. 8. Due to the power attenuation, the heterodyne signal is very weak when the accumulation is performed with the random phases, as shown in Fig. 8(a). Yet, in Fig. 8(b), the temporal profile of the heterodyne signal yielded by our approach is still apparent. From the spectral amplitudes in Fig. 8(c), one can see that the heterodyne frequency with random phases is difficult to determine. But, in our approach, the frequency can be distinguished easily from these noise frequencies because the amplitude at the frequency is enlarged by nearly 10 times.

We keep the same neutral density filter in the signal optical path and increase the heterodyne frequency to 20 kHz. The related results are shown in Fig. 9, where the sampling frequency is still 200 kHz and the random phases are in $0 \sim 2\pi$. Obviously, our approach works well in this case. Figure 9 proves that the approach is effective in a wide frequency range.

The number of the iterations in GA is an important factor for our approach. Based on the sampling data in Fig. 8, the values of r with increasing g_m are shown in Fig. 10. There is an oscillating increase of r . This is reasonable, because the appearance probability of a better chromosome is larger when g_m increases. In Fig. 10, we can see that only several tens of iterations can increase notably the strength of the heterodyne signal, which demonstrates that GA is a quite powerful search tool.

Certainly, a larger g_m will result in more processing time. For this reason, we may use a parallel genetic algorithm (PGA) [14,15] to reduce the time consumed in the iteration. GA has a natural parallelism. According to the complexity of the algorithm, a variety of parallel designs can be realized in its structure. Then, the algorithm may operate in a multithreading model. Like this, more threads will consume less time. Because the main purpose of this paper is to demonstrate the effectiveness of our approach, more details about the application

of PGA in the approach are not discussed in this paper. This study will be reported in a subsequent paper.

The performance reproducibility of GA in our approach is also an important concern. Based on the sampling data in Fig. 8, 50 values of r obtained from GA are shown in Fig. 11. Because GA is a random search tool, we set $g_m = 300$ in Fig. 11, which is different from $g_m = 488$ in Figs. 7–9. Such change is helpful for examining the performance of GA with different iteration numbers. One can find that the fluctuation of r is not quite dramatic, and no severe deterioration appears. The fact fully demonstrates the stable performance of our approach.

5. CONCLUSION AND DISCUSSION

We have proposed to eliminate the random phases in coherent accumulation using a combination of sequence shifting and GA. The experimental results prove that our approach is effective in increasing the strength of the heterodyne signal. Without the need of “remembering” the random phases, our approach is easier to realize compared with existing technologies, and it is valid for all random phases caused in the transmitter and receiver parts. To verify the approach, the controllable random phases are necessary, so the experiment was conducted based on the data of a continuous heterodyne signal. However, from the fundamentals of our approach, one can see that the approach is applicable to pulse detection.

The reproducibility and effectiveness of our approach have been verified in the experiment. So, our approach has high application value. But, it can be found that the possible limitation of the approach is mainly caused by the processing time consumed in GA. In fact, in some application occasions not requiring real-time process, the processing time is not a concern. With regard to the real-time process, we have proved that a small number of the iterations in GA may also increase notably the signal strength. On the other hand, PGA is a powerful means to reduce the time, as mentioned in Section 4. These plans will be carried out in later research. In general, the excellent performance of our approach has been demonstrated, and it is possible that the approach may become a new means to realize the coherent accumulation.

Acknowledgments

Funding. National Natural Science Foundation of China (NSFC) (61308109); China Scholarship Council (CSC) (201606075019); National Institutes of Health (NIH) (R21 EB008857, R21GM103439, R01 EY020641).

G. Li was supported in part by the National Institutes of Health, U.S.

References

1. Zhu X, Liu J, Bi D. Development of all-solid coherent Doppler wind lidar. *Chin Opt Lett*. 2012; 10:012801.
2. Frehlich RG. Velocity error for coherent Doppler lidar with pulse accumulation. *J Atmos Ocean Technol*. 2004; 21:905–920.

3. Yunfei, G., Yunlong, Z., Anke, X. Coherent integration weak target detection algorithm based on short time sliding windows. Proceedings of the 10th Congress on Intelligent Control and Automation; 2012. p. 4097-4101.
4. Wang, C., Chen, D. Laser Radar Systems Design. Harbin Institute of Technology; 2014.
5. Bassri FE, Dautre F, Mothe N. Hybrid Q-switched broadband laser with low timing jitter. Opt Express. 2012; 20:1202–1212. [PubMed: 22274464]
6. Wu J, Hong GL, Zhang HY. A coherent range and range-rate detection ladar with large ranging dynamic range and high-repetition-rate (II): signal modulation. Int J Infrared Millim Waves. 2015; 34:321–332.
7. Donahue, TH., Hammers, DE. Digital compensator for transmitter instability. US patent. 4,040,055. Jul 15. 1974
8. Jordan GB. Comparison of two major classes of coherent pulsed radar systems. IEEE Trans Aerosp Electron Syst AES-11. 1975:363–371.
9. Reedy, EK., Efyrd, RB., Yoder, MN. Impact of extremely high speed logic technology on radar performance. Proceedings of the IEEE International Radar Conference; London, UK: IEE Electronics Division; 1982. p. 82-86.
10. Trapp, RL. Improved coherent-on-receive radar processing with dynamic transversal filters Radar-82. Radar-82, Proceedings of the International Conference; 1982. p. 505-508.
11. Matsui F, Goriki S, Shimizu Y, Tomizawa H, Kawato S, Kobayashi T. Genetic-algorithm-based method to optimize spatial profile utilizing characteristics of electrostatic actuator deformable mirror. Opt Rev. 2008; 15:156–161.
12. Liu TD, Xu LY, Shao GF, Tu NN, Tao JP. Structural optimization of Pt-Pd-Rh trimetallic nanoparticles using improved genetic algorithm. J Alloys Compd. 2016; 663:466–473.
13. Ardjmand E, Willian II, Weckman GR, Bajgiran OS, Aminipour B. Applying genetic algorithm to a new bi-objective stochastic model for transportation, location, and allocation of hazardous materials. Expert Syst Appl. 2016; 51:49–58.
14. Gabriel, L., Enrique, A. Parallel Genetic Algorithms. Springer; 2011.
15. Qi RZ, Wang ZJ, Li SY. A parallel genetic algorithm based on spark for pairwise test suite generation. J Comput Sci Tech. 2016; 31:417–427.

Fig. 1.
Schematic of eliminating random phases by shifting sequences.

Fig. 2.
GA procedure for determining the shifting steps.

Fig. 3.
 (a) Block diagram of the experiment setup; (b) photograph of the experimental system.

Fig. 4.
Schematic of the generation of the random phases.

Fig. 5.
Schematic diagram of the sequence shifting.

Fig. 6.
Three adjacent sampling fragments with random phases.

Fig. 7.

Related accumulation results in the experiment. (a) shows the accumulation result with the random phases. (b) shows the accumulation result yielded by our approach. (c) gives the spectral amplitudes of the two results. In (c), both amplitudes are normalized by the value at f_h yielded by our approach.

Fig. 8.

Related accumulation results when the signal light power is decreased by a neutral density filter. (a)–(c) have the same meaning as that in Fig. 7. Other parameters are the same as those in Fig. 7.

Fig. 9.

Related accumulation results when the heterodyne frequency is 20 kHz. The optical power of signal beams is weakened by the same neutral density filter in Fig. 8. (a)–(c) have the same meaning as that in Fig. 7. Other parameters are the same as those in Fig. 7.

Fig. 10. Variation of r with increasing g_m . The results are obtained based on these sampling data in Fig. 8 and g_m lies in the range 20 ~ 745. Other parameters are the same as those in Fig. 7.

Fig. 11.
Variation of r for 50 processes. These parameters of GA are the same as those in Fig. 7.